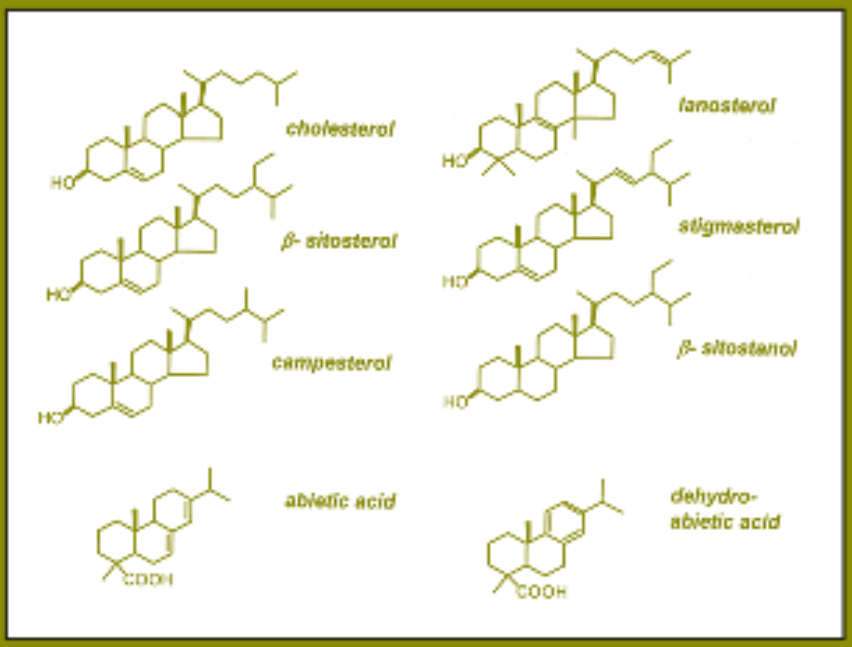
surfactant science series

volume 114

NOVEL SURFACTANTS

Preparation, Applications, and Biodegradability

Second Edition, Revised and Expanded



edited by

Krister Holmberg

NOVEL SURFACTANTS

Preparation, Applications, and Biodegradability

Second Edition, Revised and Expanded

edited by
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MARCEL DEKKER, INC. NEW YORK • BASEL

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress.

ISBN: 0-8247-4300-8

This book is printed on acid-free paper.

Headquarters
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tel: 212-696-9000; fax: 212-685-4540

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tel: 800-228-1160; fax: 845-796-1772

Eastern Hemisphere Distribution
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http://www.dekker.com

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

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Preface

The first edition of *Novel Surfactants*, published in 1998, contained 11 chapters, written by leading experts in surfactants. Each chapter covered one class of surfactant and was written as an overview of the respective area with emphasis on recent development.

In this new edition the majority of the chapters from the first edition have been updated. Many topics have been expanded to include recent advances and many recent references have been included. The substantial amount of new material included in the second edition is indicative of the rapid development currently taking place in the areas chosen as topics for the first edition.

Besides updating of the original chapters, the second edition contains six new chapters. Five of these are in some way related to the concept of *natural surfactants*. Two chapters deal with surfactant types based on sugar as a hydrophilic building block, two describe surfactant classes based on fatty acids as a hydrophobic building block, and one covers surfactants produced by microorganisms. Together with chapters from the previous edition on glucamides, alkyl polyglycosides, amino acid–based surfactants, and sterol-based surfactants, as well as a chapter on surfactants produced by enzymes, 10 of the 17 chapters relate to surfactants based on *natural building blocks* or produced by *biotechnological methods*. This emphasis on *green surfactants* is in accordance with the present research focus in the surfactant field. Environmental aspects are the single most important driving force for surfactant development today, and there is a clear trend to move toward renewable raw materials as surfactant building blocks. The new edition also

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contains a chapter on Polymeric surfactants, which is a topic of growing importance.

The authors of the previous edition were from both academia and industry, six from the former category and five from the latter. Of the six new chapter authors, three are from academia and three from industry. All six are well-known experts in their fields. The relatively large percentage of industrial contributions ensures that the surfactant types chosen for reviews are of commercial relevance. As in the first edition of the book, the intention has been to select surfactants that are not yet well established on the market but are not just research curiosities. Considering the amount of ongoing research in the surfactants field, it is reasonable to assume that many of the product classes described in this edition will be in large-scale use within a decade or two.

I thank the contributors, and in particular the new authors, for their time and effort. I hope the readers will find the book useful.

Krister Holmberg

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1

N-Alkanoyl-*N*-Alkyl-1-Glycamines

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I. INTRODUCTION

Commercial interest in polyol surfactants derived from glucose exists for several reasons: (1) glucose is an inexpensive agriculture-based (and therefore renewable) raw material; (2) surfactants derived from glucose have a "green" environmental image (and are, in fact, readily degraded in the environment [1]), and (3) their polyfunctional (yet readily accessible) molecular structures offer the possibility of distinctive performance and properties relative to presently used surfactants [2]. Short-chain polyol surfactants readily solubilize membrane polar lipids, and facilitate the isolation and study of membrane-bound proteins [3,4].

The nomenclature for the compounds of interest has become extraordinarily complex. These surfactants are best regarded as derivatives of glucitol (common name sorbitol), which is a saturated hexahydroxypolyol (hexaol) that is formed by reducing the aldehyde group of glucose to the alcohol oxidation level. They have been termed *acylamido-D-glucitols* [5]. They are often termed 'glucose amide (GA) surfactants' [6], but this name is structurally misleading. Glucose (a polyhydroxylaldehyde) does not form amides. However, two carboxylic acid derivatives of glucose exist that *do*. These are gluconic acid (a pentahydroxycarboxylic acid formed by oxidation of the 1-carbon) and glucuronic acid (a tetrahydroxyaldehyde carboxylic acid formed by oxidation of the 6-carbon) [7]. Surfactant analogs of gluconic acids (which contain an *N*-alkyl long chain) have been prepared, but the work has not been reported [8]. Key molecular structures are shown in Fig. 1.

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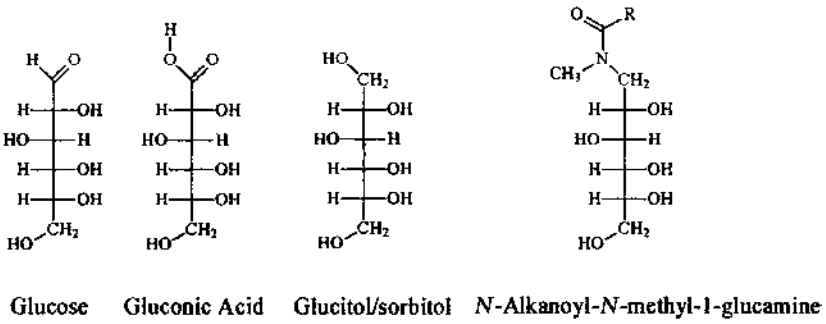

FIG. 1 Molecular structures (Fischer projections) of glucose, gluconic acid, glucitol (sorbitol), and *N*-alkanoyl-*N*-methyl-1-glucamines.

Rigorous nomenclature for the C_{12} homolog having an *N*-methyl substituent, a key member of the class, is N-*dodecanoyl*-N-*methyl-1-amino-1-deoxy*-D-*glucitol* [5]. A simpler and generally acceptable name is N-*dodecanoyl*-N-*methyl-1-glucamine* [5]. The generic name *alkanoyl glycamines* will be used for the class—it being understood that the focus is on the 1-amino regioisomer of the sugar moiety. The acronym "C_{12}MG" will here be used for the above-mentioned compound. An acronym widely used in the literature is "MEGA-*n*," where *n* is the chain length (including the carbonyl carbon) of the akanoyl group [3,4]. The above compound is "MEGA-12" using this nomenclature. The structure of C_{12}MG (or MEGA-12) is shown to the right in Fig. 1 [R is the *n*-undecyl ($C_{11}H_{23}$) group]. Its molecular formula is $C_{19}H_{39}NO_6$, and its molecular weight is 377.52.

How chain length is defined is important both with respect to communicating the correct structure and during analyses of physical data. Chain length in aliphatic surfactants is usually defined by the number of aliphatic carbons in the chain, as in the C_{12} sodium dodecyl sulfate. This is not true, however, of those that are structurally related to fatty acids. The chain length of soaps, for example, is usually defined so as to include the carbonyl carbon, e.g., sodium laurate is regarded as a C_{12} surfactant (although it has a C_{11} alkyl group). Because this convention is so firmly rooted in practice, it will be followed here. The dodecanoyl compound will be termed a C_{12} homolog, but treated as a C_{11} compound during the analysis of log(cmc) data vs. chain length.

II. SYNTHESIS AND ANALYSIS

A. Synthetic Methods

C_{12}MG can be prepared in high yield from glucose, methylamine, hydrogen, and methyldodecanoate via the following two-pot reaction scheme (Fig. 2)

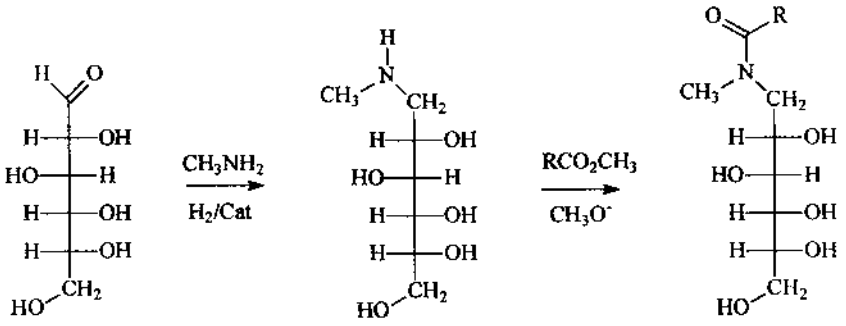

FIG. 2 The synthetic reactions for *N*-alkanoyl-*N*-methyl-1-glucamines.

[9,10]. The stereochemical configuation at the secondary alcohol carbons in glucose is presumably retained during this synthesis. The reaction product has been shown to be optically active from the fact that solutions of C_{12}MG display circular dichroism (CD) with the peak near the frequency of the UV absorption band of the amide group [11]. Few studies of optically active surfactant solutions by CD have been reported.

Both laboratory and commercial methods for the preparation of C_{12}MG have been developed, and other analogs have been prepared on a laboratory scale. The first reaction is, in effect, the reductive alkylation of methylamine by an aldehyde (glucose)—a long-known and excellent method for forming C-N bonds. Glucose syrups (obtained from corn starch) may be converted in high yield to *N*-methylglucamine by hydrogenation in the presence of methylamine using a Raney nickel catalyst. The second reaction is acylation of *N*-methylglucamine (a secondary amino polyol) by a fatty acid methyl ester. Methanol is a by-product of this reaction.

An interesting aspect of the acylation reaction is the fact that *it is catalyzed by added base*. Since the reaction of monofunctional secondary amines with methyl esters is *not* base catalyzed, this suggests that the kinetically favored initial reaction product is an aminotetrahydroxy ester (formed by base-catalyzed acylation of a hydroxyl group), which rapidly rearranges to the observed polyolamide product. That the final product is a pentahydroxyamide (not an amino ester) was proven beyond doubt by spectroscopic data (NMR and vibrational spectroscopy). This structure was independently confirmed by single-crystal X-ray studies (see later). Details of the synthetic chemistry [12] and the X-ray and calorimetric studies [13] are still to be published.

Analogs of C_{12}MG have been prepared from other starting materials using similar conditions. For example, the *N*-ethyl analog results from substituting

ethylamine for methylamine in the synthesis. Alkanoyl homologs of C_{12}MG, and also the *N*-ethyl, *N*-propyl, *N*-butyl, *N*-hexyl, *N*-2-methoxyethyl, *N*-3-methoxypropyl, and *N*-3-ethoxypropyl analogs were prepared in this way. As the chain length of the alkyl substituent on the amine is lengthened the physical chemistry of the amine–water system is changed. This alters details of the process but not the basic chemistry of the reaction. A commercial process has been developed only for the *N*-methyl analog, using various commercially available fatty acid methyl ester mixtures.

Analogs which differ in the *N*-polyol moiety may be prepared by substituting another reducing sugar for glucose. Polyol analogs were prepared from glycerose (C_3), xylose (C_5), mannose (2-epiglucose, C_6), galactose (4-epiglucose), and maltose [a reducing diglucoside, 4-(1-α-glucosyl) + glucose]. The structures of these sugars are shown in Fig. 3 in the Fischer projection (except for the maltose analog) so as to portray stereochemical configurations. The structures of the derived surfactants follow from applying the operations in the synthetic equations (Fig. 2) to the selected sugar, amine, and fatty acid methyl ester.

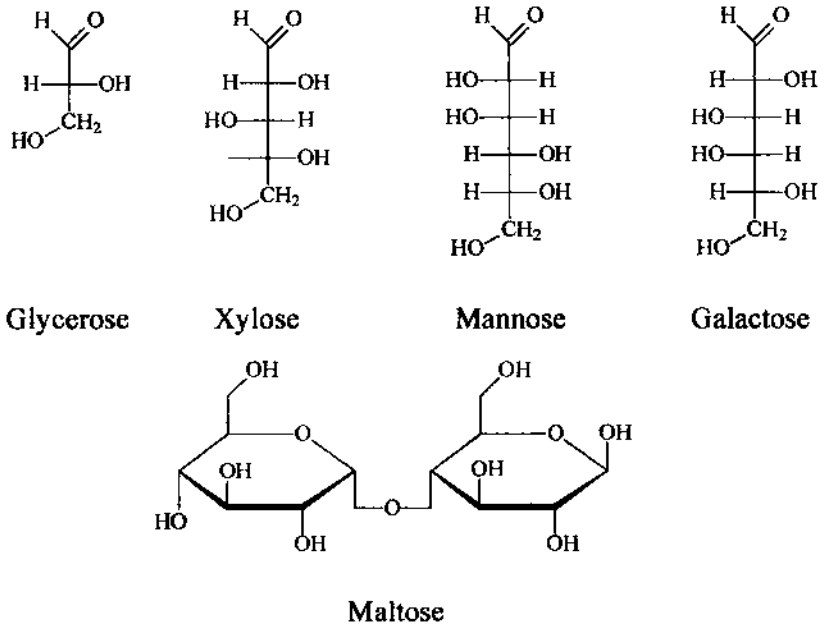

FIG. 3 Sugars used to synthesize analogs of C_{12}MG.

B. Analytical and Physical Study Methods

The pentakis(trimethylsilyl) derivative of C_{12}MG can be analyzed by gas chromatography. Complete derivatization of about 10-mg samples was cleanly accomplished by reacting 1 mL 3:1:1:9 (v:v:v:v) hexamethyldisilazane-trimethylchlorosilane-*N,O*-bis(trimethylsilyl)acetamide-pyridine mixtures with the sample at 80°C for 40 min. Chromatography was performed using a Hewlett-Packard 5890 Series II instrument having a 30-m DB-1HT nonpolar column, and FID detector (He carrier gas). The instrument was programmed from 80°C to 220°C at 10°C/min, from 220°C to 400°C at 5°C/min, then held at 400°C for 5 min. The assay of a laboratory sample prepared using the above synthetic method and recrystallized from acetone was 99.5% C_{12}MG. Methyllaurate (0.07%), the C_{10} homolog (0.13%), the C_{14} homolog (0.06%), and a dilong-chain ester amide of unknown structure (0.23%) were also detected. *N*-Methylglucamine was not detected. All of the various analogs that were prepared (including the maltose analog) could be assayed using this method.

Melting points and other phase transitions were determined using a Hoover capillary melting point apparatus with crossed polars in front of and behind the capillary. This both facilitated the determination of ordinary melting points, and permitted the determination of transitions from crystal to lamellar liquid crystal (D) phase, or from the D phase to an L (liquid) phase. The latter transition was taken as the "melting point" during the analysis of ΔT (see later).

Krafft boundary temperatures at 1% composition were determined visually, using stirred samples immersed in a bath whose temperature was varied smoothly while the sample was observed between crossed polars. These temperatures will be termed "Krafft points" [14]. Krafft points were alternatively determined in the binary C_{12}MG–water system from DSC thermograms; see the Smirnova publications for details [15,16]. In the work at St. Petersburg on ternary systems, the effect of heating rate was explored and a rate of 0.3°C/min selected as giving data most likely to reflect equilibrium data. In all studies data were collected only in the rising temperature direction, since equilibration is relatively fast in this direction and extremely slow in the cooling direction.

Critical micelle concentrations were determined at 25°C from the intersection of lines in surface tension–log (surfactant concentration) data plots. Surface tensions were measured with a platinum duNouy ring using an automated apparatus. These curves did not show minima, which indicates that impurities more surface active than the surfactant were absent.

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III. THE C_{12}MG SYSTEM: PHASE EQUILIBRIA AND PHASE REACTION KINETICS

To fully characterize the physical science of any system requires knowledge of

1. The thermodynamic states of the system (the equilibrium phase diagram)
2. The kinetic aspects of phase equilibration (rates and mechanisms)
3. The solution chemistry of the liquid phase, and
4. The colloid science of the system

Furthermore, the behavior of the two relevant unary systems (surfactant and water) must be known before the physical science of binary systems can be fully understood [17]. C_{12}MG was studied in depth following these principles, so we begin with a description of the equilibrium and kinetic aspects of the phase behavior of the unary (dry) C_{12}MG system. Then these same aspects of the binary C_{12}MG–water system will be considered. The binary phase diagram that resulted from these studies has been published [18].

A. Crystal Phases

The phase behavior of C_{12}MG was investigated using powder and single-crystal X-ray studies, programmed temperature powder X-ray scans, and calorimetry. C_{12}MG is a highly crystalline compound that displays complex polymorphism, and *the phase structures of the crystals that it forms deviate sharply from the usual crystal structures of surfactants*. Three polymorphic crystals, designated X1, X2, and X3, were prepared, and single-crystal structures determined for X1 and X2. X1 is the crystal normally isolated from synthesis of the compound, during which it is recrystallized from acetone. Single crystals of X1 suitable for structure determination were formed by evaporative crystallization from acetonitrile. Single crystals of X2 were formed by evaporative crystallization from 1:1 methanol–acetonitrile mixtures.

X3 is formed by cooling the dry lamellar liquid crystal state that exists above 94°C (see later); this polymorph was discovered during the cooling cycle of programmed temperature powder X-ray studies. X3 has been characterized only by powder diffraction data, which serve to demonstrate that its crystal structure differs from that of both X1 and X2 but provides no information as to the actual structure. X3 plays a major role in the nonequilibrium swelling behavior of C_{12}MG (see later), because the process used during the loading of DIT cells closely simulates the path by which X3 is formed. ("DIT" stands for "diffusive interfacial transport," which is a phase studies method based on the creation and analysis in situ of phases formed by isothermal swelling [19].) Powder X-ray

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diffraction data were reported earlier [2]. Figure 4 displays the powder data in stick form.

A crystal monohydrate has been prepared by solvent evaporation from methanol–water solutions, but no information about this crystal (other than its composition) *was* obtained [13]. Evidence *was* obtained (see below) that the crystal phase in equilibrium with the liquid solution at room temperature is the dry crystal X1; this monohydrate is metastable with respect to the C_{12}GA–water system.

The crystal phase structure of X1 is shown in Fig. 5. X1 has a bilayer structure, but *both the lipophilic chains and the head groups in adjacent monolayers are interdigitated with one another*. In the bilayer structure of most surfactant crystals the opposing molecules in the two bilayers lie

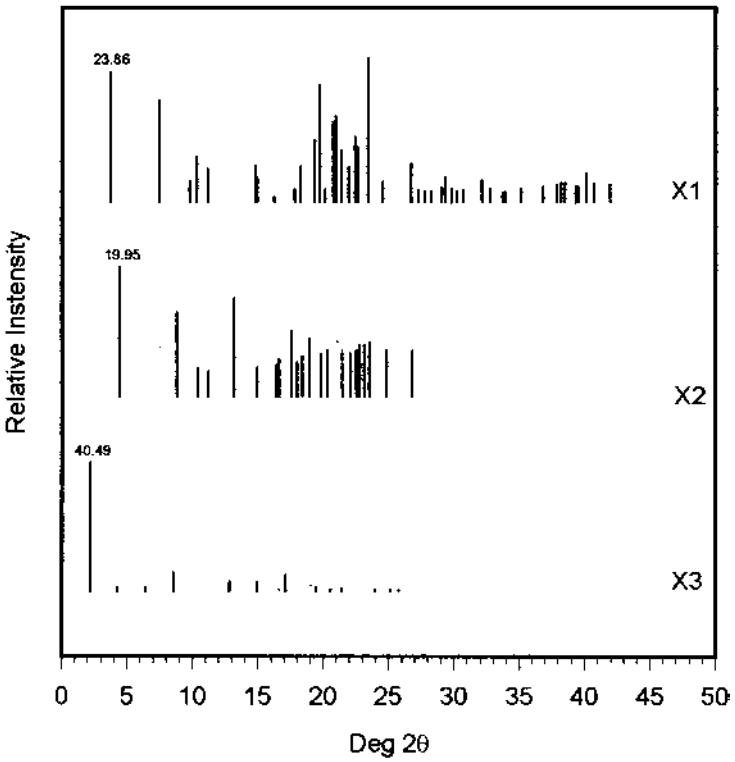

FIG. 4 X-ray powder data (in stick form) of the X1, X2, and X3 polymorphs of C_{12}MG. The intensity of the long spacing (strongest line) has been reduced by a factor of 5 (relative to that of other lines) in this figure. The numerical value of the long spacing (in Å) is inserted above this line.

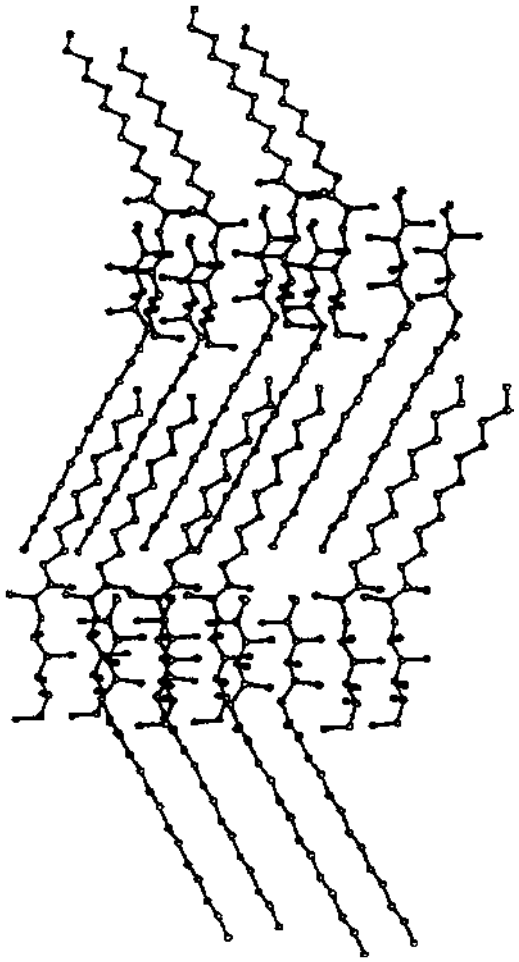

FIG. 5 The X1 crystal structure, showing overlapping (interdigitation) of both the hydrophilic and the lipophilic groups. (Reproduced with permission from Academic Press.)

end-to-end, so that planes of methyl and hydrophilic groups exist. In phase X1 of C_{12}MG, the lipophilic groups of opposing C_{12}MG molecules lie side-by-side. The head groups are also interdigitated, so that the head groups of neighboring molecules within this layer also lie side-by-side (but oriented in opposite directions). This arrangement facilitates extensive lateral hydrogen bonding between adjacent molecules.

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Polymorph X2 (Fig. 6) has an even more unusual crystal structure. The repeating structural element of this crystal is the *monolayer*, which is extremely rare. A head-to-tail arrangement between molecules in adjacent monolayers exists in this crystal. Moreover, the conformational structure of the hydrophilic group in X2 differs from that in X1. In X1 all the C-C bonds of the glucitol moiety have a trans conformation and extended structure, while in X2 a gauche bond exists at the C-2/C-3 bond so that this hydrophilic group is bent. X2 is unconventional in nearly every imaginable aspect.

X1- and X2-like crystal structures had been discovered earlier in several (mostly shorter) homologs of C_{12}MG [20–23], and the existence of thermotropic phases (see below) had been recognized [22]. The X1 type was found in

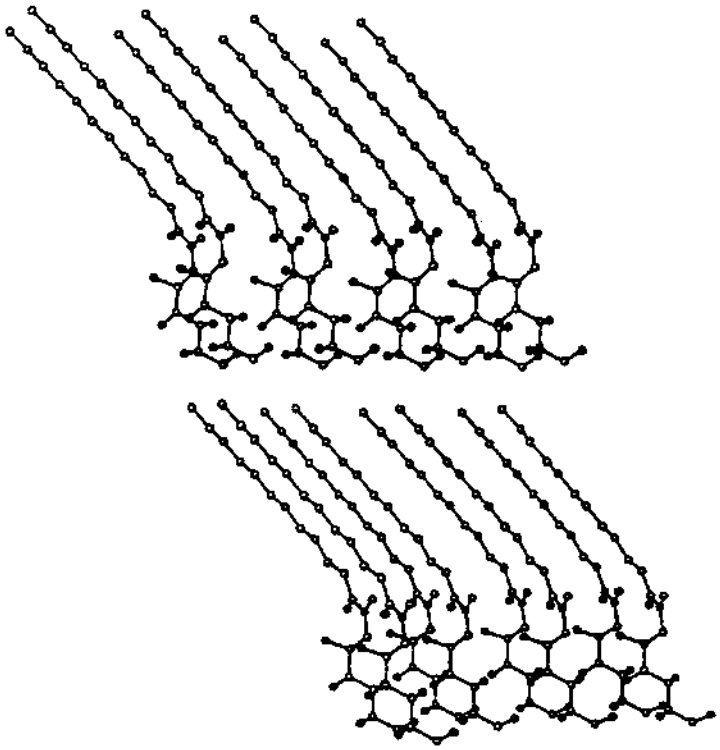

FIG. 6 The X2 crystal structure, showing the unusual monolayer arrangement within this crystal. The density of X2 (calculated from the crystal structure) is significantly lower than that of X1. (Reproduced with permission from Academic Press.)

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even-chain homologs and X2 in odd, but the thermodynamic relationship between them had not been established. It must also be noted that the "evenness" of a lipophilic group is arbitrary, as it depends on whether or not the carbonyl carbon is counted. The dodecanoyl homolog (C_{12}MG), for example, actually possess an (undecyl or C_{11}) lipophilic group, which has an odd number of carbons.

B. High-Temperature Phases of C_{12}MG

X1 is transformed reversibly at 94°C into a thermotropic (dry) lamellar liquid crystal (D) phase. The identification of this phase was based entirely on X-ray data, as it possessed an unrecognizable optical texture [24]. On further heating in a sealed tube in vacuum [25], the D phase "melts" at about 126°C to an isotropic liquid. This phase transition is *not* reversible; it is accompanied by slow chemical decomposition. Decomposition was suggested by the fact that the transition temperature decreased on repetition using the same sample. It was confirmed by the analytical detection (using thin-layer chromatography) of decomposition products. Decomposition appears to have occurred by the cyclic elimination of water from two hydroxyl groups, to form a five- or six-membered cyclic ether.

Thermal studies of X1 were also performed on samples held between an open slide and coverslip, using a Mettler hot stage on a polarized light microscope. Under these conditions the sample is exposed to both oxygen and water, and the results were perturbed accordingly. The transition to isotropic liquid was again observed at about 126°C, but on cooling and repetition the temperature of this transition was *increased* to 127.5°C. Additional repetitions gave progressively higher boundary temperatures. Furthermore the texture of the sample just below the liquidus temperature (after being kept at these temperatures for an hour or so) was transformed from the initial complex unrecognizable texture (noted above) into the familiar oily streak texture [24]. This texture changed, on cooling, into the mosaic texture [24]. Both the increase in liquidus temperature, and the change into familiar optical textures, can be understood on the basis that the sample had adsorbed atmospheric water. Water would be expected to facilitate the change in texture to classical forms by reducing the viscosity of the phase.

Analogous phase behavior has been observed at the liquidus boundary of the DOACS–water system. (DOACS is dioctadecylammonium cumenesulfonate, a thermally stable surfactant that also exists as a thermotropic lamellar liquid crystal phase at temperatures above its crystal phase.) A phase study of this system revealed that the temperature of this liquidus also increases as water is added [26]. Water would be expected to stabilize C_{12}MG, provided no hydrolytic cleavage reactions (such as amide hydrolysis) occur [27]. No

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evidence for amide hydrolysis was found (using thin-layer chromatographic analysis) in the samples recovered from these experiments.

C. Kinetics of C_{12}MG Phase Reactions

Persuasive evidence was obtained that X1 is the equilibrium crystal phase of C_{12}MG between room temperature and 94°C. X2 is a metastable crystal that is long lived. X2 remains unchanged at room temperature for at least a year and a half, but at elevated temperatures is transformed irreversibly into X1 [as shown by differential scanning cabrimetry (DSC) studies]. These studies of X2 revealed a sharp endotherm at 64°C, followed by a broad exotherm, return to baseline at 80°C, and finally at 94°C the same endotherm that is observed in the DSC of X1. If the sample is examined by X-ray after passing the first endotherm and exotherm, but before reaching 94°C, it is found to be X1. The conclusion that X2 is metastable relative to X1 is independently supported by

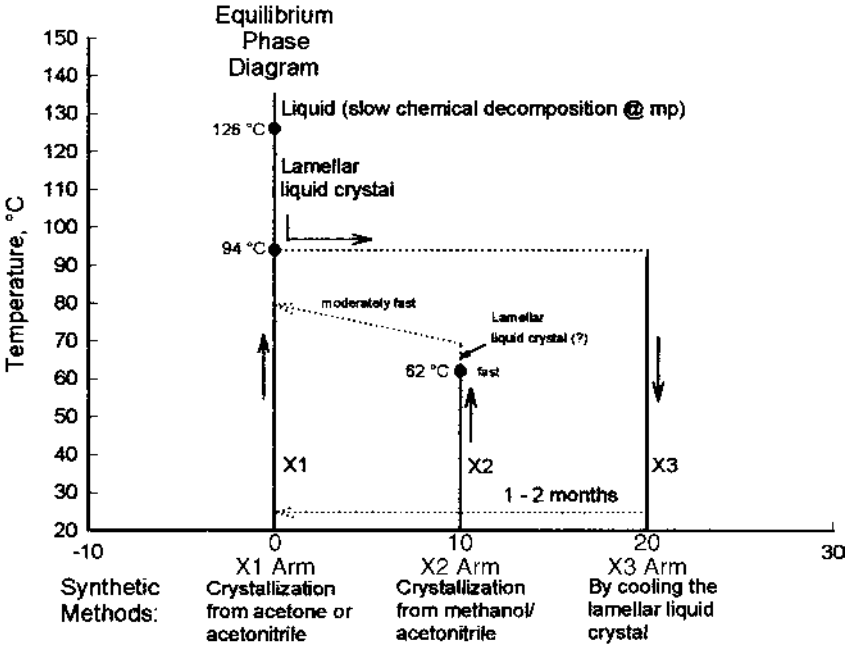

FIG. 7 The unary C_{12}MG phase diagram manifold. The temperature scale is to the left (outside the diagram). Each arm corresponds to a particular crystal structure; the left arm is the equilibrium diagram. The transformations that occur among polymorphs are indicated by dashed arrows.

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the fact that the density of the X1 crystal (from single-crystal data) is significantly greater than is that of the X2 crystal [13].

X3 is also metastable but is far less stable kinetically than is X2. X3 is transformed into X1 (*not* X2) simply on standing at room temperature for a period of 1–2 months (relative humidity about 35%). This transformation occurs much more rapidly if X3 is contacted with liquid water (as in a DIT cell). During DIT studies, X3 initially swells to form metastable liquid and liquid crystal phases (see later), but the growth of X1 crystals from the X3/lamellar liquid crystal interface was observed. The X3 → X1 transformation is also accelerated by exposing the X3 phase to an atmosphere of 90% relative humidity (RH); under these conditions the reaction is complete within about 2 weeks. Whether by reaction with liquid water or with water vapor, the path of the X3 → X1 transformation probably involves dissolution of X3 (to form a fluid liquid or liquid crystal phase), followed by the nucleation and growth of X1 crystals. These data suggest that the free energies of these three crystal phases decrease in the order X3 > X2 > X1.

The equilibrium and nonequilibrium aspects of the phase behavior of C_{12}MG are displayed in the phase manifold in Fig. 7. This manifold graphically depicts both equilibrium and nonequilibrium phase behavior in a unary system. It has several arms, each corresponding to a particular phase structure. The equilibrium phase behavior is depicted to the left, which shows the two phase transformations of X1 that occur on heating. The behavior of X2 and X3 is shown in their respective arms. Path directions (heating or cooling) are very important to phase reaction kinetics and are indicated by arrowheads.

IV. THE C_{12}MG–WATER SYSTEM: PHASE EQUILIBRIA AND PHASE REACTION KINETICS

The aqueous phase behavior of the C_{12}MG–water system was investigated using isothermal isopiestic data, the isothermal (DIT) swelling method, isoplethal DSC, and visual observations in polarized light along isoplethal paths.

A. Isopiestic Data

Isopiestic studies involve equilibration of the water in a small sample with that in a large reference mixture of known water activity, via transport through the vapor phase. Because of its poor solubility at room temperature, the activity of water in saturated solutions of C_{12}MG will be very close to 1; therefore, the reference mixture selected was pure water. Elemental analytical data established that the starting sample was dry. Isopiestic

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equilibration was approached from both the uptake of water vapor by the dry crystal, and the loss of water from a mixture of the crystal with excess water. The conclusions from these two studies were the same: the C_{12}MG crystal phase in equilibrium with its saturated aqueous solution at room temperature is the dry crystal.

The evidence (cited above) that a crystal hydrate exists was unexpected but does not contradict the isopiestic result. The hydrate precipitated from a methanol–water mixture in which C_{12}MG would have been far more soluble than it is in water. The crystal hydrate could easily be the equilibrium crystal phase in such ternary solvent systems and the dry crystal the equilibrium phase in the binary aqueous system. This same principle applies to other metastable phases, such as the polymorph X2 found in this C_{12}MG system. X2 separated from a "good" solvent mixture (acetonitrile–methanol), while X1 separated from a relatively "poor" solvent (acetonitrile). The use of good solvents to form single crystals is tempting to crystallographers because their use promotes the formation of high-quality crystals. However, we see from the present work that their use *also* enhances the probability that metastable phases will result. Gaining knowledge of the equilibrium phase diagram is the only way to address this issue.

Crystal hydrates typically form when a combination of awkward molecular geometry and poor packing, plus unsatisfied polar interactions, exist in the dry crystal. It is not uncommon for polyols (which are very strongly hydrophilic) to separate from their aqueous solutions as dry crystals. An example is found in the sucrose–water system, where the dry crystal is the coexisting equilibrium crystal phase above 46.3°C [28]. (The dry crystal is also the phase that separates from the syrup during sugar refining but it is *not* the equilibrium phase under the conditions of the process.) The data on C_{12}MG suggest that the packing energy in the equilibrium phase is sufficiently strong for this crystal to resists hydration—even at very high water activities. No fluid phase consisting of hydrophilic molecules has this capability.

B. DIT Data

Diffusive interfacial transport studies [29] involve partly filling a rectangular cross-section of amorphous silica capillary with melted C_{12}MG, cooling to room temperature, initiating the study (by filling the void space with water and creating an interface), and sealing the cell. Immediately after initiation, the cell is adjusted to the desired temperature and time is allowed for diffusive transport. Within minutes interfaces spontaneously appear that divide the cell contents into phase bands; the bands spread and the interfaces become more uniform with time. Being isothermal, the DIT method side-steps a number of troublesome problems that are inherent to

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all isoplethal methods [30]. It has its own peculiarities, however [31], and ideally both isothermal and isoplethal methods are utilized.

Composition is varied smoothly (i.e., in analog fashion) by molecular diffusion within phases and across interfaces during DIT experiments, so that all the phases that exist are formed. During isoplethal phase studies composition is varied in discrete increments (i.e., in digital fashion). Phases can be (and have been) missed during such studies. Moreover, biphasic mixtures having colloidal structures frequently result from cycling temperature. Colloidal states formed in this way have on numerous occasions been mistakenly identified as a single phase. The formation of colloidal structure does not occur during isothermal swelling—with one exception. When a water-rich lamellar phase coexists with the liquid solution of a poorly soluble compound, "anomalous swelling" (which results from the formation of colloidal structure) is observed [31,32]. No other miscibility gap displays this phenomenon.

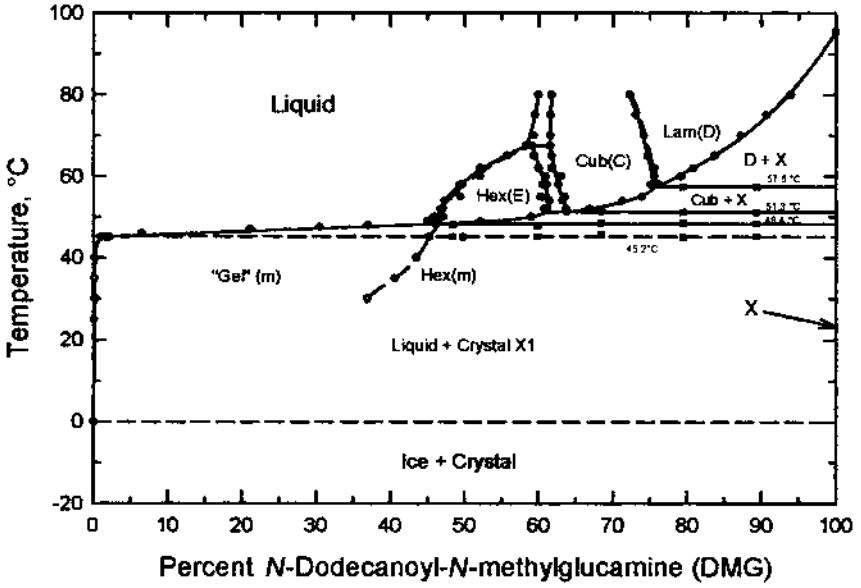

FIG. 8 The C_{12}MG-water phase diagram obtained via DIT-NDX studies. Calibration was carried out with a 49.5% liquid phase using data obtained at temperatures above the Krafft boundary, and adjusted on the basis of calorimetric data. Data on the temperatures of isothermal discontinuities obtained by calorimetric studies are indicated by solid squares.

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Compositions were estimated in the DIT-NDX phase study of C_{12}MG from the refractive indices of coexisting phases to either side of interfaces. Index data may in principle be calibrated using data on a sample of known composition—ideally, the pure compound. Since, however, pure C_{12}MG is a birefringent crystal, a concentrated liquid mixture was used instead. The handling of index data and the adjustments necessary to extract the best phase diagram of C_{12}MG were described earlier [2]. The resulting diagram is shown in Fig. 8.

C. Swelling of Metastable Phases

To obtain equilibrium data during a DIT study, it is necessary to swell the equilibrium phase. If the compound is fluid at room temperature, equilibrium is rapidly achieved and equilibrium data are invariably obtained. In order to load a crystalline compound such as C_{12}MG, however, it is necessary to melt the crystal (to form a liquid of low viscosity that will wick into the cell chamber). Once loaded, the melt is carefully cooled (so as to mimimize voids) and the study initiated. Metastable phases typically result from freezing, so it is necessary to catalyze the relaxation of these phases to equilibrium in situ. Fortunately, this is not usually difficult (see later). A priori knowledge of unary phase behavior is particularly helpful in managing this problem, for without this information the experimentalist is proceeding on an entirely empirical basis. Because C_{12}MG forms X3 on cooling of the melt, DIT studies performed shortly after loading were presumed to involve swelling of this metastable phase. The conversion of X3 to X1 is accelerated with increasing temperature, and at room temperature by contact with liquid water or water vapor.

D. Equilibrium Phase Behavior of the C_{12}MG-Water System

Five phases were found to exist between 25°C and 130°C in the equilibrium C_{12}MG–water system: a crystal phase (X1), a liquid phase (to the dilute side of the diagram), and three liquid crystal phases (lamellar, cubic, and hexagonal, in order of decreasing surfactant composition). The liquid phase is contiguous with the water border, and the liquidus boundary has a classical form. The plateau region of the Krafft boundary also has a familiar form, except that it displays an unusually shallow slope [33]. This feature is important with respect to the interpretation of DSC data.

The liquid region boundary displays (as expected) a sharp kink at the intersection of the Krafft boundary with the hexagonal liquid crystal solubility boundary. The hexagonal phase disproportionates at its upper

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temperature limit via a peritectic phase reaction [34], to form a dilute liquid plus a concentrated cubic phase. This phase reaction is described by the equation:

$$\text{Hex} + q_{\text{peri}} \rightleftarrows \text{Liq} + \text{Cub}$$

The next more concentrated liquid crystal (past the hexagonal phase) is a cubic phase, and the next is the lamellar phase. One may infer from its position that the cubic phase has a bicontinuous structure [35], but this was not established experimentally. The lower boundary of the lamellar liquid crystal phase region has a classical form, except that the region is truncated at the 100% border of the diagram.

Since the upper temperature limit of the DIT method is 80°C, detailed phase information is unavailable at higher temperatures. Where data are available, the phase behavior of C_{12}MG is classic and obeys the phase rule strictly. Finite (sometimes very narrow) miscibility gaps exist between coexisting phases. Their existence establishes that all the phase transitions in this system are first order.

E. Differential Scanning Calorimetry

To supplement the DIT study, the phase behavior of aqueous C_{12}MG mixtures was also studied using DSC. DSC data on dry C_{12}MG were in good agreement with programmed temperature X-ray scans. DSC studies of aqueous C_{12}MG mixtures at characteristic compositions (selected on the basis of the DIT-NDX phase diagram) revealed a series of complex endothermic transitions (Fig. 9). The number and magnitude of these transitions at each composition correlated well with the phase diagram. The first (lowest) onset temperature is particularly interesting because it lies *below* the temperature of the Krafft eutectic. The temperature of this eutectic was estimated first by the stepwise elevation of temperature coupled with observation of the swelling behavior during DIT studies. This approach (which follows the principle used by Strey et al. during ternary phase studies [36]) allows the temperature at which discontinuities in swelling behavior occur to be determined with considerable accuracy.

The Krafft eutectic temperature was also estimated from the return-to-baseline temperature of DSC scans at compositions below the dilute limit of the Krafft eutectic. The temperature of the Krafft eutectic from DIT studies was 48°C. The first DSC onset temperatures observed across the entire composition range averaged 45.2°C, while the return-to-base-line temperatures averaged 48.2°C. The 3°C difference between these two temperatures is significant.

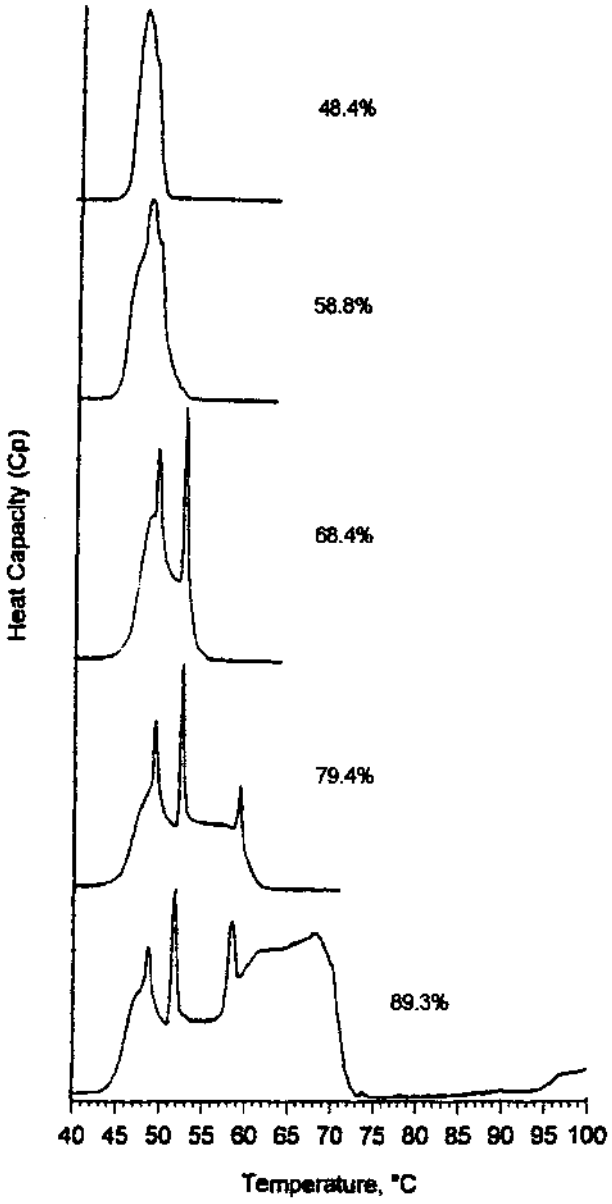

FIG. 9 Thermograms from DSC scans along key isopleths in the C_{12}MG system.

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The first onset temperature does *not* correspond to a thermodynamic discontinuity, as one usually expects. Instead, its existence is a consequence of the shape of the Krafft boundary. Below the knee of this phase boundary, it is nearly vertical and the rate of dissolution of crystals with increasing temperature is extremely small. Above the knee, the slope is extremely small, and the rate of dissolution is very fast. Dissolution requires the absorption of heat—and a heat effect is observed. Calorimetry measures heat effects, not phase behavior.

The magnitude of the total transition enthalpy (from a mixture of liquid plus crystals to a homogeneous fluid phase) is related to the integrated area under these thermograms. The magnitude of the transition enthalpies is large (from 54 to 66 kJ/mol [2]), as would be expected in passing from crystals to fluids. Transition enthalpies for the conversion of one liquid or liquid crystal to another are far smaller.

As surfactant composition increases, the water/surfactant ratio decreases. The heat required to destroy the crystal *increases* as this ratio decreases because the contribution of hydration energy to the process (which is stoichiometry limited) also decreases. Such data could in principle serve to define the intrinsic hydrophilicity of surfactant hydrophilic groups [37], but this analysis has yet to be done.

The lower parts of the various liquid crystal regions, taken together (and neglecting the gaps in miscibility between the various phases), form a smooth curve. To the left of the diagram this curve merges smoothly with the Krafft boundary. This aspect of surfactant phase behavior was recognized by McBain during his pioneering phase studies of surfactants. The C_{12}MG system follows the classical pattern, except that the curve *intersects* the 100% C_{12}MG border. Because of this, a thermotropic lamellar liquid crystal phase exists. This feature is prominent in polyol surfactants having more than two hydroxyl groups, i.e., a structural subgroup within which C_{12}MG falls [38].

In summary, the above studies provide the equilibrium phase diagram of the C_{12}MG–water system below 80°C. This work established, in addition, that the "cloud point" boundary is absent below 100°C. (This is the boundary of the liquid/liquid miscibility gap commonly found in the diagrams of nonionic surfactant–water systems). The absence of the cloud point boundary is significant with respect to analysis of the intrinsic hydrophilicity of this polyfunctional group [2]. The kinetic and nonequilibrium aspects of the phase behavior of aqueous C_{12}MG mixtures will now be considered.

F. Kinetics and Nonequilibrium Aspects

DIT studies of C_{12}MG performed immediately after loading gave results that reflect nonequilibrium or kinetically determined behavior. Swelling of

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the metastable crystal phase at 30°C produced the same phase sequence found above the Krafft eutectic temperature (L-E-C-D-X in the direction of higher concentrations), but several observations suggested that nonequilibrium swelling processes were occurring. Particularly important was the spontaneous appearance and growth of new crystals, which started shortly after initiation at the D/X interface and grew rapidly in both directions. A photograph of this effect was shown earlier [2]. Within hours (depending on temperature), these crystals had consumed all the liquid crystal phases, so that only the L/X interface remained. The L phase at this interface is supersaturated, since its concentration decreased steadily with time. Eventually equilibrium would have been reached, but this would have required a very long time and sufficient time for this to occur was not allowed.

For crystal growth to occur, supersaturation is required. An explanation of how supersaturation could have been created during these isothermal experiments must therefore be provided. This explanation is provided by the polymorphic behavior of the dry crystal. The phase originally present during DIT studies was almost certainly X3, for the loading process mimics the conditions for the synthesis of this phase. The new crystal that grew from the X3/L interface was probably the equilibrium X1 crystal, for it was elsewhere shown that water catalyzes this process.

To produce equilibrium phase data, several cells were loaded, sealed only at the filled end, and stored at room temperature within a 90% RH chamber (prepared from a saturated zinc sulfate solution in equilibrium with crystals and water vapor). After 2 weeks, initiation and DIT studies using these cells displayed none of the above-described behavior. Instead, swelling to form liquid crystal phases occurred at and above the Krafft eutectic temperature. Similar procedures were followed and similar observations made during the dioctadecyldimethylammonium chloride (DODMAC)–water DIT study [39]. The difference, in the case of DODMAC, was that much longer equilibration times were required to achieve equilibration (4 months).

Growth of the X1 crystal region in the DIT study of X3 was sufficiently slow that, in freshly initiated cells, the composition of the metastable hexagonal liquid crystal region could be determined at temperatures well below the Krafft eutectic. These data are shown in Fig. 8 as the dashed phase boundary that extends downward from the equilibrium hexagonal phase boundary. The composition of the coexisting metastable liquid phase closely follows that of the hexagonal phase, but was not determined. These observations are pertinent to the unusual kinetic behavior found on cooling various liquid mixtures (see later).

In most surfactants, crystals in equilibrium with the liquid below the Krafft boundary temperature in dilute mixtures disappear rapidly as temperature is

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raised along isoplethal paths but reform on cooling only slowly. C_{12}MG resembles other surfactants in this respect [40]. However, studies of its behavior on cooling along the 20% and 40% isopleths (starting above the Krafft boundary) revealed distinctive and unfamiliar kinetic phenomena. Cooling along the 40% isopleth to below the Krafft boundary resulted in virtually instantaneous formation of the hexagonal liquid crystal phase (which displays a characteristic and intense birefringence). This result is consistent with the position of the metastable hexagonal boundary as determined using DIT studies.

In striking contrast, cooling the 20% mixture did *not* yield a liquid crystal phase. Instead, a mixture that might be described as a "gel" was formed [2]. This gel was extremely viscous, did not scatter light intensively, but was not clear (like a liquid phase). When viewed in a 15-mm test tube in polarized light, it displayed very weak birefringence that was nonuniform and unfamiliar. The behavior at 20% thus differed strikingly from that at 40%. The structure of the biphasic (presumably also colloidally structured) state that results from cooling the 20% mixture was not determined.

C_{12}MG is far too soluble in liquid water to display in its biphasic aqueous mixture's long-lived colloidal structure (such as the vesicles that occur with dichain surfactants). At low temperatures, however, its solubility is sufficiently small that such structures could be more stable.

V. THE CRYSTAL–LIQUID (KRAFFT) BOUNDARY; INFLUENCE OF THIRD COMPONENTS

A. Thermodynamic Model for Crystal–Liquid Equilibria, and Supporting Data

Using research samples supplied by J. J. Scheibel, the group of N. A. Smirnova et al. (St. Petersburg University) conducted physico chemical studies of binary aqueous C_{12}MG mixtures, and of ternary mixtures containing various third components. How the third component influenced the temperature of Krafft points was of particular interest because the Krafft point of this analog is above the use temperature of various product formulations. A thermodynamic model for how surfactant composition affects the Krafft boundary temperature over a wide range of surfactant compositions was developed. This range included compositions that displayed micellar solution structure and was based on the pseudophase separation approach (which treats the micelle as a separate phase). The model was extended to analysis of the influence of third components. A brief description of this work follows. For a full account, one should consult the original literature [15,16,41–44].

Starting from the equation for the Gibbs energy of a generalized crystal phase containing m moles of water per mole surfactant, treating the crystal as a component in its own right (having a characteristic chemical potential), and applying the equations that define the condition of equilibrium ($\mu_i^k = \mu_i^l$, where i designates a component and k and l are two phases in equilibrium), one can arrive at the simple equation

$$\mu_1^L + \mu_2^L = \mu_S \tag{1}$$

The subscript 1 refers to surfactant, 2 to water, L to liquid, and S to solid (here crystal). From Eq. (1), by applying the Gibbs-Duhem and Gibbs-Helmholtz analyses, one can also obtain (after simplification) Eq. (2) for the case that $m = 0$ (as is found with C_{12}MG):

$$\left(\frac{dT}{dx_1^L}\right)_p = \frac{T}{\Delta H_1}\left(\frac{\partial \mu_1}{\partial x_1}\right)_{p,T}^L \tag{2}$$

This important equation relates the dependence of the Krafft temperature on composition (composition in units of mole fraction of surfactant, x_1) to three terms. These are the magnitude of T, the differential molar heat of solution of the crystal H_1, and the dependence of surfactant chemical potential (μ_1) on surfactant composition. (Pressure, p, is presumed to remain constant.) In the pseudophase separation model this dependence equals zero, which does not correspond to the actual data. However, the dependence of Krafft temperature on composition in this system is small, and this approximation is numerically satisfactory.

An important result of this analysis was the concept that those interactions that influence the Krafft boundary temperature occur strictly within the solution phase. It is unnecessary to invoke changes in the crystal phase to understand the results. This inference is supported by data which show that a plot of ΔH_1 (determined using DSC) vs. composition is linear, and the line passes (almost) through the origin [15] (Fig. 10). While unsurprising, this result had not previously been established experimentally.

B. Influence of Third Components on Crystal–Liquid Equilibria

Third components of widely varying molecular structure were explored with respect to their influence on Krafft points. Exploratory studies of various classes of additives (present at a level of a few percent) gave the following results:

1. Nonpolar solvents (the lower alkanes) have little effect on Krafft points.

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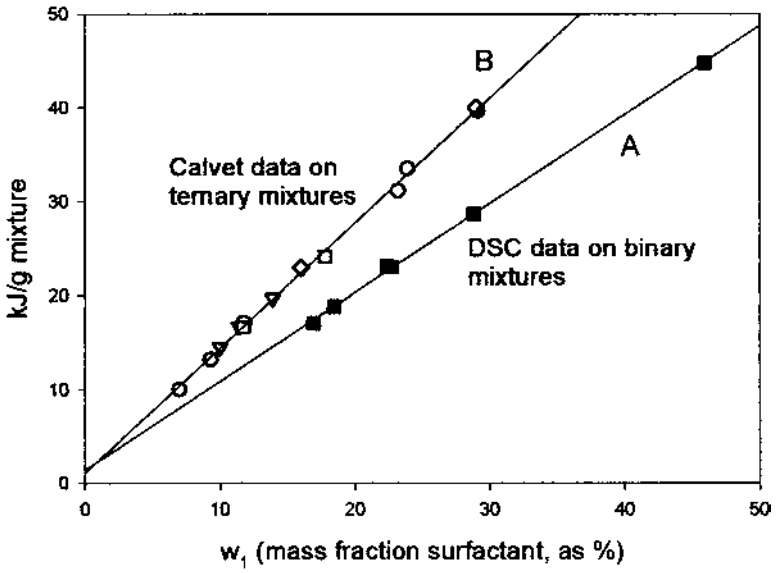

FIG. 10 DSC data on binary aqueous mixtures of C_{12}MG (A) (solid squares) and Calvet isothermal calorimetric data on ternary mixtures containing various additives (B). Ethanol, open circles; propanol, open triangles; butanol, open squares.

2. Small hydrophilic organic molecules (e.g., dimethylformamide, dimethylsulfoxide, citric acid, and glycerol) also have little effect on Krafft points.
3. Hydrophilic salting-out electrolytes (sodium, potassium, or ammonium chlorides, carbonates, nitrates, and sulfates) likewise have little effect on Krafft points.
4. *Small amphiphilic molecules (i.e., hydrotropes) have a large effect and lower Krafft points.* The lower alcohols (from ethanol through pentanol), and the lower carboxylic acids, display significant effects. The Krafft point lowering increases with increasing chain length, but (for reasons presently unclear) pentanol has a lesser effect than butanol. Straight chain amphiphilic molecules have a larger effect than do isomeric branched molecules, as expected.
5. Combinations of lower alkanols with salting out electrolytes (especially alkali metal carbonates) caused the largest lowering of Krafft points that was discovered (up to about 30°C). This is particularly interesting since these electrolytes by themselves have little effect.

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Krafft point data were supplemented with calorimetric studies here also, but a Calvet calorimeter was used instead of a differential scanning calorimeter [16]. The Calvet calorimeter yields data on heats of mixing (ΔH^{sol}) when crystalline C_{12}MG is mixed with an aqueous solution of an amphiphile. The dependence of ΔH^{sol} on surfactant composition was studied in more detail in ternary mixtures also containing ethanol, propanol, or butanol. The magnitude of ΔH^{sol} per unit mass of surfactant was found (as above) to be independent of surfactant composition. More surprisingly, it was also unaffected by the nature of the hydrotrope. Both the ΔH_1 (DSC) and the ΔH^{sol} (Calvet) data are shown in Fig. 10. Figure 10B, which displays the Calvet data, contains all the data from studies of the various hydrotropes; all these data fall on the same line.

The calorimetric data from both studies support the premise that the influence of added hydrotropes is the result of interactions on the solution side of the liquid–crystal equilibrium. The authors note that those compounds that lower Krafft points are also those which (from previous experience) are expected to mix with micellar structures. Thus, the thermodynamic nonideality of these mixtures may be correlated intuitively with the tendency of the additive to mix with micellar aggregates. When this happens, more stable micelles result. Alkane solvents (which mix only in the micellar core—and in fact stress the micelle) have little effect. Organic *and* inorganic molecules that are sufficiently hydrophilic to remain in the aqueous region have little effect. In contrast, small amphiphilic (hydrotropic) molecules, which participate in and modify micellar composition and structure, have the largest effects. These effects are further exaggerated when salting-out electrolytes are also present. Adding salting-out electrolytes as a fourth component would be expected to enhance the partitioning of hydrotropes into the micelle. This provides a qualitative explanation for the fact that, while these compounds are by themselves ineffective, they enhance the effect of the hydrotropes.

The above investigations break new ground in the study of hydrotrope–surfactant interactions, and it would be good to follow them up with ternary phase studies. From a broader perspective, it is worth noting that *no comprehensive ternary surfactant phase study has ever been conducted at a temperature below the Krafft eutectic temperature of the binary aqueous surfactant system*. This neglect of crystal chemistry—a direct consequence of the strong focus in recent times on fluid states—is unsurprising when one considers that crystal chemistry is slow and experimentally difficult. The area is nevertheless important because the crystal phases of surfactants are frequently encountered during their commercial use. Crystal chemistry presently constitutes one of the largest gaps that exist in our present knowledge of surfactant phase equilibria.

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VI. ANALOGS OF C_{12}MG

N-Alkanoyl-*N*-alkylglycamines are complex polyfunctional molecules, and numerous analogs can be imagined. C_{12}MG may be taken as the core structure, since the most information by far is available on this compound. Three kinds of structural variants of have been synthesized (Scheibel). Physical studies have been carried out on selected compounds that provide a broad view of how molecular structure influences selected physical properties. The structural elements investigated include:

1. *Chain length of the* N-*alkanoyl lipophilic group*. Varying this parameter enables lipophilicity to be varied while holding hydrophilicity constant, which is one important way of varying hydrophilic–lipophilic balance (HLB) [45].
2. *Size and structure of the* N-*alkyl group*. Early in the exploration of surfactant structure vs. phase behavior, it was noted that substituents near (proximate to) the principle hydrophilic group had a distinctive effect, compared to that of the same substituent in positions remote from the hydrophilic group [46]. The *N*-alkyl groups of alkanoylglycamine surfactants may be regarded as "proximate substituents." Proximate substituents influence *both* hydrophilicity and lipophilicity, and thus influence HLB in a very complex manner.
3. *Structure of the polyol moiety*. These hydroxyl groups (plus the *N,N*-disubstituted amide group, which is slightly more hydrophilic) constitute the principal hydrophilic site in these molecules. Polyol variation is another way of altering HLB (by varying hydrophilicity while keeping lipophilicity constant).

The data collected on analogs included melting points, Krafft points, and critical micelle concentrations (CMCs). "Melting points" (as noted earlier) were defined as that endothermic phase transition at which the D phase reacts with absorption of heat to form the isotropic liquid. Krafft points correspond approximately to the knee of the Krafft boundary. Although not a fundamental thermodynamic discontinuity (in the sense that the Krafft eutectic is), Krafft points reflect that temperature above which the dependence of solubility on temperature increases dramatically. They are therefore pertinent to performance properties. CMCs reflect the ease with which unassociated molecules in solution aggregate into micelles. CMC data are important because performance (e.g., in cleaning formulations) typically differs at concentrations above and below the CMC [47]. Studies of the CMC of C_{12}MG will be described first, and then compared with data on homologs.

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A. CMC Studies of C_{12}MG

Dilute liquid solutions of C_{12}MG behave conventionally with regard to micellization; the CMC of C_{12}MG at 25°C is 0.43 mM (162 mg/L). The limiting surface tension past the CMC is 27.3 dynes/cm (mN/m). This is a low value, but similar tensions been observed for other nonionic surfactants (such as phosphine oxides) [48]. The nature of the lipophilic group has a larger effect on this parameter than does the hydrophilic group. Ionic surfactants display much higher plateau tensions than do nonionics.

The area per molecule [estimated from the Gibbs equation using the linear part of the γ vs $\log(C)$ curve] is 37 Å^2. This area is surprisingly small considering the large mass of the hydrophilic group. Its magnitude suggests that the group is not lying flat at the air–water interface but is buried in the water phase. The small interfacial area and low interfacial tension are consistent with one another.

The relationship between log(CMC) and chain length was determined using this datum, plus published data on the C_8, C_9, and C_{10} homologs (CMC in units of moles per liter). A linear relationship was found. The equation for the linear regression was:

$$\log(\text{CMC}) = 2.884 - 0.5205n$$

if the carbonyl group is included in the value of n, and

$$\log(\text{CMC}) = 2.3639 - 0.5205n$$

if it is not.

No unusual viscosity changes in the liquid phase were observed at high concentrations. This suggests that micellar growth with increasing concentration does not occur to an unusual degree.

B. Variation of Chain Length (Homologs)

The even-chain homologs having from 8 to 18 carbons in the alkanoyl group (7 to 17 in the alkyl group) were independently prepared, carefully purified, and their CMC's determined. The data are collected in Fig. 11, and again show the expected linear decrease in log(CMC) with chain length. The equation describing these data (taking n as the length of the alkyl group) is:

$$\text{Log(CMC)} = 2.363 - 0.516n$$

which is agreeably close to the above equation. This analysis and the one mentioned above utilized different samples, and may be regarded as independent studies that are consistent with one another. Melting points rise to

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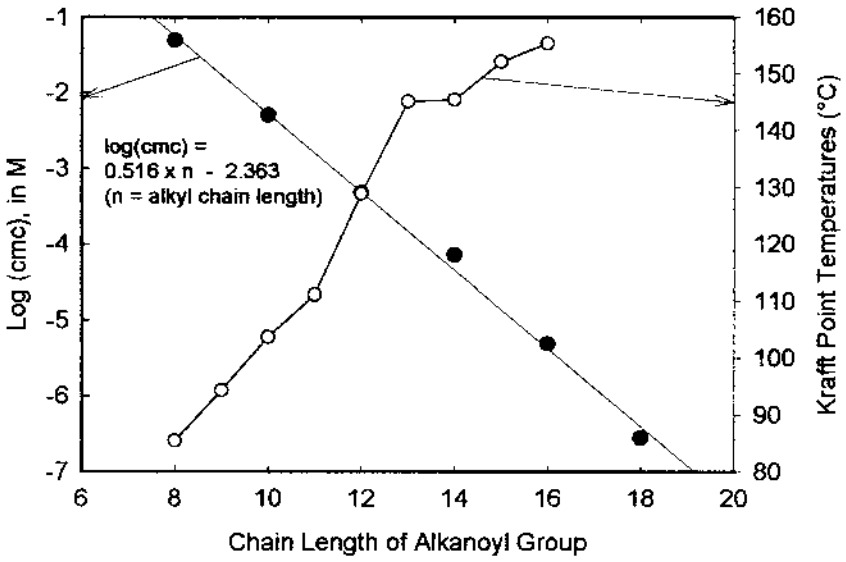

FIG. 11 Influence of alkanoyl chain length on critical micelle concentrations and Krafft points.

high temperatures as the length of the chain increases. The irregularity in the chain length region of 12–14 carbons is unexplained.

C. Variation of Proximate Substituent Structure

The influence on melting points and Krafft points of varying proximate substituent structure is displayed in the bar graph in Fig. 12. Each bar actually consists of two bars: a dark gray one inside an open bar. The length of the open bar depicts melting points, whereas that of the gray bar represents Krafft points. As required of surfactants, the Krafft point is always lower than the melting point. The difference is a measure of the hydrophilicity of the polar group [49].

One series in Fig. 12 represents the influence of varying the chain length of the *N*-alkyl proximate substituent (from methyl to hexyl). Increasing this chain-length decreases melting points but *increases* Krafft points up to propyl. After propyl, this parameter decreases. The consequence of this behavior is that ΔT decreases up to propyl, then *increases* from propyl to butyl. This increase is unexpected and its cause remains unexplained.

The *N*-benzyl compound behaves much like the *N*-ethyl analog, in spite of its much larger size and greater lipophilicity. (A benzene ring is usually

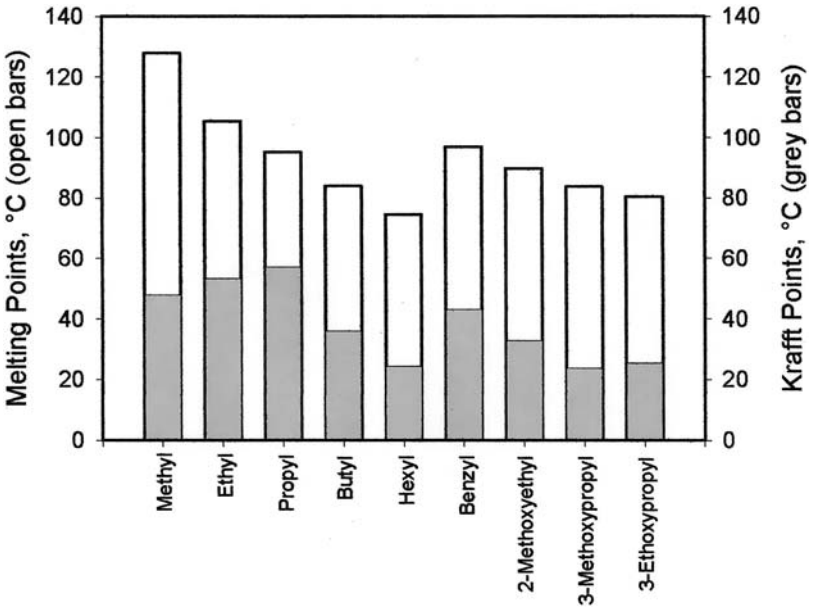

FIG. 12 Influence of proximate substituent structure on melting points and Krafft points.

equated with four aliphatic carbons.) The methoxyalkyl group, for example, causes a significant *lowering* of the Krafft point (to below room temperature). As a result, ΔT is relatively large for the methoxy compounds. This result is consistent with the small enhancement of hydrophilicity to be expected from insertion of a methoxy ether group.

D. Variation of Polyol Moiety

A hydroxyl group is more hydrophilic than an ether group [50]. One hydroxyl group does not operate as a hydrophilic group (by phase criteria), but two hydroxyls do. Further increase in the number of hydroxyl groups beyond two, e.g., in homologous vicinal (1,2-) diol structures such as the sugars, is expected to increase hydrophilicity. This increase is attenuated by intramolecular hydrogen bonding, which competes with those interactions with water that constitute hydrophilicity. Nevertheless, the net effect of increasing the number of hydroxyl groups is to increase hydrophilicity.

Strong *intermolecular* hydrogen bonding may also occur in polyols. These interactions *strengthen* crystal structures to an extent that is strongly

influenced by stereochemistry. The more stereoregular is a polyol, the more highly crystalline it is. To illustrate, pure stereoregular polyvinyl alcohol (a poly-1,3-diol) is sufficiently highly crystalline to be insoluble in water [51]. Those "polyvinyl alcohol" that are water soluble are partially acetylated.

The melting point/Krafft point data shown in Fig. 13 are consistent with the above picture. As the number of hydroxyl groups increases from 2 (glycerose) to 4 (xylose) to 5 (glucose and its isomers), both melting points and ΔT values (hydrophilicity) rise. They are roughly the same in the three isomeric hexoses (although galactose seems out of line). Maltose is a dissacharide whose alkanoylamide derivative is structurally complex. It has seven hydroxyl groups, three ether groups, and a pyranose ring; see Fig. 3. In the maltose derivative, the melting point is very high, while the Krafft point is very low—which results in an unusually large ΔT.

CMC data on these compounds are shown in Fig. 14. The raw data (in mg/L) are shown by the gray bars; the same data (in millimolar units) is shown by the open bars. A small increase in CMC occurs on increasing the number of hydroxyl groups from two to four (glycerose to xylose), but beyond this number the effect on changing the number of hydroxyl groups on the CMC is small. This result is to be expected. These authors note that

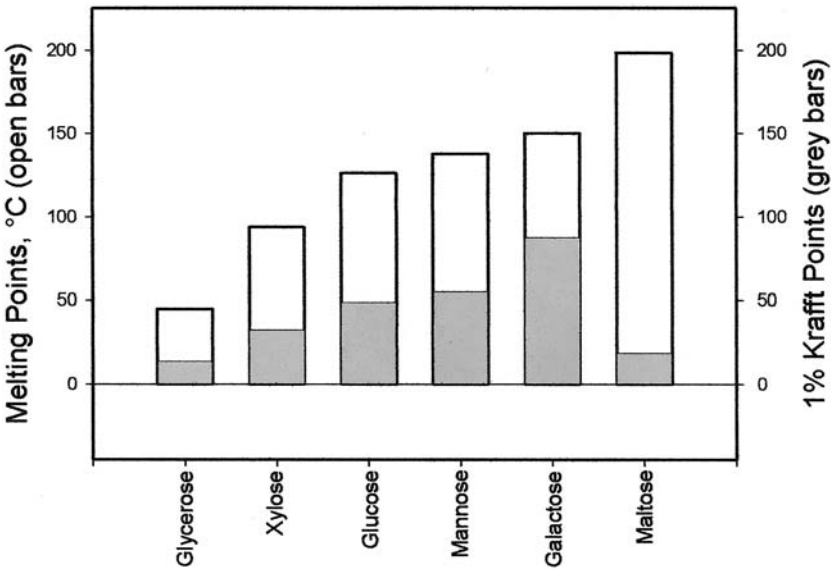

FIG. 13 Influence of the structure of the sugar starting material on melting points and Krafft points.

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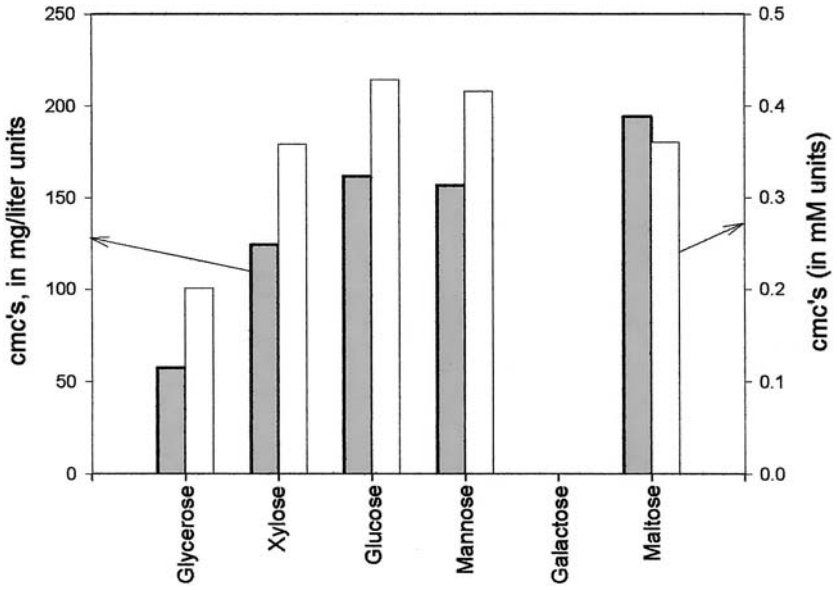

FIG. 14 Influence of the sugar starting material on critical micelle concentrations.

while the long chain largely dictates physical properties such as cmc's, the polyol moiety has a significant effect on the performance and utility of the compounds [52].

E. Miscellaneous Information

Several items of miscellaneous research on alkanoylglycamines that fall outside the scope of the above sections are worth mentioning. Greenhill-Hooper et al., for example, report the preparation and investigation of borate derivatives [53]. Their formation is to be expected, since most vicinal diols form cyclic four-coordinated borate anions by reaction with inorganic borate, under the right conditions. Being anionic, these derivatives are expected to be considerably more hydrophilic than are the polyol amides themselves.

Arenas et al. [54] report the solubilization of polychlorocarbon solvents by alkanoylglycamines, a phenomenon that is to be expected of highly water-soluble nonionic surfactants. Miyagishi et al. [55] report determination of the CMC's of these surfactants using measurements of the fluorescence of benzophenone imine. Such determinations using, for example, pyrene have long been known; the use of this particular fluorescent dye is unusual.

VII. SUMMARY

Alkanoylglycamine surfactants are interesting materials having distinctive properties. Their phase behavior suggests that they are more hydrophilic than typical polyoxyethylene surfactants, but less hydrophilic than other subclasses of nonionic surfactants (semipolar, zwitterionic). They are far less hydrophilic than ionic surfactants. The compounds are weakly basic—the pK_a of protonated dialkyl amides is about 1—so they remain unprotonated and nonionic within the usual pH range. As a result, they do not display the numerous complexities typically found in ionic compounds.

The earlier review of the physical science of C_{12}MG [2] has been retained in the present chapter, but it has been abbreviated and new information added. A thermodynamic analysis of the factors that determine the shape of the Krafft boundary plateau has been introduced by Smirnova et al. and this model extended to consideration of the effect that third components (additives) have on Krafft points. CMC's, melting points, and Krafft points have been acquired on a variety of C_{12}MG analogs, which provide insight as to how various structural features influence physical behavior. Homologation has its expected strong influence on these parameters. Varying the proximate *N*-alkyl substituent strongly influences physical behavior: For example, *N*-methoxyalkyl proximate substituent analogs are considerably more soluble in water at room temperature than is the corresponding *N*-methyl analog. Varying the polyol moiety (by varying the sugar utilized as the starting material for the synthesis) has been explored. The number of hydroxyl groups present is important, but the stereochemistry of the sugar has minimal influence [56].

Perhaps because of its polyfunctionality and complex molecular structure, C_{12}MG (and probably also its analogs) displays a high level of complexity in its physical behavior. Polymorphism exists in the dry material; three different crystalline polymorphs that vary widely in their kinetic stabilities have been discovered. Nonequuilibrium phenomena exist in unary and in binary aqueous systems. The likelihood that similar complexity also exists in ternary systems is very high. Unfortunately, one cannot be sure that this behavior is unique to these molecules because few other systems have been studied in the depth that C_{12}MG has been. It would have been desirable to have studied in depth one or two other analogs, but time did not allow this.

The polyfunctionality of the *N*-alkanoyl-*N*-alkylglucamine molecules is possibly responsible (at least in part) for their complex physical behavior. It is interesting to note, in this connection, that the relatively simple dilong-chain surfactant DODMAC displays relatively simple aqueous phase behavior (e.g., only two isothermal phase discontinuities [57]), compared with the structurally more complex polar lipids (e.g., dipalmitoylphospha-

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tidylcholine, which displays five such discontinuities [58]). Much remains to be done.

ACKNOWLEDGMENTS

The authors thank M. R. Mootz for his assistance with the X-ray studies, A. S. Glardon for execution of the calorimetric studies, Dr. R. G. Severson for development of the analytical method and for providing analytical data on C_{12}MG samples, and Dr. D. S. Connor for numerous consultations regarding the organic chemistry of C_{12}MG. The assistance of Professor N. A. Smirnova, of St. Petersburg University, in integrating the Russian work on these compounds into this chapter is also gratefully acknowledged.

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2
Alkyl Polyglycosides

WOLFGANG VON RYBINSKI Henkel KGaA, Düsseldorf, Germany

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I. INTRODUCTION

During the past years and decades, several sugar-based surfactants, such as sorbitan esters, sucrose esters, methyl glucoside esters, alkyl polyglycosides, and methyl glucamides, have been introduced to the market by different manufacturers. Among those, the recently industrially developed alkyl polyglycosides are the most successful if one considers an estimated market potential of 70,000–80,000 tons/year for 1997 [1,2]. Whereas the first alkyl glucoside was synthesized and identified in the laboratory by Emil Fischer more than 100 years ago [3] and the first patent application describing the use of alkyl glucosides in detergents was filed in Germany some 40 years later [4,5], the breakthrough in the commercial exploitation of alkyl polyglycosides was reached in 1992 with the inauguration of a 23,000 t p.a. production plant for APG® surfactants in the United States by Cognis Corporation (formerly Henkel Corporation) and in 1995 with the opening of a second plant of equal capacity by Cognis (formerly Henkel KGaA) in Germany [6].

II. TECHNOLOGY

Besides technology, science has always been interested in the synthesis of glycosides because this is a very common reaction in nature. The broad synthesis potential range has recently been reviewed in various articles [7–11].

Emil Fischer discovered the synthesis of alkyl glycosides by reaction of glucose and alcohol in the presence of an acidic catalyst. During the course of the further development of alkyl polyglycosides, several laboratory methods have been developed for synthesis of a variety of substances and to facilitate study of their physicochemical properties [3,12–15]. The various syntheses

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range from stereospecific synthesis routes using protective groups, which give defined compounds with high selectivity, to nonselective processes leading to complex isomer and oligomer mixtures, such as in the case of the Fischer glycosidation.

So far as the industrial production of alkyl polyglycosides is concerned, processes based on the Fischer synthesis have been successfully adopted. Their development began about 20 years ago and has significantly accelerated in the past 10 years. Development work over this period has enabled the efficiency of this synthesis route to be increased to a level where it has finally become attractive for industrial application. Optimization work, particularly in the use of long-chain alcohols such as dodecanol/tetradecanol ($C_{12/14}$-OH), has resulted in distinct improvements in product quality and process economy. Modern production plants built on the basis of the Fischer synthesis are the embodiment of low-waste, virtually emission-free technologies. Another advantage of the Fischer synthesis is that the average degree of polymerization of the products can be precisely controlled over a wide range. Relevant performance properties, such as hydrophilicity/water solubility, can thus be adapted to meet requirements. In addition, the raw material base is no longer confined to water-free glucose [1,16,17].

A. Raw Materials for the Manufacture of Alkyl Polyglycosides [16]

1. Fatty Alcohols

Fatty alcohols can be obtained either from petrochemical sources (synthetic fatty alcohols) or from natural, renewable resources, such as fats and oils (natural fatty alcohols). Fatty alcohol blends are used in alkyl polyglycoside synthesis to build up the hydrophobic part of the molecule. The natural fatty alcohols are obtained after transesterification and fractionation of fats and oils (triglycerides), leading to the corresponding fatty acid methyl esters, and subsequent hydrogenation. Depending on the desired alkyl chain length of the fatty alcohol, the main feedstocks are oils and fats of the following composition: coconut or palm kernel oil for the $C_{12/14}$ range and tallow, palm, or rapeseed oil for the $C_{16/18}$ fatty alcohols.

2. Carbohydrate Source

The hydrophilic part of the alkyl polyglycoside molecule is derived from a carbohydrate. Based on starch from corn, wheat, or potatoes, both polymeric and monomeric carbohydrates are suitable as raw materials for the production of alkyl polyglycosides. Polymeric carbohydrates include, for example, starch or glucose syrups with low degradation levels, whereas monomeric carbohydrates can be any of the various forms in which glucose is available,

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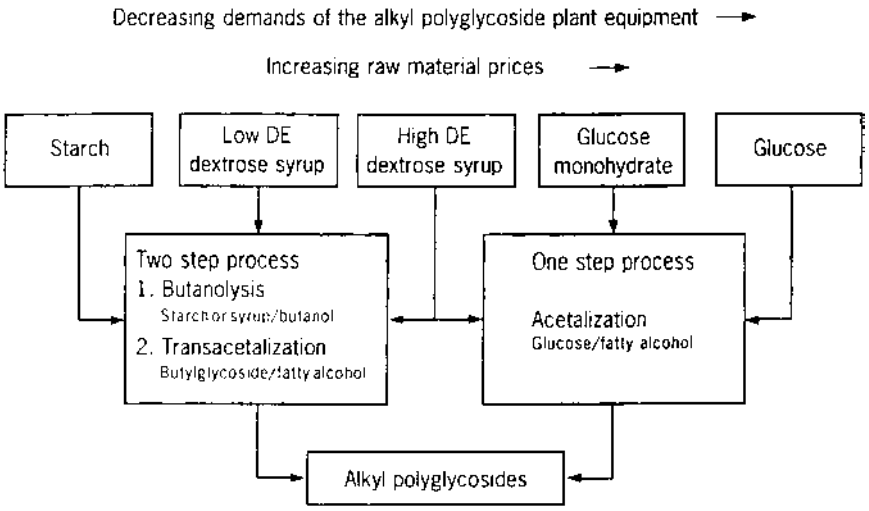

FIG. 1 Carbohydrate sources for industrial scale alkyl polyglycoside synthesis.

e.g., water-free glucose, glucose monohydrate (dextrose), or highly degraded glucose syrup. Raw material choice influences not only raw material costs but also production costs. Generally speaking, raw material costs increase in the order starch/glucose syrup/glucose monohydrate/water-free glucose whereas plant equipment requirements and hence production costs decrease in the same order (Fig. 1).

B. Synthesis Processes for the Production of Alkyl Polyglycosides

Basically, all processes for the reaction of carbohydrates to alkyl polyglycosides by the Fischer synthesis can be attributed to two process variants, namely, direct synthesis and the transacetalization process. In either case, the reaction can be carried out in batches or continuously.

Direct synthesis is simpler from the equipment point of view [18–20]. In this case, the carbohydrate reacts directly with the fatty alcohol to form the required long-chain alkyl polyglycoside. The carbohydrate used is often dried before the actual reaction (e.g., to remove the crystal-water in case of glucose monohydrate = dextrose). This drying step minimizes side reactions that take place in the presence of water.

In the direct synthesis, monomeric solid glucose types are used as fine-particle solids. Since the reaction is a heterogeneous solid–liquid reaction, the solid has to be thoroughly suspended in the alcohol.

Highly degraded glucose syrup [dextrose equivalents (DE) > 96] can react in a modified direct synthesis. The use of a second solvent and/or emulsifiers (e.q., alkyl polyglycoside) provides for a stable fine-droplet dispersion between alcohol and glucose syrup [21,22].

The two-stage transacetalization process involves more equipment than the direct synthesis. In the first stage, the carbohydrate reacts with a short-chain alcohol (e.g., *n*-butanol or propylene glycol) and optionally depolymerizes.

In the second stage, the short-chain alkyl glycoside is transacetalized with a relatively long-chain alcohol ($C_{12/14}$-OH) to form the required alkyl polyglycoside. If the molar ratios of carbohydrate to alcohol are identical, the oligomer distribution obtained in the transacetalization process is basically the same as in the direct synthesis.

The transacetalization process is applied if oligo- and polyglycoses (e.g., starch, syrups with a low DE value) are used [23]. The necessary depolymerization of these starting materials requires temperatures of more than 140°C. Depending on the alcohol used, this can create correspondingly higher pressures that impose more stringent demands on equipment and can lead to higher plant cost.

Generally, and given the same capacity, the transacetalization process results in higher plant cost than the direct synthesis. Besides the two reaction stages, additional storage facilities and, optionally, working-up facilities for the short-chain alcohol have to be provided. Alkyl polyglycosides have to be subjected to additional or more elaborate refining on account of specific impurities in the starch (e.g., proteins). In a simplified transacetalization process, syrups with a high glucose content (DE > 96%) or solid glucose types can react with short-chain alcohols under normal pressure [24–29]. Continuous processes have been developed on this basis [24]. Figure 2 shows both synthesis routes for alkyl polyglycosides.

C. Production of Water-Insoluble Alkyl Polyglycosides

If fatty alcohols containing 16 or more carbon atoms per molecule are used in the synthesis of alkyl polyglycosides, the products obtained are soluble in water in only very low concentrations. They are referred to in the following text as water-insoluble alkyl polyglycosides. In these alkyl polyglycoside types, the nonpolar character predominates due to the long-chain alkyl group. These cannot be used as surfactants but instead are mainly used as emulsifiers in cosmetic formulations [30–32].

The observations of the reaction of glucose with dodecanol/tetradecanol largely apply to the synthesis of water-insoluble alkyl polyglycosides, such as hexadecyl/octadecyl polyglycosides. The acid-catalyzed reaction is car-

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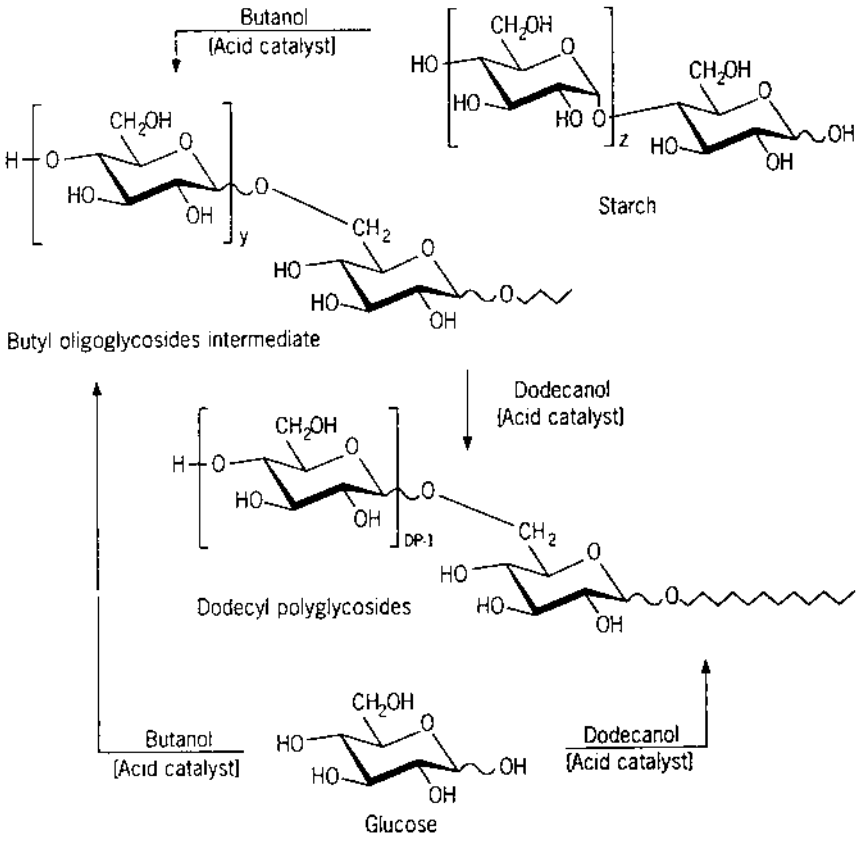

FIG. 2 Pathways for alkyl polyglycoside synthesis.

ried out at similar temperatures, pressures, and molar ratios between the starting materials. However, refining and bleaching of the product as an aqueous paste is more difficult due to the low solubility of these products. It is all the more important to produce products that are low in side products and light in color directly after the reaction step, thus avoiding further treatment. For this reason, reaction conditions had to be adjusted. The main differences are:

termination of the reaction at a glycose conversion of approx. 70%
removal of unreacted glycose by filtration
Adjustment of final product composition by controlled distillation of excess fatty alcohol

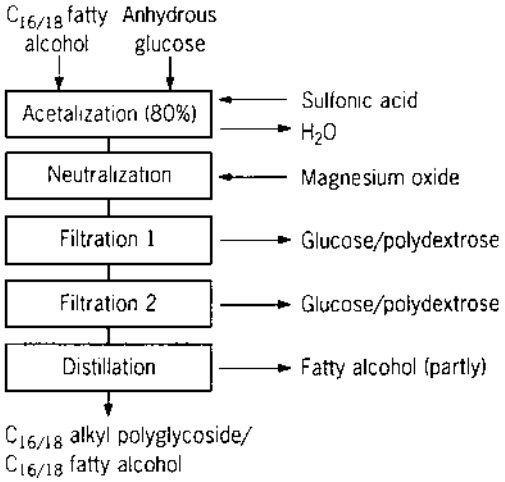

FIG. 3 Flow diagram for the synthesis of long-chain alkyl polyglycosides.

For example, a fairly recent type of water-insoluble alkyl polyglycosides contains approximately 50% of alkyl polyglycoside and 50% fatty alcohol (Emulgade® PL 68/50, Cognis). In this case, part of the fatty alcohol is removed by vacuum distillation [32], with temperatures and residence time kept as low as possible to suppress thermal decomposition (Fig. 3).

III. PRODUCT COMPOSITION

Commercial alkyl polyglycosides are complex mixtures of species differing mainly in the degree of polymerization (DP) and in the length of the alkyl chains. Through the polyfunctionality of the carbohydrate partner, the conditions of the acid-catalyzed Fischer reaction yield an oligomer mixture in which on average more than one glycose unit is attached to an alcohol molecule. The average number of glycose units linked to an alcohol group is described as the (average) DP. In the product mixture, the concentration of the individual oligomers (mono-, di-, tri-, etc., glycoside) is largely dependent on the ratio of glucose to alcohol in the reaction mixture. The degree of polymerization is an important characteristic with regard to the physical chemistry and applications of alkyl polyglycosides. In an equilibrium distribution, the DP—for a given alkyl chain length—correlates well with basic product properties, such as polarity, solubility, etc. Alkyl monoglycosides are the main group of components with a content of more than 50%, followed by

the diglycosides and higher oligomers up to heptaglycosides. Small amounts of more highly glycosidated species are also present. Species with a degree of glycosidation above 5 are not normally determined in routine analysis because the amounts involved are too small [6,16,33–36].

The analytical tasks to be performed for the characterization of commercial alkyl polyglycosides are as follows:

1. Determination of the type, amount, and distribution of alkyl mono- and oligoglycosides and the alkyl chain length and distribution of the fatty alcohol bound in the product. The average DP is calculated from these data.
2. Qualitative and quantitative analysis of minor components, such as traces of residual fatty alcohol and glucose.

Special analyses, such as color, viscosity, ash content, dry residue, foam behavior, etc., have to be carried out for quality control purposes. The data are usually provided by the alkyl polyglycoside manufacturers in the technical data sheets [33–36].

The most important analytical techniques routinely used for the characterization of main and trace components in commercial alkyl polyglycosides are high-performance liquid chromatography (HPLC) and gas chromatography (GC).

A. Alkyl Polyglycoside Determination by GC [33]

The GC technique that has proven to be particularly suitable for the analysis of alkyl mono- and oligoglycosides is high-temperature gas chromatography (HTGC). HTGC uses temperatures of up to 400°C, which enables oligomeric alkyl polyglycosides up to the very high boiling heptaglycosides to be analyzed. The hydroxyl groups in alkyl polyglycosides have to be converted to silyl ethers before analysis to prevent sample decomposition.

The best silylation results have been obtained using a mixture of 2 mL of Tri-Sil-Z (*N*-trimethylsilylimidazole in pyridine) and 0.4 mL of MSTA (*N*-methyl-*N*-trimethylsilyltrifluoroacetamide) as the silylating agent for about 30 mg of sample. The reaction is carried out at 80°C; reaction time 0.5 h. A solution of the resulting silyl ether mixture in *n*-heptane is then injected into the system. A typical high-temperature gas chromatogram of a commercial alkyl polyglycoside sample is shown in Fig. 4. Nearly all the species in this segment are baseline separated and can therefore be clearly identified and quantified. Quantification is carried out by the internal standard method using pentadecanol as internal standard. The response factors and retention times are determined using the commercially available octyl-, decyl-, and dodecyl-β-D-glucopyranoside and dodecyl-β-D-maltoside

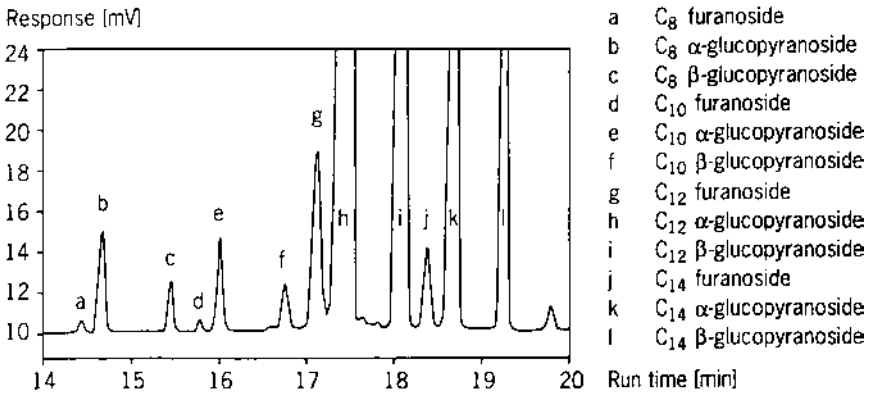

FIG. 4 Segment of alkyl polyglycoside HTGC chromatogram.

for calibration. Components for which no calibration substance is available are quantified using the response factor of the nearest calibration substance of the same type. All alkyl oligoglycosides are quantified with the response factor of dodecyl-β-D-maltoside.

All essential parameters for the characterization of alkyl polyglycoside samples, such as alkyl chain length and composition of the fatty alcohols used in the synthesis, the type and quantity of mono- and oligoglycosides present in the product, can be calculated from these data. The greatest advantage of alkyl polyglycoside analysis by HTGC is the high resolution that enables virtually all relevant components to be characterized.

B. Alkyl Polyglycoside Characterization by HPLC [33]

Alkyl polyglycoside characterization by HPLC is routinely performed using an isocratic reversed-phase system. In most cases, no particular sample preparation is necessary; after dissolution in the eluent, the sample solution is filtered and directly injected into the system. A typical chromatogram and the chromatographic conditions are shown in Fig. 5. The retention corresponds to the lipophilicity of the substances separated. The individual species are identified and quantified by the external standard method using commercially available alkyl glycosides for calibration. The alkyl monoglycosides are separated cleanly enough to allow sufficiently accurate quantification. Detailed determination of individual oligoglycosides and separation into a and b anomers, pyranosides, and furanosides are only possible with a more polar mobile phase that requires tediously long analyses times. The analysis of alkyl glycosides in commercial alkyl polyglycoside products by HPLC

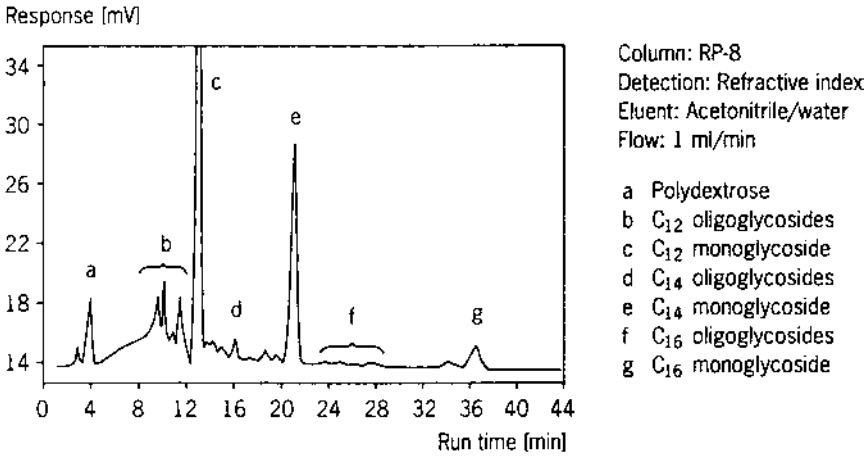

FIG. 5 HPLC chromatogram of alkyl polyglycosides.

provides good results for analytical tasks that do not require high resolution of a broad spectrum of components. Typical applications include raw material identification, comparative alkyl polyglycoside analysis, quantifications and calculations solely on the basis of the alkyl monoglycoside contents.

C. Alkyl Polyglycoside Trace Determination in Environmental Matrices [33]

Most alkyl polyglycoside containing consumer products, such as detergents, cleaners, etc., enter wastewater or the environment after use. A series of tests can be carried out to ensure environmental safety (Table 1) [37]. Substance-specific analytical methods have been developed for this purpose. Those

TABLE 1 Alkyl Polyglycosides: Selected Environmental Safety Tests

Method	Matrix	Concentration (ppm)
OECD confirmatory test	Sewage	40–< 0.2
River stimulation model	River water	10–< 0.1
Acute/chronic *Daphnia* toxicity	Synthetic test medium	100/10–< 0.1
Prolonged fish test	Tap water	10–< 0.1

enable alkyl polyglycosides to be analyzed in environmental matrices with a detection limit in the ppb range.

The first step is to preconcentrate and separate the material of interest from the matrix by solid-phase extraction. The solid-phase material used is hydrophobic silica gel (octadecyltrichlorosilane derivative). After preconditioning with methanol, 0.1–1 L of sample solution is passed through the cartridge or empore disk. After rinsing with water, the adsorbed surfactant is eluted with methanol. Recovery is in the 95–100% range. In the extract, alkyl polyglycosides are determined by HPLC or GC methods identical to or comparable with those already described.

Figure 6 shows the HPLC chromatogram of an alkyl polyglycoside analysis from sewage. Alkyl polyglycoside determination was performed with the aid of a gradient HPLC system using an electrochemical detector to achieve sufficient specificity and sensitivity. Only the peaks of the monoglycosides are clearly separated. Quantification is based on the external standard method. The alkyl polyglycoside sample used for calibration was identical with the alkyl polyglycoside used in the biodegradation test.

Gas chromatography was used to analyze a water sample from a prolonged fish test [37]. The chromatogram is shown in Fig. 7. There are no problems in separating the different alkyl polyglycoside peaks from matrix components due to the high resolution of the GC method used. The sample was analyzed by normal-temperature gas chromatography, which is more suitable for alkyl polyglycoside trace analysis than HTGC.

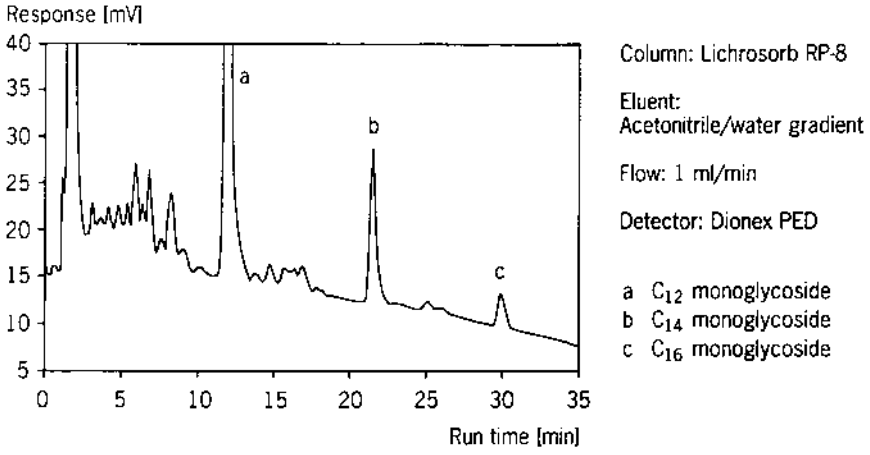

FIG. 6 Determination of alkyl polyglycosides in sewage by HPLC.

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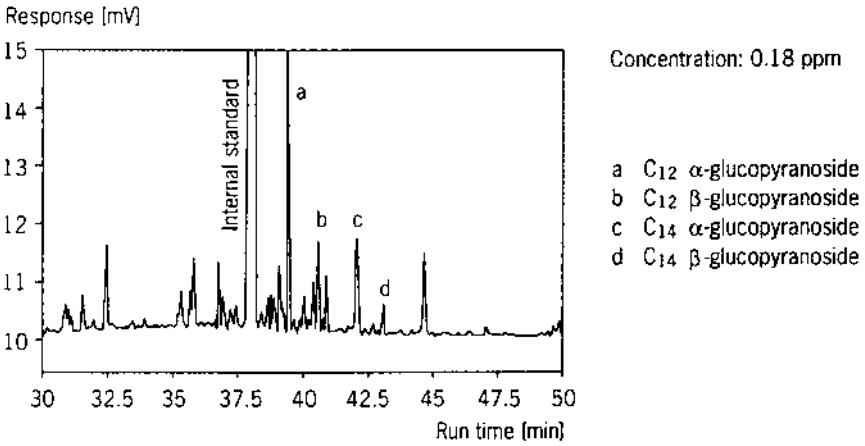

FIG. 7 Determination of alkyl polyglycosides in tap water by GC.

Figure 8 shows a typical alkyl polyglycoside concentration profile from an experiment using the river simulation model [37]. The analytical method was again GC.

D. Future Demands in Alkyl Polyglycoside Analysis

A broad range of analytical methods has been developed to meet present demands in alkyl polyglycoside analysis. Future analytical tasks will be in the environmental sector to improve the sensitivities of analytical methods to

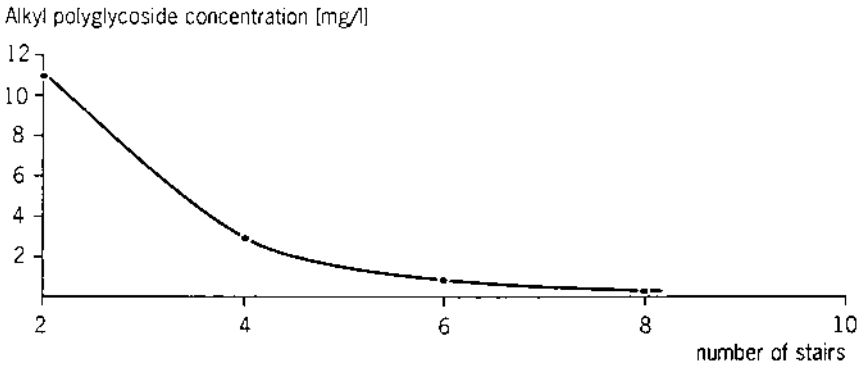

FIG. 8 River simulation model: alkyl polyglycoside concentration profile.

limits below 1 ppb. This will be a realistic range for future alkyl polyglycoside concentrations in real matrices, such as sewage treatment plant effluents, etc. Furthrmore, existing methods for the analysis of commercial alkyl polyglycosides will have to be standardized with regard to the most important quality-relevant parameters.

IV. PHYSICAL CHEMICAL PROPERTIES OF ALKYL POLYGLYCOSIDES

Alkyl polyglycosides were found to possess remarkable physical chemical properties which, in some cases, differ clearly from those of other nonionic surfactants. Significant differences, especially in relation to the behavior of fatty alcohol ethoxylates, are highlighted in the following.

A. Surfactant–Water Systems

1. Surface Tension

The surface tension of alkyl (poly)glycosides was investigated as a function of the alkyl chain and the DP [15,38]. Figure 9 shows the surface tension as a function of concentration for three alkyl monoglycosides (C_nG_1) and a technical $C_{12/14}$ alkyl polyglycoside at 60°C [39]. The critical micelle concentration (CMC) values of the pure alkyl glycosides and the technical alkyl polyglycoside are comparable with those of typical nonionic surfactants and decrease distinctly with increasing alkyl chain length. The alkyl chain length has a far stronger influence on the CMC by comparison with the number of glucoside groups of the alkyl polyglycoside.

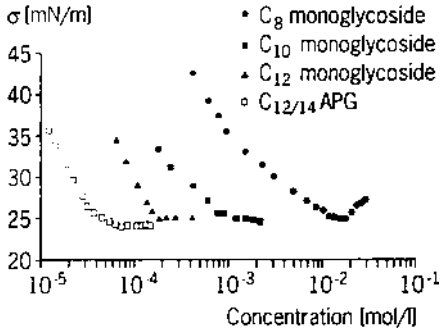

FIG. 9 Static surface tension σ of alkyl glycosides with different alkyl chain lengths as a function of the concentration c in distilled water at 60°C [39].

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There are several studies on the structure of alkyl glucosides at the air–water interface and the micelle formation. Drummond et al. present adsorption data at the air–water interface for alkyl glucosides in their α- and β-anomeric forms and alkyl maltosides in their β-anomeric forms [40]. They show that the anomeric configuration has very little effect on the interfacial adsorption properties. Nuclear magnetic resonance (NMR) self-diffusion measurements and time-resolved fluorescence quenching were used by Nilsson et al. to get information about the micellization ov β-D-glucopyranosides [41]. According to their results, nonspherical aggregates are formed with an axial ratio of approximately 11:1. Aoudia and Zana investigated aggregation behavior, CMC, and micelle aggregation number of octyl glucoside, dodecyl maltoside, and 6-*O*-(*N*-heptylcarbamoyl)methyl-β-D-glucopyranoside in water and water–polymer solutions [42]. The micelle aggregation number proved to be nearly invariant with temperature and concentration; the micelles are relatively monodisperse. The combination of X-ray and neutron scattering experiments indicates that the concentration-dependent micelle growth of β-D-glucopyranoside is restricted to the change in micelle length [43]. It is proposed that the micelles are cylinders growing in length on higher surfactant concentration. The micelles are assumed to have an irregular and dynamic structure with extensive mixing of core, shell, and solvent. Pastor et al. studied the hydration behavior of octyl β-D-glucopyranoside [44]. A hydration number of 16 for monomers below the CMC is calculated. The hydration number is strongly reduced in the micellar state. At low concentrations, a micellar aggregation number of 54 is found which increases for high concentrations to 104.

The surface tension behavior of surfactant mixtures of alkyl polyglycosides and anionic surfactants was investigated with reference to the example of an alkyl polyglycoside/fatty alcohol sulfate (FAS) mixture [39]. The values of the mixtures are near the curve for alkyl polyglycoside despite a high anionic surfactant content. This corresponds to the normally observed behavior of mixtures of anionic and nonionic surfactants differing considerably in their CMC values [45]. A weak attractive interaction between these surfactants can be derived on the basis of Rosen's theory [46]. Sierra et al. reported negative values for the interaction parameter β for mixtures of alkyl glucosides and ionic surfactants [47]. Stradner et al. studied the addition of short-chain alcohols to technical grade alkyl polyglycosides [48]. It could be shown that the addition of the alcohol leads to a reduction of the spontaneous curvature and to structural changes of the micellar aggregates. A transition from small globular aggregates to short cylindrical and giant flexible cylindrical structures is observed.

The kinetics involved in the establishment of surface tension was investigated by measurement of the dynamic surface tension. Figure 10 shows the

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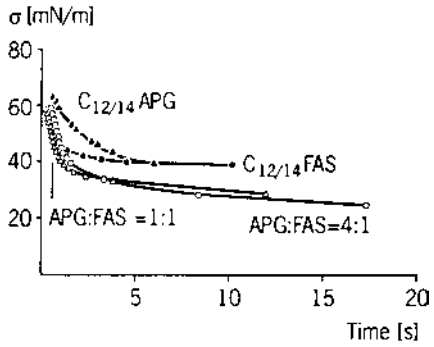

FIG. 10 Dynamic surface tension σ of $C_{12/14}$ APG and $C_{12/14}$ FAS and 1:1 and 4:1 mixtures thereof as a function of time t in distilled water at 40°C and at a concentration of 8×10^{-4} mol L^{-1} [49].

reduction in surface tension as a function of time for the same surfactant solutions at a concentration of 8×10^{-4} mol/L at 40°C [49]. The curve of the pure FAS falls more quickly for short times than that of pure alkyl polyglycoside, which shows that FAS diffuses more quickly to the surface of the liquid than alkyl polyglycoside with the same alkyl chain length. The mixtures of both surfactants reach lower surface tensions than the pure surfactants. It should be noted that surfactants of technical purity were compared with one another in these investigations. This factor can be important to the interpretation of the results of dynamic surface tension measurements because the individual components of the technical surfactants can have a different affinity for the surface [50].

2. Phase Behavior

The thermotropic and crystallization behavior of alkyl glycosides was summarized in a review by Hoffmann and Platz [51]. The α and β anomers show a quite different crystallization behavior according to their crystal structures. The melting enthalpies and Krafft points of the α anomers are essentially higher than those of the β anomers. It is possible to separate the pure β anomers as monohydrates from α/β mixtures by crystallization from water. The thermotropic behavior of glucopyranosides was compared with that of different alkyl glycosides with one or more head groups. In all cases smectic phases with bilayers are formed. The aliphatic chains almost act as a solvent between the layers of the head groups.

The phase behavior of a technical $C_{8/10}$ alkyl polyglycoside is illustrated in Fig. 11 [52]. At temperatures above 20°C, the $C_{8/10}$ alkyl polyglycoside is present up to very high concentrations in an isotropic phase of which the

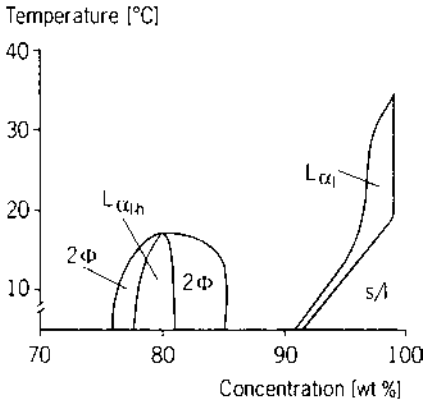

FIG. 11 Phase diagram of the $C_{8/10}$ APG–water system [52].

viscosity increases considerably. A birefringent lyotropic phase of nematic texture is formed at around 95% by weight, which changes at around 98% by weight into a cloudy two-phase region of liquid and solid alkyl polyglycoside. At relatively low temperatures, a lamellar liquid crystalline phase is additionally observed between 75% and 85% by weight.

The phase diagram of the $C_{12/14}$ alkyl polyglycoside/water system (Fig. 12) differs clearly from that of the short-chain alkyl polyglycoside. At low temperatures, a region corresponding to a solid/liquid region below the Krafft point is formed over a wide concentration range. With an increase in temperature, the system changes to an isotropic liquid phase. Since crystallization is kinetically retarded to a considerable extent, this phase boundary

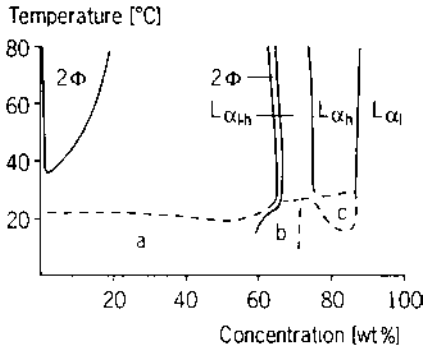

FIG. 12 Phase diagram of the $C_{12/14}$ APG–water system [52].

changes position with the storage time. At low concentrations, the isotropic liquid phase changes above 35°C into a two-phase region of two liquid phases, as is normally observed with nonionic surfactants [53]. At concentrations above 60% by weight, a sequence of liquid crystalline phases is formed at all temperatures. It is important to mention that, in the isotropic single-phase region, a distinct streaming birefringence can be observed at concentrations just below the lyotropic phases, disappearing again rapidly on completion of the shearing process. However, no multiphase regions separating this region from the L_1 phase could be found. In the dilute L_1 phase, there is another region with weaker streaming birefringence that is situated near the minimum of the liquid/liquid miscibility gap.

Investigations into the structure of the liquid crystalline phases were conducted by Platz et al. [54] using such methods as polarization microscopy. According to these investigations, there are three different lamellar regions in concentrated $C_{12/14}$ alkyl polyglycoside solutions: $L_{\alpha l}$, $L_{\alpha l-h}$, and $L_{\alpha h}$. Polarization microscopy shows that there are three different textures. Details of the different structures are given in [54]. The phase diagram of the relatively short-chain alkyl polyglycoside is considerably simpler. At low temperatures, a lamellar phase of the $L_{\alpha l-h}$ type is formed beyond about 80% by weight. Given an apparently nematic texture at around 95% by weight, an $L_{\alpha l}$ phase is probably present (Fig. 13).

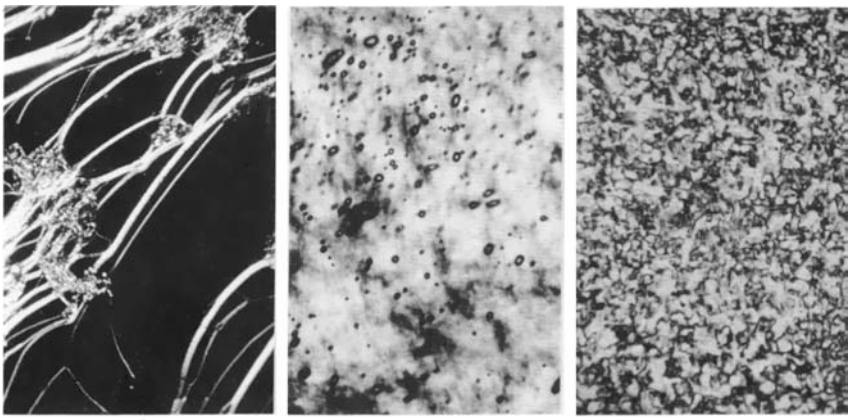

FIG. 13 Polarization micrographs of textures of lyotropic phases in $C_{12/14}$ APG solutions [52]: (a) $L_{\alpha h}$ with pseudoisotropism: 75% by weight at 25°C after heating to 70°C; (b) $L_{\alpha l}$: 90% by weight at 25°C; (c) $L_{\alpha l\text{-}h}$: 68% by weight at 70°C.

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The influence of the DP of alkyl polyglycosides on their phase behavior was described by Fukuda et al. [55]. Figure 14 is a simplified illustration of the phase diagrams of C_{12} alkyl polyglycosides containing different numbers of glucose units in the molecule. The region in which the liquid crystalline phases occurs is only slightly dependent on concentration with a slightly greater expansion in the case of alkyl polyglycosides containing a relatively large number of glucose units. For C_{12} alkyl polyglycosides with a DP of 1.1 and 1.38, it was demonstrated that the entire liquid crystalline region consists of a lamellar phase. The two more hydrophilic surfactants initially form a hexagonal liquid crystalline phase that is converted to lamellar liquid crystals at relatively high concentrations.

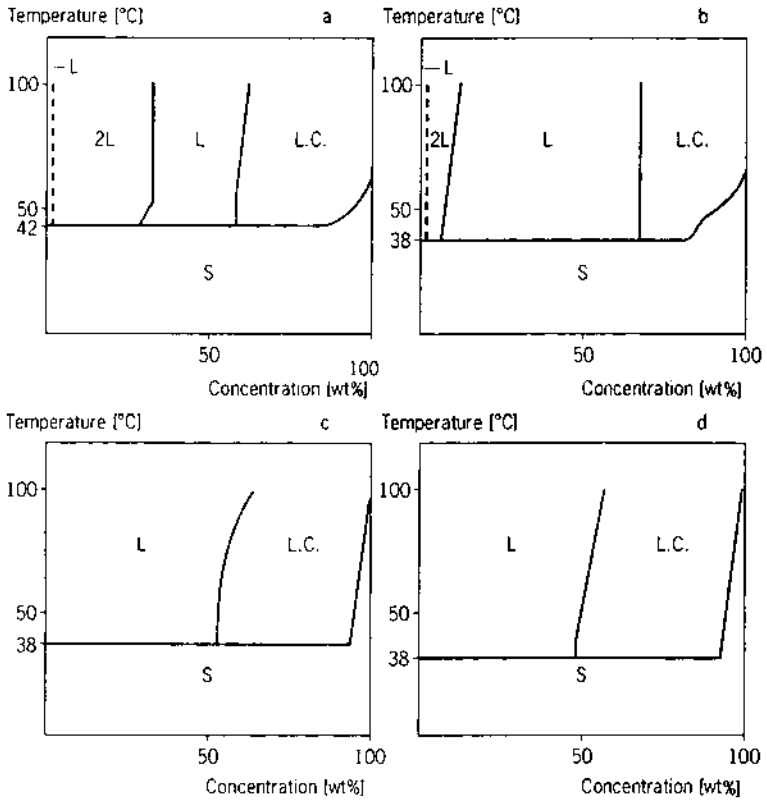

FIG. 14 Schematic phase diagrams of four C_{12} APG–water systems with different DP: (a) 1.1; (b) 1.38; (c) 1.6; (d) 1.8 [55].

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The two alkyl polyglycosides containing relatively few glucose units have a two-phase region (see also Fig. 12) at low concentrations, which is reminiscent of the clouding phenomena of nonionic surfactants of the ethylene oxide type. It can be seen from Figs. 11 and 12 that this effect is strongly dependent on the alkyl chain length so that, although the two-phase region occurs in the case of the $C_{12/14}$ alkyl polyglycoside, it is no longer in evidence in the case of a $C_{8/10}$ alkyl polyglycoside. Balzer [56] investigated the clouding phenomena in dependence on various parameters. He showed that the two-phase region is influenced to a far greater extent by the length of the alkyl chain than in the case of alkyl polyglycol ethers. If it is assumed that the cloud point of alkyl polyglycol ethers is linearly dependent on the alkyl chain length, a shortening of the alkyl chain by two carbon atoms represents an increase in the cloud point of around 15°C. By contrast, in the case of alkyl polyglycosides, the lower separation temperature of a $C_{12/14}$ alkyl polyglycoside is between about 20°C and 40°C, depending on the chain length distribution and the DP. At temperatures of up to 100°C, a $C_{10/12}$ alkyl polyglycoside no longer shows any separation so that, in this case, the differentiation is at least 60–80°C for a difference of two carbon atoms in the alkyl chain.

If small quantities of electrolyte are added to alkyl polyglycosides, clouding phenomena are also observed with relatively short-chain alkyl polyglycosides [56]. In this case, the electrolyte effect is far more clearly pronounced than in the case of alkyl polyglycol ethers (C_nE_x) for which the influence of salt type and concentration has long been known [57]. The results for a $C_{12/14}E_7$ and a $C_{12/14}$ alkyl polyglycoside with a DP of 1.8 on addition of various sodium salts are compared with one another in Fig. 15 [56]. In the case of $C_{12/14}E_7$, SCN^- and I^- anions increase the cloud point whereas all other anions investigated lead to a more or less pronounced reduction in the cloud point. The necessary concentration of electrolytes is very high. According to Balzer [56], these effects may be understood on the basis of a balance of the interactions between water and ethylene oxide (EO) groups. On the one hand, there is a highly ordered hydration shell of the EO groups and, on the other hand, a more or less strong polarization of water by the ions. The very large and weakly polarizing anions I^- and SCN^- are presumably concentrated in the vicinity of the EO group, which contributes to an increase in the repelling electrostatic interaction of the micelles and increases the cloud point. With all other electrolytes, the strong hydration of the small and highly polarizing ions, together with the high concentration, probably disturbs the entropically unfavorable hydrate structure of the EO group. According to Kjellander [58], this leads to the displacement of the electrolyte from the vicinity of the EO group with a mutually attracting interaction of the micelles; the cloud point falls.

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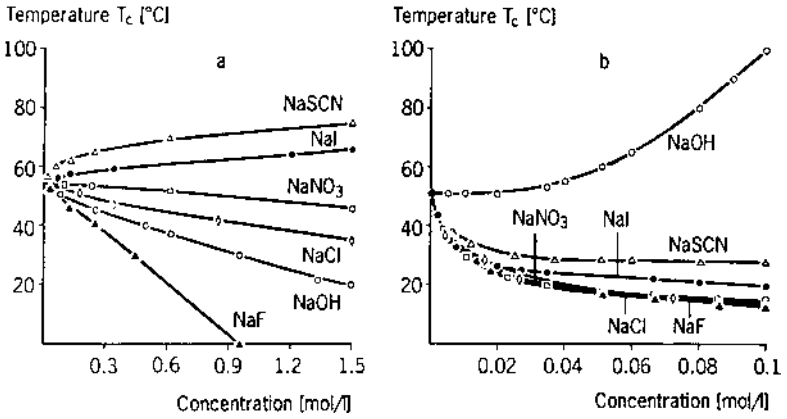

FIG. 15 Cloud point temperatures T_c of 5% surfactant solutions as a function of the electrolyte concentration c: (a) 5% $C_{12/14}E_7$; (b) 5% $C_{12/14}$ APG (DP 1.8) [56].

In the case of alkyl polyglycosides, a different picture emerges. With the exception of NaOH, all electrolytes lead to a distinct reduction in the cloud point. The concentration range of the electrolyte is lower by about one order of magnitude than in the case of alkyl polyglycol ethers. Surprisingly, there are only very slight differences between the individual electrolytes. The addition of alkali produces a distinct reduction in the clouding phenomenon. As an explanation for the difference in behavior between alkyl polyglycosides and alkyl polyglycol ethers, it may be assumed that the cumulative OH groups of the glucose units undergo a different type of hydration compared with the ethylene oxide groups. The distinctly greater effect of electrolytes on alkyl polyglycosides suggests that there is a charge at the surface of the alkyl polyglycoside micelles of which the absence is postulated for alkyl polyglycol ethers [59]. Accordingly, the behavior of alkyl polyglycosides resembles that of mixtures of alkyl polyglycol ethers and anionic surfactants [60]. Investigations of the interactions between alkyl polyglycosides and anionic and cationic surfactants and ζ potential measurements on emulsions indicate that alkyl polyglycoside micelles have a negative surface charge in the pH range from 3 to 9 [24]. By contrast, the charge of micelles of alkyl polyglycol ethers is weakly positive or approximately zero. The reasons for the negative charge of the alkyl polyglycoside micelles have not yet been fully explained.

3. Rheological Properties

The flow behavior of alkyl polyglycoside solutions is characterized by three different viscosity ranges. At low concentrations, the viscosity increases linearly with concentration. The results of measurements with an Ubbelohde

capillary viscosimeter set out in Fig. 16 show that $C_{8/10}$ alkyl polyglycoside follows this linear relation to beyond 5% while the long-chain $C_{12/14}$ alkyl polyglycoside barely follows it up to 0.05%. In the case of $C_{8/10}$ alkyl polyglycoside, the slope of the specific viscosity against the volume fraction of the surfactant weighed in is 3.9. For nonhydrated spherical micelles, a value of 2.5 would be expected on the basis of the Einstein equation. Above these concentrations, there is a region in which the viscosity of both surfactants increases considerably with concentration. In the case of $C_{12/14}$ alkyl polyglycoside, this increase is confined to a narrow concentration range of up to about 15%, whereas $C_{8/10}$ alkyl polyglycoside exhibits corresponding behavior up to the highest concentrations.

The third viscosity range is only observed in the case of $C_{12/14}$ alkyl polyglycosides. Above 15%, the viscosity only increases linearly with concentration up to almost the lyotropic phase. Therefore, at very high concentrations the viscosities of $C_{8/10}$ and $C_{12/14}$ alkyl polyglycosides are almost identical on the logarithmic scale (Fig. 17). The particularly high increase in viscosity is attributable in the case of $C_{12/14}$ alkyl polyglycoside to steric hindrances during the shearing of rod-like micelles, which are formed even at very low concentrations and overlap one another in space. By contrast, in the case of $C_{8/10}$ alkyl polyglycoside, the micelles are substantially spherical. Accordingly, viscosity remains low up to high concentrations. At the onset of the mutual steric hindrance of the spherical micelles, viscosity increases considerably and even reaches the values of $C_{12/14}$ alkyl polyglycoside solutions of equal concentration.

4. Multicomponent Systems

The addition of fatty alcohols as a third component to alkyl polyglycoside–water mixtures leads to the appearance of different lamellar phases over the

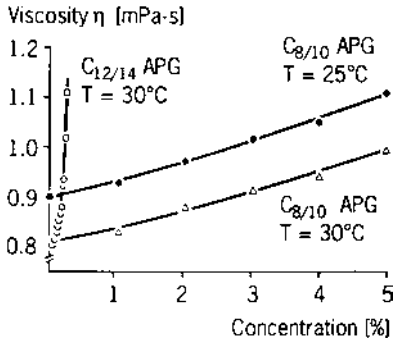

FIG. 16 Viscosities of dilute $C_{8/10}$ and $C_{12/14}$ APG solutions [52].

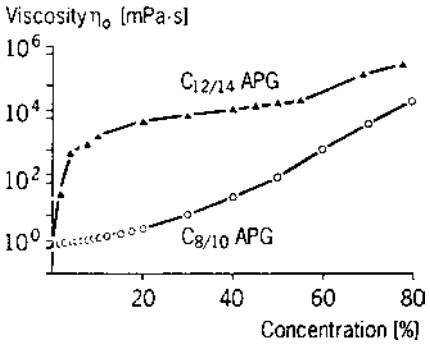

FIG. 17 Zero shear viscosities from oscillating measurements at 30°C [52].

entire concentration range [54]. This behavior is typical of the influence of fatty alcohols on the phase behavior of binary surfactant–water systems [61]. The lamellar phases are surrounded by L_3 phases that are optically isotropic and, at the same time, show strong streaming birefringence. The influence of the chain length of the fatty alcohol on the position of the phases in the ternary $C_{12/14}$ alkyl polyglycoside–water–alcohol systems is illustrated in Fig. 18 for the example of a 5% $C_{12/14}$ alkyl polyglycoside solution. The quantity of alcohol added is plotted against the chain length of the alcohols. When butanol is added, a liquid–liquid separation occurs. Alcohols with a longer

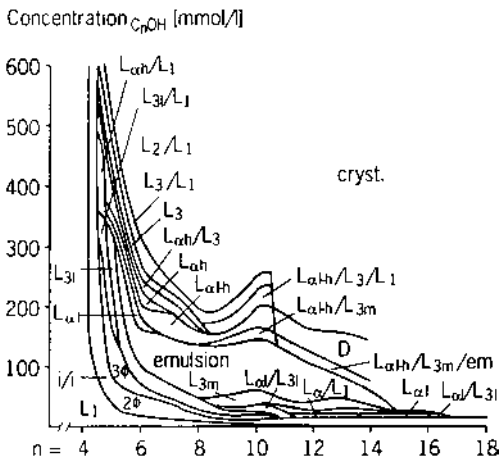

FIG. 18 Phase behavior of a 5% $C_{12/14}$ APG solution on addition of alcohols varying in alkyl chain length *n* at 25°C [54].

alkyl chain ($n > 4$) promote the formation of liquid crystalline phases. It is clear that the relative sequence of the individual phases is almost the same with all alcohols. A marked dependence on concentration is evident in particular in the case of short-chain and medium-chain alcohols. The quantity of alcohol that has to be added to ensure that a certain phase is formed decreases drastically with increasing alkyl chain length of the alcohol. When relatively long-chain alcohols are added, the $L_{\alpha l\text{-}h}$ phase becomes the dominant phase.

In principle, the phase sequences observed with mixtures of alkyl polyglycosides and anionic surfactants, which are of particular importance in practice, are similar to those observed with the ternary systems of alkyl polyglycoside, alcohol, and water [54]. The $L_{\alpha l}$ phase disappears on the addition of fatty alcohol sulfates and the $L_{\alpha l\text{-}h}$ region becomes very dominant. The phases that additionally contain ionic surfactants appear optically more transparent and have a higher viscosity and elasticity than systems consisting solely of alkyl polyglycoside and alcohol. Yield points, which increase considerably with increased concentration of FAS, are obtained in the $L_{\alpha l\text{-}h}$ and L_{3m} phases of these systems. Dilute lamellar phases can only be obtained in $C_{12/14}$ alkyl polyglycoside solutions by addition of fatty alcohol. Fatty alcohol has to be added for steric reasons. Anionic surfactants have large head groups. Accordingly, in the case of systems containing FASs, relatively large quantities of fatty alcohol are required to obtain a lamellar structure. This explains why the lamellar phases in these systems are displaced toward higher fatty alcohol concentrations. It is interesting that the repelling forces between the charged lamellae and hence the elastic shear moduli are far greater than in uncharged systems. Relatively large viscous and elastic moduli were observed with all the anionic surfactants investigated. Alkyl polyglycosides with carbon chains longer than C_{12} contribute readily to the buildup of rodlet-like mixed micelles in solutions of anionics (Fig. 19) and thus make a considerable contribution towards increasing viscosity [62,63]. This effect, on the one hand, is somewhat weaker in standard ether sulfate formulations than with alkanolamides but, on the other hand, is more pronounced with sulfosuccinates and highly ethoxylated alkyl ether sulfates, which are very difficult to thicken with alkanolamides. Alkyl polyglycoside formulations without anionics can best be thickened by adding polymeric thickeners, such as xanthan gum, alginate, polyethoxylated esters, carbomers, etc.

The addition of anionic surfactants also has an influence on the clouding phenomena. The cloud points are considerably increased by small quantities of alkyl sulfates. According to Balzer [56], small quantities of alkyl sulfate lead to a change in the electrical charge of the alkyl polyglycoside micelles. This results in a greater repelling interaction between the micelles and leads to a distinct increase in the cloud point.

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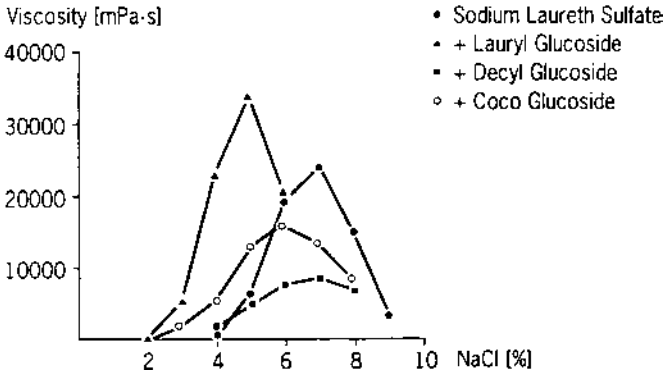

FIG. 19 Increase of viscosity by alkyl polyglycosides (10% AS SLES and 3% AS alkyl polyglycoside at 25°C) [63].

B. Surfactant Water–Oil Systems

1. Oil/Water Interfacial Tension

The interfacial tensions of various alkyl polyglycosides against three oils (decane, isopropyl myristate, and 2-octyl dodecanol) differing in structure and polarity was investigated by Kutschmann et al. [63]. Figure 20 shows the interfacial tension of C_8G_1, $C_{10}G_1$, and $C_{12}G_1$ against decane at 60°C in dependence on the surfactant concentration. The concentrations at the break in the curves (c_b) accord well with the CMC values obtained from surface tension measurements. This means that in the equilibrium state the surfactant

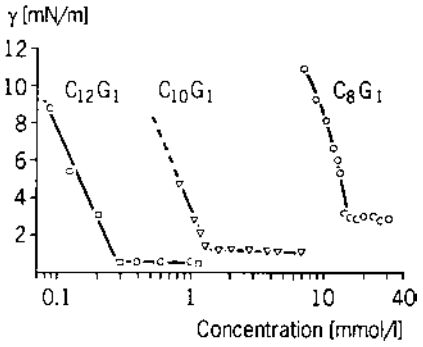

FIG. 20 Influence of alkyl glycosides (C_nG_1) on decane–water interfacial tension. Equilibrium values of the interfacial tension γ as a function of the initial concentration c of the surfactant in the water phase [64].

is completely present in the aqueous phase and is not measurably dissolved in the decane phase. In the range from 25°C to 60°C, there is no indication of dependence on temperature. This is a clear difference by comparison with the similarly nonionic fatty alcohol ethoxylates.

Since electrolyte solutions are used instead of pure water in many industrial applications, results on the influence of an electrolyte on the interfacial activity of alkyl polyglycosides are also available for a technical $C_{8/10}$ alkyl polyglycoside. Even with extremely large additions of NaCl of more than 20% to the aqueous phase, the plateau value of the interfacial tension against decane remains substantially constant. These results also confirm earlier investigations conducted by Shinoda et al. [38] in which it was shown that the addition of lyotropic salts to aqueous solutions of alkyl monoglucosides has no significant effect on surface tension. Only a slight shift in the CMC toward lower concentrations was observed.

The influence of oil polarity is clearly illustrated by comparing the interfacial tension of aqueous solutions of alkyl monoglycosides against different oils. The concentration at the breaks of the interfacial tension–concentration curves is shown in Fig. 21 as a function of the alkyl chain length of the surfactants for three different oils. It can clearly be seen how the position of the CMC apparently shifts to higher values with increasing oil polarity. This effect is more pronounced the longer the alkyl chain length of the glucoside. One possible explanation for this is the increase in the solubility of the surfactant in the oil phase with increasing alkyl chain length and, hence, hydrophobicity or increasing polarity of the oil.

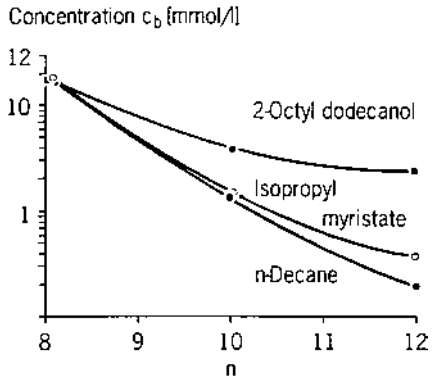

FIG. 21 Concentration at the break in the interfacial tension/concentration curves c_b in three different oil–water systems as a function of the alkyl chain length of the surfactant n at 60°C [64].

The reduction in interfacial tension that can be achieved by surfactants can be expected to depend also upon the surface-active character of the oil. This dependence is illustrated by way of example for $C_{10}G_1$ in Fig. 22. The empty circles represent the interfacial tension values γ_0 in the pure oil–water system whereas the filled-in circles represent the plateau values of the interfacial tension γ_c. The γ_0 value of octyl dodecanol/water is lower than that of isopropyl myristate/water. The reason for this may lie in the different hydrophobicity and in the different sizes of the head groups of these two oils. For octyl dodecanol, the long alkyl chain provides for an additional surface-active character, which should have a strong influence on interfacial behavior. Accordingly, the corresponding values for decanol are also included for comparison. In this case, a monolayer of decanol molecules can be expected at the boundary layer. In the presence of such a monolayer, surfactant molecules with a large head group should be incorporated less easily than might be expected for nonpolar oils or oils with a weakly pronounced surfactant character.

2. Phase Behavior

Ternary systems of water, oil, and nonionic surfactants can form microemulsions that are of particular interest because, on the one hand, they are widely used in practice and, on the other hand, they are suitable as well-defined ternary mixtures for systematic experimental studies [65,66]. One characteristic of ethoxylated nonionic surfactants is their pronounced dependence on temperature. The phase behavior of simple alkyl polyglycoside–water mixtures differs in certain aspects from other nonionic surfactants. Temperature in particular is a parameter of minor importance in any comparison of alkyl polyglycosides with fatty alcohol ethoxylates.

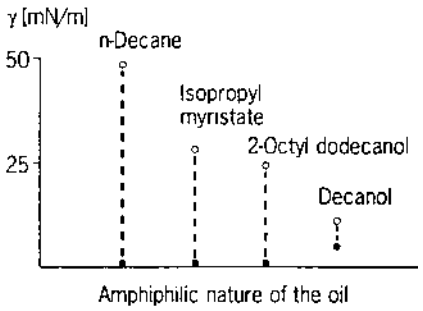

FIG. 22 Oil–water interfacial tensions γ_o (○) and plateau values of the interfacial tension γ_c (●) for $C_{10}G_1$ in oil–water systems with increasing amphiphilicity of the oil [64].

Whereas the hydrate shell of the ethoxylate head group depends largely on temperature, the interaction of the sugar unit of alkyl polyglycoside with water is only slightly influenced by temperature. This is reflected in the fact that the phase behavior of simple binary alkyl polyglycoside–water mixtures shows only comparatively weak temperature effects [54,67,68]. Whereas temperature is the basis of the known phase inversion temperature (PIT) phenomenon [65,66,69] for ethoxylated nonionic surfactants, no temperature-dependent phase inversion can be expected to occur in alkyl polyglycoside–containing emulsions.

Similarly to anionic surfactants, alkyl polyglycosides react to the addition of cosolvents that increase the solubility of the surfactant in the oil phase. In the decane–water–alkyl polyglycoside system, the addition of the cosolvent *i*-butanol results in a drastic reduction in the interfacial tension between oil and aqueous phase and, hence, in the formation of a third phase, the microemulsion [70]. As expected, the range in which this three-phase microemulsion exists is only slightly dependent on temperature and, in contrast to anionic surfactants, is also hardly affected by electrolytes [70]. Systematic investigations of the phase behavior confirm these initial results for a number of simple hydrocarbons from hexane to hexadecane and aromatics [71,72].

Another way of achieving balanced hydrophilic–lipophilic properties is to combine the hydrophilic emulsifier alkyl polyglycoside with a hydrophobic coemulsifier. With reference to the example of cyclohexane–water emulsions, Fig. 23 shows how both the mixing ratio of alkyl polyglycoside to the hydrophobic coemulsifier alkyl glyceryl ether and the oil/water ratio influence the type of emulsion [55]. A total emulsifier concentration of 4% for a balanced emulsifier mixing ratio is sufficient to form a single-phase microemulsion that extends transversely through the diagram as a single-phase channel. The inserted figure demonstrates the temperature stability of the microemulsion.

Representation of the microemulsion phases as a function of formulation parameters (e.g., temperature for systems containing fatty alcohol ethoxylate) and emulsifier concentration, as described in [65,73], has been successful as an aid for practical formulation work. A basically similar picture emerges for emulsions of oil, water, and an emulsifier mixture of alkyl polyglycoside and a hydrophobic coemulsifier when, instead of temperature as the formulation parameter, the mixing ratio of alkyl polyglycoside to hydrophobic coemulsifier is varied [73,74]. In the case of the specific emulsifier mixing ratio of 1:1, the system of dodecane, water, $C_{12/14}$ alkyl polyglycoside and sorbitan monolaurate (SML) as hydrophobic coemulsifier forms microemulsions (Fig. 24). The emulsions formed with a relatively large SML content are water-in-oil (w/o) emulsions while the emulsions formed with a relatively large alkyl polyglycoside content are oil-in-water (o/w) emulsions. By varying

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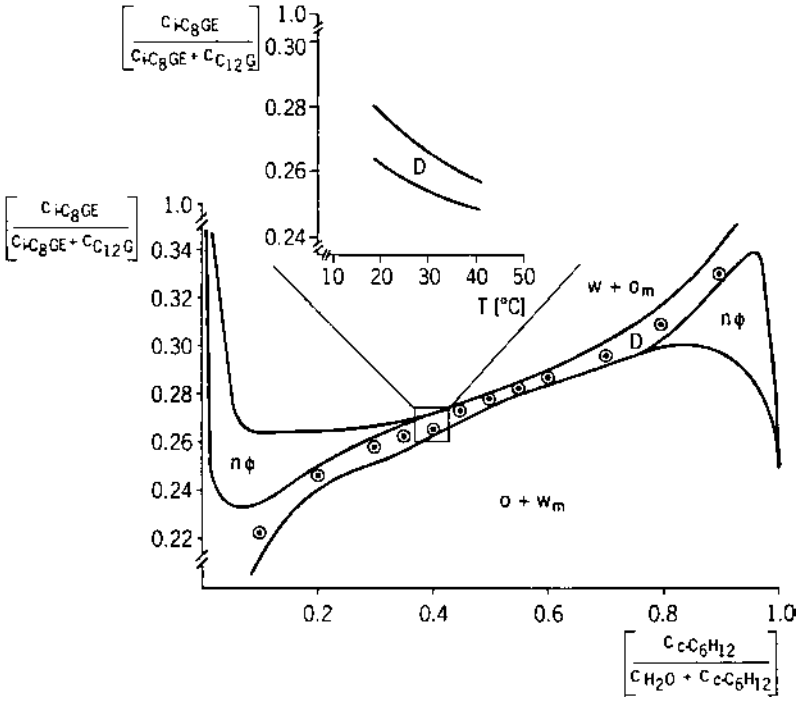

FIG. 23 Phase diagram for the system water, cyclohexane (c-C_6H_{12}), 2-ethylglycerolether (i-C_8GE), C_{12} APG at 25°C and a total emulsifier content of 4% Detail: temperature dependence of the microemulsion range for an oil content of 40% [55].

the overall emulsifier concentration, a "Kahlweit" fish again appears in the phase diagram with three-phase microemulsions in its body and a single-phase microemulsion in its tail. The similarity between alkyl polyglycosides and fatty alcohol ethoxylates is not confined to phase behavior but also applies to the interfacial tension of the emulsifier mixture. With an alkyl polyglycoside/SML ratio of 4:6, the hydrophilic–lipophilic properties of the emulsifier mixture are balanced and the interfacial tension is minimal. It is remarkable that the alkyl polyglycoside/SML mixture produces a very low minimal interfacial tension value (around 10^{-3} mN/m) which, once again, is lower by one order of magnitude than that observed in the case of the fatty alcohol ethoxylate system [55,65,75].

In the case of the alkyl polyglycoside–containing microemulsion, the high interfacial activity is attributable to the fact that the hydrophilic alkyl

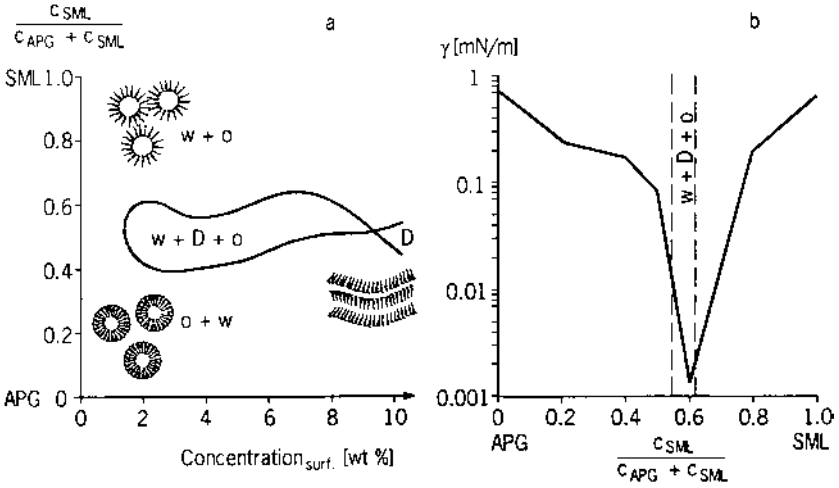

FIG. 24 (a) Phase behavior of the system dodecane–water in a ratio of 1:1, $C_{12/14}$ APG, sorbitan monolaurate in dependence on the ratio of APG to SML as a function of the total surfactant concentration. (b) Interfacial tension of the system dodecane–water in a ratio of 1:1 $C_{12/14}$ APG, sorbitan monolaurate in dependence on the ratio of APG to SML for a total surfactant concentration of 1.5% [73].

polyglycoside with the large polyglycoside head group is present in exactly the right mixing ratio with the hydrophobic coemulsifier SML with its small head group at the oil–water interface. In contrast to ethoxylated nonionic surfactants, hydration and hence the effective size of the head group are hardly dependent on temperature [55,70,76], an attribute that can be utilized for formulating temperature-stable microemulsions [76]. Figure 25 shows by way of example the phase behavior of a system of dioctyl cyclohexane and water and also 15% of an emulsifier mixture of $C_{12/14}$ alkyl polyglycoside and glycerol monooleate (GMO). Irrespective of the temperature, the system forms transparent microemulsions or very fine-particle blue emulsions (particle size around 100 nm) of the o/w type, which was determined by measurement of the electrical conductivity, for alkyl polyglycoside GMO ratios of 60:40 to 75:25. The formation of a microemulsion phase strongly depends on the structure of the coemulsifier [77]. Figure 26 demonstrates that an exchange of the coemulsifier GMO by the coemulsifier triglyceryl diisostearate leads to a strongly reduced extension of the concentration range in which the microemulsion phase is stable. Obviously, the optimal packing of the alkyl polyglycoside and the coemulsifier at the interface is an important factor for high efficiency.

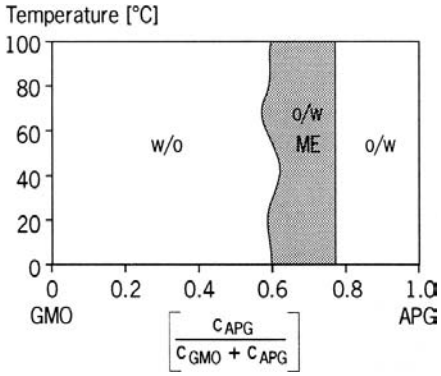

FIG. 25 Phase behavior of the system water–dioctyl cyclohexane in a ratio of 1:1 with 15% of mixtures of glycerol monooleate and $C_{12/14}$ APG at 25°C [45].

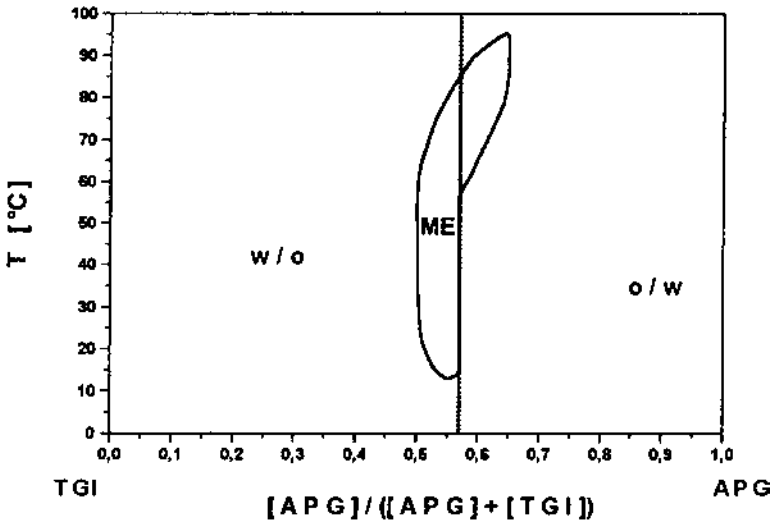

FIG. 26 Phase behavior of the system water–dioctyl cyclohexane in a ratio of 1:1 with 15% of mixtures of triglyceryldiisostearate (TGI) and $C_{12/14}$ APG at 25°C [77].

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Interesting effects can be observed for mixtures of alkyl glycosides and alkyl polyglycosides. By addition of alkyl β-D-glucopyranosides to mixtures of water, octane, and alkyl polyglycol ether, the temperature range of the microemulsion phase strongly increased [78]. The size and the extent of the three-phase region depend on the glucoside concentration and the amphiphilicity of the alkyl polyglycol ether. Combining the effect of the hydrophobic coemulsifier and the alkyl polyglycol ether it is possible to extend the microemulsion phase to a broad concentration and temperature range [79]. Figure 27 shows this effect for a system of decyl glucoside (APG), GMO, lauryl tetraglycol ether (laureth-4), dioctyl cyclohexane, and water. Even for the high water content of 90% microemulsion phases are obtained that are stable in a broad temperature range. This systematic approach of a variation of the emulsifier mixture can be used to formulate microemulsion phases with polar oils like perfume oils [78,80]. The perfume oil can act at least partially as a lipophilic cosurfactant due to the relatively low interfacial tension against water.

This provides for interesting applications because, in contrast to fatty alcohol ethoxylates, temperature-stable microemulsions can be formed with alkyl polyglycosides. By varying the surfactant content, the type of surfactant used, and the oil/water ratio, microemulsions can be produced with custom-made performance properties, such as transparency, viscosity, refatting effect, and foaming behavior. In mixed systems of, say, alkyl ether sulfates and nonionic coemulsifiers (alkyl polyglycoside), extended microemulsion areas

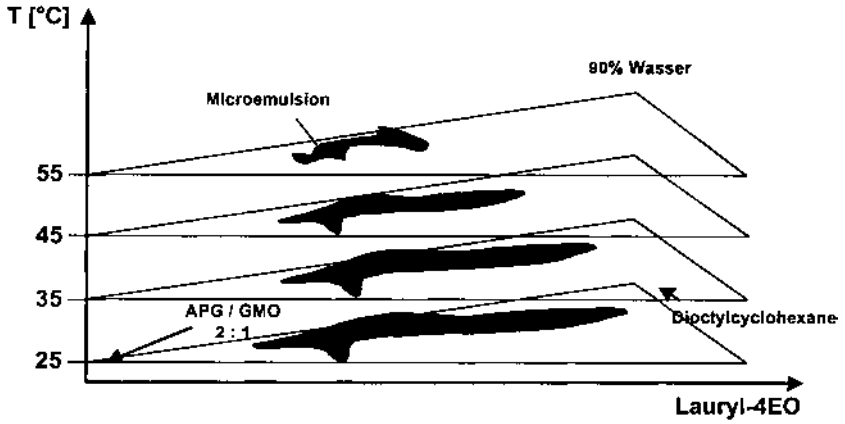

FIG. 27 Temperature effect on the microemulsion phase of a system of decylglucoside (APG), glycerol monooleate (GMO), lauryltetraglycolether (laureth-4), dioctyl cyclohexane, and water at a water concentration of 90 % weight [79].

are observed and may be used for the formulation of concentrates or fine-particle o/w emulsions [81,82].

An evaluation has been made of pseudoternary phase triangles of multicomponent systems containing alkyl polyglycoside/sodium laureth sulfate (SLES) and SML with a hydrocarbon (dioctyl cyclohexane) [82] and alkyl polyglycoside/SLES and GMO with polar oils (dicaprylyl ether/octyl dodecanol) [81]. They demonstrate the variability and extent of areas for o/w, w/o, or microemulsions for hexagonal phases and for lamellar phases in dependence on the chemical structure and mixing ratio of the components. If these phase triangles are superimposed on congruent performance triangles indicating, say, foaming behavior and viscosity properties of the corresponding mixtures, they provide a valuable aid for the formulator in finding specific and well-designed microemulsion formulations for, say, facial cleansers or refatting foam baths. As an example, a suitable microemulsion formulation for refatting foam baths can be derived from the phase triangle in Fig. 28.

The oil mixture consists of dicaprylyl ether and octyl dodecanol in a ratio of 3:1. The hydrophilic emulsifier is a 5:3 mixture of cocoglucoside (APG) and sodium laureth sulfate (SLES). This high-foaming anionic surfactant mixture forms the basis of many body cleansing formulations. The hydrophobic coemulsifier is GMO. The water content is kept constant at 60%. Starting

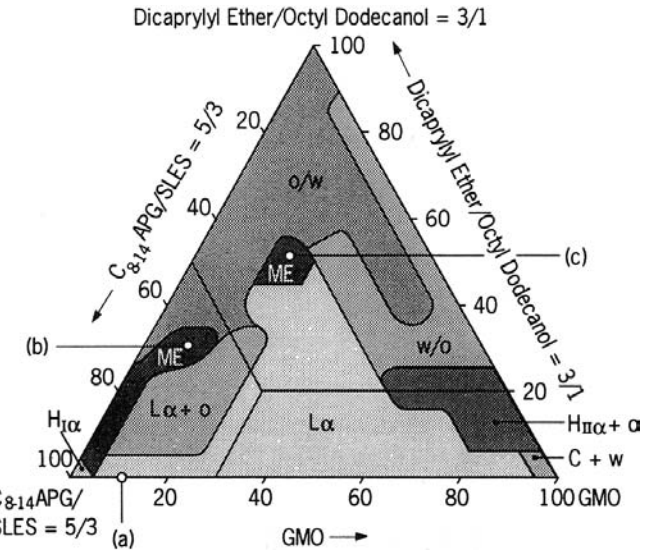

FIG. 28 Pseudoternary phase triangle of a six-component system (60% water, 25°C).

from an oil- and coemulsifier-free system, a 40% APG/SLES mixture in water forms a hexagonal liquid crystal ($H_{I\alpha}$). The surfactant paste is highly viscous and nonpumpable at 25°C. Only a fraction of the APG/SLES mixture need be replaced by the hydrophobic cosurfactant GMO to obtain a lamellar phase of medium viscosity [L_α, point (a) with a value of 23,000 mPa at 1 s^{-1}]. In terms of practical application, this means that the high-viscosity surfactant paste changes into a pumpable surfactant concentrate.

Despite the increased GMO content, the lamellar phase remains intact. However, the viscosity increases significantly and reaches levels for the lipid gel that are even above those of the hexagonal phase. In the GMO corner, the mixture of GMO and water forms a solid cubic gel. When oil is added, an inverse hexagonal liquid ($H_{II\alpha}$) is formed with water as the internal phase. The hexagonal liquid crystal, which is rich in surfactants, and the lamellar liquid crystal differ considerably in their reactions to the addition of oil. Whereas the hexagonal liquid crystal can only take up very small quantities of oil, the lamellar phase area extends far toward the oil corner. The capacity of the lamellar liquid crystal to take up oil clearly increases with increasing GMO content. Microemulsions are only formed in systems with low GMO contents. An area of low-viscosity o/w microemulsions extends from the APG/SLES corner along the surfactant/oil axis up to an oil content of 14%. At point (b), the microemulsion consists of 24% surfactants, 4% coemulsifier, and 12% oil, representing an oil-containing surfactant concentrate with a viscosity of 1600 mPas at 1 s^{-1}.

The lamellar area is followed by a second microemulsion area at point (c). This microemulsion is an oil-rich gel with a viscosity of 20,000 mPa at 1 s^{-1} (12% surfactants, 8% coemulsifier, 20% oils) and is suitable as a refatting foam bath. The APG/SLES mixture contributes to cleansing performance and foam whereas the oil mixture acts as a refatting skin care component. In order to obtain a refatting effect with a microemulsion, the oil must be released, i.e., the microemulsion must break up during application. A microemulsion of suitable composition breaks up during rinsing-off when it is heavily diluted with water, thus releasing the oil for refatting effects on the skin. In conclusion, it may be said that microemulsions can be produced with APG in combination with suitable coemulsifiers and oil mixtures. They are distinguished by their transparency and by their high temperature stability, high storage stability, and high solubilizing capacity for oils.

C. Surfactant Water–Solid Systems

Surfactants also influence the interface of liquid systems with solid substrates by virtue of their amphiphilic structure [83]. This affects many applications

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and, hence, may also be used for numerous processes [84–86]. Nickel et al. [87] reported on the adsorption of alkyl glycosides to various types of solids and demonstrate a connection with the dispersion of solids. Figure 29 shows the adsorption behavior of C_8G_1 for graphitized carbon black at 22°C. The adsorption isotherm is characterized by a very steep initial slope that did not allow adsorption on be measured at low surface coverages by any of the analytical methods available. This behavior is indicative of a high affinity of the alkyl glycosides for this solid surface. In addition to the adsorption curve, the theoretical monolayers are marked in flat and in vertical arrangements. For a flat arrangement of the molecule, the maximal monolayer concentration is 1.6×10^{-6} mol m^{-2}. If only the alkyl chain and the ether oxygen are adsorbed, which corresponds to a vertical arrangement, the monolayer concentration is 3.2×10^{-6} mol m^{-2}. The first value is reached at a very low alkyl glycoside concentration of around 0.1 g/L. Thereafter, the curve only climbs slightly and, in the concentration range investigated, does not approach the monolayer capacity for a vertical arrangement of the surfactant molecules. The simultaneous measurement of the adsorbed amounts and the enthalpy of displacement allows more thorough insight into the adsorption behavior. Kiraly and Findenegg describe such studies for the adsorption of a *n*-octyl-β-D-monoglucoside onto hydrophilic silica glass and hydrophobic graphitized carbon black [88]. The initial adsorption of the alkyl glucoside onto hydrophobic graphite is strongly exothermic (Fig. 30). The adsorbed monomers form an ordered, more or less close-packed, flat monolayer in this region. After this, the adsorption becomes endothermic, i.e., entropically driven. The alkyl glucoside is likely to form hemicylindrical aggregates

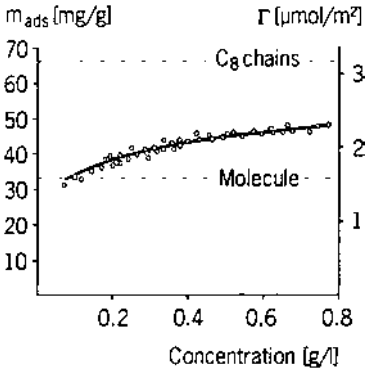

FIG. 29 Adsorbed quantity m_{ads} and surface concentration Γ of C_8G_1 on graphitized carbon black as a function of the surfactant concentration c in water at 22°C [87].

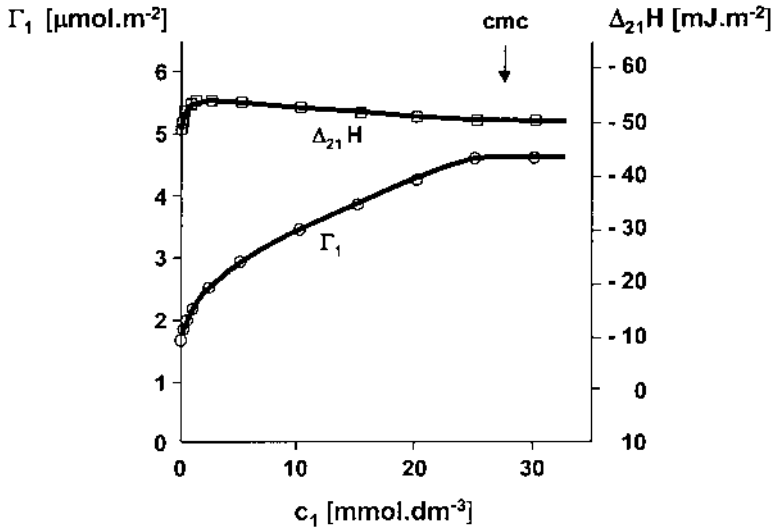

FIG. 30 Adsorption isotherm and integral enthalpy isotherm of displacement for the of *n*-octyl-β-D-monoglucoside (1) – water (2)/graphitized carbon black V3G at 298.15 K [88].

templated by the monolayer. However, the surfactant molecules in the second layer are less strongly bound to the first layer, so that the overall structure and the enthalpy of formation of this aggregate geometry are similar to those of loosely packed surface hemicylinders.

Alkyl polyglycosides are also adsorbed onto polar surfaces, e.g., a hydrophilic glass surface (Fig. 31), although the quantities adsorbed are lower by a factor of about 100 than those adsorbed onto graphitized carbon black The figure shows the adsorption isotherms of C_8G_1 and $C_{10}G_1$ on the controlled-pore glass CPG-10 at two temperatures. In the interests of a better comparison, the concentration is plotted relative to the CMC. A surface coverage with a close-packed monolayer is not remotely reached in the concentration range investigated below the CMC. This suggests that the alkyl glycoside molecules are adsorbed as isolated individual molecules. There can be no associative interactions and hence no increased adsorption. Temperature has only a slight influence in this adsorption system. Similarly to graphitized carbon black, the quantities adsorbed are slightly lower at relatively high temperatures [87]. This is in contrast to the adsorption behavior fatty alcohol ethoxylates. Comparison with the adsorption behavior of $C_{10}E_4$ on graphitized carbon black at three temperatures, as illustrated in Fig. 32, shows clear differences between the surfactant types. A marked dependence on temper-

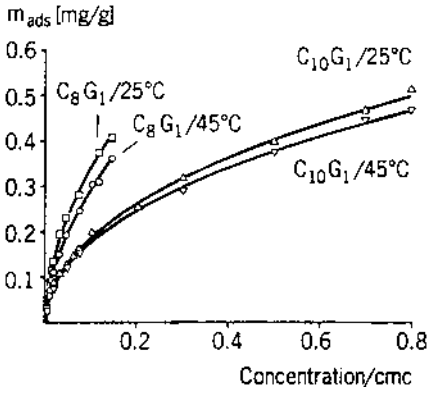

FIG. 31 Adsorbed quantity m_{ads} of C_nG_1 on CPG as a function of the surfactant concentration c relative to the CMC [87].

ature in the upper concentration range can be seen for the fatty alcohol ethoxylate. In contrast to the alkyl glycosides, adsorption increases with increasing temperature. The critical parameter for the dependence of the adsorption of $C_{10}E_4$ on temperature is clearly the cloud point (T_c = 20°C). The adsorption of $C_{10}E_4$ increases dramatically at temperatures above T_c. On the other hand, a C_8E_4 with a cloud point of 40°C also shows significant dependence of adsorption behavior on temperature below the cloud point [87].

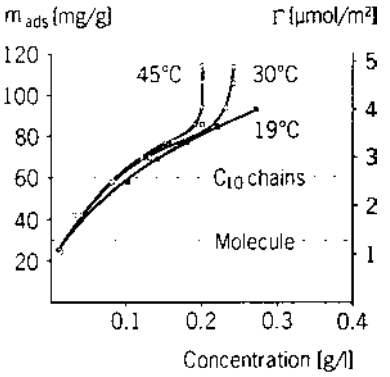

FIG. 32 Adsorbed quantity m_{ads} and surface concentration Γ of $C_{10}E_4$ on graphitized carbon black as a function of the surfactant concentration c in water at 19°C (■), 30°C (□) and 45°C (○) [87].

It is known from adsorption studies that lauryl polyglycol ethers are not adsorbed onto the surface of titanium dioxide particles [89]. It was assumed that the reason for this is that the ether bonds of the nonionic surfactants preferentially enter into hydrogen bridge bonds with the unbound water molecules by comparison with the hydroxyl groups of the polar titanium dioxide surface. Alkyl glycosides show different adsorption behavior on titanium dioxide [90]. In the identical concentration range investigated, the isotherm shapes differ depending on the chain length of the alkyl polyglycoside mixtures. In the case of the short-chain $C_{8/10}$ alkyl polyglycoside, the quantities adsorbed are almost linearly dependent on the concentration whereas a tendency toward a pronounced S form of the isotherms is observed with increasing alkyl chain length. A similar isotherm form is also observed for the adsorption of anionic surfactants onto polar solids, e.g., sodium dodecyl sulfate (SDS) onto titanium dioxide [91] and aluminum oxide [92]. By way of explanation, it was stated in these examples that individual surfactant molecules with the polar head directed to the surface are adsorbed by an acid–base interaction of the basic OH groups of the surface with the SDS anion. If the solution concentration of the surfactants is increased, two-dimensional aggregates—often referred to as "hemimicelles" [93]—are formed via a hydrophobic interaction of the alkyl chains. This leads to a marked increase in the quantities adsorbed. A similar mechanism can also be postulated for the adsorption of alkyl polyglycosides with relatively long alkyl chains. The hydroxyl groups of the surfactant have a slightly acidic character and are capable of entering into hydrogen bridge bonds with the hydroxyl groups of the titanium dioxide surface. If a sufficient number of alkyl glycoside molecules is adsorbed onto the surface, other molecules are adsorbed onto the surface through an interaction of the alkyl chains. This leads to surface coverages above a theoretical monolayer, which is confirmed by the adsorption measurements. The effects of adsorption on the dispersion of pigments in aqueous solutions of alkyl polyglycosides and the rheology of dispersions were described by Nickel et al. [75], Smith et al. [90], and Song et al. [94].

V. APPLICATIONS

Among the numerous applications of alkyl polyglycosides, three examples will be given in the following summary.

A. Personal Care Products

Alkyl polyglycosides combine properties of conventional nonionics and anionics. By far the largest proportion of commercial products is represented

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by $C_{8/14}$ alkyl polyglycosides for cleansing formulations that are characterized by their skin and hair care properties. New applications are also reported where $C_{12/14}$ alkyl polyglycoside acts as an emulsifier in specific formulations and particularly in microemulsions. In addition, the performance of $C_{16/18}$ alkyl polyglycoside as a self-emulsifying o/w base blended with fatty alcohol is discussed.

For body-cleansing formulations, a new surfactant must have excellent compatibility with the skin and mucous membranes. Dermatological and toxicological tests are essential for the risk assessment of a new surfactant and are designed above all to determine possible irritation of living cells in the basal layer of the epidermis (primary irritation). In the past, this was the basis for such claims as "mildness" of a surfactant. In the meantime, the meaning of mildness has changed considerably. Today mildness is understood to be the all-round compatibility of a surfactant with the physiology and function of human skin, or, more precisely: the epidermis.

The physiological effects of surfactants on the skin are investigated by various dermatological and biophysical methods starting with the surface of the skin and progressing via the horny layer and its barrier function to the deeper layer of the basal cells. At the same time, subjective sensations, such as the feeling on the skin, are recorded by verbalization of tactile sense and experience. Alkyl polyglycosides with C_8–C_{16} alkyl chains belong to the group of very mild surfactants for body cleansing formulations. In a detailed study, the compatibility of alkyl polyglycosides was described as a function of the pure C chain and the degree of polymerization [95]. In the modified Duhring chamber test, C_{12} alkyl polyglycoside shows a relative maximum within the range of mild irritation effects whereas C_8, C_{10} and C_{14}, C_{16} alkyl polyglycosides produce lower irritation scores. This corresponds to observations with other classes of surfactants. In addition, irritation decreases slightly with increasing degree of polymerization (from DP = 1.2 to DP = 1.65).

On the other hand, mucous membrane compatibility, as determined by the in vitro test on the choreonallantois membrane of fertilized hens' eggs (HET-CAM) as an alternative to Draize's mucous membrane compatibility test, shows a monotonic decrease from C_8 to C_{14} alkyl polyglycosides within the range of mild irritation effects in the HET-CAM. The DP causes only a slight differentiation of compatibility in this case. The commercial alkyl polyglycoside products (Plantacare® 1200, Plantacare® 2000, and Plantacare® 818) with mixed carbon chain lengths have the best overall compatibility with relatively high proportions of long-chain alkyl polyglycosides ($C_{12/14} > C_{8/14}$). They join the very mild group of highly ethoxylated alkyl ether sulfates, amphoglycinates or amphodiacetates, and the extremely mild protein fatty acid condensates based on collagen or wheat protein hydrolyzates. Comparative tests have been carried out [62,96].

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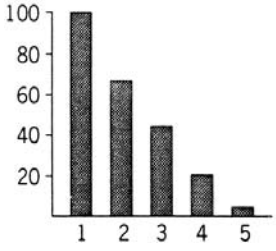
Another in vitro test (RBC, red blood cell test) investigates the hemolysis of erythrocytes under the influence of surfactants. A so-called mean index of ocular irritation (MIOI) correlating sufficiently with the Draize test has been derived. For alkyl polyglycosides, the MIOI lies at very low values as it does for other very mild surfactants [97,98]. Similarly, alkyl polyglycosides produce a very mild skin reaction in the modified Duhring chamber test [99,100]. In mixed formulations with standard ether sulfate, the score for erythema decreases with increasing levels of alkyl polyglycosides without a synergistic effect being observed (Fig. 33).

The influence of surfactants on the barrier function of the epidermis either by deterioration of the functional structure or by elution of components (horny layer lipids, NMF) is characterized by evaporimeter measurements as a change of the natural transepidermal water loss (TEWL). Investigations in connection with the arm flex wash test show that the changes in relation to the normal state of the skin barrier produced by standard surfactants are reduced in the presence of alkyl polyglycosides. This effect can be increased in the systematic buildup of formulations by incorporating further additives, such as protein derivatives [62,100]. Alkyl polyglycosides have been extensively investigated with regard to their fate and effect in the environment [37,101]. The prescribed OECD method for detecting the biological primary degradation of nonionics is not applicable to alkyl polyglycosides because they do not contain any ethylene oxide groups and are thus not BiAS active. Nevertheless, it can be extrapolated from the very favorable ultimate degradation data that the primary degradation step also proceeds with ease. This was confirmed in the OECD confirmatory test by applying an alkyl polyglycoside-specific analysis method. Ready ultimate biological degradation was observed with complete mineralization and/or assimilation of alkyl polyglycosides under both aerobic and anaerobic conditions.



	Sodium Laureth Sulfate	Decyl Glucoside
1	100	0
2	75	25
3	50	50
4	25	75
5	0	100

FIG. 33 Modified Duhring chamber test with relative irritation scores for erythema formation [6].

In the Closed Bottle Test (OECD 301), the "ready biodegradability" criterion under aerobic conditions is fulfilled with the 10-day window requirement under which 60% degradation must occur within 10 days of passing the 10% degradation level (Fig. 34). Under European standards, an overall evaluation of the environental risk of alkyl polyglycosides requires a realistic description of a scenario in which assessment of exposure in the environment of a substance (predicted environmental concentration) is compared with its effect in the environment (predicted no-effect concentration) [102]. Such an evaluation leads to the conclusion that, even under unfavorable conditions, no environmental risk is involved in the use of alkyl polyglycosides. The ecotoxicological effects which, given rapid biodegradability of the substances, continue to lose relevance in an overall ecological risk assessment show favorable findings in all test systems. The no observed effect concentrations (NOECs) for acute or chronic toxicity, as determined on single species or biocenotic communities of the aquatic and terrestrial environment, show that alkyl polyglycosides have comparatively low ecotoxicity [37].

Foaming is an essential quality feature of cosmetic cleansing formulations. Alkyl polyglycosides foam considerably better than fatty alcohol ethoxylates, the foam volume increasing with increasing percentage of short carbon chains in the alkyl polyglycosides. They are comparable with betaines and sulfosuccinates (Fig. 35) but do not match the initial foam behavior or foam volume of alkyl (ether) sulfates [62,63,96,97,99]. On the other hand, alkyl polyglycosides can stabilize the foam of anionics in hard water and in the presence of sebum so that up to 20% of surfactant can be saved for the same foaming power [62,96,99]. The structure of the foams of alkyl ether sulfates and alkyl

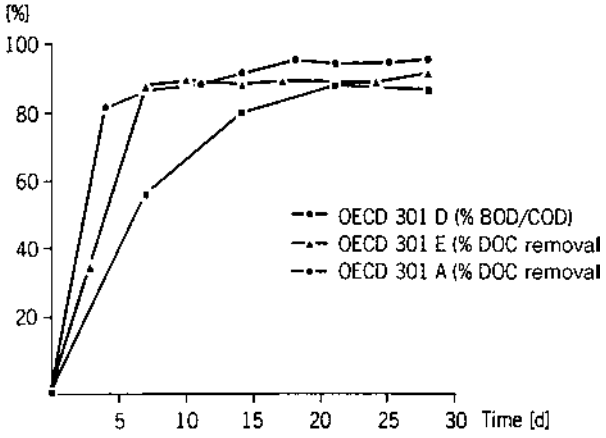


FIG. 34 Biodegration kinetics of $C_{12/14}$ APG in standard tests [6].

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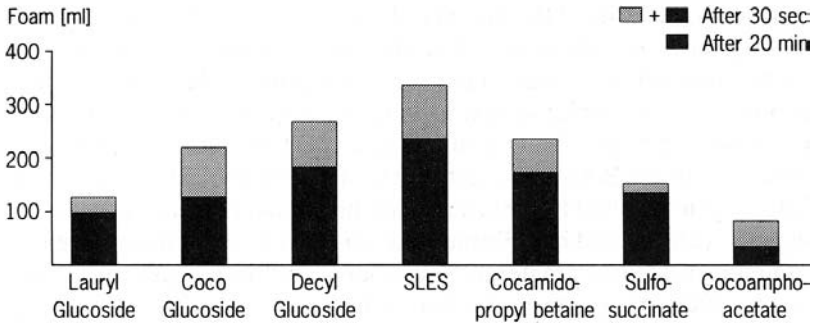

FIG. 35 Foaming properties of surfactants (1 g AS/L, 15°dH, 0.1 g/L sebum, perforated disc method DIN 53902) [6].

polyglycosides was investigated by image analysis and provides a basis for understanding the observed properties [62,99]. Alkyl polyglycoside foam consists of finer bubbles and is more creamy than sodium laureth sulfate foam (Fig. 36).

The cleansing properties of surfactants can be compared in a fairly simple test. Pig epidermis that has been treated with a mixture of sebum and soot is washed with a 3% AS solution of a surfactant for two minutes. Under a microscope, the gray value is determined by digital image analysis and compared with untreated pig epidermis. This method leads to the following ranking of cleansing properties: the best effects are produced by lauryl

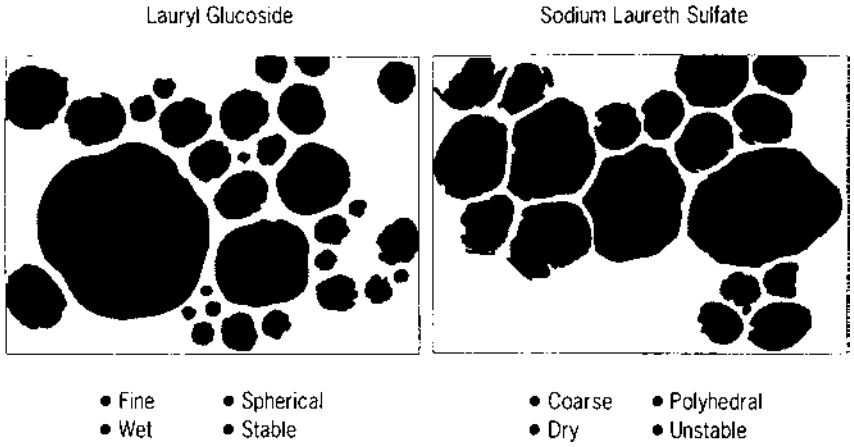

FIG. 36 Foam structure of surfactants after 15 min (magnification 30×) [6].

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glucoside and the worst by cocoamphoacetate. Betaine, sulfosuccinate, and standard ether sulfate are in the middle range and cannot be significantly differentiated from one another. Only lauryl glucoside achieved a deep pore cleansing effect in this low concentration.

The mildness of alkyl polyglycosides toward the skin is also reflected in a caring effect on damaged hair. The tensile strengths of permed hair tresses are reduced far less by treatment with alkyl polyglycoside solutions than by standard ether sulfate solutions [62,99]. By virtue of these caring properties and their alkali stability, alkyl polyglycosides are also suitable as surfactants in coloring, permanent-wave, and bleaching formulations. Investigations of permanent-wave formulations revealed that the addition of alkyl polyglycosides favorably influences the alkali solubility of the hair and the waving effect [103]. Direct proof of the adsorption of alkyl polyglycosides onto hair can be qualitatively provided by the X-ray photoelectron spectroscopy (XPS) technique. Hair tresses were divided into two halves which were respectively shampooed with 12% AS surfactant solutions of sodium laureth sulfate and lauryl glucoside at pH 5.5 and then rinsed and dried. Both surfactants can be detected on the hair surface by XPS. The oxygen signals of the keto and ether functions are increased by comparison with the untreated hair. Because this method is very sensitive even to small amounts of adsorbed material, shampooing and rinsing just once is not sufficient to differentiate between the two surfactants. However, if the process is repeated four times, no change in the XPS signals is observed in the case of sodium laureth sulfate in comparison with the untreated hair. By contrast, slightly increased oxygen contents and an increase in the keto functionality signals are measured for lauryl glucoside. This result shows that alkyl polyglycoside is more substantive to the hair than standard ether sulfate.

The substantivity of surfactants to hair influences combability. Measurements of shampoo formulations on wet hair by objective methods (combing robot) and subjective methods (half-head test) showed that alkyl polyglycoside does not significantly reduce wet combability. However, a synergistic reduction in wet combability of about 50% was observed in the case of mixtures of alkyl polyglycoside with cationic polymers. By contrast, dry combability is considerably improved by alkyl polyglycoside. Increased interactions between the single hair fibers provide the hair with volume and manageability [62,99]. In rinses and conditioners based on fatty alcohol and quaternary ammonium compounds (QUAT), the synergism of alkyl polyglycoside/QUAT is favorable in reducing wet combability whereas dry combability is only slightly reduced in these applications. Oil components may also be incorporated in the formulations, further reducing the necessary QUAT content and imparting improved luster to the hair. Such o/w emulsions may be used as "rinse-off" or "leave-on" preparations for the aftertreatment of hair [96].

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By a special process based on brief exposure to high temperatures (flash drying), a water-containing paste of $C_{12/14}$ alkyl polyglycoside can be converted to a white noncaking alkyl polyglycoside powder with a residual moisture content of less than 1%. Alkyl polyglycosides may thus also be used in soaps and syndets. They exhibit good foam and skin feel properties and, by virtue of their excellent skin compatibility, represent an attractive alternative to conventional syndet formulations based on alkyl sulfates. Similarly, $C_{12/14}$ alkyl polyglycoside may be used in toothpastes and other oral hygiene formulations. Alkyl polyglycoside/FAS combinations show improved mildness toward oral mucous membrane and, at the same time, produce a rich foam. Residual traces of free fatty alcohol in the alkyl polyglycoside can be masked in the interests of an agreeable taste. $C_{12/14}$ alkyl polyglycoside was found to be an effective booster for special antibacterial agents, such as chlorohexidine. In the presence of alkyl polyglycoside, the quantity of bactericidal agent can be reduced to about one-fourth without losing any bactericidal activity. This provides for the everyday use of high-activity products (mouth washes) that would otherwise be unacceptable to the consumer because of their bitter taste and their discoloring effect on the teeth [104].

By virtue of their physicochemical and performance profile, alkyl polyglycosides are a class of products that represent a new concept in compatibility and care in cosmetics. Alkyl polyglycosides are multifunctional raw materials that are moving closer to the center of modern formulation techniques. They may advantageously be combined with conventional components and can even replace them in new types of formulations. To exploit the rich spectrum of supplementary effects of alkyl polyglycosides on the skin and hair, changes have to be made to conventional techniques involving the widely used alkyl (ether) sulfonate/betaine combinations.

B. Hard Surface Cleaners and Laundry Detergents

For the use in hard surface cleaners and laundry detergents, alkyl polyglycosides have a number of interesting properties [105–109]:

Synergistic performance interactions with anionic surfactants
Good foaming behavior
Low skin irritation potential
Excellent ecological and toxicological properties
Completely derived from renewable resources

In conjunction with anionic surfactants in dishwashing, alkyl polyglycosides show significant synergistic effects which can be demonstrated not only by physicochemical methods but also by methods of greater relevance to the

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consumer, such as the plate test. Typical soils in the plate test are fats (as sole soil component) and so-called mixed soils (mixtures of fat, starch, and protein). Alkyl polyglycosides show pronounced synergisms with the three primary surfactants linear alkylbenzenesulfonate (LAS), secondary alkanesulfonate (SAS), and fatty alcohol sulfate (FAS). In contrast to alkyl polyglycosides, other nonionic surfactants, such as fatty alcohol polyethylene glycol ether (FAEO), do not show any synergisms with fatty alcohol ether sulfate (FAES) (Fig. 37).

Although foam volume and foam structure both in the dishwashing liquor and under running water do not directly determine product performance, they are expected by the consumer and thus lead to purchasing decisions. A feature of many conventional nonionic surfactants, such as FAEO, is their relatively low foaming capacity alone or in combination with conventional anionic surfactants. In contrast, alkyl polyglycosides, which, when combined with anionic surfactants, show favorable foaming behavior, i.e., increase the foam volume or longevity. Figure 38 shows by way of example the influence of alkyl polyglycosides on the foaming capacity of FAS and FAES. The relatively long-chain alkyl polyglycosides with an alkyl chain length of $C_{12/14}$ and a DP value of around 1.42 have proved to be of particular advantage for manual dishwashing detergents. However, the relatively short-chain alkyl polyglycosides with an alkyl chain length of $C_{8/10}$ and a DP value of about 1.53 are particularly useful in the formulation of all-purpose and specialty cleaners. Formulations for cleaners containing surfactants and surfactant combinations based on petrochemical and vegetable feedstocks are sufficiently well

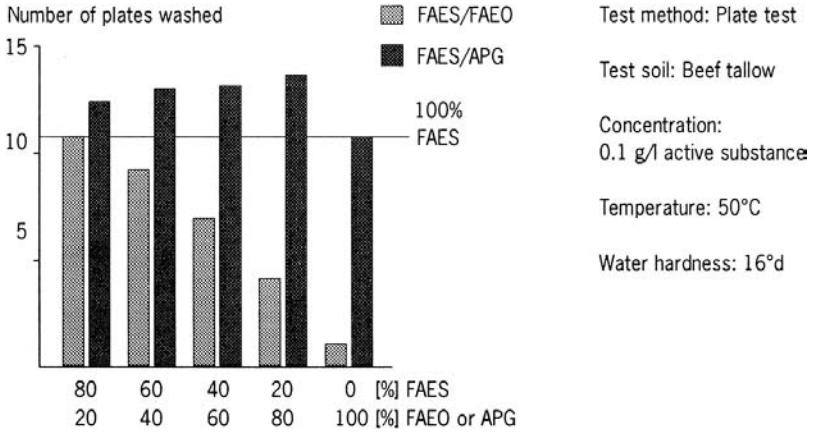

FIG. 37 Dishwashing performance of $C_{12/14}$ APG compared with FAEO in combination with FAES [6].

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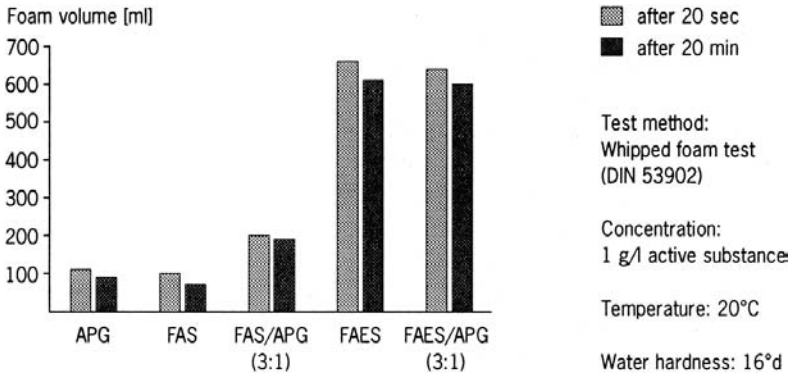

FIG. 38 Foaming behavior of $C_{12/14}$ alkyl polyglycoside-containing surfactant mixtures [6].

known. Extensive knowledge has been built up on this subject [110]. Now that light-colored short-chain alkyl polyglycosides are also available on the market, many new applications are being found for alkyl polyglycosides by virtue of their broad performance spectrum. Today alkyl polyglycoside-containing products are found both in all-purpose cleaners and in special cleaners, such as bathroom cleaners, toilet cleaners, window cleaners, kitchen cleaners, and floor care products [111].

The broad range of soil types found in the home require modern all-purpose cleaners (APC) have to perform effectively against both emulsifiable oil- and fat-containing soils and against dispersible solid soil particles. Alkyl polyglycoside-containing products are now available on the market for all three segments. Alkyl polyglycosides themselves have an excellent cleaning performance that can be determined, for example, in accordance with the IPP quality standard [112]. The cleaning performance can be further increased by small additions of anionic surfactants and/or polymeric boosters. Thus, it is possible to formulate products comparable in cleaning performance to the market leaders at significantly lower surfactant contents. All-purpose cleaners with particularly good skin compatibility should be slightly acidic rather than alkaline. With alkyl polyglycosides, the product developer has a surfactant of which the high cleaning performance level is hardly affected by changes in the pH value. Consumers today prefer all-purpose cleaners with moderate or low foaming behavior. The foaming capacity of alkyl polyglycoside–containing cleaners can readily be reduced by using small quantities of soaps or increased by adding small quantities of anionic surfactants. A suitable foaming capacity can thus be adjusted for each country. Alkyl

polyglycoside has proved to be the problem solver in the formulation of concentrated all-purpose cleaners with excellent ecological compatibility. With alkyl polyglycosides, it is possible to formulate concentrates that have a correspondingly higher content of builders and perfume oils without having to use large quantities of hydrotropes.

For many consumers, laundry detergents are a product they use daily to bring soiled clothing back into a state fit for use. The necessary formulations are marketed in various forms, e.g., as extruded, powder, paste, or liquid detergents. The choice of the particular formulation is determined by the type of soil, by consumer requirements in regard to ease of use, and, last not least, by the textile and its washing instructions. In addition, ecology has been an important factor in the development of laundry detergents, influencing the way in which they are developed [113]. The alkyl polyglycosides used in detergent formulations are those with an alkyl chain length of $C_{12/14}$ and a DP value of around 1.42. As a nonionic surfactant, they are particularly effective against fatty soils. Optimized surfactant systems generally based on mixtures of anionic and nonionic surfactants are used in modern detergent formulations. Alkyl polyglycosides occur in these surfactant mixtures preferably as so-called cosurfactants that have the property of complementing or improving the quantitatively predominant main surfactants in regard to washing performance. Besides performance, the aesthetics of a detergent play an important part. For example, wool detergents, are intended to produce a rich, stable foam. The consumer associates performance and care with foam. For machine washing, the correct foam height on the one hand determines textile care because the mechanical action on the wash load is reduced. On the other hand, this may cause a distinct reduction of the detergency performance. Alkyl polyglycosides in conjunction with anionic surfactants may alter the foaming behavior of the formulations. A general observation on foaming behavior is not possible but is to a large extent dependent on the surfactants used and their quantity ratio to one another.

Quantitatively the largest group, namely, the heavy-duty powder detergents, are based on formulations that remove virtually all the soil types normally encountered. Particular emphasis is placed on washing performance. For this reason, a distinctly higher alkalinity is adjusted so that the pH value of such detergents is in the pH range 9.5–10.5. Soil removal is thus greatly improved. In addition, heavy-duty detergents are provided with a bleaching system. Bleachable stains, such as tea, coffee, red wine, etc., are thus effortlessly removed. Fat- and oil-containing soils, such as sebum, olive oil, lipstick, and facial cream, are difficult to remove, particularly at low temperatures. By using alkyl polyglycosides in powder detergents, these stains in particular can be removed considerably more effectively (Fig. 39). By also using lipases, washing performance can be further increased.

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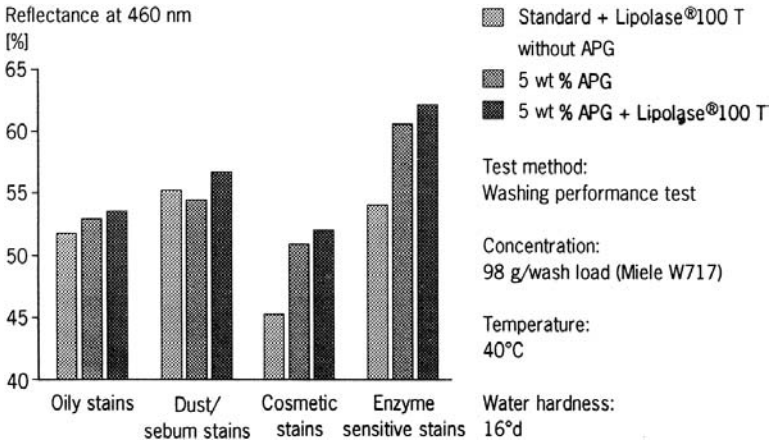

FIG. 39 Washing performance of heavy-duty detergents with $C_{12/14}$ APG [6].

Alkyl polyglycosides were first used in liquid laundry detergents in 1989. The composition of a liquid heavy-duty detergent is based on a combination of nonionic surfactants, anionic surfactants, soaps, and hydrotropes. The hydrotropes—which do not contribute to cleaning—can be partly replaced by alkyl polyglycosides. It has surprisingly been found that alkyl polyglycosides positively influence the low-temperature and storage stability of such formulations. In addition, triethanolamine soaps have been successfully replaced by the similarly acting sodium/potassium soaps [114]. The diethanolamine contamination of triethanolamine, which may cause the formation of nitrosamines, was thus avoided. In addition, sodium soaps are less expensive so that, as a net result, the use of alkyl polyglycosides gives the formulation a price advantage. The storage stability of enzymes in liquid formulations is reduced when compared with powders. On account of the high surfactant content of certain surfactants, the enzymes are partly deactivated and slowly lose their initial activity upon storage. In order to improve the storage stability of enzymes, such as proteases, lipases, amylases, and/or cellulases, in liquid detergents, stabilizers (borates, phosphates, special esters) are added and the surfactant systems adapted. It has been found that the storage stability of enzymes in liquid detergents can be distinctly improved by the use of alkyl polyglycosides (Fig. 40). The alkyl polyglycosides have the advantage over the otherwise typical stabilizers of contributing the washing result.

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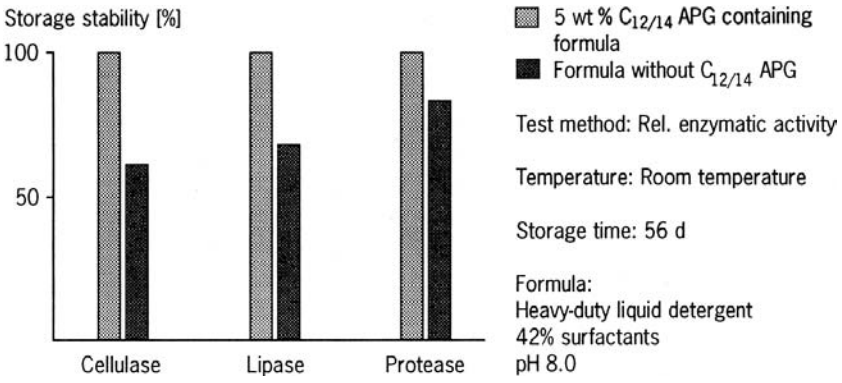

FIG. 40 Stability of enzymes in liquid detergents [6].

C. Alkyl Polyglycosides for Agricultural Applications

Alkyl polyglycosides have been known and available to agricultural formulators for many years. The features of alkyl polyglycosides that commend the products for agricultural applications are at least four in number [115–117]. First, there are the excellent wetting and penetrating properties. Wetting performance is critical to the formulator of dry agricultural formulations and spreading on plant surfaces is essential to the performance of many pesticides and agricultural adjuvants. Second, no nonionic other than alkyl polyglycoside exhibits comparable tolerance for high concentrations of electrolytes. This property opens the door to applications that were previously inaccessible to typical nonionics and in which alkyl polyglycosides provide the desired properties of nonionic surfactants in the presence of highly ionic pesticides or high concentrations of nitrogen fertilizer. Third, alkyl polyglycosides with a certain range of alkyl chain length do not exhibit the inverse solubility with increasing temperature or "cloud point" phenomenon characteristic of alkylene oxide–based nonionic surfactants. This removes a significant formulation constraint. Last, the ecotoxicity profiles of alkyl polyglycosides are among the most environmentally friendly that are known. The risk in their use near critical locations, such as surface waters, is greatly reduced in relation to alkylene oxide–based nonionic surfactants.

VI. DERIVATIVES OF ALKYL POLYGLYCOSIDES [118]

Alkyl polyglycosides are available in sufficient quantities and at competitive costs so that their use as a raw material for the development of new speciality

surfactants based on alkyl polyglycosides is arousing considerable interest. Thus, the surfactant properties of alkyl polyglycosides, such as foam and wetting, could be modified as required by chemical transformation.

The derivatization of alkyl polyglycosides is currently being pursued with great commitment [15,24,119,120]. A broad range of alkyl polyglycoside derivatives can be obtained by using relatively simple methods, such as nucleophilic substitution. Besides the reaction to esters or ethoxylates, ionic alkyl polyglycoside derivatives, such as sulfates and phosphates, can also be synthesized (Fig. 41).

Starting from alkyl polyglycosides having alkyl chains (R) of 8,10,12,14, and 16 carbon atoms (C_8–C_{16}) and an average degree of polymerization (DP) of 1.1–1.5, three series of alkyl polyglycoside derivatives were prepared. In order to investigate the change in the surfactant properties hydrophilic or hydrophobic substituents were introduced leading to alkyl polyglycoside glycerol ethers [121], carbonates [122], and butyl ethers [123].

In view of their numerous hydroxyl groups, alkyl polyglycosides are overfunctionalized molecules. By far the most alkyl polyglycoside derivatizations are carried out by chemical transformation of the free primary hydroxyl group at the C_6 atom. Although primary hydroxyl groups are more reactive than secondary hydroxyl groups, this difference is not sufficient in most cases to achieve a selective reaction without protective groups. Accordingly, derivatization of an alkyl polyglycoside can always be expected to produce a product mixture of which the characterization involves considerable

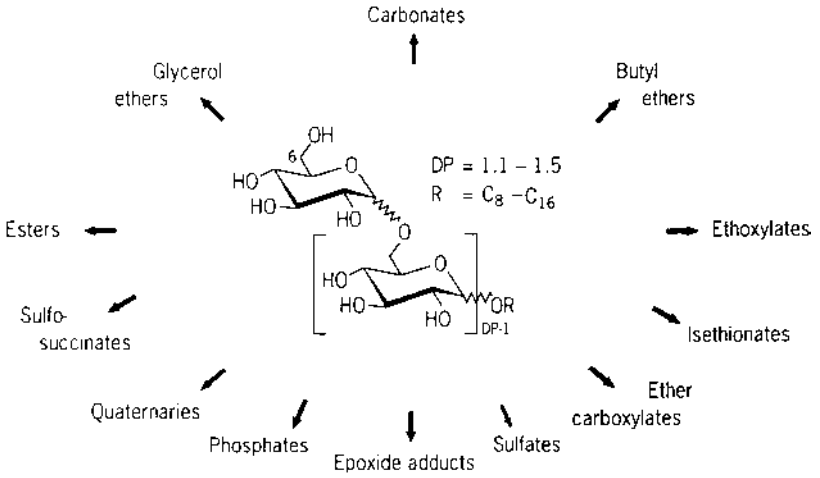

FIG. 41 Alkyl polyglycoside derivatives.

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analytical effort. A combination of gas chromatography and mass spectrometry was shown to be the preferred analysis method. In the synthesis of alkyl polyglycoside derivatives, it has proved effective to use an alkyl polyglycoside with a low DP value of 1.1, in the following referred to as alkyl monoglycosides. This leads to less complex product mixtures and, as a consequence, to less complicated analyses.

A. Synthesis of Alkyl Polyglycoside Glycerol Ethers

The synthesis of alkyl polyglycoside glycerol ethers was carried out by three different methods (Fig. 42; instead of the alkyl polyglycoside mixture, only the alkyl monoglycoside is shown as the educt). Etherification of alkyl polyglycoside with glycerol by method A proceeds under basic reaction conditions. Ring opening of an epoxide by method B likewise takes place in the presence of basic catalysts. An alternative is the reaction with glycerol carbonate by method C which is accompanied by the elimination of CO_2 and which presumably proceeds via an epoxide as intermediate stage. Under the reaction conditions accoding to patnway A, the degree of etherification of the products is independent of the alkyl chain length of the alkyl polyglycoside used. Typically, mono-, di-, and triglycerol ethers are formed in a ratio of approximately 3:2:1 and the total content of glycerol ethers is around 35% (according to GC analysis).

B. Synthesis of Alkyl Polyglycoside Carbonates

Alkyl polyglycoside carbonates were prepared by transesterification of alkyl monoglycosides with diethyl carbonate (Fig. 43). In the interests of thorough mixing of the reactants, it has proved to be of advantage to use the diethyl carbonate in excess so that it serves both as transesterification component and as solvent. Two mole percent of a 50% sodium hydroxide solution are added dropwise to this mixture with stirring at around 120°C. After 3 h under reflux, the reaction mixture is allowed to cool to 80°C and neutralized

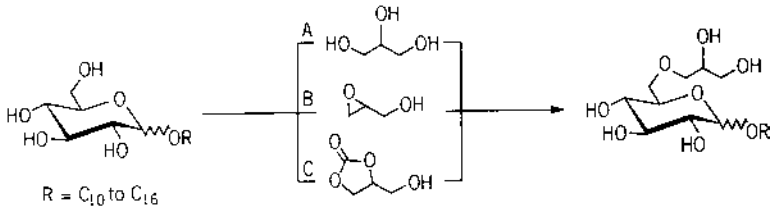

FIG. 42 Synthesis of alkyl polyglycoside glycerol ethers.

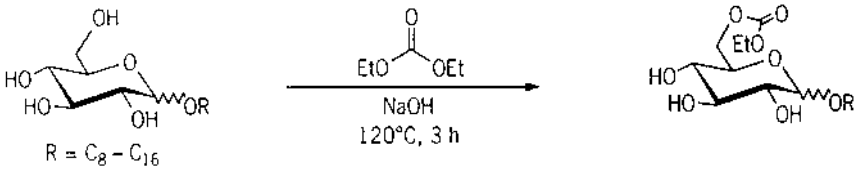

FIG. 43 Synthesis of alkyl polyglycoside carbonates.

with 85% phosphoric acid. The excess diethyl carbonate is distilled off in vacuo. Under these reaction conditions, one hydroxyl group is preferably esterified. The ratio of remaining educt to products is 1:2.5:1 (monoglycoside monocarbonate polycarbonate).

C. Synthesis of Alkyl Polyglycoside Butyl Ethers

A property of alkyl polyglycosides often in demand is enhanced foaming. However, in many applications this ability is actually regarded as a disadvantage. Accordingly, it is also of interest to develop alkyl polyglycoside derivatives which combine good cleaning performance with only a slight tendency to foam. With this goal in mind, alkyl polyglycoside butyl ethers were synthesized. It is known in the literature that alkyl glycosides can be end-capped with alkyl halides or dimethyl sulfate in aqueous alkaline solutions [124].

On an industrial scale, the reaction in aqueous solution is a disadvantage because concentrated water-free products cannot be obtained without additional working-up steps. Therefore, a water-free process was developed, which is outlined in Fig. 44. The alkyl polyglycoside is initially introduced into the reactor with an excess of butyl chloride and heated to 80°C. The reaction is initiated by addition of potassium hydroxide as the catalyst. On completion of the reaction, the reaction mixture is neutralized, the potassium chloride precipitate is filtered off, and the excess butyl chloride is distilled off. The product is composed of various alkyl polyglycosides and alkyl polyglyco-

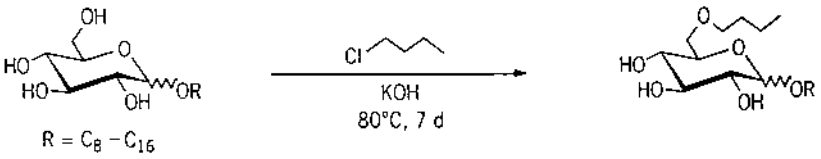

FIG. 44 Synthesis of alkyl polyglycoside butyl ethers.

side butyl ethers. According to GC analysis, the ratio of alkyl monoglycoside, alkyl monoglycoside monobutyl ether, and alkyl monoglycoside polybutyl ether is 1:3:1.5.

D. Interfacial Properties

To characterize the interfacial properties of alkyl polyglycoside derivatives, surface tension/concentration curves were recorded and the CMC and the plateau surface tension values above the CMC were determined from them. The interfacial tension against two model substances—octyl dodecanol and decane—were investigated as further parameters. The CMC values obtained from these curves are shown in Fig. 45. The corresponding data for a C_{12} alkyl monoglycoside and a $C_{12/14}$ alkyl polyglycoside are included for comparison. It can be seen that alkyl polyglycoside glycerol ethers and carbonates have higher CMC values than alkyl polyglycosides of comparable chain length whereas the CMC values of the monobutyl ethers are somewhat lower than those of the alkyl polyglycosides.

The interfacial tension measurements were carried out with a Krüss spinning drop tensiometer. To simulate practical conditions, the measurements were performed in hard water (270 ppm Ca: Mg = 5:1) at a surfactant concentration of 0.15 g/L and at 50°C. Figure 46 shows a comparison of the interfacial tension of C_{12} alkyl polyglycoside derivatives against octyl dodecanol. The C_{12} monobutyl ether has the highest interfacial tension and hence

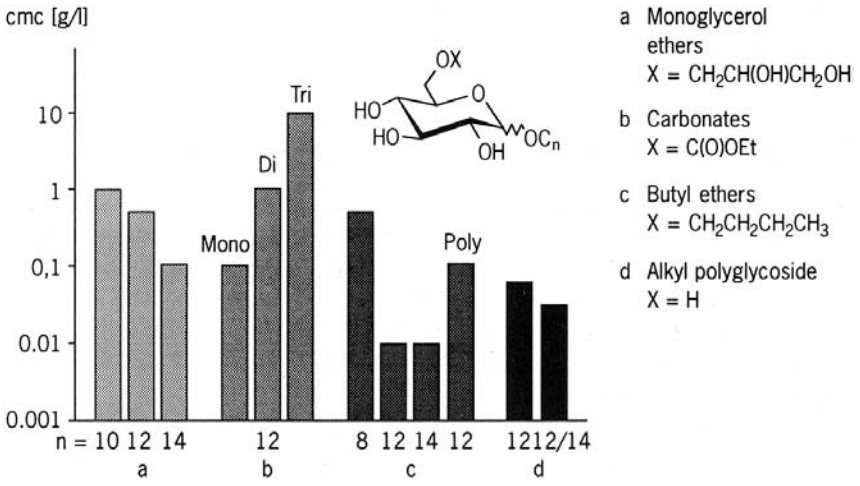

FIG. 45 The CMC values of alkyl polyglycoside derivatives.

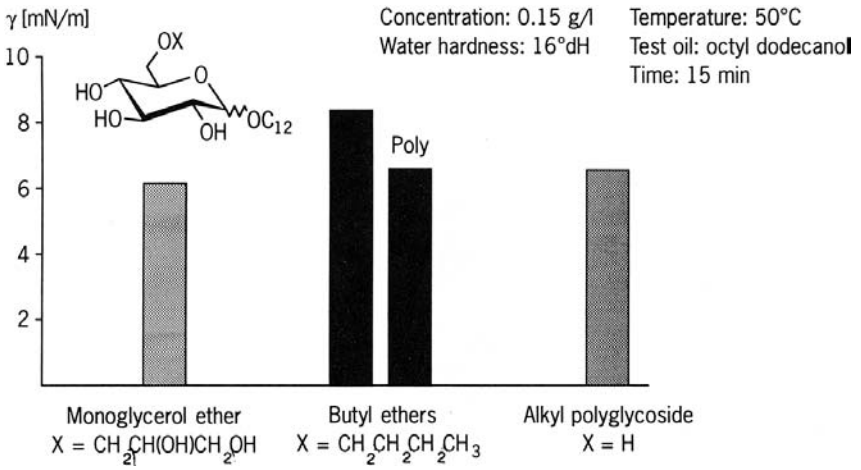

FIG. 46 Reduction of interfacial tension against octyl decanol.

the lowest interfacial activity whereas the C_{12} monoglycerol ether is substantially at the level of the C_{12} polybutyl ether. The C_{12} alkyl polyglycoside included for comparison lies at the level of the last two alkyl polyglycoside derivatives mentioned. Overall, the interfacial tension values against octyl dodecanol are relatively high. This means that, for practical applications, it is important to ensure that the surfactant mixtures used have a synergism toward polar oils.

Figure 47 shows the values for the interfacial tension of C_{12} alkyl polyglycoside derivatives against decane. The polybutyl ether is somewhat lower compared with C_{12} alkyl polyglycoside and has a more favorable value than the monobutyl ether. The interfacial tension of the monoglycerol ether is between the two alkyl polyglycoside butyl ethers. The unfavorable value for the alkyl polyglycoside tricarbonate, which is attributable to its poor solubility, even at 50°C, contrasts with very low surface interfacial tensions for mono- and dicarbonate. Compared with the C_{12} alkyl polyglycoside, the monocarbonate has a very favorable value for an individual surfactant.

The dependence of interfacial tension on the alkyl chain length of various alkyl polyglycoside monoglycerol ethers is shown in Fig. 48. Interfacial tension against decane decreases significantly with increasing chain length, the high value of the C_{10} glycerol ether being attributable to the fact that the CMC is not reached at 0.15 g/L. Accordingly, it is important to ensure that the CMC of a surfactant mixture is lower than that of the C_{10} glycerol ether.

The wetting power of two alkyl polyglycoside monocarbonates and the corresponding alkyl polyglucosides is illustrated in Fig. 49. The wetting times

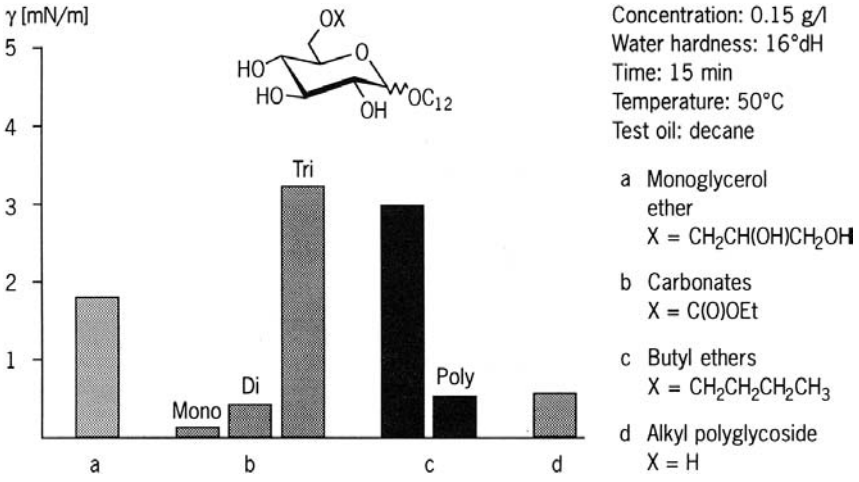

FIG. 47 Reduction of interfacial tension against decane.

were measured for two different water hardness values. The times for the monocarbonate with an alkyl chain length n - 8 are about half as long as for the corresponding alkyl polyglycoside. Less favorable values were obtained for the C_{12} alkyl polyglycoside monocarbonate than for the $C_{12/14}$ alkyl polyglycoside. This monocarbonate shows poor wetting behavior above all at a water hardness of 16° dH.

The results of the foam tests are set out in Fig. 50. The foaming behavior of various alkyl polyglycoside monoglycerol ethers and monocarbonates was

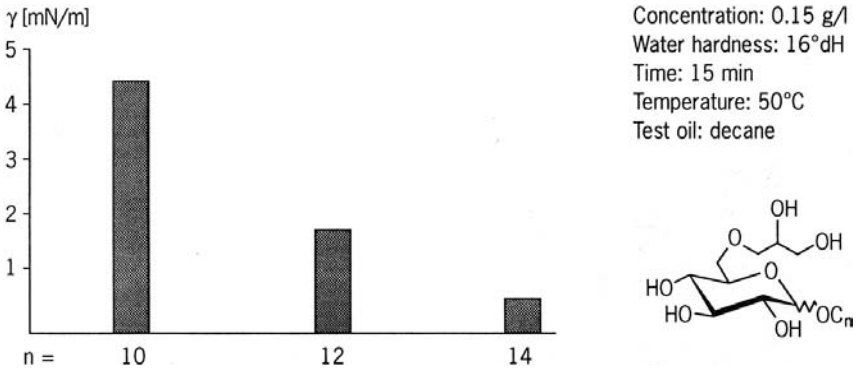

FIG. 48 Reduction of interfacial tension by alkyl polyglycoside monoglycerol ethers.

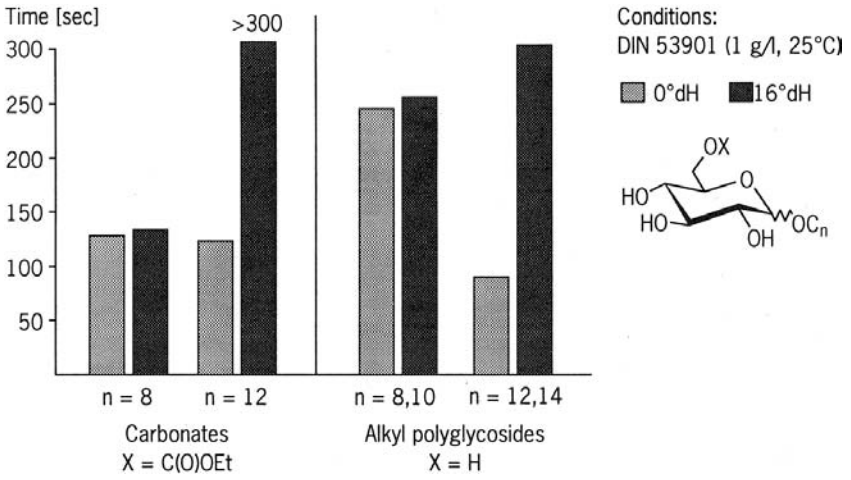

FIG. 49 Wetting time for alkyl polyglycoside carbonates.

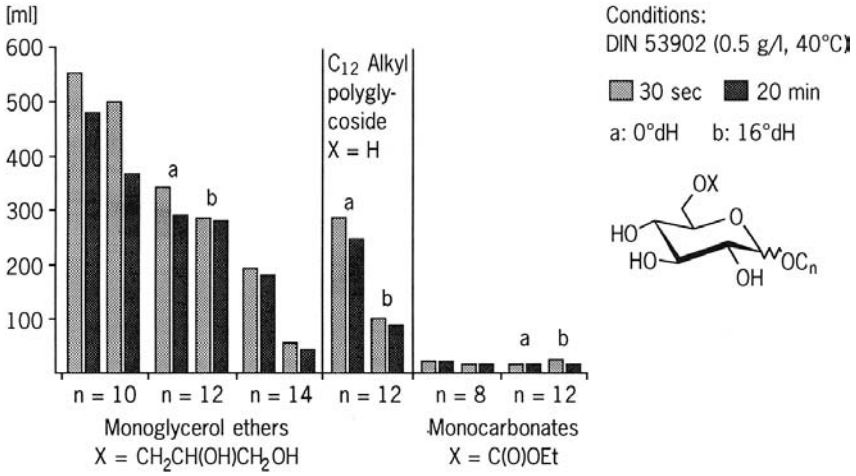

FIG. 50 Foam volume of alkyl polyglycoside derivatives.

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measured by comparison with C_{12} alkyl polyglycoside for two water hardness values in the absence of fatty soil. The measurements were conducted in accordance with DIN 53902. The C_{10} and C_{12} alkyl polyglycoside monoglycerol ethers produced a larger foam volume than the C_{12} alkyl polyglycoside. Foam stability is significantly greater in the case of the C_{12} monoglycerol ether than in the case of the C_{10} derivative at 16° dH. The C_{14} alkyl polyglycoside monoglycerol ether does not compare with the C_{10} and C_{12} derivatives in its foaming power and, overall, rates worse than the C_{12} alkyl polyglycoside. The monocarbonates with alkyl chain lengths *n* of 8 and12 are distinguished by very low foam volumes, as would be expected of a hydrophobic alkyl polyglycoside derivative.

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3

Sugar Fatty Acid Esters

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I. INTRODUCTION

There has been a resurgence in the study and use of natural surfactants in recent years. The primary reasons are that these surfactants are generally viewed as possessing the potential to have less adverse impact on the environment and to be nontoxic. Sugar fatty acid esters are one group that has been receiving renewed attention for these very reasons. Condensation of one of the reactive sugar hydroxyl functionalities with a fatty acid yields a biosurfactant that has potential application in food, cosmetics, and pharmaceuticals.

From the mid-1950s until now there has been a significant number of publications on sugar fatty acid esters, in particular sucrose fatty acid esters. Sucrose fatty acid esters have been commercially manufactured at reasonably high volume since the early 1960s.

This book chapter is not meant to be a comprehensive review of all the previous work on sugar fatty acid esters, as there have been many excellent review articles published on this topic. In this chapter, we have chosen to highlight either select areas of recent activity or areas where we have decided that it is worthwhile considering the background to claims.

We have sectioned this chapter into four main parts: synthesis, biodegradation, toxicology, and single- and multicomponent phase behavior and dilute solution properties. The synthesis is discussed because it is an area of

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very active research and presents many challenges. It is frequently stated that sugar-based surfactants are less toxic and have less impact on the environment than many of the commodity surfactants. We examine these claims. Application of these surfactants usually requires knowledge of their phase behavior and their dilute solution properties, and we look at recent work in this area.

II. SYNTHESIS

The synthesis of carbohydrate surfactants is a challenging area of chemistry as there are many different possibilities for attachment of the hydrophobic alkyl chain to the hydrophilic sugar unit with each leading to a different subclass of sugar surfactant. Examples of the most common linkages include the ether link produced by Fischer synthesis in the alkyl polyglucosides, the attachment of hydrophobes with two or more alkyl chains in glycolipids, and the introduction of amine/amide and ester linkages.

The synthesis of sugar fatty acid esters has recently been described in several reviews [1–6]. In the following section, we highlight recent trends and provide a brief historical overview of the production of sugar fatty acid esters with particular emphasis on the sucrose esters.

A. Stereochemistry of Sucrose

Understanding the chemistry of sucrose is important because of the low cost and availability of this sugar. Sucrose is available at very high purity and is one of the world's most abundantly produced organic compounds being synthesised as a by-product of photosynthesis.

Sucrose is a nonreducing disaccharide containing multiple functionalities: three primary alcohols, five secondary alcohols, and two anomeric carbons (Fig. 1). Monoesterification of the molecule is extremely difficult as the

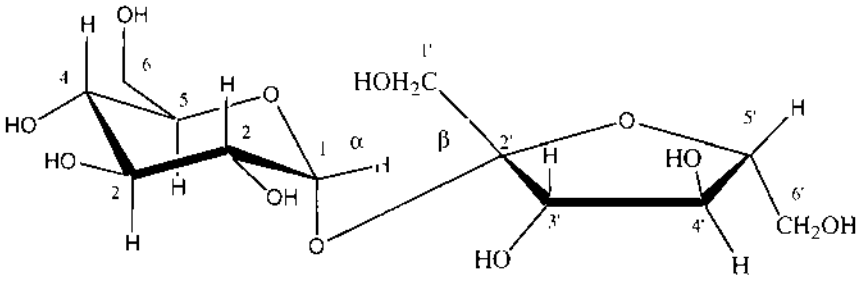

FIG. 1 Stereochemistry of the sucrose molecule.

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similarity in reactivity of the alcohol groups provides several reaction centers. This may be partially overcome by different reaction conditions. The facile intramolecular acyl migration of the unprotected ester derivatives and the sensitivity of the glycosidic bond to acid hydrolysis present additional challenges. Consequently, synthesis is largely restricted to neutral or basic media.

In the preparation of sucrose derivatives much attention is focused on methods that afford selective acylation of the molecule. Fortunately, the reactivity of the primary and secondary alcohols differ slightly. The activity of the primary alcohols is significantly higher as these are the least sterically hindered with 6-OH $\geq$ 6′-OH $>$ 1′–OH. Regioselectivity on the 6′-OH may be achieved through acylation with 3-acyl-5-methyl-1,3,4-thiadiazole-2[3H]-thiones in dimethyl formamide (DMF) [7]. Synthesis of the 6-*O*-acyl sucrose may be achieved via the dibutylstannylene acetal intermediate as described by Vhalov et al. [8]. Intramolecular hydrogen bonding plays a key role in determining the acidity of the sucrose hydroxyls with the order of acidity evaluated from semiempirical calculations given as 2-OH $\gg$ 3-OH $>$ 3′-OH $>$ 1′-OH $\sim$4-OH $>$ 4′-OH $\gg$ 6-OH $\gg$ 6′-OH [9]. The 2-OH position is preferentially functionalized under strongly basic reaction conditions [3,10]. Chauvin et al. [11] reported yields of 70% of the 2-*O*-acyl sucrose using an initiator (NaH) with 3-acythiazoledine-2-thione and triethylamine.

B. Chemical Synthesis of Sugar Fatty Acid Esters

Sugar esters may be produced by either chemical or enzymatic pathways. Hass [12], Parker et al. [13], and Allen and Tao [1] provided an interesting historical perspective on the development of sucrose fatty acid ester chemical synthesis. These were first commercialized by Dai-Nippon Manufacturing Company (now Mitsubishi-Kasei Food Corporation) in the late 1960s for use in the food industry using the process outlined by Hass et al. [14]. The method is based on transesterification with alkaline catalyst in DMF or dimethyl sulfoxide (DMSO) using the fatty acid methyl ester as acylating agent and operating at high temperature (Scheme 1). The permissible levels of residual DMF for food applications is less than 50 ppm, which is achieved by the Ryoto process by chromatography. Sugar esters prepared by chemical means are usually a complex mixture of compounds differing with respect to the degree of esterification and in the positions of the acyl groups on the sugar head group. Typical yields for the Ryoto method where sucrose and beef tallow were employed are 25% sucrose monoester with 16% of the diester as well as 60% mono-, di-, and triglycerides. The lack of selectivity results in costly separation, purification, and waste treatment of the toxic

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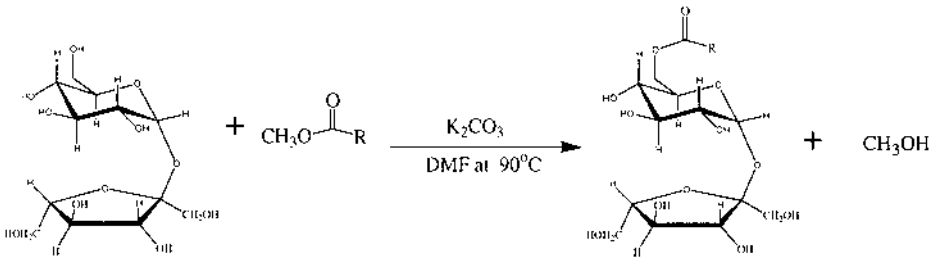

SCHEME 1 Ryoto sugar ester synthesis is based on transesterification of sucrose with a methyl fatty acid ester under conditions in which methanol is continuously removed. The product includes a complex mixture of K-soaps, diesters and mono-/diglycerides, as well as the sucrose monoester when produced from crude beef tallow. An excess of sucrose is required (3 mol) to enhance the yield of the monoester over higher substituted products. DMF must be recovered for economic operation and because of its toxicity.

solvents, thereby restricting their usage to high-value-added applications such as the food and cosmetics industries.

Numerous workers have modified the process to utilize nonpolar solvents [15], acid chlorides [16], anhydrides [17], and triglycerides [18]. The issue of solvent toxicity has also been addressed, and Osipow and Rosenblatt [19] employed two-phase-systems of sucrose solubilized in propylene glycol and an emulsifier containing the fatty acid ester. The reaction proceeds in the microemulsion. Sucrose esters have also been prepared in water [3]. The Tate and Lyle process developed by Parker et al. [13,20] involves the solvent-free reaction of sucrose and triglycerides. The typical crude product comprises 26% monoester with substantial potassium salts, reduced glyceride, and higher order esters. Many improvements of the original Tate and Lyle process have since been reported in the patent literature [20–22]. Another solventless process has been suggested in which the transesterification of molten sucrose and fatty acid esters occurs at high temperature (170–190°C) in the presence of a catalyst and a solubilizer such as a sodium or potassium salt [23]. Regioselective esterification can be achieved by partial protection of the hydroxyl groups of the sugar followed by activation, acylation, and deprotection, using methods such as those outlined by Chauvin [7], Vhalov et al. [8], and Chauvin et al., [11] for the formation of the 6′-*O*, 6′-*O* and 2′-*O* acyl sucrose, respectively. The Mitsunobu reaction [24] has also significantly improved chemical regioselective synthesis through the intermolecular dehydration of alcohols with acids using diethylazodicarboxylate and triphenylphosphine.

Lactitol and lactose monoesters esters have been prepared by Drummond and Wells [25] with the acid chloride fatty acid derivatives of C_8–C_{16}

chain length as per the method described by Scholnick [26] using a mixed 2-pyrrolidone/pyridine solvent. Raffinose and stachyose monoesters have also been synthesized by Söderberg et al. [27] using the method of Osipow and coworkers [28].

Various purification methods have been proposed for the isolation of sucrose monoesters. Osipow et al. [28] have recommended partitioning of the solids obtained after distillation of the solvent between an aqueous salt solution and alcohol. The Tate and Lyle process [13] suggests the conversion of the fatty acids and salt into soaps and the extraction of the insoluble material with ketone solvent followed by extraction with alcohol. Söderberg et al. [27] purified raffinose and stachylose dodecanoate esters as pure isomers using flash chromatography. A quantitative procedure for determining the ester distribution in the product was proposed by Weiss et al. [29] using thin-layer chromatography.

C. Enzymatic Synthesis of Sugar Fatty Acid Esters

An alternative method for the synthesis of sugar esters is the enzymatic approach. Enzymatic catalysis in the field of carbohydrate synthesis has been actively explored over recent years and offers distinct advantages for the control of stereoselectivity and regioselectivity under milder reaction conditions (caramelization often occurs during transesterification). Thus, unlike chemical processes, enzymatic reactions afford sugar esters a high degree of selectivity and control over the amount of substitution. However, a fundamental problem with enzyme-catalyzed synthesis is the efficient solubilization of the starting materials. For a long time, conventional wisdom maintained that enzymes could only function in aqueous media, requiring the structuring of the non-covalent interactions to maintain the native, catalytically active conformation. The recent recognition that certain enzymes can operate in nonaqueous or low water environments has revolutionized organic synthesis [30 and references therein].

There are three main classes of enzymes used in carbohydrate chemistry [31]:

1. Enzymes (aldolases, kinases, synthetases) for the synthesis of complex sugars and sugar derivatives
2. Sugar hydrolases (glycosidases) for derivization of glycosides
3. Hydrolytic enzymes (lipases, proteases) for the regioselective acylation/deacylation of carbohydrates

The enzymatic synthesis of sugar fatty acid esters has been reviewed in recent times [2,6,32]. The biocatalytic properties of lipases and the basic principles governing lipase-catalyzed esterification have been described in the literature [30,33].

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Typically, lipases are employed in esterification; however, proteases have also been utilized in organic medium although their normal function is peptidic bond hydrolysis. Their action in ester bond formation is rationalized in terms of the similarity between the active center that is mechanistically essential for transesterification. Several lipases originating from various sources have been utilized in sugar fatty acid synthesis. The activity of these enzymes is highly dependent on the reaction conditions employed and whether they are used in the free state or immobilized on a support. Immobilization confers better homogeneity of the enzyme for reaction and promotes greater thermostability of the protein [30]. The prochiral selectivity and substrate preference of lipases and protease also depend on the solvent system [34,35].

There are two main strategies for the enzyme-catalyzed preparation of sugar esters. The first employs organic solvents similar to those used in chemical synthesis, e.g., DMF, DMSO, and pyridine, which can solubilize both the enzyme and the sugar molecule. The second method involves modification of the sugar followed by solvent free enzyme–mediated esterification. Each of these routes will be discussed in turn below.

Regioselective activity of specific enzymes in organic solvents have been demonstrated by numerous workers including Therisod and Klibanov [36, 37], Riva et al. [38], and Carrea et al. [39]. Klibanov and coworkers [36,37] performed regioselective acylation of glucose, galactose, mannose, and fructose of primarily the 6-OH position in anhydrous pyridine using porcine pancreatic lipase with activated acyl donors such as trichloroethylcarboxylate esters. Selectivity of the secondary alcohols was achieved using lipase (*Chromobacterium viscosum*) with protection of the primary alcohols required first. Acylation of higher order sugars was affected through protease subtilisin (*Bacillus subtilis*). Similarly, Riva et al. used protease subtilisin in the regioselective transesterification of the disaccharides of maltose, cellobiose, lactose, and sucrose with fatty acids to produce the monobutyryl esters in DMF [38]. The lipases used were not active in DMF, and protease subtilisin is the first known example of an enzyme expressing significant activity in DMF.

Although sugars are reasonably soluble in hydrophilic organic solvents such as those used above, most enzymes demonstrate a low activity in these systems which require long reaction times and induce rapid inactivation of the biocatalyst. The instability of enzymes in polar solvents can be partially overcome by immobilization on hydrophilic supports [30]. Overall, this approach is unattractive for large-scale manufacturing.

Chen and Shih [30] and Coulon and Ghoul [2] have summarized the requirement of different solvents systems for transesterification based on the partition coefficient of the solvent between octanol and water, log *P*.

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Polar solvents have a log $P < 2$, moderate solvents have a log P in the range $2 < \log P < 4$, and for apolar solvents log $P > 4$ (Table 1). Synthesis is best achieved in solvents of intermediate polarity that are able to partially solubilize both the sugar and enzyme, or in solvents with a log P value greater than 1.5 that do not affect the hydration shell of the enzyme and so denature the protein. Tertiary alcohols are particularly effective solvents in this respect as they cannot react with lipases due to steric hindrance at the hydroxy group and their boiling points facilitate their removal after reaction. *tert*-Butyl alcohol catalyzed by lipase has been employed for sugar acylations [40–42]. Other solvents that have been utilized include 2-pyrrolidone [43] for the synthesis of sorbitol ester derivatives. Pyridine and biphasic mixtures of solvents such as benzene/pyridine and *tert*-butyl alcohol/hexane have also been used.

Following the pioneering work of Randolph et al. [44], Nakamura [45] conducted several studies describing enzymatic reactions in supercritical

TABLE 1 Log P Values of Common Solvents [30]

Solvent	Log P	
Dodecane	6.6	Apolar solvents
Octane	4.5	
Heptane	4.0	
Hexane	3.5	
Cyclohexane	3.2	
Toluene	2.5	
Benzene	2.0	Moderate to highly polar solvents.
Chloroform	2.0	Immobilization of the enzyme on a
Butyl acetate	1.7	substrate is recommended due to
Diethyl ether	0.85	possible loss of enzyme activity
Butanol	0.80	
Pyridine	0.71	
Ethyl acetate	0.68	
Tetrahydrofuran	0.49	
Acetone	−0.23	
Ethanol	−0.24	
Acetonitrile	−0.33	
Methanol	−0.76	
Dimethylformamide	−1.0	
Dioxane	−1.1	
Dimethylsulfoxide	−1.3	

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fluids, and the method has been transferred to the synthesis of sugar fatty acids. The advantages of supercritical carbon dioxide, ($SCCO_2$) over conventional organic solvents are its lack of toxicity, nonflammability, and inexpensiveness. The problem of low solubility of sugars in nonpolar solvents was remedied by Stamatis and coworkers [4,46,47] by preadsorption of monosaccharides such as glucose and fructose onto silica gel or α-cellulose *prior* to regioselective esterification catalysed by lipase *Mucor miehei* (Lipozyme). This was achieved with up to 50% yields. Heo et al. [48] also demonstrated the feasibility of acylation of methyl-β-D-fructofuranoside with caprylic acid with immobilized lipase Novozyme 435 (*Candida antarctica*) in $SCCO_2$ and *t*-butanol cosolvent to enhance solubility of the sugar. However, pressures of up to 16 MPa were required to optimize the reaction.

Alternatively, enzymatic catalysis can proceed in a solventless mixture of substrates. As mentioned above, this method relies on the esterification of hydrophobic sugar derivatives with fatty acids under solvent-free conditions to overcome the problem of poor solubility of the sugar [7,49,50]. Several methods have been proposed in the literature to overcome this, including acetalization [49,51], complexation of sugars and polyols to phenylboronic acid [52], and alkylation [50,53] of the sugar. "Hydrophobization" is particularly useful for disaccharides as these are difficult to solubilize in solvents that maintain enzyme activity.

Activation of the disaccharide has been achieved via acetalization with isopropylidene formation followed by acylation using immobilized *M. miehei* lipase (lipozyme IM-60) in the molten state. This technique has been utilized by Sarney and coworkers on numerous mono- and disaccharides, including glucose [49], sucrose [54], galactose [49], lactose [55], xylose [51], and maltose [55]. Regioselectivity was achieved at the 6′-OH position via isopropylidene intermediates to yield conversions of up to 80% in the monoester. Sarney and Vulfson [6] provide details for several routes of enzymatic synthesis in solvent free media via acetalization. Currently, the challenges of commercial manufacture by such a multi-step process has yet to justify the implementation of this methodology.

Complexation of sugars to phenylboronic acid has also been employed to assist sugar solubility in organic solvents. High conversions of glucose and sucrose were achieved using lipase (*Pseudomonas* sp) in *t*-butyl alcohol [52]. However, the use of high concentrations of complexing agent have been observed to inhibit the action of some lipases such as *Rhizomucor meihei* [56].

Adelhorst et al. [53] and Björkling et al. [50] developed a high yielding (85–90%) enzyme-catalyzed synthesis of 6-*O*-alkyl glucopyranosides utilizing immobilized lipase (*C. antarctica*) under solvent-free conditions at 70°C. It was observed that alkylation proceeded more rapidly with longer chain fatty

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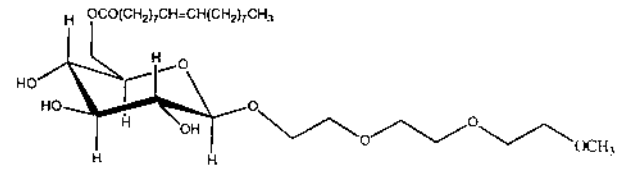
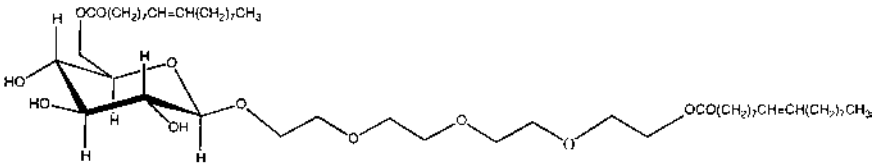
acids (C_{12}–C_{18}) compared with shorter chain acids (C_8–C_{10}), which was consistent with the general preference of lipases for lipophilic substrates. This technique has been patented as the Novo-Nordisk process and underwent pilot scale trials in the early 1990s [57,58]. Mutua and Akoh [59] reported lipase-catalyzed synthesis of alkyl glycosides through the generation of trichloroethyl esters in benzene/pyridine.

D. Anionic Sucrose Esters

To enhance the aqueous solubility of sugar esters, particularly sucrose, an environmentally friendly sulfo functionality may be introduced. Sulfonation of the sugar ester may be achieved by either regioselective sulfonation of the sugar ester using excess $Pyr.SO_3$ in pyridine to yield primarily the 6-*O*-acyl-4′-sulfosucrose with yields of about 25% whereas stoichiometric conditions promote yields of 70%. Similarly, the 1′-*O*-acyl-6′-sulfosucrose may be prepared from the appropriate sucrose ester. Another strategy for the sulfation of sucrose employs a sucrose cyclic intermediate obtained from the reaction of the sugar with thionyl chloride followed by oxidation with cyclic sulfite. The 6-*O*-acyl-4-sulfate sucrose may be attained in 75% yield by nucleophilic ring opening with an excess of the desired fatty acid in DMF catalyzed by potassium bicarbonate [60].



6-Oleoyl Glc-PEG$_3$OMe

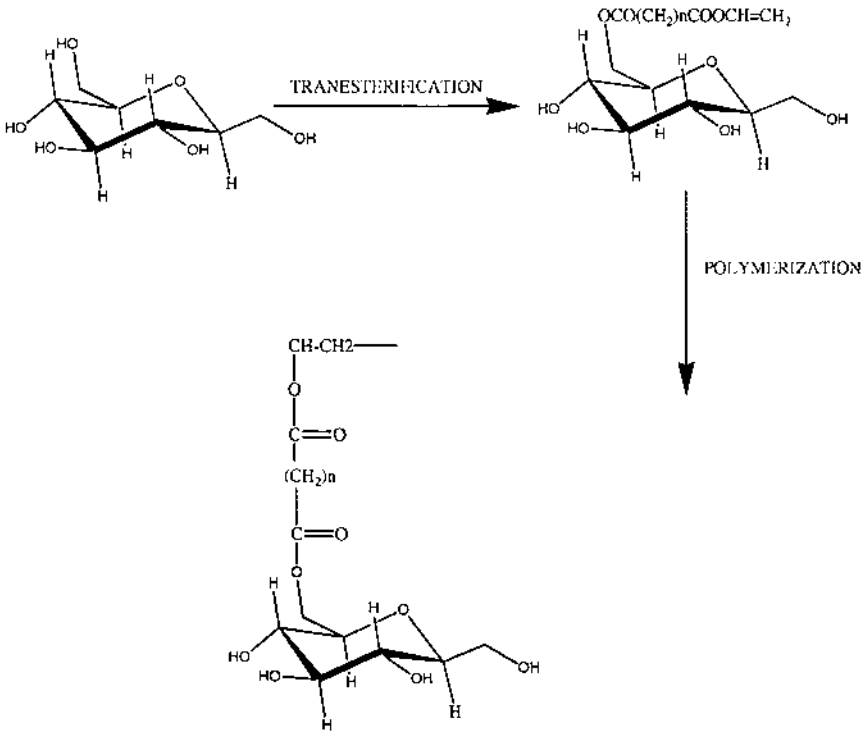


6, 8′-dioleoyl Glc-PEG$_4$

FIG. 2 Examples of enzyme-mediated products of ethoxylated sugar fatty acid esters. (From Ref. 61.)

E. Ethoxylated Sugars

Vulfson and workers recently utilized lipases Novozyme (*C. antarctica*) and Lipozyme (*M. miehei*) for esterification of ethoxylated glycosides of glucose and xylose with oleic and caprylic acids [61]. Lipozyme showed a marked regioselectivity for the primary alcohol on polyethylene glycol (PEG) to yield the monoester of the glucose-PEG with less than 3% formation of the sugar ester. Similarly, the regioselectivity of Novozyme for the PEG hydroxy was observed to be significantly greater than for the sugar hydroxy moiety for equimolar ratios of fatty acid and glucose-PEG after 4 h incubation. However, as the reaction time was increased the yield of the two monoesters changed to approximately 1:1 (Fig. 2).



SCHEME 2 Synthesis of polymerizable sugar esters. The first step is preparation of the sugar monomer via enzyme-mediated synthesis (*Alcaligenes* sp in pyridine) followed by polymerization with a chemical catalyst AIBN in DMF at 60°C. (From Ref. 65.)

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F. Dimeric and Trimeric Sugar Fatty Acid Esters

The preparation of gemini and trimeric sugar fatty acid esters was recently reported by Gao et al. [62,63]. Enzymatic acylation (*A. antarctica and M. miehei*) of isopropylidene derivatives of mono- and disaccharides of methyl-α-glucoside with 2-bromomyristic acid was followed by chemical modification to dimeric and trimeric surfactants using the appropriate acid in DMF/potassium carbonate at 70°C. The final yields were reasonable in each case, being up to 50% recovery. Several structures were synthesized containing xylose, glucose, galactose, and lactose connected via different hydroxy groups in the parent sugar or alternatively via the 2-hydroxytetradecanoic acid hydrophobe.

G. Polymerizable Sugar Esters

Synthetic polymers containing sugar branches have attracted considerable interest in recent years. These are typically produced via chemoenzymatic routes where the first step is the enzyme-mediated synthesis of the sugar ester monomer followed by chemical polymerization (Scheme 2). Several workers have developed sugar ester–based polymers containing vinyl, styrene, acrylamide, etc., functionalities. A discussion of the synthesis methods of these compounds are not in the scope of the current work and interested readers are referred to some recent literature by Patil et al. [64], Kitagawa and Tokiwa [65], and Raku and Tokiwa [66].

III. BIODEGRADATION

Primary and ultimate biodegradabilities of sugar esters have been monitored by surface tension measurements, dissolved organic carbon (DOC), biological oxygen demand (BOD), and CO_2 evolution. Early studies showed that water-soluble sucrose esters promoted the oxygen uptake by inoculated media at a rate similar to that of linear alkylbenzenesulfonate (LAS), and to a much greater extent than tetrapropylenebenzenesulfonate (TBS) [67,68]. Sucrose esters of cottonseed oil showed 65.8% of theoretical BOD in 250 h. Less soluble esters promoted oxygen uptake to a smaller extent; mixed sucrose stearate and palmitate gave only 11–23% of theoretical BOD in 250 h. However, the biodegradation of sucrose stearate in a model sewage treatment plant was found to occur readily. A laboratory scale semicontinuous activated sludge plant was fed daily with sucrose stearate to give a total concentration of 200 ppm (BOD of 400–450 ppm). Throughout 2 months of operation good quality effluent was produced with a BOD consistently less than 10 ppm [69].

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The disappearance of sucrose ester surfactants from river water samples was studied by measuring the consequent increase in surface tension. This showed 100% primary biodegradation within 2 days [70,71]. An advantage of sugar fatty acid esters is their ready anaerobic biodegradation. Complete primary biodegradation within 2 days was also observed under anaerobic conditions [70].

The biodegradation of a related surfactant formed by ethoxylation of sucrose tallowate has also been studied [72]. Surface tension measurements indicated complete biodegradation in an inoculated medium within 7 days. Gas chromatography was used to analyze samples, taken from the medium during biodegradation, for fatty acids content. This revealed that ester hydrolysis occurred almost instantaneously upon addition of the surfactant to the culture, releasing fatty acids. The subsequent removal of the fatty acids from solution was found to occur within about 7 days. Stearic acid was removed more rapidly than palmitic acid. The levels of myristic and lauric acid initially decreased but then increased. The observed increase in the levels of the shorter chain fatty acids was attributed to the presence of partial degradation products of the longer chain fatty acids. Sucroglycerides derived from coconut oil showed rapid ultimate aerobic biodegradation reaching 60% theoretical CO_2 production within 15 days [73].

A. Effect of Structure on Biodegradability

The number of investigations into the effects of structure on the biodegradability of sugar-based surfactants is relatively few. In one early study the rates of primary biodegradation of sucrose laurate, palmitate, and stearate (indicated by surface tension increase) were found to differ slightly, increasing with alkyl chain length [71]. Another study measured the ultimate biodegradation of the same sucrose esters by measurement of CO_2 evolution [74]. They all gave greater than 70% biodegradation within 30 days. In this study, the biodegradation rate (indicated by CO_2 evolution) was found to decrease with increasing chain lengths. The discrepancy between the findings of these two studies may be due to the different biodegradation methods and measurement techniques employed in each case. It has been demonstrated that the presence of extensive alkyl chain branching greatly reduces the biodegradability of sugar ester surfactants, as is the case for surfactants in general [75].

A systematic study of the impacts that structural changes have on the ultimate aerobic biodegradability of sugar ester surfactants has revealed some correlations between the structure and biodegradability of these surfactants [76,78]. An array of sugar ester surfactants whose molecular

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structures were systematically varied was studied. The size of the sugar head group was varied between a monosaccharide and a trisaccharide; the length of the alkyl chain was varied between 12 and 16 carbons; structures with two alkyl chains attached were studied, and structures where a sulfonate or alkyl side group had been attached in a position α to the ester bond were also included. The only structural variation that was found to have a significant affect was the α substitution. The biodegradation profiles determined for sucrose laurate and sucrose sulfonyl laurate are shown in Fig. 3. It is clearly seen that sucrose laurate is completely degraded within a day, while the sucrose sulfonyl laurate degrades more slowly reaching about 90% degradation after 25 days.

The results obtained for sucrose methyl laurate, with a methyl group α to the ester bond, and sucrose ethyl laurate, with an ethyl group α to the ester bond, indicated reduced biodegradability of these esters relative to the

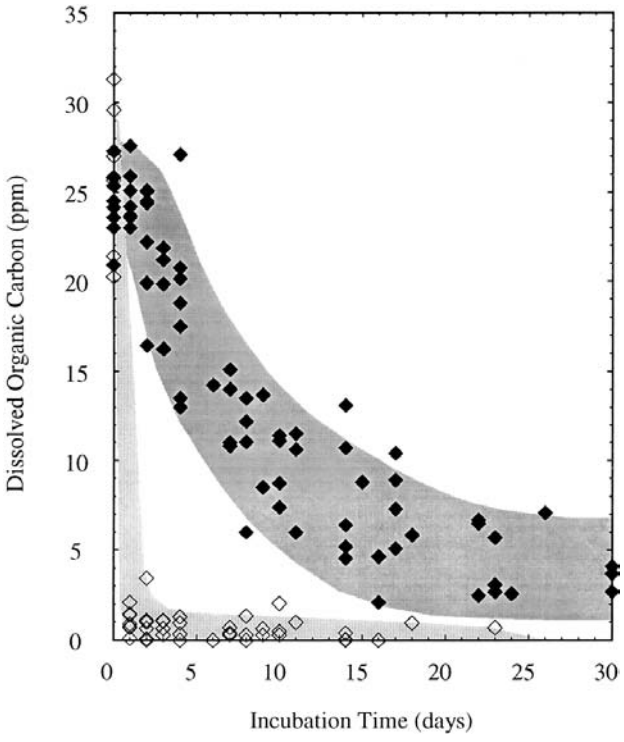

FIG. 3 Biodegradation profiles determined forsucrose laurate and sucrose sulfonyl laurate [76–78]. (Reprinted with permission of AOCS press.)

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underivatized sucrose ester, but not as low as in the presence of a sulfonate group in the same position. This indicates that the inhibitory effect of the α-sulfonate group is unlikely to be solely due to its charge but also a consequence of its size.

B. Biodegradation Pathways

In the work on structural affects mentioned above, further study revealed that the reasons for the differences in biodegradation rates lay in the biodegradation pathways followed in each case. Sucrose laurate was determined to be degraded by initial hydrolysis of the ester bond forming free lauric acid and sucrose as shown in Fig. 4. This pathway is consistent with previously reported findings [72]. In contrast, the degradation of sucrose sulfonyl laurate shown in Fig. 5 does not occur by initial hydrolysis but by a pathway analogous to those previously reported for LAS and α-sulfonyl methyl esters. The ultimate biodegradation behavior of sucrose sulfonyl laurate, shown in Fig. 5, was very similar to that of LAS which is also known to be degraded via initial oxidation of the alkyl chains.

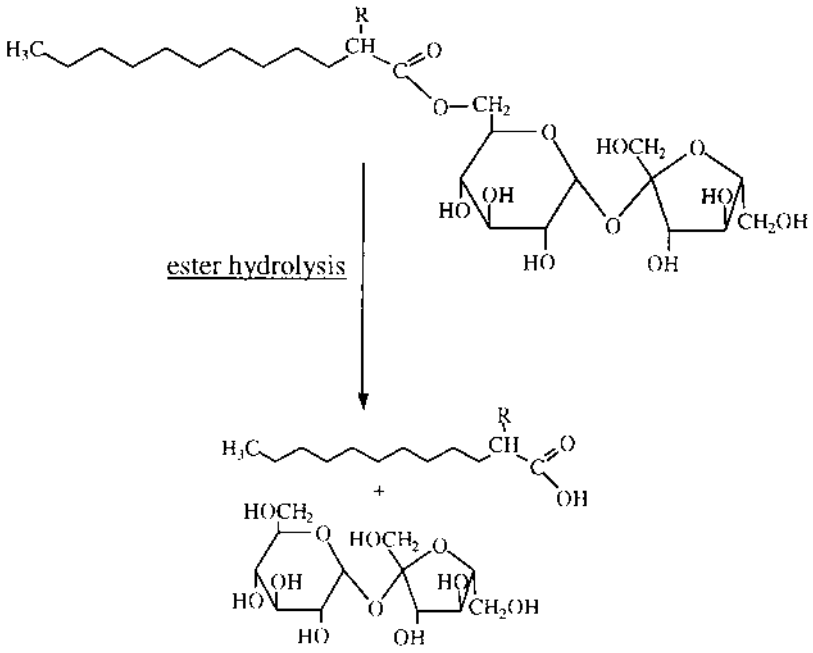

FIG. 4 Biodegradation pathway determined for sucrose laurate.

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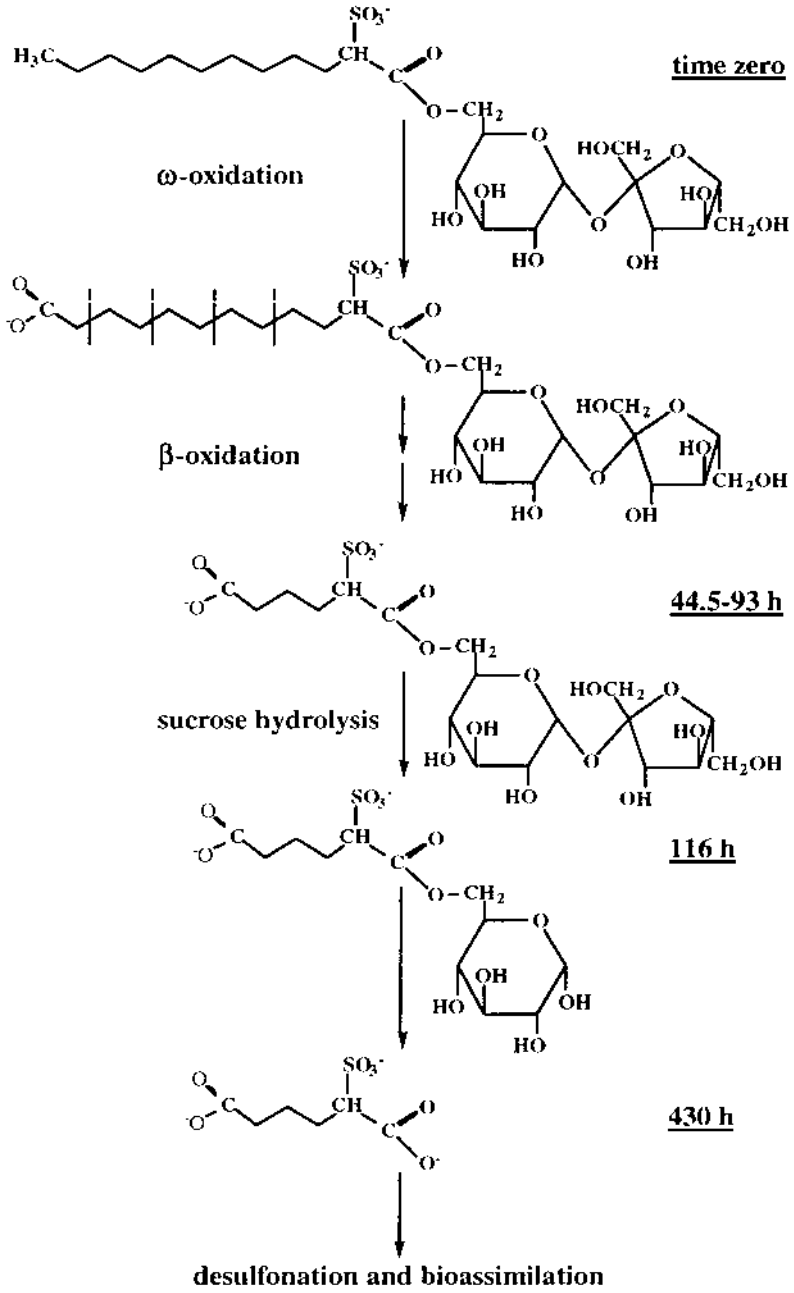

FIG. 5 Biodegradation pathway determined for sucrose sulfonyl laurate. (Reprinted with permission of AOCS Press [76].)

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IV. TOXICOLOGY

It is often claimed in the preamble of publications on sugar surfactants that a major benefit of these materials lies in their low toxicity. The increased use of such surfactants as food additives has led to a number of detailed investigations into the toxicology of sucrose esters by the World Health Organization (WHO). In particular, the sucrose esters of fatty acids and monoglycerides were reviewed in terms of their pharmacokinetics, pharmacodynamics, acute toxicity, and short- and long-term tolerability. This section summarizes and discusses some of the toxicity results from these reports (WHO Food Additive Series 10, 15, 35, and 40).

A. Toxicity in Animal Models

The acute toxicity for a number of different compounds in this general class has been studied in a range of animal models. The results summarized in Table 2 reveal that no significant toxic events can be associated specifically through oral ingestion of sugar fatty acid esters. One exception appeared to be the higher dose of lard and tallow sucrose esters administered to the rat, which resulted in death. Also notable is the positive hemolytic result for sucrose monopalmitate when administered intravenously to the rat. Surfac-

TABLE 2 Studies of Acute Toxicity of Sucrose Esters in Various Animal Models

Surfactant	Test animal	Admin. route	Test condition	Result
Sucrose monopalmitate	Rat	IV	Hemolysis	Positive[a]
		Oral	Lethality	Negative[b]
	Mouse	Oral	Lethality	Negative[b]
Sucrose monostearate	Mouse	Oral	Lethality	Negative[b]
	Rat	Oral	Lethality	Negative[b]
Palm oil sucrose	Rat	Oral	LD_{50}	> 30mg/kg[c]
Esters	Mouse	IV	Hemolysis	Negative[a]
Lard and tallow	Rat	Oral 5 g/kg	Lethality	Negative[d]
Sucrose esters		Oral 10 g/kg	Lethality	Positive[d]
	Dog	Oral 3.8 g/kg	Lethality	Negative[d]
	Rabbit	Oral 2 g/kg	Tolerability	Negative[d]
	Rat	Intragastric	Hemolysis	Negative[a]
	Rabbit	Intragastric	Hemolysis	Negative[a]
	Mouse	IV	Hemolysis	Negative[a]
	Dog	Oral	Tolerability	Negative[e]

[a][122], [123]; [b][124]; [c][125]; [d][126]; [e][127].

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tants often cause lysis of red blood cells when injected intravenously, which has limited their utility in injectable parenteral drug formulations. The palm oil sucrose esters did not show hemolytic activity.

The effects of oral ingestion of different sucrose esters over short periods of time have also been studied in rat and dog models, which are summarized in Table 3. There was only one report of adverse reaction to relatively high levels of sucrose monopalmitate in the diet, while the rest of the studies indicated that short-term ingestion has no consequence in these animal models. Similarly, long-term dietary ingestion of these materials (Table 4) showed no effects on the reproduction of the animals under study over two generations, and no evidence of increased level of tumors or other abnormalities.

As a consequence of these results, the human acceptable daily intake (ADI) for sucrose esters as a general class of compound was set by the WHO

TABLE 3 Studies of the Short-Term Toxicology of Sucrose Esters Administered Orally in Diet for Animal Models

Surfactant	Test animal	Effects of exposure (percentage by weight in diet of maximal dose given)
Sucrose monopalmitate	Rat	>5% caused diarrhea and death 100 days[a]
		<2% no adverse effects 60 days[b]
	Dog	<3% no adverse effects 2 years[c]
Sucrose monostearate	Rat	<2% no adverse effects 60 days[b]
Mixed palmitic and stearic acid esters of sucrose	Rat	<2% no adverse effects 60 days[b]
	Dog	3% no adverse effects over 26 weeks[d]
Palm oil sucrose esters	Rat	<10% no adverse effects 150 days[e]
		<10% no adverse effects 100 days[f,g]
		<2%, 100 days, no reproductive effects or neonatal abnormalities[h]
Lard and tallow sucrose esters	Rat	<10% no adverse effects 15 days, 25% only reduced body weight[e]
		25% no adverse effects 200 days[i]
	Dog	>3% 182 days resulted in soft feces, but no other adverse effects[j]
Commercial product S-570 (mixed sucrose esters of stearic and palmitic acids)	Rat	5% No adverse effects after 7 weeks[k]

[a][128],[129]; [b][130]; [c][131]; [d][132]; [e][126]; [f][125]; [g][133]; [h][134]; [i][135]; [j][136]; [k][137].

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TABLE 4 Studies of the Long-Term Toxicology of Sucrose Esters Administered Orally in Diet for Animal Models, Especially Reproductive and Carcinogenic Potential

Surfactant	Test animal	Effects of exposure (percentage is by weight in diet)
Sucrose monopalmitate	Rat	>3% for 2 years caused loss in body weight; <3% no adverse effects[a] 1% no effect on reproduction or offspring over 3 generations[b]
Palm oil sucrose esters	Rat	0.5% for 14 months, no tumors or abnormalities[c] 10% for 28 months, no tumors or abnormalities[d] 0.5% over two generations, no reproductive effects or neonatal abnormalities[e]
Lard and tallow sucrose esters	Rat	10% for 28 months, no tumors or abnormalities[c,d] 0.5% for 14 months, no adverse effects[f] 0.5% over two generations, no reproductive effects or neonatal abnormalities[g] 3% No adverse effects, no carcinogenicity over 18 months[h]
Commercial product S-570 (mixed sucrose esters of stearic and palmitic acids)	Rat	No adverse effects on condition, survival or carcinogenicity over 2-year study[i]

[a] [131]; [b] [138]; [c] [139]; [d] [126]; [e] [140]; [f] [141]; [g] [142]; [h] [143]; [i] [144].

at 0–16 mg/kg, which was based on a no observable effect level (NOEL) in animals of 50 g/kg (WHO Report on Food Additive Series 35).

B. Toxicity in Humans

Although data on the toxicology of sucrose esters in humans is less common than in animal models, some studies are reported. A pharmacokinetic study of human volunteers fed 1 g of sucrose tallowate showed no adverse effects, and plasma and urine analyses indicated rapid hydrolysis of the ester in the gastrointestinal tract and almost complete absorption and subsequent excretion of the hydrolysis products. This indicated little tendency for the ester to accumulate in body tissues [79].

Clinical trials have been conducted with humans [80,81] on the effects of ingestion of up to 7.5 g/day of S-1170, a commercially available sucrose ester mixture. Analysis of blood and feces showed that around 80% of the esters were hydrolyzed, and was variable for mono-, di-, and triesters, and alkyl

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chain length. Plasma levels were extremely low and close to the limit of assay sensitivity (~0.1 μg/mL) or not detectable. However, the group receiving 7.5 g/day of S-1170 reported adverse gastrointestinal effects such as diarrhea, soft stools, and flatulence, which were not reported in animal models at similar or greater doses.

As a result of these adverse effects, and perceived deficiencies in the prior studies, a further clinical trial was conducted, at a dose level of approximately 30 mg/kg/day [82]. There were no apparent differences between the treatment or control groups, and as such the ADI for sucrose esters was adjusted by the WHO to 0–30 mg/kg in 1998. By way of comparison, the WHO has set an ADI for Tween 80, another nonionic surfactant commonly used in food, at 25 mg/kg. The ADI level indicates the general safety of this class of compounds.

V. SINGLE- AND MULTICOMPONENT PHASE AND DILUTE SOLUTION BEHAVIOR

The expanding interest in alternative surfactants made from renewable resources has been driven somewhat by the perceived environmental benefits that these materials have over those from nonrenewable sources. While it is true that these aspects have been a significant driver in the level of interest in carbohydrate-based surfactants in particular, the unique physicochemical properties of these materials offer significant advantages over other materials in some applications.

The hydrogen bonding capacity of the carbohydrate headgroup of these surfactants imparts a wide range of thermotropic, lyotropic, and solution behavior on these materials, not often found among other classes of amphiphiles. The huge range of different carbohydrate moieties that may comprise the headgroup, combined with the range of candidate hydrophobic groups provides for a vast potential number of compounds in this category.

In addition, the phase boundaries for these materials in the binary surfactant–water phase diagrams are often vertical or near-vertical; this translates to temperature invariant phase behavior, which is a major attraction to formulators of surfactant-based products. A further attraction of sugar-based surfactants without ionic or ionizable functional groups is that their behavior is often very stable at high salt concentrations and in alkaline conditions.

These points apply also to the subset of carbohydrate-based surfactants that comprises a fatty acid hydrophobic group attached to a sugar-based head group, sugar fatty acid esters.

Sugar fatty acid esters have been reviewed as a subclass of the more general sugar-based surfactants on a number of occasions. A very recent issue

of the journal *Current Opinion in Colloid and Interface Science* [Volume 6, 2001] was devoted to natural surfactants, which included some excellent reviews on sugar-based surfactants. In that issue, Holmberg reviewed the subject of "natural surfactants" of which sugar fatty acid esters are obviously only a small subset [83]. Stubenrauch focused on reviewing the physicochemical properties and interfacial behavior of sugar-based surfactants [84]. In particular, work on the formation of micelles by α and β anomers of methyl 6-*O*-octanoyl-D-glucoside were discussed [85]; however, this review concentrated primarily on the rapidly expanding subject of alkylpolyglucosides. Earlier reviews on the subject of sugar fatty acid ester surfactants would include those highlighted by Johansson and Svensson [86] in that issue, namely, the work of Allen and Tao, Lewis, and Hill and Rhode [references in 86]. The review of Johansson and Svenson comprehensively covers many derivatives of fatty acids in addition to sugar derivatives and is an excellent starting point for the wider subject of fatty acid esters.

The subject of the physicochemical properties of a number of sugar ester surfactants was reviewed relatively recently by Söderman and Johansson [87]. In particular, the solution behavior of lactose and lactitol esters was discussed, as was ability of the sucrose alkanoates to stabilize temperature-insensitive microemulsions. The article covered the more general subject of polyhydroxylated surfactants, generally concluding that while the knowledge of these systems is certainly growing, there is a great deal of work to be done to understand the behavior of these types of surfactants.

The subject of sucrose alkanoates and alkanoylglucosides was also included in the review of sugar surfactants by Fukada [88].

Due to the wide spectrum of behavior exhibited by this class of compounds, the discussion is broken up into the major areas of surfactant behavior, namely, thermotropic liquid crystal formation, microemulsions, lyotropic liquid crystalline behavior, reverse micellar systems, and dilute solution. This spectrum of available modes of self-assembly facilitates their use in an increasing range of applications.

A. Thermotropic Behavior

It has been known for a long time that the hydrogen bonding ability of sugar headgroups allows the formation of thermotropic liquid crystal phases on heating of sugar-based surfactants in the absence of water. For a recent review on the subject of the thermotropic behavior of sugar surfactants in general, the reader is directed to the work of Paleos and Tsiourvas [89]. This review did not specifically cover the subject of thermotropic liquid crystal formation by sugar ester surfactants; however, it has been known for some time that sugar fatty acid esters do indeed form thermotropic liquid crystals

of the smectic type, in agreement with the general behavior of carbohydrate surfactants. Jeffrey reviewed early work in this area and gave the specific examples of the nonanoic, decanoic, and dodecanoic 3-*O*-glucose derivatives displaying broad liquid crystalline regions on heating [90]. As well, sucrose fatty acid esters have been shown to form thermotropic liquid crystalline phases on heating [27,91] as have lactose, lactitol, raffinose, and stachyose fatty acid esters [25,27]. Glucose, which has been completely esterified with mesogenic side chains, has also been shown to form thermotropic liquid crystals of the chiral nematic type [92].

Abe et al. recently prepared and studied an extensive series of methyl 6-*O*-alkanoyl-β-D-glucosides and α-D-galactosides [93]. The purpose was to study the nonlinear changes in thermotropic behavior with increasing chain length, the so-called "odd–even effect." It was found that the even and odd chain lengths pack differently in the crystal due to disruption of the hydrogen bond lengths in the headgroups, thereby affecting the melting temperatures, and that the glucosides were affected more by the effect than the corresponding galactosides.

B. Microemulsions and Macroemulsions

Perhaps the most extensive area of research for sugar fatty acid esters is formulation of microemulsion systems. The potential applicability of these low-toxicity surfactants in the areas of cosmetics and food products has been the principle driving force for this research.

Garti et al. have studied extensively the growing potential for microemulsions based on sugar fatty acid esters for utility in food products and have published a fairly recent review on the subject [94]. Since that review their work has continued in this important area of application for these materials, with a number of publications in the past 3 years.

The earlier of these studies concentrated on the behavior of water in a model sucrose ester–based water-in-oil (w/o) microemulsion [95]. The behavior of water in w/o microemulsions is of particular importance to the behavior of solutes in the aqueous compartments. The ratio of bulk to free water was examined in microemulsions of this type, comprising sucrose esters and butanol, with linear alkanes as the oil component. Subzero differential scanning calorimetry (DSC) was used to show that the hydroxyl groups of the surfactant are the principal determinant of the maximal level of bound or "interfacial" water and that it is essentially independent of the oil used. Butanol occupies the interface and thereby also influences the water binding capacity. Variation in the chain length of the surfactant induced substantial differences in the dilutability of the microemulsions with water, possibly indicating a change in the structure of the microemulsions.

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Garti et al. published another study in the same year, this time focused on sucrose monostearate as the surfactant, and its use with oils that are acceptable for use in foods, such as *R*-limonene, vegetable oils such a long- and medium-chain triglyceride, and oleic acid [96]. The ability of these systems to solubilize water is important for the application, but it was found that significant amounts of pentanol were required as a cosolvent to incorporate water in the medium-chain triglyceride single-phase microemulsions. The use of shorter chain cosolvents, butanol and propanol, allowed a significant increase in water solubilization to occur, which was also true for the other oils and oleic acid. Subzero DSC revealed that high levels of water, up to 25% by weight, may be bound to the sugar ester head groups in these microemulsions, an important consideration when using these types of systems in applications where the mobility of a dissolved solute is important.

Further work by this group in the area of four-component microemulsions containing sucrose esters/butanol/oil and water, where the oil is a medium-chain triglyceride, dodecane, or hexadecane, has also been reported recently [97]. Dilution with water at different surfactant concentrations and using the different oils provided the samples for study by pulsed gradient spin echo–nuclear magnetic resonance (PGSE-NMR) and small angle X-ray scattering (SAXS) analysis. NMR revealed restricted water mobility in these systems consistent with the findings for DSC in the previous report, due to high binding of water to the interfacial region. The microemulsion formed with hexadecane undergoes an inversion, indicated by the diffusion of entrapped water in the microemulsion approaching that of bulk water at high water content. Diffusion of oil components in these systems was quite different from that of the water, which argues against the formation of a bicontinuous structure in these systems, which would be characterized by similar diffusion characteristics in the oil and water domains. Data are presented to illustrate the temperature and ionic strength independence of the microemulsion formed using medium-chain triglyceride (MCT) as the oil, for the application in food products; however, the point is again stressed that these systems do not solubilize water effectively without the addition of cosolvent, in this case butanol.

Building on the previous work was a more extensive study of potential o/w microemulsions for food applications, engaging a fifth component in the form of propylene glycol and glycerol [98]. Various surfactants were studied of which sucrose monolaurate, sucrose monostearate, and the Tween surfactants could all be classified as sugar fatty acid esters. Again solubilization was greatly enhanced by the presence of alcohols and the polyol solvents, and some systems were generated that could be diluted without deleterious phase changes with oil in some cases and with water in others. The dilutability of these systems, combined with their stability to temperature, provides for microemulsions with potential application in food products.

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The group of Garti have also collaborated with Glattner and workers [99] to investigate the structure of the microemulsion formed with commercial grade sucrose monostearate (SES), butanol, and tetradecane, in the presence of water. The microemulsion formed by these constituents melts at 37°C, making it a suitable system for a microreactor. Using SAXS, small angle neutron scattering (SANS) and differential light scattering (DLS), it was found that SES and butanol form inverse mixed micelles in the absence of water. An increasing SES to butanol ratio was found to increase micellar size. Water can be added to the system up to almost 50% while maintaining a single-phase region. It was shown that the micelles behave essentially as hard spheres and that some overlap of surfactant hydrocarbon tails between the micelles occurs, which impart particular dynamic behavior on the system.

Macroemulsions comprising the pseudoternary system of mixed sugar ester surfactants, medium-chain triglyceride, and water were prepared by Ismail et al., and particle size, rheology, and stability were studied [100]. Mixtures of commercial glucose ester surfactants were used to cover a wide hydrophilic–lipophilic balance (HLB) range from 6.6 to 15. Stability was optimal between HLB of 13 and 7, which correlated well with reduced droplet diameter. The yield stress increased greatly around pH 8, indicating that a network was developed, possibly due to liquid crystal formation, although this was not investigated further.

Aramaki et al. [101] prepared a cubic phase microemulsion by the judicious blending of commercial sucrose alkanoates of mixed composition to systematically alter the HLB of the system when combined with a range of oils. The two sucrose-based surfactants were principally composed of the mono-, di-, and tridodecanoates, with one comprising substantially greater percentage of the higher esters, which was used to moderate the hydrophilicity of the second surfactant. Birefringence and SAXS were used to confirm the existence of a single cubic phase region, which was shown to be of the normal discontinuous micellar cubic phase type.

Blending of sucrose distearate with $C_{12}EO_6$ was shown by Aramaki et al. to have a synergistic effect on lamellar phase production in the pseudobinary system with water [102]. This translated into a substantial increase in ability to solubilize water and *n*-decane in the bicontinuous microemulsion formed by these materials. Addition of only 10% sucrose distearate increased the capacity by approximately three times that of $C_{12}EO_6$ alone. Interestingly, the same effect was not found with sucrose monostearate as the HLB of the added surfactant was important.

The microstructure of sucrose alkanoate single-phase microemulsion, with a short-chain hexanoate ester as the oil, has been studied in some detail by Bolzinger-Thevenin et al. using freeze fracture micrography and SANS [103]. The microstructure of the Winsor IV single-phase region was shown

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to be bicontinuous and at some compositions could be diluted substantially with water up to 40 wt% without encountering a phase boundary.

Nakamura et al. have also studied these types of microemulsions, using either hexanol or sucrose polydodecanoate as the cosurfactant in sucrose monolaurate, alkane, and water systems [104]. The microemulsions were studied using NMR, electron spin resonance (ESR) and SAXS to investigate the properties of the phases produced in these systems. The particular area of interest for this work was on the progression from lamellar liquid crystal to bicontinuous isotropic phase with oil and water. The three-phase microemulsion region formed by the sucrose monolaurate/hexanol/decane/water system at 9–13% hexanol is bicontinuous with approximately equivalent size of water and oil domains. Using a mixed surfactant system of high and low HLB sucrose esters results in greater solubilizing power for the oil, and also results in the formation of a water continuous micellar cubic phase at equal parts oil and water for decane and hexadecane. A bicontinuous three-phase microemulsion is produced on addition of propanol, indicating a disruption of the rigid lamellar structure formed at the interface in the case of the sugar esters alone.

The cosmetics and transdermal drug delivery fields are also expected to further benefit from the formulation of microemulsions from mild sugarbased surfactants. Lehmann et al. have studied the effect of such a microemulsion on dermal and corneal irritation, and hydrocortisone incorporation [105]. A microemulsion containing commercially available sucrose esters, isopropyl myristate, and propylene glycol and water was prepared as a water continuous system, and 16.5% hydrocortisone was loaded into the anhydrous base mixture. The formulation spread well on the skin due to the low surface tension of the system at 26 mN/m. While the microemulsion provided greater drug penetration, it also resulted in irritation and barrier compromise. The authors make the point that the formulation may be better suited to drugs that do not induce an irritation themselves.

The petrochemical industry also has a need for environmentally friendly surfactants for use in oil recovery, clean-up operations, and emulsion formation for handling and application purposes. Pruthi and Cameotra report the behavior of a novel sucrose glycolipid, produced by *Serratia marcescens,* that could be classed as a sugar ester surfactant, and its potential use in oil recovery and cleaning applications [106].

C. Lyotropic Liquid Crystalline Phases

The lyotropic phase behavior of the fatty acid esters of sucrose, namely, sucrose monolaurate, sucrose monooleate, sucrose dilaurate, sucrose dioleate, and the more complex sucrose monotallowate, was studied in the late

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1980s by Herrington and Sahi [91]. The rich lyotropic phase behavior spurned further interest in sugar fatty acid ester surfactants from a phase behavior perspective. Soderberg et al. [27] reported phase diagrams for laurate surfactants where the number of saccharide head group units is sequentially increased (i.e., glucose, sucrose, raffinose, and stachyose). Drummond and Wells [25] reported the phase behavior for fatty acid esters of lactose and lactitol. For sugar fatty acid ester–water systems, micellar, lamellar, hexagonal, and cubic phases have been identified. Most of the self-assembly behavior in water can be readily explained in terms of the geometric packing constraints.

One area of rapidly expanding interest is the use of reverse micellar systems of sugar-based surfactants in the extraction of proteins and other sensitive materials. The use of hydrophilic, nonionic, sugar-based surfactants for membrane protein extraction is well known to be effective due to the mild, nondenaturing properties of these surfactants when compared with ionic surfactants or polyoxyethylene derivatives. For the same reasons, protein extraction into reverse micellar systems is now becoming a popular medium for such applications. Alkyl sorbitan esters and ethoxylated sorbitan esters, such as Tween 85 [107] and Span 60 [108], have been used successfully to form reverse micellar systems for protein extraction. Blends of Tween and Span have also been found to be effective for this purpose [109]. More recently, commercially available sucrose fatty acid esters have been shown to form biocompatible reverse micellar systems into which cytochrome *c* is effectively extracted [110].

The rich lyotropic phase behavior exhibited by membrane lipids is well known. The lyotropic phase behavior of membrane lipids whose structure can be described as diacylglucosylglycerols can be classified as sugar fatty acid esters, and have been studied by Mannock et al. [111]. These types of surfactants often exhibit lamellar phases at low temperature, and a transition to a different inverted nonlamellar mesophase, often reverse hexagonal (H_{II}) or reverse micellar cubic (Q_{II}) phase. In this particular study acyl chains with different terminus, based on stearic and palmitic acid, were studied. Only the shorter chained derivatives tended to form a Q_{II} phase; the remainder formed H_{II} phases over a range of temperatures above 70°C.

D. Dilute Solution Behavior

Coppola et al. [112] have prepared a series of three acyl derivatives of glucose with dodecanoyl, stearoyl, and oleyl chains attached at the 6-O position. The anomeric purity of the resulting surfactants was variable through the series. Dilute solution behavior and self-assembly, as well as thermotropic and lyotropic phase behavior were studied.

Interestingly, these materials did not display the "double melting point" behavior when studied by DSC, as no thermotropic liquid crystalline phase was displayed on heating or cooling the neat surfactants. This is not consistent with the analogous anomerically pure, 6-*O*-alkyl-α-D-galactopyranose series studies by Bault et al. [113], which all showed liquid crystalline behavior. The reason for this major behavioral difference is not known, but the authors speculate that it may be due to a lack of hydrogen bonding network between the hydroxyl groups of the sugar headgroup. The melting point of the oleyl derivative was significantly lower than that of the *n*-alkyl derivatives as expected. The binary surfactant–water lyotropic behavior was very reminiscent of the alkylglucoside analogs, dominated by the two-phase region between a micellar and lamellar phase. The near-vertical boundaries between phases exemplifies the temperature invariance of the sugar surfactants in general.

The decanoyl derivative forms micelles up to around 15 wt % surfactant, while the stearoyl and oleyl only form micelles at less than 2 wt % surfactant. In addition, the decanoyl derivative displays a significantly depressed Krafft temperature boundary, around 30°C compared to more than 40°C for the other two. The micelles formed by the decanoyl derivative were shown by NMR to be spherical in the dilute region but become more disk-shaped as the phase boundary is approached. This work provides data that complements that of Soderberg et al. [27] in that it examines the systematic change in hydrophobe rather than the systematic change in headgroup structure as performed by Soderberg et al.

Another recent systematic study of the effect of surfactant structure on the solution behavior of sugar esters was presented by Garofalakis et al. [114]. A series of essentially pure sugar monoesters of differing hydrophobic chain lengths and differing carbohydrate head groups, were prepared enzymatically, and their air–water interfacial properties compared to a range of chemically synthesized, purified, commercially available materials. Perhaps surprisingly, there was little difference between the corresponding sucrose monoesters of either origin. Of the enzymatically prepared surfactants, stearic acid derivatives, with sucrose, lactose, galactose, and xylose, were essentially insoluble in water at 32°C. With the exception of sucrose esters, the palmitic and myristic acid derivatives also appeared to approach a solubility limit, signified by the appearance of turbidity in solution corresponding to a plateau in the surface tension curves. Sucrose palmitate and sucrose myristate were a clear solution, allowing reliable measurement of a CMC value for this material comparable to prior reports. Lactose palmitate has been investigated previously by Drummond and Wells [25] and was found to have a similar CAC value, and similar surface tension reduction,

but gave a value for the headgroup area around half that found in this study. This perhaps exemplifies the difficulty in obtaining accurate head group areas from these types of measurements. The commercial sucrose esters provided similar reduction in surface tension with increasing concentration to the enzymatically prepared equivalents and interfacial occupational areas of around 50 $Å^2$. The determination of accurate interfacial data from the surface tension curves for these materials was even more difficult probably due to the presence of surface-active impurities in the commercial grade materials. As expected for these nonionic surfactants, addition of low levels of electrolytes did not affect the interfacial properties.

There is also overlap of this work with the earlier work of Söderberg et al. [27], who studied the behavior of sucrose dodecanoate (laurate) at the air–aqueous solution interface, among a series of sugar dodecanoate surfactants. The CMC value for the material was very different between the two groups, at 0.45 mM and 0.21 mM for Söderberg et al. and Garofalakis et al., respectively. However, the surface tension reduction and occupational area at the interface were very similar, which led to the conclusion by both parties that the aggregates formed were rod-like micelles, based on critical packing parameter considerations. Söderberg et al. also determined approximate partial phase diagram for sucrose dodecanoate and found that at higher concentrations of surfactant there is a conversion to a hexagonal phase from the micellar phase, which further supports the hypothesis of rod-like micelles in solution of this surfactant. Thus, the difference between the CMC values is puzzling.

The formation of vesicles by sugar ester surfactants has been known for some time, Schenk et al. studying these systems as early as 1989 [115]. The formation of temperature-insensitive vesicles in the presence of cholesterol was studied by Bouwstra et al. using sucrose, mallitol, and methylglucose esterified to different degrees with fatty acids, covering a range of HLB values [116]. These commercial grade surfactants were found to only form vesicles in the presence of cholesterol and aggregate rapidly in the absence of a charge-inducing agent. Nevertheless, it was possible to form vesicle structures that were more stable to temperature than those prepared from polyoxyethylene alkyl ether surfactants.

Commercial sugar ester surfactants have also been shown to provide steric stabilization for solid lipid nanoparticles and, due to their nonionic headgroup, are stable in electrolyte solutions [117]. However, they were less effective as a stabilizer in the low-pH environment of artificial gastrointestinal fluids.

The rheological properties of surfactant solutions are impacted strongly by the types of aggregates formed in solution. The viscous and viscoelastic

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properties of sucrose surfactants with different acyl chain lengths have been studied for quite some time [118–120], and for sucrose oleate has been related to a rod-like or disk-like micellar structure.

The interaction of proteins with surfactant films is important for application of emulsions and foams in food products. Garofalakis and Murray have studied the interaction between β-lactoglobulin and sucrose monoesters of varying chain length, in terms of foam production and stability, and rheological properties of surfactant films [121]. The dilatational elastic modulus was determined by the Langmuir trough/Wilhelmy plate method. When studied without added protein, the foam height and stability was maximal for sucrose monododecanoate (SM1200), while longer and shorter chain lengths provide less initial foam and lower stability in the rank order SM1000, SM1600, SM800 at constant solution concentrations. Higher solution concentration increased the overall production and stability, but not the rank order. On addition to the protein solution at the same constant concentrations, the behavior changed, such that the protein stabilized the more hydrophilic SM1600, while the effect of SM800 was to rapidly disrupt the foam. The behavior is attributed to the protein stabilizing the monomer-depleted film for SM1600, whereas for the hydrophilic SM800 there is adequate monomeric surfactant to stabilize the film. The films themselves were found to be generally destabilized by the presence of the surfactant that displaced the protein. Incompatibility of the two materials in the film was expected from previous studies.

VI. CONCLUSIONS

The evidence supports claims that sugar fatty acid esters are readily biodegradable and possess low toxicity. At the moment, the complexity and expensive nature of both commercial and noncommercial synthetic and purification procedures restricts large-scale usage to predominantly food, cosmetic, and pharmaceutical products. Despite being produced commercially for around 40 years, sugar fatty acid esters have been a relatively understudied class of surfactants. However, this situation is changing as more researchers recognize the great potential of these environmentally friendly surfactants for high-value-added applications.

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4

Novel Saccharide-Based Surfactants

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I. INTRODUCTION

For several reasons, saccharide-based surfactants have evoked increased interest over the last two decades. The postulated sustainable development of our civilization requires that the rate of depletion of nonrenewable resources, such as fossil fuels and minerals, should be slowed and as few potential resource options as possible should be excluded from consideration. This means that humanity's resource base must be conserved and enhanced [1]. In this context, biomass seems to be of great value as a feedstock for the chemical industry. The main constituents are mono- and polysaccharides, which together make up three-fourths of the world's biomass. It is estimated that about 400 billion tons of sugars is produced annually through natural photosynthesis; among them, cellulose takes first place (about 50 billion tons), and starch second [2]. Their major advantage over petrochemical feedstock is that they do not pose significant hazards in terms of acute or chronic toxicity to human health and the environment. This is why saccharide-based chemicals meet the environmental requirements for feedstock: they are biodegradable, biocompatible, and fulfill the principles of green chemistry [3].

Mono- and disaccharides are highly hydrophilic substances. They are produced in large volumes, are available in highly pure form, and are relatively cheap [4,5]. They may be, and indeed have been, used as hydrophilic substrates for the synthesis of nonionic surfactants. In 1999, the worldwide production of the latter was about 3.6–3.8 million metric tons, i.e., approximately 38% of total surfactant production [6]. The majority of the conventional nonionic surfactants are oligooxyethylene (and oxypropylene) chain–containing compounds obtained in the reaction of oxirane (ethylene oxide) or methyloxirane (propylene oxide) with hydrophobic intermediates that contain a functional group with an active hydrogen atom [7]. Only recently, the direct reaction of oxirane with fatty acid methyl esters in the

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presence of heterogeneous catalysts was reported on (this volume, Chapter 14). However, oxirane, a colorless gas or liquid, is toxic, combustible, and explosive, and decomposes into carbon monoxide and methane. Moreover, it can polymerize in the presence of concentrated bases with the evolution of large amounts of heat. Thus, oxirane can pose a hazard to people and the environment [6]. For all these reasons, the most accessible mono- and disaccharides—glucose, fructose, sacharose, lactose, maltose, and cellobiose—seem to be valuable raw materials, alternative to oxirane, for nonionic surfactant synthesis. In fact, it has recently been reported that from 63 major classes of surfactants that are commercially available, 14 are based entirely on renewable materials (including sugar fatty acid esters, alkyl polyglycosides, and alkyl glucamides), and 21 are made from petrochemical and natural feedstock. Furthermore, that report indicated that the growth of carbohydrate surfactant consumption in western Europe increased from about 20,000 tons in the early 1990s to 60,000 tons in 1997 [8].

In saccharide-based surfactants, the carbohydrate moiety is attached to a hydrophobic fragment, normally the hydrocarbon chain of a fatty acid, long-chain (fatty) alcohol or fatty amine, by either the oxygen atom (as in sugar fatty acid esters, in alkylpolyglycosides, or, as reported recently, in cyclic acetal-type sugar surfactants) or by the nitrogen atom (as in *N*-alkylaldosylamines and their derivatives, *N*-alkanoyl-*N*-methylglucamines, and *N*-alkylaldo(bio)namides). There is, however, a marked difference between the O-linked and *N*-linked products. Sugar fatty acid esters (this volume, Chapter 3) fall into the class of polyol ester surfactants. Their synthesis is an example of nonselective synthesis for several reasons: mono- and disaccharides contain both primary and secondary hydroxyl groups which differ in their reactivity; the configuration of the hydroxyl groups is another factor influencing the rates of ester formation; and, finally, inter- and intramolecular transesterification processes occur [9]. This is why the reaction products are mixtures of mono- and polyesters. Recently, it was shown that the use of enzymes as catalysts (this volume, Chapter 8) in the synthesis of sugar fatty acid esters led to a marked reduction in the level of by-products and enhanced the regioselectivity of the reaction. Alkyl polyglycosides are also complex mixtures of isomeric compounds with various numbers of glucose units in their molecules (this volume, Chapter 2). During the reaction of glucose with fatty alcohols (or the transglycosidation of short-chain alkyl polygycosides), several isomers are formed: the α and β anomers, $1 \rightarrow 4$- and $1 \rightarrow 6$-linked glucose oligomers ($1 \rightarrow 2$- and $1 \rightarrow 3$-linked compounds are also present), and ring isomers [10]. On the other hand, N-linked saccharide-based surfactants are individual compounds with well-defined chemical structures. This is achieved by using the aldehyde group of reducing sugars (aldoses) as the reactive function. Three reaction routes are possible and have been exploited. The first one is the

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reaction of alkylamines with aldoses, usually mono- and disaccharides to yield *N*-alkylaldosylamines [11–15]. The reaction products may be further acylated or hydrogenated; in the latter case the products are *N*-alkyl-1-amino-1-deoxy-D-alditols [12,16,17]. This reaction is often the called reductive amination reaction [18]. The third reaction pathway is the oxidation of aldoses to aldonic acids, which in this form or that of their lactones react with long chain *N*-alkylamines to give *N*-alkylaldonamides [19]. The use of the carbonyl function of aldoses as a reaction centre has several advantages: (1) there is no need to protect the hydroxyl groups to obtain individual compounds, (2) the hydrocarbon chain is linked to the C-1 carbon atom (the anomeric center) of the carbohydrate molecule; and (3) the reductive amination reaction is a selective one, which neither involves depolymerization of di- and polysaccharides nor cleavage of the pyranoside ring [20]. Both *N*-alkylaldosylamines and *N*-alkyl–1-amino-1-deoxy-D-alditols, like aldonic acids, have been used as intermediates for nonionic saccharide-based surfactant synthesis.

The main subject of this chapter is saccharide-based surfactants containing the amide group. Saccharide surfactants with an oxygen atom as a link between the sugar moiety and the hydrophobic group are the topic of the above-mentioned chapters in this book, and, other than cyclic acetal-type sugar surfactants, will not be described here.

II. *N*-ALKANOYL-*N*-METHYLGLUCAMINES AND *N*-ALKANOYL-*N*-METHYLLACTITOLAMINES

The title compounds belong to a family of fatty acid amides. The interest in this type of nonionic surfactant grew after Hildreth published a paper on *N*-D-gluco-*N*-methylalkanamide compounds [21], although some patents on the synthesis of such products for use as detergents appeared much earlier [22,23]. Since Hildreth's work, several papers referring to those surfactants have been published. Unfortunately, a variety of chemical structures, nomenclature proposals, and acronyms have been used to describe the compounds under consideration, which has led to some confusion. Figure 1 gives examples of glucose derivative chemical formulas, which are drawn by various means. This is because glucose exists in both the acyclic and the cyclic form. The acyclic form may be represented by an open-chain structure **I**, without or with conformational depiction of the acyclic chain **II**, and by the acyclic Fischer projection **III**. The cyclic structure, on the other hand, can be depicted by the planar Haworth representation and in a chair conformation with the heterocyclic pyranose structure of a hemiacetal [19]. Structures **IV** and **V** are derived from the cyclic form of monosaccharides. Various trivial names, such as: *N*-D-gluco-*N*-methylalka-

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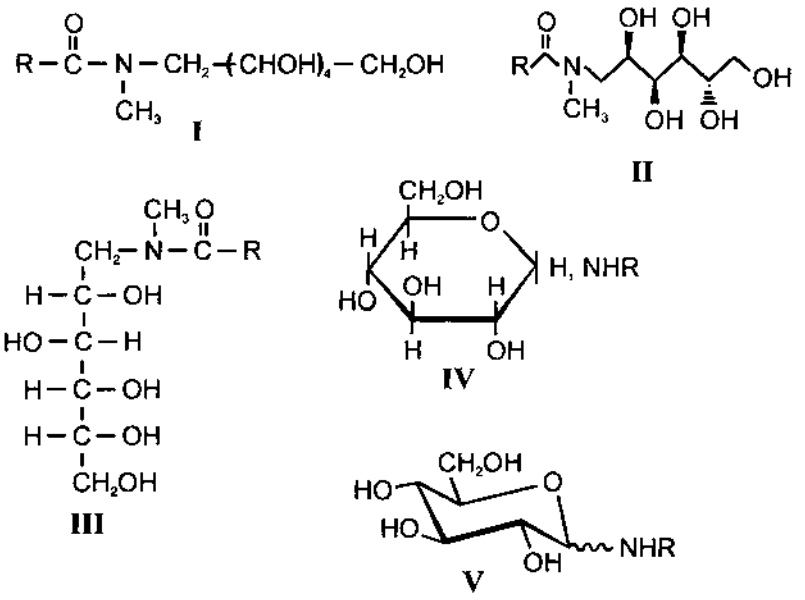


FIG. 1 Acyclic (I–III) and cyclic (IV–V) structures of D-glucose derivatives.

namides [21], *N*-alkanoyl-*N*-methylglucamines [24] (and this book, Chapter 1), *N*-alkanoyl-*N*-methylglucosamines [24], alkylmethylglucamides [25], fatty acid *N*-methylglucamides [26], acyl-*N*-methylglucamides [27], glucose amides [28], or glucamides [29] have been used. Several acronyms were proposed as well: MEGA-*n* (*n* = the number of carbon atoms in the acyl chain, including the carbonyl atom) [21], Mega-*n* [30], C_n -MGA [31], and GA [24,29]. According to the IUPAC nomenclature of carbohydrates (Recommendations 1996 [32]), the systematic nomenclature for the discussed compounds is *N*-alkanoyl-*N*-methyl-1-amino-1-deoxy-D-glucitols. In this section, the trivial names *N*-alkanoyl-*N*-methylglucamines and *N*-alkanoyl-*N*-methyllactitolamines [the systematic nomenclature of the latter is *N*-alkanoyl-*N*-methyl-4-*O*-(β-D-galactopyranosyl)-1-amino-1-deoxy-D-glucitol] will be used, as they seem to be preferred by the majority of authors.

A. Synthesis

The synthesis of *N*-alkanoyl-*N*-methylglucamines is a two-step process as shown in Fig. 2. In the first step (Fig. 2a), glucose **VI** (or maltose, lactose) undergoes a reaction with C_1–C_4 alkylamines, preferable *N*-methylamine, at a mole ratio of about 1:1 amine sugar in a methanol, ethanol, or 1,2-propane-

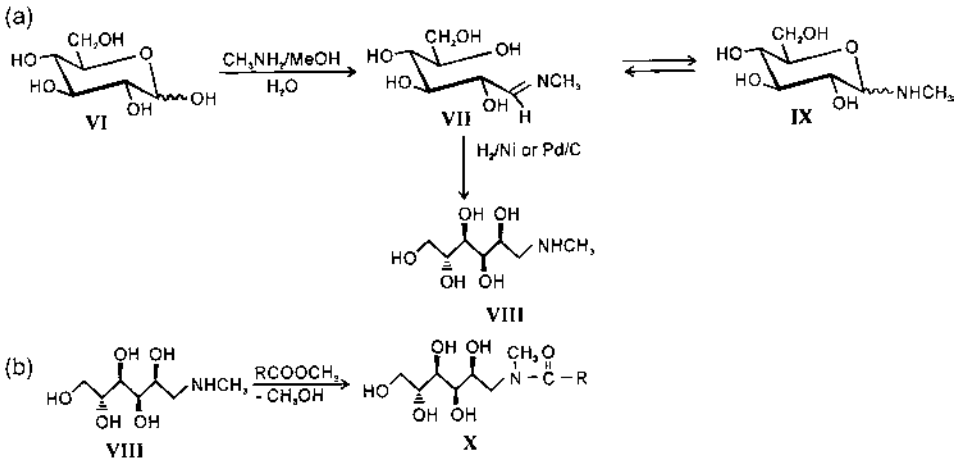


FIG. 2 Synthetic routes for the preparation of (a) *N*-methylglucamine (VIII) and *N*-methylglucosylamine (IX) and (b) *N*-alkanoyl-*N*-methylglucamines (X).

diol solvent, at temperatures ranging from 30°C to 60°C for 1-10 h. The formed intermediate product **VII**, dissolved in the mentioned solvents, reacts further with hydrogen gas in the presence of a catalyst at temperatures between 40°C and 120°C. After completion of the reaction, the catalyst, water, solvent, and unreacted alkylamine are removed, and almost pure *N*-methyl(alkyl)glucamine **VIII** is obtained [33]. On a preparative scale, the intermediate imine **VII** can be reduced with sodium borohydride ($NaBH_4$) [34] or sodium cyanoborohydride ($NaCNBH_3$) [35]. On an industrial scale, hydrogen gas and the metal catalysts Ni or Pd/C are preferred. As the formed imines are often not stable, and thus are hard to isolate, the most convenient way to obtain *N*-alkylglucamines is to synthesize and reduce the imine in a single, one-pot reaction. *N*-Alkylglucamines are crystalline solids, stable in water and quite stable to heat. On the other hand, the intermediate imines and the respective *N*-alkyl-α,β-D-aldosylamines **IX** are susceptible to hydrolysis [13,36] and isomerization reactions, among them the so-called Amadori rearrangement [12,37]. Their aqueous solutions, when heated, change color and become yellow to brown. The mechanism of the Amadori rearrangement, taking glucose **XI** as an example in Fig. 3, explains the formation of the 1-methyl-1-amino-1-deoxy-2-ketose **XIV** from the intermediate imine **XII**. Other by-products that lower the quality of the synthesized *N*-alkylglucamines can also be formed. Thus, several attempts were made to obtain *N*-alkylglucamines (also called *N*-alkylaminopolyols) with low odor and low color characteristics [33,38–41].

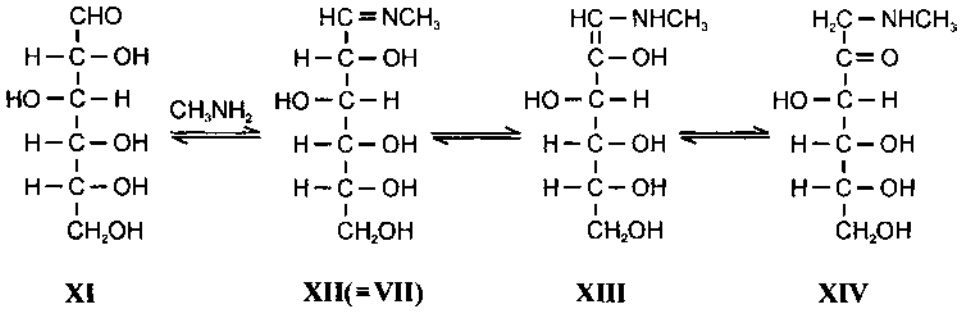
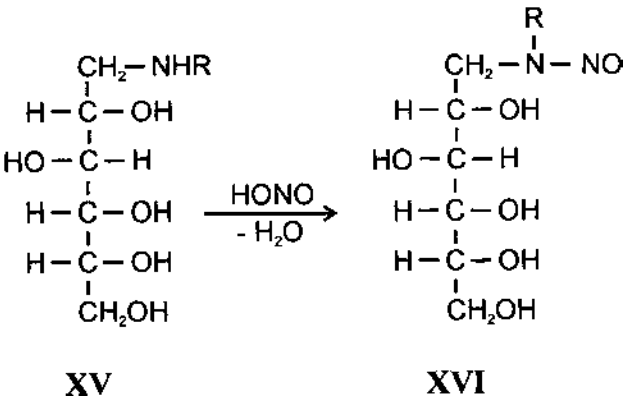


FIG. 3 Formation of 1-methyl-1-amino-1-deoxy-2-ketose (XIV) from imine (XII) in the Amadori rearrangement. (From Ref. 12.)

In the second step, *N*-alkylglucamines, preferably *N*-methylglucamine, react with fatty acid esters, preferably C_6–C_{20} fatty acid methyl esters, to yield the desired amide **X** (Fig. 2b). This reaction is base catalyzed. Hildreth [21] used mixed anhydrides formed from fatty acids and ethyl chloroformate in the presence of pyridine, and performed the reaction in a methanol solvent. On an industrial scale, high yields of amides could be obtained in a reaction of fatty acid methyl esters and *N*-methylglucamine, in an organic hydroxy solvent (preferably methanol), in the presence of basic catalysts such as sodium bicarbonate, sodium silicate [42] or sodium methoxide, at a temperature from about 40–100°C [38,43]. High conversions of reactants and minimal formation of by-products were achieved by conducting the reaction in MeOH-NaOMe solution at 80°C [44]. Amides were also synthesized from *N*-alkylpolyhydroxyamines obtained from mixtures glucose and maltose [45].

The presence of even small amounts of *N*-methylglucamine in the final product is undesirable as the secondary amines can undergo an N-nitrosation reaction, which leads to *N*-nitroso compounds (called nitrosamines) (Fig. 4, **XVI**) [46]. This reaction occurs when secondary amines are treated with nitrous acid, which is formed in the environment as a product of the microbial reduction of nitrates. Gaseous NO, N_2O_3, and N_3O_4 can also react with secondary amines to give *N*-nitroso compounds [47]. *N*-Methyl-*N*-nitrosoglucamine is a cancerogenic compound [36]. To avoid production of even a small amount of unreacted *N*-methylglucamine, the final product is subjected to reaction with acetic anhydride and the formed disubstituted amides do not pose a hazard to human health; thus, they can remain in the final product [48].

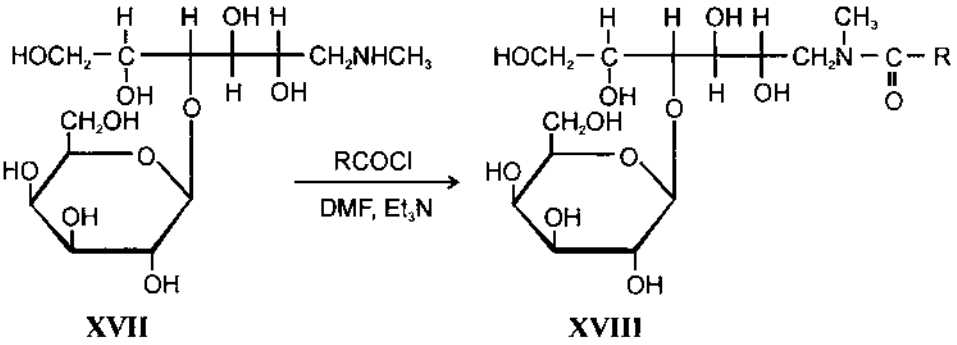
The preparation of *N*-alkanoyl-*N*-methyllactitolamines was recently reported on [49]. Their synthesis protocol differs from that of *N*-alkanoyl-



XV **XVI**

FIG. 4 Nitrosamine (XVI) formation. (From Ref. 46.)

N-methylglucamine synthesis in the second reaction step; in the first step, *N*-methyllactitolamine was obtained from lactose in a reductive amination reaction similar to that shown in Fig. 2a. Long-chain acyl chlorides were used for the amidation of the *N*-methyllactitolamine (**XVII**, Fig. 5) and the reaction was conducted in dimethylformamide (DMF) using triethylamine as catalyst at 5–10°C for 2 h. The yield of pure products **XVIII**, for which the



XVII **XVIII**

R = C_9H_{19}(MELA-10); $C_{11}H_{23}$(MELA-12); $C_{13}H_{27}$(MELA-14);
$C_{15}H_{31}$(MELA-16); $C_{17}H_{35}$(MELA-18)

FIG. 5 Synthesis of *N*-alkanoyl-*N*-methyllactitolamines (XVIII) from *N*-methyllactitolamine (XVII). (From Ref. 49.)

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acronym MELA-*n* was proposed, ranged from 97% for *N*-dodecanoyl-*N*-methyllactitolamine (MELA-12) to 57% for *N*-octadecanoyl-*N*-methyllactitolamine (MELA-18).

Another interesting route to *N*-alkanoyl-*N*-alkylglucamines via an enzymatic amidification reaction was given by Maugard et al. [50]. They reacted, for example, *N*-methylglucamine with oleic acid at an amine/acid

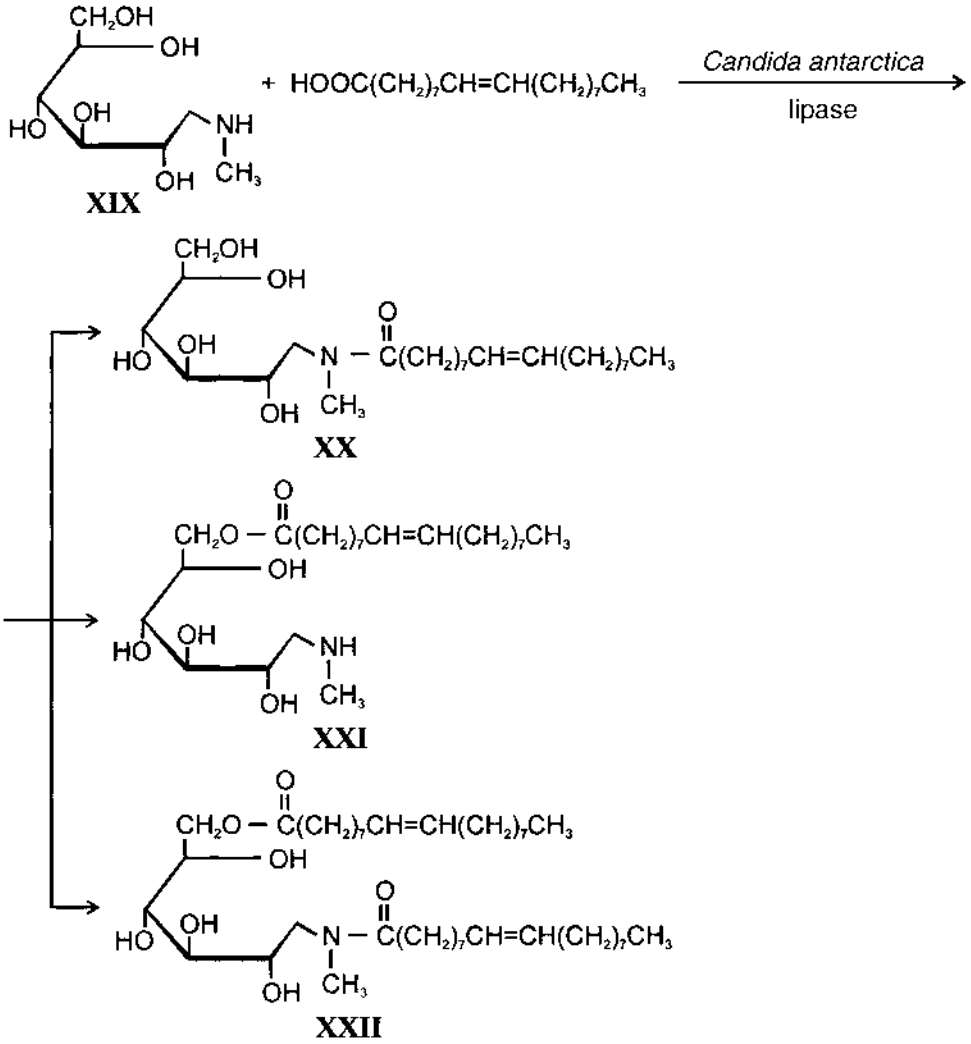

FIG. 6 Enzymatic synthesis of oleyl-*N*-methylglucamines. (From Ref. 50.)

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ratio of 1, in the presence of immobilized lipase from *Candida antarctica*, in a 2-methyl-2-butanol solvent at 90°C. A 100% conversion and high yield of amides was observed. The products, shown in Fig. 6, are: *N*-oleyl-*N*-methylglucamine **XX**, 6-*O*-oleyl-*N*-methylglucamine **XXI**, and 1-*N*-6-*O*-dioleyl-*N*-methylglucamine **XXII**.

N-Alkanoyl-*N*-methylglucamines are commercial products. Their production capacities are about 30,000–50,000 metric tons/year, and the producers are Pfizer and Hatco in the United States and Clariant (formerly Hoechst) in Germany [26]. It is expected that their usage will grow 15% in the United States and 20% in western Europe [51]. Procter and Gamble first developed the technology of alkanoylglucamine manufacture and use in household laundry and hand dishwashing detergents [24,51].

B. Physicochemical Properties

As mentioned above, *N*-alkanoyl-*N*-methylglucamines and -lactitolamines are crystalline substances. Rather unexpectedly, these amides are only slightly soluble in water. It was observed that 0.2 wt % C_{11}–C_{14}-*N*-methylglucamines was insoluble in water at 25°C [24]. MELA-10, 12, 14 are readily soluble in water at 0.1 wt % concentration, whereas MELA-16 and 18 dissolved at the same concentration upon warming, but precipitated on cooling to 25°C [49]. Gel and fiber formation was observed on cooling 1–2 wt % aqueous solutions of *N*-alkanoyl-*N*-methylglucamines and *N*-alkylaldonamides [52]. The phase behavior of the systems MEGA–water will not be discussed here, as a review on this topic already exists (this book, Chapter 1).

In this section, the focus is on the surface-active properties of aqueous solutions of MEGA and MELA surfactants. Their surface properties and micelle formation have been studied by light scattering [25,53], spectrofluorimetry, ultrasonic absorption and time resolved fluorescence quenching [30], differential scanning calorimetry (DSC) [54], and measurements of aqueous solution densities [27] and surface tensions [24,49,55]. The results can be summarized as follows:

1. A characteristic feature of the described nonionics is that their aqueous solutions do not show cloud points, even when heated to the boiling point. This suggests a different mechanism of interaction of the hydroxyl groups of the surfactant molecule with water molecules to that between the oligooxyethylene chains of polyoxyethelene alcohols and water molecules.
2. Apparent Krafft points were observed and determined for both MEGA and MELA series. Their values are collected in Table 1.

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TABLE 1 Adsorption and Micellization Properties of MEGA and MELA Surfactants in Aqueous Solutions at 25°C

Surfactant acronym	$10^6\ \Gamma_{CMC}$ (mol m^{-2})	$10^{20}\ A_{min}$ (m^2)	pC_{20}	CMC (mol dm^{-3})	γ_{CMC} (mNm^{-1})	CMC/C^{20}	Krafft temp. (°C)[a]	Ref.
MEGA-6				3.37×10^{-1}[b]				52
MEGA-7				1.32×10^{-1}				52
MEGA-8				3.0×10^{-2}				52
				5.13×10^{-2}[c]				25
				6.9×10^{-2}[d]				53
				7.4×10^{-2}[e]				27
				7.0×10^{-2}[f]				30
MEGA-9				2.1×10^{-2}				53
				2.4×10^{-2}				27
MEGA-10				1.6×10^{-2}				25
				6.7×10^{-3}				53
				6.8×10^{-3}				27
				4.8×10^{-3}				25
	4.0	41.0		6.28×10^{-3}[g]				55
MEGA-11	3.80	43.7	3.78	1.58×10^{-3}[h]	30.9	10.5	40.0	24
MEGA-12	4.10	40.5	4.40	3.47×10^{-4}	30.0	8.7	51.0	24
MEGA-13	4.60	36.1	5.02	7.76×10^{-5}	28.4	7.8	50.0	24
	(4.45	37.3	4.98	8.70×10^{-5}	28.4	8.31)[h]		24
MEGA-14	4.68	35.5	5.43	1.48×10^{-5}	36.3	4.0	67.0	24
	(4.68	35.5	5.43	1.48×10^{-5}	36.3	4.0)[h]		24
MELA-10	3.29	50.4	3.06	3.82×10^{-3}	40.3	3.82	< 0	49
MELA-12	3.32	49.9	4.02	4.47×10^{-4}	37.2	4.68	< 0	49
MELA-14	3.26	50.8	4.87	6.76×10^{-5}	37.0	5.01	< 0	49
MELA-16	3.36	49.4	5.46	1.75×10^{-5}	36.5	5.05	45	49
MELA-18	3.32	49.5	5.95	5.62×10^{-6}	35.7	5.01	45	49
C_{12}-XA[i]	4.29	38.7	4.67	3.31×10^{-4}	27.6	10.9	—	24
	(4.29	39.2	4.67	3.63×10^{-4}	28.0	10.9)		24

[a] Determined for 0.1 wt % solutions in distilled water.
[b] Data from [52] are from surface tension measurements at room temperature.
[c] Data from [25] are from light scattering measurements.
[d] Data from [53] in (mol kg^{-1}) are from light scattering measurements.
[e] Data from [27] in (mol kg^{-1}) are from solution densities measurements.
[f] Value obtained from spectrofluorimetry measurements.
[g] Data from [55] are from surface tension measurements at 20°C.
[h] Data from [24] are from surface tension measurements of 0.1 M NaCl solutions; values in parentheses are for solutions in distilled water.
[i] XA is *N*-methylxylamine.

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3. Adsorption properties: surface excess concentration (Γ_{CMC}) and minimal area per molecule at the water–air interface (A_{min}) show somewhat different structure–property relationships in both series. In the MEGA 11–14 series, Γ_{CMC} increases slightly with alkyl chain length increase, which in turn causes A_{min} decrease. In the MELA series, Γ_{CMC} and A_{min} values practically do not change with the alkyl chain increase. MELA surfactants show greater A_{min} values than MEGA surfactants do; this can be attributed to the different size of the hydrophilic group (lactitolamine is a disaccharide derivative, whereas glucamine a monosaccharide one). The pC_{20} parameter, i.e., the efficiency of surface tension reduction, increases with an increase in alkyl chain length in both series. The values of the CMC/C_{20} parameter, which is a measure of the tendency of the surfactant to adsorb at the aqueous–air interface relative to its tendency to form micelles in the surfactant solution [24], do not allow to draw any conclusion, as they are in contradiction with each other. They decrease with alkyl chain length increase in the MEGA series, whereas they first increase (for C_{10} up to C_{14}) and then are almost constant (for C_{14} to C_{18}) in the MELA series.
4. The values of critical micelle concentrations (CMCs), shown in Table 1, are similar to those of polyoxyethylene alcohols with comparable alkyl chain lengths and approximately eight oxyethylene units [56]. This observation holds true for both shorter (MEGA-8, 9, 10) and longer (MEGA-11, 12, 13, 14) alkyl chain length and for the MELA series as well. A minimum in the CMC vs. temperature curve in the range 30–55°C was observed for MEGA-8, 9, and 10. It was stressed that the occurrence of such a minimum is rather a characteristic of ionic surfactants; the CMC of polyoxyethylene alcohols decreases monotonically with increasing temperature [53]. The size of the hydrophilic group, i.e., the number of hydroxyl groups in the sugar moiety, does not substantially affect the CMC values, as follows from the data for C_{12}-XA (XA is *N*-methylxylitolamine), MEGA-12, and MELA-12 (Table 1).
5. The thermodynamic parameters of adsorption and of micellization reveal similar structure-dependent relationships. Both $-\Delta G^{\circ}_{mic}$ and $-\Delta G^{\circ}_{ads}$ increase with the increase of alkyl chain length in MEGA and MELA surfactants. The $-\Delta G^{\circ}_{mic}/CH_2$ and $-\Delta G^{\circ}_{ads}/CH_2$ values, i.e., the increase of standard free energy of micellization and of adsorption per methylene group, have been reported for the MEGA series to be 3.8 kJ mol^{-1} and 2.8 kJ mol^{-1}, respectively [24]; for the MELA series, the respective values are 2.01 kJ mol^{-1} and 2.05 kJ mol^{-1} [49]. Okawauchi et al. [53] report a $-\Delta G^{\circ}_{mic}/CH_2$ of 2.88 kJmol^{-1} for MEGA-8, -9, and -10 and a $-\Delta G^{\circ}_{mic}$ /W of –9.48 kJmol^{-1} for the contribution of the hydrophilic group (W) in micelle formation.

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The presented results show that some properties of MEGA and MELA surfactants differ to some extent from those of polyoxyethylene alcohols. It has been stressed that the interaction of hydroxyl groups in a carbohydrate moiety with water molecules is directed by a different mechanism from that in the case of conventional nonionics in which the hydrophilicity arises from formation of two hydrogen bonds between water and one oxyethylene grouping [53]. Intra- and intermolecular hydrogen bonds of the carbohydrate hydroxyl groups as well as their steric configurations may play an important role in the solution properties of the compounds under consideration. Moreover, it has been reported that the amide group present in the molecules of the surfactants enhances their solubility [52].

C. Performance Properties and Applications

In terms of performance properties, the results of studies on the foaming and wetting abilities of MEGA and MELA have been published. An interesting dependence of foaming ability on the number of CHOH groups in the surfactant molecule was found: the foam height (i.e., volume) increased in the order: C_{12}-*N*-methylglyceramine < C_{12}-*N*-methylxylamine < C_{12}-*N*-methylglucamine [24]. Moreover, synergism was observed in the both foaming ability and the stability in mixtures of the mentioned amides with sodium dodecylmono(oxyethylene) sulfate. The mentioned C_{12} amides also display a high wetting ability, exceeding that of the sulfate. MELA surfactants also generate foams of high volume and stability. The best results were achieved with MELA-12: its foam volume and stability were higher than those for Glucopon 600 EC/HH (an alkyl polyglycoside), which is taken as a standard surfactant. The wetting properties of the MELA series, as measured by the contact angle for 0.1 and 1.1 M CMC solutions on a paraffin wax surface, were found to be almost the same regardless of the number of carbon atoms in the acyl chain. The values obtained confirmed that these compounds have a wetting ability of interest [49]. MEGA compounds were also used as emulsifiers for the formation of chlorocarbon-in-water microemulsions. No electrolyte was needed to obtain said result [57].

The main application of *N*-alkanoyl-*N*-methylglucamines is in powdered and liquid detergents for household laundry and in liquid hand dishwashing detergent [26,51]. They show good detergency in combination with alkyl sulfates and alkyl ether sulfates [29]. Their use as thickeners was also reported on [58]. Surfactants with $C_{12/14}$ and $C_{16/18}$ alkyl chains are used exclusively by Procter and Gamble [26]. A vast patent literature exists concerning the applications of MEGA surfactants. A review given by Lif and Hellsten [59] covers the patent literature up to 1996. There is no space nor intention to give here an up-to-date survey of the patents that have

appeared since that time. However, it is worth mentioning that they mainly cover the use of fatty acid *N*-methylglucamines in personal care products (shampoos, toothpastes, soaps, cosmetic products) and in cleaning formulations (hard surface and textile cleaning).

D. Biochemical and Environmental Properties

Fatty acid *N*-methylglucamines may be considered to be synthetic biosurfactants of glycolipid structure. The aim of Hildreth's work was to find a surfactant suitable for the solubilization of biological membrane components. MEGA surfactants fulfill the desirable properties of solubilizing agents as they manifest (1) electrical neutrality thus avoiding alteration of the charge properties of solubilized proteins; (2) a low CMC permitting rapid removal by dialysis; (3) optical transparency in the UV region, allowing spectrophotometric detection of protein; and (4) a well-defined chemical composition and high purity, ensuring experimental reproducibility. In addition, they are commercially available at relatively low cost [21,60]. The work of many authors has shown that MEGA compounds might prove to be useful mild surfactants for solubilizing membrane components while preserving their enzymatic, antigenic, and other activities [25,61].

From the point of view of environmental protection, the fate of MEGA and MELA surfactants in environmental compartments and their impact on aqueous biocenosis are of crucial value. A comprehensive study of MEGA surfactants was done by Stalmans et al. [28], from Procter and Gamble. The authors investigated the biodegradability of MEGA-12, MEGA-12/14, and MEGA-14, as well as their acute and chronic toxicity to sensitive aquatic organisms. Figure 7 presents the biodegradation of ^{14}C-radiolabeled MEGA-12 in a biomass batch activated sludge (BAS) test. It was stated that at the end of the test, an average of 94% (three replicate test units; range 91.5–95.5%) of radiolabeled ^{14}C was recovered as $^{14}CO_2$; after 28 days, an average of 89% was observed as $^{14}CO_2$. The presented results confirm an ultimate and rapid biodegradation of the compound under study in an activated sludge system. The results were further confirmed by a continuous activated sludge (CAS) test, i.e., during wastewater treatment, in which the removal of MEGA-12 was calculated to be greater than 99.6%.

The summary of acute and chronic toxicity to some representatives of aqueous biocenosis is presented in Table 2. Inspection of the collected data leads to conclusion that the toxicity of MEGA surfactants is chain length dependent for the tested biocenosis representatives. The toxicity values change in the order: the longer the alkyl chain, the greater the toxicity. On the basis of the determined NOEC ("no observable effect concentration") values and estimated PEC ("predicted environmental con-

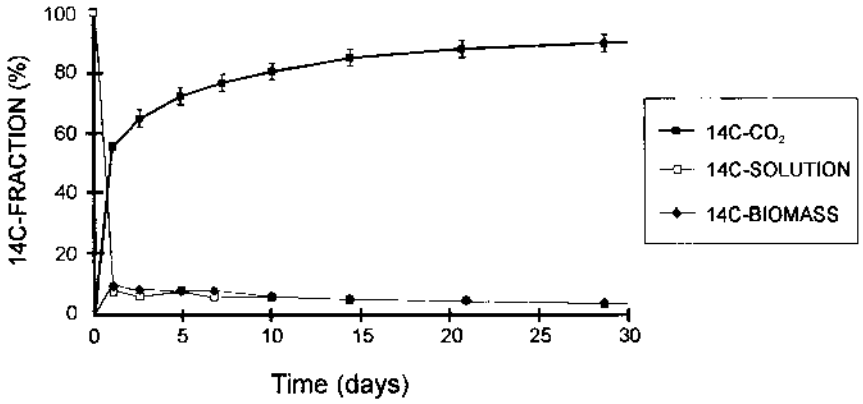

FIG. 7 Biodegradation of the [^{14}C]-glucose amide in a batch-activated sludge study. (From Ref. 28 with permission of Verlag für Chemische Industrie.)

centration") values of MEGA in surface waters, risk assessment could be predicted. The chronic environmental safety factor was found to be in excess of 3000 for aquatic biocenosis.

MELA surfactants have been tested for biodegradability with the closed bottle test using activated sludge [49]. This test uses the biochemical oxygen demand, i.e., the consumption of oxygen, as a parameter of ultimate biodegradation [62]. The theoretical oxygen demand is a calculated value. The biodegradability results, presented in Table 3, confirm the satisfactory elimination of MELA compounds by the microorganisms in activated sludge, comparable to biodegradability of conventional nonionic surfactants taken as standards. Thus, MELA surfactants may be considered to be readily biodegradable.

The antimicrobial activity of MELA surfactants was determined on three gram-positive bacteria (*B. cereus, S. aureus, S. lutea*), three gram-negative bacteria (*E. coli*, *S. marcescens*, *P. putida*) and the yeast *S. cerevisiae* as representative microorganisms. The results are collected in Table 4. From the data, one may draw the conclusion that MELA surfactants are completely inactive toward the yeast, two of the gram-positive and one of the gram-negative bacteria. Except for MELA-10, the amides with longer alkyl chains exhibited slight antimicrobial activity toward *S. lutea*, *E. coli*, and *P. putida*. It is worth mentioning that the investigated surfactants are less toxic to gram-positive bacteria than the conventional polyoxyethylene alcohols and the alkyl polyglycoside surfactant Glucopon 600 EC/HH. In other words, they seem not to be harmful to the environment.

TABLE 2 Summary of Acute and Chronic Toxicity Test Results for Glucose Amide

	Species	C_{12} glucose amide	$C_{12/14}$ glucose amide	C_{14} glucose amide
Invertebrates:				
EC_{50} (48 h)	*Daphnia magna*	44.3 (37.5–52.8)	18 (16–21)	5.0 (3.3–9.2)
NOEC (21 d)	*Daphnia magna*	ND	4.3 (survival[a])	ND
Fish				
LC_{50} (96 h)	*Pimephales promelas*	39.1 (30.7–51.1)	ND	2.9 (2.4–3.7)
LC_{50} (96 h)	*Brachydanio rerio*	ND	7.5 (No. CI)	ND
NOEC (21 d)	*Pimephales promelas*	ND	4.8 (hatching[a])	ND
Algae:				
EC_{50}(96 h)	*Selenastrum capricornutum*	56.8 (50.4–63.9)	12.6 (11.6–13.6)	3.9 (2.5-6.4)
NOEC(96 h)	*Selenastrum capricornutum*	21.3	5.6	2.9
Activated sludge	(Oxygen consumption inhibition test)			
EC_{50}(3 h)	Activated sludge inoculum		115 (83–224)	ND

[a] Most sensitive end point, analytically confirmed.
All data are expressed in mg/L. Values between brackets are the 95% confidence intervals (CI).
ND: not determined.
Source: Ref. 28 with permission of the Verlag für Chemische Industrie.

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TABLE 3 Influence of *N*-Alkanoyl-*N*-methyllactitolamines and Conventional Surfactants on the Growth of Microorganisms

	Microorganism						
Surfactant	*S. aureus*	*B. cereus*	*S. lutea*	*E. coli*	*S. marcescens*	*P. putida*	*S. cerevisiae*
MELA-10	NI[a]	NI	NI	NI	NI	NI	NI
MELA-12	NI	NI	NI	512[b]	NI	512[b]	NI
MELA-14	NI	NI	256[b]	512[b]	NI	256[b]	NI
MELA-16	NI	NI	512[b]	512[b]	NI	256[b]	NI
MELA-18	NI	NI	NI	512[b]	NI	256[b]	NI
$C_{10}E_4$	64[c]	64[c]	64[c]	NI	NI	NI	NI
$C_{12}E_5$	128[b]	128[b]	512[c]	NI	NI	32[b]	NI
Glucopon 600 EC/HH	64[c]	64[c]	64[c]	NI	NI	NI	NI

[a] NI, no inhibitory effect was observed at concentrations up to 512 μg/mL For other abbreviations, see Fig. 5.
[b] IC_{50} (μg/mL) is defined as the concentration required to reduce the growth of the culture in the liquid medium to 50% of the control value.
[c] MIC (μg/mL) is defined as the lowest concentration of the tested compounds that completely inhibits bacterial growth Microorganisms: *Staphylococcus aureus, Bacillus cereus, Sarcina lutea, Escherichia coli, Serratia marcescens, Pseudomonas putida, Saccharomyces cerevisiae*. $C_{10}E_4$ and $C_{12}E_5$ denote oligooxyethylene alcohols, Glucopon 600 EC/HH is alkyl polyglycoside.
Source: Ref. 49 with permission of the AOCS Press.

TABLE 4 Biodegradability of *N*-Alkanoyl-*N*-methyllactitolamines and Conventional Nonionic Surfactants

Compound	TOD[a] (mg O/mg)	BOD[b] (mg O/mg)	BOD/TOD (%)
MELA-10	1.41	1.27	90
MELA-12	1.82	1.64	90
MELA-14	1.89	1.68	89
MELA-16	1.62	1.39	86
MELA-18	1.67	1.39	83
$C_{10}E_4$	2.33	2.07	89
$C_{12}E_5$	2.48	2.13	86

[a] TOD, theoretical oxygen demand.
[b] BOD, biochemical oxygen demand.
For other abbreviations see Fig. 5.
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III. DERIVATIVES OF *N*-ALKYLALDOSYLAMINES

N-Alkylaldosylamines are compounds that are easy to obtain in a reaction of *N*-alkylamines with aldoses (e.g., Fig. 2a). They have been synthesized for many years with the application of rather mild reaction conditions [11–13,15]. The products of the reductive amination reaction of glucose and lactose with methylamine have been shown to serve in the synthesis of fatty acid sugar-based amides (Fig. 2b). In the early 1990s, the research group of Rico and Lattes focused their attention on the derivatives of long-chain *N*-aldosylamines, particularly on *N*-alkyllactosylamines **XXV** and *N*-alkylglucosylamines **IX**, shown in Fig. 8 (the systematic names of which are, according to [32]: *N*-alkyl-[4-*O*-(β-D-galactopyranosyl)-α,β-D-glucopyranosyl]amines and *N*-alkyl-α,β-D-glucopyranosylamines, respectively). Since that time, they have published significant papers devoted to this new class of saccharide-based surfactants. Using the reaction conditions of Erickson [15], a series of *N*-alkyllactosylamines was obtained by Latgé et al. [63], who determined the relative proportions of the α and β anomers in the reaction products. Later on, the synthesis of both *N*-alkyllactosylamines and *N*-alkylglucosylamines was reported by other authors [64]. As pointed out earlier, *N*-alkylaldosylamines undergo hydrolysis and isomerization reactions in aqueous media. However, it turned out that at least two possibilities exist that allow those compounds to be used as intermediates for surfactants synthesis. The first one is the already mentioned reduction of *N*-alkylaldosylamines to *N*-alkyl-1-amino-1-deoxyalditols (Fig. 8, **VIII**, **XXVI**); the second one is the acylation of the secondary nitrogen atom with short-chain acyl anhydrides or acyl chlorides. The products (Fig. 8: **XXIII**, **XXIV**, **XXVII**, **XXVIII**) are stable in aqueous solution and the acyl derivatives are additionally preserved from nitrosamine formation.

A. *N*-Alkyl-1-amino-1-deoxyalditols

N-Alkyl-1-amino-1-deoxyglucitols and *N*-alkyl-1-amino-1-deoxylactitols [their respective systematic names are *N*-alkyl-1-amino-1-deoxy-1-D-glucitols and *N*-alkyl-4-*O*-(β-D-galactopyranosyl)-1-amino-1-deoxy-D-glucitols] can be obtained via the hydrogenation/reduction of respective *N*-alkylaldosylamines with either hydrogen gas on PT/C as the catalyst [64,65], or with sodium borohydride [34,66] (Fig. 8). The reaction parameters are those described earlier. Mitts and Hixon were the first to observe that alkylglucamines (i.e., *N*-alkyl-1-amino-1-deoxyglucitols) lower the surface tension of water noticeably and are good wetting agents [12]. The surface active properties of aqueous solutions of *N*-C_8H_{17}, *N*-C_9H_{19}, *N*-$C_{10}H_{21}$, and *N*-$C_{12}H_{25}$-1-amino-1-deoxylactilols **XXVI** have been determined by surface tension and

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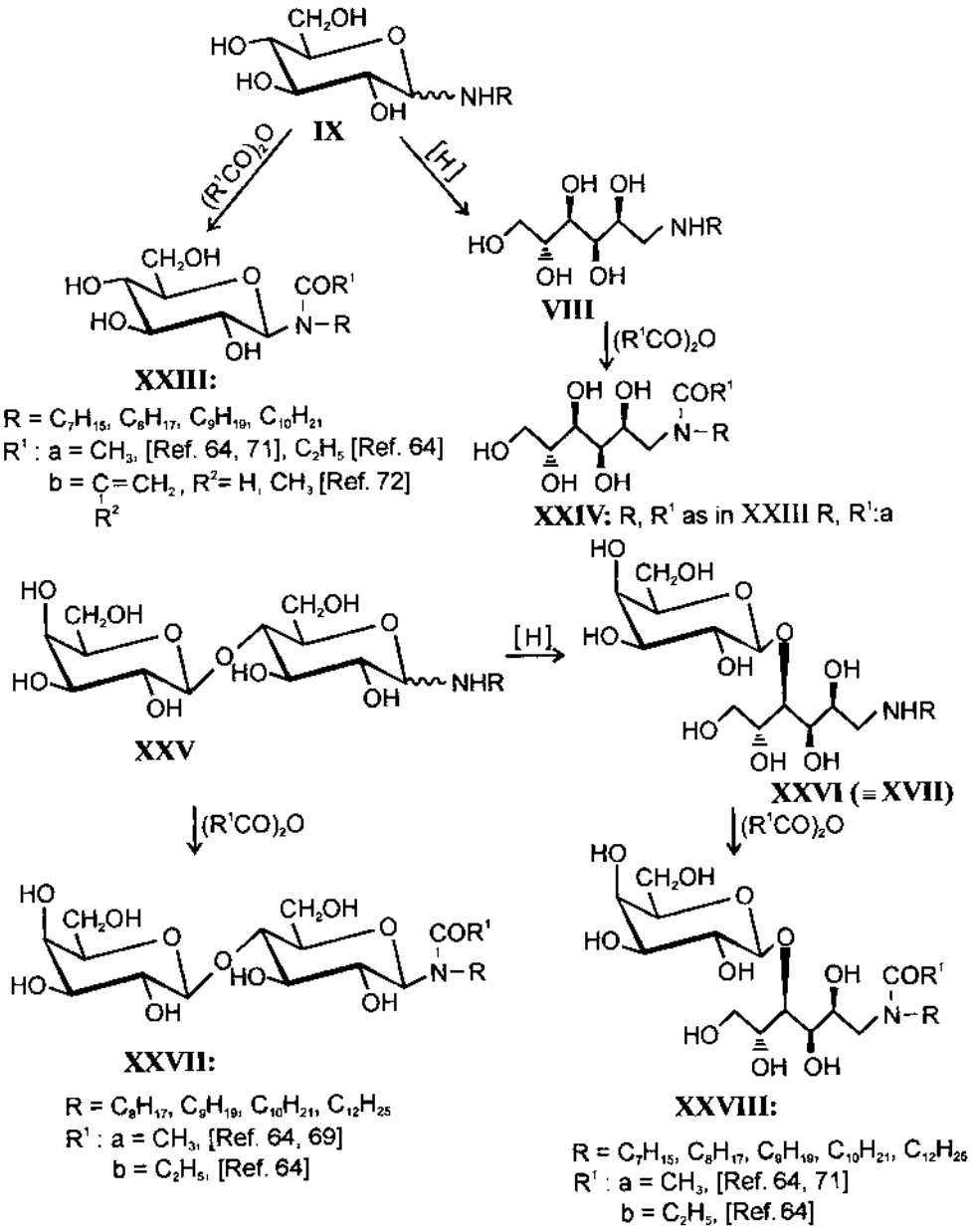

FIG. 8 Structures of *N*-alkylglucosylamines (IX), *N*-alkyl-1-amino-1-deoxyglucitols (VIII), *N*-alkyllactosylamines (XXV), *N*-alkyl-1-amino-1-deoxylactitols (XXVI), and their *N*-acyl derivatives (XXIII, XXIV, XXVII, and XXVIII, respectively).

small-angle X-ray and neutron scattering measurements. The obtained CMC values ranged from 1.5×10^{-2} mol dm^{-3} for C_8 to 6.0×10^{-4} mol dm^{-3} for C_{12}, and the respective aggregation numbers were from 34 to 88 [67]. Moreover, it was observed that the micelle size was weakly dispersed at low concentrations. A study of lyotropic phases in surfactant–water systems using X-ray diffraction measurements was done with C_8, C_{10}, and C_{12} compounds, and normal phases were observed, similarly to what was seen in other binary ionic and nonionic surfactant–water systems [68].

B. *N*-Acyl-*N*-alkylaldosylamines and *N*-Acyl-*N*-alkyl-1-amino-1-deoxyalditols

Costes et al. [69] synthesized a new group of *N*-acetyl-*N*-alkyllactosylamines (Fig. 8, **XXVII** R^{1}a) by subjecting *N*-alkyllactosylamines to a reaction with acetyl anhydride, with DMF as the solvent, in the presence of Et_3N, at room temperature. Via structural analysis (^{1}H and ^{13}C NMR) they further showed that, starting with a mixture of α and β lactosylamine, the obtained reaction product was exclusively the β anomer. This finding seems to be interesting, since β anomers are stronger inducers of chirality in micelles than α anomers [70]. *N*-Acetyl-*N*-alkylglucosylamines (Fig. 8, **XXIII** R^{1}a) were synthesized as well [71]. CMCs for both series were determined. The CMC values for lactosylamine derivatives are somewhat higher than those for glucosylamine derivatives with comparative alkyl chain lengths [71]. This result concurs with that observed for the MEGA vs. MELA surfactants (Table 1). In general, the CMC values for this type of nonionic surfactants are close to those for conventional nonionics.

Pestman et al. [64] synthesized eight homologous series: *N*-acetyl- and *N*-propionyl-*N*-alkylglucosyl/lactosylamines **XXIII R^{1}a**/**XXVII** R^{1}a,b and *N*-acetyl- and *N*-propionyl-*N*-alkyl-1-amino-1-deoxyglucitols/lactitols **XXIV**/**XXVIII** R^{1}a,b (Fig. 8) with high yields of the final acyl derivatives. They determined the CMC values and the thermodynamic parameters of micellization by titration microcalorimetry. The results can be summarized as follows:

The CMC values are comparable to those of conventional nonionic surfactants. The CMCs decrease by a factor of 10 with an increase of alkyl chain length by two CH_2 groups.

The head group size (monosaccharide/disaccharide, cyclic/acyclic) has a rather small effect on the CMC.

Glucose-derived surfactants show lower CMC values than lactose-derived surfactants (similarly to the case of MEGA vs. MELA surfactants, Table 1).

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Propionyl derivatives show slightly lower CMCs than acetyl derivatives.
The contribution of one CH_2 group to the standard free energy of micellization, $-\Delta G^{\circ}_{mic}$, was found to be 3.0 kJ mol^{-1} for each series. This value is comparable to that reported by Okawauchi et al. [53] for the MEGA series (2.88 kJ mol^{-1}), but higher than that obtained for the MELA series [49].

A new group of acyl derivatives of *N*-alkylglucosylamines, i.e., *N*-alkylglucosylacrylamides and *N*-alkylglucosylmethacrylamides (Fig. 8, **XXIII**, R: C_8H_{17}, $C_{10}H_{21}$, $C_{12}H_{25}$, $C_{14}H_{29}$, $C_{18}H_{37}$, R^1b), obtained in a commonly used two-step procedure, was reported on as an example of reactive surfactants (polymerizable ones) [72]. The existence of rotational isomerism, strongly dependent on the steric hindrance of the carbonyl substituent, was shown. Both endo and exo rotamers were observed for *N*-alkylglucosylacrylamides, whereas only endo isomer was formed in the case of *N*-alkylglucosylmethacrylamides. CMC values were determined with the surface tension measurements; they ranged from 1.2×10^{-2} to 3.0×10^{-5} mol dm^{-3} for *N*-octyl- to *N*-tetradecylglucosylacrylamides, respectively.

Finally, it is worth mentioning the work of Plusquellec et al. [73,74] and of Lubineau et al. [14], who synthesized *N*-acylaldosylamines. The former authors reacted glucosylamine, galactosylamine, and lactosylamine with 3-acyl-5-methyl-1,3,4-thiadiazole-2(3H)-thiones or 2-acylthio-5-methyl-1,3,4-thiadiazoles as acylating agents, and obtained high yields of the respective *N*-acylaldosylamines. However, they did not investigate their surface active properties. Lubineau et al. improved the method of aldosylamine synthesis and obtained several *N*-acylaldosylamines using acyl chlorides as acylating reagents. The CMCs of *N*-octanoyl-β-D-glucosylamine, *N*-octanoyl-β-maltosylamine, and *N*-decanoyl-β-maltosylamine were determined [14].

C. Double-Chain Derivatives of *N*-Alkyl-1-amino-1-deoxyalditols

Double-chain surfactants are chemically *N*-acyl-*N*-alkyl-1-amino-1-deoxyalditols or their derivatives, and they differ from the above-described compounds by the alkyl chain length in the acyl group [75]. They were obtained from *N*-alkyl-1-amino-1-deoxyglucitols and *N*-alkyl-1-amino-1-deoxylactitols (Fig. 9, **XXIX**, **XXX**) which were allowed to react with 3-alkylcarbonylthiazoline-2-thione **XXXI**, a mild acylating agent selective to amino groups [76]. By varying their acyl chain length, compounds **XXXII a–c** and **XXXIII a–f**, soluble in organic apolar solvents, were obtained [75]. As a consequence, they form reverse micelles in such solvents and can incorporate a large amount of water. This was shown by studying the systems: double-chain glucitol(lactitol)/*n*-hexane or chloroform/water. The best results were

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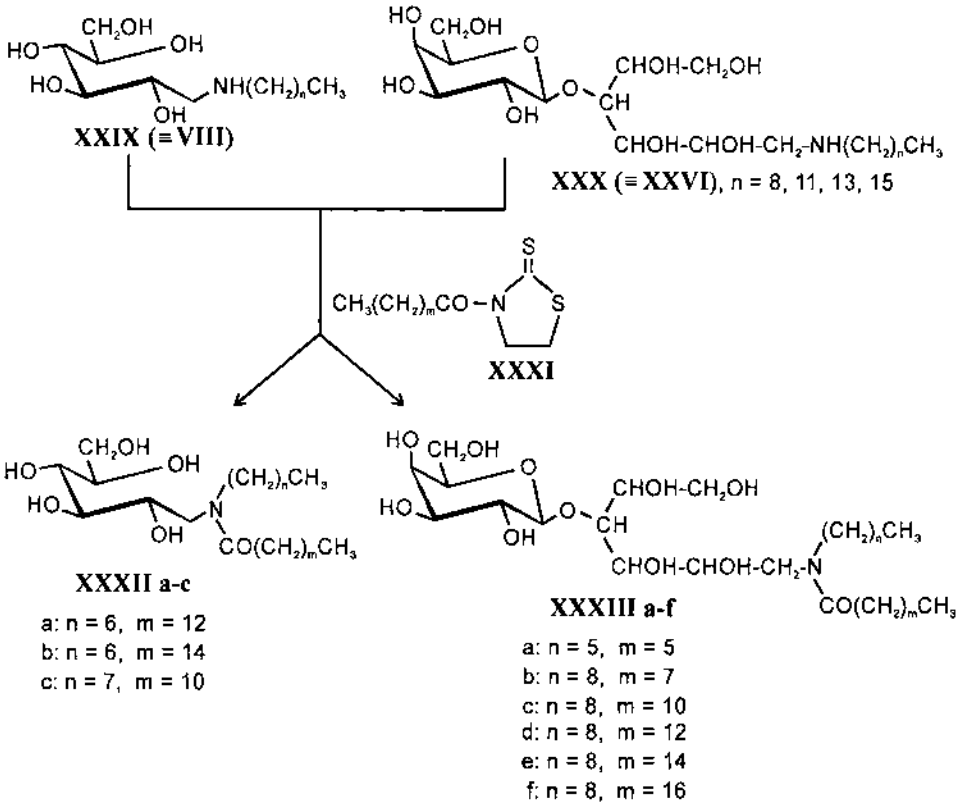

FIG. 9 Synthetic route for the preparation of double-chain derivatives of *N*-alkyl-1-amino-1-deoxyglucitols (XXXII) and *N*-alkyl-1-amino-1-deoxylactitols (XXXIII). (Adapted from Ref. 75.)

obtained with lactitol derivative **XXXIIIc** (Fig. 9) in chloroform, which solubilized 23 molecules of water per surfactant molecule. This result is better than that obtained with AOT [sodium bis(2-ethylhexyl)sulfosuccinate]. Several series of double-chain lactose-based surfactants have been synthesized by Rico, Lattes et al. [77–82]; their structures are presented in Fig. 10. The synthetic routes leading to compounds **XXXII** [64,65,77] and **XXXIII** [77] are shown in Figs. 8 and 9, respectively. Compounds **XXXIV**, the *N*-[ω-(sodium oxycarbonyl)alkyl]-*N*-acyl-1-amino-1-deoxylactitols, were obtained in a two-step procedure: lactose was first subjected to a reductive amination reaction with long-chain ω-aminocarboxylates, and the resulting products were further acylated with reagent **XXXI** [78,79]. These compounds may also be

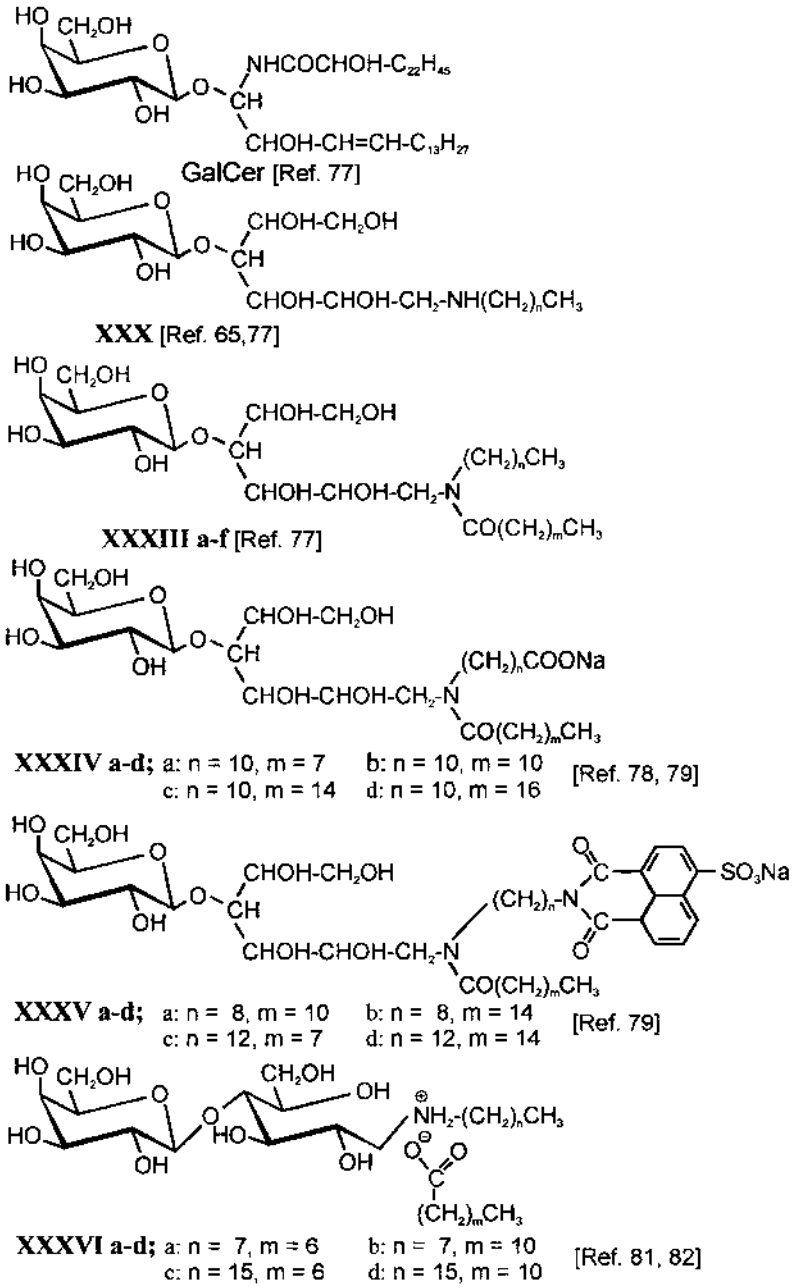

FIG. 10 Structures of various double-chain lactose derivatives.

regarded as dyssymmetrical, branched bolaform surfactants with one nonionic and one anionic polar head group. Details on the synthesis of surfactants **XXXV**, the *N*-{ω-[-4-(sodium sulfo)-1,8-naphthalimidyl]alkyl}-*N*-acyl-1-amino-1-deoxylactitols can be found in [79]. The surface properties of compounds **XXXIV** and **XXXV** were investigated using surface tension measurements. CMC and the area per molecule at the interface were determined and shown to be dependent on the number of methylene groups *n* (alkyl spacer) and *m* (side chain) (Fig. 9), ionic strength, and temperature [80]. These surfactants show a behavior similar to that of gemini surfactants. Surfactants **XXXVI** represent catanionic glycolipids. They are mixtures of *N*-alkyl-1-amino-1-deoxylactitols with middle- to long-chain carboxylic acids [81,82]. Their surface and aggregation properties were determined [82]. A characteristic feature of catanionic surfactants is their ability to form various aggregates: micelles, vesicles, and lamellar phases [83]. It was reported, for instance, that a mixture of 12-(4-aminocoumarin)dodecanoic acid and *N*-octyl-1-amino-1-deoxylactitol in water developed a variety of aggregated structures: vesicles, helices, and tubules [84].

D. Biological Properties

Double-chain, lactose-based surfactants with the structures presented in Fig. 10 may be regarded as synthetic analogs of one of the galactosphingolipids, namely, the galactosylceramide **GalCer** (Fig. 10). This naturally occurring substance has been found to be a human immunodeficiency virus (HIV) receptor. In fact, it turned out that the componds with the structures shown in Fig. 10 possess anti-HIV activity and display activity against the fungal strain *Aspergillus fumigatus*, a yeast causing opportunistic infection in AIDS patients. Detailed investigations on the anti-HIV activity of those compounds [77–79,81,82] allowed some conclusions to be drawn on structure–biological activity relationships in this new series of surfactants. An interesting observation was made on the dominant role of the hydrophobicity of those compounds on anti-HIV activity [78,82], and there is a hope that these compounds might be the basis of potential low-cost anti-HIV drugs [79].

The discussed double-chain surfactants are not the only example of derivatives of *N*-alkylaldosylamines possessing biological properties. One may find many other biological, pharmaceutical (drug delivery, solubilizing agents), and medicinal applications of those compounds. It is known that different nonionic, sugar-derived surfactants were employed in the extraction of membrane proteins [85]. *N*-Alkyllactosylamines have been claimed to be useful in protein solubilization [65]; they showed better activity than the reference substance Hecameg [6-*O*-(*N*-heptylcarbamoyl)methyl-α-D-glu-

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copyranoside]. Another example of their application is the extraction of opiate receptors from frog brain tissue using *N*-alkyl-1-amino-1-deoxylactitols [66]. The latter compounds have also been claimed to be virucides [86]. Readers interested in this subject should refer to review articles on the subject [71,85,87]. It ought to be stressed that the described surfactants are in general thought to be biocompatible and biodegradable, like other saccharide-based surfactants.

IV. *N*-ALKYLALDO(BIO)NAMIDES

A. Synthesis and Properties

The nomenclature of *N*-alkylaldonamides is rather simple and not confusing, as the trivial names are accepted by the IUPAC rules [32]. Amides derived from disaccharide, e.g., lactose or maltose are named: *N*-alkyllactobionamides and *N*-alkylmaltobionamides (also: *N*-alkylaldotrionamides when obtained from maltotriose, for example). This class of surface-active sugar-based amides is synthesized from aldonic acids or their lactones and primary and/or secondary amines containing at least one long-chain alkyl substituent. Both reactants are easy accessible. Aldonic acids are obtained from the oxidation of reductive mono-, di-, and oligosaccharides with either halogens (usually bromine, iodine, or hypobromite and hypoiodite potassium) or calcium salts, in neutral aqueous solution [88] or in water–methanol [89], or using the electrolytic method [90], which is easy to perform and permits the desired acids (as salts) to be obtained at both high yield and purity [91]. The second reaction partner—*N*-alkyl- or *N*,*N*-dialkylamines—are commercial products manufactured by the oleochemical industry [92].

The synthesis of the hitherto described *N*-alkylaldo(bio)namides is rather simple, as shown in Fig. 11: D-glucono-1,5-lactone **XXXVII**, α-d-glucoheptono-1,4-lactone **XXXIX**, lactonic acid **XLI**, and maltono-1,5-lactone **XLIII** are subjected to reaction with *N*-alkylamines or *N*-alkyl-*N*-methylamines to obtain the desired *N*-alkylgluconamides **XXXVIII a** or *N*-alkyl-*N*-methylgluconamides **XXXVIII b**, *N*-alkylglucoheptonamide **XLa** or *N*-alkyl-*N*-methylglucoheptonamide **XLb**, *N*-alkyl-*N*-methyllactobionamides **XLII** and *N*-alkylmaltobionamides **XLIV**, respectively. The reactions are mainly conducted using methanol as a solvent at room temperature (sometimes, as in [19], under methanol reflux), for about 20–24 h. High yields of crude products are obtained that give white crystalline products after extraction and repeated crystallization, usually from methanol, methanol–water mixtures [93], or further purification by column chromatography, followed by recrystallization from MeOH-MeCN [94]. Early papers reported on the synthesis of *N*-alkylgluconamides with an alkyl chain

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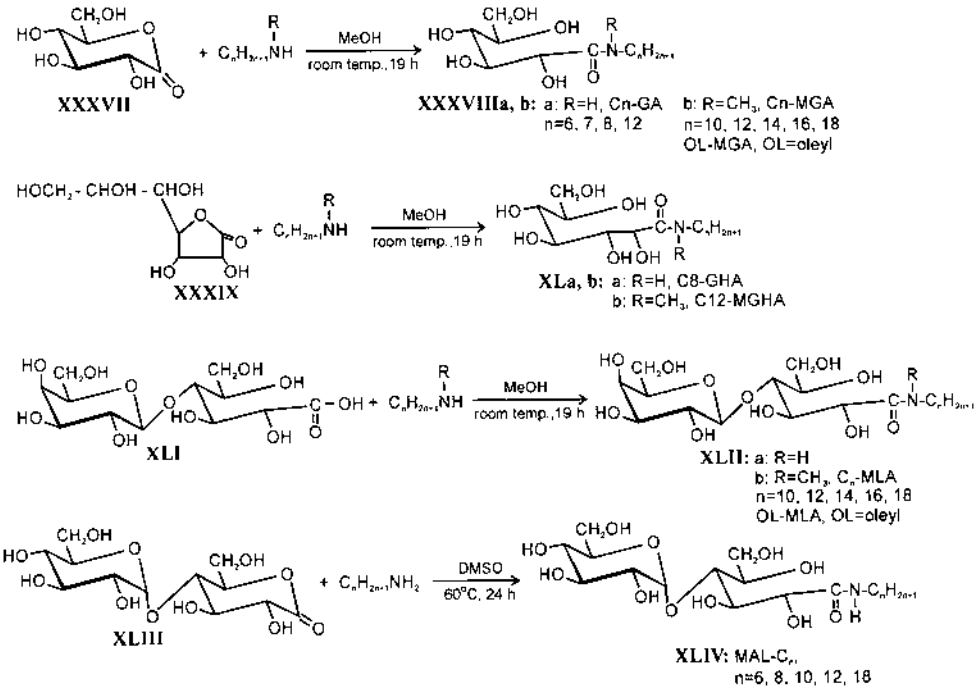

FIG. 11 Synthetic route for the preparation of *N*-alkylaldonamides (XXXVIIIa, b; XLa, b) and *N*-alkylaldobionamides (XLII, XLIV).

length ranging from C_8 to C_{14} [19]. As the amides are sparingly soluble in water, they were subjected to reaction with chlorosulfonic acid in dry methylene chloride to give *N*-alkylgluconamide sodium sulfates, mainly monosulfates, after neutralization of the formed products with aqueous NaOH [95]. The surface tension of aqueous solutions of the sulfates and some of their performance properties were determined. Williamson et al. [96] synthesized five series of aldobionamides—*N*-alkyllactobion-, maltobion-, melibion-, cellobion-, and gentiobionamides (alkyl: from *n*-octyl to *n*-octadecyl)—as model glycolipids, with the aim of studying lectin–glycolipid interactions. They observed gel formation during the recrystallization of *N*-alkyllactobionamides and *N*-alkylmaltobionamides. Preparing aqueous solutions of the obtained aldobionamides required heating and sonication. The CMC values of the studied glycolipids were determined using the fluorescence method, and a linear dependence of $-\ln$ CMC on alkyl chain length was observed for *N*-alkyllactobionamides, *N*-alkylmaltobionamides, and *N*-alkylmelibionamides.

In recent years, the focus has been on the surface active and some of the performance properties of *N*-alkylaldo(bio)namides and *N*-alkyl-*N*-methylaldo(bio)namides. *N*-Alkylmaltobionamides **XLIV** [97], *N*-alkyllactobionamides **XLIIa** [98], and *N*-alkylglucoheptonamides **XL** [93] were synthesized (Fig. 11). The structures of the described compounds were verified by ^{1}H NMR, and their purity was checked by elemental analysis. The reported adsorption and micellization parameters obtained from surface tension measurements are collected in Table 5. The solubility of these compounds in water depends both on the sugar moiety and the alkyl chain length. MAL-C_n surfactants are soluble at 10% concentration, except for MAL-18 (and C_{12}-GA), which are insoluble even at 0.1% concentration. It turned out that the introduction of one additional CHOH group to the glucose moiety, as in *N*-octylglucoheptonamide, did not enhance its solubility. On the contrary, it was estimated that the CHOH group causes a hydrophobic effect comparable to that of 0.2 CH_2 group in the main alkyl chain of the C_n-MGA series [93]. The values reported for the

TABLE 5 Adsorption and Micellization Properties of *N*-Alkylaldo(bio)namides in Aqueous Solution

Sufactant acronym	Temp. (°C)	$10^6 \times \Gamma_{cmc}$ (mol m^{-2})	$10^{20} A_{min}$ (m^2)	pC_{20}	CMC (mol dm^{-3})	γ_{CMC} (mN m^{-1})	Π_{CMC} (mN m^{-1})	Ref.
C_6-GA[a]	rt				9.3×10^{-2}			52
C_7-GA	rt				2.06×10^{-2}			52
C_8-GA	rt				1.0×10^{-2}			52
C_{12}-GA[b]	25							97
C_8-GHA[c]	25	2.95	58		4.0×10^{-4}	50.7		93
MAL-C_6	25	4.53	66	2.5	8.3×10^{-2}		39.8	97
MAL-C_8	25	4.26	39	3.1	5.7×10^{-3}		40.2	97
MAL-C_{10}	25	4.57	36	3.6	1.3×10^{-4}		38.1	97
MAL-C_{12}	25	3.8	43	4.4	3.1×10^{-4}		38.4	97
MAL-C_{18}[b]								97
C_{10}-LA	25	4.28	40		1.32×10^{-3}	33.0		93
C_{10}-LA	40	3.78	44		3.4×10^{-3}	33.4		98
C_{12}-LA	25	4.39	39		2.5×10^{-4}	35.1		93
C_{12}-LA	40	3.78	44		1.8×10^{-4}	36.1		98
$C_{10}E_8$	40	2.53	66		7.6×10^{-4}	33.5		98
$C_{12}E_8$	40	2.82	59		5.8×10^{-5}	32.7		98

[a] Data from [52] are from surface tension measurements at room temperature.
[b] No data reported (compound insoluble in water at 0.1 wt % concentration).
[c] Data obtained at solubility point.

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surfactant C_8-GHA in Table 5 are at the solubility point, which means it did not reach the CMC, whereas C_8-GA did. None of the surfactants displayed cloud points of their 1% aqueous solutions, even when heated to boiling point. In the *N*-alkylmaltobionamide series, there is a weak dependence of Γ_{CMC}, A_{min}, and π_{CMC} on alkyl chain length, other than for the C_6 derivative. On the other hand, the efficiency of surface tension reduction, pC_{20}, increases linearly with alkyl chain length. The A_{min} values of MAL amides and C_{10} and C_{12} lactobionamides are smaller than those reported for $C_{10}E_8$ and $C_{12}E_8$ nonionics, which for the latter amount to 66×10^{-20} and 59×10^{-20} m^2 at 40°C, respectively [98]. The size of the saccharide moiety seems to be an important factor determining the area occupied at the water–air interface. This is supported by the values obtained for MAL-C_{12} and dextranamide-C_{12} (the latter contains nine glucose units in the hydrophilic part of the molecule)—43×10^{-20} and 60×10^{-20} m^2, respectively [97]. The CMC values of MAL-C_{10} and -C_{12} and LA amides with comparable alkyl chain lengths (determined at 25°C) are similar to each other; they are, however, higher than those reported for $C_{10}E_8$ and $C_{12}E_8$ [56]. The micellar sizes of C_{10} and C_{12} lactobionamides are comparable with those of $C_{12}E_6$ and $C_{12}E_8$ surfactants, but the number of water molecules per lactonic moiety is greater than that per oxyethylene unit [98].

Two series—*N*-alkyl-*N*-methylgluconamides **XXXVIIIb** and *N*-alkyl-*N*-methyllactobionamides **XLIIb**—have been synthesized and their surface-active properties measured [94]. The synthetic routes and the alkyl chain lengths follow a reaction scheme as shown in Fig. 11. Their chemical structures were determined by ^{1}H NMR spectra and their purity was checked by elemental analysis and electron ionization mass spectra. The surfactants did not display cloud points of their 0.1 wt % aqueous solutions, even when heated to boiling point. Their apparent Krafft temperatures, collected in Table 6, and the CMC Krafft temperatures [99], less than 20°C for both series, were determined; the values allow us to draw some conclusions about solubility/chemical structure relationships. *N*-alkyl-*N*-methylgluconamides have lower Krafft temperatures than those obtained for 1 wt % solutions of *N*-alkylgluconamides and *N*-alkyllactobionamides [100]. This confirms the observation of Pfannemüller and Welte [52] that the insertion of a methyl group to the amide linkage enhances the solubility of amides. The presence of a double bond in the acyl chain, as in *N*-oleyl-*N*-methylamides, lowers the Krafft points comparitively to that of C_{18} methylamides. Lactobionamides exhibit lower Krafft temperatures than their respective gluconamides, a fact that arises from the presence of two glucose units (one cyclic pyranoside unit and one open-chain structure) in the saccharide moiety of Cn-MLA.

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TABLE 6 Adsorption and Micellization Parameters of *N*-Alkyl-*N*-methylgluconamides and *N*-Alkyl-*N*-methyllactobionamides in Aqueous Solution at 20°C

Surfactant	$10^6\ \Gamma_{CMC}$ (mol m^{-2})	$10^{20}\ A_{min}$ (m^2)	pC_{20}	CMC (mol dm^{-3})	Π_{CMC} (mN m^{-1})	CMC/C_{20}	Krafft temp.[a] (°C)
C_{10}-MGA	3.96	42	3.60	1.29×10^{-3}	36.1	5.2	< 0
C_{12}-MGA	3.99	42	4.78	1.46×10^{-4}	37.6	8.8	< 0
C_{14}-MGA	3.97	42	5.55	2.36×10^{-5}	37.8	8.5	20
C_{16}-MGA	3.65	45	6.11	7.74×10^{-6}	38.5	10.1	41
C_{18}-MGA	3.97	42	6.46	2.85×10^{-6}	39.7	8.1	49
C_{10}-MLA	4.14	40	3.29	2.31×10^{-3}	33.9	4.6	< 0
C_{12}-MLA	3.98	42	4.45	2.49×10^{-4}	36.8	7.1	< 0
C_{14}-MLA	3.76	44	5.40	3.64×10^{-5}	37.1	9.2	< 0
C_{16}-MLA	3.76	44	6.01	9.30×10^{-6}	37.2	9.5	< 20
C_{18}-MLA	3.96	42	6.34	3.30×10^{-6}	38.2	7.2	< 20
OL-MGA	3.89	43	5.37	3.22×10^{-5}	38.0	7.5	< 20
OL-MLA	3.84	43	5.09	5.38×10^{-5}	37.0	6.7	< 0
C_{10}-GA[b]							84
C_{12}-GA[b]							95
C_{14}-GA[b]							> 100
C_{10}-LA[b]							0
C_{12}-LA[b]							38
C_{14}-LA[b]							46

[a] Apparent Krafft temp determined for 0.1 wt % solutions in distilled water.
[b] From Ref. 100.
Source: Ref. 94 with permission of Academic Press.

The surface properties of the compounds were evaluated on the basis of surface tension measurements of their aqueous solutions at 20°C. The data are given in Table 6. As in the case of MEGA and MELA series, the Γ_{CMC} and A_{min} values practically do not change with alkyl chain length increase in both series. Once again, it turned out that the A values are lower than those for polyoxyethylene alcohol surfactants with respective alkyl chain length and more than three oxyethylene units. The values of the pC_{20} parameter increase linearly with the increase in alkyl chain length in both the C_n-MGA and C_n-MLA series. The values for the C_n-MGA series are slightly greater than those for the C_n-MLA series, indicating a somewhat higher surface activity in the former. The same dependence holds true for the π_{CMC} values, i.e., the effectiveness of surface tension reduction. The CMC values are greater for the C_n-MLA than for the C_n-MGA, again indicating that the latter are more surface active. This may be understandable taking into account that the lactonic group is more hydrophilic than the gluconic grouping. This observation concurs with the values of the standard free energies of adsorption (ΔG°_{ads}) and of micellization (ΔG°_{mic}). They show a linear dependence vs.

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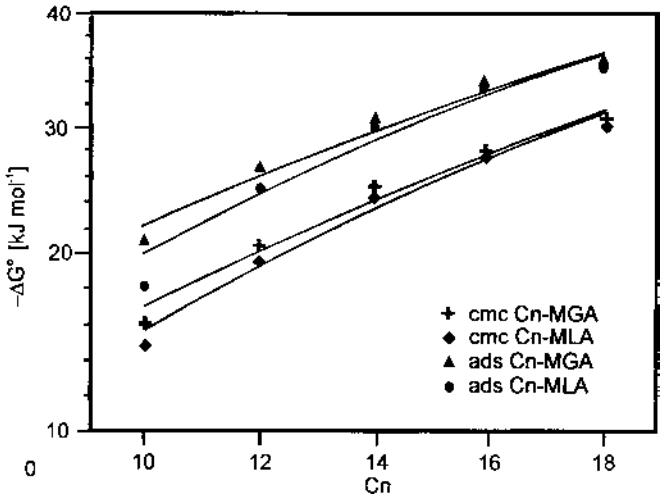

FIG. 12 The standard free energies of adsorption (ΔG°_{ads}) and of micellization (ΔG°_{mic}) of *N*-alkyl-*N*-methylgluconamides (Cn-MGA) and *N*-alkyl-*N*-methyllactobionamides (Cn-MLA) vs. alkyl chain length, Cn. (From Ref. 94 with permission of Academic Press.)

alkyl chain length as follows from Fig. 12. The estimated ($\Delta G^{\circ}_{ads}/CH_2$ and $\Delta G^{\circ}_{mic}/CH_2$ values are: for the C_n-MGA series –1.9 and –1.8 kJ mol^{-1}; and for the C_n-MLA series –2.2 and 2.0 kJ mol^{-1}, the latter two values being close to those of the MELA series [49]. The CMCs of the oleyl-amides OL-MGA and OL-MLA are higher than those of the respective C_{18}-MGA and C_{18}-MLA. This concurs with other observations [101] that the presence of one double bond in the hydrocarbon chain increases the CMC in comparison with that of the saturated alkyl chain.

Information on the performance properties of the compounds under consideration is rather sparse. Mehltretter et al. [19,95] determined the detergency as well as the foaming, wetting, and lime soap-dispersing abilities of sulfated *N*-alkylgluconamides. Au et al. [100] proposed the use of novel detergent compositions, containing *N*-alkyl- or *N*,*N*-dialkyllactobionamides and/or *N*-alkyl- or *N*,*N*-dialkylmaltobionamides, for cleaning fabrics and hard surfaces. *N*-Alkylmaltobionamides showed emulsifying ability, stabilizing oil(octane)-in-water emulsions [97]. The best results from research on emulsion stability were achieved with MAL-C_{18}. C_{12}-MGA and C_{12}-MLA demonstrated high foaming ability and foam stability, which in the case of C_{12}-MGA approached that of sodium dodecyl sulfate (SDS) [93]. On the other hand, C_{12}-MGA showed less wetting ability than the monododecyl

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ether of pentaoxyethylene glycol ($C_{12}E_5$). It was also reported that *N*-dodecyllactobionamide is a less efficient wetting agent than other sugar group containing surfactants [102]. A review on the physicochemical properties and applications of polyhydroxy-based surfactants was recently published [103].

The preliminary results of research on the environmental properties of Cn-MGA and C_n-MLA surfactants were published [104]. Both C_n-MGA and C_n-MLA surfactants were practically inactive toward some representatives of gram-positive (*S. aureus*, *B. subtilis*, *S. lutea*) and gram-negative (*E.coli*, *S. marcescens*, *P. putida*) bacteria, and completely inactive towards the fungi *S. cerevisiae*, *P. citrinum*, and *A. niger*, to a concentration of 512 mg dm^{-3}. Biodegradation of the compounds studied was determined using the OECD screening test for ultimate biodegradation [62]. The results are collected in Table 7. The data support the expectation that the two series of *N*-alkylaldo(bio)namides may be considered to be readily biodegradable. However, their biodegradation rates are a little lower than those of oxyethylene alcohols. Although the described compounds may be promising

TABLE 7 Biodegradation of *N*-Alkyl-*N*-methylgluconamides and *N*-Alkyl-*N*-methyllactobionamides

Surfactant	TOD[a] (mg O/mg)	BOD[b] (mg O/mg)	Biodegradation BOD/TOD (%)
C_{10}-MGA	2.02	1.3	64.4
C_{12}-MGA	2.12	1.6	75.5
C_{14}-MGA	2.21	1.6	72.4
C_{16}-MGA	2.29	1.5	65.5
C_{18}-MGA	2.36	1.5	63.5
Oleyl-MGA	2.33	1.5	64.3
C_{10}-MLA	1.75	1.0	57.1
C_{12}-MLA	1.84	1.2	65.2
C_{14}-MLA	1.91	1.2	62.8
C_{16}-MLA	1.99	1.2	60.3
C_{18}-MLA	2.05	1.2	58.5
Oleyl-MLA	2.03	1.2	59.1
$C_{10}E_4$[c]	2.33	2.07	88.8
$C_{12}E_5$[c]	2.48	2.13	85.8

[a] TOD, theoretical oxygen demand.
[b] BOD, biochemical oxygen demand.
[c] Conventional nonionics.
Source: Ref. 104, with permission of Springer-Verlag GmbH & Co. KG.

from an ecological point of view, no information on their manufacture was found in the literature.

B. Aggregation Behavior

N-Alkylaldo(bio)namides are able to form different aggregates with unique structures in water. This phenomenon was observed as studies were undertaken with the aim to prepare a new type of membranes, consisting of well-ordered monolayers comparable to the structure of biological membranes [52,105]. *N*-Alkylgluconamides with medium-length alkyl chains (C_8–C_{12}) formed gels over a wide range of concentrations when the temperature dropped below 80°C, and with an increase in alkyl chain length (C_8, C_{10}, C_{12}) solid gels were formed slightly below 100°C. Electron microscopy has shown that the gels formed from *N*-alkylgluconamides are composed of thin, regularly twisted helical ropes [31,52]. The crystal structure of *N*-octylgluconamide reveals extensive intra- and intermolecular hydrogen bonding [106]. It was assumed that the gel formation is favored by intermolecular hydrogen bonding between the gluconamide fragments of the molecule, as the compounds with -NH-CO- grouping form gels at low concentrations, whereas the corresponding amides with -N(CH_3)-CO- grouping are more water soluble at room temperature [52]. A superior piece of research was done by Fuhrhop and his group, who investigated the aggregation behavior in water of eight diastereomeric *N*-octylaldonamides, three enantiomers (galacton, mannon, glucon) and the corresponding racemates, via electron microscopy [107]. It was discovered that the solubilities and aggregate structures of the studied compounds depend directly on the stereochemistry of the polyol head group, leading either to "whisker"-type bimolecular sheets, or cylindrical micelles with high curvature, or to the prevention of fiber formation. The alkyl chains are forced to form spherical or planar molecular bilayers in water, and the amide group tends to form linear hydrogen bond chains, and thus transforms the spheres to fibers. As a result, the stereochemical fine structure of the fibers is observable [108].

A series of *N*-alkylmaltobion- (alkyl: C_8, C_{10}, C_{12}, C_{14}, C_{16}) and C_{16} maltooligoamides with 2, 3, 4, and 6 glucose units were synthesized, and the structures of their aggregates in water were examined with static and dynamic light scattering measurements [109,110]. Small spherical micelles with a radius of about 3 nm were observed for $C_n < 14$. These micelles aggregate further to form increasingly larger spherical clusters which eventually precipitate [110]. When $C_n \geq 14$, long rod-like micelles and filamentous micellar structures of remarkable rigidity were formed [109].

Studies of aggregate structures in water have been extended to the study of adsorbate structures of *N*-alkylaldo(bio)amides on solid surfaces. The mor-

phology and microcrystal structures of *N*-alkyl-D-gluconamides (alkyl: C_7, C_8, C_9, C_{10}) on graphite and mica were characterized by optical and atomic force microscopy (AFM) [111,112]. The observed layers are double layers with a hexagonal packing and a thickness twice the length of the molecules in their extended conformation. In the thin overlayers of the *N*-alkylgluconamides, the molecules lie parallel to the solid surface and form lamellar structures in which the molecules have a head-to-head packing. A structural model was presented in which the supramolecular structures are formed by the fusing of spherical micelles of the *N*-alkylgluconamide molecules [112]. Another study documented a ready adsorption of *N*-alkylmaltobionamides on highly oriented pyrolytic graphite from aqueous or methanol solutions [113]. Amides with alkyl chains $C_n \geq 10$ exhibited epitaxial adsorption on graphite, and the formation of ordered hemicylinders with diameters that increase with increasing alkyl chain length was observed. Review articles that cover this interesting area of study are available [114,115].

V. MISCELLANEOUS

A. Derivatives of D-Glucosamine

D-Glucosamine (2-amino-2-deoxy-D-glucopyranose or 2-amino-2-deoxy-D-glucose) is a building block of chitin, a polysaccharide that is a component of the cell wall of fungi and of the external skeleton of arthropods. According to some estimates, in terms of occurrence in nature, chitin is second only to cellulose [116]. D-Glucosamine is an interesting substrate in organic synthesis, as it contains two different functional groups—the amine group and the hydroxyl group—that can be derivatized in different ways. This possibility and the ease with which D-glucosamine can be obtained via the acidic hydrolysis of chitin make this compound an interesting intermediate for saccharide-based surfactant synthesis.

Three different synthetic protocols have been used to link the hydrophobic moiety with the glucosamine molecule: acylation of the amine group with fatty acid anhydrides or acyl chlorides; glycosidation of the C_1 hydroxyl group with long-chain alcohols; and acetalization of the (mainly) C_4 and C_6 hydroxyl groups with long-chain aldehydes or ketones. Figure 13 shows the structures of surfactants obtained by Matsumura et al. [117] according to the two first methods: methyl-2-acylamino-2-deoxy-D-glucopyranosides (α-anomers **XLV** = MeαNC_n, β anomers **XLVI** = MeβNC_n); *n*-alkyl-2-acetylamino-2-deoxy-D-glucopyranosides (α anomers **XLVII** = $C_n\alpha$NAc, β anomers **XLVIII** = $C_n\beta$Nac); and *n*-alkyl-2-amino-2-deoxy-D-glucopyranoside hydrochlorides (α anomers **XLIX** = $C_n\alpha$N, β anomers **L** = $C_n\beta$N). Of the synthesized compounds, only **XLIX** and **L**, the hydrochlorides containing

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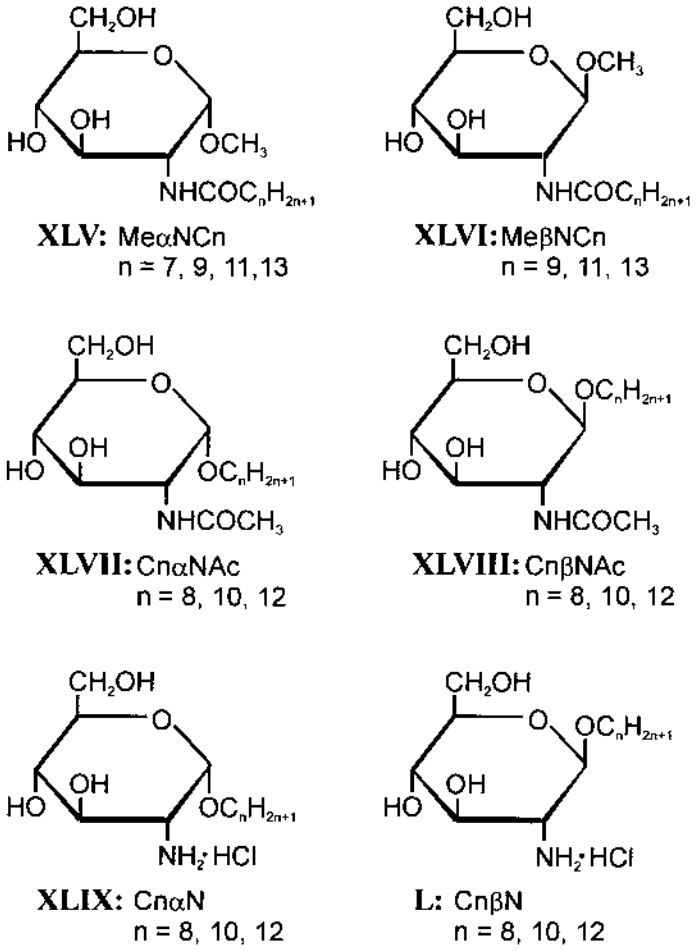

FIG. 13 Structures of methyl-2-acylamino-2-deoxy-D-glucopyranosides (XLV, XLVI), *n*-alkyl-2-acetylamino-2-deoxy-D-glucopyranosides (XLVII, XLVIII), and *n*-alkyl-2-amino-2-deoxy-D-glucopyranoside hydrochlorides (XLIX, L). (Adapted from Ref. 117.)

C_8, C_{10}, and C_{12} carbon atoms in their alkyl chain, showed surface activity with CMC values in the range of about 10^{-2} to 10^{-3} mol dm^{-3}. The CMC–alkyl chain relationship was typical—the longer the alkyl chain, the lower the CMC. The α anomers exhibited slightly lower CMC values than the β anomers. The hydrochlorides are good foaming agents with high foam stability above CMC. The nonionic compounds **XLV**, **XLVI**, **XLVII**, and

XLVIII, containing C_{10} and C_{12} alkyl chains, exhibited low solubility in water; the surface tensions of aqueous solutions of C_8 derivatives could be measured, but no CMCs were reached. The authors ascribed the low solubility of these compounds to hydrogen bonding by the C_2 amide group.

Reports were made on interesting environmental properties of the studied surfactants. The antimicrobial activity of the obtained compounds against 12 microorganisms—3 gram-positive, 3 gram-negative bacteria, and 5 fungi—were determined by measuring the minimal inhibitory concentrations (MIC). Table 8 contains the MIC values obtained for compounds **XLV** (MeαNC$_n$) and **XLVI** (MeβNC$_n$), i.e., the acyl derivatives of methylglucosamine and, for comparison, the values for *n*-octyl-, *n*-decyl-, and *n*-dodecyl-β-D-glucosides ($C_8\beta$Glc, $C_{10}\beta$Glc, $C_{12}\beta$Glc, respectively). The results allow some conclusions to be drawn. *N*-Alkylglucosides may be considered inactive to all the microorganisms tested, as their MIC values are high, except those for *B. subtilis* and *S. lutea*, i.e., gram-positive bacteria. The MeαNC$_n$ and MeβNC$_n$ compounds show a diverse spectrum of antimicrobial activity. All MeαNC$_n$ and MeβNC$_n$ substances exhibit high activity against *S. lutea*, *E. coli*, and *P. aeruginosa*, which may be compared to that of cetyltrimethylammonium bromide (CTAB), reported on in this book (see Chapter 5). On the other hand, the discussed compounds are practically inactive toward *S. aureus*, *B. subtilis*, and *A. niger*. Table 9 contains the MIC values measured for *n*-alkyl-2-acetylamino-2-deoxy-D-glucopyranosides **XLVII** ($C_n\alpha$NAc) and the **XLVIII** ($C_n\beta$Nac) series, and for the $C_n\alpha$N and $C_n\beta$N hydrochlorides (Fig. 13, **XLIX** and **L**, respectively). The former compounds are completely inactive against all the microorganisms. The hydrochlorides, which are cationic surfactants, differ in their antimicrobial activity. A relationship between their alkyl chain length and activity may be observed: the longer the alkyl chain, the higher the activity. The C_{12} hydrochlorides show high activities against 9 of the 12 microorganisms investigated (the exceptions are *C albicans*, *P. chrysogenum*, and *A. niger*), and they may be compared to the biocide CTAB.

The biodegradability data for the compounds are collected in Table 10. They were obtained by the closed bottle test, a screening test for ultimate biodegradation determination [62]. The obtained values are in the range from 11.2 % (MeαNC$_8$) to 46.8% ($C_{10}\beta$N) and are, in general, lower than that obtained for C_{10}- polyglycoside, yet comparable to those for the polyoxyethylene alcohols. The BOD_5 method is, as mentioned, a screening test and does not permit the drawing of reliable conclusions; surprisingly, the best results were obtained by the authors for both the $C_n\alpha$N and $C_n\beta$N series, i.e., the hydrochlorides, which are cationic surfactants, the rates of biodegradation for which are rather lower than those for conventional nonionic and anionic surfactants.

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TABLE 8 Antimicrobial Activity of Glucosamine Derivatives Containing Alkyl Chain and Alkylglucopyranosides[a]

Organisms	Compounds [MIC(μg/mL)[b]]									
	$Me\alpha NC_8$	$Me\alpha NC_{10}$	$Me\alpha NC_{12}$	$Me\alpha NC_{14}$	$Me\beta NC_{10}$	$Me\beta NC_{12}$	$Me\beta NC_{14}$	$C_8\beta Glc$[c]	$C_{10}\beta Glc$[c]	$C_{12}\beta Glc$[c]
S. aureus	> 400[d]	> 400	100	200	400	50	100	400	100	10
B. subtilis	> 400	> 400	100	400	400	50	> 400	400	100	25
S. lutea	10	10	10	10	10	10	10	100	50	10
E. coli	10	10	10	10	10	10	10	400	200	400
S. typhi	400	> 400	400	200	400	50	> 400	400	400	400
P. aeruginosa	10	5	5	5	5	25	10	400	200	200
C. albicans	> 400	> 400	200	100	100	100	> 400	> 400	200	400
S. cerevisiae	> 400	> 400	50	200	200	50	> 400	> 400	100	400
T. interdigitale	50	100	50	50	50	50	25	400	200	200
M. gypseum	50	100	50	50	50	50	25	400	200	200
P. chrysogenum	50	100	50	50	50	50	25	400	400	200
A. niger	> 400	> 400	> 400	200	200	400	> 400	> 400	400	200

[a] Control always produced growth of the microorganism.
[b] MIC, minimal inhibitory concentration.
[c] C8βGlc: *n*-octyl β-D-glucoside, $C_{10}\beta Glc$: *n*-decyl β-D-glucoside, $C_{12}\beta Glc$: *n*-dodecyl β-D-glucoside.
[d] No inhibition, maximal concentration tested listed.
Source: Ref. 117, with permission of AOCS Press.

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TABLE 9 Antimicrobial Activity of Glucosamine Derivatives[a]

Organisms	Compounds [MIC(μg/mL)[b]]											
	$C_8\alpha$NAc	$C_{10}\alpha$NAc	$C_{12}\alpha$NAc	$C_8\beta$NAc	$C_{10}\beta$NAc	$C_{12}\beta$NAc	$C_8\alpha$N	$C_{10}\alpha$N	$C_{12}\alpha$N	$C_8\beta$N	$C_{10}\beta$N	$C_{12}\beta$N
S. aureus	400	200	>400	>400[c]	>400	>400	400	100	10	400	50	10
B. subtilis	>400	200	>400	>400	>400	>400	400	100	10	400	100	10
S. lutea	>400	200	>400	>400	>400	>400	400	50	10	400	100	10
E. coli	>400	>400	>400	>400	>400	>400	400	50	10	400	50	25
S. typhi	>400	>400	>400	>400	>400	>400	400	100	10	>400	200	25
P. aeruginosa	400	>400	>400	>400	400	400	400	200	50	>400	200	50
C. albicans	>400	>400	>400	>400	>400	>400	>400	400	200	400	400	400
S. cerevisiae	>400	>400	>400	>400	>400	>400	>400	100	10	400	100	25
T. interdigitale	400	400	>400	400	>400	400	400	50	25	400	100	25
M. gypseum	400	400	>400	400	>400	400	400	100	25	400	200	50
P. chrysogenum	>400	400	>400	400	>400	400	>400	400	200	>400	400	200
A. niger	>400	400	>400	400	>400	>400	>400	400	400	>400	>400	400

[a] Control always produced growth of the microorganism.
[b] MIC, minimal inhibitory concentration.
[c] No inhibition, maximal concentration tested listed.
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TABLE 10 Biodegradability of Glucosamine Derivatives[a]

Compounds	TOD (mg O/g)	BOD_5 (mg O/g)	BOD_5/TOD (%)
MeαNC_8	1930	590	30.6
MeαNC_{10}	2052	400	19.5
MeαNC_{12}	2150	240	11.2
MeβNC_{10}	2052	700	30.7
$C_8\alpha$NAc	1991	430	21.6
$C_{10}\alpha$NAc	2103	410	19.5
$C_8\beta$NAc	1991	574	28.8
$C_{10}\beta$NAc	2103	400	19.0
$C_8\alpha$n	2050	350	17.1
$C_{10}\alpha$N	2158	555	25.7
$C_{12}\alpha$N	2250	645	28.7
$C_8\beta$N	2050	672	32.8
$C_{10}\beta$N	2158	1010	46.8
$C_{12}\beta$N	2250	916	40.7
$C_{10}\alpha$Glc	2100	1220	58.1
$C_{12}EO_{10}$	2200	736	33.5
$C_{18}EO_{10}$	2340	669	28.6

[a] TOD, theoretical oxygen demand; BOD5, 5-day biochemical oxygen demand; $C_{10}\alpha$Glc, Decyl α-D-glucopyranoside; $C_{12}EO_{10}$, dodecylpoly(oxyethylene) ether $n = 10$; $C_{18}EO_{10}$, Octadecyl poly(oxyethylene) ether $n = 10$.
Source: Ref. 117, with permission of AOCS Press.

Another paper reported on the synthesis, surface-active properties, and micellar aggregation of alkyl 2-amino-2-deoxy-β-D-glucopyranosides with *n*-alkyl chain lengths of 8, 9, and 12 carbon atoms [118]. Surface tension measurements were performed at 25, 37, and 60°C because the Krafft temperature of the C_{12} compound was 54°C. Like other nonionic saccharide-based surfactants, the compounds did not show a cloud point. The determined CMCs decreased with alkyl chain length increase, and did not depend on the temperature. The A_{min} values were close to 50×10^{-20} m^2, irrespective of alkyl chain length. The aggregation numbers of the C_8 surfactant did not depend on temperature in the range from 25°C to 60°C, and equaled 41–43; that of the C_{12} surfactant determined at 60°C was 320. The conclusion of the study was that the surfactants behave as neutral alkyl glucosides.

The third synthetic methodology of D-glucosamine transformation into surfactants was applied by Kida et al. [119], who reacted this sugar amine with long-chain aldehydes. The obtained surfactants may be regarded as chemodegradable (cleavable) surfactants (this volume, Chapter 10). They are stable

in neutral and alkaline aqueous media but undergo easy hydrolysis reaction in acidic solutions. Three surfactant types were synthesized: two anionic ones with a carboxylate group **LIa–d** (sodium methyl 4,6-*O*-alkylidene-2-(carboxymethylamino)-2-deoxy-D-glucopyranosides) and **LIIa–c** (sodium methyl 2-acetamido-4,6-*O*-alkylidene-3-*O*-[(1-carboxylato)ethyl]-2-deoxy-D-glucopyranosides), and one cationic **LIIIc** (methyl 4,6-*O*-alkylidene-2-deoxy-[2-(trimethylammonio)-D-glucopyranoside]iodide). Their structures, shown in Fig. 14, are very interesting as the cyclic acetal function present in the molecules builds a six-membered 1,3-dioxane ring condensed with the pyranose ring. The anionic surfactants **LI** and **LII** were readily soluble in water at 1 wt % concentration, except those with a C_7 alkyl chain, which were only slightly soluble at 1 wt % in water. The Krafft temperatures of **LIa–d**, **LIIa–c**, and **LIIIc**, measured at 1 wt % concentration, were less than 0°C. **LI** showed better surface activity than **LII**, as measured by the effectiveness of surface tension reduction, γ_{CMC}. The cationic surfactant **LIII** showed higher CMC and γ_{CMC} values than the sodium carboxylate **LIc** bearing an equal hydrophobic chain and the same configuration at the anomeric center. **LI b–d** carboxylates exhibited high foaming ability and excellent foam stability. The difference between the α and β anomers (**LIc** and **LId**) was negligible as regards their foaming ability; this is in contrast to the data obtained for the α and β anomers of alkylglycosides [120]. The rates of acid hydrolysis of the described compounds were estimated by determining the quantity of the aldehyde formed in 2% aqueous HCl solution. High hydrolysis rates were achieved, and the order of the rates was as follows: **LIa** ≫ **LIb** > **LIc** = **LId**. Cationic surfactant hydrolyzed more slowly than the corresponding **LIc** compound, a fact that the authors ascribed to the electrostatic repulsion between the protons in the bulk phase and the positively charged micellar surface.

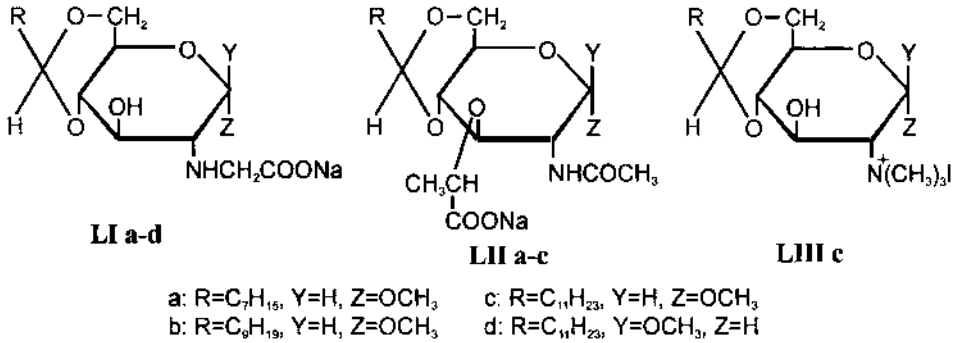

FIG. 14 Acetal derivatives of D-glucosamine: sodium carboxylates (LI, LII) and quaternary ammonium iodide (LIII). (Adapted from Ref. 119.)

The biodegradability of the studied compounds was estimated as well. Biochemical oxygen demand (BOD) was determined after 1 and 2 weeks. The biodegradabilities of the **LI** and **LII** surfactants were comparable to that of sodium dodecanoate under the same experimental conditions, whereas the biodegradability of the cationic **LIIIc** compound was very low (even negative after 2 weeks), due to its possible high antimicrobial activity.

Other types of D-glucosamine surfactants were reported on only recently [121–123]. Bazito and El Seoud synthesized anionic surfactants in a sequence of reactions presented in Fig 15a [121]. D-Glucosamine hydrochloride **LIV** was first acylated, followed by methylation of the anomeric OH group. The obtained methyl 2-acylamido-2-deoxy-D-glucopyranosides **LV** were sulfated, and the reaction products neutralized to obtain sodium methyl 2-acylamido-2-deoxy-6-*O*-sulfoglucopyranoside **LVI**. The apparent Krafft temperatures of the C_7H_{15}, $C_{11}H_{23}$, and $C_{15}H_{31}$surfactants were <0, 14, and 39°C, respectively. The CMCs were determined by conductivity measurements at 40°C; they decreased with increasing alkyl chain length. The calculated aggregation numbers were 28, 56, and 95 for compounds with C_7, C_{11}, and C_{15} alkyl chain lengths, respectively. A detailed study of the adsorption and micellization properties of the **LVI** surfactants was reported [122].

LVII cationic surfactants (Fig. 15b) with similar structure to the above-described anionic ones were obtained by the same authors [123]. The first two reaction steps were identical to those shown in Fig. 15a. The **LV** compounds were first subjected to reaction with *p*-toluenesulfonyl chloride, which was further reacted with anhydrous trimethylamine in DMF, and the reaction products were converted to the desired chlorides by passing their methanolic solution through an ion-exchange column (packed with the chloride form of Amberlyst 27 resin). Aggregation of the **LVII** surfactants (which were mixtures of anomers) was studied, and the micellar degrees of dissociation, α, in water at 25°C were determined.

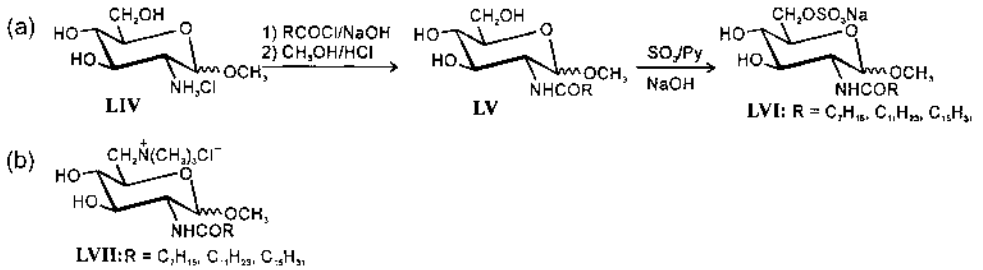

FIG. 15 Derivatives of D-glucosamine: sodium sulfates (LVI) and quaternary ammonium chlorides (LVII). (Adapted from Refs. 121 and 123.)

B. Bolaamphiphiles

Bola-amphiphiles, also called bolaform amphiphiles, bolaform surfactants, α,ω-type surfactants, boliones, and bolytes (i.e., bolaform electrolytes), are compounds having two or more hydrophilic groups (heads) linked by one or two long alkyl chain(s) [124,125]. Their solubility and surface properties depend both on the length of the bridging alkyl chain and on the polar groups. The presence of a second polar group should, and in many cases does, induce higher solubility compared with that of surfactants containing only one such group. Bolaform surfactants are characterized by increased CMC and decreased aggregate number. They aggregate to form spherical micelles, cylinders, small and large discs, and vesicles. Most of these compounds have been studied differently for their polymorphic behavior in water depending on their structures. They can form nanoscale fibers [126], microtubules [127], and helical ribbons [128] with solid surfaces. Water-insoluble bola-amphiphiles may aggregate in aqueous media to form monolayer lipid membranes with a specific type of reactivity and stereochemistry [129]. Such monolayers provide interesting new properties when compared with the usual bilayer lipid membranes formed from one-headed amphiphiles; for instance, they may be thinner than bilayer lipid membranes, which permits the use of relatively short molecules for the formation of membrane pores; moreover, the formed vesicles resist fusion [125].

Polar (head) groups in bolaform surfactants may be linked to the long-chain spacer (bridge) by an oxygen (ether) atom, a nitrogen atom, an amide group, a carbamate group, or other groups. Figures 16 and 17 present some examples of bolaform surfactants or insoluble amphiphiles, containing saccharide head groups. **LVIII** surfactants containing an oxygen atom as a link and different sugar head groups (D-glucose, D-galactose, DL-xylitol) have been synthesized from α,ω-dibromo- or dimesylalkanes and the respective sugar [130]. The hydrophilic groups attached to the alkyl chain ($n = 4, 8, 10$) were identical or different. Surface tension measurements of aqueous solutions of the compounds were performed at 25°C and their CMC determined. For $n = 10$, the values of CMC ranged from 4.2×10^{-4} to 6.5×10^{-4} mol dm^{-3}, depending on the head group chosen. **LIX** compounds with a nitrogen atom connecting both moieties were obtained by reductive amination of D-glucose with α,ω-diaminoalkanes to yield the respective bis(1-amino-1-deoxy-D-glucityl)alkanes [131,132]. The compounds ($n = 6, 8, 10$) only dissolve in water at high temperatures and do not form lyotropic mesophases [132]. Compounds **LX**, **LXI**, and **LXII** (Fig. 16) were obtained by a reaction of α,ω-diamines with 1,5-D-gluconolactone [133,134], lactonic acid [133,134], and D-maltonolactone [135,136], respectively. Compounds **LX** with $n = 6, 7, 8$ and **LXI** with $n = 6$–19, 12 were sufficiently soluble in water to allow surface

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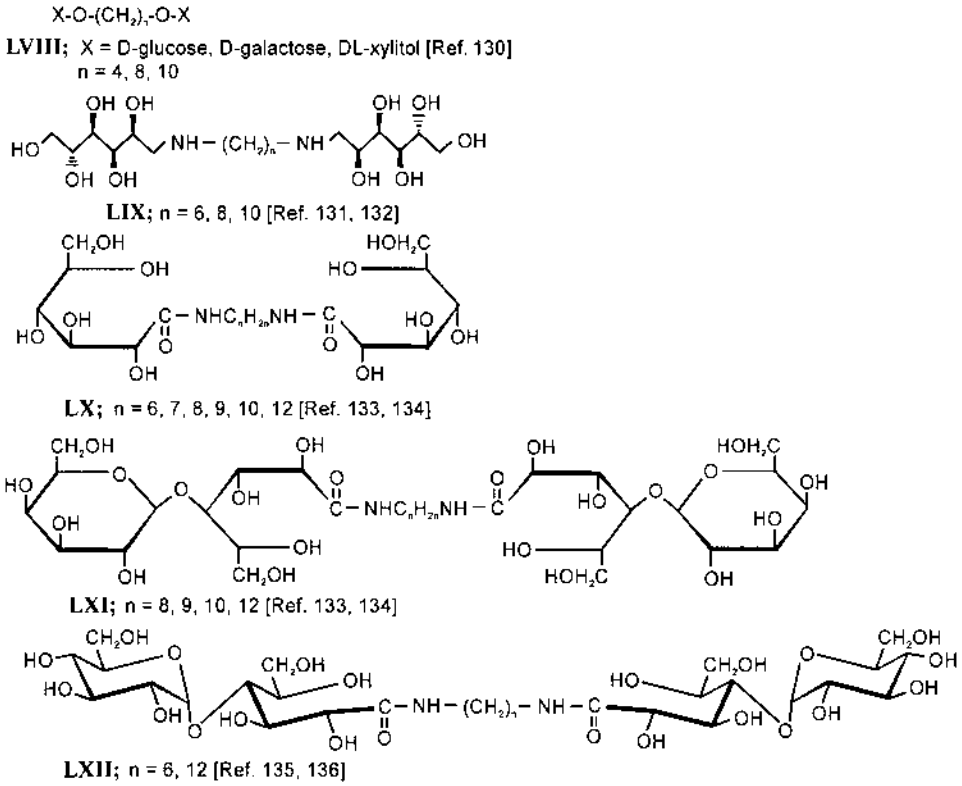


FIG. 16 Structures of various bola-amphiphiles with head groups linked by hydrocarbon chain through oxygen (LVIII) or nitrogen (LIX) atoms, or amide groups (LX, LXI, LXII).

tension measurements at 40°C [137]. They reduced the surface tension of water to 22 mN m^{-1}. The authors attributed the absence of a micellization process of compounds **LX** and **LXI** with $n = 6$–12 to the inability of the short alkyl spacer to bend. Quasi-elastic light scattering measurements permitted the detection of spherical aggregates after the sonication of solutions of compounds **LXI** and an increase in the maximal aggregate diameter was observed with the increase of alkyl chain length. *N*,*N*′-bis(maltobionamide)alkanes **LXII** and *N*,*N*′-bis(dextranamide)alkanes (dextran with nine glucose units, not shown in Fig. 16), were prepared, as analogs of triblock ABA-type copolymers, by reacting the respective lactone with α,ω-diamines [135,136]. Their surface properties were compared with those of compounds **XLIV** (Fig. 11), which contain one sugar head and one hydrocarbon chain.

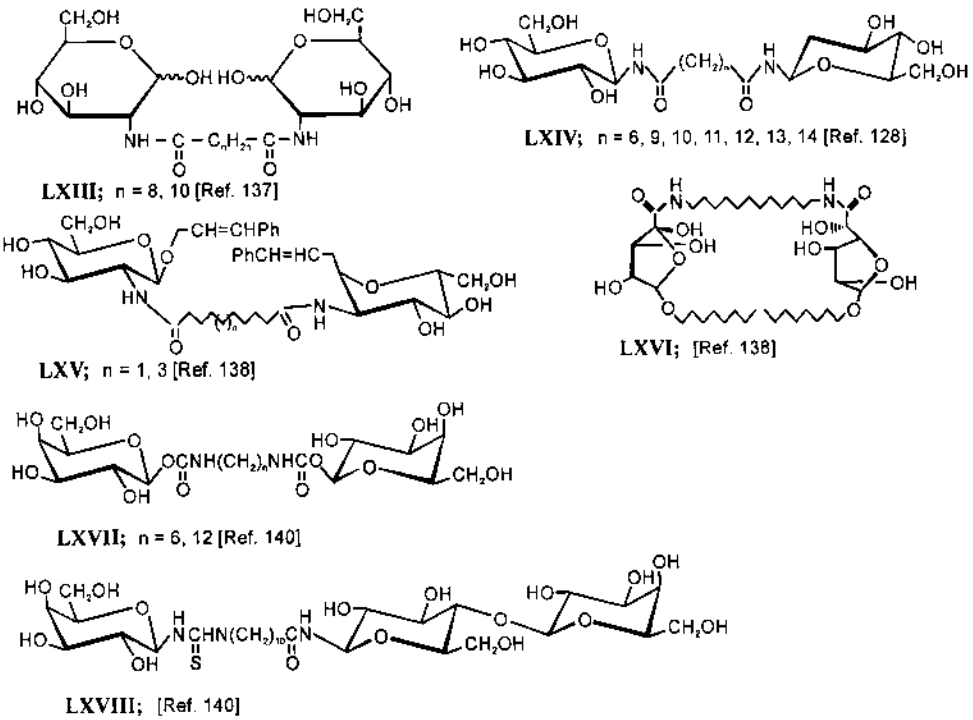


FIG. 17 Bola-amphiphiles with amide groups (LXIII, LXIV, LXV), pseudomacrocyclic bola-amphiphiles (LXV, LXVI), bis(*O*-galactopyranosyl)bis(carbamates) (LXVII), and thiocarbamate (LXVIII).

Surface tension measurements showed that the compound **LXII** with $n = 12$ and a dextran head group did not form micelles [136].

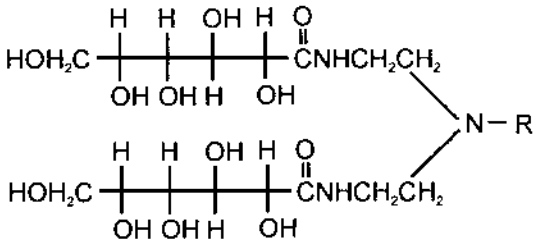
Bola-amphiphiles **LXIII**, **LXIV**, and **LXV**, shown in Fig. 17, also contain an amide link. However, they were synthesized from sugar amines and α,ω-dicarboxylic acid derivatives. Compounds **LXIII,** *N*,*N*′-bis(pyranosylamido)alkanes, were prepared by reacting D-glucosamine hydrochloride with an acylating agent: *N*,*N*′-diacyldithiozalidine-2-thione (**XXXI** in Fig. 9) [137]. The use of this reagent allowed the pyranosyl ring and the anomeric hydroxyl group in D-glucosamine to be preserved. No data on the surface active properties of these compounds were reported. Another example is **LXIV** compounds. They were prepared from acetobromo-α-D-glucose, which was converted to a β-1-azide derivative with 100% selectivity to β-anomer, by heating with sodium azide. The azide was hydrogenated in the presence

of platinum oxide into 1-β-amino-D-glucose, which was condensed with α,ω-dicarboxylic acid dichlorides [128]. Self-assembled structures in water were detected; they depend strongly on whether the *n* in **LXIV** is even or odd—the former situation gives rise to fibrous assemblies or planar platelets, and the latter to amorphous solids. **LXV** and **LXVI** compounds represent pseudo-macrocyclic bola-amphiphiles [138]. They are synthetic analogs of the macrocyclic lipid constituents of the highly stable membranes from archaebacteria [139]. **LXV** compounds, containing a long alkyl chain and two short chains possessing a combined length equal to that of the bridging chain, have the potential to be incorporated into membranes by bridging a monolayer or a bilayer. They were obtained in a sequence of reactions starting with *N*-acylated-2-amino-2-deoxy-D-glucose which, after glycosidation with cynamyl bromide, separation of the anomers, and deacylation, reacted with α,ω-dicarboxylic acid dichlorides to give **LXV** compounds. The bolaform compound **LXVI**, another example of a pseudo-macrocyclic bola-amphiphile, was prepared in a two-step process. The readily available D-glucofuranurono-3,6-lactone was converted to octyl-D-glucofuranosiduro-no-3,6-lactone, which was treated with 1,12-diaminododecane to give the desired product.

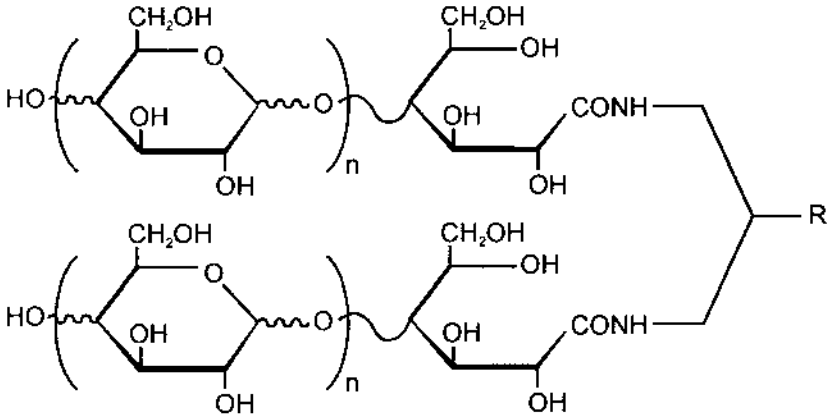
Some other bola-amphiphiles with carbamate and thiocarbamate groups are also known. Bis(*O*-galactopyranosyl)-bis(carbamates) **LXVII**, bis(lactosyl)-bis(carbamate) (not shown in Fig. 17), as well as an asymmetrical thiocarbamate, **LXVIII**, which was recognized as a galactopyranosylthiourea derivative, were synthesized, and a preliminary study of their aggregation in water was reported [140]. Surface tension measurements of aqueous solutions at 20°C showed the absence of micelles. Quasi-elastic light scattering measurements confirmed the formation of vesicles after sonication of solutions of the compounds with a longer spacer (**LXVII**, $n = 12$, lactose derivative, and **LXVIII)**, whereas the compounds with a short chain and galactose as a head group (**LXVII**, $n = 6$) did not form vesicles. Dyssymmetrical, branched bola-amphiphiles (Fig. 10, **XXXIV**) represent another group of compounds whose synthesis and surface properties were reported [79,80].

C. Dicephalic Surfactants

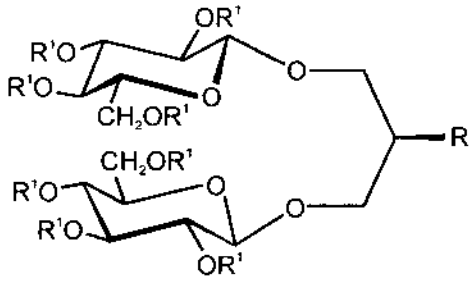
The term "dicephalic surfactants" was introduced by Sommerdijk et al. [141] to describe surface-active compounds that contain one hydrocarbon chain and two polar head groups in their molecule. However, unlike bola-amphiphiles, dicephalic surfactants contain the two hydrophilic groups at one end of the hydrophobic group. Some structures of nonionic dicephalic surfactants are shown in Fig. 18. The first examples of such compounds were probably patented and described by Ulsperger et al. [142–144], who reacted 1,5-D-



LXIX; R = H, $C_nH_{2n+1}NHCO$, $C_mH_{2m+1}CO$ [Ref. 144]
n = 8, 10, 11, 12, 17
m = 7, 9, 11,17



LXX; R = C_8H_{17}, $C_{10}H_{21}$, $C_{12}H_{25}$ [Ref. 145]
n = 0, 1, 2



LXXI; R = $C_{10}H_{21}$, $C_{12}H_{25}$, $C_{14}H_{29}$, $C_{16}H_{33}$ [Ref. 146]
R' = Ac, H

FIG. 18 Structures of various dicephalic surfactants (LXIX, LXX, LXXI).

gluconolactone with *N″*,*N″*-bis(2-aminoethyl)amine in anhydrous methanol to obtain *N″*,*N″*-bis[(2-gluconylamido)ethyl]amine (Fig. 18, **LXIX**, R = H). This intermediate product was further reacted with either *n*-alkylisocyanates or mixed anhydrides formed from fatty acids and ethyl chloroformate to give the respective *N′*-alkyl-*N″*,*N″*-bis[(2-gluconylamido)ethyl]urea derivatives **LXIX**, R = $C_nH_{2n+1}NHCO$, and *N′*-alkanoyl-*N″*,*N″*-bis[(2-gluconylamido)ethyl]amines **LXIX**, R = $C_mH_{2m+1}CO$. Surface tension measurements of aqueous solutions of **LXIX** compounds were performed at 22°C and their CMC values, γ_{CMC}, and wetting abilities were determined.

Another possibility of synthesizing dicephalic surfactants was developed. It involved using derivatives of malonic acid as a starting reagent. By monoalkylation of malonitrile with alkyl bromides, 2-alkyl-1,3-propanedinitriles were prepared. They were reduced with lithium aluminum hydride to diamines, and the latter were subjected to reaction with sugar lactones—1,5-D-gluconolactone, lactobionolactone, maltobionolactone, and maltotrionolactone—to obtain the respective 2-alkyl-1,3-bis(aldonamido)propanes, shown in Fig. 18 (**LXX:** gluconamides $n = 0$, lactobioamides $n = 1$, maltobionamides $n = 1$, and maltotrionamides $n = 2$) [145]. The prepared surfactants exhibited higher water solubility than gluconamide surfactants with one hydrophilic group. The CMCs decreased with an increase in the alkyl chain length but were independent of the sugar units in the hydrophilic head group. Their binding properties to lectins, highly specific sugar-binding proteins, were also studied.

Monoalkylation of diethylmalonate with alkyl bromides as a first reaction step leading to **LXXI** surfactants was applied by Schmidt and Jankowski [146]. Reduction of the diethylalkylmalonates with $LiAlH_4$ gave diols, which were reacted with *O*-(2,3,4,6-tetra-*O*-acetylglucopyranosyl)trichloroacetimidate, and the obtained products, after the removal of the *O*-acetyl groups by the method of Zemplén [147], gave the desired **LXXI**. From surface tension measurements, the CMC values and γ_{CMC} were determined. The former were in the range from 5.9×10^{-4} (for C_{10} compound) to 2.6×10^{-6} mol dm^{-3} (for C_{14} surfactant), whereas γ_{CMC} were from 43.3 to 38.5 mN m^{-1}, respectively.

A new type of dicephalic surfactants was synthesized and a study of their surface active properties was reported on more recently [148,149]. The synthetic protocol applied follows from Fig. 19. Long-chain alkylamines ("fatty amines") were reacted with acrylonitrile, an easy accessible, relative cheap monomer, to give *N*-alkyl-*N*,*N*-bis(2-cyanoethyl)amines, which, after hydrogenation with gaseous H_2 on Ni-Ranay as a catalyst, afforded *N*-alkyl-*N*,*N*-bis(3-aminopropyl)amines **LXXII**. The latter were reacted with an appropriate lactone or lactonic acid leading to the desired surfactants—*N*-dodecyl-*N*,*N*-bis[(3-D-gluconylamido)propyl]amine **LXXIII** (C_{12}-DGA), *N*-

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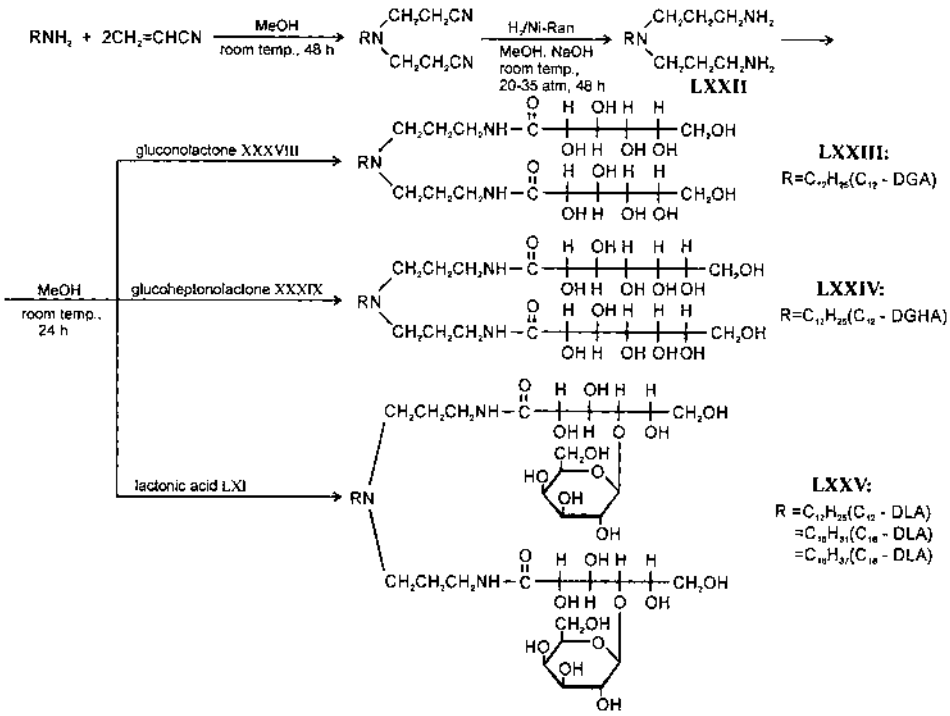

FIG. 19 Synthetic route for the preparation of dicephalic surfactants LXXIII, LXXIV, and LXXV. (Adapted from Ref. 149.)

dodecyl-*N,N*-bis[(3-D-glucoheptonyl)propyl]amine **LXXIV** (C_{12}-DGHA), and *N*-alkyl-*N,N*-bis[(3-lactobionyl)propyl]amines **LXXV** (C_{12}-, C_{16}-, and C_{18}-DLA). The reactants were chosen so as to permit the determination of the effects of both the sugar polar group (C_{12}-DGA, C_{12}-DGHA, C_{12}-DLA series) and the alkyl chain length (C_{12}-, C_{16}-, and C_{18}-DLA series) upon the surface active properties of the synthesized compounds. They are readily soluble in water at 1 wt % concentration, except C_{12}-DGA and C_{12}-DGHA. Their Krafft temperatures, collected in Table 11, are low, and the compounds did not show a cloud point up to the boiling temperature of their solutions. The water–air surface tension and water–*n*-octane interface tension isotherms, the latter shown in Fig. 20, have a classic trend, typical for that of conventional nonionics. From surface tension measurements performed at 25°C, Γ_{CMC}, A_{min}, CMC, and γ_{CMC} were determined for both interfaces. The data are presented in Table 11. At the water–air interface the A_{min} values

TABLE 11 Adsorption and Micellization Parameters of Dicephalic Saccharide-Derived Surfactants at 25°C

Surfactant	Krafft temp.[a] (°C)	Interface	$10^6 \cdot \Gamma_{CMC}$ (mol m^{-2})	$10^{20} \cdot A$ (m^2)	CMC (mol dm^{-3})	γ_{CMC} (mN m^{-1})	$-\Delta G°_{CMC}$ (kJ mol^{-1})
C_{12}-DGA	<10	Air–water	4.754	34.9	2.51×10^{-4}	38.6	30.50
C_{12}-DGHA	<20		4.671	35.5	3.16×10^{-4}[b]	38.5[b]	29.93[b]
C_{12}-DLA	<0		4.482	37.0	7.94×10^{-4}	38.5	27.65
C_{16}-DLA	<0		4.127	40.2	8.91×10^{-5}	41.1	33.07
C_{18}-DLA	<0		3.367	49.3	1.67×10^{-5}	45.4	37.23
C_{12}-DGA		Octane–water	6.225	26.7	3.52×10^{-4}	2.7	29.67
C_{12}-DGHA			6.955	23.9	4.17×10^{-4}	1.7	29.25
C_{12}-DLA			6.419	25.9	8.35×10^{-4}	6.4	27.53

[a] Determined for 0.1 wt % solutions in distilled water.
[b] Solubility point.
Source: Ref. 149, with permission of AOCS Press.

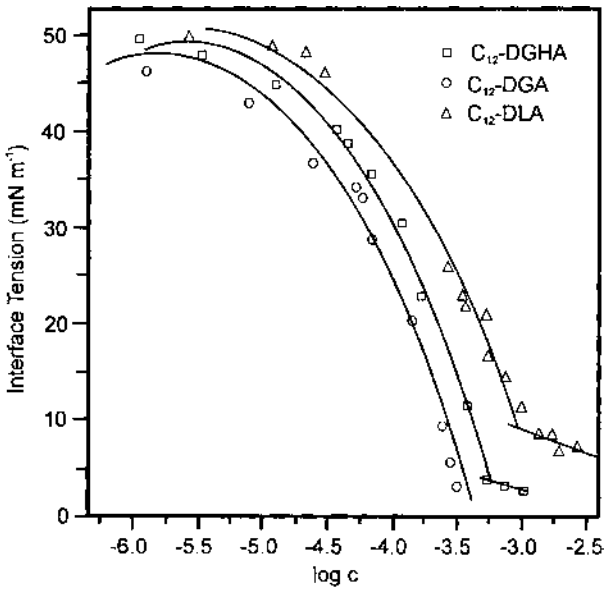

FIG. 20 Plot of water–*n*-octane equilibrium interface tension at 25°C vs. the logarithm of molar concentration (log *c*) of C_{12}-dicephalic surfactants. (From Ref. 149 with permission of AOCS Press.)

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increase with the increasing size of the polar group only slightly, whereas at the water–oil interface they are independent of the polar group but markedly smaller. This permits the conclusion that the presence of *n*-octane seems to affect the close packing of the alkyl chains in the surfactant film. On the other hand, the CMC values of the *N*-dodecyl derivatives are only slightly affected by the interface character. At the water–air interface, CMCs decrease with alkyl chain length increase (C_{12}-, C_{16}-, and C_{18}-DLA surfactants), but increase as the size of the polar head group increases (the C_{12}-DGA, C_{12}-DGHA, and C_{12}-DLA series). From the standard free energies of micellization determined for the C_n-DLA series, the increment $-\Delta G^0_{mic}/CH_2$, i.e., the increase of standard free energy of micellization per methylene group, could be evaluated. The obtained value, 1.56 kJ mol^{-1}, is slightly lower than that for *N*-alkyl-*N*-methylaldonamides [94].

The environmental properties of the discussed surfactants were estimated by measuring their antimicrobial activity and biodegradability [104]. Table 12 contains the MIC values determined for some gram-positive and gram-negative bacteria. From the data it follows that all the tested surfactants show high antimicrobial activity against gram-positive bacteria. In the C_{12} series, the most active substance was *N,N*-bis[(3-gluconylamido)propyl]-amine, the less active was *N,N*-bis[(3-lactobionyl)propyl]amine. All the surfactants were practically inactive toward gram-negative bacteria and the fungi: *P. citrinum, A. niger,* and *S. cerevisiae*.

The closed bottle test of ultimate biodegradability determination [62] was also performed [104]. The data, collected in Table 13, indicate the biodegradation rates to be markedly lower than those of *N*-alkyl-*N*-

TABLE 12 Minimal Inhibitory Concentration (μg/mL) of C_{12}-DGA, C_{12}-DGHA and C_n-DLA Surfactants

	Microorganisms					
	Gram-positive bacteria			Gram-negative bacteria		
Surfactant	*S. aureus*	*B. subtilis*	*S. lutea*	*E. coli*	*S. marcescens*	*P putida*
C_{12}-DGA	4	512	8	> 512	512	> 512
C_{12}-DGHA	8	512	256	> 512	512	256
C_{12}-DLA	16	512	256	> 512	512	512
C_{16}-DLA	64	512	32	512	256	> 512
C_{18}-DLA	32	512	32	512	256	> 512
$C_{10}E_4$	64	64	64	> 512	> 512	> 512
$C_{12}E_5$	> 512	> 512	512	> 512	> 512	32

Source: Ref. 104, with permission of Springer-Verlag GmbH & Co. KG.

TABLE 13 Biodegradation of C_{12}-DGA, C_{12}-DGHA, and C_n-DLA Surfactants

Surfactant	TOD (mg/O/mg)[a]	BOD (mg/O/mg)[b]	Biodegradation BOD/TOD (%)
C_{12}-DGA	1.80	0.7	38.8
C_{12}-DGHA	1.74	0.4	22.9
C_{12}-DLA	1.60	0.9	56.2
C_{16}-DLA	1.74	0.6	34.4
C_{18}-DLA	1.70	0.5	29.4
$C_{10}E_4$[c]	2.33	2.07	88.8
$C_{12}E_5$[c]	2.48	2.13	85.8

[a] TOD, theoretical oxygen demand.
[b] BOD, biochemical oxygen demand.
[c] Conventional nonionics.
Source: Ref. 104, with permission of Springer-Verlag GmbH & Co. KG.

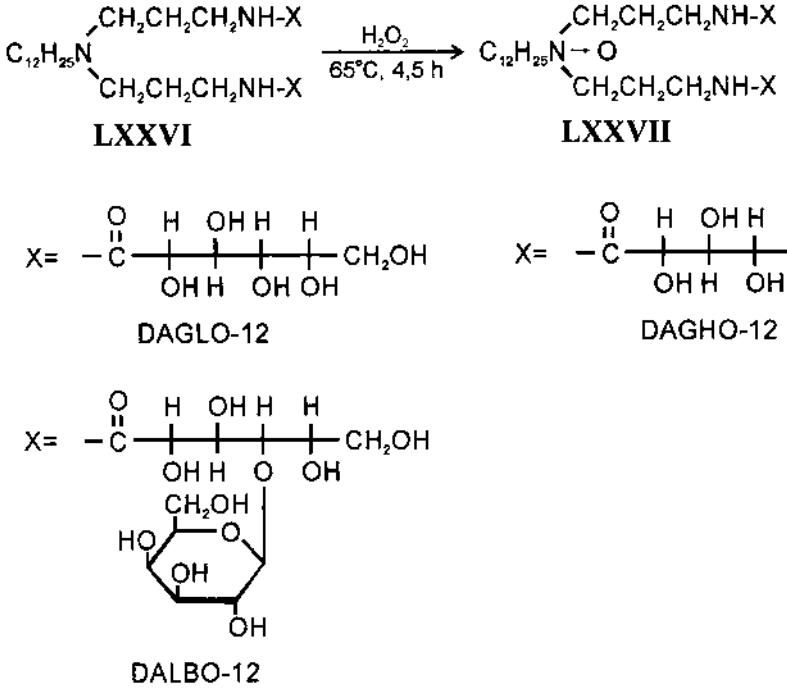

FIG. 21 Synthesis of dicephalic *N*-oxide surfactants (LXXVII). (Adapted from Ref. 152.)

methylaldonamides (see Table 7) and of conventional nonionic surfactants. This may be understandable when taking into account that the synthesized surfactants are in fact tertiary amines whose biodegradation takes place, in general, at lower rates [150]. Nevertheless, they may be classified as inherently biodegradable surfactants.

As the considered surfactants are tertiary amines, this gave the impetus to prepare *N*-oxides from them. Such work was done, and a few derivatives of **LXXVI** surfactants were prepared [151,152]. The reaction route is shown in Fig. 21. High yields of the **LXXVII** *N*-oxides were obtained in an easy to perform reaction, using a 30 wt % aqueous solution of hydrogen peroxide as an oxidant. The *N*-oxides are more water soluble than the respective *N*-dodecyl-*N,N*-bis[(3-aldonamido)propyl]amines. Figure 22 shows the surface tension isotherms of aqueous solutions of the compounds, from which the CMC data were extracted. They were similar to those reported for the starting amines **LXXVI** (Table 11). The *N*-oxides exhibit low foaming ability, but form high-volume and stable foams in mixtures with SDS. From measurements of their environmental properties, it follows that the compounds are practically nontoxic toward selected gram-positive and gram-negative bacteria as well as toward some fungal strains [153]. Their antimicrobial activity was shown to be lower than that

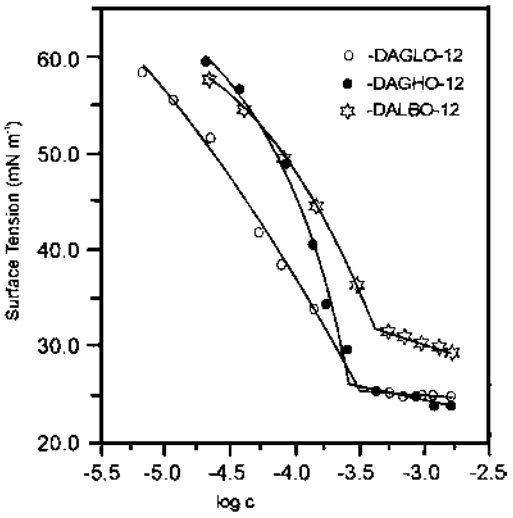

FIG. 22 Plot of equilibrium surface tension vs. the logarithm of molar concentration (log *c*) of dicephalic *N*-oxides. (From Ref. 152 with permission of AOCS Press.)

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of the standard *N*-alkyl-*N*,*N*-bis(2-hydroxyethyl)amine-*N*-oxide and ultimate biodegradation was high (in the range from 86% to 92%), and comparable to that of polyoxyethylene alcohols. Thus, the *N*-oxides may be considered to be readily biodegradable surfactants.

D. Gemini Surfactants

Gemini (or dimeric) surfactants are, according to Zana, "amphiphiles made up of two identical amphiphilic (surface active) moieties connected at the level of, or very close to, the head groups by a spacer group" [154]. Those surfactants are the subject matter of Chapter 12 (by Zana) in this book, which covers this topic comprehensively. Here the aim is to list only saccharide-based geminis that appeared in the literature more recently. Most of them are of nonionic character. Briggs et al. [155] and Eastoe et al. [156,157] synthesized a new group of dialkylbis(gluconyl)amides **LXXVIII**, the structure of which is presented in Fig. 23. Compounds containing a glucose moiety are known under the acronym di-(C_n-Glu) (the systematic name for the compound with $n = 6$ is 7,7-bis[(1,2,3,4,5-pentahydroxyhexanamido)-methyl]-*n*-tridecane). They were assigned to the gemini family by Zana [154]. Thereafter, some series of compounds appeared in which the nitrogen atoms of the head groups are connected by a spacer, as in compounds **LXXIX** [132,158], **LXXX** [159,160], and **LXXXI** [161,162]. Another group represent gemini surfactants in which oxygen atoms, as in **LXXXII** [146], or ester groups, as in **LXXXIII**, **LXXXIV**, **LXXXV** [163–165], Fig. 24, link the two amphiphilic moieties with the spacer. The structures of **LXXXIV** and **LXXXV** differ from each other in that the sugar moiety is linked by a spacer either through the O-2, or O-6 atom of glucose; moreover, the configuration of the butoxy group at the anomeric center is opposite in both compounds. A regioselective, chemoenzymatic synthesis of dimeric and trimeric saccharide-based surfactants was also reported [166].

Recently, Menger and Mbadugha reported on two trehalose gemini series: one nonionic **LXXXVI** and one cationic **LXXXVII**, Fig. 25 [167]. The characteristic feature of the compounds is that the disaccharide trehalose plays the role of a polar spacer separating the amide groups bearing a long-chain acyl moiety as in **LXXXVI**, or the quaternary ammonium ions, as in **LXXXVII**. The catanionic gemini surfactants **LXXXVIII** were prepared by mixing equimolar quantities of *N*-alkyl-1-amino-1-deoxylactitol with dodecyldicarboxylic acid [81]. They show high anti-HIV activity in the monomeric state, and form CMC in diluted and mesophases in concentrated water solutions at room temperature.

Saccharide-based gemini surfactants, like bolaform amphiphiles, exhibit diverse properties depending on the structure of the hydrophilic and

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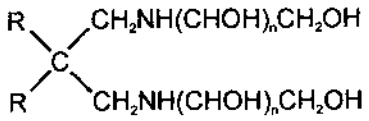
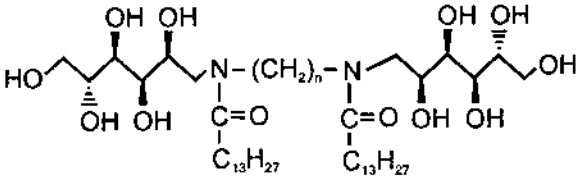
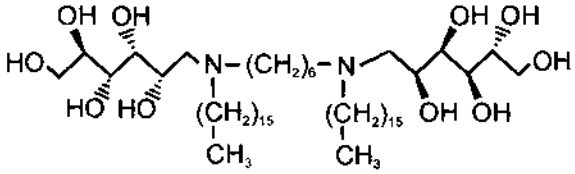


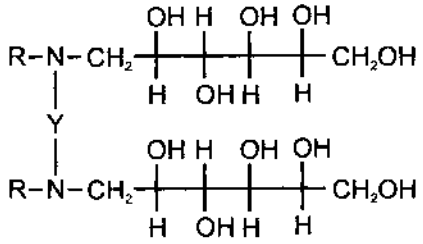
LXXVIII; R = C_mH_{2m+1} n = 3, 4, 5 [Ref. 155-157]



LXXIX; n = 6, 8, 10 [Ref. 132, 158]



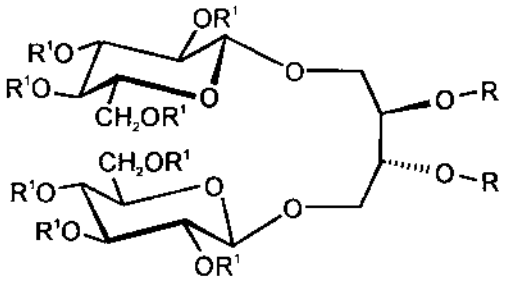
LXXX; [Ref. 159, 160]



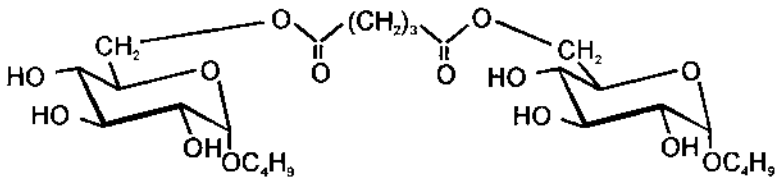
LXXXI; R = $C_nH_{2n+1}CO$, n = 5-19 [Ref. 161, 162]
Y = $-((CH_2)_2O)_2-(CH_2)_2-$; $-(CH_2)_3-O-((CH_2)_2-O)_z-(CH_2)_3-$

FIG. 23 Structures of gemini surfactants with amphiphilic moieties connected by a spacer through nitrogen atoms.

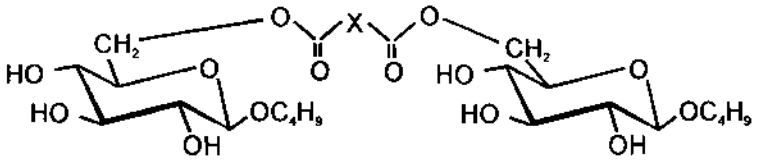
hydrophobic moiety and on the spacer used. Water-soluble compounds form micelles (and other aggregates depending on the concentration), whereas water-insoluble geminis form several different aggregate structures: thread-like micelles, vesicles, tubular structures, monomolecular layers, and bilayer membranes (Chapter 12, this book) [132,154,158]. Owing to the surface properties of water-soluble geminis, they were



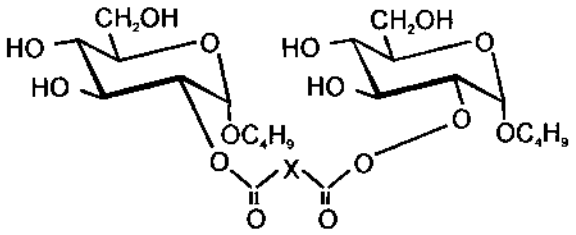
LXXXII; R = $C_{10}H_{21}$, $C_{12}H_{25}$, $C_{14}H_{29}$, $C_{16}H_{33}$ [Ref. 146]



LXXXIII; [Ref. 163]

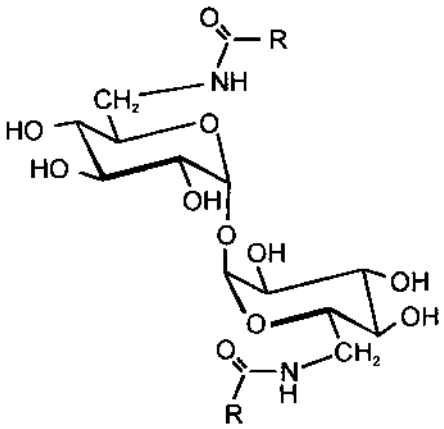


LXXXIV; X = $(CH_2)_{10}$ [Ref. 164]

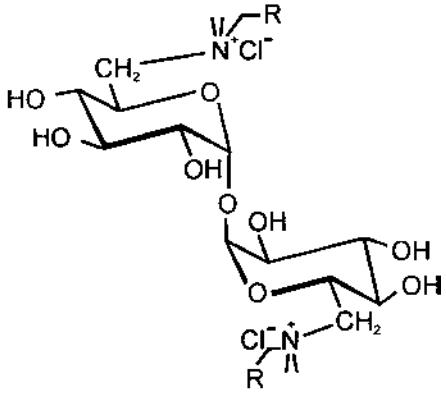


LXXXV; X = CH_2, $(CH_2)_3$, C_6H_4 [Ref. 165]

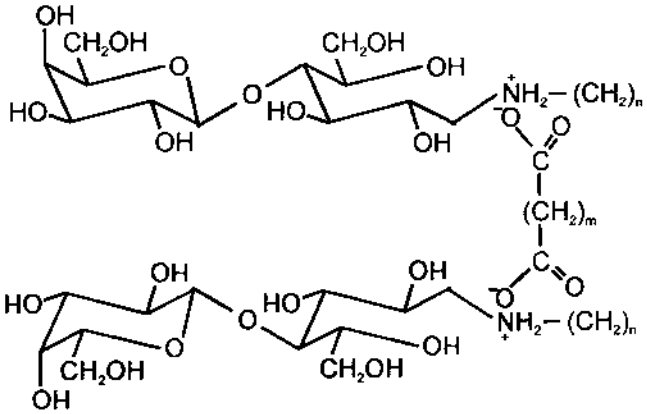
FIG. 24 Structures of gemini surfactants with amphiphilic moieties connected by a spacer through oxygen atoms.



LXXXVI; R = C_nH_{2n+1}; $C_{17}H_{33}$,(cis-9) [Ref. 167]
n = 7, 9, 11, 13, 15, 17



LXXXVII; R = $C_{11}H_{23}$; $C_{13}H_{27}$,
[Ref. 167]



LXXXVIII; n = 7, m = 12 [Ref. 81]
n = 15, m = 12

FIG. 25 Gemini surfactants (LXXVI, LXXVII) with a disaccharide trehalose as a polar spacer and catanionic geminis (LXXXVIII).

proposed for use as components of laundry, cleaning, and personal care products [168–170].

E. Cyclic Acetal-Type Saccharide-Based Surfactants

Cyclic acetal-type surfactants constitute a class of chemodegradable surfactants, also known as cleavable or destructible surfactants (this book, Chapter 10). An increasing interest in such compounds is observed, and several review articles appeared that describe their synthesis, surface properties, and kinetics of hydrolysis [171–176]. Recently, mono- and disaccharides were chosen as polyols, suitable for the synthesis of cyclic acetals exhibiting surface-active properties. As mentioned already in this chapter, Kida et al. [119] reacted long-chain aldehydes with D-glucosamine and obtained three series of surfactants (**LI**, **LII**, and **LIII**, Fig. 14). In an earlier paper, Kida et al. [177] reported on the preparation of sodium trihydroxycarboxylates from long chain aldehydes and 1,5-D-gluconolactone. After an acetalization reaction, the gluconolactone moiety was cleaved with bases to give the **LXXXIX** compounds shown in Fig. 26. Another series of compounds with **XC** structures was obtained by acetalization of 1,5-D-gluconolactone with octanal, 2-octanone, or 2-undecanone, followed by amidation with monoethanolamine, diethanolamine, or morpholine [178]. The described compounds are soluble in water and form micellar solutions; they show relatively high effectiveness of surface tension reduction (γ_{CMC}) taking into account their medium alkyl chain lengths.

A successful attempt was made to use sucrose as a polyol suitable for acetalization reactions with long-chain aldehydes [179]. In order to synthesize **XCI** compounds (Fig. 26), the hydroxyl groups of sucrose were first protected by acetylation and then sucrose reacted with aldehydes. After the reaction was completed, the removal of the *O*-acetyl groups gave the desired surfactants. It was pointed out that the acetal synthesis is regioselective and only 4,6-*O*-monoacetals were formed. Surface tension measurements permitted the determination of the CMC values, which were comparable to those of the respective alkylpolyglucosides. The lowest CMC exhibited compounds with C_{11} and C_{13} carbon atoms in the alkyl chain. Of the disaccharides, trehalose was also used for acetal synthesis [180]. The reaction of 2,2-dimethoxytridecane with trehalose, followed by acetylation, led to a mixture of diastereoisomeric monoacetals, which were separated from small amounts of diacetal by column chromatography. After deacetylation, a mixture of diastereoisomeric monoacetals **XCII** was obtained. Surface tension measurements of aqueous solutions of **XCII** showed that a micellization process occurs.

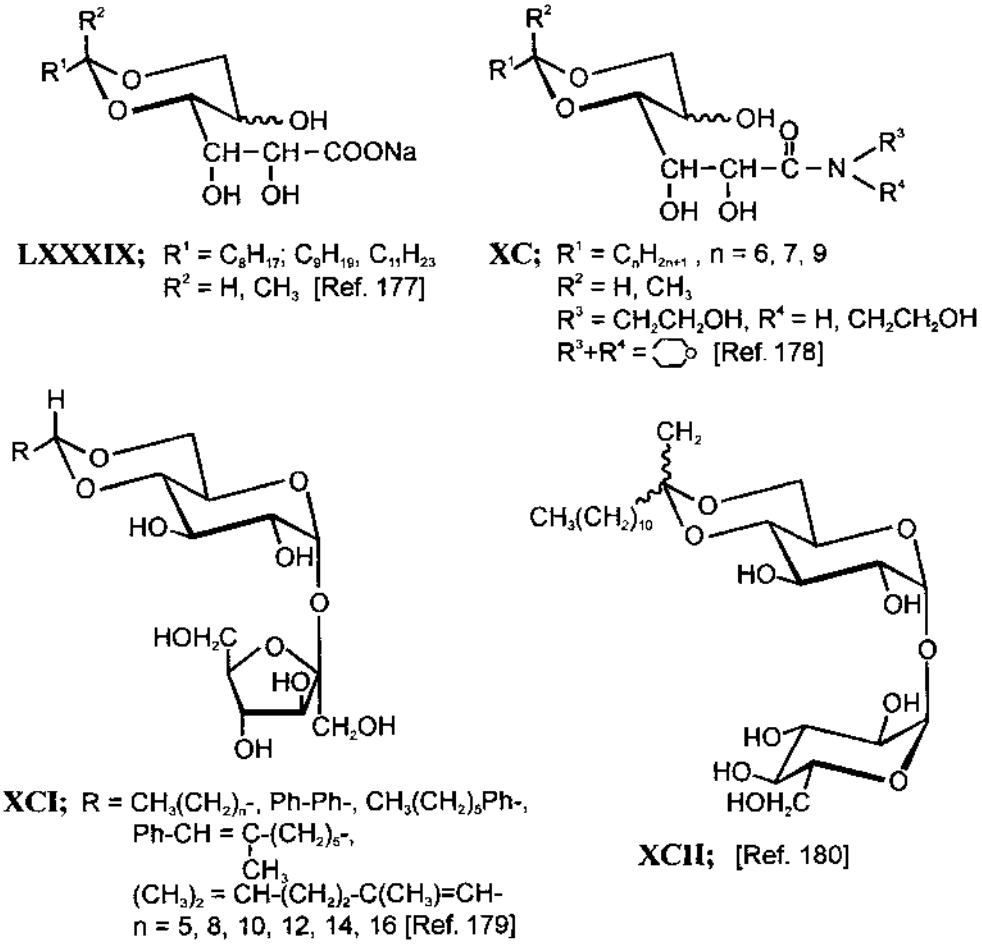


FIG. 26 Acetal-type surfactants prepared from gluconolactone (LXXXIX, XL), sucrose (XCI), and trehalose (XCII).

It is worth mentioning that cyclic acetal-type saccharide-based surfactants are promising not only with respect to their environmental properties but also as concerns their synthesis. Recently, the Mitsubishi Chemical Corporation elaborated and commercialized a process of direct hydrogenation of aliphatic carboxylic acids to the corresponding aldehydes [181,182]. This process allows long-chain aliphatic aldehydes to be obtained from natural fats and oils, and, as a consequence, to produce cyclic acetal-type saccharide surfactants entirely from renewable feedstock.

VI. CONCLUSIONS

There are several reasons why saccharide-based surfactants seem so very attractive. They can be synthesized from renewable, practically nondepleting agricultural and biochemical feedstock. Mono- and polysaccharides are nontoxic substances to human health and benign to the environment, and so are saccharide-based surfactants. Moreover, many of them show interesting biochemical and medicinal properties. Last but not least, carbohydrates allow almost unlimited structural variations because of their molecular diversity. This opens the way to study their structure–surface activity relationships and to design new surfactants with desired performance properties.

The synthesis and manufacture of the considered surfactants fulfill the principles of green chemistry. Industrial processes can be conducted that are significantly less hazardous than when conducted with petrochemical feedstock because in many cases mild conditions, such as ambient temperature and low pressure, can be employed. They generate less waste, water being often the sole by-product. No derivation/blocking of the hydroxyl groups in the used feedstock is needed when amide group–containing surfactant synthesis is performed. Finally, they fulfill the principle of atom economy, meaning that maximal incorporation of the initial substrates into the final products is achieved.

All these advantages of saccharide-based surfactants meet the requirements of environmentally educated consumers for safe, high-performance chemicals and open promising perspectives for the continuous growth of their production and applications.

ACKNOWLEDGMENTS

This study was supported by Wrocław University of Technology (Grant No. 342070). The author expresses many thanks to Professor Ludwik Syper and Professor Kazimiera A. Wilk from Wrocław University of Technology for their fruitful cooperation in research on saccharide-based surfactants, the results of which are included in this chapter. Many thanks are also due to Marek Andrzejewski, M.Sc., for his kind technical assistance in preparing this review.

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Amino Acid–Based Surfactants

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I. INTRODUCTION

The design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances is a highly effective approach to pollution prevention because it applies innovative scientific solutions to real-world environmental situations. Promoting this new approach to pollution prevention through the environmentally conscious design of chemical products and processes is the focus of our research group since the last years.

Surfactants are one of the most representative chemical products, which are consumed in large quantities every day on a worldwide scale. Since it has been known that surface-active compounds can adversely affect the aquatic environment, the biodegradability and biocompatibility of surfactants have become almost as important as their functional performance to the consumer. Because of this, there is a pressing need for developing efficiently surfactants that are biodegradable and biocompatible.

Naturally occurring amino acids have been of particular interest in the field of environmentally friendly surfactants. Surfactant molecules from renewable raw materials that mimic natural lipoamino acids are one of the preferred choices for food, pharmaceutical, and cosmetic applications. Given their natural and simple structure they show low toxicity and quick biodegradation.

The value of amino acids as raw materials for the preparation of surfactants was recognized as soon as they were discovered early in the last century. Initially they were used as preservatives for medical and cosmetic applications [1]. Moreover, they were found to be active against various disease-causing bacteria, tumors, and viruses [2–4]. The combination of polar amino acids/

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peptides (hydrophilic moiety) and nonpolar fatty acids (hydrophobic moiety) for building up the amphiphilic structure has produced molecules with high surface activity [5]. There is a large variety of amino acid/peptide structures. Moreover, the fatty acid chains can vary in their structure, length, and number. These facts explain their wide structural diversity and different physicochemical and biological properties [6,7]. Takehara [8], Infante et al. [9], and Clapés and Infante [10] revised the chemical and enzymatic synthesis of amino acid–based surfactants together with their properties, applications and commercial interest.

Our group has wide experience with the synthesis (chemical, enzymatic, or, usually, a combination of both methodologies) of amino acid–based surfactants obtained from the combination of natural saturated fatty acids, alcohols, and amines with different amino acid head groups through ester and amide linkages. Thus, saturated single-chain (from arginine, leucine, thyptophan), double-chain (from lysine, glutamic and aspartic acids), and gemini (from arginine) surfactants of different ionic character have resulted in products that are highly biodegradable, with low toxicity, ecotoxicity, and irritation effects. Water solubility and self-aggregation properties were directly associated with the chemical structure of the molecule and only cationic lipoamino acids possessed antimicrobial activity. We report here fundamental structure–activity relationship studies of amino acid–based surfactants of single-chain, gemini, and glycerolipidic structure for adsorption, self-assembling, and biological applications. The areas revised include phase behavior, biomembranes, drug delivery systems, antimicrobial activity, biodegradability, and toxicity through the most recent years.

II. SINGLE-CHAIN AMINO ACID–BASED SURFACTANTS

A. Physicochemical Properties

Contrarily to fatty acid salts (i.e., sodium laurate soap), the long-chain N^{α}-acyl amino acids have excellent water solubility (due to the presence of additional CO-NH linkages), quick biodegradability and good lime resistance (i.e., calcium ion tolerance) [11]. The surfactant properties of pure sodium salts of N^{α}-acyl amino acids (anionic surfactants) with different alkyl chains (saturated and unsaturated with 10–18 carbon atoms) and amino acid residues have been described and compared with those of sodium lauryl sulfate (SLS) and sodium laurate [11–14]. The authors showed that the critical micelle concentration (CMC) of the amino acid–based surfactants was lower than that of the SLS but higher than that of sodium laurate. The surface activity increased and the CMC decreased by raising the alkyl chain

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length and the hydrophobicity of the amino acid residue. In addition, the CMC increased with the molecular volume, the weight, the polarity of the amino acid residue, and the degree of unsaturation of the alkyl chain.

Gallot and Diao [5] and Gallot and Hassan [15] have carried out studies on the phase behavior of lipopeptides by X-ray diffraction studies. Dry lipopeptides of Gly, Ala, Sar, Ser, Tyr, Lys, Glu, and derivatives with alkyl chains containing 12–18 carbon atoms were dissolved in water at concentrated conditions. The solutions exhibited microdomains of lamellar, hexagonal, and body-centered cubic mesophases. This polymorphism was found to require a minimum hydrophilicity for the amino acids.

N-Acyl amino acid–based surfactants are chiral amphipathic structures. The effect of chirality on the structure of aggregates and CMC of several *N*-acyl amino acids has also been reported [16,17]. Measurements of circular dicroism of optically active acyl amino acids revealed the existence of chiral aggregates, which are formed because of hydrogen bonding between the surfactant molecules. Racemic homologs showed higher CMC values than that of optical pure compounds [16]. Moreover, the position of the amide bond (CO-NH) influences the behavior of these surfactants in aqueous solutions: shifting the hydrophilic acyl linkage away from the polar carboxylate head group has a destructive effect on the solubilization power of the surfactant [16].

Long-chain N^{α}-acylarginine methyl ester cationic surfactants (series **1** Scheme 1) have been subject of our investigations for a long time [18,19]. We have demonstrated that the morphology of their micelle aggregates and lyotropic phases depends on the hydrophobic moiety, temperature, composition, and electrolyte content in the system. As a result, we have found that compounds of series **1** show a rich and unusual phase behavior [20–22]. For instance, reversed vesicles (dispersion of lamellar liquid crystals in nonpolar media) with biocompatible properties occurred in the lecithin–LAM/squalane system [23]. The PAM homolog was the only compound that showed lamellar lyotropic liquid crystals in the binary water–surfactant system [22]. These properties make them good alternatives for a wide range of applications in the personal care, pharmaceutical, and food sectors, as well as in the design and synthesis of biomaterials. Furthermore, the arginine residue gives antimicrobial activity to the amphipathic molecule, a valuable property for a biocompatible surfactant [24].

A systematic investigation into structure–property relationship of novel long-chain N^{α}-alkylamide series **2** and *O*-alkyl ester series **3** arginine-based surfactants (Scheme 1) was carried out [25]. Compared to series **1**, the new series **2** and **3** (Scheme 1) have two positively charged groups in the hydrophilic moiety, one in the primary amine and a second in the guanidine function.

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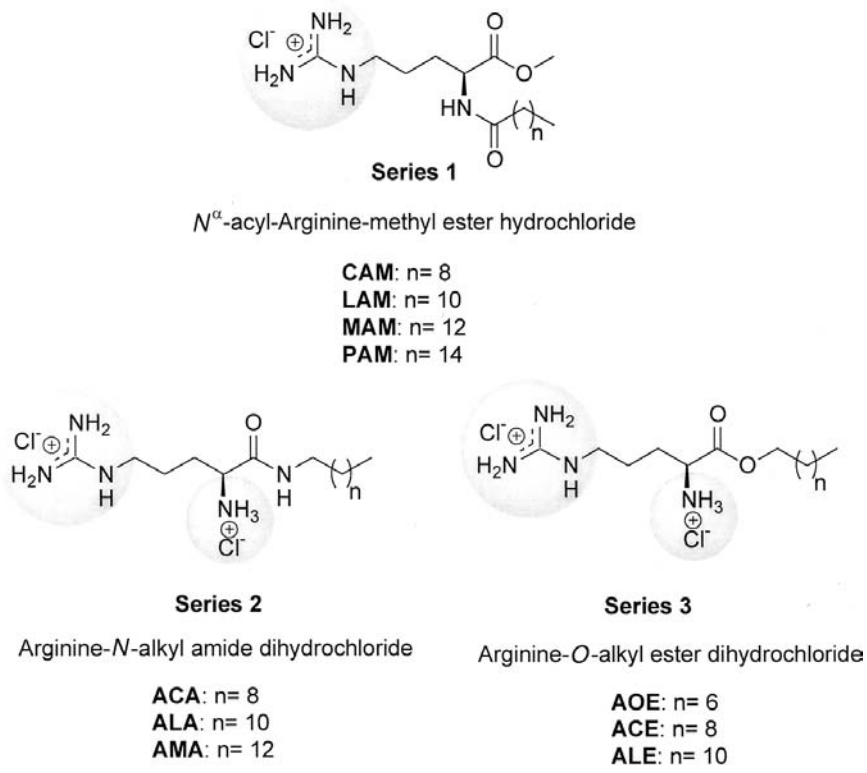

SCHEME 1 Structure of single-chain arginine-based cationic surfactants.

From the surface tension/concentration curves at 25°C (Fig. 1a, b) the saturation adsorption (Γ_m) at the air–water interface and the area per molecule (A_{min}) values were calculated. The smaller the A_{min} the more effective it is its adsorption at the interfaces. We found that the A_{min} values for series **2** and **3** (62–114 × 10^{-2} nm^2, and 96–122 × 10^{-2} nm^2, respectively) were higher than that for series **1** with the same alkyl chain length (67–62 × 10^{-2} nm^2). This result indicates that the new molecules are less packed at the interface than those of series **1**. The two charged groups in series **2** and **3** tend to spread them out on the interface due to an increase in the inter-intra-molecular electrostatic repulsion forces [26].

The application of synthetic acylamino acid/peptide vesicles as drug carriers as well as for the preparation of functional liposomes with lipo-peptide ligands has been examined by several authors in the last years [27,28].

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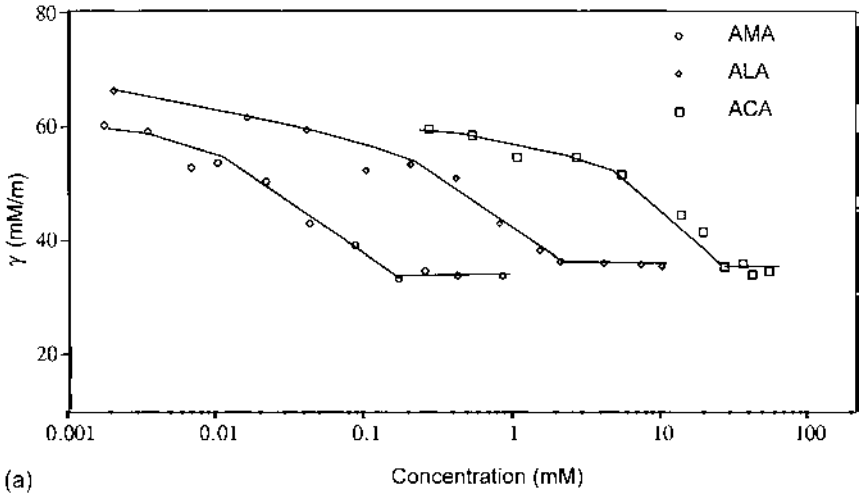
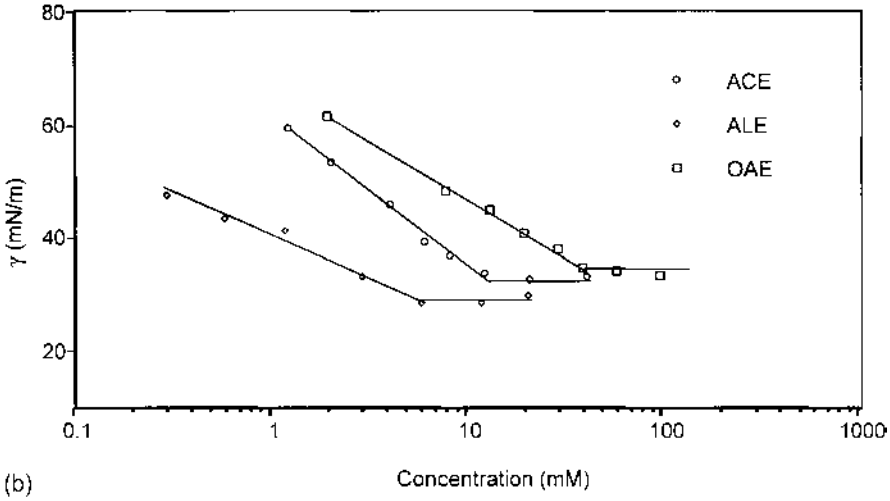


(a)



(b)

FIG. 1 (a) Surface tension (γ) vs. concentration at 25°C of single-chain arginine alkyl amide derivatives. (b) Surface tension (γ) vs. concentration at 25°C of single-chain arginine alkyl ester derivatives.

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Vesicles of long aliphatic chain *N*-acyl amino acids showed encapsulation efficiencies for solutes comparable to that of conventional liposomes of lecithin. Recently, a new technology has emerged for the transfer of foreign DNA into cells. Claffey et al. [29] demonstrated that it is possible to promote the transport of polyionic acidic drugs such as DNA and RNA into cells by forming nontoxic hydrophobic ion-paired complexes between long-chain arginine alkyl esters (Scheme 1 series **3**) with DNA.

Lipoamino acids are also particularly attractive as antiviral agents. Certain acylamino acid derivatives have been found to produce inhibition on influenza neuraminidase [30]. A number of N^{α}-palmitoylated amino acids/peptides have been incorporated into model membranes affecting the transition temperature between the bilayer to hexagonal aggregation, a property associated with antiviral activity. Epand et al. [31] demonstrated the inhibition action of N^{α}-palmitoyltryptophan against the Cantell strain of Sendai virus (parainfluenza type 1).

In the last decade, many efforts have been devoted to the study of the influence of chiral molecules on the enzymatic processes at the membrane surfaces. N^{α}-Acyl-L-and D-amino acid derivatives have been employed as model substances for simulating biomembranes and interfacial processes at biomembrane surfaces [32]. It has been found that chiral monolayers of N^{α}-acylamino acid methyl esters on a pure water surface showed that hydrogen bond formation via NH, COOH, and p-hydroxyphenyl groups (i.e., tyrosine side chains) lead to a pronounced chiral discrimination [33,34]. Homochiral (D–D or L–L interactions) and heterochiral (D–L interaction) discrimination can be observed depending on the area per molecule ($A_{\min}$), which depends on the conformation of the amino acid residue and on the alkyl chain length.

B. Biological Properties

1. Antimicrobial Activity

The use of antimicrobial agents for controlling or preventing infections is of paramount practical importance. Given the adaptability of microorganisms and their tendency to acquire resistance, the development of new antimicrobial agents is a constant challenge. However, antimicrobials carry inherent risks with respect to both environmental and mammalian toxicity [24]. Hence, the development of biodegradable antimicrobials with low toxicity profiles is a challenge for the surface activity investigation.

Nature produces antimicrobial peptides to prevent and eliminate infections [35]. Although these peptides exhibit great structural diversity, the presence of a segment capable of forming amphiphilic α-helix or β-sheet elements, surface activity on the membranes, and the presence of basic

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amino acid residues (Lys and Arg) are all important requirements for their biological activity [36–41].

One important milestone in our research is the design and development of new amino acid–based surfactants with antimicrobial properties, which mimic natural amphiphilic cationic peptides [42,43]. To this end, Lys and Arg derivatives of long-chain N^{α}-acyl, COO-ester, and *N*-alkyl amide have been prepared. In particular, the N^{α}-acylarginine methyl ester derivatives series **1** (Scheme 1) have turned out to be an important class of cationic surface active compounds with a wide bactericidal activity, high biodegradability, and low toxicity profile. We have shown that essential structural factors for their antimicrobial activity include both the length of the fatty residue (akin with their solubility and surface activity) and the presence of the protonated guanidine function [43,44].

The antimicrobial activity of compounds from the three series **1**, **2**, and **3** (Scheme 1) has been evaluated on the basis of their minimal inhibitory concentration (MIC) measured against 15 selected microorganisms [25]. The results obtained are summarized in Table 1. The compounds exhibited a

TABLE 1 Antimicrobial Activity of Single Chain Arginine-Based Surfactants. Minimum Inhibitory Concentration (MIC)[a] Values in μg/mL

Microorganism	ACA	ALA	AMA	AOE	ACE	ALE	CAM	LAM	MAM
Gram-negative									
Alcaligenes faecalis	32	16	32	256	64	32	128	64	128
Bordetella bronchiseptica	16	8	R	64	8	8	128	32	64
Citrobacter freundi	64	32	32	128	64	64	128	64	128
Serratia marcenses	64	32	64	R	128	64		128	
Salmonella typhimurium	64	32	32	256	64	R	R	64	256
Streptococcus faecalis		R				R	128	8	256
Escherichia coli	R	R	R	R	256	R	R	256	256
Klebsiella pneumoniae	32	16	R	256	256	R	256	128	256
Pseudomonas aeruginosa	128	64	64	R	256	128	R	128	256
Arthrobacter oxydans	64	4	4	128	32	64	128	64	256
Gram-positive									
Bacillus cereus	128	32	64	256	32	64	128	64	256
Bacillus pumilus	32	32	256	R	128	R		256	
Staphylococcus aereus	32	16	64	256	16	32	256	32	128
Staphylococcus epidermidis	32	16	16	256		64	128	128	128
Candida albicans	64	16	32	256	128	64	128	64	128

R (resistant): >250.

[a] MIC is defined as the lowest concentration of the antibacterial agent inhibiting the development of visible growth after 24 h of incubation at 37°C.

broad spectrum of activity, with homologs **2** and **3** showing the wider preservation capacity at the lowest MIC values. Probably the presence of two ionic charges in the molecule enhanced the interaction with the polyionic components of the cell surface triggering the membrane-disrupting properties in the cell bacteria. Moreover, the alkylamide derivatives, series **2**, showed higher antimicrobial activity than that of the ester compounds, series **3**. This suggested that the bacteria may hydrolyze the ester more easily than the amide linkage, thus deactivating the compound much faster. It is well known that serine and cysteine proteases cleave ester bonds faster than amide bonds [45].

In all instances, the alkyl chain length of the molecules influenced their bactericidal behavior showing bell-shaped curves with a maximal efficacy at 12 carbon atoms. This can be related to a combination of several physicochemical parameters: surface activity, adsorption, CMC, and solubility. The cooperative interactions of these variables seem to determine the best tendency of the molecules to be adsorbed at the bacterial–water interface and then exert their antimicrobial action by penetration into the cell membrane [46]. It is known that the outer membranes of a number of gram-negative bacteria are impermeable to some amphiphilic compounds [47,48]. It was observed that for the arginine derivatives of series **1**, **2** and **3** the gram-negative bacteria were somewhat more resistant than the gram-positive ones. Interestingly, this fact is indeed beneficial since it facilitates the subsequent biodegradability process of these surfactants.

Xia, et al. [49] studied a series of α-amino-(*N*-acyl)-β-alkoxypropionate surfactants and found a correlation between their CMC and MIC values. However, the antimicrobial effect took place at concentrations of surfactant below the CMC. This suggests, in a good agreement with our results, that the antimicrobial activity is due to the individual molecules and not to the aggregates.

Mahskar et al. [11,50] studied the effect of the structural variation in the aliphatic alkyl chain on the antibacterial activity of *N*-acylleucine derivatives. They found that the presence of a cyclopropane, hydroxyl group, or unsaturation in the acyl chain increased the antibacterial activity. However, the position of these groups has also influence on the activity: for instance shifting the OH function toward the CO-NH linkage resulted in a diminished effect of the antibacterial activity.

2. Aquatic Toxicity and Biodegradability

Many cationic surfactants are acutely toxic against aquatic organisms including algae, fish, molluscs, and others at milligram per liter range or lower. There is evidence that the toxicity of these surfactants is caused by their ability to disrupt the integral membrane. This is due to the adsorption–ionic

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interaction phenomena of the surfactant molecules at the cell membrane–water interface [24] in a similar fashion of the antimicrobial mode of action. Acute toxicity was determined on *Daphnia magna* crustaceous and bioluminescent marine bacteria *Photobacterium phosphoreum* [51]. Values of IC_{50} and EC_{50}, respectively, for series **1**, **2**, and **3** are summarized in Table 2. Arginine-based surfactants of the series **1** and **2** were both somewhat more toxic than that of the series **3** but in all instances less toxic than the conventional cationic surfactant hexadecyl-*N,N,N*-trimethylammonium bromide (HTAB). It has been observed that for all three series the lower the CMC of the surfactant the higher the acute toxicity. Moreover, the lower the CMC values the stronger the surfactant is adsorbed at the interfaces. Thus, the adsorption of the surfactant at the cell membranes of the aquatic organisms depends, to great extent, on hydrophobic interactions.

The biodegradability data for the three series of arginine-based cationic surfactants are shown in Table 2 [51]. All homologs (except AMA) can be considered biodegradable. Furthermore, relationships between biodegradability rate and chemical structure variations were observed. Whereas all **2** homologs are rapidly biodegraded in 7 days, the rate of biodegradation

TABLE 2 Toxicity and Biodegradation Properties of Single Chain Arginine-Based Surfactants

Compound	IC_{50}[a] μg/mL	EC_{50}[b] μg/mL	Ultimate Biodegradation[c] % (days)	L/D
ACA	43.2	1.6	100 (7)	∞ (No irritant)
ALA	6.3	0.7	100 (28)	∞ (No irritant)
AMA	0.8	0.9	7 (28)	∞ (No irritant)
AOE	22.3	5.7	100 (7)	∞ (No irritant)
ACE	4.03	0.6	100 (7)	∞ (No irritant)
ALE	1.3	0.4	100 (7)	∞ (No irritant)
CAM	77	12	—	—
LAM	15	4	90 (14)	—
MAM	—	—	—	—
HTAB	0.3	0.2	—	—

[a] Concentration of the product causing 50% inhibition in *Daphnia Magna* mobility after 24 h.
[b] Concentration of the product causing the 50% reduction in the light emitted by *Photobacterium phosphoreum* after 30 min.
[c] The Modified OECD Screening Test, was applied to determine the ultimate biodegradation as the percentage of Total Organic Carbon (TOC) removal instead of Dissolved Organic Carbon (DOC) removal, after 7, 14, 21, and 28 days.

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for the series **1** depends on the alkyl chain length. Using ester-type bonds to link the hydrophobic and hydrophilic moieties accelerates their biodegradation considerably. This fact has also been described for sugar-based surfactants [52].

3. Toxicity

The haemolytic activity [53] of the arginine-based surfactants of series **1**, **2**, and **3** was studied. The values of HC_{50} (concentration of surfactant that causes 50% of hemolysis of red blood cells from healthy human donors) were higher than 1000 μg/mL regardless of both chemical structure and hydrophobicity of the molecule. Thus, these compounds can be considered nonhemolyzing agents with antimicrobial properties. For comparison's sake, commercial cationic surfactants have HC_{50} ranging from 4 to 15 μg/mL.

The L/D ratio is the relationship between the HC_{50} and the hemoglobin denaturation index (DI). This ratio is used to predict the potential ocular irritation of these surfactants relating to the SDS compound (L/D_{SDS}: 0.44; irritant). According to the results of the L/D ratio first and by the in vivo eye irritation Draize test later (see Table 2), these linear arginine-based surfactants have no irritant effect in the eyes (non–eye irritants, $L/D > 100$).

III. GEMINI AMINO ACID–BASED SURFACTANTS

Gemini surfactants are relatively new surface-active compounds with unique physicochemical properties [54]. They consist of two hydrophobic chains, symmetrical or unsymmetrical, and two hydrophilic polar groups per molecule connected by a spacer chain of different nature (polar, nonpolar, rigid, or flexible). During the last 10 years, the synthesis and structure–activity relationship studies of gemini surfactants have thrived. Significant issues covered by these studies are self-assembled aggregation, micellar characterization, vesicle formation, gels, films, antimicrobial activity, solubilization, anticorrosion application, etc., and, recently, as phase transfer catalysts [55–58]. In the light of these studies, it can be concluded that for most of the properties, gemini surfactants are superior to the corresponding conventional monomeric surfactants. Owing to their extraordinary activity, they are regarded as an outstanding new generation of surfactants with excellent performance.

The gemini-containing cationic [quaternary ammonium salts, called bis (Quats)], anionic (phosphate, sulfate, carboxylate), amphoteric and nonionic (polyether or sugar), polar groups have been a matter of numerous investigations [59]. Only few studies have been done on the physicochemical and biological properties of amino acid–based gemini surfactants [60–62].

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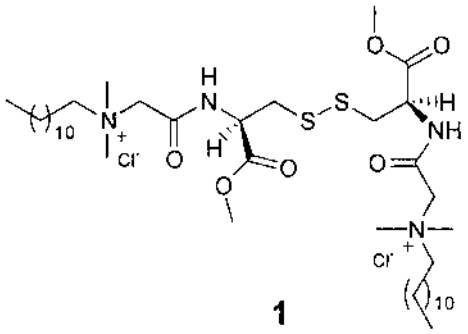
A. Bis(Quats)

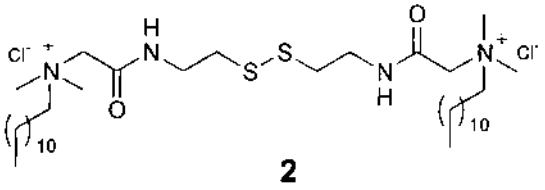
Our group designed and synthesized a new class of amino acid–based gemini surfactants of the bis(Quats) type (quaternary ammonium salt) (Scheme 2). These consist of 2 hydrophobic chains of 12 carbon atoms, 2 quaternary ammonium groups, and 1 spacer chain containing amide and disulfide bonds [63,64]. They derived from the condensation of *N*-dodecyl-*N,N*-dimethylglycine (a well-known "soft" amphoteric surfactant) with amino acid derivatives containing disulfide bonds, i.e., cystine **1** and cystamine **2** (Scheme 2).

These amino acid–based gemini surfactants of the bis(Quats) type were designed for modifying the chemical, physical, and biological properties of substrates such as keratin of the wool fibers. The wool fibers modified by **1** and **2** have three interesting properties: (1) high degree of wetability, of potential use in making perspiration-conducting sportswear fabrics; (2) rapid



1

$N^{\alpha}N^{\alpha}$ bis(N-lauryl-N,N-dimethylglycine) cystine dimethyl ester dihydrochloride



2

N,N'-bis(N-dodecyl-N,N-dimethylglycine)cystamine dihydrochloride

SCHEME 2 Structures of bis(Quats) gemini cationic surfactants.

dyeability at very low temperatures (at 40°C) with both high adsorption and fixation of a reactive dye; and (3) wool fabrics with microbial resistance against gram-positive and gram-negative bacteria, observed by scanning electron microscopy in treated wool fibers for preventing biological damage of textiles [65].

1. Physicochemical Properties

In spite of their high hydrophobic content (2 alkyl chains of 12 carbon atoms), **1** and **2** (Scheme 2) present a water solubility comparable to that of the conventional single-chain cationic mono(Quat) of 12 carbon atoms, *N*-dodecyl-*N,N,N*-trimethylammonium bromide (DTAB) [63]. Interestingly, their CMC values (10^{-5} M) were similar to that of an ideal single-chain surfactant of the DTAB type with 24 carbon atoms in the alkyl chain. This ability to aggregate at an extraordinary low concentration has also been reported for surfactants of the conventional bis(Quats) type [56]. According to Rosen and Tracy [66], it seems likely that in gemini surfactants the inter- or intramolecular hydrophobic interactions are greatly favored probably due to the spacer chain nature. Gemini surfactants are therefore more likely to adsorb at the aqueous solutions surfaces rather than to form micelles.

2. Biological Properties

The antimicrobial activity of **1** and **2** was determined on the basis of their MIC values against 16 selected bacteria. At concentrations in the range from 2 to 16 μg/mL they inhibited the bacterial growth, being more efficient than the corresponding mono(Quats).

The evaluation of their potential toxic effects was carried out by in vivo rabbit dermic irritation Draize test. At a concentration of 0.5% (w/v), these compounds did not irritate the skin. However, as other quaternary ammonium salts, they are very stable molecules with a poor chemical and biological degradability [67].

B. Bis(Args)

An obvious strategy to increase the efficiency of cationic surfactants and reduce their environmental impact and potential toxicity is to build up gemini structures from environmentally friendly single-chain arginine-based surfactants. To this end, our group [68] recently synthesized a new class of gemini cationic surfactants derived from the arginine: the N^{α},N^{ω}-bis(N^{α}-acylarginine)α,ω-alkylendiamides or bis(Args) $C_n(XA)_2$ (Scheme 3). These compounds can be considered dimers of the long-chain N^{α}-acylarginine methyl ester cationic surfactants series **1** (Scheme 1) [69]. They consist of two symmetrical long-chain N^{α}-acyl-L-arginine residues

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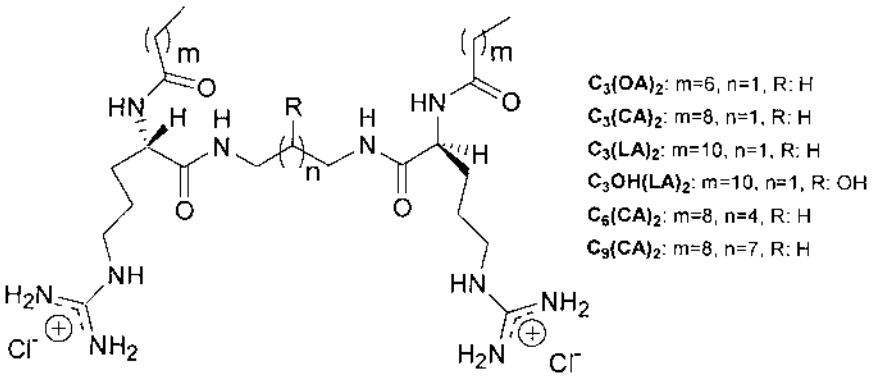

SCHEME 3 Structures of bis(Args) gemini cationic surfactants.

linked by amide bonds through an α,ω-alkylenediamine spacer chain of varying length and chemical nature. This particular alkylenediamine spacer chain was chosen to control the distance between the charged sites of the molecule that modify the inter- and intra-hydrophilic-hydrophobic interactions and consequently the properties of their interfaces [70].

1. Physicochemical Properties

Physicochemical properties of $C_n(LA)_2$ and $C_n(CA)_2$ were investigated and compared with those of the corresponding LAM and CAM single-chain counterpart surfactants [60–62]. Bis(Args) presented lower water solubility than the single-chain surfactants because of their increased hydrophobicity induced by the hydrophobic spacer group. They were found to be more efficient surface-active molecules than the single-chain structures: about three orders of magnitude for the equilibrium surface tension and about 20 times for the tension equilibration [61,62] and foam stability [71]. It was observed that the shorter the spacer chain (i.e., $n = 1$) the faster was the equilibration time and the more stable were the foams formed than that with long spacer chains (i.e., $n = 3$).

2. Biological Properties

Investigation of the biological properties of bis(Args) such as $C_3(LA)_2$, $C_n(CA)_2$ (for $n = 1$, 2, and 3 (Scheme 3), $C_3(OA)_2$, and $C_3OH(LA)_2$ and their correlation with some specific parameters of the surfactants was carried out [60,69,72].

(a) Antimicrobial Activity. Data of MICs (Table 3) [60,69] demonstrated that bis(Args) exhibited a broad spectrum of preservation capacity at concentration of inhibition values in the range of 4–125 μg/mL. The

TABLE 3 Antimicrobial Activity of Gemini Arginine-Based Surfactants. Minimum Inhibitory Concentration (MIC)[a] Values in μg/ml

Microorganism	$C_3(LA)_2$	$C_3(CA)_2$	$C_6(CA)_2$	$C_9(CA)_2$	$C_3(OA)_2$	$C_3OH(LA)_2$	CAM
Gram-negative							
Alcaligenes Faecalis	125	16	8	128	32	62	125
Bordetella Bronquiseptica	125	125	16	128	32	32	16
Citrobacter Freundi	62	16	16	32	32	R	125
Enterobacter Aerogenes	R	32	64	125	62	250	R
Salmonella Typhimurium	16	16	16	32	62	32	250
Streptococus Faecalis	31	8	8	16	32	—	125
Escherichia coli	62	4	64	32	32	16	R
Klebsiella Pneumoniae	R	R	—	32	R	R	250
Pseudomonas Aeruginosa	R	62	64	125	62	125	R
Arthrobacter Oxidans	—	—	—	—	32	8	125
Gram-positive							
Bacillus cereus (mycoides)	R	4	64	125	32	R	125
Bacillus Subtilis	8	2	64	125	32	16	32
Staphylococcus Aureus	31	16	64	64	32	16	32
Staphylococcus Epidermidis	R	31	64	125	32	32	125
Micrococcus Luteus	125	16	8	32	62	16	—
Candida albicans	250	16	16	32	62	16	125

R (resistant): >250.

[a] MIC is defined as the lowest concentration of the antibacterial agent inhibiting the development of visible growth after 24 h of incubation at 37°C.

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dimerization enhanced the antimicrobial activity for the geminis $C_n(CA)_2$ compared with CAM. Moreover, two trends were observed. First, when holding the alkyl chain length constant, the activity decreased with the spacer chain length *n*. Second, when holding the spacer chain length ($n = 1$, Scheme 3) the relationship between the alkyl chain length and the activity was not linear, showing a maximum for the homologs $C_3(CA)_2$. Similar behavior was reported for the single-chain amino acid–based surfactants [25]. Moreover, studies reported by Devinsky et al. [57] about antimicrobial activity of conventional bis(Quats) also showed that the antimicrobial activity had an optimum in the range C_{10}–C_{12}.

(b) Aquatic Toxicity. Values of IC_{50} and EC_{50} for the bis(Args) together with those of LAM and CAM are summarized in Table 4 [72]. Values reported for two series of the conventional mono (Quats) DTAB and HTAB are also indicated. When increasing the hydrophobicity of the molecule, the acute toxicity raised for each series of surfactants in agreement with their CMC values. Thus, $C_n(CA)_2$ were less toxic than the $C_n(LA)_2$ compounds due to their lower hydrophobic character. Interestingly, IC_{50} values for $C_n(CA)_2$ compounds were similar to that of LAM. Furthermore, all of them were one order of magnitude less toxic than the conventional mono(Quats).

(c) Biodegradation. The experimental results showed that the biodegradation rate of single-chain structures such as LAM (90% in 14 days) was

TABLE 4 Aquatic Toxicity of Gemini Arginine-Based Surfactants

Compound	IC_{50}[a] μg/mL	EC_{50}[b] μg/mL
$C_3(LA)_2$	2.1	2.4
$C_3(CA)_2$	16	1.1
$C_6(LA)_2$	2.4	3.0
$C_6(CA)_2$	15	1.3
$C_9(LA)_2$	2.2	13
$C_9(CA)_2$	5.5	1.1
LAM	15	12
CAM	77	4
DTAB	0.38	0.24
HTBA	0.13	0.63

[a] Concentration of the product causing 50% inhibition in *Daphnia Magna* mobility after 24 h.

[b] Concentration of the product causing the 50% reduction in the light emitted by *Photobacterium phosphoreum* after 30 min.

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higher than that of the bis(Args) (50–90% in 14 days). This was probably due to the complexity and hydrophobicity of the gemini compared with the single-chain structures. In agreement with data available on biodegradability of mono- and bis(Quats) [73], the biodegradation rate of bis(Args) decreased when both the spacer chain and the alkyl chain length increased. Hence, the higher the hydrophobicity of the surfactants the poorer was their biodegradation rate.

(d) Toxicity. The hemolysis test showed again that the highest HC_{50} values were obtained for the compounds with the highest hydrophobic character, namely, those with the longest alkyl and spacer chain lengths. Values for $C_n(CA)_2$ surfactants were between 8.7 and 110 μg/mL. There is considerable difference between the HC_{50} of these new gemini surfactants and those bearing a quaternary ammonium group at the polar head [46]. Mono(Quats) have HC_{50} values between 0.05 and 0.1 μg/mL.

IV. AMINO ACID GLYCERIDE CONJUGATES

Amino acid glyceride conjugates constitute a novel class of lipoamino acids, which can be considered analogs of partial glycerides and phospholipids (Fig. 2). They consist of one or two aliphatic chains and one polar head, the amino acid, linked together through a glycerol moiety. The resulting structures resemble the acid esters of monoglycerides such as lactic, citric, tartaric, and succinic glyceride esters widely used as food emulsifiers [74].

The physicochemical and biological properties of amino acid glyceride conjugates have not yet been extensively explored. However, our group has carried out an intense research activity on their synthesis and evaluation of physicochemical and biological properties on these new compounds in the last few years [75–79]. These novel compounds combine the advantages of both partial glycerides and lipoamino acids. For instance, we have observed that they possess antimicrobial activity, like long-chain N^{α}-acyl amino acid derivatives, and form lamellar phases and vesicles, characteristic of partial glycerides and phospholipids [25]. Moreover, the possibility of introducing different ionic groups (i.e., by selecting the appropriate amino acid) increases the swelling properties by promoting the electric repulsion between charged group bilayers [80,81]. Furthermore, mono- and diacylglyceride amino acid conjugates may lead to a number of lipid analogs of potential therapeutic interest and as adjuvants for drug and gene delivery (i.e., transfection) [29,82–86]. For all these reasons, they constitute a promising family of compounds with a great potential interest in pharmaceutical and food formulations.

Novel tryptophan-based surfactants of glycerol ether type with different alkyl chain length (C_9–C_{16}) were synthesized at lab scale (79) (**1**–**8**, Scheme 4).

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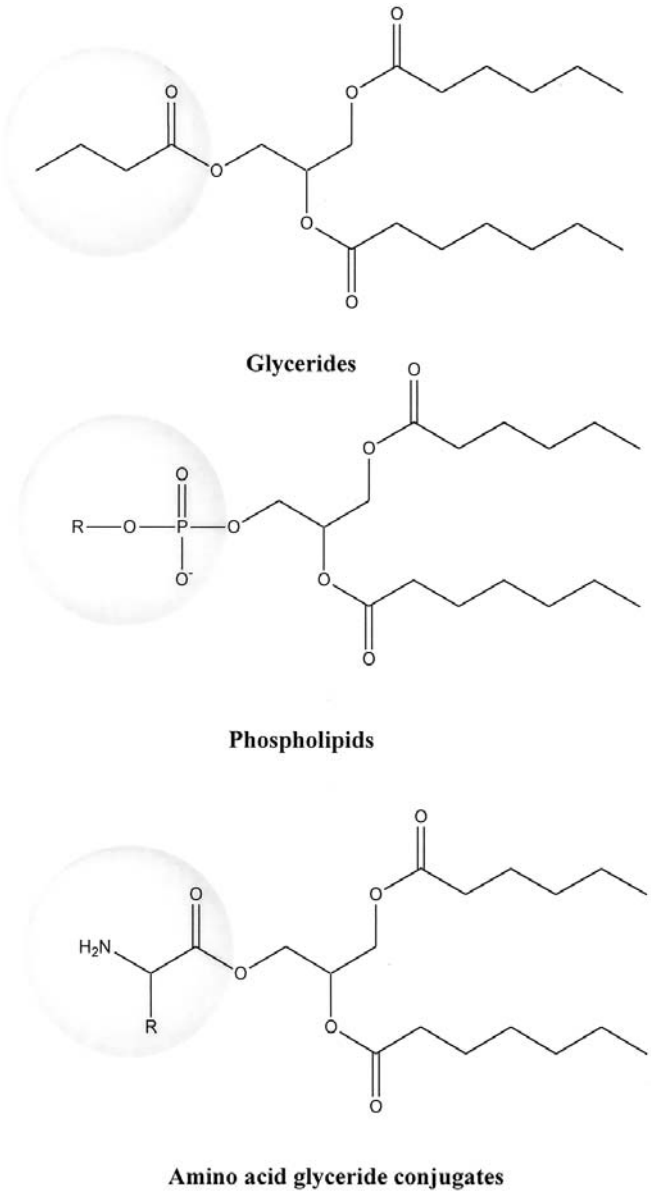

FIG. 2 Structures of amino acid glyceride conjugates that can be considered analogs of partial glycerides and phospholipids.

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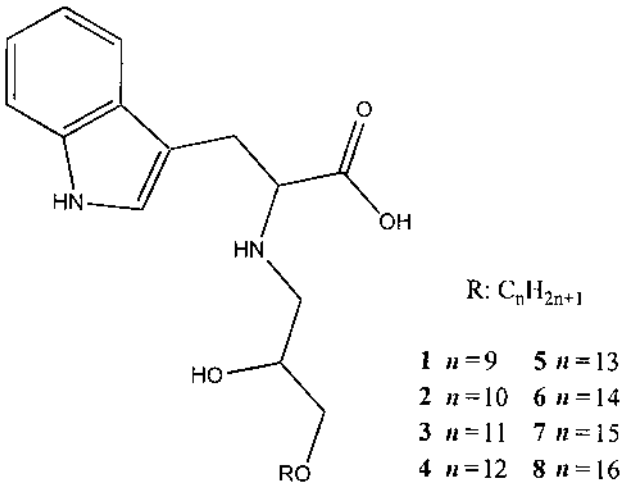

SCHEME 4 Structures of tryptophan-based surfactants of glycerol ether type.

TABLE 5 Surface-Active Parameters of Tryptophan-Based Surfactants of Glycerol Ether Type in Aqueous Solution at pH 12 at 25

Compound	CMC[a] ($\times 10^4$ mol/dm^{-3})	pC_{20}[b]
1	5	4.6
2	3.6	4.7
3	0.65	5.2
4	0.38	5.5
5	0.22	6.0
6	0.20	6.1
7	0.17	6.3
8	0.12	6.3

[a] CMC, critical micelle concentration.
[b] Negative log of the surfactant molar concentration required to reduce the surface tension of the solvent by 20 mN/m.

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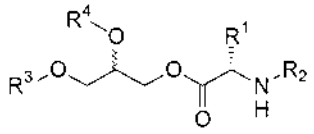
Tryptophan was conjugated with glycerol from its α-amino group, through a C-N bond yielding an amphoteric-type surfactant.

The CMC values of compounds **1**–**8** show a fall with the rise in the number of methylene groups in the alkyl chain, as would be expected from the increase in the hydrophobic character of the molecule. The CMC values are around 10^{-5} M. As in a conventional series of homologs with a different alkyl chain length, the efficiency of adsorption, pC_{20}, increases with the number of carbon atoms (Table 5).

In general, the CMC values of these novel surfactants are lower than those of other carboxylate-containing anionic surfactants with the same hydrocarbon chain, i.e., soaps and lysolecithins [87–89]. However, the low CMC values in alkaline media obtained for compounds could be compared with those of some cleavable carboxylate-containing surfactants [90–92] which



1a R^1 = -$CH_2CH_2CH_2NHC(NH_2)_2^+Cl^-$, R^2 = H, R^3 = $CH_3(CH_2)_nCO$-; n=8, 10, 12 and 14, R^4 = H

1b R^1 = -$CH_2CH_2CH_2NHC(NH_2)_2^+Cl^-$, R^2 = H, R^3 = R^4 = $CH_3(CH_2)_nCO$-; n=8, 10, 12 and 14

2a R^1 = -$CH_2CH_2CH_2NHC(NH_2)_2^+Cl^-$, R^2 = CH_3CO-, R^3 = $CH_3(CH_2)_nCO$-; n=8, 10, 12 and 14, R^4 = H

2b R^1 = -$CH_2CH_2CH_2NHC(NH_2)_2^+Cl^-$, R^2 = CH_3CO-, R^3 = R^4 = $CH_3(CH_2)_nCO$-; n=8, 10, 12 and 14

3a R^1 = -CH_2COOH, R^2 = CH_3CO-, R^3 = $CH_3(CH_2)_{10}CO$-, R^4 = H

3b R^1 = -CH_2COOH, R^2 = CH_3CO-, R^3 = R^4 = $CH_3(CH_2)_{10}CO$-

4a R^1 = -CH_2CH_2COOH, R^2 = CH_3CO-, R^3 = $CH_3(CH_2)_{10}CO$-, R^4 = H

4b R^1 = -CH_2CH_2COOH, R^2 = CH_3CO-, R^3 = R^4 = $CH_3(CH_2)_{10}CO$-

5a R^1 = -CH_2CONH_2, R^2 = CH_3CO-, R^3 = $CH_3(CH_2)_{10}CO$-, R^4 = H

5b R^1 = -CH_2CONH_2, R^2 = CH_3CO-, R^3 = R^4 = $CH_3(CH_2)_{10}CO$-

6a R^1 = -$CH_2CH_2CONH_2$, R^2 = CH_3CO-, R^3 = $CH_3(CH_2)_{10}CO$-, R^4 = H

6b R^1 = -$CH_2CH_2CONH_2$, R^2 = CH_3CO-, R^3 = R^4 = $CH_3(CH_2)_{10}CO$-

7a R^1 = -$CH_2C_6H_5OH$, R^2 = CH_3CO-, R^3 = $CH_3(CH_2)_{10}CO$-, R^4 = H

7b R^1 = -$CH_2C_6H_5OH$, R^2 = CH_3CO-, R^3 = R^4 = $CH_3(CH_2)_{10}CO$-

SCHEME 5 Structures of amino acid glyceride conjugates.

show CMC values in alkaline water solution at about pH 12. Similarly, the surface activities of these compounds are closely related to their water solubility properties and thus can be controlled by the pH. These compounds can be considered cleavable surfactants since they become a non-surface-active species at pH 3.

A novel family of amino acid glyceride conjugates (Scheme 5) with basic, acidic, and nonionic amino acids such as arginine **1** and **2**, aspartic acid **3**, glutamic acid **4**, asparagine **5**, glutamine **6** and tyrosine **7** were chemically and enzymatically prepared [75–78]. They have one hydrophobic tail (compounds type **a**) or two hydrophobic tails (compounds type **b**) of identical fatty acid and an amino acid moiety both attached to the glycerol backbone through ester bonds. These structures resemble the lecithins in which the polar phospho derivative group was substituted by an amino acid residue. These new compounds can be classified as multifunctional surfactants with a self-aggregation behavior comparable to that of short-chain lecithins. We have also found that they possess antimicrobial activity, which is a function of the amino acid residue. For instance, those having arginine as polar group showed similar antimicrobial activity to that of the conventional cationic surfactants and are as harmless as amphoteric betaines. Further investigation of their properties is currently in progress.

V. CONCLUSIONS AND FUTURE TRENDS

In summary, amino acid–based surfactants constitute a class of bio-based surfactants with excellent surface properties, wide biological activity, low potential toxicity, and low environmental impact. Moreover, they can be prepared efficiently by clean biotechnologies such as enzymatic catalysis. All of these features make them an outstanding alternative to conventional specialty surfactants. Amino acid mono- and diglyceride conjugates may become the next generation of bio-based specialty surfactants. The incorporation of an amino acid residue to simple mono- and diglycerides may lead to amphipathic structures with new physicochemical proprieties and biological activities. Moreover, the enzyme technology can be applied to the preparation of these molecules. Hence, these new generations of amino acid–based surfactants will contribute to meet the increasing demand of pharmaceutical and food industries for multifunctional ingredients based on natural products.

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6

Surfactants Based on Sterols and Other Alicyclic Compounds

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I. INTRODUCTION

For centuries man has used natural products as raw materials in the manufacture of soaps and detergents. The natural sources were mainly fats and oils; however, more expensive sources, such as naturally occurring detergents (saponins) from plants, were also used. The development of synthetic surfactants from petroleum products has led to a significant improvement in the versatility and quality of surfactants and detergents. However, this development soon led to environmental drawbacks. The first example of this was probably the adverse effects that tetrapropylene benzene sulfonates had in river waters in the 1950s. This problem was soon resolved by the development of linear alkylbenzenesulfonates [1]. In recent years concerns have grown regarding nonylphenol as a raw material in surfactants. Originally these concerns were about the toxicity to aquatic life and poor biodegradability of some derivatives; more recently, nonylphenol has also been under discussion for its potential action as an estrogenic compound, which may cause damage to animals' reproductive systems.

This increasing concern about a very versatile surfactant raw material has called for a replacement to be found from naturally occurring substances. The combination of an aromatic ring and a short and bulky hydrophobic group is almost impossible to find among common natural products. Nevertheless, sterols and other alicyclic compounds can offer a molecular structure that in some respects resembles the structure of nonylphenol. The ring structures, sometimes with several unsaturated bonds, together with a branched hydrocarbon tail, appear in both sterols and rosin acids. This chapter deals with

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nonionic derivatives of several types of sterol compounds, and also contains a brief overview of other alicyclic compounds from nature that have been used as surfactants.

II. STEROLS AND OTHER NATURAL ALICYCLIC COMPOUNDS

Sterols are synthesized in both plants and animals. Sterols and their derivatives, such as hormones and vitamin D_2, perform various important functions in living organisms depending on their structure. Consequently, sterol products can be derived from several sources. Plant sterols, or phytosterols, are obtained from the unsaponifiable fraction of vegetable oils and fats. The amount of sterol, as well as its composition including fraction of unsaponifiable portion of the respective oil and fats, depends on the raw materials and is characteristic of the particular base material (Table 1). Soya oil represents a widely available source for commercial production of phytosterols. The unsaponifiable portion is separated into a sterol fraction and a tocopherol fraction. A small amount of tocopherol is usually left in the sterol fraction (approximately 4%), which acts as a natural antioxidant in the final product [2]. Plant sterols are also obtained from the black-liquor soap skimming in commercial pulping of wood. The neutral fraction of this so-called tall oil is relatively rich in sterols (approximately 32% of the neutral fraction [3]), and the sterol

TABLE 1 Phytosterol Quantities in Different Vegetable Raw Materials

Oil source	Total sterol content (g/ kg)	Unsaponifiable part (%)	Sterol content of the unsaponifiables (%)
Corn oil	9.0	1.3	69.2
Rapeseed oil	8.4	0.9	93.3
Sesame oil	5.9	1.4	42.2
Sunflower oil	4.5	0.7	64.3
Linseed oil	4.0	0.7	57.1
Soybean oil	3.7	0.6	61.6
Cocoa butter	2.5	0.4	62.5
Coconut oil	2.0	0.4	50.0
Olive oil	1.6	0.6–0.8	20–26
Palm oil	0.6	0.4	15.0

Source: Adapted from Ref. 2.

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portion is isolated through extraction and crystallization on a commercial basis [4].

Sterols from animal sources are dominated by cholesterol, which is obtained from the alcohols in wool wax (lanolin) [5]. This alcohol contains numerous products of which sterols compose approximately 80%; the rest made up of various aliphatic alcohols. The lanolin alcohols are used in many different applications, including raw materials for surfactants. However, it appears that in only a few cases the cholesterol is isolated and used for surfactant production.

It is not surprising that the composition of sterols varies depending on the source from which they have been derived. Table 2 shows the composition of sterols from soy oil, tall oil, and lanolin alcohol. Despite the very different sources the molecular structure is fairly similar in all types of sterols. Figure 1 depicts the structure of the most commonly found sterols; it should be noted that the most abundant sterols in animal sources (cholesterol) and vegetable sources (sitosterol) differ only by an ethyl group in the hydrocarbon tail of the sterol.

The rosin acid, or abietic acid, is obtained as a side product in the digestion of wood in the pulp and paper industry. This product is found together with fatty acids in the saponifiable part of the tall oil. Rosin derivatives are widely used as dispersions in the production of adhesives but have also, to a smaller extent, been used as surfactants, in the form of polyoxyethylene or soap derivatives. Abietic acid is easily oxidized to dehydroabietic acid; yielding a structure containing both an aromatic ring and a saturated ring. Figure 1 also shows the structure of abietic acid and dehydroabietic acid.

TABLE 2 Major Components (%) of the Sterol Fraction from Soya Oil, Tall Oil, and Lanolin Alcohols

Sterol	Soya oil [2]	Tall oil [4]	Lanolin alcohols [5]
β-Sitosterol	58.1	65	
α-Sitosterol	0	25	
Campesterol	29.8	7	
Stigmasterol	4.5	0	
Cholesterol			56
Lanosterol			22
Dihydrolanosterol			15

Source: Computed based on data from Refs. 2, 4, and 5.

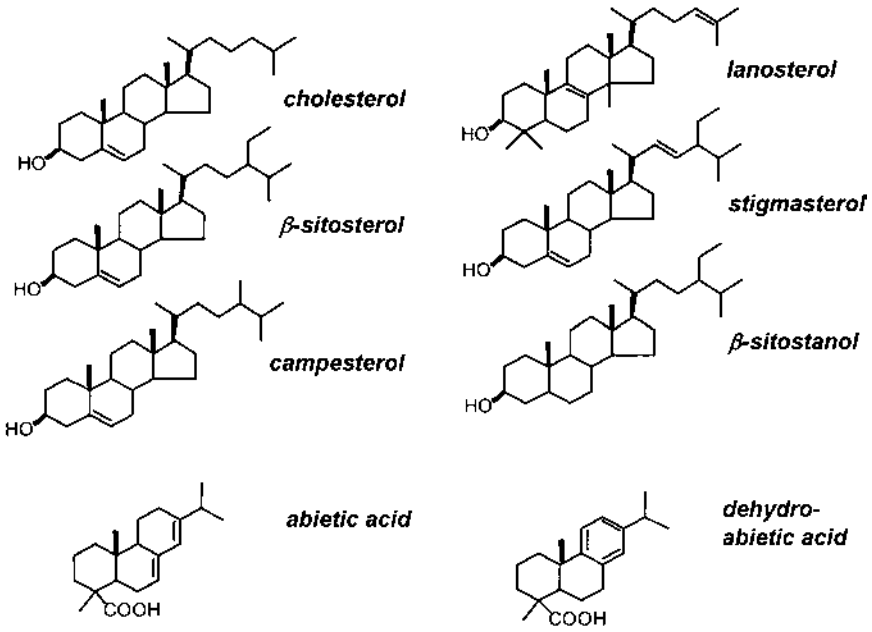

FIG. 1 Molecular structure of different sterols and alicyclic compounds commonly found in plants and animal sources.

III. POLYOXYETHYLENE STEROLS

A. Available Material

Synthesis of polyoxyethylene sterol was first reported by Scotney and Truter [6] in 1971. They simply mixed cholesterol and the appropriate amount of ethylene oxide in a sealed vial during 4 months. Later workers have applied more sophisticated methods to synthesize better defined products. Khachadurian et al. [7] synthesized both polyoxyethylene and methoxypolyoxyethylene derivatives of cholesterol. The former reaction was carried out in dichloromethane using boron trifluoride as catalyst. Derivatives with a methoxy terminal were prepared by condensing methoxypoly(oxyethylene)methanesulfonate with cholesterol in xylene. Commercially available products are produced by the reaction of sterol with ethylene oxide, resulting in a product with a distribution in the number of ethylene oxide (EO) units in the hydrophilic group. Meissner et al. also described the synthesis of sterol sulfate and sulfonate with oxyethylene spacers [8]. The synthesis of sterol surfactants has been covered in a review by Folmer [9]. There are only a few producers of polyoxyethylene

sterols of higher purity. The names of these together with the available product range are given in Table 3.

B. Surface Activity

There has been relatively few reports regarding polyoxyethylene sterols, as compared with other polyoxyethylene surfactants. However, in recent years there has been an increase in the number of published reports concerning the surface activity and solubility of polyoxyethylene derivatives of different sterols.

The first report regarding characterization of polyoxyethylene derivatives concerned the sterol fraction in lanolin alcohols. Scotney and Turner [6] prepared derivatives of cholesterol and lanostanol (dihydrolanosterol) in order to compare these surfactants with the ethoxylated alcohols from wool wax. Their study of the surface chemical properties was limited only to the variation in the interfacial tension between water and benzene at different surfactant concentrations. They found that the properties of the ethoxylated wool wax alcohols were inferior to that of the pure cholesterol derivative with the same average number of ethylene oxide groups. The inferior behavior was accounted for by the heterogeneity of the starting materials, i.e., the presence of large amounts of aliphatic alcohols with lower molecular weight, and the properties could be enhanced by an improved fractionation of the starting material prior to ethoxylation. In 1976 a Russian group [10] reported a systematic study of the critical micelle concentration (CMC) for a series of polyoxyethylenated alcohols from wool wax. They found that the CMC initially decreased (to a minimum of 0.2% at 15 EO units) and then increased as the hydrophilic portion of the surfactant increased.

TABLE 3 Producers of Polyoxyethylene Sterols

Producer	Raw material	Range of ethoxylation	Product name
Cognis (Europe)	Rapeseed, phytosterol	5, 10	Generol
Cognis (USA)	Soya phytosterol	5, 10, 16, 25	Generol
Nikkol	Phytosterol, cholestanol, phytostanol	5, 10, 20, 30	BPS
		30	BPSH
		25	BPSH
UPM Kymmene Kaukas	Wood sitosterol	5 to 50	Tall oil sterol ethoxylates

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In 1984, Miyajima and coworkers [11] studied the aggregation behavior of three different sterol derivatives; cholesterol with an average number of 25 and 30 oxyethylene units (Chl-EO25 and Chl-EO30) and hydrogenated cholesterol with 30 oxyethylene units (DHC-EO30). They determined the CMC and micellar weight of the surfactants by means of measurements of surface tension and osmotic pressure in aqueous solutions. The surfactants exhibited a cooperative aggregation behavior similar to that of normal polyoxyethylene surfactants, and it was possible to determine CMC and thermodynamic parameters such as ΔG, ΔH, and ΔS of micellization (Table 4). The CMC values as well as the thermodynamic parameters were similar to what had been reported for other nonionic surfactants. The authors concluded that the cholesteryl group has a similar hydrophobic character to the dodecyl or nonylphenyl groups. Furthermore, they observed that despite the similarities in the geometrical form of the lipophilic group (flat and bulky), the cholesterol ethers behaved very differently to cholic acids and their conjugates. These compounds form micelles with small aggregation numbers in much higher concentrations.

Funasaki and coworkers [12] studied intermolecular interactions in mixed micelle formation of polyoxyethylene (15) dihydrocholesterol (DHC-EO15) with polyoxyethylene (7) dodecanol (C12EO7), by means of volumetric methods. The objective of their study was to investigate the condensing effect of cholesterol on phospholipid monolayers and the membrane-thickening action of cholesterol on lecithin bilayers. The volume

TABLE 4 Thermodynamic Parameters of Polyoxyethylene (30) Cholesterol; CMC Values, Micellar Weight, and Aggregation Numbers of Polyoxyethylene Cholesteryl Ethers in Water

Temp. (°C)	CMC (M)	ΔG^{o}_{m} (J/mol)	Δh^{o}_{m} (J/mol)	Δs^{o}_{m} (J/K mol)	Γ (mol/cm^2)	A (nm^2/molecule)
15	1.17×10^{-4}	−21.7	14.6	126	1.8×10^{-10}	0.92
25	1.12×10^{-4}	−22.6	15.7	128	1.7×10^{-10}	1.00
35	0.79×10^{-4}	−22.2	16.7	133	1.2×10^{-10}	1.40

Surfactant	CMC[a] (M)	Micellar weight[b]	Aggregation number[b]
Chl-EO30	1.12×10^{-4}	1.5×10^{5}	90
Chl-EO25	1.15×10^{-4}	—	—
DHC-EO30	0.79×10^{-4}	8.1×10^{5}	470

[a] at 25°C.
[b] at 23°C.
Source: Adapted from Ref. 11.

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change on mixing micelles (ΔV_m) were determined for three systems; sodium dodecyl sulfate (SDS)–C12EO7, dodecyl trimethylammonium bromide (DTAB)–C12EO7, and DHC-EO15–C12EO7. Only the ΔV_m values for the mixed DHC-EO15–C12EO7 system was found to be positive, which suggests that the surfactant membrane generally thickens more than expected because of shrinkage of the membrane surface area when membrane from two amphiphilic compounds with steroidal and linear alkyl groups are mixed. The authors demonstrated, using solubility parameter theory, that the positive ΔV_m values stem from the interaction between the two surfactants in the micelle interface. In 1989, Söderlund et al. [13] reported the phase behavior and surface activity of a number of polyoxyethylene derivatives of cholesterol. The shape of the surface tension vs. concentration curves revealed a reasonably sharp discontinuity for the shorter homologs that could be interpreted as a CMC. However, the authors decided that it was not evident that the aggregation process was of a cooperative nature and refrained from giving values of the CMC.

The properties of phytosterol derivatives from soy (Generol 122) have been extensively reported by coworkers at former Henkel, Germany. These reports mainly concern practical properties like melting point, PIT, hydrophilic–lipophilic balance (HLB), etc., and not many details regarding their physicochemical properties [2,14]. Lundmark et al. [15] reported the CMC values of two of these surfactants, polyoxyethylene (16) and polyoxyethylene (25) phytosterol (Generol 122E16 and Generol 122E25), to be 0.22% and 0.46%, respectively, which is equal to approximately 2 mM and 3 mM.

The aggregation behavior of these surfactants appears to be unusual and requires a deeper analysis. A comparison of the CMC values reported for different polyoxyethylene sterols and polyoxyethylene octylphenols, which have lipophilicities similar to that of cholesterol, is shown in Fig. 2. As the hydrophilicity of the surfactant increases, the trend in the CMC values is quite opposite; the CMC values for sterol surfactants are reduced when the number of oxyethylene units is increased, which is contrary to that found for other polyoxyethylene surfactants. The observation of lanolin alcohols can be viewed as an intermediate behavior. At lower numbers of oxyethylene units the CMC trend follows the behavior of sterols, whereas at a higher degree of ethoxylation the behavior becomes dominated by the ethoxylated alcohols. These comprise only about 20% of the weight but approximately 40% of the molar composition.

In addition, the adsorption of sterol surfactant to the air–water interface appears to be unusually slow. Folmer et al. examined the dynamics of oxyethylene phytosterols in the micellar region [16,17]. The surface tension was measured as a function of time, and even after 3 h a stable value was not obtained (Fig. 3). The slow dynamics at the surface, compared with smaller

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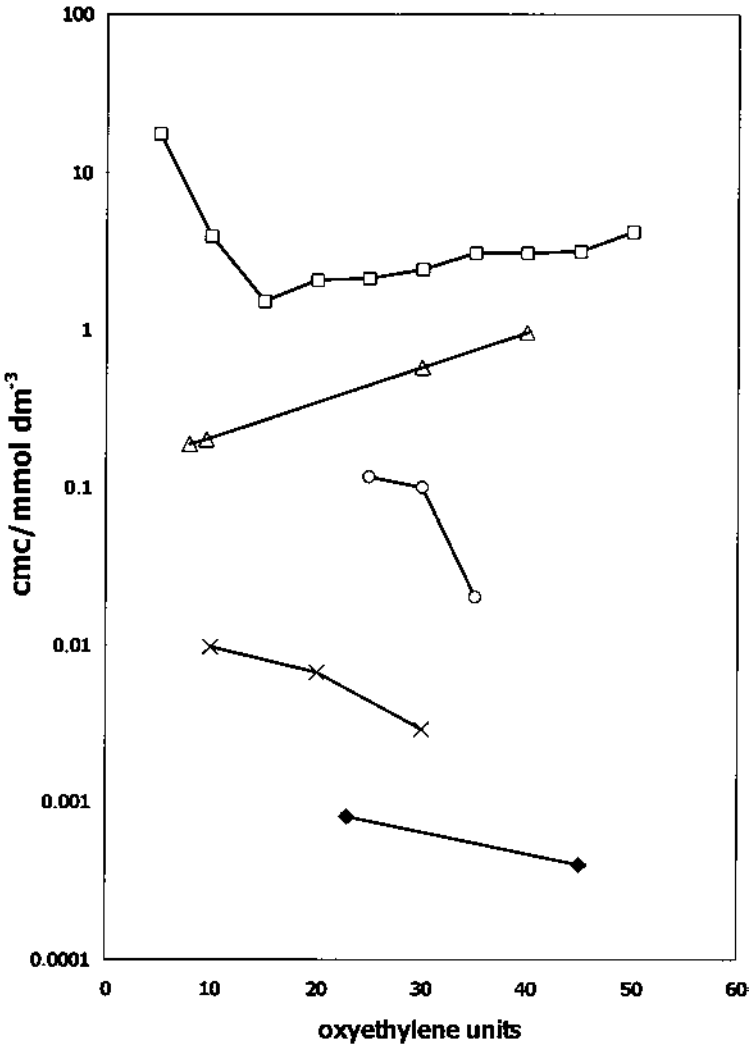

FIG. 2 Critical micelle concentration (CMC) of polyoxyethylene derivatives of (–○–) cholesterols (from [11,13]), (□) lanolin alcohols [10], (×) phytosterol [16], (♦) cholesteryl carbonate [24], and (△) octylphenol [21]. Increasing the length of the polyoxyethylene chain causes a decrease in the CMC for the sterol derivatives, initially causes a decrease in the CMC (minimum at 15 oxyethylene units) for the lanolin alcohols and then an increase, while for the octylphenol derivatives the CMC increases with increasing hydrophilicity.

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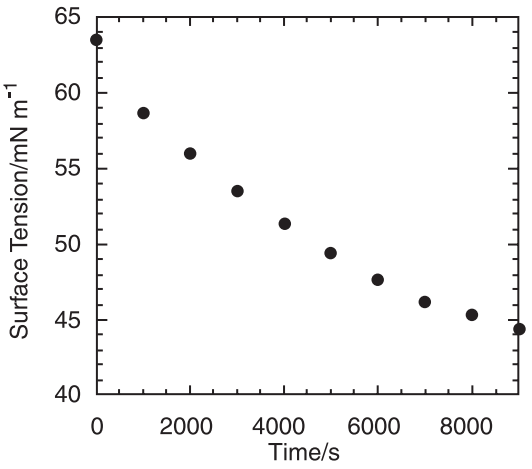

FIG. 3 Surface tension for phytosterol with 20 oxyethylene units as a function of time at a fixed concentration (3.44 μM), from Folmer et al. [16]. The adsorption to the air–water interface appears to be unusually slow and even after 3 h a stable value has not been obtained.

and more flexible surfactants, was attributed to a more complicated alignment process due to the large and rigid hydrophobic group of the surfactant. Thus, for sterol-based polyoxyethylene surfactants the geometrical constraints in the aggregation process will be more important in determining the CMC than the balance of the hydrophilic–hydrophobic moieties of the molecule. The anomalous CMC trend observed for the sterol surfactants was attributed to the same reasons. The authors also investigated shape and size of the micelles using dynamic and static light scattering as well as self-diffusion ^{1}H NMR. The surfactant with 10 oxyethylene units formed very large, highly elongated aggregates, whereas the surfactant with 20 and 30 oxyethylene units formed smaller structures with growing axial ratio upon increasing surfactant concentration. Self-diffusion ^{1}H NMR was used for a more in-depth study of the surfactant with 30 oxyethylene units, which concluded that the dynamics of the surfactant aggregates in the micellar region cannot be modeled according to hard-sphere interactions [17].

The unusual micellization behavior of sterol surfactants appears to require a more extensive study of the surfactant aggregation in water at low concentrations. Aspects of the dynamics in phase transitions and surface adsorption need to be considered, since these may play an important role in the behavior of these relatively large surfactants.

C. Solution Behavior

The solubility and phase behavior of ethoxylated sterols can be expected to be different from that of nonionic surfactants with straight or branched hydrophobic moieties. The rigid and bulky hydrophobic group is believed to hinder the packing of surfactant monomers into spherical or rod-like micelles [11].

In 1984, Müller-Goymann performed schematic phase studies of phytosterol surfactants in water with 5, 10, 16, and 25 oxyethylene units [18]. Since then three groups have systematically investigated the phase behavior of ethoxylated sterols in water as a function of temperature [13,16,19]. Söderlund et al. determined the binary phase diagrams and cloud points for a range of polyoxyethylene cholesterols with an average number of oxyethylene units equal to 13, 35, and 50 [13]. Folmer et al. investigated ethoxylated phytosterols with average hydrophilic polyoxyethylene chain lengths of 5, 10, 20, and 30 oxyethylene groups [16]. The phytosterols consisted of sitosterol, stigmasterol, and campesterol in a 2:1:1 ratio. A phase diagram of a homogeneous trioxyethylene cholesterol ether has been published by Rodríguez et al. [19]. The three studies on the temperature dependence of the phase behavior of ethoxylated sterols in water present analogous results that are summarized below.

The presence of three to five oxyethylene groups coupled to the very large sterol skeleton allows for a lamellar phase to form at high surfactant-to-water ratios. At lower surfactant concentrations a water-rich phase separates out from the liquid crystalline phase. This is exemplified in Fig. 4a by the pentaoxyethylene phytosterol ether–water phase diagram. Surfactants with 10–13 oxyethylene units produce one-phase systems with water already at very low surfactant concentrations and display micellar, hexagonal, lamellar, and reverse micellar regions with increasing surfactant concentrations (Fig. 4b). Increasing hydrophilicity of the molecule (for 20–35 ethylene oxide units) results in the formation of a viscous isotropic cubic phase and the disappearance of the lamellar phase (as exemplified in Fig. 4c, d). Finally, a further increase of the hydrophilicity to the surfactant polyoxyethylene (50) cholesterol leads to destabilization of all anisotropic phases, and only a cubic liquid crystalline phase is observed together with micelles and reverse micelles [13].

The increase in spontaneous curvature at a given concentration with increasing length of the hydrophilic chain is clear as the number of units increases from 3 to 50 [13,16,19]. The cubic phases for 20–35 oxyethylene units are located between the micellar and the hexagonal phases, which implies micellar cubic phases. It can be noted that the temperature stability of the liquid crystalline phases for sterol surfactants with 20 and 30 polyoxyethylene units is remarkably high compared with those formed by polyoxyethylene alkyl surfactants (see Fig. 4c, d) [16].

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Müller-Goymann also studied the lamellar swelling behavior in the previously mentioned phytosterol surfactants in water [18]. The two most hydrophobic surfactants (5 and 10 units) formed vesicles at low concentrations in water. Above a concentration of 20% and 30%, respectively, a lamellar liquid crystalline phase was formed. The authors have investigated the interlayer spacing of the lamellar phase with increasing water content. No vesicles were found for the two more hydrophilic surfactants. Vesicles in systems containing sterol surfactants have been studied by other groups as well [22–24]; see Section E.2, ''Pharmaceuticals'' for further information.

Some studies have also been performed on Solulan C24, which is a mixture containing polyoxyethylene cholesterol and polyoxyethylene cetyl ether [23,25]. Uchegbu et al. [25] studied the phase transitions in aqueous dispersions of hexadecyldiglycerol ether, cholesterol, and Solulan C24. The phase diagram was determined for the components at low concentrations in water (3%). It was found that a wide range of structures was formed: vesicles, tubules, discomes, and micelles. Vesicle formation in a system containing homogeneous trioxyethylene cholesterol ether has been investigated by Rodríguez et al. [19].

Sulfated and sulfonated ethoxylated cholesterol surfactants have been synthesized and studied by Meissner et al. [8]. The oxyethylene spacers consisted of three and four units. The investigated surfactants all formed lamellar phases upon addition of water at room temperature. The sulfonate variants displayed a richer phase behavior with hexagonal or micellar cubic phases at water concentrations higher than those of the lamellar phases.

The phase behavior of mixtures of polyoxyethylene phytosterol surfactants and paraffin as well as ternary mixtures of the surfactants, water, and paraffin has also been studied [18]. The objective of this work was to find creamy mixtures to be used in topical preparations. Uchegbu et al. investigated the phase behavior of cholesterol with 24 oxyethylene units with free cholesterol and hexadecyldiglycerol in order to find phases that can be used as drug delivery systems [25]. No liquid crystalline phases were found.

D. Biological Activity

The inclusion of biologically active and versatile substances like sterols and steroids in amphiphilic compounds has obviously led to several investigations of the possibility of utilizing these as active agents in cosmetics or even drugs. In contrast to the physicochemical behavior, the origin of the hydrophobic group, either from plant (phytosterol) or from animal (cholesterol), plays a significant role in these applications.

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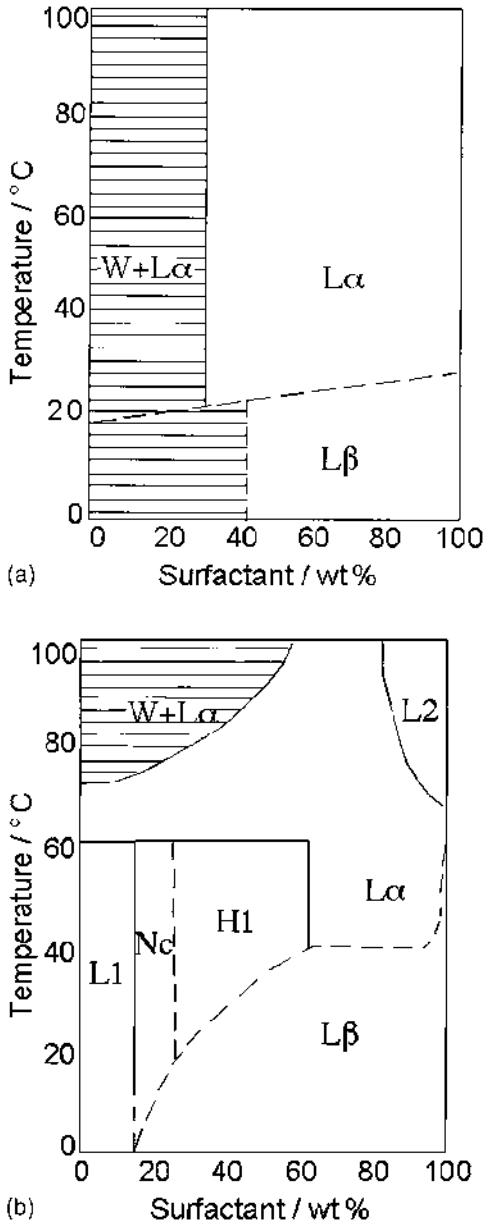

FIG. 4 Phase diagram of phytosterol with (a) 5 oxyethylene units; (b) 10 oxyethylene units; (c) 20 oxyethylene units; (d) 30 oxyethylene units. L1, L2, L_α, L_β, I1, Nc, and H1 indicate a micellar phase, a reversed micellar phase, a lamellar and a gel phase, a cubic phase, and a nematic and a hexagonal phase, respectively. Increasing hydrophilicity of the surfactant results in the formation of a remarkably temperature stable isotropic cubic and hexagonal phases. (From Ref. 15.)

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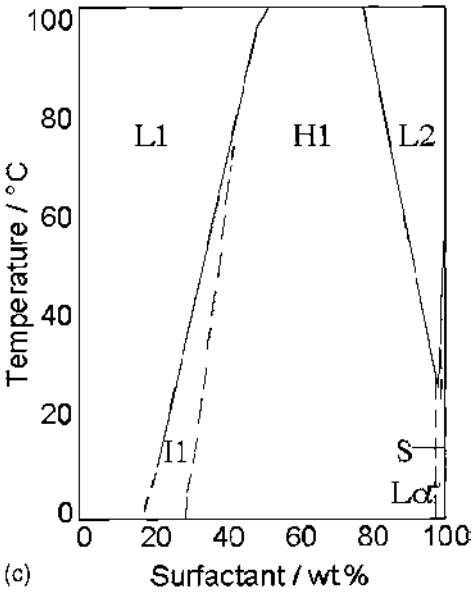
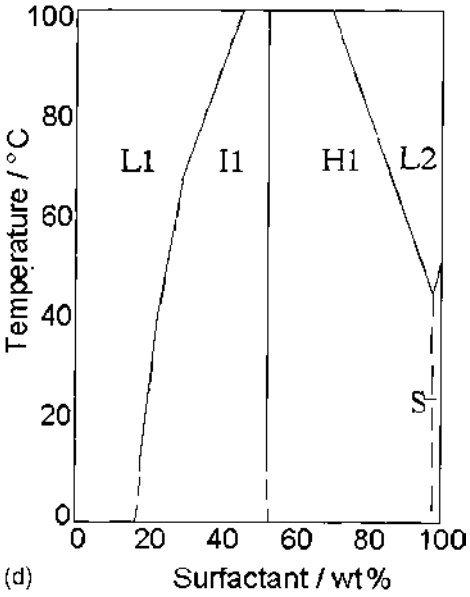


(c)



(d)

Even though phytosterols, unlike cholesterols, cannot be synthesized by animal organisms, it has been shown that they can be taken up from external sources and be present in the skin's surface even 25 days after uptake [26]. It is assumed that phytosterols are incorporated in the basal membrane of the epidermis and pass to the surface of the skin through cell differentiation. The effect of phytosterols is exhibited mainly on skin that has been damaged or harmed by environmental influences [2]. Both the antiphlogistic and antiprurignous effects of phytosterols have been demonstrated by Cholau et al. [27]. It was reported that phytosterols provide a similar antiphlogistic effect to cortisone derivatives. However, the action mechanism is believed to differ. Tests have shown that phytosterols exert an influence on the arachidonic acid cascade by reducing the level of leukotrienes, thus impeding inflammatory reactions [28]. These beneficial effects on skin have made phytosterol derivatives popular as an active ingredient in several different cosmetic formulations.

Khachadurian et al. [7] studied the cellular uptake and effect on lipid metabolism of polyoxyethylene cholesterol in cultured skin fibroblasts. The uptake of the surfactant was linear in the skin tissue up to a concentration of 60 μM. It was also seen that the surfactant inhibited the incorporation of acetate into cholesterol and the activity of the enzyme 3-hydroxy-3-methylglutaryl-CoA reductase. Furthermore, the incorporation of acetate in fatty acids was suppressed by the surfactant but not by 25-hydroxycholesterol. After uptake, the efflux of the surfactant was rapid and the recovery of enzyme activity was faster than the activity of acetate incorporation. It was suggested that the surfactant remained within the cell, where it continued to exert an inhibitory effect on lipid synthesis. The study concluded that water-soluble cholesterol derivative can be useful in the study of the regulation of lipid and lipoprotein metabolism and may help to elucidate the relationship between cellular cholesterol synthesis and the activity of the low-density lipoprotein receptors. Khachadurian and coworkers extended their study of polyoxyethylene derivatives of cholesterol to include the adsorption in the body. They found that the surfactant decreased the uptake of cholesterol in rats without affecting the body weight and fatty acid excretion [29]. Similar results have been obtained with sitosterol from tall oil, which lowered the levels of damaging cholesterol in the blood when it was added to food [30]. This has recently led to the development of functional food margarine containing sitosterol or phytosterol, which is claimed to lower the uptake of cholesterol.

Finally, the safety assessment of Chl-EO24 has shown that the surfactant has a very low toxicity, is nonirritating to mildly irritating to skin (according to Draize test), and is practically nonirritating when installed in the eyes [31]. The surfactant is therefore considered safe for topical applications to humans.

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E. Applications

Because of the beneficial effects on biological tissues that have been reported for sterol derivatives and also because of the rather exclusive natural raw materials, the use of this type of products has mainly been reported in personal care applications. Manufacturers recommend the products to be used in day creams, body lotions, and hair conditioners. In addition, the use of biological materials like sterols as a hydrophobic group has attracted studies of these surfactants in drug delivery applications. This section of the chapter discusses the use of polyoxyethylene sterols in these two very different applications. In addition, it can also be noted that unexpected and surprising uses of these types of surfactants in ink-jet inks was recently patented [32].

1. Cosmetics

The application of polyoxyethylene sterols in cosmetics and personal care products has been governed not only by the ameliorating effects of phytosterol on skin, but also on the strong interfacial activity and good emulsifying properties of the products. Schrader [33] reports that the emulsifying properties of sitosterol cannot be derived from the structural formulas alone, on account of the single hydroxyl group attached to four lipophilic carbon rings. The interfacial activity of sterols is dependent on the stereochemistry of the hydroxyl group, which should be in cis formation with respect to the methyl group at C-19 of the sterol skeleton. Sterol is an example of a water-in-oil (w/o) emulsifier that in combination with other emulsifiers facilitates formation of an emulsion containing large quantities of water. That fact and its derivatives' properties have permitted its use as an additive for prevention of sedimentation in suspensions. Owing to their predominantly hydrophobic character, mixtures of phytosterol and an ethoxylated form (Phy-EO5) represent typical w/o coemulsifiers [34], but analog couples have also been included in oil-in-water (o/w) creams [4]. Products with more oxyethylene units are characterized by quite good solubilizing properties and are used as emulsifiers in a range of combinations. Table 5 summerizes some important physical properties of the different polyoxyethylene phytosterols (Generol series). In combination with the beneficial effect of phytosterol on skin, this has led to the use these compounds in, for example, creams, skin lotions, and sun-screen lotions [35,36]. The use of sterol emulsifiers to produce gel-type oil-free cosmetics has been patented [37]. The emulsifier is added to obtain a soft gel or mousse-like structure. In addition, phytosterol derivatives have been reported to have a mild influence on hair's wet combability and texture [2]. Consequently, these compounds have also been used in hair rinse and conditioner products.

TABLE 5 Some Characteristics of Polyoxyethylene Phytosterols

Product	PIT (°C)	HLB value	Melting range (°C)
Phytosterol	−10	n/a	136–140
Phy-EO5	+13	5	75–78
Phy-EO10	+65	12	55–58
Phy-EO16	+113	15	46–50
Phy-EO25	+189	17	44–48

Source: Compiled based on data from Refs. 2 and 33.

2. Pharmaceuticals

The important role of sterols and steroids in animal organisms has led to several attempts to use amphiphilic derivatives of sterols in pharmaceutical applications. In addition, the tendencies of sterol derivatives to form micelles and vesicles have made them interesting with respect to the solubilization of lipophilic drugs.

In an early study by Thakker et al. [38], the solubilization of some steroids in aqueous solutions of Chl-EO24 was reported. It was believed that the similarities in the hydrophobic portion between the surfactant and the steroids would improve the solubilization capacity in comparison with other polyoxyethylene derivatives, according to the principle "like dissolves like." Surprisingly, the order of magnitude of the solubilizing capacity of this surfactant was found to be comparable to that of other polyoxyethylene surfactants. The results demonstrated that the solubilization of the steroids probably takes place by association with the polyoxyethylene exterior of the surfactant aggregates rather than with the hydrophobic interior of the micelle. Baade and Mueller-Goymann [39] studied the solubilization of the anesthetic drug lidocaine by a sterol surfactant (Phy-EO16). Even though the drug is amphiphilic there was no evidence of mixed micelle formation between the two compounds, most likely because of the large differences in CMC.

Several groups have used polyoxyethylene derivatives of cholesterol to study liposomes for drug delivery applications. These are believed to combine a condensing and stabilizing effect of cholesterol on the lamellar shell of the liposome, with a steric stabilization by the polyoxyethylene chain, thus preventing breakdown and fusion of the entities [24,40,41]. Ishiwata et al. [42,43] have in several reports illustrated how polyoxyethylene cholesterols form a protective coating on liposomes, thereby preventing binding and uptake of liposomes in biological systems. As mentioned previously, Uchegbu et al. [25] used mixtures of Chl-EO25, cholesterol, and hexadecyldiglycerol ether to make vesicles and discomes suitable for solubilization of the lipophilic

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tubulin inhibitor paclitaxel. The drug was easily solubilized by discomes made from this system; however, the formulation was found to be too toxic in mice for use by intravenous or intraperitoneal routes. This problem was believed to be due to the high levels of the sterol surfactants in the formulation. Beugin et al. [24] also studied formation and solubilization of vesicles containing polyoxyethylene cholesterol and hexadecyl diglycerol. They synthesized a polyoxyethylene derivative of cholesterol carbonate and found that stable liposomes were formed in a narrow concentration ratio of the different surfactants. This confirmed the bivalent role that sterol surfactants have in liposome stabilization; while behaving as solubilizing surfactants (which can disrupt the liposome bilayer), they also provide an efficient steric barrier and stabilizer preventing liposomes from aggregation and fusion over a time period of several days.

Lafont et al. [44] used oligooxyethylene cholesterol as D-glucosamine anchors in phospholipid vesicles. Glucoside derivatives of the oligooxyethylene cholesterol with D-glucosamine were synthesized and incorporated in vesicles. The aim of the study was to stabilize vesicles for intravenous drug delivery. The cholesterol moiety was used as a lipophilic anchor, which is able to stabilize the bilayer, the *N*-acetyl-D-glucosamine as a model carbohydrate ligand for molecular recognition, and the oligooxyethylene moiety as a spacer between carbohydrate and lipid fractions. The derivative could easily be incorporated in the vesicles with no adverse effects.

Stadler and coworkers [45] synthesized a bifunctional, or bola form, polyoxyethylene sterol derivative (Fig. 5). This compound was designed as a prototype for a new class of compounds intended to serve as functional equivalents to the antibiotic drug amphotericin B. Analysis of the surface pressure–area isotherm, at the air–water surface, indicated a limiting area of about. 0.60 nm^2 per molecule. This value was consistent with a model in which

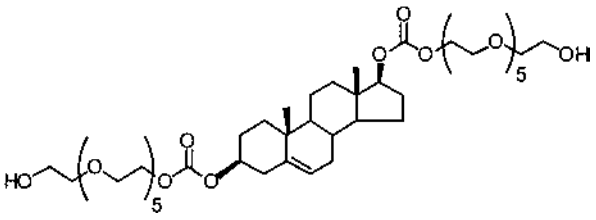

FIG. 5 A sterol-polyoxyethylene conjugate synthesized by Stadler and coworkers [45]. This compound, 5-androstane-3β,17β-bis((oxycarbonyl)hexaethylene glycol), was designed as a prototype for a new class of compounds intended to serve as functional equivalents to the antiobiotic drug amphotericin B.

the sterol nucleus and one pendent polyoxyethylene chain define the area of the surfactant, i.e., the existence of a folded conformation at the interface. Incorporation of the substance in the membranes of a phospholipid vesicle led to ion channel formation, thus mimicking the behavior of the drug. A conjugate with only one polyoxyethylene chain did not form this ion channel or tunnel effect through the membrane. However, the ionophoric activity of the molecule was significantly less than that of amphotericin B.

IV. OTHER SURFACTANTS BASED ON STEROL AND ALICYCLIC COMPOUNDS

A. Sterol Glucosides or Sterolins

Besides the polyoxyethylene type of derivatives, carbohydrates have been used as hydrophilic groups for sterol-based surfactants [46,47]. The rigidity of the obtained surfactants confers a poor water solubility. Piispanen et al. [47] observed a difference in surface activity, as noted in the formation of mixed micelles with the anionic surfactant sodium dodecyl sulfate (SDS), as the structure of the sterol moiety was altered. Whereas cholesterol and cholestandiol glucoside showed little or no effect on the micellization process, the cholestanon derivative cooperated in the micelle formation leading to a significant reduction of CMC. To achieve sufficient water solubility a polyoxyethylene chain has been included as a spacer between the glucose group and the sterol. An example of this is the previously mentioned study by Lafont et al. [44] who synthesized an aminoglucoside of several oligooxyethylene cholesterols, which were subsequently incorporated into the bilayers of liposomes.

In this context it should also be mentioned that plants produce glycosidic derivatives of sterols naturally. Such compounds are commonly known as sterolins. One of the first reports demonstrating the presence of natural sterolins, as a component of wheat flour, was by Myhre in 1968 [48]. Since then sterolins have been found and isolated from several plants, e.g., tobacco [49] and rice bran [50]. The physicochemical properties of these amphiphilic compounds are not well known. To date, studies of these compounds have been confined to their biological activity and several claims have been made on their physiological effects. These indications of beneficial properties have led to a plethora of natural sterolin products that can be found in the health food and alternative medicine market.

A naturally occurring group of surfactants similar to the sterolins are found in saponins from plants. This is a class of substances with a rigid (steroid or triterpenoid) skeleton of at least four hydrocarbon rings to which sugars in groups of one or two are attached (usually not more than 10 units).

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For example, the gypsoside found in saponin from white soapwort (*Gypsophila* ssp) comprises a hydrophobic group of four fused rings to which a tetrasaccharide and pentasaccharide are attached via glycoside and ester bonds (Fig. 6) [51]. In an early report, Barla et al. [52] studied the phase equilibrium of a ternary system of technical monoglyceride–soapwort saponin–water. They concluded that the saponin forms aggregates in water, which are roughly globular. The phase diagram showed the presence of normal micelle, reverse micelle, cubic phase, and lamellar phase regions. More recently, Mitra and Dungan [53,54] studied micellar and solubilization properties of saponin from Quillaja. Saponin was found to solubilize cholesterol significantly better than linear hydrocarbon chain surfactants. Micellization behavior of a saponin from acacia, in mixed micelles with a nonionic surfactant (Triton X-100) was investigated by Majhi et al. [55]. The structural differences give rise to an antagonistic effect, and the mixed systems were found to have a higher CMC than expected by regular solution theory.

B. Abietic Acid Derivatives

Abietic acid and dehydroabietic acids have been used as surfactants, either as soaps (sodium salts) or as polyoxyethylene derivatives. The soaps of abietic acids are complex mixtures of fatty acids and rosin acids, and are present in wood extracts from the paper pulp process. The existence of liquid crystals containing these soaps and the effect this has on the tall oil recovery was recognized early [56]. The phase behavior of these mixtures was later investigated by Palonen et al. [57]. It was found that whereas the abietic acid soap only forms a lamellar phase, in the mixture with fatty acid micelles are easily formed that are more soluble in salt solutions than the individual soaps. In order to increase the knowledge regarding the

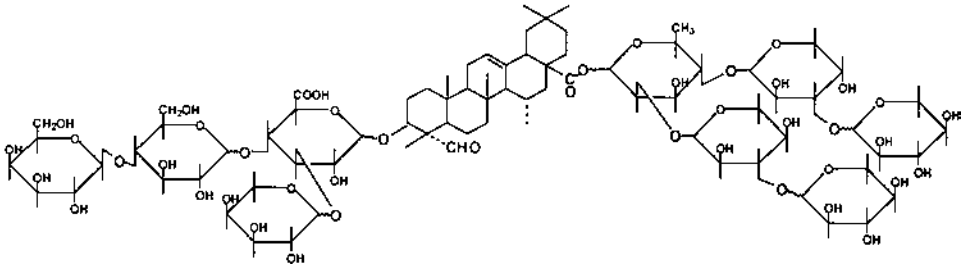

FIG. 6 The structure of the gypsoside, a saponin found in white soapwort (*Gypsophila* spp) [51].

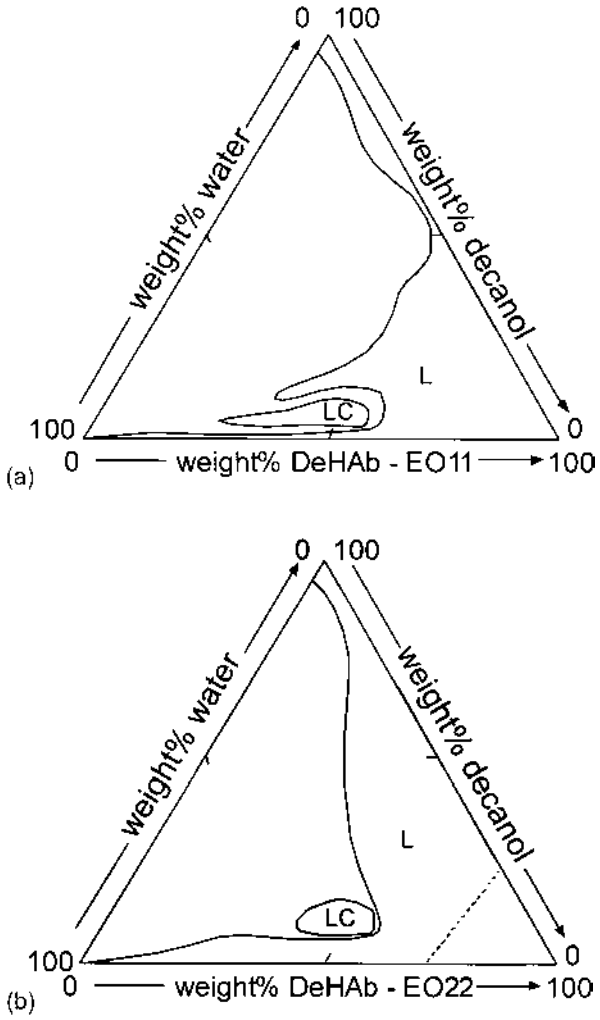

FIG. 7 Phase diagram (incomplete) for the three-component system water–dehydroabietic acid surfactant–1-decanol at 25°C. The one-phase areas are LC lamellar liquid crystalline phase and L isotropic solution: (a) DeHAb-EO11, (b) DeHAb-EO22. (Reproduced from Ref. 59.)

mechanism for removal of neutrals during the washing stage of the pulp production, further studies concerned the solubilization capacity of the individual soaps and soap mixtures [58]. It was found that the solubilization capacity of various organic substances depended in a subtle way on the concentration of salt in the solutions.

The surface chemical properties of polyoxyethylene dehydroabietate (DeHAb-EOx) were investigated by Persson and coworkers in 1980 [59], and recently by Piispanen et al. [60]. The first group determined the phase diagrams of the surfactants (DeHab-EO11 and DeHabEO22) and their solubilization capacity of different organic solvents. The ternary phase diagrams of the two surfactants in decanol and water are shown in Fig. 7. The cloud point of the surfactants was determined to 31°C (DeHAb-EO11) and 72°C (DeHAb-EO22). The solubilization capacity of DeHAb-EO22 derivative was compared to polyoxyethylene (20) nonylphenol. The latter group concluded that the CMC and foaming behavior could be compared to the corresponding polyoxyethylene dodecyl ether, with the exception that the cloud point was found to be significantly lower for the DeHab-EO surfactants. In the patent literature polyoxyethylene derivatives of abietic and rosin acids are reported to be useful in a multitude of applications, e.g., deinking agents [61], fabric conditioners [62], acidic cleaning solutions [63], dyeing aids [64], and emulsifiers [65].

V. CONCLUSIONS

The interest in sterols and alicyclic compounds has increased considerably during the last few years. The raw materials are present in many industrial processes, related to oils and fats as well as wood pulp, and are therefore relatively easy to obtain. The extensive and interesting variation in the molecular structure of the sterols make these compounds suitable for a more detailed study of the structure–performance relationship with respect to the hydrophobic group of the surfactants. The increased knowledge with respect to physicochemical properties that has been obtained during the last few years facilitates mapping of future uses. The reports in the literature concerning the surface chemical properties of the polyoxyethylene sterols indicate that the aggregation and adsorption behavior is in some respects similar to the alkyl phenol surfactants, but in some respects they differ, most notably in their solution behavior. Less is known regarding the properties of carbohydrate derivatives of sterols. In these molecules two structurally interesting classes of natural products are combined, and the scope for a systematic investigation regarding structure–performance relationships is even more obvious.

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7

Fatty Acid Monoethanol Amide Ethoxylates

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I. INTRODUCTION

Surfactants based on natural products are currently attracting much industrial and academic interest. Some of the more common surfactants in use today are questioned with regard to their biodegradability and toxicity. A well-known example are ethoxylated alkylphenols, which have been found to have severe impact on the environment and biological functioning of rats and fish [1–3]. Due to their good surfactant properties, it has not been straightforward to find a replacement. Alcohol ethoxylates of the same hydrophilic–lipophilic balance (HLB) do not always give satisfactory results. For instance, in the stabilization of dispersed systems, emulsions, or suspensions, it is often found that nonylphenol ethoxylates are superior to alcohol ethoxylates [4]. It is believed that one cause of this is the bulkiness of the hydrophobe of the nonylphenol ethoxylates as compared with that of the alcohol ethoxylates. The nonylphenol consists of a highly branched nonyl group attached via a nonterminal carbon to the para position of the aromatic ring, whereas the hydrophobic part of the alcohol ethoxylate is either a straight hydrocarbon chain or a methyl branched chain normally in the $C_{10–16}$ range. Due to the different degrees of bulkiness of the hydrophobic groups of the alcohol ethoxylate and the nonylphenol ethoxylate, the surfactants will aggregate differently when dissolved in water or at an interface. The very bulky nonylphenol ethoxylate cannot spontaneously form as highly curved micelles or oil-in-water structures as the alcohol ethoxylates. Since most surfaces and interfaces have a low curvature on the scale of the surfactant, nonylphenol ethoxylates generally align better than alcohol ethoxylates at boundaries. Furthermore, good packing properties can be expected for the nonylphenol ethoxylates due to interactions of the π electrons in the benzene rings with the neighboring aromatic rings.

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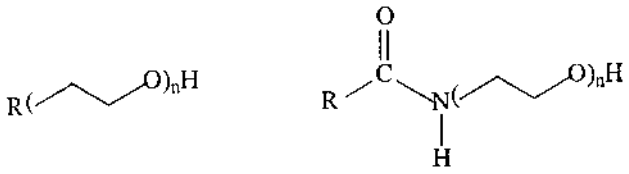

Alcohol ethoxylate Fatty amide ethoxylate

FIG. 1 Chemical structure of the fatty amide ethoxylates.

Against this background, the importance of finding substitutes with equally functioning nonionic surfactants, yet environmentally benign, can easily be understood. The focus of both industry and academic research is on finding surfactant replacements with similar functional properties but better environmental compatibility. The introduction of an amide bond in the surfactant leads to enhanced biodegradability. By varying the unsaturations in the hydrophobe the bulkiness of the surfactant can be varied. In addition, the hydrophilic group can be modified with a carboxylate, a sulfate, or a phosphate to give the surfactant an ionic character. Surfactants of these types are already used in several practical applications, e.g., in detergents, lubricants, and paints. In this chapter, the physicochemical behavior of fatty acid monoethanolamide ethoxylates is discussed as possible replacements for certain applications. In Fig. 1, the structures of alcohol ethoxylates and fatty amide ethoxylates are shown.

II. ENVIRONMENTAL ASPECTS

Environmental awareness and protection have led to the development of more environmentally benign surfactants. There is a trend of substituting petrochemicals by renewable raw materials. For this reason there is currently much interest in fatty acid–based surfactants. For both fatty alcohol ethoxylates and fatty amide ethoxylates the raw material for the hydrophobic group are triglyceride oils. The triglycerides are present in plants such as rapeseed, coconuts, soya, canola, sunflour, and tallow. Fatty acids, as used for the production of fatty amide ethoxylates, are obtained from saponification of the triglycerides. Fatty alcohols, which are used to produce fatty alchol ethoxylates, need a saponification step to obtain the fatty acid, followed by a reduction, usually via the methyl ester, to obtain the alcohol.

Fatty amide ethoxylates differ from the fatty alcohol ethoxylates in terms of aquatic toxicity and biodegradation. The toxicity of the fatty amide ethoxylates has been found lower than for alkylphenol and alcohol ethoxy-

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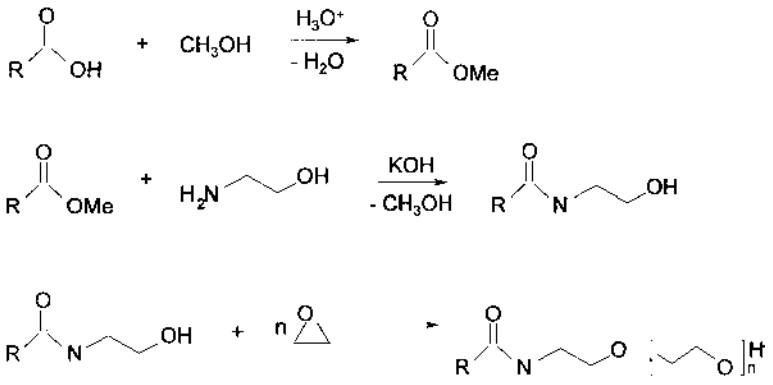
lates [5]. Furthermore, the amide bond is a naturally existing linkage that can be expected to be readily biodegradable due to enzymes present in sewage treatment plants, which can catalyze cleavage of the surfactant amide bond to give a fatty acid and an amino-terminated poly(ethylene glycol) [6,7]. To analyze the ready biodegradability of the fatty amide ethoxylates, so called OECD 301D tests can be performed where the requirement is to reach 60% biodegradation within 28 days. In general, it can be stated that large variations in biodegradability occur due to (locally) different, sometimes adapted, bacteria present in the sludge. A comparison of the biodegradability of tallow amide ethoxylate to tallow amine ethoxylates was made by Ginkel et al. [6]. It was shown that the first phase of the biodegradation in the closed-bottle test of the amides was completed on day 5 (about 30% biodegraded) whereas the alkyl chain of the amines was biodegraded on day 15 (25% biodegraded). This difference clearly indicates the difference between the naturally occurring amide bond and the amine, which has to be split by an oxidative reaction.

III. SYNTHESIS

The synthesis of fatty acid amide ethoxylates can be described in three steps (see Scheme 1). The first step concerns the preparation of fatty acid methyl esters. The fatty acid is heated in sulfuric acid in the presence of methanol. The lower phase of the resulting two-phase system then contains the fatty acid methyl ester. Second, the fatty acid methyl ester is reacted with mono-



SCHEME 1 Synthetic route to ethoxylated fatty acid monoethanolamides. R = hydrocarbon chain; n = number of oxythylene units.

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ethanolamine and sodium methoxide in methanol upon heating, resulting in a fatty acid monoethanolamide. The final step concerns the ethoxylation of the fatty acid monoethanolamide. The ethoxylation is performed under pressure at high temperature in an autoclave. Predetermined amounts of ethylene oxide are added to obtain ethoxylated fatty amides of varying molecular weights. During the above-described ethoxylation procedure some side reactions may occur [8]. The ethoxylation is performed at 140°C. At this temperature in the presence of an alkaline catalyst, rearrangement reactions may lead to the formation of ethoxylated fatty acid esters of ethanolamines and ethoxylated fatty acid diethanolamides. More detailed descriptions of the synthesis of fatty acid amide ethoxylates can be found in [8–10].

The above-described procedure for the ethoxylation of surfactants is the commonly used commercial ethoxylation procedure. This procedure always leads to a polydispersity in the head group. Figure 2 shows the homolog distribution curve for technical $C_{12}E_7$, as prepared by ethoxylation using potassium hydroxide (KOH) as catalyst. The amount of the average homolog $C_{12}E_7$ is 12%. For higher homologs a Poisson distribution is obtained, while for the shorter homologs the Poisson distribution is partially set aside by the difference in acidity of the starting alcohol and the terminating alcohol group of the ethoxylated species. Since the latter have a higher acidity, the reaction of the second oxyethylene group will be

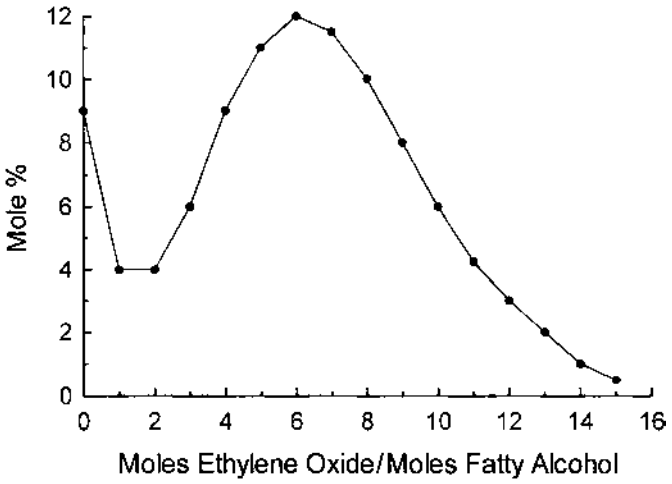

FIG. 2 A homolog distribution curve for technical $C_{12}E_7$.

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favored compared to ethoxylation of the fatty alcohol [11,12]. The distribution of the oxyethylene chain length can be affected by the choice of catalyst. Industrial ethoxylation processes are usually performed using potassium hydroxide (KOH) as catalyst. The alkaline earth hydroxides $Ba(OH)_2$ and $Sr(OH)_2$ give a more narrow distribution than KOH and are used to prepare "peaked ethoxylates," i.e., ethoxylates with a narrower homolog distribution. Ethoxylation can also be performed in acidic environment; the use of a Lewis acid, such as $SnCl_4$ or BF_3, gives rather narrow distributions. The drawback of acid catalysis is that considerable amounts of 1,4-dioxane are formed as a by-product. Also, remainders of the catalyst are usually left in the product after the synthesis and are very difficult to remove. The presence of the catalyst can lead to degradation of the poly(ethylene glycol) head group. Furthermore, the use of an acidic catalyst may lead to corrosion of the reactor [13,14]. Surfactants with monodispersed well-defined oxyethylene chain lengths are exclusively synthesized for research purposes. Such surfactants are synthesized by stepwise addition of activated oligo(ethylene glycol) to the fatty alcohol. Mesylates and tresylates are examples of activating groups and the coupling step is performed under strong alkaline conditions. The final product is purified by distillation [15].

It should be realized that an ethoxylated technical surfactant might not only be polydisperse in the hydrophilic head group. Hydrophobic groups stemming from both natural and petrochemical raw material consist of many different homologs. The purity of a surfactant hydrophobe is thus dependent on the manufacturing process. Although all industrial applications are based on technical products that often are composed of two or more surfactants, it is important from both a scientific and an industrial point of view to have basic knowledge of the behavior of pure surfactants. It has been shown that when two surfactants are mixed, synergistic effects often lead to improved physicochemical properties. Thus, a polydisperse surfactant may be technically better then a homologous pure one.

Several methods may be employed to get an indication of the purity of the surfactant. Gas chromatography can be used to determine the amount of unreacted hydrophobe. ^1H nuclear magnetic resonance (NMR) is a good method to analyze the average number of oxyethylene per hydrophobe. Free poly(ethylene glycol) will, however, interfere with the NMR signals. High-performance liquid chromatography (HPLC) can be used to analyze the amount of free poly(ethylene glycol), the amount of unreacted hydrophobe and the distribution of homologs. However, there is a difficulty in ascribing the peaks to the correct oxyethylene number when no pure homolog is available as standard.

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IV. PHYSICOCHEMICAL PROPERTIES

A. Bulk Behavior

The introduction of the amide group leads to an increase in HLB of the surfactants. On the other hand, amide groups are known to form hydrogen bonds and may increase the attraction between the surfactants, even though the hydrogen bonds may be formed between the amide and the surrounding water as well. Hydrogen bonds from amide groups are known to be important for the stabilization of proteins, and are believed to affect the binding between polymers and vesicles in solution [16,17]. The CMC value of a highly purified dodecylamide with five oxyethylene units was compared to dodecyl with five oxyethylene units. It was found that the amide group renders the surfactant more hydrophilic leading to an increase in the CMC value [18]. The CMC values and micellar shape of a series of fatty amide ethoxlates have been measured [8,19] (Fig. 3). The length of the hydrophilic head group was varied as was the degree of saturation in the hydrophobic chain. Additionally, the measurements have been compared to conventional alcohol ethoxylates. Both tensiometry and fluorescence were used to obtain CMC values. The micellar shape was studied using ^{1}H NMR self-diffusion. Contrary to the results on the dodecyl amide

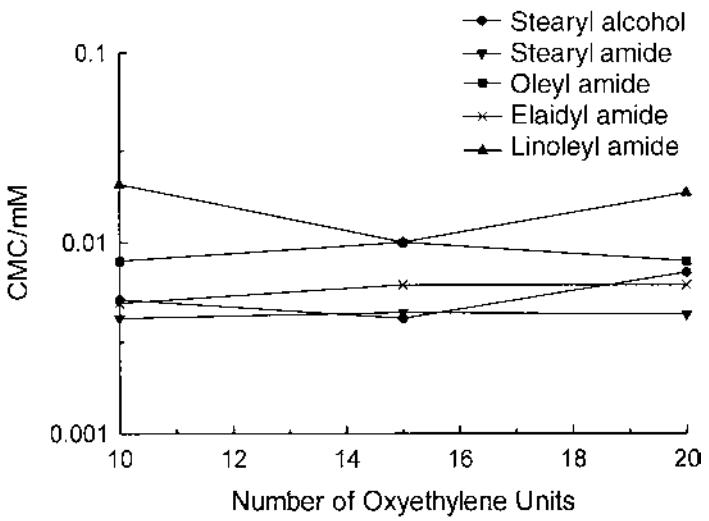

FIG. 3 CMC values for several fatty amide ethoxylates as a function of oxyethylene units, as determined by fluorescence. (Adapted from Ref. 8.)

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with five oxyethylene units, it was found that the effect of the amide group leads to somewhat lower CMCs, which in turn leads to the conclusion that the formation of hydrogen bonds has a stronger effect on the formation of micelles than the increased hydrophilicity. In both studies it is found that the surface tension at the CMC is increased when an amide bond is present in the surfactant. The hydrodynamic radii as determined from ^{1}H NMR self-diffusion measurements are shown in Fig. 4. It can be seen that the radii of the fatty amides with 10 oxyethylene units increase upon concentration increase, indicating a nonspherical micelle shape. The temperature and polyoxyethylene chain length seem not to affect the hydrodynamic radius significantly. From phase studies it is found that at higher surfactant concentrations hexagonal phases are formed, hence, a prolate structure of the micelles is assumed. The shape of the micelles is somewhat changed when an amide bond is present in the surfactant. It is found that the hydrodynamic radii for the stearyl alcohol ethoxylates are somewhat larger than the radii of the stearyl amide ethoxylates. The axial ratio of the stearyl alcohol with 10 oxyethylene units is found to be 2.3, compared to 1.4 for the stearyl amide with the same head group. This change in shape of the micelles is ascribed to the decrease in critical packing parameter (CPP) value for the latter surfactant type leading to a more spherical micellar shape. The axial ratios were calculated and are shown in Table 1 [19].

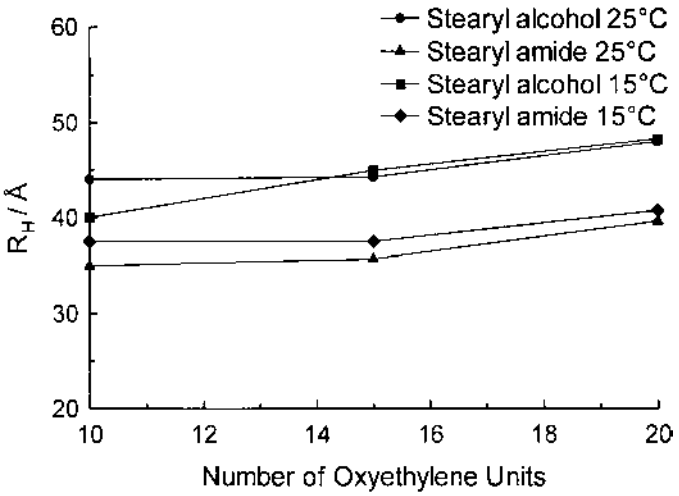

FIG. 4 The hydrodynamic radii as a function of oxyethylene chain length at 15°C and 25°C. The effect of the amide bond. (Adapted from Ref. 18.)

TABLE 1 Micellar Data Obtained from ^{1}H-NMR Self-diffusion from Fatty Amide Ethoxylates Containing 10 Oxythelene Units

Surfactant hydrophobe	$D \cdot 10^{-11}$ ($m^2\ s^{-1}$)	R_h [A (10^{-2} M)]	α	R_h [A (10^{-4} M)]	L/(A)
Stearyl alcohol	4.53	43.8	2.25	31.5	70.8
Stearyl amide	5.67	35.0	1.35	34.5	46.6
Oleyl amide	4.95	40.1	1.54	32	49.3
Elaidyl amide	5.52	35.9	1.44	31.4	45.2
Linoleyl amide	5.91	33.6	1.82	26.7	48.6

D, diffusion coefficient at 10^{-2} M; R_h, hydrodynamic radii at 10^{-2} M and 10^{-4} M; a, axial ratios at 10^{-2} M with L the micellar long axis and R_h at 10^{-4} M the micellar short axis.
Source: Data from Ref. 18.

Kahn et al. [9] studied the micellar size of a fatty amide ethoxylate with a polydisperse hydrocarbon chain stemming from rapeseed oil fatty acids. It was observed from both the lineshape of ^{1}H NMR measurements and cryo-transmission electron microscopy that at low concentrations (up to 1%) a mixture of spherical and rod-like micelles is present. From ^{1}H NMR self-diffusion studies a biexponential distribution for the self-diffusion coefficient is found. The fast component, indicating the presence of small spherical aggregates gave a radius of 21 Å at 0.6 wt %, increasing to 30 Å at 40 wt %. The radii observed by Folmer et al. [19] were somewhat larger. The slow component of the diffusion coefficient was found to go through a minimum with increasing concentration. The authors explain this effect by diffusion of surfactant aggregates. At low surfactant concentration the diffusion of closed surfactant aggregates in a continuous aqueous medium is the dominating effect. At high surfactant concentration the self-diffusion coefficient is dominated by molecular diffusion, i.e., the diffusion of surfactant in surfactant-continuous domains. At the intermediate region a minimum is observed, most likely due to the gradual merging of aggregates that start to form surfactant-continuous domains [20]. The hydrodynamic radius of the large micelles is calculated to be 115 Å at 0.6 wt % growing to 626 Å at 22 wt %. The dynamic viscosity calculated at constant shear rate reflects the merging of aggregates, in agreement with the self-diffusion measurements. The presence of large aggregates in the intermicellar region causes the viscosity to reach a maximum.

The introduction of unsaturations in the hydrocarbon chain can be considered to give rise to a decrease in the hydrophobicity of the hydrocarbon chain because the delocalized π electrons will increase the polarizability of the chain. In addition, the unsaturation decreases the flexibility

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of the hydrocarbon tail. The lost degree of rotational freedom causes an increased bulkiness and rigidity in the chain. This bulkiness varies with the conformation and number of unsaturated bonds [21,22]. The presence of a double bond in the hydrocarbon chain was found to increase the CMC, indicating a decrease in hydrophobicity of the tail [8]. An interesting observation was that the cis bond in oleyl amide ethoxylate has a much stronger effect on the CMC than the trans bond in elaidyl amide ethoxlate. This is ascribed to two effects. First, the cis conformation is much more polarized and thus more hydrophilic, leading to a higher unimer concentration in bulk solution. Second, the cis conformation is more bulky than the trans conformation [22]. Hence, the cis isomer may prevent the amide groups to form hydrogen bonds with neighboring surfactants, thus losing a driving force for the formation of micelles. The length of the head group seemed not to change the CMC significantly. This is in line with the observation that the hydrocarbon chain has a much stronger effect on the CMC than the oxyethylene chain length [23]. The structure and size of the micelles formed by the fatty amide ethoxylates vary slightly depending on the amount of unsaturation present in the hydrocarbon chain. The radius of the micelles at low concentration (where they are considered spherical) decreases with the amount of unsaturated bonds in the hydrophobe, which is explained by the induced rigidity. It was also observed that the axial ratios at the higher surfactant concentration (10^{-2} M) vary with the degree of unsaturation. The relative increase from stearyl amide ethoxylate ($\alpha = 1.4$) to linoleyl amide ethoxylate ($\alpha = 1.8$) is 35%. The increase in size of the hydrodynamic ratio of the presumably spherical micelles, at the low surfactant concentration (10^{-4} M), when going from linoleyl amide ethoxylate ($R_h = 26.7$) to stearyl amide ethoxylate ($R_h = 34.5$) is 29%. Thus, most of the variation in axial ratio seems to be due to a decrease of the short axis with the number of double bonds in the hydrophilic tail of the surfactant. The long axis, i.e., the length of the rod-like micelles, seems not to vary much with the degree of unsaturations [19].

B. Adsorption at an Interface

The adsorbed amount and the apparent head group area obtained from the ellipsometry meaurements are shown in Table 2 together with the cross-sectional head group area as determined from the surface tension measurements for a series of fatty amide ethoxylates in comparison with fatty alcohol ethoxylates [18,19]. For the surfactants as measured by Folmer et al. [19], it can be seen that the adsorption areas as obtained from ellipsometry are up to 3.5 times larger than the areas observed from the surface tension measurements. As mentioned by the authors, there are two important differences

TABLE 2 Adsorption Data Obtained from Ellipsometry and Tensiometry

Surfactant	Γ/[μmol m^{-2} (max)]	A/(A^2 from ellipsometry)	A/(A^2 from tensiometry)	Ref.
Stearyl alcohol E10	3.00	55 (>CMC)	29	19
Stearyl alcohol E20	1.72	94 (>CMC)	37	19
Stearyl amide E10	2.49	65 (>CMC)	34	19
Stearyl amide E10	1.53	104 (>CMC)	30	19
Oleyl amide E10	2.57	66 (>CMC)	24	19
Elaidyl amide E10	2.13	79 (>CMC)	31	19
Linoleyl amide E10	2.52	61 (>CMC)	47	19
Dodecyl amide E5	3.2	52 (>CMC)	49	18
Dodecyl alcohol E4	3.8	44 (>CMC)	42	18
Dodecyl alcohol E5	3.2	52 (>CMC)	47	18

Γ is the adsorbed amount as obtained from ellipsometry, A is the surfactant cross sectional area as obtained from ellipsometry (above the CMC) in comparison to the area as determined from tensionmetry (at the CMC).
Source: Data from Refs. 18 and 19.

between the two methods that must be taken into account when analyzing the observed differences. First, ellipsometry is measured at the solid–liquid interface whereas tensiometry is measured at the liquid–air interface. At the latter interface, the surfactant molecules will form a close-packed monolayer with the full hydrocarbon tails aligned in parallel. On the hydrophobic solid surface one may assume formation of a surfactant monolayer, but a strong interaction between the surface and the surfactant hydrocarbon tail in combination with the large head groups may distort the packing of the individual molecules. Second, the head group area derived from tensiometry is determined from the slope of the CMC curve at concentrations just below the CMC, whereas the area from the ellipsometry measurements is determined at a concentration much higher than the CMC. Polydisperse surfactants at concentrations below the CMC undergo selective adsorption at an interface [24,25]. The most hydrophobic species present in solution, i.e., the surfactants with the shortest poly(oxyethylene) chains, will adsorb preferentially at the interface, leading to a surfactant head group area not representative of the average surfactant present in bulk solution. In the adsorption experiments on fatty amide ethoxylates made by ellipsometry at a concentration much higher than the CMC, the most hydrophobic species will be solubilized into micelles [19]. Hence, the area obtained by ellipsometry does not reflect selective adsorption. Furthermore, the structure of the adsorbed layer is not known. Due to the large head groups, it is likely that the surfactants form a distorted monolayer at the surface. The area calculated

from the ellipsometry measurements thus reflects the average area per surfactant that is adsorbed at the solid–liquid interface. The areas obtained for the purified dodecyl surfactants [18] show that the adsorbed amount is only slightly lower at the solid–liquid interface than at the liquid–air interface, which reflects the purity of the surfactants.

The effect of the amide group can be seen when the adsorption results of stearyl amide ethoxylate are compared with those of stearyl ethoxylate. It is found that the adsorption areas at a solid–liquid interface and at the air–liquid interface are somewhat larger for the stearyl amide ethoxylate. It is concluded that the attractive force between the amide groups plays a smaller role than the decrease in CPP, resulting in less favorable packing at the interface. These results are in agreement with the effect of the amide group as seen in pure dodecyl surfactants [18].

Theoretical lattice mean field calculations on the dodecyl amide ethoxylates lead to the important conclusion that the presence of the amide group makes the boundary between the tail and head group regions more defined. This finding is further used to explain observations from surface force measurements [26]. The steric repulsion between adsorbed layers of dodecyl with five oxyethylene units begins at a larger separation than for the surfactant without amide group. Hence, the more diffuse adsorbed layer of dodecyl amide leads to longer ranging steric repulsions. Attractive forces are also observed in the surface force curves. It is found that the dodecyl amide ethoxylate has a stronger adhesive force than the surfactant without amide. Since the amide group is not present at the surface of the adsorbed layer this phenomenon cannot be explained by interlayer hydrogen bonds. Instead, due to the more diffuse adsorbed layer of the dodecanyl ethoxylate, more water will be present in the polar region of the surfactant layer and thus decrease the attractive forces. Furthermore, from the surface force curves it is concluded that the adsorbed layer of dodecyl amide ethoxylate is about 3 nm thick. It is stated that upon increasing force the layer thickness can be compressed to 2 nm. Even stronger forces make it possible to press out the adsorbed layers.

The effect of unsaturations in the hydrocarbon chain of the fatty amide ethoxylates is found to be significant at the liquid–air interface as compared with the solid–liquid interface [8,19]. This effect is ascribed to a decrease in rotational freedom of the chain, causing increased bulkiness and rigidity in the hydrocarbon chain [21,22,27]. When looking at the solid–liquid interface the head group area seems only to be slightly affected. This is explained by the phenomenon that at the liquid–air interface selective adsorption occurs, leading to a CPP closer to 1, and therefore the effects of the hydrocarbon chains become more pronounced. At the solid–liquid interface the effect of the oxyethylene chain is the dominant factor.

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C. Phase Behavior

Heusch [10] studied in detail the phase behavior of an oleyl amide with seven oxyethylene units. He observes the formation of several liquid crystaline phases and interprets the results depending on the formation of various hydrates in water.

The phase behavior of fatty amide ethoxylates is compared with that of alcohol ethoxylates [19]. At low surfactant concentrations micellar isotropic phases are formed for both surfactant types. At higher concentrations, hexagonal phases are formed when 10 oxyethylene units are present. For surfactants with longer head groups a cubic region appears between the micellar and the hexagonal region. When double bonds are present in the hydrophobe an isotropic melt is formed while the saturated amide and alcohol ethoxylates form crystals for 100% surfactant.

In a study by Kahn et al. [9] on a polydisperse octadecyl amide with nine oxyethylene units, the pure surfactant is found to be a viscous liquid at room temperature. Upon solubilization in water, a clear isotropic solution phase is observed for all concentrations between the cloud point and the solidification temperature. No liquid crystal formation is observed.

V. APPLICATIONS

In 1997 the surfactant production in western Europe was 1.83 million tonnes of which 660,000 tonnes were ethoxylated nonionic surfactants. The main application is detergents (42%). The production of nonylphenol ethoxylates was 100,000 tons with applications in, i.e., industrial and institutional cleaning, emulsion polymerization (15%), textile auxiliaries (12%), and leather auxiliaries (10%) [28,29]. In all these areas, there is an interest of replacing the nonylphenol ethoxylates. Fatty amide ethoxylates have been shown to be good candidates for several applications. In Table 3 different functions and applications have been summarized. The main functions for fatty amides with short oxyethylene chains are as thickening and foaming agents, whereas for the more highly ethoxylated amides suspending and emulsifying are important functions. In this chapter several applications will be discussed. More information on applications can be found in the overview on nonionic surfactants containing an amide bond by Lif et al. [7].

A. Paint

In the area of paint and coatings complex interactions between surfactants, polymers, and latex particles play an important role. In most formulations, a mixture of several surfactants is used. Alkylphenol ethoxylates are tradi-

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TABLE 3 Functions and Applications of Polyoxyethylene Amides

Function	Applications
Foam stabilizer	Liquid detergents, hard-surface cleaners, general-purpose cleaners, hand cleaning gels, personal care products
Emulsifiers	Cutting fluids, lubricants, rust inhibitors, plant protections agents, emulsifier for solvents and fuels, paints
Suspending agent	Industrial degreasers, cleaning formulations, detergents
Antistatic agent	Polymers, fabric softeners
Solubilizer coupling agent	Personal care products, detergents
Fulling agent, scouring agent	Textile-processing agents
Wetting agents	Low-temperature detergents, hand cleaners

Source: Adapted from Ref. 7.

tionally used for the steric stabilization of latex particles while anionics are present for the electrostatic stabilization. Amide ethoxylates based on highly unsaturated vegetable oils, such as soybean oil or linseed oil, have been found to be good substitutes for alkylphenol ethoxylates as dispersants [30]. The emulsifying properties of fatty amide ethoxylates in water-borne alkyd paints is reported [31,32]. It is found that temperature affects the HLB of the surfactant and thus the emulsion stability. The study showed that for increased concentration of nonionic surfactant the stability under shear is increased. However, increased surfactant concentration in paints increases the water sensitivity of the paint film. An increase in hydrophilic chain length of the fatty amide ethoxylates was found to reduce the shear-induced coalescence due to greater steric stabilization.

B. Drag Reduction

Drag reducing agents are molecules that form linear structures in water flow and thereby minimize the drag. Applications for drag reducing agents are, for example, fire fighting operations, petroleum recovery, and district heating and cooling systems. Traditionally quaternary ammonium surfactants have been added in small amounts as drag-reducing agents. The environmental impact of these surfactants has, however, led to the search for replacements. Oleyl amide ethoxylates as drag-reducing agents have been studied [33,34] and patented [35]. It was found that the fatty amide ethoxylates have viscoelastic properties and showed flow-induced birefringence. The substances with short polyoxyethylene chains seemed to have the best properties although they are

less appropriate for high temperatures as the cloud point is easily reached. For longer oxyethylene chains the cloud point is increased, but due to the increased hydrophilicity more sphere-like aggregates are being formed, leading to a reduced functionality for drag reduction. At increased salt concentrations, the mixture of the oleyl amide ethoxylate with an oleyl alcohol ethoxylate was found to work well.

C. Antistatic Agents

The ethoxylated fatty acid amides are good as antistatic agents, applicable for polymeric packaging materials on which electric charges can be built up, thus preventing damage to, for examples, microelectronics packaged in them [36]. The component is claimed to have no amine corrosion and good thermal processing stability [37].

D. Detergents

Many patents claim the good foaming properties of the fatty amide ethoxylates and ionic derivatives thereof. Most applications where the foaming properties are used are in cleaning applications. In addition, the component has been reported to have a mild effect on the skin [38–40]. Hence, applications are found for shampoos, skin cleaners, dishwashing liquids, and light-duty cleaning compositions [41–46]. In addition, it was found that in shampoos the presence of ethoxylated fatty amide ether carboxylate increased the deposition of cationic polymers on the hair [47]. Cold-resistant liquid detergents with good foaming power based on fatty amide ethoxylate phosphates, sulfates, and sulfosuccinate have been patented [48–50]. In the presence of magnesium ions the alkyl amide polyethoxycarboxylate has been shown to give improved cleaning properties [51]. The component has been found functional as a thickener in detergents [52].

E. Other Applications

Other applications for the fatty amide ethoxylate have been found in textile softeners, especially for cellulosic fibers. The component is claimed to give a finished web with a soft, smooth, and yielding hand [53]. Fatty amide ethoxylate phosphate esters have been utilized in lubricating conveyors with moving beverage containers such as glass, metal, or plastic containers [54]. The component has found applications as an antifogging agent. In [55] it is shown that a blown LDPE film containing lauric acid amide with five oxyethylene units placed in water of 60°C remained transparent and

covered with a continuous film of water condensate, free from opaque mist and droplets.

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8

Enzymatic Synthesis of Surfactants

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I. INTRODUCTION

Surfactants constitute an important class of industrial chemicals widely used in almost every sector of modern industry, with the worldwide production output exceeding 3 million tonnes per annum and an estimated market value of U.S. $4 billion [1]. To satisfy this hugely diverse market a large variety of individual compounds and blends are available commercially from more than 200 companies worldwide. Due to the sheer volumes of detergents required, the synthesis of surfactants has traditionally been considered solely within the capabilities of organic chemistry. However, rapid advances in biotechnology over the last decade have led to considerable interest in the development of biological methods of manufacturing, i.e., the application of biological catalysts in the form of microorganisms or isolated enzymes [2]. Increased environmental awareness of the consumer has provided a further impetus for more serious consideration of "biological" surfactants as possible alternatives to existing formulations. Thus, the biodegradability and toxicity of industrial detergents have become almost as important an issue as the functional performance of the products. Similarly, more stringent regulations are being introduced in the food industry to minimize the adverse allergic effects of artificial additives, including emulsifiers.

In this chapter I shall describe the latest advances in the application of isolated enzymes to the synthesis of surface-active agents. In particular, processes such as the syntheses of sugar fatty acid esters, amino acid–based surfactants, (lyso)phospholipids, and anomerically pure alkylglycosides will be discussed in some detail. The production of biosurfactants via fermentation will not be considered at all as this topic has been well covered in a number of recent reviews [3–6]. Where appropriate, the advantages of enzymatic methods over conventional organic syntheses and systems relying on the use of microorgnisms are highlighted.

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II. USE OF ENZYMES: GENERAL REMARKS

By their nature, surfactants are amphiphilic molecules containing a hydrophilic and a hydrophobic moiety. Hence, one of the fundamental problems in applying isolated enzymes to their synthesis is the efficient solubilization of the starting materials as it is by no means easy to find a solvent that would dissolve high concentrations of both hydrophobic and hydophilic constituents in the reaction mixture at ambient temperature and that will not be deleterious for the enzyme activity. Another problem is the choice of enzymes. Biosynthesis of surface-active compounds in vivo is always catalyzed by a cascade of complex, multisubunit enzymes that rely on activated substrates to shift the equilibrium toward the final product. The purification and stabilization of these enzymes in vitro is a huge task in its own right. This, combined with the requirement for activated substrates and/or coenzymes, makes it prohibitively expensive even as a laboratory scale process, let alone any industrial applications. The problem does not arise if living cells are used in fermentations, and in the past decade considerable research effort has been directed to the isolation and characterization of suitable microorganisms, especially those that can efficiently utilize long-chain hydrocarbons for growth and biosynthesis.

However, the above does not answer the main question: how can one employ isolated enzymes for the preparation of surfactants? In fact, the answer is simple: Use hydrolytic enzymes in nonaqueous media. Indeed, many hydrolytic enzymes, such as lipases, proteases, and glycosidases, available in large quantities, are very robust and inexpensive, and do not require any cofactors to manifest their catalytic activity. As any other catalyst, enzymes cannot influence the equilibrium of a chemical reaction and therefore the removal of water from the reaction medium forces them to work "in reverse," i.e., to synthesize a chemical bond rather than to break it. Consequently, there is a principal difference between microbial and enzymatic synthesis of surfactants regarding the type of enzymes involved and the reaction medium. The former is a biosynthetic process catalyzed by living microorganisms and as such dependent solely on their viability, whereas the latter is an organic synthesis whereby enzymes are used as substitutes for chemical catalysts. The two approaches are complementary not only in terms of the production methods but because the surfactant structures amenable to both methodologies are quite different.

The use of nonaqueous reaction media also offers a number of attractive options for increasing the productivity of enzymatic syntheses. In particular, it has been conclusively shown that enzyme-catalyzed reactions proceed readily in nearly stoichiometric mixtures of substrates in the absence of bulk solvents, e.g., enzymatic solvent-free processing [7] and biocatalysis in

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eutectic mixtures [8]. These approaches combine the precision of biological catalysis with high productivity, which is essential for a large-scale manufacturing. Admittedly, not every reaction can be carried out as a solvent-free process but in many cases a substantial improvement in productivity can be achieved through the design of a continuous bioreactor.

III. ENZYMATIC SYNTHESIS OF MONOGLYCERIDES

Monoglycerides are currently produced by the glycerolysis of fats and oils, which is operated at temperatures of 240–260°C and high pressure, primarily to achieve satisfactory miscibility of the reactants [9]. This reaction can also be carried out at ambient temperatures in a solvent-free mixture of substrates using 1,3-specific lipases [10–13]. In this case, the temperature in the bioreactor was first maintained at 60–70°C and then decreased to below the melting point of the monoglycerides that crystallized out of the reaction mixture. Yields of up to 90% were obtained with a variety of fats and oils of animal and plant origin (beef tallow; lard; rapeseed, olive, and palm oils). The important feature of this approach is that heat-sensitive oils can be processed without prior hydrogenation. Alternatively, monoglycerides have been prepared by enzymatic hydrolysis [14,15] and alcoholysis [15–17] of oils catalyzed by the same enzymes. The former reaction is especially attractive as it can be carried out either in batch or continuously in a packed-bed reactor. The production of monoglycerides rich in high-value, polyunsaturated fatty acids is a particulary good example of the successful implementation of this technology [18].

Alternatively, mono- and diglycerides have been prepared by the direct condensation of fatty acids and glycerol [19–21]. An especially good example is the synthesis of speciality (poly)glycerol esters by esterification of di-, tri-, and tetraglycerols with linolenic acids [22,23]. High conversion was achieved in batch experiments conducted vacuum to provide an equilibrium shift to the final product by evaporation of water produced during the reaction. The resulting products, especially tetraglycerol linolenate, were found to stabilize unusually high concentrations of water-in-oil microemulsions. This is of great interest to the food industry as a means of including water-soluble ingredients (e.g., antioxidants, vitamins, coloring agents) in edible oils and high-fat foods.

IV. SYNTHESIS OF SUGAR FATTY ACID ESTERS

Sugar fatty acid esters are employed as industrial detergents and food emulsifiers in numerous products and processes. The main drawback of the

current manufacturing methods is the high energy consumption and, in particular, the formation of undesirable by-products. Also, a multitude of structural isomers are obtained due to the presence of numerous hydroxyl groups in carbohydrate substrates. For example, gas chromatographic (GC) analysis of food grade sorbitan esters carried out in the author's laboratory showed the presence of at least 65 individual compounds [24], identified as various dehydration products of sorbitol and their mono-, di-, and triesters. Understandably, there is increasing concern over the allergenicity and carcinogenicity of some of these by-products [25].

Traditionally, sorbitan esters are prepared by esterification at 180–260°C in a solvent-free mixture of fatty acids and molten sorbitol [26,27]. Under these conditions, sorbitol undergoes rapid dehydration to yield various regiosomers of sorbitan and isosorbide (Fig. 1), which are then esterified using the same acid catalyst in a one-pot reaction. However, it has been

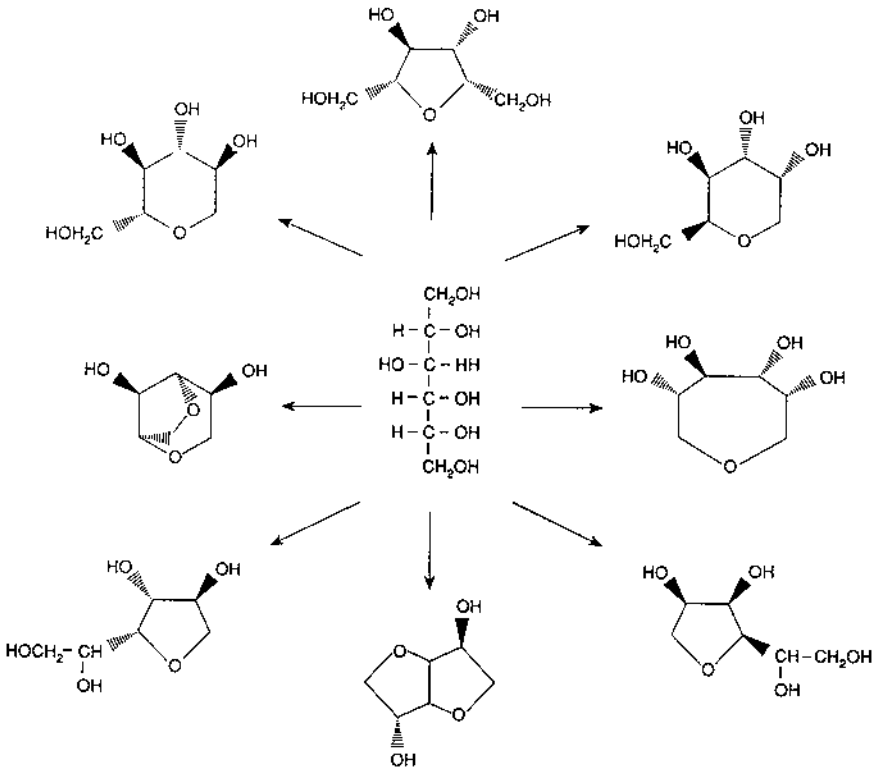

FIG. 1 Structures of sorbitol dehydration products.

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shown that the dehydration of sorbitol can be accomplished under much milder conditions (i.e., a few hours a 100–110°C) to minimize the formation of side products and prevent browning [28]. Typically, longer reaction times, higher temperatures, and harder vacuums yield "sorbitans" richer in isosorbide and lower in sorbitol. Recently, we have performed enzymatic esterification of several sorbital preparations with up to 80% conversion being observed after 8 h of incubation in the presence of immobilized *Candida antarctica* lipase [29]. The resulting product contained about 20% of unreacted sugar, an amount similar to that found in several commercially available sorbitan esters. However, the ratio of monoesters to diesters (up to 8:1) was higher and, more importantly, can be controlled by the composition of the reaction medium. The synthesis was performed in a batch bioreactor at a temperature as low as 64°C in specially formulated azeotropic mixtures containing *tert*-butanol [29].

The polyoxyethoxylated sugar esters, such as Tween, are another example of industrially important surfactants whose traditional manufacturing methods may face competition from the emerging enzyme-based technology. It has been shown in the author's laboratory [30] that ethoxylated glycosides can be readily esterified using several enzymes, notably *Candida antarctica* (Novozyme) and *Mucor miehei* (Lipozyme) lipases. The latter enzyme showed a much greater selectivity for the primary hydroxyl group on the polyethylene glycol chain of the glycoside substrate, thus enabling us to obtain exclusively the corresponding monoester, *O*-oleoyltetraethylene glycol β-D-glucoside (Fig. 2). Novozyme was used for the preparative synthesis of two other monoesters, 6-*O*-oleoyl(methoxytriethylene glycol) β-D-glycoside and *O*-oleoyltetraethylene glycol β-D-xyloside, as both of these substrates contained a single primary hydroxyl group. Two diesters, dioleoyltetraethylene glycol-β-D-glycoside and tetraethylenebis (6-*O*-oleoylglucoside), were also synthesized in good yields using these lipase (Fig. 2). The starting materials, tetraethylene glycol β-D-glucoside, tetraethylene glycol β-D-xyloside, and methoxytriethylene glycol β-D-glucoside, were prepared via enzymatic (trans)glycosylation carried out in supersaturated solutions of glucose/*p*-nitrophenyl-β-D-xyloside and the respective polyethylene glycols [30,31]. Although this procedure relies on the use of a very inexpensive enzyme (almost β-glucosidase) and gives reasonable yields, the chemical synthesis of substrates from glucose or directly from starch is probably a preferred route for large-scale production. Also, more work will be required to improve volumetric productivity and the overall yield of the final products. However, there is no apparent reason for this reaction not to proceed in a solvent-free mixture of substrates or at least in the absence of bulk solvents.

Enzymatic solvent-free synthesis of sugar fatty acid esters was first reported by Adelhorst et al. [32] who performed regioselective acylation of

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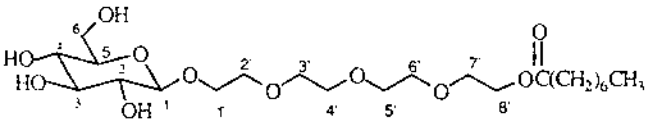
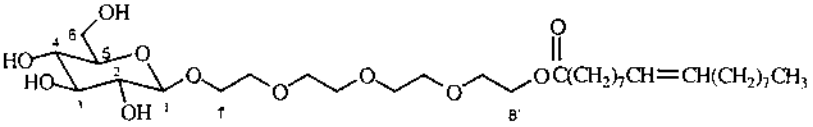
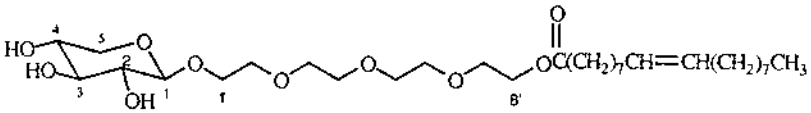


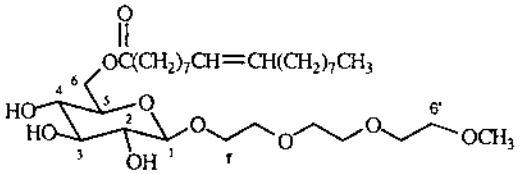
1. 8'-Capryl Glc-PEG$_4$



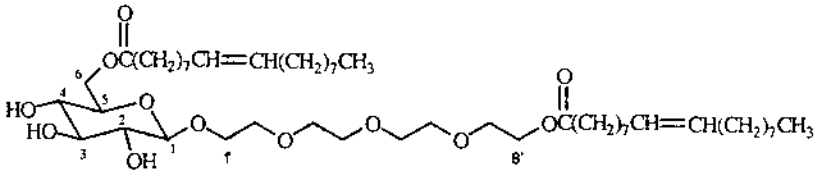
2. 8'-Oleoyl Glc-PEG$_4$



3. 8'-Oleoyl Xyl-PEG$_4$



4. 6-Oleoyl Glc-PEG$_3$-OMe



5. 6,8'-Dioleoyl Glc-PEG$_4$

FIG. 2 Enzymatically prepared ethoxylated glucoside (Glc) and xyloside (Xyl) esters.

simple alkylglycosides in molten fatty acids. The rate of esterification was found to be markedly dependent on the length of the alkyl group. Thus, only 20% yield was obtained with glucose and methylglucoside after 1 and 21 days of incubation, respectively, whereas when ethyl, *n*-, and isopropyl or butylglucosides were used in the reaction was completed in a few hours. A range of 6-*O*-acylglucopyranosides was prepared in up to 90% yield using a slight mole excess of free fatty acids and the process has been tried on a pilot scale [33]. Some technical difficulties of handling highly viscous liquids on an industrial scale were subsequently overcome by converting the reactants to a microemulsion by addition of a surface-active agent (e.g., the reaction product itself) and a small amount of solvent [34]. The resulting alkylglucoside fatty acid esters are claimed to be nontoxic, rapidly biodegradable, and are expected to find applications in personal care products and/or as household detergents.

So far we have considered the enzymatic synthesis of sugar esters which are the same or very similar to those manufactured by conventional methods, i.e., solvent free (trans)esterification at elevated temperatures. However, these conditions are too drastic for using reducing mono- and disaccharides. In addition, a mixture of regiosomers is invariably obtained as it is virtually impossible to control the selectivity of esterification. The obvious attractions of using enzymes as biocatalysts is that neither of these problems arises. Since the first demonstrations of the utility of enzymes in the regioselective acylation of monosaccharides [35,36], numerous elegant transformations have been described in the literature. Thus, the synthesis of mono- and disaccharide fatty acid esters in anhydrous organic solvents has been successfully accomplished by several groups [37–47]. In the earlier work, solvents like dimethylsulfoxide, pyridine, and 2-pyrrolidone were used, which led to very low catalytic activity displayed by enzymes and rapid inactivation of the biocatalyst. This resulted in long reaction times and low overall productivity, making this approach unattractive for the manufacturing of bulk products. More recently, it has been found that *tert*-alcohols are much better solvents for the enzymatic esterification of sugars [44–46]. The solubility of monosaccharides in *tert*-butanol is sufficient for the reaction to proceed satisfactorily and, with an excess of the solid substrate added to the reactor, high concentrations of the final product are obtained. The synthesis can also be carried out under reflux conditions in azeotropic *tert*-butanol/hexane mixtures at 65–70°C and atmospheric pressure [29].

Alternatively, sugar acetals have been used as starting materials for the solvent-free esterification to produce mono- and disaccharide fatty acid esters [48–52]. The final products were obtained in good yields after mild acid hydrolysis of the corresponding sugar acetal esters. Although large-scale acetalization and subsequent deprotection do not present serious

technological difficulties, the overall synthetic sequence is undoubtedly more complicated as compared to the esterification of unmodified monosaccharides. It remains to be seen, therefore, as to whether these additional steps can be justified by improved productivity. At any rate, there is little doubt that this methodology provides a more efficient route to the synthesis of disaccharide esters [51,52], which are poorly soluble in most organic solvents, including *tert*-alcohols.

It should be noted that the use of isopropylidene groups in these syntheses was designed to improve the miscibility of the reactants and must be distinguished from the conventional protecting strategy employed in a regioselective organic synthesis. For example, 6′-*O*-acyl lactose was obtained as sole product after the cleavage of isopropylidene groups, even when a crude mixture of partial lactose acetals was enzymatically esterified [51]. Due to the strict enzyme regioselectively toward the 6′-hydroxyl group, no acylation was observed with 4′,6′-isopropylidene lactose, whereas the reaction with 3′4′-isopropylidene derivative and lactose tetraacetal led to the formation of the same 6′-monoester after mild acid hydrolysis (Fig. 3). Consequently, no separation of partial acetals from a rather complex mixture, obtained by acetalization of lactose with 2,2-dimethoxypropane, was necessary prior to the esterification with the desired regioselectivity achieved solely through the lipase specificity.

The strict regioselectivity of enzymes has been further exploited in the modification of chemically synthesized sugar esters. Thus, the hydroxyl group at C-6 of the glucose moiety of sucrose is the most reactive under the conditions of chemical acylation employed in industry; 6-*O*-acyl sucrose amounts for 46% of the monoesters (40% of total esters) present in the commercial preparations (Fig. 4, top). On the other hand, Novozyme shows a marked preference for the 6′ position [52]. As a result, the treatment of the commercial preparation of sucrose monoesters with this enzyme led to selective cleavage of 6′-*O*-acyl sucrose and subsequent isolation of highly enriched fraction of 6-*O*-acyl sucrose (up to 80% of the required regioisomer) in 39–54% yield (Fig. 4, bottom). A similar approach was described by the Chauvin and Plusquellec [53] who successfully hydrolyzed the unwanted 6-*O* regioisomer, using *Candida rugosa* lipase, from a mixture of sucrose monoesters prepared by a chemical acylation method employing 3-acyl-5-methyl-1,3,4-thiodiazole-2(3H)-thiones.

Finally, it has been shown in the author's laboratory that lipases are rather useful catalysts for the synthesis of dimeric "gemini" surfactants. Our interest in these compounds was due to several recent reports dealing with the preparation and properties of geminis, which are effectively two molecules of a conventional monomeric surfactant linked through a flexible spacer. It appeared that dimeric surfactants display most unusual patterns

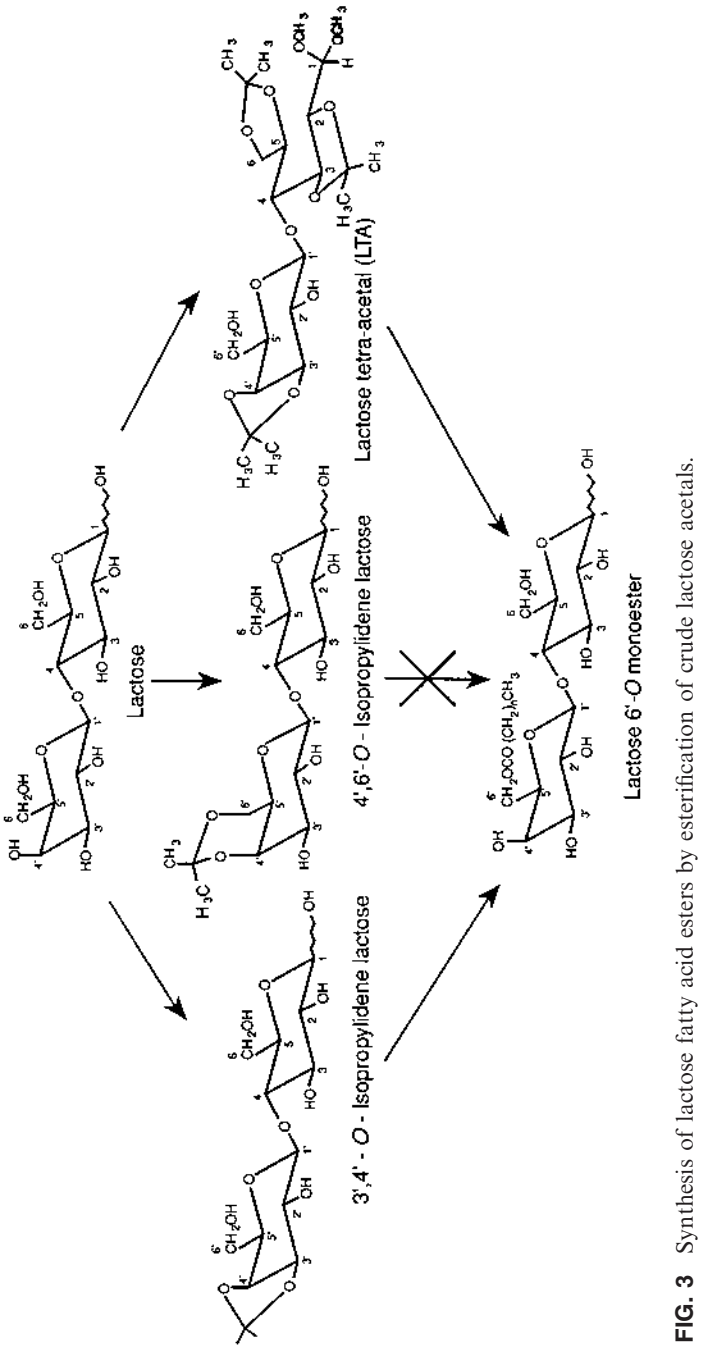


FIG. 3 Synthesis of lactose fatty acid esters by esterification of crude lactose acetals.

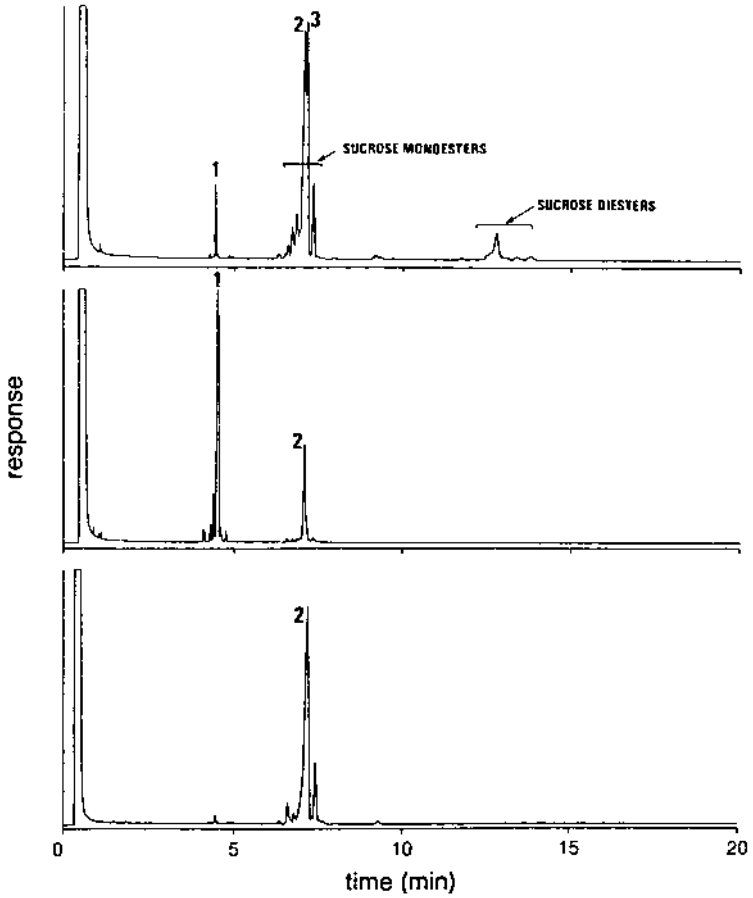


FIG. 4 Enzymatic modification of commercial sucrose monoesters. Gas chromatograms of sucrose monolaurate Ryoto L1695 (top); the product obtained after treatment with Novozyme in 2-propanol and subsequent precipitation of 6-*O*-lauroyl sucrose before (middle) and after (bottom) column chromatography on silica gel. See Ref. 52 for experimental details, 1, sucrose; 2,6-*O*-lauroyl sucrose; 3,6′-*O*-lauroyl sucrose.

of self-assembly [54–56] and intriguing physicochemical properties. For example, ionic geminis have two orders of magnitude lower CMC values than the monomeric alkylsulfonate analogs are very efficient at reducing surface tension both on their own and in combination with conventional surfactants [57]. Other useful properties of geminis are the much lower Krafft points and higher solubility in water was compared to their monometric

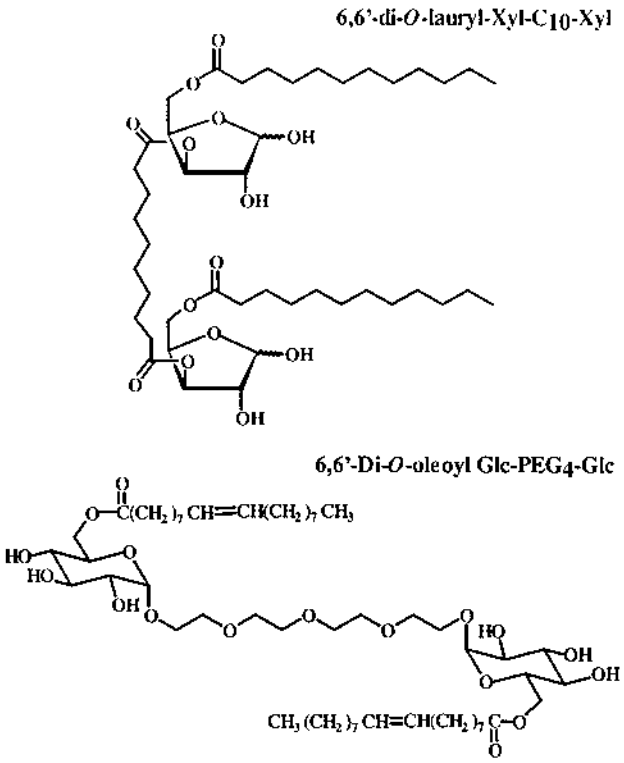


FIG. 5 Examples of enzymatically prepared glucose (Glc)– and xylose (Xyl)–based gemini surfactants.

counterparts [57,58]. Some examples of enzymatically prepared sugar-based geminis are shown in Fig. 5. This work is currently being prepared for publication [59].

V. SYNTHESIS AND MODIFICATION OF PHOSPHOLIPIDS

Processed phospholipids ("special lecithins") are used in the manufacturing of paints, leather, and numerous foods such as bakery goods, chocolate, margarines, etc. Derivatized phospholipids also have specific applications in pharmaceuticals and personal care products [60]. Although several chemical and physical modifications of lecithins have been adopted by industry [61], there is a clear scope for the application of enzymes to the transformation of

phospholipids due to the requirement for control over the regioselectivity and/or the degree of modification necessary for obtaining a product with the desired functional properties.

Phospholipase D has been extensively studied as a catalyst for the synthesis of phospholipids which are naturally occurring in minor quantities. Phosphatidylserine [62] and phosphatidylglycerol [63] have been prepared in excellent yields from phosphatidylcholine (the major component in natural extracts) and glycerol and serine, respectively. Alternatively, enrichment in phosphatidylcholine can be achieved by transphosphatidylation under low-water conditions with minimal formation of contaminant phosphatidic acid [64]. Some phospholipase D–mediated syntheses have been carried out on a multikilogram scale.

Lysophospholipids, obtained by complete or partial hydrolysis of lecithins, constitute another class of industrially important surfactants that are currently prepared on a large scale. This hydrolytic reaction, catalyzed by phospholipase A_2, is typically carried out in 30% phospholipid emulsion in water. However, the process suffers from several complications, one of which is the necessity to inactive phospholipase A_2 after completion of the hydrolysis because it is practically impossible to recover and reuse the enzyme from the heterogeneous reaction mixture. Irreversible inactivation of the phospholipase is achieved either by a combination of alkalization and heat treatment

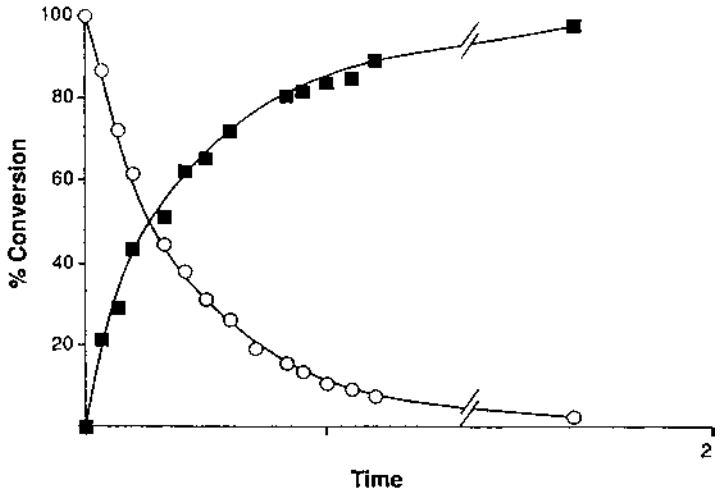


FIG. 6 Kinetics of lipase-catalyzed transesterification of crude lecithin (50 g/L) catalyzed by Lipozyme IM-60 in ethanol containing 5% water. The consumption of lecithin (open symbols) and the accumulation of lysolecithin are shown.

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or by digestion with protease(s) followed by temperature-induced inactivation of the latter. Thus, the production of lysophospholipids presents a rare case where the enzyme stability is a drawback rather than an advantage for the manufacturing process. The above complications would be avoided, however, if it was possible to run the process in a homogeneous reaction mixture with immobilized enzyme. This was achieved by replacing phospholipase A_2 with Novozyme, which was shown to catalyze the transesterification of lecithin in alcohols (Fig. 6). The lipase displayed strict regioselectivity toward *sn*-1 fatty acid in the phospholipid molecule, thus yielding exclusively *sn*-1 lysophospholipid as the final product [65]. The *sn*-2 lysophospholipids were also obtained by subsequent acyl migration catalyzed by ammonia vapor. Unlike phospholipase A_2, lipases do not require cofactors and the reaction was performed continuously for 1200 h in a packed bed bioreactor with no appreciable loss of enzyme activity [65].

VI. SYNTHESIS OF AMINO ACID–BASED SURFACTANTS

Amino acid esters and amides have been a subject of intensive investigations due to their excellent emulsifying properties, biocompatibility, and strong antimicrobial activity [66–74]. These features have made them attractive for applications in cosmetics and personal care products, food, and pharmaceutical formulations. Additionally, there are also good reasons for considering amino acid–based surfactants as potential bulk detergents for industrial and household cleaning usages. Indeed, their production would rely on the use of renewable and inexpensive raw materials (i.e., amino and fatty acids) with expected rapid and complete biodegradability in the environment. Furthermore, the structural diversity of amino acids should enable manufacturers to "tailor" the functional properties of these surfactants to suit particular applications.

Although the diverse functionalities of amino acids is a great asset for fine-tuning the surfactant's performance, it is a potential drawback from a synthetic viewpoint due to the requirement for the temporary protection of any reactive functional groups. It is somewhat surprising, therefore, to find that relatively few attempts have been made so far to circumvent at least some of the synthetic difficulties by utilizing the selectivity of enzymes [75–78].

Nagao and Kito [75] have prepared L-oleoyl homoserine and assessed some of its emulsifying properties. The product was highly efficient in stabilizing oil-in-water emulsions but exceedingly low yields were obtained with L-homoserine and practically no reaction was observed with inexpensive, natural hydroxyamino acids such as serine, threonine, and tyrosine. In the

author's laboratory L-acyl serine was prepared in 50% overall yield on a multigram scale via solvent-free esterification of N-protected derivatives of the amino acid [76].

Enzymatic acylation of the α-amino group of amino acid amides using free fatty acids or their methyl esters has been reported by Novo-Nordisk scientists [77]. A range of *N*-α-acylamino acid amides was prepared in up to 50% yields. The products were quantitatively converted to *N*-acylamino acids by means of a second enzyme, carboxypeptidase. A similar approach has been applied by Montet et al. [78] for the preparation of *N*-ε-acyllysines. The authors used a suspension of free amino acid in organic solvents containing vegetable oils that was incubated for 7 days at 90°C in the presence of *Mucor miehei* lipase. However, we found that this reaction can be performed much more efficiently via chemical acylation of lysine–copper complexes in water giving *N*-ε-acyllysines in up to 64% yield with excellent regioselectivity [76]. It has also been found in our study that lipases are excellent catalysts for the acylation of amino acid glycerol esters, including that of lysine and several others, giving the corresponding 1(3)-aminoacylmonoglycerides in good yields (Fig. 7). The developed methodology provides easy access to a range of compounds that are interesting cationic/zwitterionic surfactants in their own right and can be used as building blocks for further

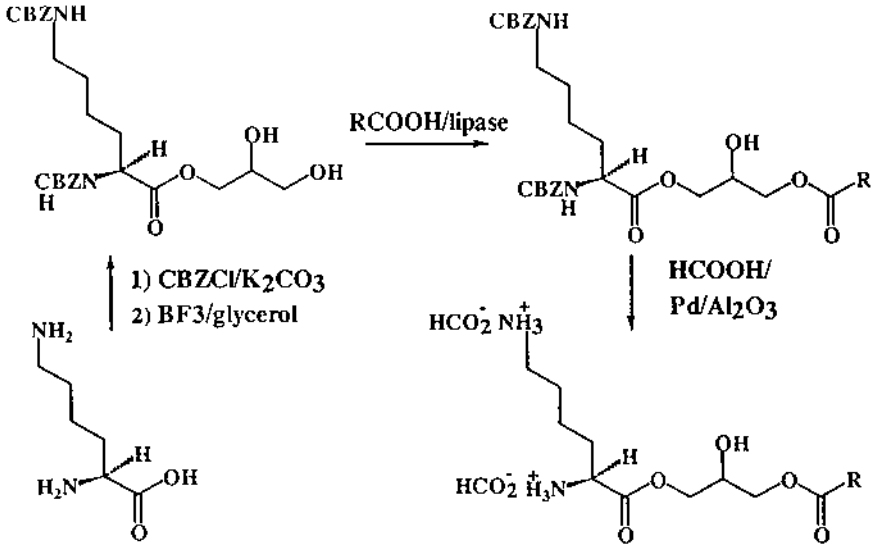
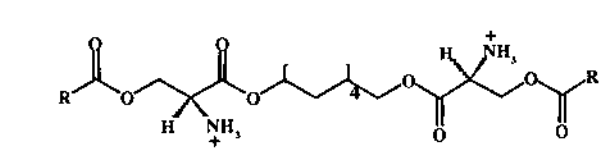
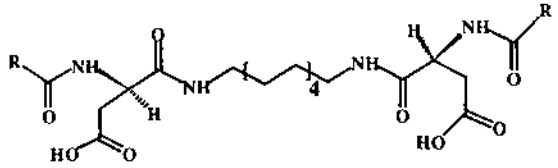


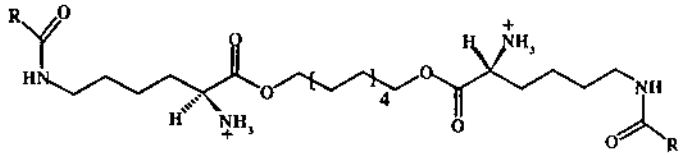
FIG. 7 Synthesis of aminoacylmonoglycerides. CBZ, carbobenzyloxy group.



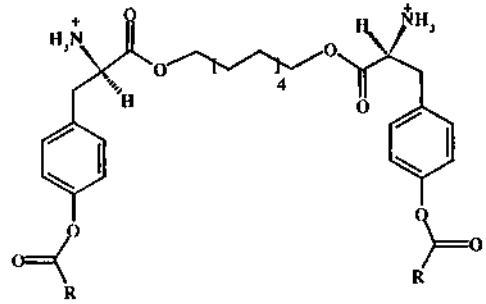
Bis(O-myristoyl-L-serine) 1,10-decanediyl ester



Bis(N-myristoyl-L-glutamic) 1,10-decanediamide



Bis(Nε-myristoyl-L-lysine) 1,10-decanediyl ester



Bis(O-myristoyl-L-tyrosine) 1,10-decanediyl ester

FIG. 8 Structures of amino acid–based gemini surfactants as exemplified by lysine.

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transformations (e.g., the synthesis of peptide–lipid conjugates and novel oligopeptide-based structures).

More recently, we have developed an alternative chemoenzymatic route to the preparation of a variety of amino acid–based surfactants ranging from simple monoesters to more complex gemini amphiphiles [79]. This approach was based on the observation that some lipases, notable immobilized *Candida antartica* and *Rhizomucor miehei*, readily accept N-Cbz amino acids as substrates and catalyze their esterification/amidation with α,ω-diols/α,ω-diamines in excellent yields. The resulting alkanediyl-α,ω-bis-(*N*-Cbz-amino acid) was further modified to obtain a range of amino acid–based gemini surfactants. Some examples of the products obtained in this work are shown in Fig. 8.

VII. SYNTHESIS OF ANOMERICALLY PURE ALKYLGLYCOSIDES

The major attraction of alkylglycosides as compared to sugar fatty acids esters is their much better stability under alkaline conditions. Anomerically pure alkylglycosides are also useful in biomedical and pharmaceutical applications. In order to prepare a product of high anomeric purity by traditional chemical methods, it is necessary either to perform a conventional protection/activation/coupling/deprotection sequence or to synthesize the glucoside as a mixture of anomers that require subsequent chromatographic resolution. Enzymes have a dual attraction as a catalyst for this type of reaction. First, a wide range of very inexpensive glucosidases are currently available on the market and, second, they provide absolute stereochemical control at the anomeric center of the newly synthesized glycosidic bond. Consequently, the synthetic potential of glycosidases has been actively explored over the last decade.

Unfortunately, attempts to perform the synthesis of alkylglycosides in nearly anhydrous organic solvents have been largely unsuccessful because glycosidases, unlike esterases, do not seem to function particularly well in very low water environments, even after immobilization [80] or chemical derivation [81]. In some instances, this problem has been overcome by using appropriate water-miscible cosolvents to keep both reactants, i.e., the sugar and alcohol, in solution. Indeed, there are examples in the literature when enzymatic transglycosylations have been carried out in the media containing up to 50% of acetone, acetonitrile, or an alcohol [82,83]. Unfortunately, most enzymes are too unstable under these conditions and undergo rapid and irreversible denaturation in the presence of intermediate to high concentrations of water-miscible cosolvents [84]. However, when a cosolvent content in

the reaction mixture is further increased to approximately 90%, the stability of glycosidases improves dramatically. Several groups have described the synthesis of alkylglycosides in predominantly organic media, although in most cases the yields obtained were not very high [85–87].

Aqueous-organic two-phase systems offer a good alternative in terms of enzyme stability. However, a general drawback of two-phase systems is that of relatively low reaction rates displayed by the enzymes. Nonetheless they have been successfully employed by several authors for the preparation of medium-chain alkylglycosides [80,88–94]. In principle, the reaction kinetics and hence the overall productivity of aqueous organic two-phase systems should improve if it is possible to disperse the aqueous phase in the solvent and to stabilize the dispersion, at least for the time necessary for the biotransformations to occur. Recently, we have shown this to be the case by performing the reaction inside permeable polymeric microcapsules prepared by interfacial polymerization using the procedure, originally developed in our laboratory for the immobilization of microorganisms [95].

Almond β-glucosidase has been microencapsulated at neutral pH and room temperature to avoid the inactivation of biocatalyst and subsequently used for the preparation of alkylglucosides [96]. As above, the synthesis was carried out in a two-phase reaction mixture: polymeric microcapsules, containing enzyme and a saturated solution of glucose (aqueous phase), were suspended in primary alcohol that formed the organic phase. Glucose and a small amount of oligosaccharide by-product usually formed in this reaction were confined to the aqueous interior of the capsule, whereas the relatively hydrophobic alkylglucoside was extracted into the solvent where it accumulated in a practically pure form (Fig. 9). The major advantages of this methodology are improved productivity due to enhanced mass transfer and

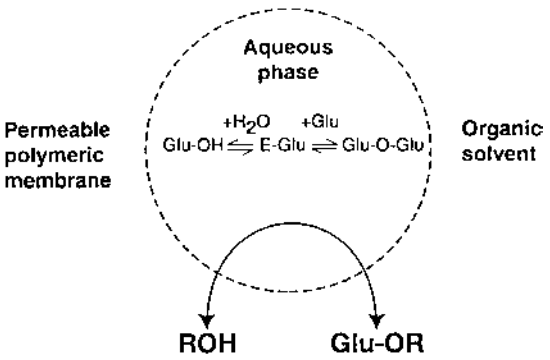

FIG. 9 Alkylglucoside synthesis in an aqueous organic two-phase system.

the possibility of performing the synthesis continuously in a specially designed bioreactor [96].

VIII. CONCLUSION

Enzyme-catalyzed reactions have gained considerable importance in synthetic organic chemistry due to the high selectivity and mild reaction conditions associated with the use of biocatalysts. However, with a few notable exceptions, the industrial application of enzymes is still limited to the production of specially rather than bulk chemicals. The cost of enzymes remains the single biggest issue hampering their widespread commercial usage. However, the advances in genetic and protein engineering should enable enzyme manufacturers to offer large quantities of recombinant biocatalysts with superior characteristics and at much reduced costs. For example, the cost of enzymes for use in washing powders has come down significantly n the last few years reaching the level of £8–10 per kg. In addition, enzymatic methods can now offer high volumetric productivity, and in many instances the efficient reuse of enzymes does not present a serious problem. Indeed, there is nothing unusual about bioreactors containing immobilized lipases that were operated continuously for 1000 h. Admittedly, it would be overly optimistic to expect that the enzymatic manufacture of surfactants will become economically significant in the near future; this is a conservative industry with the high capital investment cost. In the author's view, we are most likely to see a gradual introduction of "biosurfactants" to the marketplace starting, perhaps, from the low-volume/high-added-value products. In conclusion, I hope that this chapter demonstrates that enzymes offer real advantages over traditional manufacturing methods and that it is only a matter of time before this technology will make a move from the laboratory factories.

ACKNOWLEDGMENT

The author is grateful to BBSR, EC, Unilever, Mitsubishi, ICI, and Pernod-Ricard for financial support of work carried out in this area over the years.

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Surfactants Produced by Microorganisms

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I. INTRODUCTION

Certain microorganisms are able to convert preferably carbohydrates, *n*-alkanes (C_{10}–C_{20}), and triglycerides (fatty acids C_{10}–C_{22}) into biosurfactants. The carbon sources may be used separately or in combination with each other. Representative examples are low molecular mass glycolipids and lipopeptides as well as high molecular mass lipopolysaccharides and lipoproteins. Summaries on the microbial "workhorses," the chemical structures of biosurfactants, the microbial production data and, additionally, their potential commercial applications were presented recently [1–5]. Precondition for the overproduction of biosurfactants is, in principle, that first sufficient biomass, which provides the corresponding biosynthetic enzymes, has to be produced (Fig. 1). After initially studying a lot of parameters for the best cultivation conditions of the microorganism, e.g., nutrients, pH, temperature, aeration rate, etc., subsequently the conversion of special carbon sources to individual biosurfactants has to be investigated in detail (Fig. 2). Because of different substrates capable to be converted to glycolipids, e.g., their general biosynthesis pathways concerning degradation, gluconeogenesis, and lipid synthesis are presented in Fig. 3. If biosynthesis details of certain biosurfactants are amenable, they have been reported in later chapters. As for the cultivation methods to produce biosurfactants, generally the following routes are possible:

1. Growth-associated production
2. Production under growth-limiting conditions
3. Semicontinuous production with resting cells (free or immobilized)
4. Fed-batch and continuous production

In most cases, the yields of method 1 are substantially lower than those of methods 2–4. Depending on the carbon sources used for cultivation, the low

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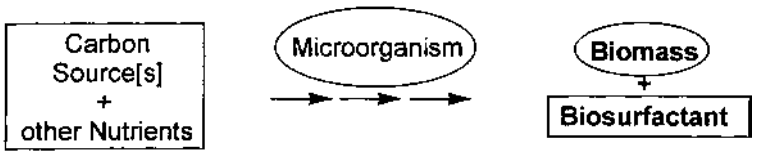

FIG. 1 Scheme of the bioconversion of nutrients into products.

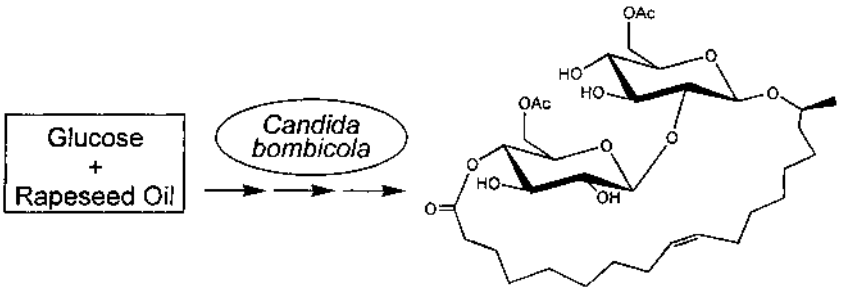

FIG. 2 Scheme of the bioconversion of suitable carbon sources into sophorolipid (classic-type, major product).

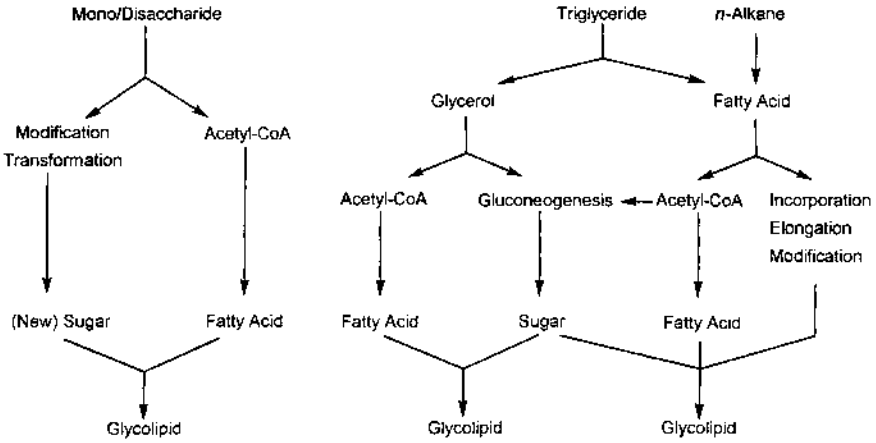

FIG. 3 Possible routes for the microbial dissimilation and assimilation of different carbon sources leading to glycolipids.

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molecular mass biosurfactants, which are isolated by solvent extraction or other procedures, are often mixtures of related compounds. They differ in the number of carbohydrate units, fatty acid/fatty alcohol units, and chain length and double-bond content of lipid moiety. As for high molecular mass biosurfactants, the variability of their compositions is some magnitudes higher than that of the aforementioned products.

In this chapter, I would like to give an overview (1) on the "first generation" microbial biosurfactants (detected between 1950 and 1990), but focusing on recent developments in production and new application potentials, and (2) on the "last decade" microbial biosurfactants (found during the last 10 years), their physicochemical properties, as well as some of their other properties.

II. FIRST-GENERATION BIOSURFACTANTS: RECENT DEVELOPMENTS IN MICROBIAL PRODUCTION AND APPLICATION POTENTIALS

Recent literature data on the molecular structure elucidation of biosurfactants have shown that, depending on different kinds of carbon substrates, it may be possible to obtain more structurally diverse versions of well-known products, e.g., variations of chain lengths of fatty acids. In the following, these related compounds have not been classified to the last-decade biosurfactants, which are substantially new-type products.

A. Rhamnose Lipids

The occurrence of rhamnolipids produced by *Pseudomonas aeruginosa* was first reported in 1949. In liquid culture, this opportunistic human pathogen produces primarily two forms of rhamnolipids: monorhamnolipid RL-1 and dirhamnolipid RL-2 (Fig. 4).

1. Biosynthesis Studies

Studies on the biosynthetic pathway have been descibed recently [6], showing that their precursors, deoxythymidinediphospho-L-rhamnose (dTDP-L-rhamnose) and fatty acids, are produced by central metabolic pathways. The synthesis of monorhamnolipid is catalyzed by the enzyme rhamnosyltransferase 1 (*rhlAB* gene product) and proceeds by a glycosyl transfer reaction in which dTDP-L-rhamnose (an activated sugar) is transferred to the fatty acid acceptor molecule, β-hydroxydecanoyl-β-hydroxydecanoate. As for rhamnosyltransferase-2, the second glycosyltransferase involved in rhamnolipid production, the first report on the identification and functional characterization of the encoding gene (*rhlC*) appeared recently [7].

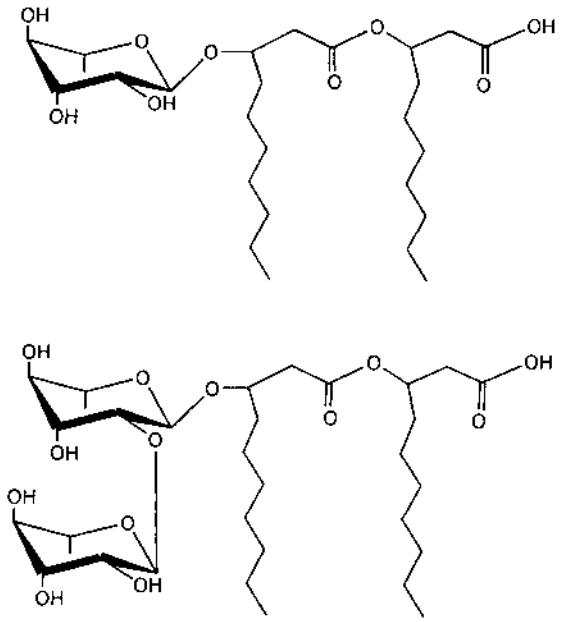

FIG. 4 Monorhamnolipid RL-1 (top) and dirhamnolipid RL-2 (bottom) from *Pseudomonas aeruginosa*.

The gene expression product (RhlC) is a protein consisting of 325 amino acids with a molecular mass of 35.9 kDa. A gene replacement strategy was used to generate chromosomal mutation in *rhlC*. Examination of these knockout strains confirmed the involvement of RhlC in dirhamnolipid biosynthesis. Since *P. aeruginosa* is capable of biosynthesis of alginate and of polyhydroxyalkanoic acid (PHA), the interrelations of genetics and enzymes have been studied. Olvera et al. showed that the *algC* gene product participates in rhamnolipid synthesis, the conversion of glucose-6-phosphate to glucose-1-phosphate [8]. Rehm et al. studied the role of fatty acid de novo biosynthesis for rhamnolipid and PHA production using various *fab* mutants [9]. Transacylase (PhaG) catalyzed diversions of intermediates of fatty acid de novo biosynthesis toward PHA biosynthesis, whereas the β-ketoacyl reductase (RhlG) catalyzed diversion toward rhamnolipid biosynthesis. The genetic regulation of rhamnolipid production is beginning to be understood. It forms part of a very complex regulatory network also regulating the expression of virulence-associated traits. The development of a metabolic engineering strategy for the production of

rhamnolipids in heterologous hosts is an important alternative for the production of these biosurfactants.

2. Microbial Production

As for the state of the art, yields of approximately 100 g/L of rhamnolipid mixture were derived in maximum [10] (Table 1). An overview on the development of the biotechological processes from the beginning up to 1997 is given by Lang and Wullbrandt [11]. In later studies, high autoinducer activity, e.g., *N*-(3-oxohexanoyl)-L-homoserine lactone, caused enhanced rhamnolipid production (32 g/L) in ethanol fed-batch culture of *P. aeruginosa* IFO 3924 [12]. Recently, to investigate the possible relationship between the above-mentioned PHA and rhamnolipid syntheses, the aerobic *n*-hexadecane fermentation of *P. aeruginosa* ATCC 10145 was studied [13]. PHA synthesis was found to occur only during active cell growth, while substantional rhamnolipid production began at the onset of the stationary growth phase. Five rhamnolipid structures were identified. In addition to the two major components (Fig. 4), three minors also have β-hydroxydodecanoic or β-hydroxydodecenoic acid as the second acid. Another study focused on the reuse of olive and sunflower cooking oils (frying oils) as substrates for biosurfactant production by different genera of bacteria and yeasts [14]. *P. aeruginosa* 47T2 was selected for further studies. The effect of nitrogen and a C/N ratio of 8:1 gave a final production of rhamnolipids of

TABLE 1 Characteristic Data on the Microbial Production of Rhamnose Lipids (RLs), Trehalose Corynomycolates (TL-Cs), and Anionic Trehalose Lipids (TLs), Respectively

Microorganism and carbon source (g/L)	Biosurfactant and yield (g/L)	$Y_{P/S}$ (g/g)	P_V (g/L × h)	Ref.
Pseudomonas aeruginosa:	*RL*			
Soybean oil (163)	112.0	0.68	0.42	10
Ethanol (65)	32.0	0.49	0.16	12
Rhodococcus erythropolis:				
	TL-C			
n-C_{12}–C_{18} (20)	2.0	0.10	0.05	25
	TL			
n-C_{10} (100)	32.0	0.32	0.20	29
n-C_{16} (90)	40.0	0.44	0.16	31

General conditions: shake flasks and bioreactor cultures; mineral salt and complex media; 25–35°C; pH 6–7.5. $Y_{P/S}$, specific production based on substrate; P_V, volumetric productivity.

2.7 g/L as rhamnose, and a production yield of 0.34 g/g. Using *P. aeruginosa* UG2, Mata-Sandoval et al. [15] investigated the influence of different substrates and culture conditions. With 2.9 g/L after 10 days the strain produced between 64% and 80% more rhamnolipids using corn oil as carbon source as compared to lard, 1-dodecanol, 1-tetradecanol, and glucose. To overcome foaming problems in aerobic cultivation of *P. aeruginosa*, a new strategy for rhamnolipid production was developed using strain ATCC 10145 [16]. In the absence of oxygen and under denitrification conditions fatty acids were successfully assimilated and converted to rhamnolipids. P-limitation was necessary. The specific productivity and dentrification was found to be about one-third that of the aerobic condition.

3. Physicochemical Properties

Rhamnolipid mixtures produced with *P. aeruginosa* UG2 and with corn oil as sole carbon source solubilize the hydrophobic herbicide trifluralin [2,6-dinitro-*N,N*-dipropyl-4-(trifluoromethyl)benzamine] to a greater extent [17]. Incompletely metabolized hydrophobic by-products seem to increase the solubilization capacity. As for the cell-free aqueous supernatants of strains grown on frying oils, those of *P. aeruginosa* 47T2 and of other eight *Pseudomonas* strains showed surface tension values from 32 to 36 mN/m [14]. The emulsion with kerosene remained stable for 3 months. In addition, two *Bacillus* strains were found to accumulate lipopeptides and decreased the surface tension to 32–34 mN/m. Abalos et al. [18] cultured *P. aeruginosa* AT10 in a mineral salts medium with 5% of waste free fatty acids (major components: 21% oleic acid, 48% linoleic acid) of a food oil refinery. The final production of rhamnolipids was 9.5 g/L after 96 h. The surface tension of the supernatant reached 28 mN/m at this time. The identification of the glycolipids indicated a mixture M_7 consisting of seven rhamnolipids. Among known products, a monorhamnolipid containing an alkyl polyunsaturated chain C8:2 is reported for the first time. The M_7 mixture lowered the surface tension to 27 mN/m at a CMC of 150 mg/L. Peker et al. [19] showed that in aqueous solutions at a rhamnose/rhamnolipid ratio of 0.5 the surface viscosity increased, the surface tension decreased, and the foam volume decreased. The metal-complexing properties of monorhamnolipid RL-1 produced by *P. aeruginosa* ATCC 9027 were studied by Sandrin et al. [20] and Ochoa-Loza et al. [21]. As for the former one, metal toxicity could be reduced to allow enhanced organic biodegradation by *Burkholderia* sp RL-1 eliminated cadmium toxicity (by complexing) when added at a 10-fold greater concentration than cadmium. Concerning the latter publication, using an ion-exchange resin technique stability constants for many metals were determined. The data indicate that monorhamnolipid will preferentially complex metal contaminants such as lead, cadmium, and mercury in the

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presence of common soil or water cations. These results help delineate the conditions under which rhamnolipid may be successfully applied as a remediation agent in the removal of metal contaminants from soil, as well as surface waters, groundwater, and waste streams. Studies on rhamnolipids testing for use in soil remediation are summarized in [11]. In addition, a facile remediation procedure of mousse oil waste using that biosurfactant was recently reported [22]. Another group found significant positive effects on the biodegradation of gasoline-spilled soil [23].

4. Biological Activities

Pure mono- and dirhamnolipids indicated zoosporicidal activity on species of three representative genera of zoosporic phytopathogens [24]. The rhamnolipids M_7 described in [18] also showed excellent antifungal properties against the phytopathogenic fungi *Botrytis cinerea* and *Rhizotecnia solani* (minimal inhibitory concentration: 18 μg/mL).

5. Commercial Production

Rhamnolipids are commercially available from Jeneil Biosurfactant Company, Saukville, Wisconsin, USA.

B. Trehalose Lipids

Arthrobacter, *Corynebacterium*, *Gordonia*, *Mycobacterium*, *Nocardia*, and *Rhodococcus* are characterized as mycolic acid–containing genera. Mycolic acids, 3-hydroxyl long-chain fatty acids substituted at the 2-position with a moderately long aliphatic chain, are the most characteristic components of the cell wall. The carbon chain length of mycolic acids varies greatly from 22 to 90. Acyl linked to carbohydrates like glucose, fructose, or sucrose (functioning as carbon sources), they were first isolated in the 1970s. Using *n*-alkanes for growth, particularly acyltrehalose (coryno)mycolates were produced. Figure 5 (top) shows such a glycolipid of *Rhodococcus erythropolis*, the lipid moiety of which was dominated by $C_{32}H_{64}O_3$ to $C_{38}H_{76}O_3$ in position 6 and 6′ of the disaccharide.

1. Biosynthesis Studies

Biosynthesis studies revealed that the lipid component as well as the trehalose unit were first synthesized independently of each other and subsequently were linked together. As for the above-mentioned strains, an exemplary synopsis on biosynthesis, production, and potential applications was presented for surface-active lipids of rhodococci [25]. Only recently using *Corynebacterium matruchotii* the following facts were clarified: (1) Trehalose-6-phosphate, but not trehalose, stimulated corynomycolate synthesis

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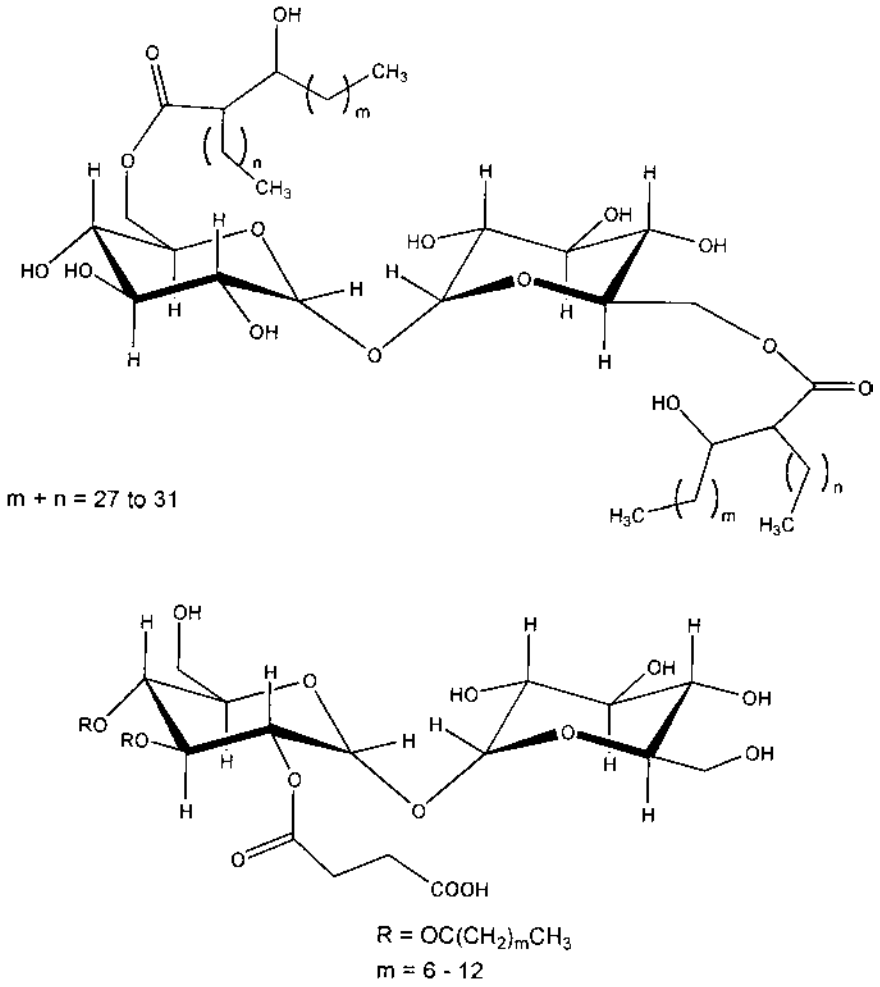

FIG. 5 Nonionic trehalose dicorynomycolates (top) and anionic trehalose esters (bottom) from *Rhodococcus erythropolis*.

from the lipophilic carbon source (palmitate) in the presence of ATP. The immediate product was trehalose-6-corynomycolate (TMM), which showed a rapid turnover to give α-trehalose-6,6′-dicorynomycolate (TDM). Since the turnover was blocked by addition of α-trehalose, only TMM accumulated among corynomycolate-containing substances. (2) TMM was the precursor not only to TDM and free corynomycolic acids but also to cell wall corynomycolate [26].

2. Microbial Production

As for the cell growth–associated production, a maximum of 2 g/L of nonionic trehalose dicorynomycolates were derived from 2% (w/w) *n*-alkanes (Table 1). Only recently Philp et al. [27] examined both the batch as well as the continuous cultivation of *Rhodococcus ruber* on *n*-hexadecane. In all chemostat studies, the minimal surface tension and highest critical micelle dilution achieved were poorer than in batch mode. Three glycolipids were purified. All had trehalose as the hydrophilic moiety. One of these was a typical trehalose dicorynomycolate with long α-branched, β-hydroxy fatty acids (ranging up to C_{39}). Similar nuclear magnetic resonance (NMR) and mass spectrometric (MS) data for compound 2 indicated this was also a pseudosymmetrical disubstituted trehalose derivative; however, the C-6 acyl substituents were a heterogeneous mixture of linear fatty acid units. For the third glycolipid spectra indicated the presence of an unsymmetrical trehalose moiety with an acyl substituent (linear fatty acid mixture) at one of the C-6 positions.

An anionic trehalose lipid was first documented in 1981 from *Mycobacterium paraffinicum*. Two years later a similar product, 2-*O*-succinoyl-3,4,2′-tri-*O*-acyl-α,α-D-trehalose (Fig. 5, bottom) was found culturing *Rhodococcus erythropolis* DSM 43215 under nitrogen-limiting conditions [28]. After optimization of the process more than 30 g/L of trehalose lipids could be isolated (Table 1) [29]. In addition, similar monosuccinoyl and disuccinoyl trehalose lipids have been reported from another *R. erythropolis* strain, SD-74 [30,31].

3. Physicochemical Properties

Aqueous solutions of nonionic trehalose corynomycolates and of anionic trehalose tetraesters indicated surface tension values of 32/36 mN/m (CMC, 5 mg/L) and of 26 mN/m (CMC, 15 mg/L), respectively. Studies on potential applications in environmental remediation, oil industry, cosmetics, and use in activated sludge plants have been summarized by Lang and Philp [25]. Recently, the enhanced oil desorption from mineral and organic materials using biosurfactant complexes produced by *Rhodococcus* species, particularly *R. ruber*, was observed [32].

4. Biological Activities

As for medical applications two types of succinoyl trehalose lipids produced by *R. erythropolis* SD-74 were found to induce cell differentiation instead of cell proliferation in the human promyelocytic leukemia cell line HL60. Both compounds induced HL60 to differentiate into monocytes. Furthermore, they also inhibited protein kinase C (PKC) activities of HL60 cells indicating potential for antitumoral agents [33]. Other investigations showed that

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succinoyl trehalose lipid induced differentiation of human monocytoid leukemic cell line U937 into monocyte-macrophages [34].

C. Sophorose Lipids (Classical Type)

In classical sophorolipids known since 1961, a sophorose unit is linked glycosidically to a hydroxyl fatty acid residue, as shown in Fig. 2. The C17 carbon atom of the 17-hydroxy-octadecenoic acid moiety has been determined to be *S*-configurated.

1. Biosynthesis Studies

In brief, important milestones were proofs for monooxygenase, fatty alcohol oxidase, fatty aldehyde dehydrogenase, and of glycosyltransferase, acetyltransferase, and acetylesterase; more information is given in [35].

2. Microbial Production

Sophorolipid production by *Candida bombicola* (Table 2) is a two-step process where the glycolipids are mainly produced after a first stage of

TABLE 2 Characteristic Data on the Microbial Production of Sophorolipids (SLs) and Mannosylerythritol Lipids (MELs), Respectively

Microorganism and carbon sources (g/L)	Biosurfactant and yield (g/L)	$Y_{P/S}$ (g/g)	P_V (g/L × h)	Ref.
Candida bombicola:	*SL*			
Glucose (304) + rapeseed oil fatty acid ethyl esters (184)	317.0	0.65	1.66	36
Cyrptococcus cell debris (34) + single cell oil (20) + rapeseed oil (400)	422.0	0.92	0.75	41
Glucose (300) + rapeseed oil (140)	300.0	0.68	2.37	44
Ustilago maydis:	*MEL*[a]			
Sunflower oil fatty acids (45)	30.0	0.67	0.18	50
Pseudozyma sp (*C. antarctica*):	*MEL*			
Soybean oil (72)	40.0	0.56	0.20	53
n-C_{18} (24%, v/v)	140.0	0.76	0.20	55
Glycerol (30) + oleic acid (70)	41.0	0.41	0.21	58

General conditions: shake flasks and bioreactor cultures; mineral salt and complex media; batch or fed-batch methods; 22–30°C; pH 2.5–6. $Y_{P/S}$, specific production based on substrate; P_V, volumetric productivity.

[a] Containing 10% of cellobiose lipids.

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growth, ending because of nitrogen limitation. In general, the influence of pH, temperature, and cosubstrates along with glucose as major C-sources was individually studied for the stages of growth and product formation. For instance, using *C. bombicola* CBS 6009, glucose and rapeseed oil fatty acid ethyl esters or other vegetable oil products were supplied individually or as a dual carbon source. The lipophilic substrate was added by continuous feeding. It was found that supplying both carbon sources during production step was crucial for obtaining a high production performance ranging from 250 g/L to 300 g/L or more [36–38]. In attempts to link sophorolipid production with the solution of a growing problem in the dairy industry, the disposal of cheese whey, initially Syldatk's group did not succeed because the whey lactose was not consumed by *C. bombicola* ATCC 22214 [39]. Therefore, a two-stage process was investigated: first *Cryptococcus curvatus* ATCC 20509 was cultivated on deproteinized whey concentrates, thereby totally consuming the lactose and accumulating up to 60% triglycerides (single cell oil) of its cellular dry weight as intracellular lipid under nitrogen limitation. After cell disruption, cell debris as well as single cell oil served as media for growth and sophorolipid production by *C. bombicola* but yielded only 12 g/L sophorolipids [40]. This low production yield caused by an unfavorable C/N ratio was improved by feeding of rapeseed oil during the production phase, thus leading to high concentrations of 422 g/L [41]. The crude sophorolipid mixture, obtained by this two-stage process, showed moderate to good surface-active properties (σ_{min} = 39 mN/m, CMC = 130 mg/L) [42]. In contrast, purified sophorolipids are surface active to a higher extent (σ_{min} = 35 mN/m, CMC = 10 mg/L). For cultivation of *C. bombicola* NRRL Y-17069, the resting cell method was found to produce the highest final concentration of sophorose lipids. Under the best operational conditions, 120 g/L was obtained from 100 g/L glucose, 100 g/L sunflower oil, and 1 g/L yeast extract in 8 days. The carbon yield was 0.60, the volumetric productivity 0.625 g/L × h [43]. Combining a controlled glucose and rapeseed oil (C18:1 rich) feeding (portion-wise and semicontinuously) during growth and production phase, Rau et al. [44] reached increased sophorolipid productivities. In particular, the variable coupling of oil addition to the cells maximum uptake rate enabled *C. bombicola* ATCC 22214 to produce 300 g/L in 125 h, resulting in a high productivity of 2.37 g/L × h. Additionally, the results of this fed-batch cultivation were applied to a two-stage continuous process. First stage (dilution rate $D = 0.1\ h^{-1}$): biomass production in a nitrogen-limited chemostat with glucose as primary carbon source and small amounts of oleic acid for preconditioning of the cells. Second stage ($D = 0.06\ h^{-1}$): sophorolipid production with exclusion of nitrogen. Oleic acid was the precursor for the lipid moiety; glucose served as energy source and also as precursor for the carbohydrate backbone synthesis. Increasing the stationary

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biomass of the first stage to 13.5 g/L (by increasing NH_4Cl addition), the productivity could be enhanced up to 3.18 g/L × h [44]. Using 100 g/L soybean oil and 100 g/L glucose, Kim et al. [45] studied the influence of the dilution rate (0.01–0.05) on the sophorolipid production. The maximum was at $\mu = D = 0.03\ h^{-1}$, with a productivity of approximately 1.8 g/L × h. More basic studies, not with the goal of a high overproduction, but with view on changes in lipid moiety of the product by use of different lipid precursors have been reported recently [46,47].

3. Properties

The crude sophorolipid mixture reduces the surface tension of water to 35–36 mN/m. Recently, Schippers et al. [48] studied the influence of native sophorolipids on microbial degradation of poorly soluble phenanthrene in liquid and soil suspension culture. For planning the cultivations, the CMC under the conditions used in the work were determined. The CMC of 4 mg/L in the medium was approximately 10 times lower that in soil suspension (45 mg/L). In the following cultivations with liquid and soil suspension media, enhancements of the biodegradation of phenanthrene by *Sphingomonas yanoikuyae* with surfactant addition were measurable. Fluorescence measurements showed that this effect was not due to an increasing biomass, but to an augmentation of bioavailability of the phenanthrene through increasing the apparent dissolved pollutant.

Sophorolipids did not show great antifungal and antibacterial activities except against *Candida parapsilosis* and *Staphylococcus aureus* [49].

4. Commercial Production

Sophorolipids (classic-type) are commercially available from the company Soliance, Pomacle, France.

D. Cellobiose Lipids and Mannosylerythritol Lipids

1. Biosynthesis and Microbial Production

From *Ustilago maydis* strains two types of glycolipids are known since 50 years: cellobiose lipids (CLs) and mannosylerythritol lipids (MELs). Only recently, when grown on vegetable oils or their derivatives, *U. maydis* DSM 4500 produced above mixture under nitrogen-limited condition. With 45 g/L sunflower oil fatty acids a yield of 30 g/L glycolipids was achieved. The resulting mixture contained predominantly mannosylerythritol lipids together with smaller amounts of cellobiose lipids. The production of the latter was enhanced when glucose was used as carbon source [50]. Similar cellobiose lipids, but not in association with mannosylerythritol lipids, were

detected in the mycocidal complex secreted by *Cryptococcus humicola* (Fig. 6). The peculiarities of *C. humicola* cellobiose lipids are their high degree of acetylation (up to five acetyl groups) and the β-glycosidic linkage of the cellobiose disaccharide to the terminal (ω-)hydroxyl group of one of the hydroxy fatty acids, [16:0-(α,ω-di-OH)], [18:0-(α,ω-di-OH)], [18:0-(α,ω-1, ω-tri-OH)], and [18:0-(α,ω-2, ω-tri-OH)], with open carboxyl group [51]. 0.5 g/L of the complex reduced the surface tension of 0.1 M $NaHCO_3$ from 71 mN/m to 37 mN/m and the interfacial tension against *n*-hexadecane from 39 mN/m to 10 mN/m (CMC $= 2 \times 10^{-5}$ M, at pH 4).

Mannosylerythritol lipids (Fig. 7), but not in association with cellobiose lipids, are also known from *Candida antarctica* T-34 [52,53], recently retermed to *Pseudozyma* sp. For biosynthesis studies, inhibitors of β-oxidation were used to clarify the fatty acid metabolism of MEL [54]. 2-Bromooctanoic acid drastically inhibited the lipid synthesis under growing and resting cell conditions. Moreover, the degree of the inhibition increased along with increases in both the inhibitor concentration and the chain length of the fatty acid substrate used. These results clearly provide additional

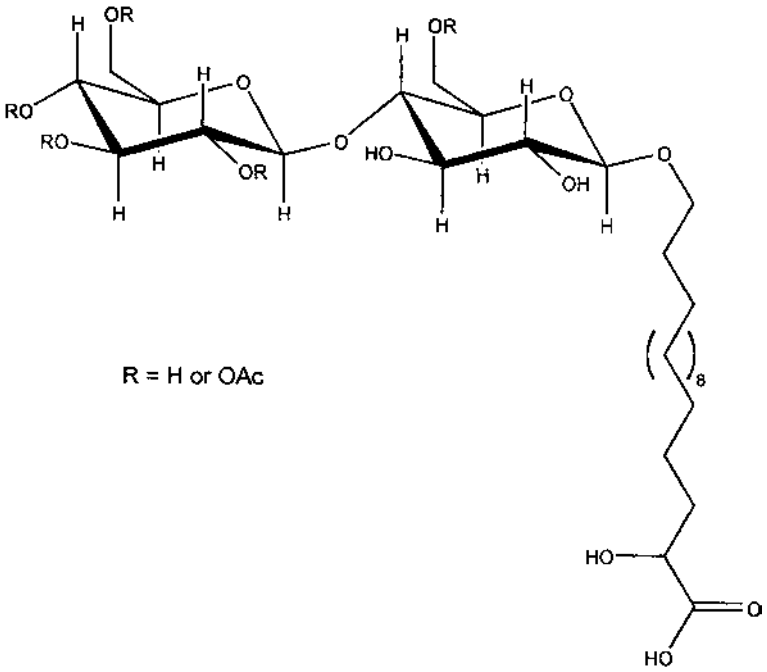

FIG. 6 Cellobiose lipid from *Cryptococcus humicola*.

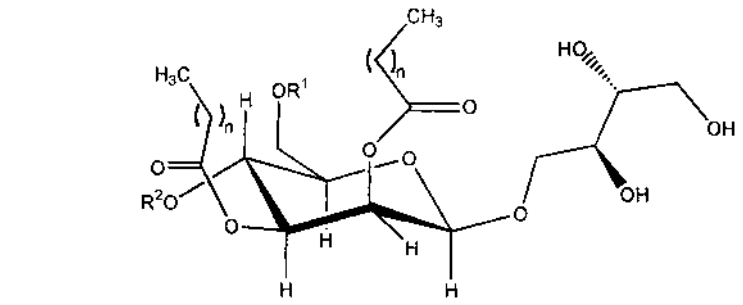

FIG. 7 Mannosylerythritol lipids from *Pseudozyma* sp. (*Candida antarctica*).

support for the essential contribution of the mammalian type of chain-shortening pathway (partial β-oxidation) to the biosynthesis of the extracellular glycolipids. Kitamoto et al. [55] studied the shake flask cultivation of *Pseudozyma antarctica* T-34 on *n*-alkanes (C_{12}–C_{18}). The highest yield (0.87 g/g substrate) was obtained from 6% (v/v) of *n*-octadecane after 7 days reaction. The amount of glycolipids reached 140 g/L by intermittent feeding of totally 24% *n*-alkane (Table 2). The fatty acid profiles of MEL-A which was the main component of MELs produced from *n*-alkanes, were then examined to address the biosynthetic pathway of the fatty acids. The major fatty acids of MEL-A were C_8 and C_{10} acids when even-chain alkanes were used, while they were C_9 and C_{11} acids when the odd-chain ones were used. In all cases, the major fatty acids of MEL-A were found to have carbon chains shortened by one or more acetyl (C_2) units from the alkane substrate employed. Adamczak and Bednarski [56] used *Pseudozyma antarctica* ATCC 20509 for cultivation on 80 g/L soybean oil. Maintaining the oxygen partial pressure at 50% with an air flow rate of 1 v/vm in a 2-L bioreactor 46 g/L of glycolipids were produced. Using *Candida antarctica* sp SY16, Kim et al. [57] found a MEL, determined to be 6-*O*-acetyl-2,3-di-*O*-alkanoyl-β-D-mannopyranosyl-(1→4)-*O*-mesoerythritol containing C6:0, C12:0, C14:0, and C14:1 acids. Continuing these studies, in a two-stage culture with glycerol and oleic acid as initial and as feeding carbon source, respectively, 41 g/L biosurfactant was observed to be produced after 8 days [58]. A similar structure of MEL, with C8:0, C12:0, and C14:2, has been reported very recently using the yeast *Kurtzmanomyces* sp I-11 [59].

2. Physicochemical and Other Properties of Mannosylerythritol Lipids

At CMCs of 2–5 $\times$ 10^{-6} M, the mannosylerythritol lipids reduced the surface tension of water and the interfacial tension between water and *n*-tetradecane to about 28 and 2 mN/m, respectively [60]. To examine the emulsifying activity (o/w emulsions, optical density measurements at 620 nm) of MEL-A and B produced from *n*-octadecane, various oils were used [55]. They showed much higher activity for soybean oil than did Tween 80 at 50 mg/L. With respect to *n*-tetradecane, the activity of MEL-A was higher than that of Tween 80 whereas that of MEL-B was similar. MEL-SY16 from *C. antarctica* sp SY16 lowered the water surface tension to 29 mN/m at CMC of 1.5 $\times$ 10^{-5} M (10 mg/L); the minimum interfacial tension was 0.1 mN/m against kerosene [57]. Evaluating the properties of mannosylerythritol lipids from *Pseudozyma candida* ATCC 20509, it was observed that the culture broth decreased the water surface tension to 35 mN/m [56].

MELs efficiently self-assemble in water to form giant vesicles, which show excellent binding affinity toward the mannose-binding protein, concanavalin A [61]. Kitamoto et al. [62] recently demonstrated that MEL acts as a potential antiagglomeration agent in an ice-water slurry system to be used for cold thermal storage. Im et al. [63] reported that the yeast glycolipid also shows a significant binding affinity toward a natural polyclonal human immunoglobulin G.

3. Biological Activities of Mannosylerythritol Lipids

MEL from *Pseudozyma* (*Candida*) sp T-34 exhibited antimicrobial activity particularly against gram-positive bacteria, and their minimal inhibitory concentrations were significantly smaller than those of commercially available sucrose and sorbitan monoesters of fatty acids [60]. In addition, MEL seems to show similar effects such as those known from gangliosides and glycosphingolipids (GSLs). These ubiquitous components of the plasma membranes of mammalian cells are reported to modulate cell growth, cell adhesion, and transmembrane signaling. MEL induced cell differentiation in the human leukemia cells [33,64], mouse melanoma cells [65,66], and rat pheochromocytoma cells [67–69].

E. Spiculisporic Acid

Spiculisporic acid has been known as a trace component of lichenous bodies since 1941. Tabuchi's group developed a new bioindustrial process for the efficient production of this tricarboxylic-type surfactant (Fig. 8) from glucose as carbon source with yields up to 110 g/L (Table 3) using the fungus *Penicillium spiculisporum* [70,71]. The native product has been chemically

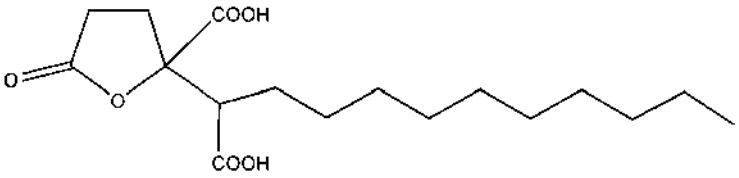

FIG. 8 Spiculisporic acid from *Penicillium spiculisporum*.

modified to produce derivatives for different applications such as new emulsion-type organogels, superfine microcapsules (vesicles or liposomes), heavy-metal sequestrants, and many other applications in specialty chemicals [72]. For instance, the di(*n*-hexylamine) salt of spiculisporic acid showed the largest surface tension lowering capacity of all, and the surface tension at CMC (1×10^{-2} mol/L) reached a value of 27 mN/m.

Spiculisporic acid (4,5-dicarboxy-4-pentadecanolide) is supplied from Iwata Chemical Co. Ltd. (Shizuoka, Japan).

F. Lipopeptides

1. Introduction to Surfactin and Related Structures

The *B. subtilis* lipopeptides are members of a particular antibiotic class formed by surfactin, iturin, and fengycin families. The general structure of these lipopeptides is a peptide cycle of seven (surfactin and iturin) or ten amino acids (fengycin) linked to a fatty acid chain. The length of the fatty acid

TABLE 3 Characteristic Data on the Microbial Production of Nonglycolipid Biosurfactants

Microorganism and carbon source (g/L)	Biosurfactant and yield (g/L)	$Y_{P/S}$ (g/g)	P_V (g/L × h)	Ref.
Penicillium spiculisporum:	*Spiculisporic acid*			
Glucose (275)	110.0	0.40	0.45	71
Bacillus subtilis:	*Surfactin*			
Glucose (40)	3.5	0.09	0.03	77
Acinetobacter calcoaceticus:	*Emulsan*			
Soybean oil (90)	25.0	0.28	0.63	91

General conditions: shake flasks and bioreactor cultures; mineral salt and complex media; 30°C, pH 2.5–7. $Y_{P/S}$, specific production based on substrate; P_V, volumetric productivity.

chains can vary from C_{13} to C_{16} for surfactins, from C_{14} to C_{17} for iturins, and from C_{14} to C_{18} for fengycins, giving different homologous compounds and isomers (*n*, *iso*, *anteiso*) for each lipopeptide. The history of surfactin (Fig. 9) dates back to 1968. Its name refers for its exceptional surfactant power since it lowers the surface tension of water from 72 to 30 mN/m. Although surfactin was discovered more than 30 years ago, there has been a revival of interest in this compound over the past decade, triggered by an increasing demand for effective biosurfactants for difficult contemporary ecological problems. This simple molecule also looks very promising as an antitumoral, antiviral, and anti-*Mycoplasma* agent. Surfactin biosynthesis is catalyzed nonribosomally by the action of a large multienzyme complex consisting of four modular building blocks, called surfactin synthethase. Further recent trends in the biochemistry and genetics of surfactin formation have been reported recently [73,74]. Iturin and fengycin have a wide antifungal activity.

2. Microbial Production of Surfactin

As for the overproduction of surfactin, some efforts with different *Bacillus* species were undertaken to make this lipopeptide more available. For instance, the ability of *B. subtilis* MTCC 1427 to grow and produce biosurfactant on different carbon and nitrogen sources under thermophilic and

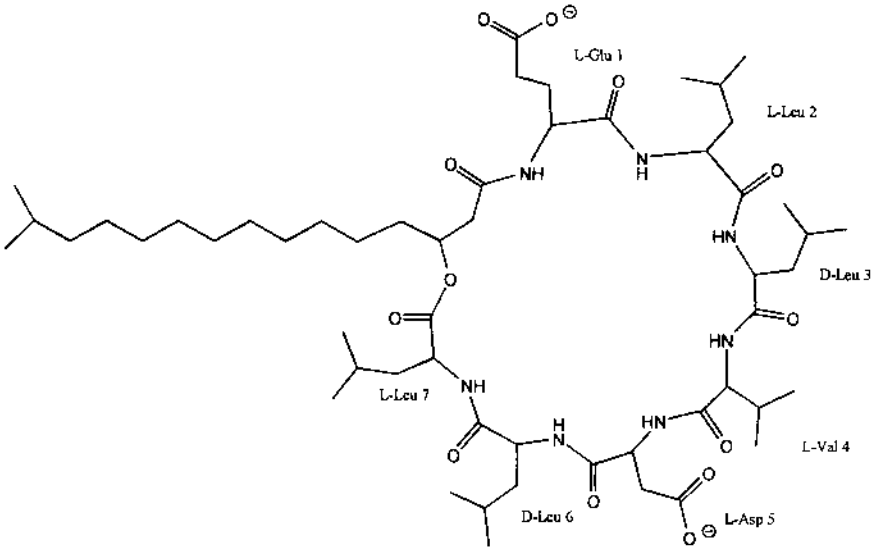

FIG. 9 Surfactin from *Bacillus subtilis*.

mesophilic conditions was studied [75]. Biosurfactant (surfactin) yield was maximal (1 g/L) at 96 h of fermentation at 30°C when 2% sucrose was used as a carbon source and nitrate ions as nitrogen source. The product was stable at 100°C within a wide pH range [3–11]. *Bacillus subtilis* ATCC 21332 was used in a series of other studies. Davies et al. [76] demonstrated a link between the enhanced production of surfactin (up to 440 mg/L) and the onset of nitrate-limited growth by using a defined medium with ammonium nitrate as a nitrogen source. In addition, oxygen-depleted conditions were favorable. Wei and Chu [77] showed that surfactin production was highly enhanced when iron concentration in the medium was raised from 4 μM to the few mM level. By simply adding 2–4 mM iron either initially or during batch culture (40 g/L glucose as C-source) and keeping the pH above 5.0 by adding NaOH, 3.5 g/L of surfactin could be obtained (Table 3). Recently, this group reported that the yield was increased from 0.33 g/L to 2.6 g/L by adding 0.01 mM Mn^{2+} to a defined glucose medium [78]. The authors draw attention to the fact that in earlier studies of surfactin production, the concentration of the surfactant was always determined by nonsatisfactory methods (surface tension of fermentation broth, thin-layer chromatography). In contrast, the HPLC assay used here is specific for the surfactin concentration. The quantification is somewhat complex since surfactin has a number of isomers, leading in minimum to six major peaks. A continuous production from potato process effluent in an airlift reactor was reported by Noah et al. [79].

3. Properties of Surfactin

Ishigami et al. [80] found that surfactin forms long large rod-shaped micelles (micellar weight 179,000, aggregation number $n = 173$) having a CMC of 9.4×10^{-6} M and a surface tension at the CMC of 30 mN/m in 0.1 M $NaHCO_3$ (pH 8.7). This excellent surface-active behavior was attributed to the ease of piling of surfactin molecules organized by β-sheet formation. Linear surfactin prepared by alkaline cleavage of the lactone ring easily forms micelles in aqueous solutions by coordinating β sheet from α-helical monomolecules [81]. The CMC value was found to be 1.28×10^{-5} M. Using the *Bacillus subtilis* O9 biosurfactant (surfactin), a biosurfactant-enhanced degradation of residual hydrocarbons from ship bilge wastes was observed [82,83].

4. Commercial Production of Surfactin

Surfactin is commercially available from Sigma (Deisenhofen, Germany).

5. Other Lipopeptides

As for *B. subtilis* C9 KCTC 8701P, a lipopeptide biosurfactant, C9-BS, was determined to be a compound consisting of a C_{14}/C_{15} fatty acid tail linked to a peptide moiety consisting of 7 amino acid residues identical to

peptide moiety of surfactin [84]. Using 40 g/L glucose and working under oxygen-limited conditions, in shake-flask experiments a maximum of 7 g/L and in 1.5-L bioreactor cultivations a maximum of 4.5 g/L of C9-BS was produced. C9-BS was able to decrease the surface tension of water to 29 mN/m at a CMC of 40 μM. It showed a lower minimal surface tension than that of LAS (31 mN/m) and a smaller CMC value than that of commercial surfactin (100 μM).

Studying the HPLC analysis of the culture supernatants of seven *B. subtilis* strains, Ahimou et al. [85] showed that the lipopeptide profile varied greatly according to the strain. Among the three lipopeptide types, only iturin A was produced by all *B. subtilis* strains. Bacterial hydrophobicity, evaluated by the water contact angle measurements and hydrophobic interaction chromatography, varied according to the strain. Prior treatment of strains with additional iturin or surfactin indicated that the latter one was more active (stronger increase of hydrophobicity) than the former one. As for iturin A (sequence: L-Asn→D-Tyr→D-Asn→L-Gln→L-Pro→D-Asn→L-Ser; 12-methyltridecanoic/tetradecanoic acid) dispersed at concentrations above its CMC (40 μM), its ability to encapsulate water-soluble 5,6-carboxyfluorescein has been successfully examined [86]. For iturin A micelles, a Stokes radius of 1.3 nm and an aggregation number of 7 were obtained. Negative-staining electron microscopy of 3 mM concentration showed the presence of vesicles with an average size of 150 nm. To screen for new lipopeptide analogs when culturing *B. subtilis* NT02 on L-glutamate rich media, Akpa et al. [87] found one homologuous product. It belongs to the iturin family and was identified as bacillomycine L c15.

Lichenysin resembles surfactin that possesses a L-glutamate residue at position 1 instead of L-glutamine in lichenysin. This local variation causes significant changes in the properties of the molecules. Grangemard et al. [88] showed that lichenysin has a higher surfactant power, the CMC being strongly reduced from 220 μM (surfactin) to 22 μM (lichenysin). Lichenysin is also a better chelating agent because its association constants with Ca^{2+} and Mg^{2+} ions are increased by a factor of 4 and 16, respectively. This effect is assigned to an increase in the accessibility of the carboxyl group to cations owing to a change in the side chain topology induced by the glutamate/glutamine exchange.

Hino et al. [89] discovered a novel series of lipopeptide compounds structurally related to, but highly superior to, echinocandin B. Echinocandin-type compounds are lipopeptides consisting of a cyclic hexapeptide nuclear structure acylated with a long fatty acid chain. The producing strains were classified into two groups, the *Coleomycetes* group and the *Hyphomycetes* group. One of these compounds is currently in phase III clinical development as a novel antifungal antibiotic. As for current literature on

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antifungal (lipo)peptides, including their in vitro and in vivo activities, the mechanisms of action and structure–function relationships, when known, have been reported [90].

G. Emulsan

Emulsan (Fig. 10), a lipopolysaccharide isolated from *Acinetobacter calcoaceticus* RAG-1 ATCC 31012 and mentioned for the first time in 1979, has a molecular weight of approximately 1000 kDa. It is able to stabilize oil-in-water emulsions.

1. Microbial Production

In terms of overproduction, a fermentation process has been established using a triglyceride carbon source in a coordinated carbon-nitrogen feed strategy. The emulsifier was produced at a volumetric productivity of about 0.5 g emulsan/L × h while utilizing only the fatty acids portion of soybean oil or free fatty acids that were fed into the medium. A specific yield of 0.28 g emulsan/g fatty acids was obtained and a final concentration of over 20 g/L was reached [91] (Table 3).

2. Emulsan Modifications and Their Consequences on Emulsifying Activities

After previous reports that by selectively feeding RAG-1 with various saturated *n*-alkanoic acids, the hydrophobic substituents of the emulsan could be controlled [92,93]; additional studies on this subject followed.

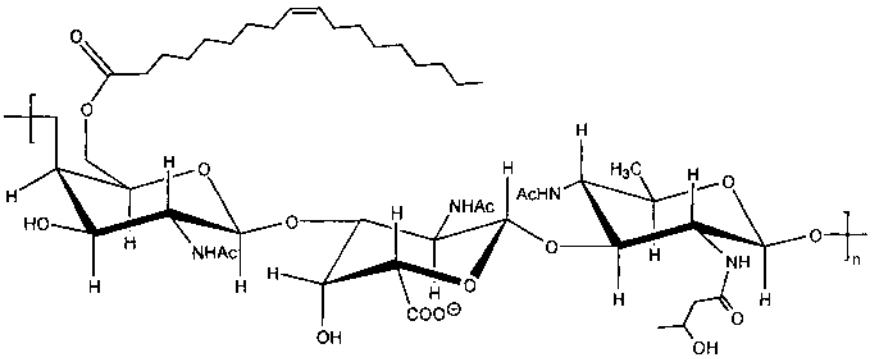

FIG. 10 Emulsan from *Acinetobacter calcoaceticus*.

Zhang et al. [94] investigated the colloidal properties of emulsan formed by incubations of *A. calcoaceticus* on different carbon sources such as sunflower oil or butter oil. Certain structural features, such as the total content of fatty acids and hydroxy fatty acids, were found to have a significant effect on emulsifying activity. The maximum emulsifying activity occurred for emulsan containing about 460 nmol of total fatty acid per mg of emulsan (nmol/mg). Emulsifying activity also showed a maximum at about 170 nmol/mg emulsan of 2- and 3-hydroxydodecanoic acids. For substituents having chain lengths $\geq$15 carbon atoms, the emulsifying activity on hexadecane increased with their content up to 190 nmol/mg. As for aqueous solutions of emulsan analog III (311 nmol/mg of total fatty acids), for which the carbon source was methylmyristate, the surface and interfacial tension were measured. The lowest values attained at high concentrations were 46 and 14 mN/m, respectively, which obviously are higher than those of the low molecular mass glycolipids. Transposon mutants of strain RAG-1 with disrupted genes involved in fatty acid biosynthetic pathway influenced the level and types of fatty acids incorporated into emulsan [95]. Growing them on a series of fatty acids of different chain lengths from C_{11} to C_{18}, particularly those products with a high mole percentage of C_{16} and C_{18}, indicated good emulsification behavior. Various emulsan samples of different degrees of branching of the carbohydrate backbone were obtained under various culture conditions such as different temperatures, shaking conditions, concentrations

TABLE 4 Essential Data on Minimal Surface Tension Values (σ_{min}) of Aqueous Solutions of Microbial Biosurfactants

Biosurfactant	σ_{min} (mN/m)	CMC (mg/L or M)	Ref.
Rhamnolipid RL-2 ($R_2C_{10}C_{10}$)	29	110 mg/L	18
Rhamnolipid mixture M_7	27	150 mg/L	18
Trehalose dicorynomycolates	36	5 mg/L	29
Anionic trehalose lipids	26	15 mg/L	29
Sophorolipids (classical-type)	35	40 mg/L	123
Mannosylerythritol lipids	28	$2–5 \times 10^{-6}$ M	60
Cellobiose lipids	37	2×10^{-5} M	51
Spiculisporic acid, di(*n*-hexylamine) salt	27	1×10^{-2} M	72
Surfactin	30	9.4×10^{-6} M	80
Emulsan[a]	46	250 mg/L	94

T, 25–40°C; CMC, critical micelle concentration.
[a] Emulsan III, from methylmyristate cultivation.

of inhibitor (cerulenin), addition of fatty acids, and culture times [96]. The emulsifying activity of emulsan had a linear correlation to the branching degree. Recently, this group also found that the biological modification of the fatty acid group (C_8–C_{20}) in emulsan, caused by supplementation of fatty acids under conditions inhibiting native fatty acid biosynthesis, influenced the emulsifying activity. Among the emulsans produced from

TABLE 5 Recent Data on Emulsifying Abilities of Microbial Bioemulsifiers

Bioemulsifier (weight)	Components of oil and water phase	Optical density (at appr. 600 nm or KU)	Ref.
Mannosylerythritol lipids:			
MEL-A (250 μg)	Soybean oil (100 μL)/water (5 mL)	1.50 (620 nm)	55
MEL-A (250 μg)	*n*-Tetradecane (100 μL)/water (5 mL)	1.70 (620 nm)	
MEL-A (250 μg)	*n*-Hexadecane/2-methylnaphthalene (1:l, v/v, 100 μL)/water (5 mL)	0.83 (620 nm)	
MEL-B (250 μg)	Soybean oil (100 μL)/water (5 mL)	1.80 (620 nm)	55
MEL-B (250 μg)	*n*-Tetradecane (100 μL)/water (5 mL)	0.88 (620 nm)	
MEL-B (250 μg)	*n*-Hexadecane/2-methylnaphthalene (1:l, v/v, 100 μL)/water (5 mL)	1.02 (620 nm)	
Emulsans:			
Emulsan[a] (1 mg)	*n*-Hexadecane/2-methylnaphthalene (1:l, v/v, 100 μL)/aqueous buffer (7.5 mL)	2.44 (600 nm)	96,97
Emulsan III[b] (41.5 mg)	*n*-Hexadecane (100 μL)/aqueous buffer (7.5 mL)	197 (KU)	94
Emulsan[c] (1 mg)	*n*-Hexadecane (100 μL)/aqueous buffer (7.5 mL)	196 (KU)	95
	n-Tetradecane (100 μL)/aqueous buffer (7.5 mL)	338 (KU)	95
Alasan:			
Alasan (5 μg)	*n*-Hexadecane/2-methylnaphthalene (1:1, v/v, 20 μL)/aqueous buffer (1.5 mL)	0.35 (600 nm)	127
45-kDa protein of alasan (5 μg)	*n*-Hexadecane/2-methylnaphthalene (1:1, v/v, 20 μL)/aqueous buffer (1.5 mL)	0.39 (600 nm)	127

KU, Klett units (after turbidity measurement in a Klett-Summerson colorimeter and calculating final reading times the dilution).

[a] From cultivation of RAG-1 on 10 g/L ethanol + 1 mg/L cerulenin.

[b] From methylmyristate cultivation of RAG-1.

[c] From cultivation of mutant 13D on Luria-Bertani/*n*-C_{16} medium.

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TABLE 6 Some Interesting Bioactivities of Pure Biosurfactants

Biosurfactant	Effects	Ref.
SL, MEL, OSL	Antimicrobial activity (vs. gram-positive bacteria)	49,60,102
Surfactin	Anti-*Mycoplasma* activity	73
RL	Control of zoosporic plant pathogens	24
	Ganglioside/glycosphingolipid-like effects: Induction of cell differentiation in:	
MEL, SL, TL	• the human leukemia cells	33,64
MEL	• the mouse melanoma cells	65
MEL	• the rat pheochromocytoma cells	69
GGL	Inhibition of tumor promotion	104,105,106,114

RL, rhamnolipid; TL, anionic trehalose lipid; SL, sophorolipid (classic-type); MEL, mannosylerythritol lipid; OSL, oligosaccharide lipid; GGL, glycoglycerolipid.

even-numbered fatty acids, the emulsan produced from myristic acid (C_{14}) contained the greatest amount of the same-numbered fatty acids. When the amount of supplemented myristic acid was increased, the myristic acid content in the emulsan increased, but its emulsifying activity decreased [97].

H. Summary on Surfactant Properties and Biological Activities of Biosurfactants

The essential literature data on the influence of native microbial biosurfactants on the surface tension of water are summarized in Table 4, and those on the emulsifying activity in Table 5. Interesting biological activities are presented in Table 6.

III. LAST-DECADE MICROBIAL BIOSURFACTANTS: NEW MOLECULAR STRUCTURES AND PROPERTIES

Actual values on the microbial production of new products and their surfactant properties are summarized in Tables 7 and 8.

A. Glucose Lipids

Screening for crude oil degraders among marine bacteria, in 1992 our group isolated a novel gram-negative bacterium, initially called strain MM1 and later termed *Alcanivorax borkumensis* [98]. An anionic glucose lipid was

TABLE 7 Characteristic Data on the Microbial Production of Last-Decade Biosurfactants

Microorganism and carbon sources (g/L)	Biosurfactant and yield (g/L)	$Y_{P/S}$ (g/g)	P_V (g/L × h)	Ref.
Alcanivorax borkumensis:	*Glucose lipid*			
n-$C_{14/15}$ (30)	1.7	0.05	0.020	99
Tsukamurella sp:	*Oligosaccharide lipids*			
Sunflower oil (137)	12.0	0.13	0.150	103
Microbacterium sp:	*Diglycosylglycerolipid*			
Glucose (20)	0.2	0.02	0.007	114
Candida bombicola:	*2-Alkylsophorosides*			
Glucose (130) + 2-OH-C_{12} (15)	22.0	0.13	0.100	122
Glucose (120) + 2-OH-C_{14} (27)	25.0	0.20	0.130	123
Acinetobacter radioresistens:	*Alasan*			
Ethanol (5)	2.5	0.50	0.031	127

General conditions: shake flasks and bioreactor cultures; mineral salt and complex media; batch and fed-batch methods; 22–30°C; pH 2.5–8. $Y_{P/S}$, specific production based on substrate; P_V, volumetric productivity.

TABLE 8 Essential Data on Minimal Surface Tension Values (σ_{min}) of Aqueous Solutions of Last-Decade Microbial Biosurfactants

Biosurfactant	σ_{min} (mN/m)	CMC (mg/L)	Ref.
Glucose lipid	30	50	99
Trisaccharide lipid GL2	24	100	102
Tetrasaccharide lipid GL3	24	100	102
Glucosylmannosylglycerolipid	33	200	114
2-Dodecylsophoroside	30	200	122
2-Tetradecylsophoroside	30	40	123
Sophorolipid-*n*-butylamide	45	80	123

T: 25–40°C; CMC, critical micelle concentration.

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produced on culturing this strain on seawater-based media with $C_{14/15}$ *n*-alkanes. The lipid moiety is composed of four β-hydroxydecanoic acids (Fig. 11). Data presented by Passeri et al. [99] concerning the biosynthesis suggest that, besides the glucose unit, also the D-β-hydroxydecanoic acid moieties are synthesized de novo. Close correlation of growth and glycolipid formation as a result of shake-flask experiments and batch cultivations led to fed-batch cultivation of strain MM1 by feeding sodium nitrate when nitrogen became limiting. Nitrate feeding was controlled by the oxygen partial pressure value of the culture broth. After a cultivation period of 80 h and consumption of 30 g/L *n*-alkane the yield of anionic glucose lipid increased up to 1.7 g/L. The glycolipid reduced the surface tension of water to 30 mN/m while the interfacial tension toward *n*-hexadecane was lowered to values smaller than 5 mN/m. Harvesting *Alcanivorax borkumensis* in the late logarithmic phase after cultivation on seawater-based medium with pyruvate as main carbon source, additional compounds were detected [100]. The

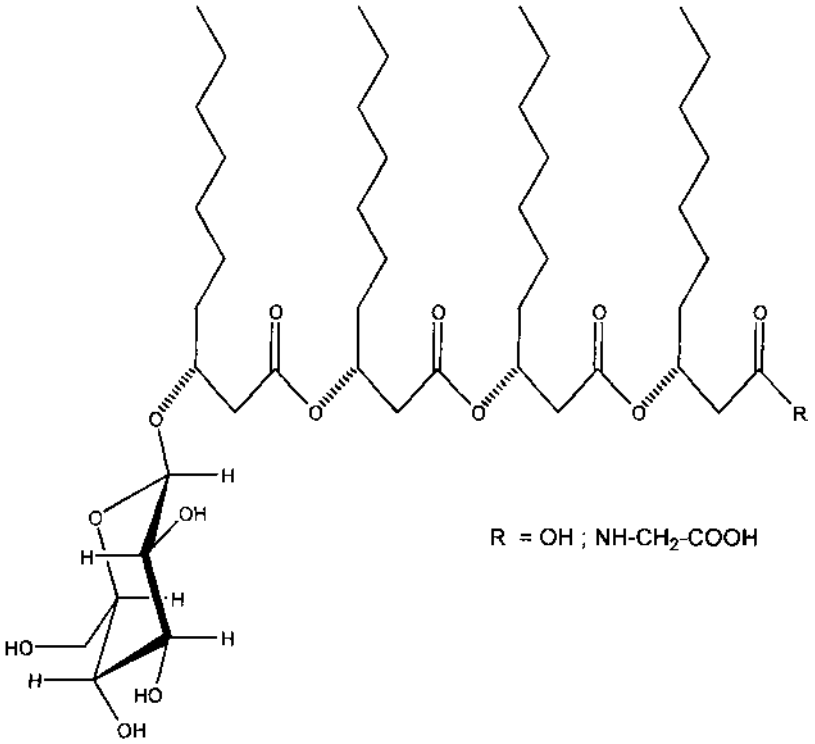

FIG. 11 Glucose lipids from *Alcanivorax borkumensis*.

glycolipids extracted from the cell wall consisted of the basic anionic structure (seen before) N-terminally esterified with glycine. Ten different derivatives of this lipid type were identified. They vary by the chain length of one or two of the four β-hydroxy fatty acids (C_6, C_8, and C_{10}) and by the location of these different fatty acids within the molecule. In addition, a first report was given on carotenoid glucoside mycolic acid esters synthesized by *Rhodococcus rhodochrous* [101].

B. Oligosaccharide Lipids

Looking for new triglyceride-utilizing microorganisms from soil, recently we isolated a gram-positive bacterium, a *Tsukamurella* species, which produced new types of glycolipids. Especially sunflower oil as the sole carbon source favored their synthesis [102]. For comparison, water-soluble substrates such as glucose or complex media (e.g., malt extract, peptone, yeast extract) led to excellent growth but no or, in the case of glucose, only low traces of glycolipids were observed. The molecular structures are shown in Fig. 12. GL1 presents a new trehalose lipid containing one short-chain saturated and one long-chain unsaturated acid. In GL1B a third hydroxyl group is occupied by an additional long-chain fatty acid. In GL2 and GL3 the carbohydrate backbone consists of a trisaccharide and a tetrasaccharide, respectively. Both products are carrying four short-chain acyl groups at identical hydroxy functions of the sugar moiety. Following the cultivation course by HPLC analyses, the composition of the glycolipid mixture changed from disaccharide- to tri- and tetrasaccharide lipids. Finally, the concentration of GL3 was as high as that of GL1, GL1B, and GL2 combined. As for initial studies on the overproduction using a 10-L bioreactor, 6.5 g/L biomass and 4.5 g/L oligosaccharide lipids were produced from 20 g/L sunflower oil. These results could be improved in the meantime by working under nitrogen/phosphate-limited conditions; in addition, using the fed-batch method to add more of the lipophilic carbon source during the late-logarithmic and stationary phase, leading to more than 10 g/L of products [103].

Surfactant properties of the crude product and of the purified compounds were investigated. The minimum values of surface tension and interfacial tension (vs. hexadecane) of their aqueous solutions were 25 mN/m and 5–10 mN/m. The glycolipids show antimicrobial activity particularly against gram-positive bacteria.

C. Glycoglycerolipids

Glycoglycerolipids have been known for several decades as certain microbial cell envelopes. Their potential value for taxonomic and diagnostic purposes

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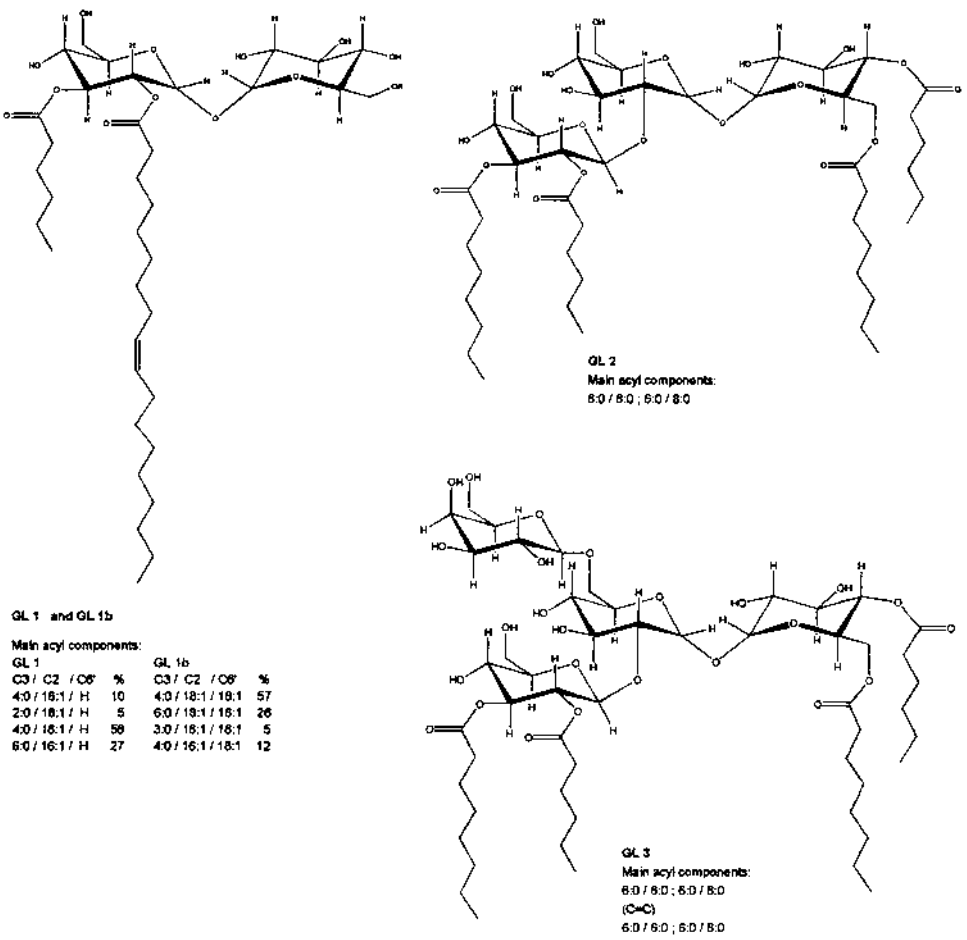

FIG. 12 Disaccharide lipids GL1, GL1B, and oligosaccharide lipids GL2, GL3 from *Tsukamurella* sp.

was recognized very early. They are generally involved in a variety of membrane functions. As for their molecular structures, in most cases unambiguous spectroscopic elucidation for the location of the fatty acids at the sugar or glycerol moiety is missing. But during the last decade new analysis methods, including different NMR techniques and FAB-MS/MS in the positive and negative modes, facilitated the structural assignment. These data findings and, additionally, first studies on bioprocess engineering for the microbial production as well as on surfactant properties, respectively, allow

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us to classify glycoglycerolipids within the last-decade biosurfactants. As for definitely new structures, here are some examples:

Studies on cyanobacterial monogalactosyl- and digalactosyldiacylglycerols are reported in particular from *Phormidium tenue* [104–106] and *Fischerella ambigua* [107]. Some of the products from *P. tenue* showed potent inhibitory activity towards tumor promotion (in in vitro assay of Epstein-Barr virus activation in Raji cells induced by 12-*O*-tetradecanoylphorbol-13-acetate). Additional novel structures with difference in carbohydrate backbone and fatty acid moieties have been published for glycoglycerolipids of *Rhodobacter sphaeroides* [108], *Saccharopolyspora* sp [109], *Thermus aquaticus* [110], the sponge-associated bacterium *Micrococcus luteus* [111], *Arthrobacter atrocyaneus* [112], and from the *Mycobacterium avium-intracellulare* complex [113].

Recently, Wicke et al. [114] reported on a *Microbacterium* sp isolated from the marine sponge *Halichondria panicea*, the production of a cell-associated glucosylmannosylglycerolipid (fatty acids: *anteiso*-C15:0 and -C17:0; see Fig. 13). Favorable condition was growth on marine broth or on artificial seawater supplemented with glucose, leading to approximately 0.2 g/L product. The major compound, GGL.2, decreased the surface tension of water to 33 mN/m and the interfacial tension of the water/*n*-hexadecane system from 43 mN/m to 5 mN/m. Cultivating *Microbacterium* sp M874 another glycoglycerolipid, di-*O*-12-methyltetradecanoyl-3-*O*-β-D-galactosylglycerol (M874B), was detected by Matsufuji et al. [115]. After previously

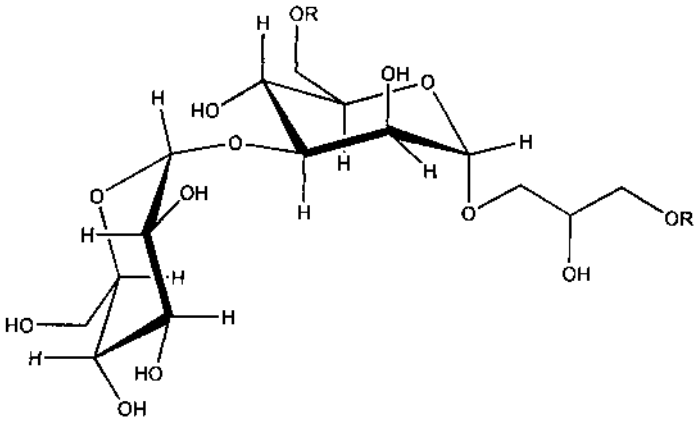

FIG. 13 Diglycosylglycerolipid GGL.2 from *Microbacterium* sp. R = anteiso-C15:0 and -C-17:0, iso-C16:0.

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characterized as an alkylperoxyl radical scavenger, it was shown that it was also capable of protecting cells from death caused by heating and exogenous hydrogen peroxide [116]. M874B was also found to increase the growth of the human promyelocytic leukemia cell HL60, but suppresses the 12-*O*-tetradecanoyl phorbol-13-acetate induced differentiation [117]. M874B was successfully applied for the bioremediation of monohalogenated aromatic compounds [118]. With *Corynebacterium aquaticum*, newly isolated from soil, glucosylmannosylglycerolipid S361A and dimannosylglycerolipid S365A were detected [119]. These products indicated influenza A virus binding activity [120].

D. Alkyl Sophorosides

Initial experiments with *Candida bombicola* ATCC 22214 to obtain sophorose lipids with a fatty acid chain shorter than 16 carbon atoms were unsuccessful. In general, short-chain precursors (C_{10} to C_{14} *n*-alkanes, fatty acids/esters) were not incorporated into the glycolipid but degraded and used for de novo synthesis of $C_{16/18}$ fatty acids, to give the classical lactonic sophorolipid, as mentioned before under first-generation biosurfactants. Theoretically, the S enantiomers of 2-alkanols could be incorporated directly by a glycosidic linkage to the sophorose unit biosynthesized from the glucose substrate. Therefore the racemic 2-alkanols containing 12, 14, and 16 carbon atoms were tested. These co-substrates were added in a fed-batch mode after the biomass production on glucose as carbon and energy source was finished. All trials were successful. A novel type of sophorolipid (Fig. 14) was isolated as a major product [121–123]. Among all lipophilic constituents 2-alkanol was found as the main hydrophobic moiety (> 75%) involved in sophorolipids differing only in the degree of acetylation of the disaccharide. In the case of racemic 2-dodecanol as cosubstrate, as presumed, the configuration of the incorporated secondary alcohol was determined to be *S* form. The production yields on new alkylsophorosides was one magnitude lower compared to the classical products. For instance, Fig. 15 shows our 2-L fed-batch cultivation of *C. bombicola* for the production of just 25 g/L of 2-tetradecyl-sophoroside. Since yeasts enzymes are able to catalyze the asymmetrical reduction of ketones to secondary alcohols (with low values of enantiomeric excess), also various C_{12} alkanones were tested as cosubstrates. All experiments, using 2-dodecanone, 3-dodecanone, or 4-dodecanone, showed positive results. After reduction the 2-, 3-, and 4-alcohols were linked directly (but in different amounts) to the sophorose moiety [124]. In additional studies, 1-dodecanol as cosubstrate was also found attached without change to the carbohydrate unit, but with lower yields compared to 2-dodecanol cultivations.

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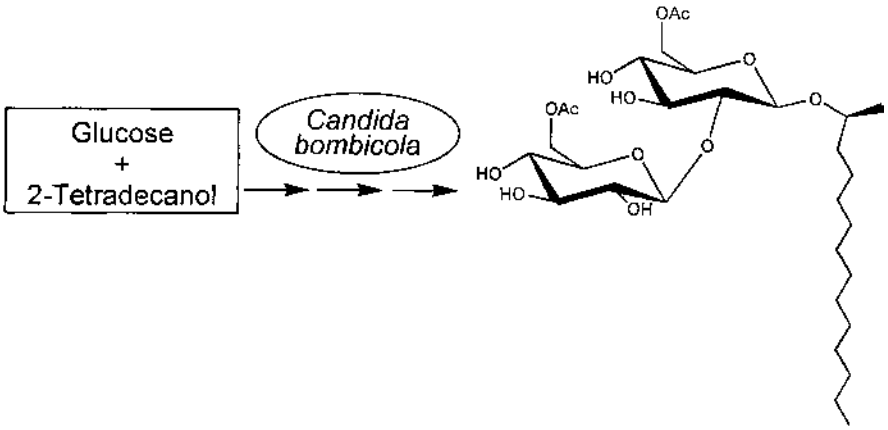

FIG. 14 Scheme of the bioconversion of suitable carbon sources into alkylsophoroside.

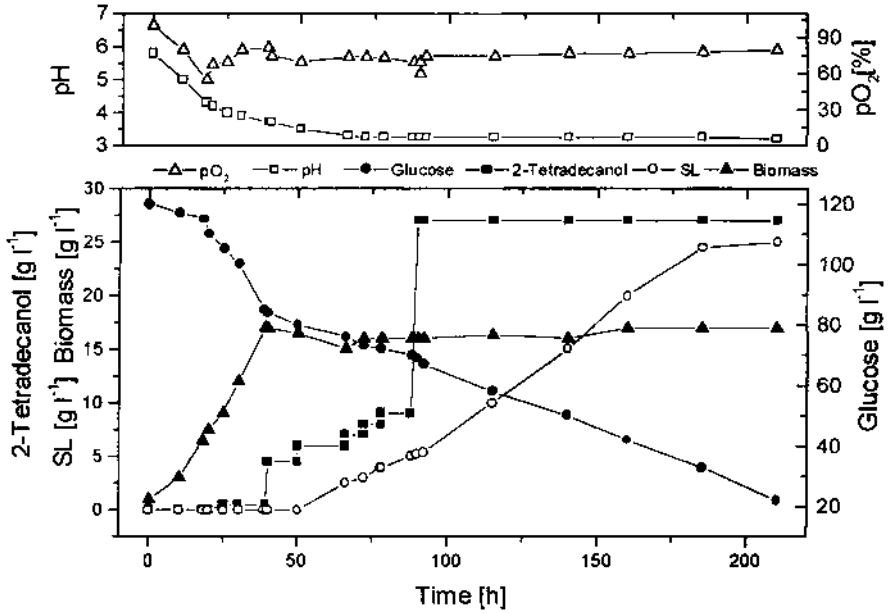

FIG. 15 Growth and 2-tetradecylsophoroside (SL) production of *Candida bombicola* in a 2-L bioreactor. Conditions: mineral salts medium including 120 g/L glucose, 4 g/L yeast extract; 28 g/L 2-tetradecanol (semicontinuous addition). 30°C; 900 rpm; aeration rate 0.35 v/vm.

Native 2-dodecylsophoroside and 2-tetradecylsophoroside lower the surface tension to a minimum value of 30 mN/m.

E. Alasan

The bioemulsifier of *Acinetobacter radioresistens* KA53, referred to as alasan, is a high molecular weight complex of polysaccharide and protein [125]. The proteins of alasan appeared to play an essential role in both the structure and surface activity of the complex because apoalasan had no emulsifying activity and did not show the large temperature-induced hydrodynamic shape changes that were characteristic of alasan [126]. The active components are the proteins [127]. After purification of three alasan proteins, the 45-kDa protein showed the highest specific emulsifying activity.

F. Chemo/enzymatic Modification of Native Glycolipids

The acidic form of classical sophorolipid (a deacetylated compound) produced by alkaline hydrolysis of the native lactonic form (Fig. 2) was successfully converted by enzymatic biotransformation (glycosidase catalysis) to an acidic glucose lipid [44]. Another modification was performed with alkylamines leading to alkylamides of the acidic sophorolipid [123]. Bisht et al. [128] reported an efficient chemoenzymatic route that led to an 6-*O*-acryloylsophorolipid macrolactone analog. The homopolymerization of this monomer as well as its copolymerization with acrylic acid and acrylamide led in maximum to a molecular weight of 4.2×10^4 Da. The first total synthesis of a major component of the microbial classical lactonic sophorolipid was described by Fürstner et al. [129].

IV. CONCLUSION AND OUTLOOK

Recently, four microbially derived biosurfactants—rhamnolipids, sophorolipids, spiculisporic acid and surfactin—are commercially available. Nevertheless, the use of biosurfactants is limited by the cost of production and insufficient experience in applications. However, since there is increasing awareness of water quality and environmental conservation, as well as expanding demand for natural products in cosmetics or in pharmaceutical products, it appears inevitable that high-quality microbially produced biosurfactants will replace the currently used chemical products in many applications outlined above. In addition, in the future chemically or bio-

catalytically synthesized derivatives of the native biosurfactants should be studied for use in special applications.

ACKNOWLEDGMENTS

I thank F. Lang and S. Potrykus for technical assistance in the preparation of the manuscript.

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10
Cleavable Surfactants

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I. INTRODUCTION

Until relatively recently, hydrolytic instability of a surfactant was seen as a problem. For this reason a weak linkage in the surfactant molecule was avoided. Among the surfactant workhorses: anionics such as alkylbenzenesulfonates and alkyl sulfates, nonionics such as alcohol ethoxylates and alkylphenol ethoxylates, and cationics such as alkyl quats and dialkyl quats; only alkyl sulfates are not chemically stable under normal conditions. Through the years the susceptibility of alkyl sulfates to acid-catalyzed hydrolysis has been seen as a considerable problem, particularly well known for the most prominent member of the class, sodium dodecyl sulfate (SDS). The general attitude has been that weak bonds in a surfactant may cause handling and storage problems and should therefore be avoided.

In recent years the attitude toward easily cleavable surfactants has been changed. Environmental concern has become one of the main driving forces for the development of new surfactants and rate of biodegradation has become a major issue. One of the main approaches taken to produce readily biodegradable surfactants is to build into the structure a bond with limited stability. For practical reasons the weak bond is usually the bridging unit between the polar head group and the hydrophobic tail of the surfactant, which means that degradation immediately leads to destruction of the surface activity of the molecule, an event usually referred to as the primary degradation of the surfactant. Biodegradation then proceeds along various routes depending on the type of primary degradation product. The ultimate decomposition of the surfactant, often expressed as amount of carbon dioxide evolved during 4 weeks exposure to appropriate microorganisms counted as a percentage of the amount of carbon dioxide that could theoretically be produced, is the most important measure of biodegradation. It seems that

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for most surfactants containing easily cleavable bonds also the values for ultimate degradation are higher than for the corresponding surfactants lacking the weak bond. Thus, the strong trend toward more environmentally benign products favors the cleavable surfactant approach on two accounts.

A second incentive for the development of cleavable surfactants is to avoid complications such as foaming or formation of unwanted, stable emulsions after use of a surfactant formulation. Cleavable surfactants present the potential for elimination of some of these problems. If the weak bond is present between the polar and the nonpolar part of the molecule, cleavage will lead to one water-soluble and one water-insoluble product. Both moieties can usually be removed by standard workup procedures. This approach has been of particular interest for surfactants used in preparative organic chemistry and in various biochemical applications.

A third use of surfactants with limited stability is to have the cleavage product impart a new function. For instance, a surfactant used in personal care formulations may decompose on application to form products beneficial to the skin. Surfactants that after cleavage impart a new function are sometimes referred to as functional surfactants.

Finally, surfactants that in a controlled way break down into nonsurfactant products may find use in specialized applications, such as in the biomedical field. For instance, cleavable surfactants that form vesicles or microemulsions can be of interest for drug delivery, provided the metabolites are nontoxic.

Most cleavable surfactants contain a hydrolyzable bond. Chemical hydrolysis is either acid- or alkali-catalyzed, and many papers discuss the surfactant breakdown in terms of either of these mechanisms. In the environment bonds susceptible to hydrolysis are often degraded by enzymatic catalysis but few papers dealing with cleavable surfactants have dealt with such processes in vitro. Other approaches that have been taken include incorporation of a bond that can be destroyed by UV irradiation or use of an ozone cleavable bond. This review is subdivided according to the type of weak linkage present in the surfactant. Emphasis is put on the development that has taken place in recent years.

II. ALKALI-LABILE SURFACTANTS

A. Normal Esters

The ester bond is the typical linkage to use in the design of alkali-labile surfactants. The concept is by no means new. Poly(ethylene glycol) (PEG) esters of fatty acids have been around for a long time. They are produced by ethoxylation of the fatty acid; the product obtained is a mixture of roughly

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50% of the desired PEG monoester and 25% each of the corresponding diester, i.e., PEG esterified at both ends with the fatty acid, and of free PEG. In addition, the PEG has the usual broad homolog distribution.

The mechanism of ester hydrolysis and the influence of substituents in the vicinity of the ester bond on the hydrolysis rate are well understood for esters that lack surface activity. The degradation rate becomes very different for surface-active esters, however, because surfactants in the form of micelles may behave differently from free surfactant molecules. If the ester bond is buried in the interior of the micelle, the attacking hydroxyl ions may have difficulty in reaching it. In addition, charge effects are likely to be important. A PEG ester of a fatty acid is a nonionic surfactant, i.e., uncharged, but the hydrolysis yields PEG and a fatty acid salt, i.e., an anionic surfactant. The fatty acid salt that is generated is likely to form mixed micelles with the starting PEG ester and such micelles will carry a negative charge. It is likely that the rate of attack by the negatively charged hydroxyl ion will be slowed down if the micelle becomes more and more anionic in character as the reaction proceeds.

In order to learn about the effect of substituents close to the ester bond of surface-active esters on the kinetics of the hydrolysis, a series of well-defined PEG esters of fatty acids were synthesized and their hydrolysis rates were investigated both below and above the critical micelle concentration (CMC) [1]. The ester surfactants studied are shown in Fig. 1. They were synthesized in pure form by reacting the acid chloride with a large excess of tetra(ethylene glycol) using pyridine as nonnucleophilic base. The desired product, i.e., the PEG monoester, was removed from the excess tetra(ethylene glycol) by extraction into ethyl acetate from a saturated sodium chloride solution (so-called Weibull extraction). The degradation profile at various pH values was

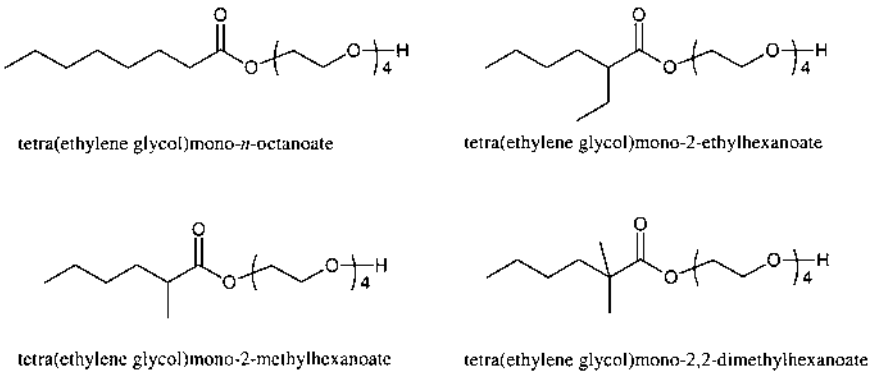

FIG. 1 Four monoesters of tetra(ethylene glycol) with different substituents on the carbon next to the ester carbonyl.

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studied both below and above the CMC. Figure 2 shows the reaction profiles for the four surfactants at pH 13 and at concentrations below the CMC. As can be seen, the hydrolysis rate is not much affected by one methyl group in α position to the ester carbonyl carbon. The presence of two methyl groups, or one ethyl group, in the α position leads to a marked reduction in hydrolysis rate, however. Hydrolysis performed above the CMC showed that whereas the surfactant half-life was constant below the CMC, it increased linearly above the CMC. The experiments showed that the amount of surfactant degraded per unit time was constant above the CMC, regardless of the surfactant concentration. This implies that only nonmicellized surfactant is degraded. Evidently, aggregation into micelles protects these nonionic ester surfactants from undergoing alkaline ester hydrolysis. This is opposite to the behavior of esters containing a quaternary ammonium group in the vicinity of the ester bond, as is shown below for betaine esters.

Due to their natural origin sugars are attractive as polar head groups of surfactants. Sugar esters have received considerable attention in later years, partly due to recent development in procedures for bioorganic synthesis. The main advantage with the biochemical route as compared to conventional organic synthesis is the much higher regioselectivity obtained in the synthesis. Long reaction time is a typical disadvantage of the enzymatic process. Enzymatic synthesis of sugar esters is the topic of Chapter 8 of this book and will not be further dealt with here.

Sugar esters can also be made by nonenzymatic methods. In a systematic investigation of the effect of the number of condensed hexose units on surfactant properties, monododecyl esters of glucose, sucrose (2 sugar units), raffinose (3 units) and stachyose (4 units) were prepared by organic synthesis

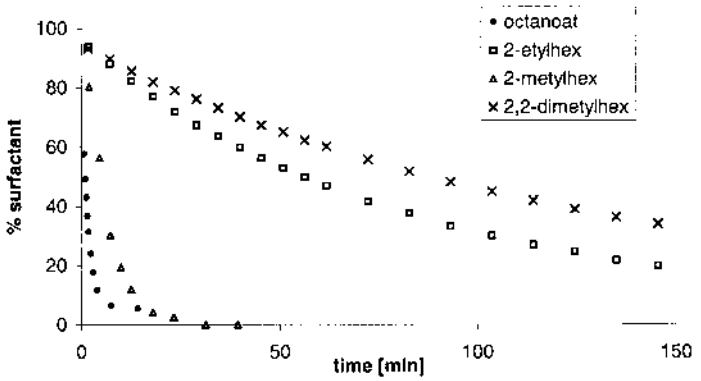

FIG. 2 Reaction profiles for hydrolysis of the surfactants of Fig. 1 at pH 13.

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followed by careful chromatographic purification [2]. As can be seen from Fig. 3, all compounds had the acyl substituent at the 6-position of a glucose ring, i.e., the ester bond had the same environment in all four surfactants. The phase behavior and the surfactant properties of the compounds were studied. It was concluded that the self-assembly of the surfactants was primarily governed by geometrical packing constraints which, in turn, depended on the size of the polar head group. The phase behavior was practically independent of temperature and, as expected, none of the surfactants exhibited the clouding phenomenon characteristic of polyoxyethylene-based nonionic surfactants.

In a study on the effect of α substituents on rate of alkaline hydrolysis of sugar esters it was, somewhat surprisingly, found that a sulfonate group did

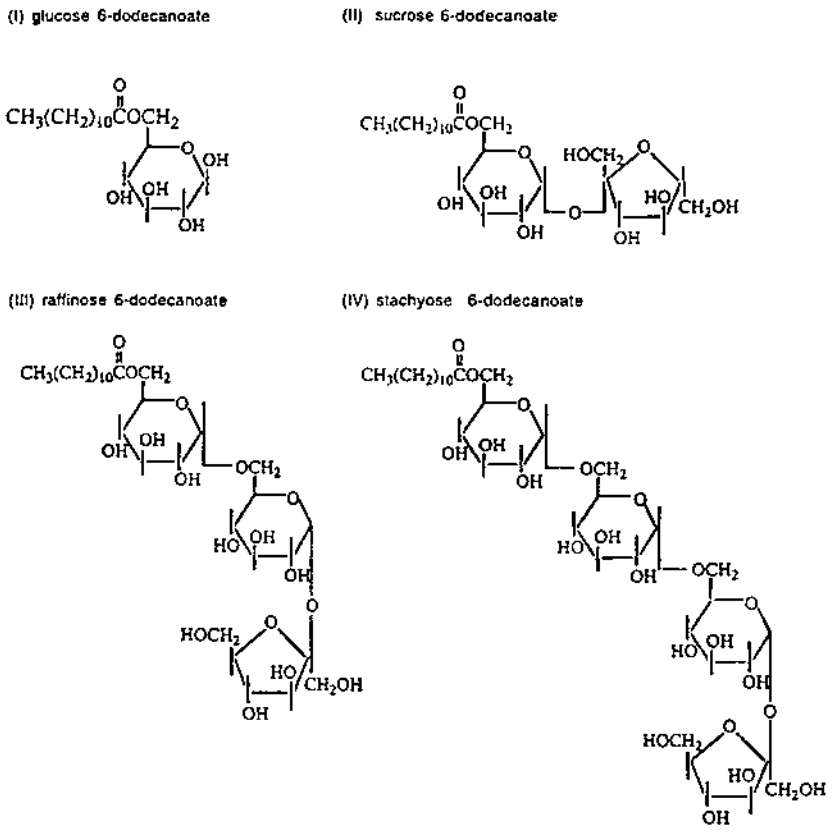

FIG. 3 Structures of surface-active sugar esters. (From Ref. 2.)

not severely retard the hydrolysis, in spite of the fact that a negative charge had been introduced close to the carbonyl carbon at which attack by the hydroxyl ion occurs [3]. This is interesting because bacterial hydrolysis is known to be inhibited by α-sulfo groups.

Sugar esters, including hydrolysis aspects, will be discussed in depth in Chapter 3 of this book.

B. Normal Esterquats

By the term esterquat one usually refers to surface-active quaternary ammonium compounds that have the general formula $R_4N^+X^-$ and in which the long-chain alkyl moieties, R, are linked to the charged head group by an ester bond and with X^- being a counterion. With normal esterquats we mean surfactants based on esters between one or more fatty acids and a quaternized amino alcohol. Figure 4 shows examples of three different esterquats, all containing two long-chain and two short substituents on the nitrogen atom.

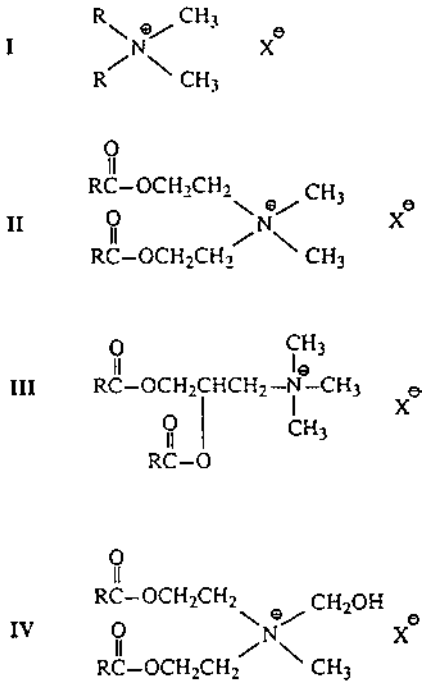

FIG. 4 Structures of one conventional quaternary ammonium surfactant (I) and three esterquats (II–IV). R is a long-chain alkyl, and X is Cl, Br, or CH_3SO_4.

The figure also shows the "parent," noncleavable quat. As can be seen, the ester-containing surfactants contain two carbon atoms between the ester bond and the nitrogen, which carries the positive charge. Cleavage of the ester bonds of surfactants II–IV yields a fatty acid salt in addition to a highly water-soluble quaternary ammonium di- or triol. These degradation products exhibit low fish toxicity and are degraded further by established metabolic pathways. The overall ecological characteristics of esterquats are much superior to those of traditional quats as represented by compound I of Fig. 4.

During the last decade, the dialkyl esterquats have to a large extent replaced the stable dialkyl quats as rinse cycle softener, which is the single largest application for quaternary ammonium compounds. The switch from stable dialkyl quats to dialkyl esterquats represents one of the most dramatic changes of product type in the history of surfactants and it is entirely environment driven. Unlike stable quats, esterquats show excellent values for biodegradability and aquatic toxicity. Esterquats have also fully or partially replaced traditional quats in other applications of cationics, such as hair care products and various industrial formulations. Normal esterquats are covered in a special chapter of this book and are not discussed further here.

C. Betaine Esters

The rate of alkali-catalyzed ester hydrolysis is influenced by adjacent electron-withdrawing or electron-donating groups. A quaternary ammonium group is strongly electron withdrawing. The inductive effect will lead to a decreased electron density at the ester bond; hence, alkaline hydrolysis, which starts by a nucleophilic attack by hydroxyl ions at the ester carbonyl carbon, will be favored. Compounds II–IV of Fig. 4 all have two carbon atoms between the ammonium nitrogen and the $-O-$ oxygen of the ester bond. Such esters undergo alkaline hydrolysis at a faster rate than esters lacking the adjacent charge, but the difference is not very large. If, on the other hand, the charge is at the other side of the ester bond, the rate enhancement is much more pronounced. Such esters are extremely labile on the alkaline side but very stable even under strongly acidic conditions [4]. The large effect by the quaternary ammonium group on the alkaline and acid rates of hydrolysis is due to a stabilization/destabilization of the ground state, as illustrated in Fig. 5. The charge repulsion, involving the carbonyl carbon atom and the positive charge at the nitrogen atom, is relieved by hydroxide ion attack but augmented by protonation. The net result is that compared with an ester lacking the cationic charge the rate of alkaline hydrolysis is increased 200-fold whereas the rate of acid hydrolysis is decreased 2000-fold [5]. For surface-active betaine esters based on long-chain fatty alcohols the rate of alkaline

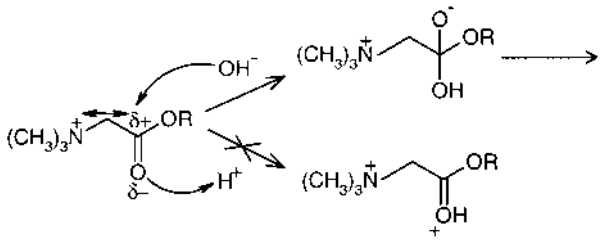

FIG. 5 Mechanism for the acid- and base-catalyzed hydrolysis of betaine ester.

hydrolysis is further accelerated due to micellar catalysis [6]. However, the presence of large, polarizable counterions, such as bromide, can completely outweight the micellar catalysis [7].

The extreme pH dependence of surface-active betaine esters makes them interesting as cleavable cationic surfactants. Shelf life is long when stored under acidic conditions and hydrolysis rate will then strongly depend on the pH at which they are used. Single-chain surfactants of this type has been suggested as "temporary bactericides" for use in hygiene products, for disinfection in the food industry and in other instances where only a short-lived bactericidal action is wanted [6]. The patent literature also contains examples of betaine esters containing two long-chain alkyl groups [8–10]. Two examples are given in Fig. 6.

The kinetics of hydrolysis of a series of surface-active betaine esters was studied both below and above the CMC of the surfactants [11]. Figure 7 shows the compounds used in the study and the synthesis route employed in the preparation. The rate constant for the hydrolysis reaction as a function of

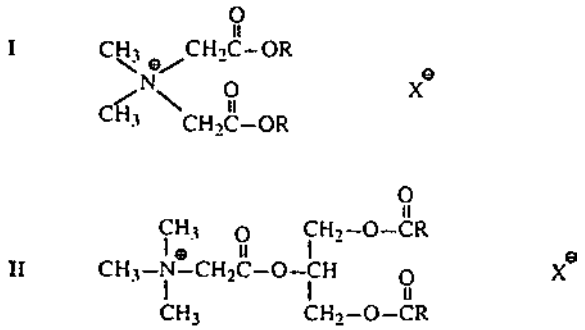

FIG. 6 Structures of two surface-active betaine esters. R and X are the same as in Fig. 4.

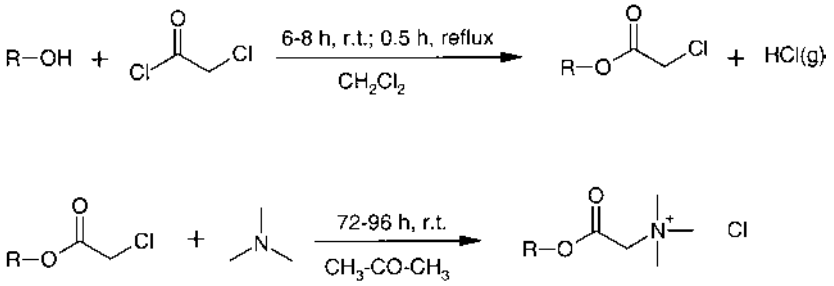

FIG. 7 Route of preparation of betaine esters. R is ethyl, decyl, dodecyl, and tetradecyl.

surfactant concentration at constant pH is shown in Fig. 8. As can be seen, there is a pronounced effect of micelle formation, and the effect is opposite to that discussed above for nonionic PEG esters, i.e., the hydrolysis is accelerated when micelles are being formed. This is a typical example of micellar catalysis and can be explained by the higher hydroxyl ion concentration around the surface of the positively charged micelle than in the bulk water

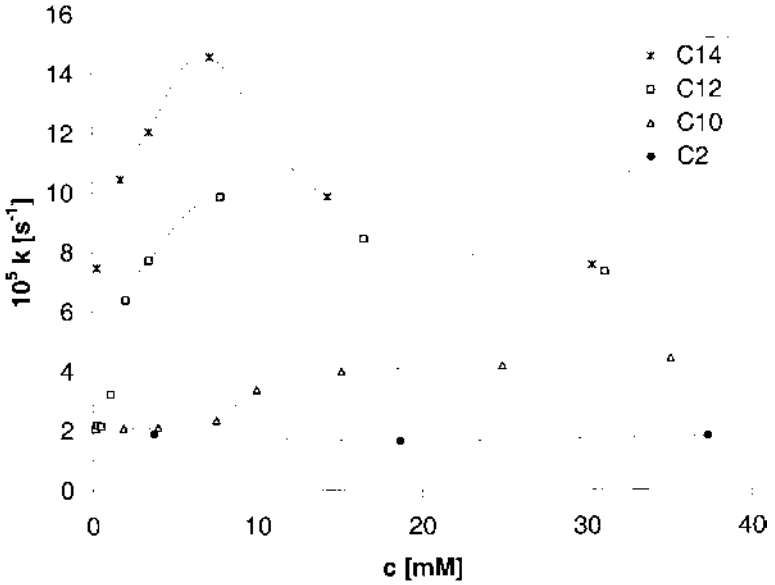

FIG. 8 Hydrolysis of betaine esters at pH 7.5. k is the pseudo-first-order rate constant and c is the concentration of betaine ester.

phase. It can also be seen that the micellar catalysis is more pronounced when the betaine esters become more surface active, or, expressed differently, the rate increases as the CMC decreases. As shown in the figure, the rate increase starts well below the CMC of the surfactant. This is probably due to the fatty alcohol that is generated in the hydrolysis forming mixed micelles with the cationic betaine ester. Such mixed micelles are known to form at considerably lower concentrations than the CMC of the cationic surfactant only [12]. Hence, the rate increase that occurs below the CMC of the betaine ester surfactant is due to hydrolysis of nonmicellized surfactant generating a surfactant mixture with lower CMC than the starting surfactant.

D. Monoalkyl Carbonates

Alcohol ethoxylates with short polyoxyethylene chains are viscous oils. Their incorporation into powder detergents constitutes a well-known problem. Carbonate salts of such surfactants have been used as labile derivatives from which the surfactant can be readily regenerated. Such derivatives could be named "prosurfactants" in analogy with the term *prodrug* in medicine. Reaction of an alcohol ethoxylate with carbon dioxide gives a solid carbonate salt that decomposes under the alkaline washing conditions to give the starting nonionic surfactant and carbonate, as is illustrated in Fig. 9 [13]. (Strictly speaking, also the prosurfactant is a surfactant although it is not meant to serve as such in the application step.) Conversion of an alcohol ethoxylate into a solid carbonate enables the incorporation of high levels of this surfactant into granular detergents of high bulk density.

E. Surfactants Containing the Si-O Bond

The silicon–oxygen bond is susceptible to both alkaline and acid hydrolysis. In addition, the bond is specifically cleaved by fluoride ions also at relatively

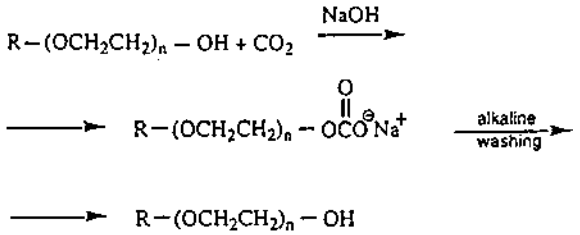

FIG. 9 Formation of a carbonate salt of a nonionic surfactant and subsequent regeneration of the starting surfactant during the washing step. (From Ref. 13.)

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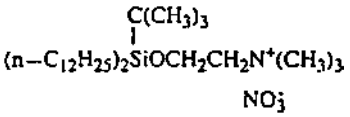

FIG. 10 Structure of a surfactant containing the Si-O bond. (From Ref. 14.)

neutral pH. (In nonaqueous media, where the ions are not hydrated, the cleavage by F^- is extremely fast.) Single- and double-tailed cationic surfactants of the structures shown in Fig. 10 have been synthesized and tested with regard to degradation characteristics [14]. However, the route of preparation is relatively sophisticated, which means that such surfactants may be of limited practical value.

F. Surfactants Containing a Sulfone Group

An anionic and a cationic surfactant containing the ethylenesulfone moiety have been synthesized by oxidation of the corresponding sulfide [15]. These surfactants are stable in acid but break down to nonsurfactant products, a vinylsulfone and a phenol, in weak alkali, as is shown in Fig. 11. The cleavage reaction is considerably faster for the cationic than for the anionic surfactant. This is mainly a micellar phenomenon: positively charged micelles are surrounded by a pseudophase of much higher hydroxyl ion activity than the bulk aqueous phase and the reverse is true for negatively charged micelles (see discussion above for betaine esters). A comparative hydrolysis study with a nonsurfactant analog of the anionic surfactant confirmed this view since the non-surface-active sulfone decomposed much faster than the surfactant.

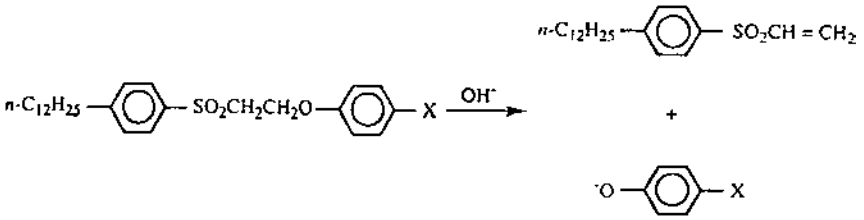

FIG. 11 Alkaline hydrolysis of a sulfone-containing surfactant. X may be $(CH_3)_3N^+$ or SO_3^-. (From Ref. 15.)

III. ACID-LABILE SURFACTANTS

A. Cyclic Acetals

Cyclic 1,3-dioxolane (five-membered ring) and 1,3-dioxane (six-membered ring) compounds, illustrated in Fig. 12, have been studied in depth by the groups of Burczyk, Takeda, and others as examples of acid-labile surfactants. They are typically synthesized from a long-chain aldehyde by reaction with a diol or a higher polyol. Reaction with a vicinal diol gives the dioxolane [16–18] and 1,3-diols yield the dioxane [19,20].

If the diol contains an extra hydroxyl group, such as in glycerol, a hydroxy acetal is formed and the remaining hydroxyl group can subsequently be derivatized to give anionic or cationic surfactants, as illustrated in Fig. 13. It is claimed that glycerol gives ring closure to dioxolane, yielding a free, primary hydroxyl group, but it is likely that some dioxane with a free, secondary hydroxyl group is formed as well. The free hydroxyl group can be treated with SO_3, e.g. in the form of the SO_3–pyridine complex, and then neutralized to give the sulfate [21,22]. It can be reacted with propane sultone to give the sulfonate [23], or it can be substituted by bromine or chloride and then reacted with dimethylamine to give a tertiary amine as polar group. Quaternization of the amine can be made in the usual manner, e.g., with methyl bromide [24,25]. An analogous reaction with pentaerythritol as diol yielded a 1,3-dioxane with two unreacted hydroxymethyl groups which can be reacted further, e.g., to give a dianionic surfactant [23]. An elegant way to prepare an anionic dioxane surfactant in a one-step reaction is to react the long-chain aldehyde with a diol containing a carboxyl group, such as 2,2-bis(hydroxymethyl)propionic acid [26]. Nonionic surfactants can be prepared by ethoxylation of the remaining hydroxyl group of glycerol and such acetal surfactants have been commercialized

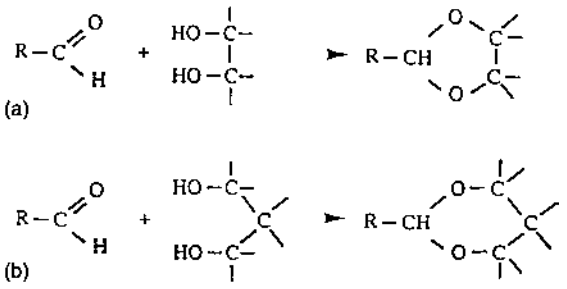

FIG. 12 Preparation of 1,3-dioxolane surfactant (a) and 1,3-dioxane surfactant (b) from a long-chain aldehyde and a 1,2- and a 1,3-diol, respectively.

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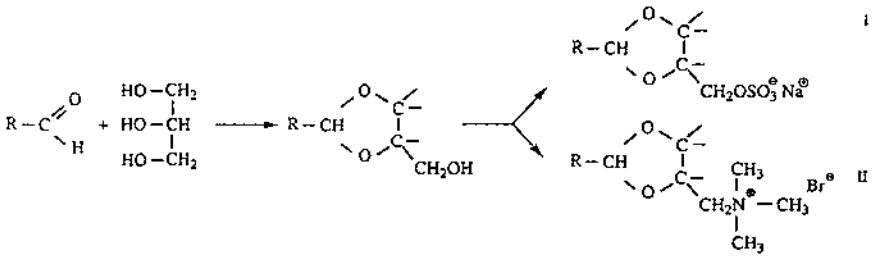

FIG. 13 Examples of anionic (I) and cationic (II) 1,3-dioxolane surfactants.

[27]. The rate of decomposition in sewage plants of this class of nonionic surfactants is much higher than for normal ethoxylates [28]. Nonionic dioxolane surfactants can also be made by reacting the remaining hydroxyl group with a reactive derivative of a monomethyl-PEG. When the dioxolane is made from a ketone, a double-tailed, easily degradable nonionic surfactant is obtained, and this surfactant has been used for formulation of microemulsions that decompose in weak acid [29].

Hydrolysis splits acetals into aldehydes, which are intermediates in the biochemical β oxidation of hydrocarbon chains. Acid-catalyzed hydrolysis of unsubstituted acetals is generally facile and occurs at a reasonable rate at pH 4–5 at room temperature. However, electron-withdrawing substituents such as hydroxyl, ether oxygen, and halogens reduce the hydrolysis rate [30]. Anionic acetal surfactants are more labile than cationic [16], a fact that can be ascribed to the locally high oxonium ion activity around such micelles. The same effect can be seen also for surfactants forming vesicular aggregates, again undoubtly due to differences in the oxonium ion activity in the pseudophase surrounding the vesicle. Acetal surfactants are stable at neutral and high pH.

The advantage of using a cleavable acetal surfactant instead of a conventional amphiphile has been elegantly demonstrated in a work by Bieniecki and Wilk [31]. A cationic 1,3-dioxolane derivative was used as surfactant in a microemulsion formulation that was employed as reaction medium for an organic synthesis. When the reaction was complete, the surfactant was decomposed by addition of acid and the reaction product easily recovered from the resulting two-phase system. By this procedure the problems of foaming and emulsion formation, frequently encountered with conventional surfactants, could be avoided.

The 1,3-dioxolane ring has been found to correspond to approximately two oxyethylene units with regard to effect on CMC and adsorption characteristics [18]. Thus, surfactant type I in Fig. 13 should resemble ether sulfates

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of the general formula R-$(OCH_2CH_2)_2OSO_3Na$. This is interesting since the commercial alkyl ether sulfates contain two to three oxyethylene units.

B. Acyclic Acetals

Alkylglucosides, often somewhat erroneously referred to as alkylpolyglucosides or APGs, are cyclic compounds. However, since the ring does not involve the two geminal hydroxyl groups of the aldehyde hydrate, they are here included in the category of acyclic acetals. Alkylglucosides are by far the most important type of acetal surfactant. Since this surfactant class is the topic of one chapter in this book, it will be only briefly outlined below.

Alkylglucosides are made either by direct condensation of glucose and a long-chain alcohol or by transacetalization of a short-chain alkylglucoside, such as ethylglucoside, with a long-chain alcohol, in both cases using an acid catalyst (Fig. 14). The procedure leads to some degree of sugar ring condensation, the extent of which can be governed by various means, e.g., the ratio of long-chain alcohol to sugar.

The alkylglucoside surfactants break down to glucose and long-chain alcohol under acidic conditions. On the alkaline side, even at very high pH, they are stable to hydrolysis. Their cleavage profile along with their relatively straightforward synthesis route makes these surfactants interesting candidates for various types of cleaning formulations.

Polyoxyethylene-based cleavable surfactants have been synthesized by reacting end-capped PEG with a long-chain aldehyde, as is shown in Fig. 15 [32,33]. During acid hydrolysis, these compounds revert to the original fatty

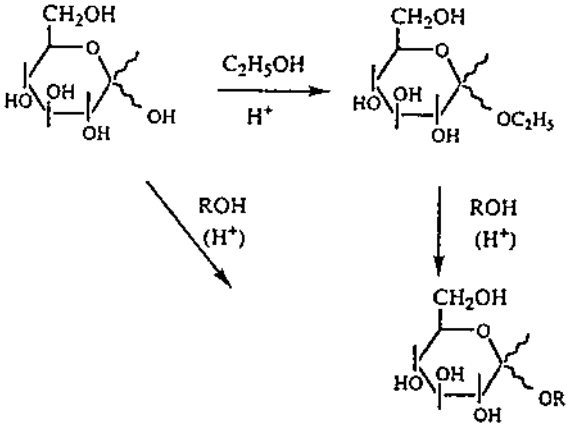

FIG. 14 Two routes of preparation of alkylglucosides. R is a long-chain alkyl.

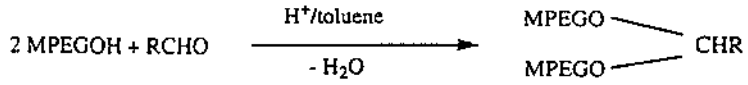

FIG. 15 Preparation of a cleavable surfactant containing two polyoxyethylene chains. R is a long-chain alkyl.

aldehyde and end-capped PEG. Studies of relationship between structure and hydrolytic reactivity have shown that the hydrolysis rate increases as the hydrophobe chain length decreases when the hydrophilic part was kept the same. This has been attributed to decreased hydrophobic shielding of the acetal linkage from oxonium ions. No effect on the hydrolysis rate was seen when the hydrophilic part was varied while the hydrophobic part was kept constant or when the structure of the hydrophobe was varied from linear to branched. Furthermore, the hydrolytic reactivity of nonaggregated surfactants is higher than of micellized surfactants [34,35].

Ono et al. have synthesized series of open acetal surfactants—anionics, nonionics, cationics, and amphoterics—and made a systematic study of the influence of the polar head group on hydrolytic reactivity (Fig. 16) [36,37]. The hydrophobic tail as well as the connecting group was kept constant and the time for complete decomposition was recorded. The results, shown in Table 1, constitute an illustration of the effect of the micelle surface on the hydrolysis rate. With negatively charged micelles the reaction is very fast, with

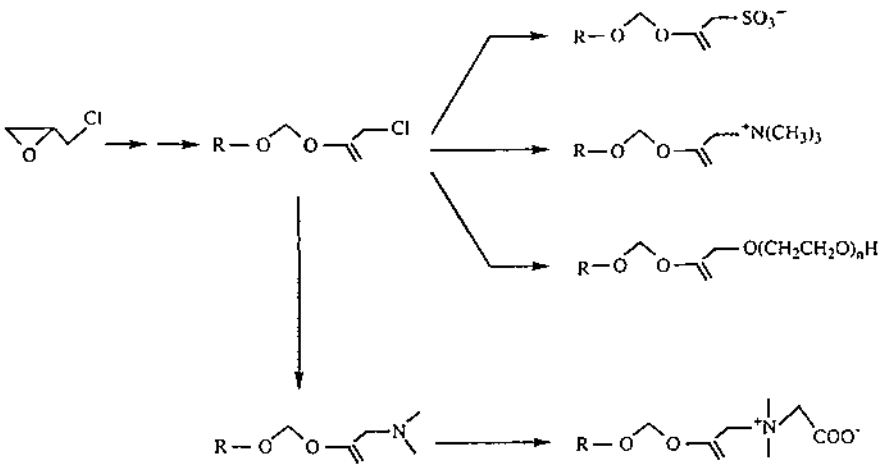

FIG. 16 Schematic synthesis routes of noncyclic acetal surfactants.

TABLE 1 Times for Complete Decomposition of Four Acetal-Based Surfactants at 25°C and at Varying Conditions [36]

Surfactant type	2% DCl	pD 1	pD 3
Anionic	Immediately	Immediately	30 min
Cationic	48 h	1 week	>2 weeks
Nonionic	Immediately	15 min	90 h
Amphoteric	3 h	24 h	>1 week

Reactions were carried out in deuterated solvent to enable the hydrolysis reactions to be monitored by NMR.

positively charged micelles the process is sluggish, and with the noncharged micelles the rate is intermediate.

Acetal surfactants have been found to resemble traditional surfactants in terms of physicochemical properties. However, it has been reported that the CMC values for acetal-containing surfactants are somewhat lower than for the corresponding conventional surfactants. Furthermore, the efficiency of the surfactants, expressed as the concentration required to produce a 20 mN/m reduction in surface tension, was higher for the cleavable surfactants [36]. Evidently, the acetal linkage connecting the hydrophobic tail and the polar head group gives a contribution to surfactant hydrophobicity, resulting in higher adsorption efficiency at the air–water interface and increased tendency to aggregate into micelles.

Acetal linkages have also been used in end-capped surfactants. By reacting a fatty alcohol alkoxylate with an alkyl vinyl ether, such as isobutyl vinyl ether, low-foaming surfactants with excellent biodegradation have been obtained [38]. Through a transacetalization process, a mixture of an isobutyl-blocked fatty alcohol alkoxylate and a di(fatty alcohol alkoxylate)acetal is formed, as shown in Fig. 17. The transacetalization has made it possible to

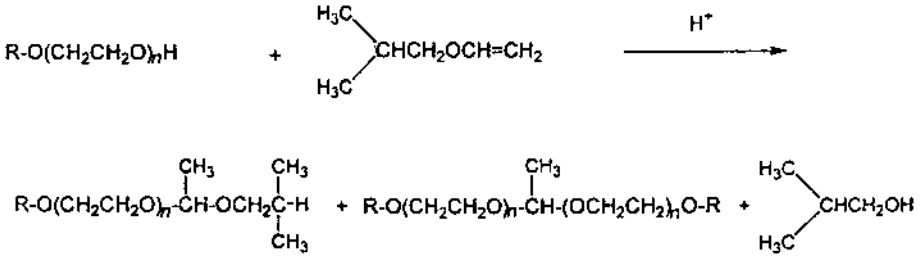

FIG. 17 Preparation of an end-capped surfactant with acetal linkage, starting from fatty alcohol ethoxylate and isobutyl vinyl ether.

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prepare PEG-PPG block copolymers with improved biodegradation characteristics [39]. Hydrolysis of these compounds yields 1 mol of acetaldehyde and 2 mol of alcohol [which might be fatty alcohol alkoxylate, poly(alkylene glycol) or isobutanol].

C. Ketals

Surfactants containing ketal bonds can be prepared from a long-chain ketone and a diol in analogy with the reaction schemes given in Figs. 12 and 13 for the preparation of acetal surfactants [40]. Recently, nonionic cleavable surfactants based on long-chain carbonyl compound, glycerol, and a polyoxyethylene chain have been commercialized. Both long-chain ketones and aldehydes can be used. Upon condensation with glycerol, they form cyclic ketals and acetals, respectively, as discussed above for cyclic acetals. Ketones give primarily 4-hydroxymethyl-1,3-dioxolanes, whereas aldehydes give a mixture of 4-hydroxymethyl-1,3-dioxolanes and 5-hydroxy-1,3-dioxanes. The remaining hydroxyl function is alkoxylated in the presence of a conventional base catalyst [27,28].

Jaeger et al. have studied the kinetics of hydrolysis of cationic ketal-based surfactants [41]. A comparison was made between acid hydrolysis of surfactants in nonaggregated form and in the form of either micelles or vesicles. (Ketal surfactants with one hydrophobic tail formed micelles and those with two hydrophobic tails formed vesicles.) It was found that both types of aggregation caused about two orders of magnitude reduction of the hydrolysis rate. Aggregation is evidently a way to protect these acid-labile cationic species from acid hydrolysis just as aggregation is a way to speed up alkaline hydrolysis of cationic alkali-labile surfactants, such as esterquats.

Ketal-based surfactants have also been prepared in good yields from esters of ketoacids by either of two routes, as shown in Fig. 18 [42,43].

The biodegradation profiles of the dioxolane surfactants of Fig. 18 are shown in Fig. 19 [42]. As expected, the degradation rate is very dependent on the alkyl chain length. The process is markedly faster for the labile surfactants (and particularly for structure I which contains an extra ether oxygen) than for the conventional carboxylate surfactant of the same alkyl chain length used as reference. Ketal surfactants are in general more labile than the corresponding acetal surfactants [44]. As an example, a ketal surfactant kept at pH 3.5 was cleaved to the same extent as an acetal surfactant of similar structure kept at pH 3.0 [45]. The relative lability of the ketal linkage is due to the greater stability of the carbocation formed during ketal hydrolysis compared to the carbocation formed during acetal hydrolysis. (It is noteworthy that biodegradation of an acetal surfactant has been found to be faster than for a ketal surfactant of very similar structure [42]. Evidently,

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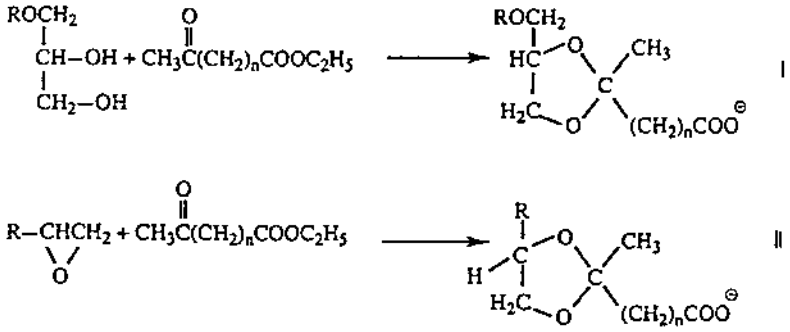

FIG. 18 Preparation of anionic 1,3-dioxolane surfactants from ethyl esters of ketoacids.

there is no strict correlation between ease of biodegradation and rate of chemical hydrolysis.)

Jaeger has introduced the term "second-generation cleavable surfactant" for labile surfactants that on cleavage give another surfactant together with a small water-soluble species. The daughter surfactant generally has a higher CMC than the parent surfactant [46–49]. Figure 20 shows a typical example of a second-generation cleavable surfactant. The concept has been applied to a variety of structures, including phospholipid analogs [49], and several

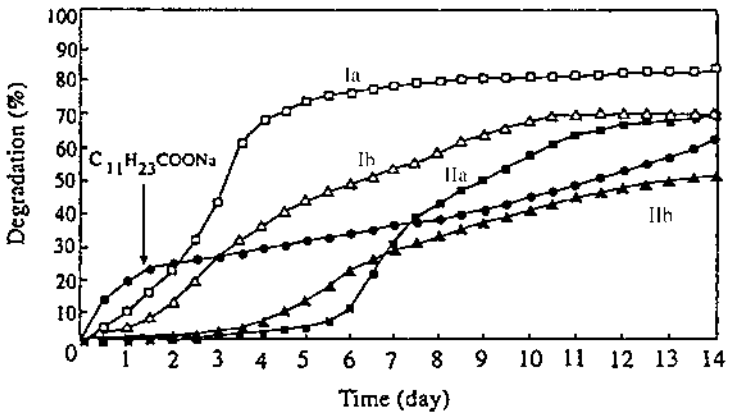

FIG. 19 Rate of biodegradation vs. time for four ketal surfactants and for sodium decanoate as reference. I and II relate to the compounds of Fig. 6; a: R = $C_{12}H_{25}$, $n = 2$; b: R = $C_{16}H_{33}$, $n = 2$. (From Ref. 42.)

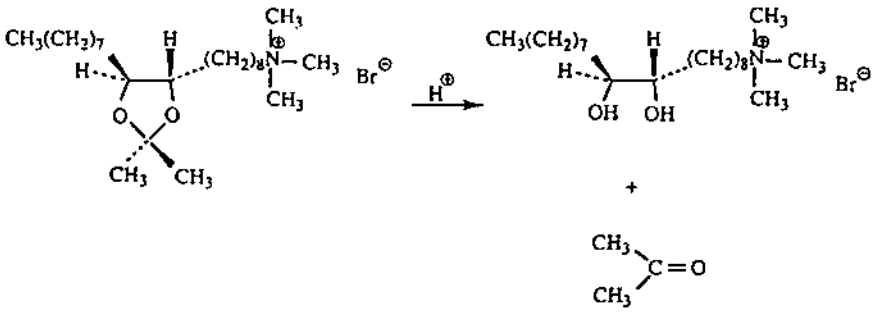

FIG. 20 Acid-catalyzed hydrolysis of a second-generation cleavable surfactant. (From Ref. 16.)

applications of this specific type of cleavable surfactants have been proposed in the papers by Jaeger et al.

Double-chain, double-head-group, second-generation surfactants have also been synthesized. The geometry of the molecules may be varied by the position of the link between the hydrocarbon tails. Both symmetrical and unsymmetrical cross-linking with respect to the head groups have been prepared [16,50,51]. These surfactants can be seen as examples of gemini surfactants, and in one approach labile gemini surfactants were synthesized which on acid treatment broke down into single-chain, single-head-group surfactants [51]. They are of interest in model investigations, e.g., to study the morphology of aggregates. However, their preparation is cumbersome, which means that their practical usefulness is limited.

D. Ortho Esters

Ortho esters are a new class of surfactants that have been described recently [52,53]. Surfactant ortho esters are conveniently prepared by transesterification of a low molecular weight ortho ester (such as triethylorthoformate) with a fatty alcohol and a metyl-capped PEG. An example of structure and a typical method of preparation are given in Fig. 21. Due to the trifunctionality of the ortho ester, a complex mixture of species is obtained, each of which can be identified by nuclear magnetic resonance using the chemical shift of the central methine proton as a marker [53]. Furthermore, if the reactant alcohol is difunctional, cross-linking will occur and a large network may be formed. Such compounds have been shown to be effective foam depressants and an example based on poly(propylene glycol) (PPG) and methyl-capped PEG is shown in Fig. 22 [54]. By varying the number and types of substituents (fatty alcohol, alkyleneoxy group, end blocking), the

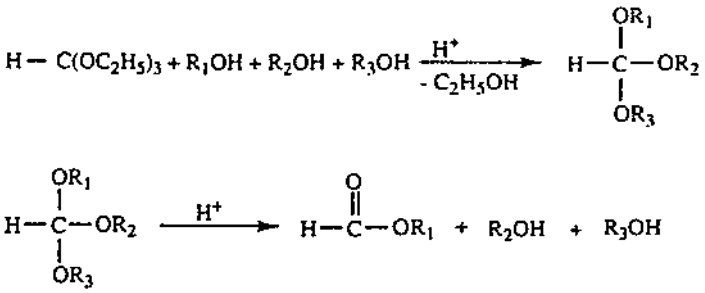

FIG. 21 Synthesis and hydrolysis of ortho esters. R_1, R_2, and R_3 are alkyl groups.

properties of the ortho ester–based surfactant or block copolymer can be tailor-made for a specific field of application.

Hydrolysis of ortho esters occurs by a mechanism analogous to that of acetals and ketals and gives rise to 1 mol of formate and 2 mol of alcohols [55,56]. Both formates and alcohols can be regarded as nontoxic substances and recent research by Bergh et al. has shown that surface active formates (similar to surface-active alcohols and esters but in contrast to surface-active aldehydes) have no or little dermatological effect, evaluated in terms of sensitizing capacity and irritancy [57]. Ortho ester–based surfactants undergo acid-catalyzed cleavage much more readily than acetal-based surfactants under the same conditions [58]. For instance, a water-soluble ortho ester based on octanol and monomethyl-PEG is hydrolyzed to 50% in 2 h at pH 5. The structure of the surfactant has been found to influence the hydrolysis rate and, in general, a more hydrophilic surfactant has a higher decomposition rate.

Ortho ester linkages can also be used to improve biodegradation properties in long-chain ethoxylates or block copolymers. It has been shown that a conventional PEG-PPG copolymer with a molecular weight of 2200 biodegrade to only 3% in 28 days. However, if an equivalent molecule is built up from PEG 350 and PPG 400, connected by ortho ester links, it will reach 62% biodegradation within 28 days and thus be classified as "readily biodegradable" [54].

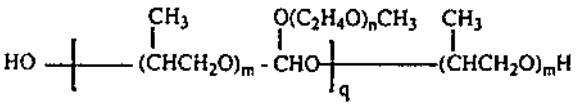

FIG. 22 An ortho ester–based block copolymer.

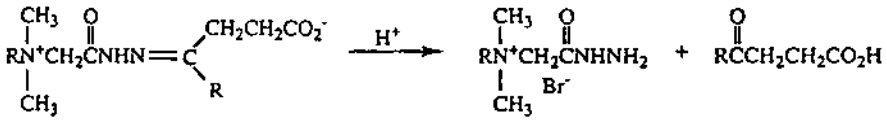

FIG. 23 Hydrolysis of a surfactant containing the N═C bond. R is a long-chain alkyl. (From Ref. 60.)

Cationic ortho ester surfactants have also been described [59]. They can be synthesized by a route analogous to that used for nonionic ortho ester surfactants (Fig. 21), using an amino alcohol, such as *N*,*N*-dimethylamino-ethanol, instead of the methyl-capped PEG. Cationic ortho esters have been suggested as surfactant or bactericidal agent with pH-dependent half-life [58,59]. The surfactants are completely stable at pH 10 whereas they break down readily under mild acidic conditions. In this respect they are the reverse to the betaine esters discussed above.

E. Surfactants Containing the N═C Bond

Jaeger et al. has synthesized surfactants consisting of two parts connected with a CONHN═C moiety. Each part is a surfactant of its own with a hydrophobic tail and a polar head group, and the two head groups are of different sign [60]. The structure is shown in Fig. 23. As can be seen, the two charges are far apart in the molecule; thus, the type is conceptually different from double-chain zwitterionic surfactants such as phosphatidylcholine. Instead, they may be viewed as a kind of heterogemini surfactant.

Figure 23 also illustrates the acid-catalyzed breakdown of the surfactants. Hydrolysis into the cationic and the anionic surfactant parts occurs readily in weak acid. The surfactant forms giant vesicles on sonication, and a suggested application is as entrapment and release devices that can be triggered by a change in pH from 7 to about 3.

IV. UV-LABILE SURFACTANTS

The concept of triggering cleavage by UV light is attractive because it allows an extremely fast breakdown of the surfactant to occur. An alkyl aryl ketone sulfonate, which bears some structural resemblence with alkylbenzenesulfonate surfactants, was synthesized [61]. This compound is photocleaved into a water-soluble arylsulfonate and a mixture of two methyl-branched olefins, as is shown in Fig. 24. The surfactant is of interest for solubilization of proteins since the workup procedure is greatly facilitated by the instantaneous elimination of surfactant from the solution. The wavelength required for this

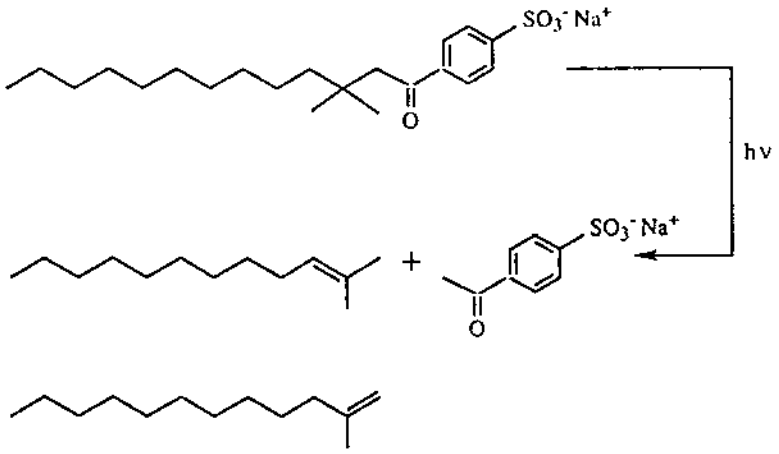

FIG. 24 Photocleavage of a surface-active alkyl aryl ketone. (From Ref. 61.)

type of photolysis, a so-called Norrish type II cleavage, is 300 nm and above. This low-energy radiation should be harmless to proteins.

Another approach has been to incorporate the light-sensitive diazosulfonate group between the polar head group and the tail of an anionic surfactant [62–64]. As can be seen from Fig. 25, also these surfactants are similar in structure to the commonly used alkylbenzenesulfonates. A comparison of CMC values for the diazosulfonate and the normal sulfonate surfactants with

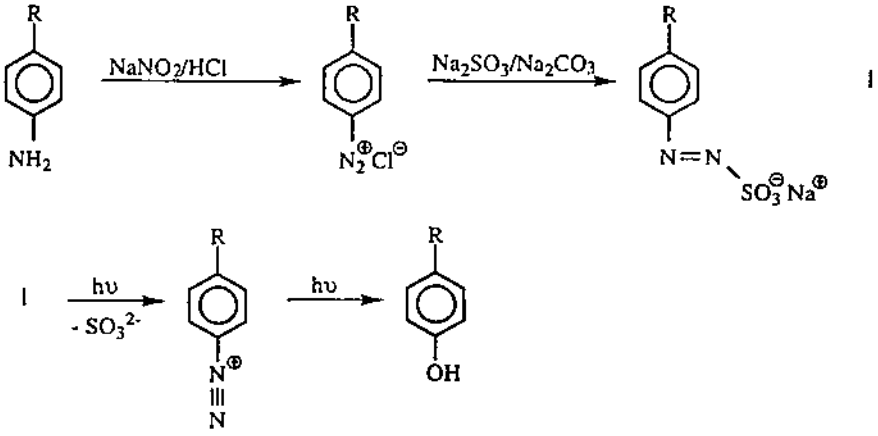

FIG. 25 Preparation and light-induced degradation of a diazosulfonate surfactant. (From Ref. 64.)

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the same R substituent shows lower values for the former, indicating a contribution of hydrophobicity from the azo linkage. Photochemical cleavage yielded sulfate ion and the remaining diazonium compound, which was further photolyzed in a second step.

An interesting use of photolabile surfactants is as emulsifiers in emulsion polymerization [65,66]. The use of a photolabile emulsifier opens the possibility to control the latex coagulation process simply by exposing the dispersion to UV irradiation. The ionic head group of the surfactant will be split off by photolysis leading to aggregation of the latex particles. Such latexes could be of interest for coatings applications.

In a more recent paper, a double-chain surfactant has been synthesized which contained Co(III) as complexing agent for two single-chain surfactants based on ethylenediamine in the polar head group. UV irradiation, or merely sunlight, causes reduction of Co(III) to Co(II). The latter gives a very labile complex and the double-chain surfactant immediately degrades into two single-chain moieties [67].

V. MISCELLANEOUS

Apart from the product classes discussed above, which include the most important types of cleavable surfactants, several more or less exotic examples of surfactants with limited half-life have been reported. For instance, isethionate esters with very high degrees of alkali lability have been developed. These products, made by esterification of an alkylpolyoxyethylene carboxylic acid with the sodium salt of isethionic acid, have been claimed to be partially cleaved when applied to the skin [68]. Cleavable quaternary hydrazinium surfactants have been explored as amphiphiles containing a bond which splits very easily. The surfactants are cleaved by nitrous acid under extremely mild conditions [69]. Ozone cleavable surfactants have been developed as examples of environmentally benign amphiphiles. These surfactants, which contain unsaturated bonds, break down easily during ozonization of water, which is a water purification process of growing importance. Both normal surfactants [70] and geminis [71] have been synthesized and tested in ozonolysis. The latter surfactants contained unsaturation either in the hydrophobic tails or in the linker unit.

Glucose-based surfactants having a disulfide linkage between the anomeric carbon of the sugar ring and the hydrophobic tail were synthesized and evaluated for use as solubilizing agent for membrane proteins [72]. Cleavage into nonsurfactant products was performed by addition of dithioerythritol, which is known to split disulfide linkages under physiological conditions.

Surfactants with thermolabile bonds have been synthesized and evaluated as short-lived surfactants. Amine oxide surfactants with an ether oxygen in

the 2-position are examples of such structures. They decompose at elevated temperature to the corresponding vinyl ether [73].

VI. CONCLUDING REMARKS

Cleavable, or splittable, or chemodegradable surfactants are likely to become increasingly important as the environmental concern with regard to surfactant formulations becomes even more widespread. The development that has occurred to this point has brought about a vitalization of the surfactants area in terms of new structures and synthesis strategies. The effort to make surfactants with bonds that break down in a controlled way to yield non-surface-active or less surface-active products has probably involved more creative thinking in terms of organic synthesis than any other area in the surfactant domain, possibly with the exception of the gemini surfactants. It will be interesting to monitor in the years to come which of the many research avenues employed to prepare cleavable surfactants become important commercial processes.

Splitting by hydrolysis is the most straightforward way to achieve controlled breakdown of the surfactant. Taken together, the work accomplished so far has resulted in a versatile toolbox of surfactant structures with different degradation profiles. Figure 26 illustrates the point. The figure is based on data in the literature and from assumptions based on extrapolation of such data. The effect of micellization on the degradation rate has not been studied for all classes of surfactants but the general trends shown in the figure should hold true. Since there may be a conflict between storage stability and

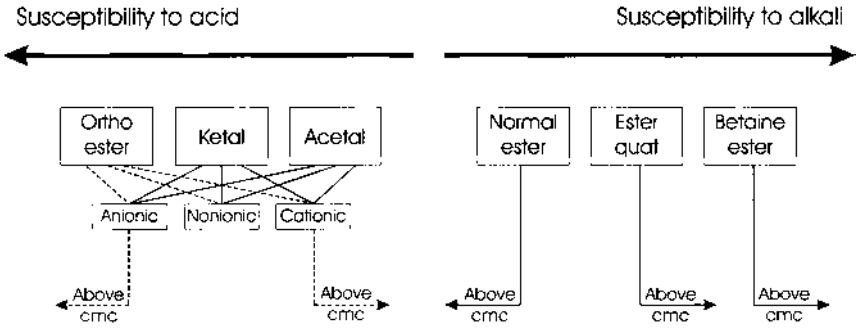

FIG. 26 Scheme showing relative rates of acid and alkaline hydrolysis of different classes of cleavable surfactants and the effect of micellization of hydrolysis rate. Full lines represent experimentally verified results and dashed lines indicate predicted behavior.

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ease of breakdown after use, it is important to have a range of products with varying hydrolysis stabilities to choose from. Besides the hydrolysis profile of the individual surfactant molecules, i.e., of nonmicellized surfactant, the effect of micellization on the hydrolysis rate is interesting. Whereas micelle formation protects the surfactant from hydrolysis in some cases (*micellar retardation*), aggregation accelerates the breakdown in other instances (*micellar acceleration* or *micellar catalysis*). This is obviously of considerable practical importance.

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11

Esterquats

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I. INTRODUCTION

The term *esterquat* is commonly used to describe a family of cationic surfactant compounds that is heterogeneous in the chemical sense. In this chapter, we define esterquats as a class of surface-active quaternary ammonium compounds having the general formula $R_4N^{(+)}X^{(-)}$, characterized by the fact that the hydrophobic parts of the moieties "R" are linked to the charged head group via *ester bonds R-C(O)O- or ROC(O)-, with* $X^{(-)}$ *being any anionic counterion*. Somewhat arbitrarily, we further propose that any alkyl chain in a moiety R that contains more than four carbon atoms shall be considered as belonging to the hydrophobic part of the molecule. By application of this definition, an ester compound that contains a moiety R directly bonded to a cationic nitrogen, with R containing more than four carbon atoms, is not considered an esterquat.

As a consequence of this specific structure, esterquats upon hydrolysis decompose into non-surface-active fragments. They may be referred to as "cleavable surfactants." As a matter of fact, esterquats usually biodegrade more rapidly than the related alkylquats. The hydrolytic instability, on the other hand, comprises a challenge to the user and formulator. While traditional alkylquats are virtually stable under the conditions of use, esterquats

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are stable in aqueous solutions only in a narrow pH window for a certain period of time. Although this limitation seems acceptable to the formulator for specific applications, it remains unclear as to whether esterquats can replace alkylquats in other applications. However, new legislation might be a driving force to replace products with environmental risk with products that are safer to use. Most esterquats are readily biodegradable and show low toxicity, partly caused by their hydrolytic instability.

The earliest mention of esterquats in the open literature dates back to the 1930s [1]. Early uses of esterquats were as textile auxiliaries and dye-leveling agents. However, until recently their commercial relevance was limited. This changed dramatically when in the early 1990s, overnight, a market was created for several thousands of tons when European detergent manufacturers started to reformulate their rinse cycle softener products to esterquats. Today rinse cycle softeners based on esterquats are in broad use in Europe and the United States, and constitute by far the largest commercial use of this class of compounds. Esterquats are also applied in personal care products, and some industrial areas are following slowly. It is expected that the use of esterquats will grow. Existing products will be used for new and existing applications and technologies and formulations will be adapted to deal with the specific use of esterquats. New products with improved performance and environmental properties will be developed and applied in existing and new applications.

II. CHEMISTRY

A. Raw Materials

Esters are generally prepared by reaction of an acid with an alcohol. In the presence of a catalyst the raw materials are heated to temperatures up to 250°C to remove water and to obtain high conversion. Due to the thermal instability of quaternary ammonium compounds, they are not recommended for use with alcohol or acid functions in the esterification. In the case of esteramines, the esterification is usually carried out with tertiary alkanolamines and fatty acids. The corresponding esteramine is reacted with an alkylating agent like dimethyl sulfate or methyl chloride to obtain the corresponding quaternary ammonium compound.

The alkanolamines most frequently used are triethanolamine (TEA), methyldiethanolamine (MDEA), dimethylethanolamine (DMEA), and 3-(dimethylamino)-l,2-propanediol (DMAPD). Other types of esteramines are prepared from aminoethylethanolamine (AEEA) or other ethoxylated amines (Fig. 1). Some physical properties of the alkanolamines are listed in Table 1 [2]. Most alkanolamines are soluble in water.

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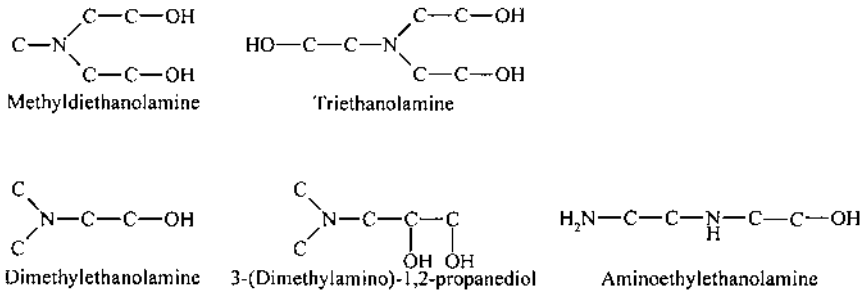

FIG. 1 Some alkanolamines used for the preparation of esterquats.

The hydrophobic building block of the esteramines is usually derived from fatty acid, which is readily available at low prices. Most esterquats are prepared from fatty acids with chain lengths of 8–18 carbon atoms. The fatty acids can be applied in their native form or (partly) hydrogenated. Most commonly used are tallow or (partially) hydrogenated tallow, but other fatty acids like coco, oleic, palmitic, fish oil or beef tallow [3,4], to name a few, are mentioned frequently. For use in personal care products, fatty acids from a vegetable source are preferred. Alternatives to the fatty acids are methyl esters, triglycerides [5], and acid chlorides. Triglycerides are cheap but lead to mixtures of components including glycerol and mono- and diglycerides. Acid chlorides are generally more expensive but can be used when a higher reactivity is required and the higher price is acceptable. The most commonly used acyl building blocks are listed in Fig. 2. The most commonly applied alkylating agents are dimethyl sulfate and methyl chloride, but other alkylating agents can be used as well.

TABLE 1 Physical Properties of Some Alkanolamines

Alkanolamine	MW	Freezing point (°C)	Boiling point (°C)	Specific gravity (20°C, g/cm^3)	Viscosity (20°C, mPa.s)
Dimethylethanolamine	89	−59	135	0.888	3.8
Methyldiethanolamine	119	−21	247	1.042	101
Triethanolamine	149	18	360	1.126	1013
3-(Dimethylamino)-1,2-propanediol	119	—	216–217	1.004	—
Aminoethylethanolamine	104	−38	244	1.0304	141

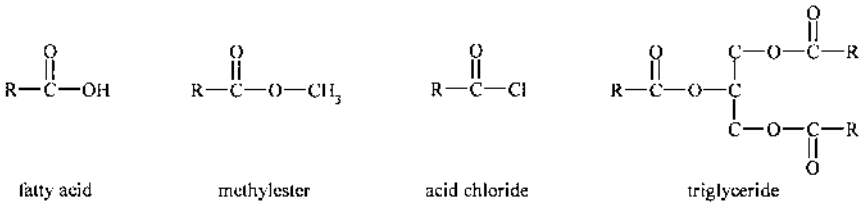

FIG. 2 The acyl building block for the preparation of esterquats.

B. Preparation

Most often, the esterquats are prepared by reaction of a tertiary alkanolamine with a fatty acid, followed by reaction with an alkylating agent to the corresponding quaternary [6]. Other sources of the acyl chain include triglycerides, methyl esters, and acid chlorides. The reaction scheme for the preparation of the diester of bis-2-hydroxyethyldimethylammonium chloride from methyldiethanolamine and fatty acid is given in Fig. 3.

1. Procedure to Prepare a Diesterquat

In order to prepare a diesterquat, 2 mol of fatty acid is charged to 1 mol of alkanolamine. An acidic catalyst is often used to accelerate the reaction. The temperature is raised to 200°C, and stripping with an inert gas or under vacuum enhances water removal. As esterifications are equilibrium reactions, it

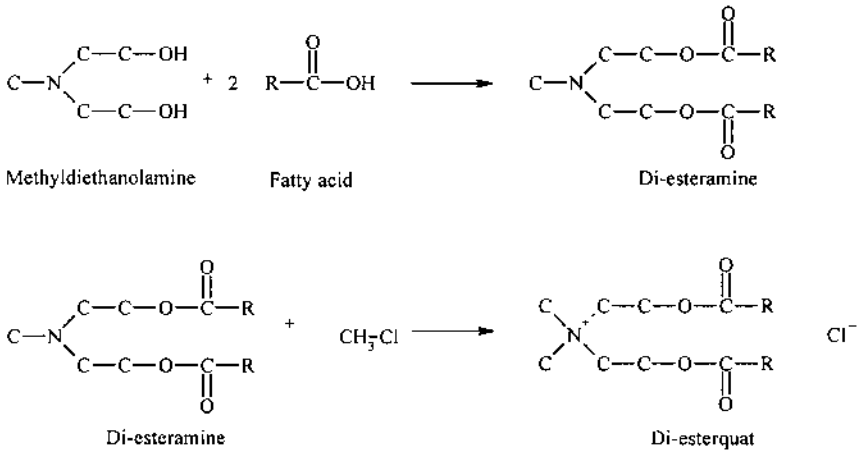

FIG. 3 Preparation of a diesterquat.

is necessary to remove the condensation water to reach full conversion. Because most raw materials have high boiling points, the losses are low and the diesteramine can be obtained in good yield. In case of volatile alkanolamines precautions should be taken to prevent losses. Reaction times vary from a few hours to more than 10 h, depending on the reaction conditions and the reactivity of the components. The yield of diesteramine is generally more than 90%, and residual amounts of monoesteramine and fatty acid are the main impurities. Alkanolamines can be removed under vacuum to low levels, whereas residual fatty acid usually remains in the esteramine. It is obvious that in case methyl esters, acid chlorides, or triglycerides are used, residual amounts of these raw materials may be found in the esteramine. In the case of diesteramines in general, up to 10% of monoesteramines are present.

Complete conversion to the diesteramine is usually not achieved, as this would require very long reaction times and/or an excess of fatty acid. The esterification of alkoxylated alkanolamines with fatty acid can be done in a similar way [6,7]. If the esterification has to be carried out at low temperatures, acid chlorides have to be used instead of a fatty acid [8]. Most acid chlorides will react readily below 100°C. Esterifications in which triglycerides are used are described by Hofinger [9].

The quaternization is generally carried out with methyl chloride or dimethyl sulfate, but other alkylating agents can be used as well [6,7,10]. A polar solvent like 2-propanol is often added to keep the reaction mixture liquid, although reactions without solvents are reported [11]. The quaternizations are carried out at temperatures up to 100°C, as higher temperatures lead to decomposition of the quaternary product. The reaction can be completed in a few hours but may take longer with less reactive esteramines. In general, the reactivity decreases with the number of side chains, other than methyl, of the quaternary nitrogen. Esteramines are slightly less reactive to alkylating agents when compared with the traditional alkylamines. The diesterquats can be obtained in good yield; the main impurities are residual esteramine, esteramine salt, and fatty acid. In most cases, the pH of the reaction product is close to the range of optimum stability, which means that no adjustment is necessary.

2. Reactions with Triethanolamine

Triethanolamine can react with up to 3 mol of fatty acid to give the triesteramine. If less than 3 mol of fatty acid is used, the equilibrium reaction product is always a mixture of mono-, di-, and triesteramines. The composition of the equilibrium reaction product of triethanolamine with fatty acid is given in Fig. 4.

It can be seen that the reaction product of 2 mol of fatty acid with triethanolamine contains the diesterquat as the major component, but mono- and

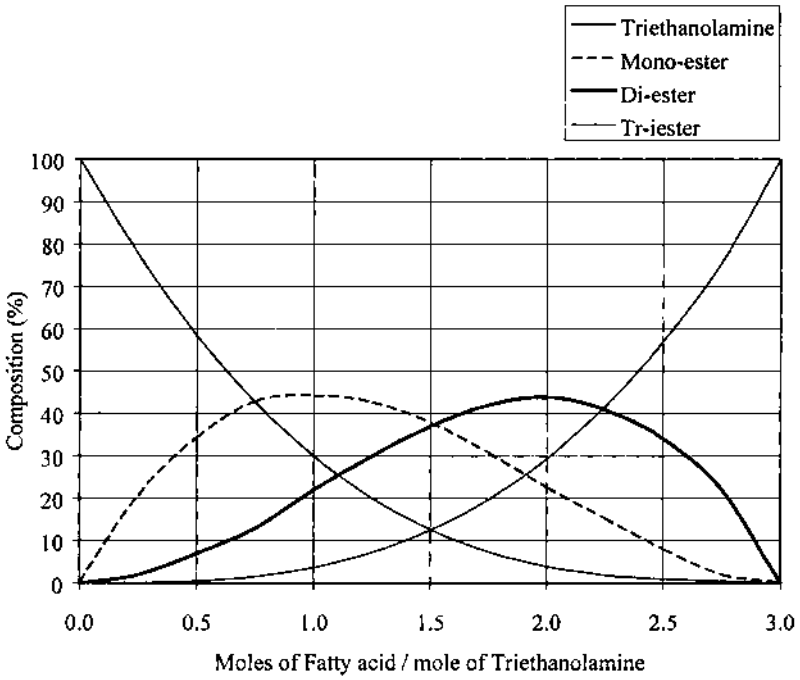

FIG. 4 Reaction products of triethanolamine and fatty acid. (From internal reports.)

triesterquats are present in considerable amounts as well. It is possible to shift the equilibria by choosing other reaction conditions or other raw materials, e.g., methyl esters or glycerides instead of fatty acids. Because triethanolamine is not volatile, high temperatures and vacuum can be used to bring the reaction to completion. The quaternization of the esteramine mixture is carried out with dimethyl sulfate. The reaction is usually carried out in 2-propanol at temperatures up to 100°C. In general, a substoichiometric amount of dimethyl sulfate is charged in order to avoid traces of residual dimethyl sulfate in the end product.

3. Reactions with Dimethylethanolamine

When methyldiethanolamine is reacted with 1 mol of fatty acid, a mixture of di- and monoesteramine together with methyldiethanolamine is the reaction product [9]. The monoesteramine cannot be prepared selectively via this route as the reactivity of methyldiethanolamine and the monoesteramine is roughly the same, and thus statistic reaction mixtures are obtained.

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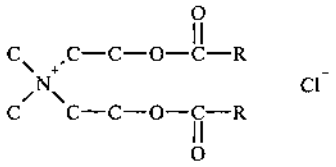
Pure monoesteramines can be prepared with dimethylethanolamine and 1 mol of fatty acid. The esterification is carried out under somewhat different conditions, as due to the volatility of the dimethylethanolamine measures have to be taken to avoid losses of the alkanolamine during esterification.

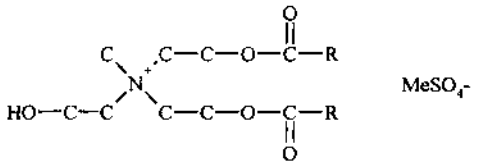
Quaternization of the monoesteramines with a variety of alkylating agents proceeds well under mild conditions similar to the quaternization of the traditional dimethylalkylamines. In general, polar solvents like water, alcohols, and glycols are used to obtain liquid products at room temperature. Esterquats from other alkanolamines can be prepared by similar procedures.

C. Classes of Esterquats

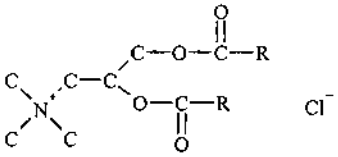
The most frequently applied esterquats are those derived from alkanolamines and fatty acid. They can be divided in mono-, di-, and triesterquats,



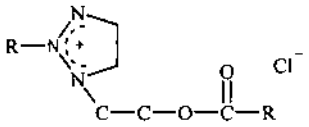
Di-esterquat of dimethyldiethanolammonium chloride



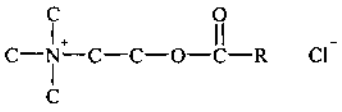
Di-esterquat of triethanolammonium methosulfate



Di-esterquat of 2,3-dihydroxypropylammonium chloride



Dialkyl imidazolinesterquat



Monoesterquat of Dimethylethanolamine

FIG. 5 Examples of diesterquats.

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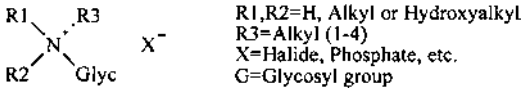

FIG. 6 Esterquats derived from sugar derivatives.

depending on the structure of the alkanolamine and stoichiometry of the reaction. Some examples are given in Fig. 5 [12–16]. Other esterquats are those derived from sugar derivatives (Fig. 6). Examples are reported in which glucose [17], sorbitol [17,18], or gluconic acid [19] is incorporated in the molecule via esterification of the carboxylic acid or hydroxyl group.

Another important class of esterquats is the betaine esters (Fig. 7), which are derived from aminocarboxylic acids and thus have a reverse ester group compared to regular esterquats based on alkanolamines [20,21]. Other examples include esterquats derived from amino acids [22,23] or dicarboxylic acids [11,24,25].

Esterquats with two different ester bonds, RC(O)O– and ROC(O)–, in the same molecule are reported by Nieuwenhuis (Fig. 7) [26]. They are prepared by reacting dimethylethanolamine with fatty acid and subsequent quaternization with alkylchloroacetate.

It has been demonstrated recently in the literature that cationic surfactants with *ortho*-ester links can be prepared [194]. The main application areas for these novel *ortho*-ester cationic surfactants are seen in fields where high pH formulations are used, since the *ortho*-ester link shows a good hydrolytic stability at higher pH and decomposes at lower pH.

Esteramides (Fig. 8) are prepared as alternative to diesterquats. In general, the reaction is carried out with primary or secondary alkanol(poly)amines [28,29], which may include heterocycles [30,31] that are reacted with fatty

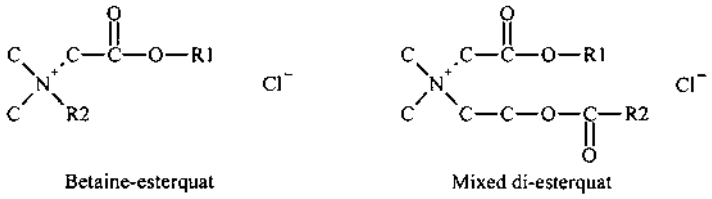

FIG. 7 Betaine esters.

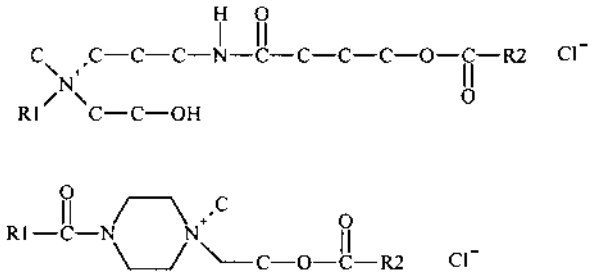

FIG. 8 Amide esterquats.

acids. The hydroxyl group will form an ester function and the primary or secondary amine will react to an amide.

III. PROPERTIES

A. Physical Properties

Most esterquats are solid materials that do not have a defined melting point but decompose upon heating [12]. Most monoesterquats show a good water solubility and the formulations have low melting points, especially those derived from dialkylethanolamines (C_1–C_3 alkyl) [32]. Thus, *N*-(2-cocoyloxyethyl)trimethylammonium chloride can be prepared up to 30% in water at ambient temperature. A method to make clear high concentrated aqueous monoesterquat solutions is demonstrated [33]. The solubility of esterquats decreases with growing chain length. Branching in the fatty acid chain improves the aqueous solubility [34]. The influence of the unsaturation on the properties of esterquats is given by Idris [35]. The melting point decreases with increasing unsaturation of the fatty acid chains. The viscosity of the aqueous solution increases with the concentration and the number of C-atoms in the fatty acid chain and also depends on the nature of the used alkanolamine. Addition of diethanolamine to triethanolamine gives a higher viscosity [36]. Di- and triesterquats are usually less soluble in water, and particularly products with long alkyl chains are basically insoluble [37]. These products are often applied in the form of aqueous dispersions.

Most esterquats are readily soluble in lower alcohols and glycols, and liquid formulations at room temperature can be obtained. Like most traditional quats, esterquats can be quite hygroscopic. Monoesterquats in particular can pick up to 20% of water at ambient conditions. The physical

properties of the solids change with increasing moisture contents. The di- and higher esterquats are less hygroscopic.

B. Biodegradation and Ecotoxicity

1. Biodegradation

Since the early 1990s, three esterquats based on tri-2-hydroxyethylmethyl-ammonium (MTEA), di-2-hydroxyethyldimetyl-ammonium (DMDEA), and 2,3-dihydroxypropyltrimethylammonium (DHPA) have gained wide use for environmental reasons (see Fig. 14 for structures). Consequently, the biodegradation of esterquats and their degradation products has been extensively studied using ready biodegradability and continuous activated sludge (CAS) tests. Di-(tallow fatty acid)ester of di-2-hydroxyethyldimethyl-ammonium chloride (DEQ) is readily biodegradable as approximately 80% of the theoretical carbon dioxide formation was produced in a Sturm test within 28 days [38]. In another Sturm test, 85% of di-(hardened tallow fatty acid)ester of 2,3-dihydroxypropyltrimethylammonium chloride (PDQ) degradation could be accounted for as carbon dioxide. Puchta [14] demonstrated that *N*-methyl-*N*,*N*-bis(C_{16}/C_{18}acyloxy)ethyl)-*N*-(2-hydroxyethyl) ammonium methosulphate (TEQ) is readily biodegradable. The hydrolysis products of esterquats have also been tested. Many tests measured sufficient degradation to conclude that fatty acids are readily biodegradable [39]. The biodegradation percentages for MTEA ranged from 76% to 94% in Sturm tests [14]. DHPA was biodegraded to carbon dioxide with a level of 80% [37]. Additional evidence for the rapid degradation of DHPA was obtained with a *Pseudomonas putida* strain. This strain capable of growth on DHPA at a maximal specific growth rate of 0.4 h^{-1} mineralized this intermediate completely [40].

Consequently, high removals of all three esterquats and their biodegradation products may be expected during sewage treatment. Indeed, CAS studies conducted showed very high removal, i.e., more than 99% [14,37,38]. Confirmation of these high removals was provided by a monitoring study showing effluent levels of MTEA, DMDEA, and DHPA of approximately 4 μg/L. This led to removal estimations of more than 90% for all three cationic surfactant intermediates. Comparison of estimated and measured influent concentrations indicated that DEQ is already degraded for 50% in the wash and/or sewers [41]. The degradation of DEQ was examined in sewage. Degradation in sewer systems took place with a half-life of 8–10 h confirming the result of the monitoring study [42].

Total mineralisation is assumed when biodegradation percentages of more than 60% in screening test are achieved. More decisive evidence for complete degradation may be obtained through biodegradation pathways. Degradation pathways of esterquats can be formulated, using research with

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mixed cultures and radiolabeled chemicals. Activated sludge extensively degraded ^{14}C-methyl-labeled DEQ during 28 days of incubation [38]. Solid-phase extraction of quaternary ammonium salts, followed by thin-layer chromatography with radiochemical detection, clearly showed the disappearance of DEQ. Concurrent with the loss of DEQ was the appearance of tallow fatty acid ester of di-2-hydroxyethyldimethyammonium chloride and di-2-hydroxyethyldimethylammonium chloride. Subsequently, the levels of these compounds declined. Degradation of DEQ was observed in raw sewage whereas no degradation of DEQ was detected in a sterilized control. The absence of abiotic degradation strongly suggests that the hydrolysis of the ester bonds is primarily biologically mediated. The proposed pathway for DEQ is presented in the Fig. 9.

Further proof that microorganisms degrade esterquats through initial hydrolysis of the ester bonds was afforded by experiments with three ^{14}C-

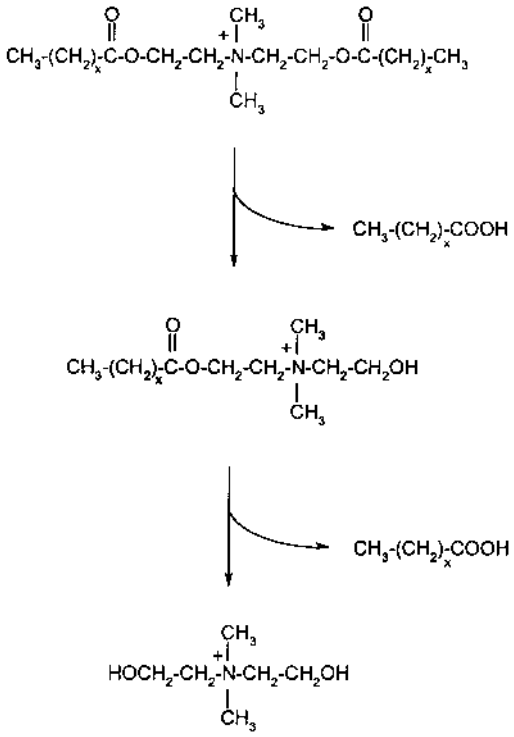

FIG. 9 The microbial degradation pathway of DEQ. The hydrolysis of the ester bonds giving rise to fatty acids and polyalcohol quaternary ammonium salts is probably a general mechanism for esterquats.

labeled PDQs. More than 80% of the labeled PDQs was recovered as ^{14}C-CO_2 during the incubation period with river water. In these die-away experiments, the microorganisms consumed the labeled PDQs within 10 days. The rate of disappearance varied with the location of the radiolabel. PDQ labeled in the fatty acid moiety was rapidly degraded without a detectable lag period. Mineralization of ^{14}C-methyl- and ^{14}C-dihydroxypropyl-labeled PDQ was preceded by a lag period, followed by extensive degradation. The mineralization of ^{14}C-methyl- and ^{14}C-dihydroxypropyl-labeled PDQ following that of the ^{14}C fatty acid labeled PDQ supports the removal of fatty acid moieties prior to the degradation of the polyalcohol quaternary ammonium compound [37].

Cleavage of the ester bonds can also take place in the absence of oxygen. Under anaerobic conditions released fatty acids undergo biodegradation. As expected, TEQ degraded under anaerobic conditions in a screening test [43].

2. Ecotoxicity

The ecotoxicity data for esterquats is provided in Table 2. Acute and chronic data on aquatic algae, invertebrates, and fish exist for several major esterquats. As explained above, the esterquats are susceptible to hydrolysis and it was necessary to take this factor into consideration prior to testing. Giolando et al. [38], for instance, found that DEQ remained stable when dosed into their studies as an acidified dispersion. While EC_{50} concentrations for the esterquats appear at first glance to be relatively low (lowest NOEC 0.3 mg/L), it must be borne in mind that these molecules have a water solubility in the low μg/L range. The relevance of testing at several orders of magnitude above the solubility level is questionable, as physical rather than toxicological effects may have been responsible for the end points observed.

Because of the likelihood of hydrolysis occurring under environmental conditions, some authors considered the toxicity of the main degradation products of the esterquats. For PDQ, Waters et al. [37] reported ecotoxicological studies performed on the suspected and known primary degradation products, the 3-monoester and the unesterified diol quaternary. In the case of the quaternary, EC_{50} values were found to be greater than 100 mg/L for the fauna and flora tested. In the case of the 3-monoester, toxicity of this substance was observed to be slightly higher than or as high as that of the mother substance. The solubility is likely to be higher too, although no value is provided. In the same publication the authors showed that primary degradation of PDQ to the fatty acid was so rapid that significant concentrations of either the 2- or 3-monoester intermediate would not be expected to occur. The relevance of the toxicity data of the 3-monoester intermediate is therefore very limited. Puchta et al. [14] state that the chronic ecotoxicological NOECs of the main metabolite of TEQ, MTEA, is greater than 1 mg/L.

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TABLE 2 Compilation of Acute and Chronic Toxicity Data of Esterquats and Their Degradation Products to Aquatic Organisms [14,37,38]: Physical Properties of Some Alkanolamines

Test compound	Test organism	End point (mg/L)	Remark
PDQ	*Pseudomonas putida* (bacteria)	130 (NOEC 16 h)	Growth
PDQ	*Scenedesmus* sp (algae)	1.8 (EC_{50} 72 h)	Acute
PDQ	*Daphnia magna*	7.7 (EC_{50} 48 h)	Acute
PDQ	*Daphnia magna*	1.0 (NOEC 21 d)	Chronic
PDQ	*Oncorhynchus mykiss* (trout)	7.0 (LC50 96 h)	Acute
PDQ	*Oncorhynchus mykiss* (trout)	≥3.5 (NOEC 28 d)	growth
3-Monoester	*Daphnia magna*	0.6 (EC50 48 h)	Acute
3-Monoester	*Scenedesmus* sp. (algae)	3.7 (EC50 72 h)	Acute
3-Monoester	*Scenedesmus* sp. (algae)	1.8 (NOEC 72 h)	Chronic
DHPA	*Scenedesmus* (algae)	> 100 (EC_{50} 72 h)	Acute
DHPA	*Daphnia magna*	> 100 (EC_{50} 48 h)	Acute
DHPA	Zebra fish	> 100 (EC_{50} 96 h)	Acute
TEQ	Bacteria	> 90 (EC_{50}[a])	Acute
TEQ	Algae	0.3 (NOECa[a])	Chronic
TEQ	Daphnids	78 (EC_{50}[a])	Acute
TEQ	Daphnids	3 (EC_0 21 d)	Chronic
TEQ	Fish	3 (EC_{50}[a])	Acute
TEQ	Fish	4 (EC_0 14 d)	Sub-chronic
TEQ	Biocenosis	0.15 mg/l (EC_0[a])	microcosm
MTEA	Bacteria	> 10000 (NOEC)	Acute
MTEA	Algae	300 (EC_0[a])	Chronic
MTEA	Daphnids	180 (EC_0[a])	Acute
MTEA	Daphnids	3 (NOEC 21 d)	Chronic
MTEA	Fish	> 300 (LC_0[a])	Acute
MTEA	Fish	1000 (EC_0 14 d)	Sub-chronic
MTEA	Biocenosis	1.5 mg/l (EC_0[a])	Microcosm
DEQ	Activated sludge	> 50 (NOEC 3 h)	OECD 209
DEQ	*Selenastrum capricornutum* (green algae)	2.9 (ErC_{50} 96 h)	OECD 201
DEQ	*Daphnia magna*	14.8 (EC_{50} 24 h)	OECD 202
DEQ	*Daphnia magna*	1.0 (NOEC 21 d)	TSCA 40
DEQ	*Pimephales promelas* Fathead minnow	0.68 (NOEC 35 d flow-through)	TSCA 40
DEQ	*Brachydanio rerio* (zebra fish)	5.2 (LC_{50} 96 h)	OECD 203

[a] Time not specified.

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From the data presented in Table 2, and by following the approach recommended in the EU Technical Guidance Document for the Risk Assessment of New Notified and Existing Chemicals, Predicted No Observed Effect Concentrations (PNECs) can be obtained by applying uncertainty factors on the NOECs. The resulting PNECs are as follows: TEQ with factor of 10 = 30 μg/L or with factor of 2 on microcosm = 75 μg/L MTEA with factor of 10 = 300 μg/L; factor of 2 on microcosm = 750 μg/L; PDQ with factor of 10 = 100 μg/L; DEQ with factor of 100 (two chronic studies but not on the most sensitive species, algae) = 6.8 μg/L.

The following predicted environmental concentrations (PECs) in surface water were estimated for the esterquats: 60 μg/L for total esterquats as worst case [14], 0.29 μg/L for PDQ [37], and 2.5 μg/L for DEQ [38].

Based on this assessment of surface waters, environmental effects in this compartment from esterquats are considered unlikely because comparison of PEC/PNEC ratios are in all cases lower than 1. Moreover, the PNECs are based on values that are higher than the water solubility of the substances and are therefore not due to the direct toxicity of the compounds.

3. Conclusions

The esterquats discussed are readily biodegradable and effects are found only at concentrations greater than their water solubility. The (bio)degradation pathway demonstrates that formation of persistent toxic compounds is circumvented. The main degradation products, i.e., polyalcohol quaternary ammonium salts, are not toxic. The ready biodegradability and determined effect concentration strongly indicate that esterquats are safe at the intended maximum usage volumes. PEC/PNEC ratios are lower than 1 for all esterquats examined.

C. Hydrolytic Stability

Traditional quaternaries undergo thermal decomposition upon heating. The main reactions are given in Fig. 10. Due to their additional ester linkage,

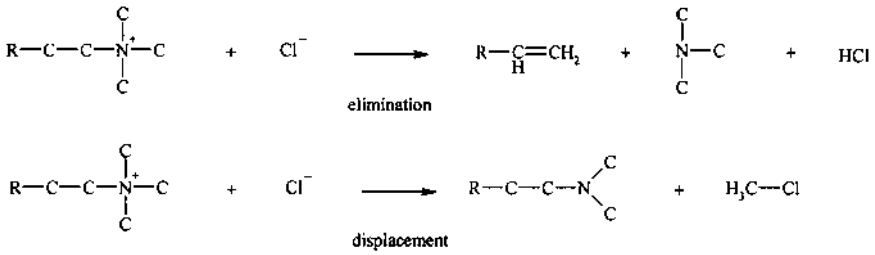

FIG. 10 Decomposition reactions of quaternary ammonium compounds.

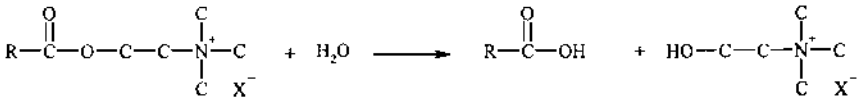

FIG. 11 Hydrolysis of esterquats.

esterquats have more possibilities to react. An important decomposition reaction is the hydrolysis of the ester bond in the presence of water. In general, ester hydrolysis can be acid or base catalyzed. In the case of esterquats, acid-catalyzed hydrolysis is slow, as the initial protonation of the ester carbonyl group is hindered by the positively charged nitrogen. For the same reason, alkali-catalyzed hydrolysis is faster than with normal esters. As a consequence, esterquats are most stable at acidic pH [27]. The hydrolysis of a monoesterquat is shown in Fig. 11. In neutral-to-alkaline media the ester

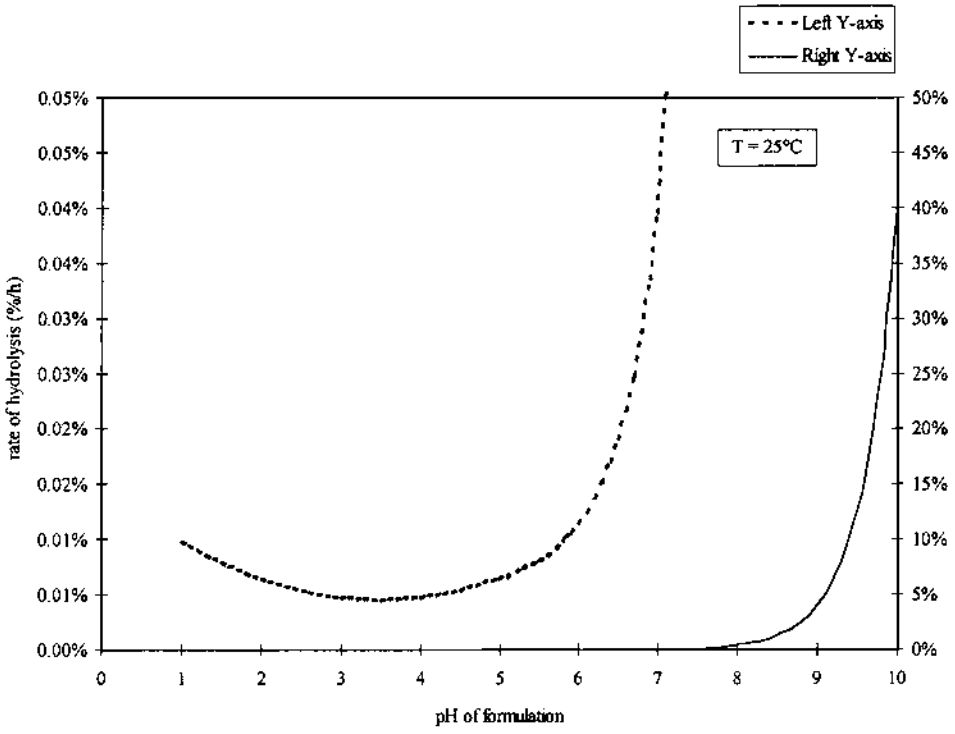

FIG. 12 Influence of the pH on the hydrolytic stability of dicetylester of bis-2-hydroxyethylammonium chloride at 25°C. (From internal reports.)

bond hydrolyzes quickly to yield fatty acid and a small hydrophilic quaternary. A diesterquat hydrolyzes in the same way in which case two fatty acid molecules are released. The remaining quaternaries are very soluble in water.

The hydrolytic stability of esterquats is influenced by the temperature, pH, and composition of the formulation, and by the chemical structure of the molecule. The pH is the main parameter for controlling the stability of esterquats. In Fig. 12, a typical pH/hydrolytic stability plot for an esterquat is given. At low pH values the esterquat is quite stable, but at pH values greater than 6 hydrolysis is fast.

As expected, the temperature also has an important influence on the hydrolytic stability of esterquats. A typical curve for the hydrolytic stability of an esterquat is given in Fig. 13.

In very dilute systems, the rate of hydrolysis increases with increasing ester concentration and reaches a maximum close to the critical micelle concentration (CMC) [21,44]. The micelle structure of the esterquat close to the CMC catalyzes the hydrolysis of the ester function, as there is a layer of hydroxide ions around the micelles, and the true concentration of hydroxyl ions is higher at the interface than in the bulk. This phenomenon is referred to

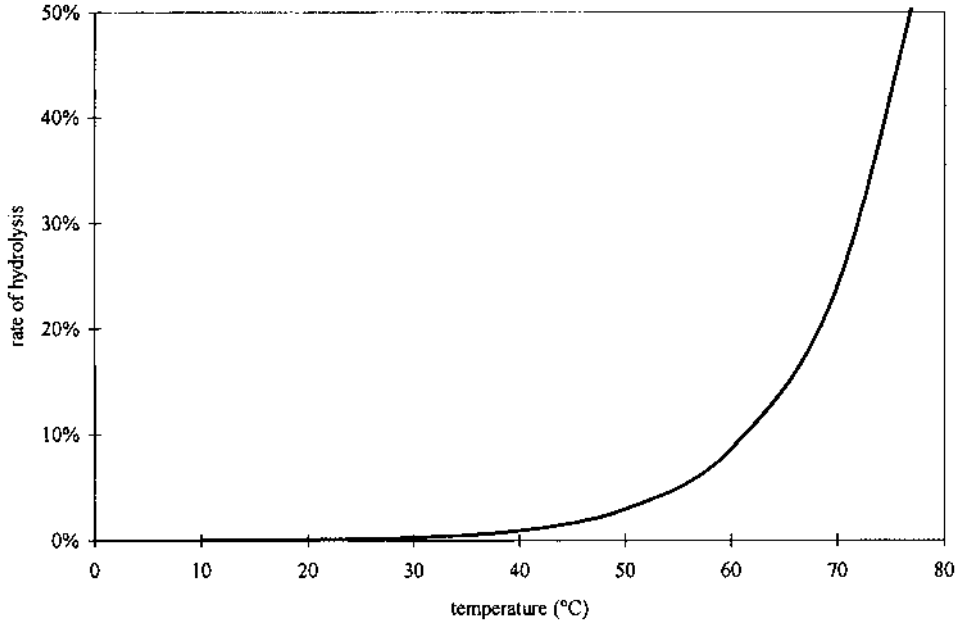

FIG. 13 Influence of the temperature on the hydrolytic stability of Colchester of trimethylhydroxyethylammonium chloride at pH 4. (From internal report.)

as micellar catalysis [44]. Addition of compounds that disturb the micellar structure lowers the rate of hydrolysis. Also halide ions have a retarding effect, as they partly replace hydroxyl ions and thus lower the pH at the interface. Other "soft" anions may show this effect as well.

Other reactions that esterquats can undergo are ester rearrangements, such as transesterification of the esterquat with alcohols and glycols that might be present as solvents.

IV. USE OF ESTERQUATS

Uses of quaternary ammonium compounds are many, ranging from surfactants in household products and many diverse industrial applications to germicides. Very comprehensive overviews were given by Dery in 1996 [12] and Steichen in 2001 [45].

While esterquats in principle can fulfill the same functions as alkylquats, today they are commercially applied in a limited number of applications. The production volume of esterquats worldwide is between 150,000 and 200,000 tons. More than 95% of this material is used in fabric care.

A. Fabric Care

By far the largest use of esterquats today is as actives in rinse cycle softener formulations. Softeners at the same time have the largest single use of quaternary ammonium compounds. The breakthrough of esterquats in this application was in 1991, when European detergent manufacturers reformulated their rinse cycle softeners due to pressure from environmental authorities. The active compound under concern, di(hydrogenated-tallow)dimethylammonium chloride (DHTDMAC), which had been used "safely" for more than 30 years in fabric softeners, was given an environmentally hazardous classification suddenly. The reason was that there was evidence from laboratory studies that the PEC of DHTDMAC may have exceeded its PNEC, particularly in poorly diluted surface waters.

Although this safety assessment of DHTDMAC has met with controversy from the industry, as studies under more realistic conditions [46] showed that there was a significant safety margin between PEC and PNEC of DHTDMAC, the industry reacted rapidly, and the detergent manufactures in Europe agreed to eliminate DHTDMAC from their formulations. Overnight esterquats were introduced in Europe while they are readily biodegradable and less toxic to aquatic organisms than DHTDMAC [14,38,41].

Part of the U.S. market moved also from DHTDMAC to esterquats. This change was initially only for rinse cycle softeners. At this moment esterquats are also used in tumble dryer sheets. The rest of the world shows more and more interest in the use of esterquats as fabric softener.

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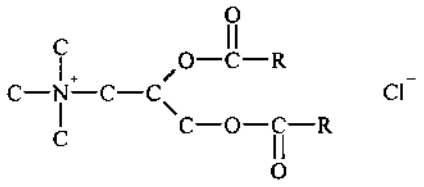
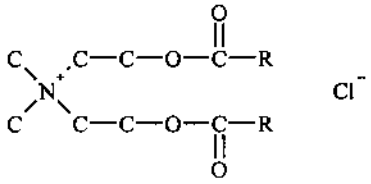
1. Alkanolamine-Based Softener Actives

Alkanolamine-based esterquats compose by far the largest group in fabric care applications. Three different types are used commercially, each in significant quantities (Fig. 14).

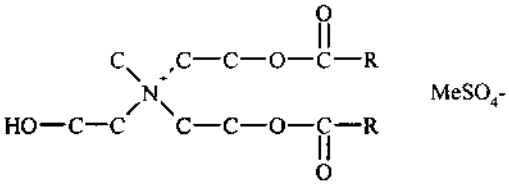
The esterquats may be considered structural homologs of DHTDMAC. Esterquats (1) and (2) contain two alkyl chains per molecule. These are direct homologs of the traditional quats used in fabric softening for many years. The triethanolamine-based esterquat (3) is a mixture and in addition to the dialkyl chain molecules considerable amounts of mono- and trialkyl esterquat are present.



Diesters of 2,3-dihydroxypropyl-trimethylammonium chloride (1)



Diesters of bis-2-hydroxyethyl-dimethylammonium chloride (2)



Mixed esters of tris-2-hydroxyethyl-methylammonium methosulfate (3)

FIG. 14 Alkanolamine-based esterquats applied in fabric care. R is C_{16} and C_{18}, saturated or unsaturated.

There are indications that the performance of triethanolamine-based products increases with the diesterquat content. Products with high diester content have been developed [47–49].

The fatty acids used to manufacture esterquats for fabric softeners usually have a high C_{16} and C_{18} content. The used fatty acids are tallow or palm based. The alkyl groups are partially or fully hardened. Softening performance and physical properties like dispersion viscosity and melting point depend on chain length and the degree of unsaturation of the alkyl chains in the esterquat [50]. Dispersion stability is an important item, especially in the United States for the ultraconcentrated formulations.

Fabric softeners are available to consumers in three different forms. The majority is used as rinse cycle softener. A second application is as tumble dryer sheets, and is important in the United States. The third application is as detergent-containing softeners, also known as softergents.

Rinse cycle fabric softeners are liquid aqueous dispersions. These dispersions are added to the wash during the last rinse cycle. There are esterquats available that have the same overall performance and efficiency as the traditional DHTDMAC. The fabric softeners provide softening, solubilize fragrances, reduce the buildup of static charge in a tumble dryer, shorten the drying time, and allow easy ironing of washed fabric [13,51]. Aqueous dispersions with only DHTDMAC as active ingredient can go up to concentrations of 15% [52]. The concentration that can be obtained in aqueous esterquat dispersions is dependent on the type of esterquat and degree of unsaturation of the alkyl chain [53–56]. However, as dispersion in water concentrations up to 15% are possible. Upon addition of additives like ethoxylated alcohols, cationic concentrations up to over 20% can be obtained [54,57–59]. The development of new formulations based on the three main commercial types of esterquat is an ongoing process. Recent developments are wrinkle reduction and easy ironing [60–65] and clear softeners [66–70]. The clear softeners can reach concentrations of over 40% of softener active. These formulations contain organic solvents. Stable, low-viscosity aqueous dispersions up to 40% have been achieved with polyesterquats [71].

The market products are available in different concentrations. Various parts of the world have different concentrations. Most parts of the world have dilute products. These products contain about 5% of the active. In Europe there are also concentrated products (15–20% active) in addition to the dilute formulations. In the United States ultraconcentrated products are also on the market, which contain over 20% of active.

For more detailed information about fabric softeners and mechanisms of softening, reference is made to a review by Jacques and Schramm [72].

Tumble dryer sheets contain fabric softener actives (quaternary ammonium compounds) applied to a nonwoven sheet. These sheets are added to

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the tumble dryer along with the wet laundry and prevent buildup of static charge in the tumble dryer. Esterquats are also introduced in dryer sheets [73–81].

The third form of fabric softeners, the softergents, provides detergency and softening during the wash cycle. These formulations contain quaternary ammonium compounds together with nonionic, anionic surfactants and other detergent ingredients. Esterquats can be used in these formulations as well [82–87].

Softener esterquats based on alkanolamines have been extensively investigated for their environmental properties. A number of very comprehensive studies has been published [14,37,41]. All materials biodegrade rapidly and show comparatively low toxicity to aquatic organisms. It has been suggested that abiotic degradation (hydrolysis of esterbonds) contributes to the favorable environmental profiles of these esterquats [37].

2. Other Esterquats for Fabric Softening

Protonated esteramines are claimed for use as low-cost, biodegradable fabric softener agents [88]. Quaternized amines prepared from fatty acids and methylethanolisopropanolamine show good softening and improved rewetting compared with the methyldiethanolamine-based products [89].

Alkylbetaine esters [90–92], quaternized aspartic acid esters [23], and polyolesters of betaine [71] have been suggested for use in fabric care. The ester bond in betaine esters is strongly activated by cationic nitrogen in the α position, and therefore these materials can undergo rapid abiotic degradation and have very low aquatic toxicity.

B. Other Detergent Use

Triethanolamine-based esterquats have been found to improve the cold water dispersibility of detergent granules containing fatty alcohol sulfates [93].

Monoesterquats based on dimethylethanolamine [94] have been suggested in a number of patent applications for use in granular detergents, in the presence of other additives like anionic, nonionic, or zwitterionic surfactants, enzymes, various soil release polymers, and hydrophobic bleach additives. These compositions showed improved detergency on specific stains [82,95–101]. Esterquat-containing formulations for detergent compositions (powder, liquid, or tablet) are described [102].

C. Personal Care

Cationic surfactants, characterized by their amphiphilic properties, contain an alkyl hydrophobe and a hydrophilic positively charged head group. Among cationic surfactants, quaternary ammonium salts are notable for

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their ability to reduce surface and interfacial tensions by ready adsorption to a surface or interface, such as hair and skin. This ability to adsorb onto substrates makes the use of cationic surfactants extremely important in the personal care industry. For conditioning and improving the substrate (hair and skin), the cationic surfactants or conditioning agents must first deposit onto such substrates. Because of the proteinaceous surface structure of both hair and skin, quaternary ammonium compounds are attracted to the negatively charged cuticle surface of hair and the stratum corneum of skin. The interactions of quaternaries with hair or skin surfaces contribute to surface improvements such as smoothness, softness, enhanced manageability, etc. This improvement of surface quality on hair or skin is called "conditioning."

1. Hair Care

Human hair is a biological composite consisting of the cortex, a spindle-shaped assemblage of cells that serves as supporting material for the hair fiber, plus surrounding cuticle layers overlapping each other to provide the hair outer surface. The cuticle surface consists of amino acid functional side groups, which are potential binding sides for cosmetic components. The deposition and uptake of cationic surfactants on the cuticle surface ultimately neutralizes the negatively charged surface and thereby reduces the repulsive forces between the cuticle scales.

Frequent shampooing and treatments, such as perms, dyes, and straighteners, leave hair deficient in luster, difficult to comb, and prone to "fly away." These problems can be overcome through use of conditioning agents in shampoos or separate treatments such as cream rinses, balms, hair cures, tonics or intensive conditioners. Quaternary ammonium compounds are the key raw materials for hair conditioners. Quaternaries are highly substantive to the hair via attraction to the anionic charges on the hair shafts providing reduction of combing forces, increased luster, and improved antistatic properties [103,104]. The variety of structure and performance qualities of quaternary ammonium compounds makes possible the tailoring of formulas around specific requirements [105,106].

Monoalkyl quaternaries are relatively easy to formulate, and cetyltrimethylammonium chloride is the most important cationic surfactant used in cosmetics. Ethoxylated quaternary ammonium compounds are ideal bases for conditioning shampoos due to their compatibility with anionic surfactants. With increasing number of alkyl chains the conditioning properties are strongly improved. Dialkyl quaternaries, e.g., dicetearyldimethylammonium chloride (originated from a mixture of a C_{16} and C_{18} fatty acid) and distearyldimethylammonium chloride, are the preferred choice for use with difficult-to-manage or damaged hair (Table 3) [105].

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TABLE 3 Comparison of the Properties of Different Alkyl Quaternaries

Alkyl quaternary	Conditioning intensity	Solubility in water
Cetyltrimethylammonium chloride	Moderate	Soluble
Dicetearyldimethylammonium chloride	Strong	Dispersible
Tricetylmethylammonium chloride	Intensive	Separation
Oleylbis(2-hydroxyethyl)methylammoniumchloride	Light	Soluble

2. Esterquats in Hair Care

In the last years the behavior of chemical substances in the environment gained increasing importance for nearly all kinds of consumer products. Therefore the industry has developed new raw materials with a better environmental profile. For cosmetic products the biodegradation, toxicity, and dermatological behavior (especially for leave-on products) are the major issues. New classes of cationic surfactants that fulfill the new demands are the esterquats [107].

Several esterquats have been developed commercially for hair care applications [108–110]. These products are derived from alkanolamines, mainly triethanolamine, methyldiethanolamine, or dimethylamino-l,2-propanediol [111], and preferably fatty acids of vegetable origin like oleic and palmitic sources. Some examples are given in Fig. 15.

Esterquat compounds demonstrate excellent conditioning effects on all types of hair. In addition to the interaction of the quaternary nitrogen of conventional cationics the esterquats introduce dipolar interaction with the hair surface. Not only the ester bond but also the unesterified free hydroxy groups play a role in this mechanism [112]. The improvement in wet and dry hair combability with esterquats is comparable to that achieved with the established hair care additives cetyltrimethyl- and distearyldimethylammonium chloride [108,113–116]. In general, the biodegradability is better and the toxicity is lower when esterquats are compared with the traditionally used quaternaries. In addition to this, the handling and manufacturing process of formulations with esterquats is easy, provided that the right measures are taken. Esterquats are only stable in a certain pH range (2–5.5) [117,118] and the pH of the formulations is therefore limited. The costs of formulations prepared with esterquats are equal to conventional systems. Table 4 gives an example for a hair rinse conditioner formulation [113].

3. Alkanolamine-Based Esterquats

A number of patent publications disclose alkanolamine-derived esterquats for use in cosmetic hair care and skin care preparations. Several trietha-

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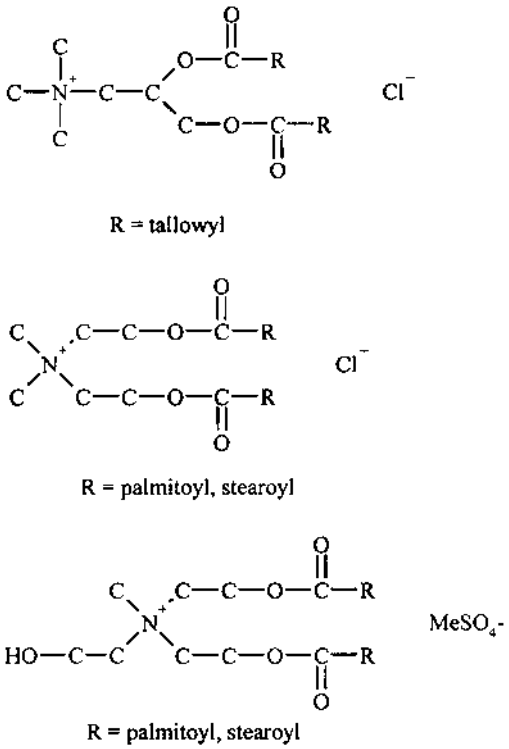

FIG. 15 Esterquats developed for use in hair conditioners.

TABLE 4 Composition of a Typical Hair Rinse Conditioner

Component/INCI declaration[a]	wt %	Function
Dipalmitoylethyldimonium chloride	2	Conditioning agent
Propylene glycol	7.5	Solubilizer
Hydroxyethylcellulose	0.6	Thickening agent
Cetyl alcohol	2.5	Consistency regulator
Methoxy PEG-17/dodecyl glycol copolymer	3	Emulsifier
Water	ad 100	Solvent
pH	3.5	

[a] International Nomenclature Cosmetic Ingredient according to CTFA.

nolamine methosulfate esterquats are used in hair conditioning formulations. Differences between the esterquats in the formulations are the origin of the fatty acid, which is mainly oleic based [119–123], and the chemical composition.

Triethanolamine based esterquats are a mixture of mono- di- and triesterquats. It is claimed that for softeners and hair conditioners an esterquat with at least 50% diester content is preferred [49]. Methyldiethanolamine-based esterquats are mainly diesterquats with only slight amounts of monoesterquat. Monoesterquats are useful as cationic surfactants in hair care formulations [124]. Solid esterquats with improved dispersibility and emulsifying properties are obtained by quaternization of fatty acid triethanolamine esters in the presence of a dispersing agent or nonionic emulsifier [125–127]. Esterquats can be used in sprayable conditioning systems for hair care [128].

Application of esterquats in hair-coloring formulations [121,129] and conditioners with sunscreen protection [120] are claimed.

Mixtures of esterquats with alkylpolygycosides, oils and protein hydrolyzates [130,131], and emulsions of esterquats with long-chain alkylpolyglycosides and fatty alcohols [132] are investigated. Also, mixtures of glucose amide and esterquats with protein hydrolyzates are claimed [133].

Hair conditioner formulations with mixtures of esterquats and sucrose [123] or cellulose ethers [134] have improved the manageability and combability of wet and dry hair. Formulations with esterquats and urea are said to be useful as a conditioner giving improvements in compatibility and volume as well as good gloss [135]. Damaged hair can be improved with esterquat formulations containing ceramide [122]. Mixtures of fatty acid amides or alkylamidoamines with esterquats show synergism as conditioning agents for hair [136–138] and are useful in hair tonics that improve the fiber structure of damaged hair [137]. Sterols are used as thickeners of aqueous solutions of quaternized fatty acid triethanolamine esters [139]. Esterquats potentiate the action of silicone conditioners [140] and a combination of liquid lipids and esterquats gives a viscous hair treatment formula [141].

4. Other Esterquats

Other complex reaction mixtures of esterquats based on triethanolamine with fatty acids and hydroxycarboxylic acids or dicarboxylic acids or polyols and dicarboxylic acids have been suggested for use in hair and body care [18,19,24,142]. Sorbitan esterquats are claimed for personal care applications like skin and hair cleansing [143].

Betaine esters (Fig. 16) have been suggested as potential alternatives to alkyltrimethylammonium salts. They have been reported to be stable in slightly acidic formulations and to degrade in sewage into betaine and fatty alcohol [144–147].

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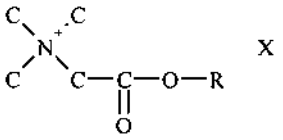

FIG. 16 Betaine esterquats.

Hair cosmetic compositions containing amide esterquats of the following structures give smooth touch to hair and prevent tangling [148,149] (Fig. 17).

A new type of ester amide as an alternative to diesterquats has gained attention in the personal care area in recent years. These ester amidoamines are prepared from diethanolamines and 2 mol of fatty acid. The hydroxyl group forms an ester function and the primary amine forms an amide bond. The resulting ester amidoamines are then quaternized with dimethyl sulfate or methyl chloride. These ester amidoamine dialkylquats are typically used as fabric softeners or in hair care formulations where they showed good hair softening and smoothing effect [150] (Fig. 18).

Polyolesterquats with betaine function, developed for fabric softening, are useful for hair care applications; they are readily biodegradable and exhibit low aquatic toxicity [71]. A glycerol derivative showed good conditioning and antistatic action and is recommended for use in shampoos and hair rinses [151] (Fig. 19).

5. Skin Care

Skin is a living organism and has a more complex structure than hair. Irritation and skin compatibility are major items for skin care and cosmetic

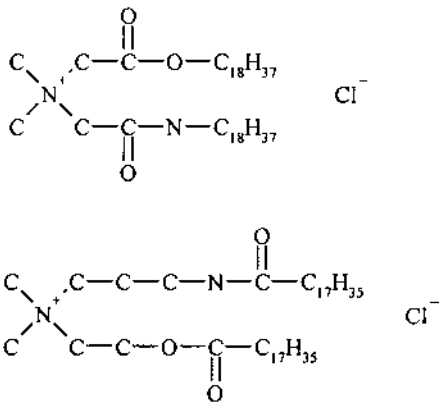

FIG. 17 Amide esterquats.

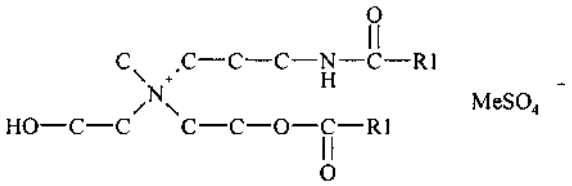

FIG. 18 Amidoamine esterquats.

formulations. One of the most important functions of skin conditioning is to prevent dehydration of the skin. Consequently, emollients and humectants are commonly used in skin care formulations [45].

Cationics such as quaternary ammonium compounds play an important role and offer specialized benefits for certain cosmetic, skin care, and sun care formulations. The emollients, humectants, and cationic emulsifiers used in skin care products provide smoothness, moisturizing effects, increased elasticity, less irritation, and improved appearance [152–154]. Skin care compositions containing these agents are claimed to provide a high degree of moisturization to the skin [155].

Since some categories of conventional cationics are under environmental stress alternatives are becoming increasingly important for application in cosmetic and skin care formulations.

6. Esterquats in Skin Care

The use of esterquats in cosmetic compositions has gained interest since it is believed that esterquats can form vesicles that can incorporate emollient material, such as oils. These emollient materials are needed for the skin in order to retard the loss of moisture, and they also have a protective function. Cosmetic compositions containing various esterquats and amide esterquats that can form vesicles are claimed to provide a good moisturizing effect with

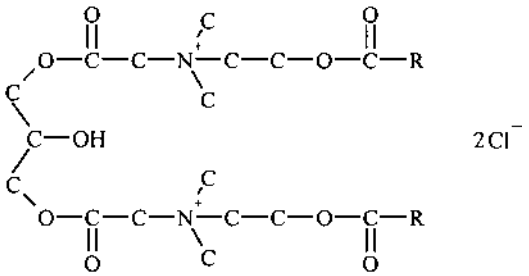

FIG. 19 Glycerol-based esterquat.

low levels of stickiness [156]. Such agents used in skin creams have also been shown to give a good skin feel and also provide a low skin irritating action [157]. In the recent patent literature a series of quaternized fatty acid alkanolamine esters have been effectively used as dispersants for oil-based pigments, especially in cosmetics [158].

Esterquats with improved stability and biodegradability are prepared by quaternization of a fatty acid (partially hydrogenated tallow) alkanolamine ester with an alkylating agent (dimethyl sulfate) in the presence of nonionic emulsifiers [126] or cosmetic oils [159]. This procedure avoids problems associated with the use of lower alcohols as solvents in the reaction, such as low ignition point, poor emulsifying capacity for perfume oils, poor skin compatibility, and a defatting action on the skin. Formulations of a triethanolamine-based Coco esterquat, oil, and a C_1–C_6 alcohol are useful in cosmetic and sunscreen formulations [160].

The use of cosmetic preparations containing esterquats (i.e., quaternized fatty acid triethanolamine ester salts) and sterols as skin care agents is claimed [161].

Esterquats prepared from fatty acid methyldiethanolamine esters reacted with diethyl sulfate are useful as emulsifying and consistency-providing agents in cosmetic and/or pharmaceutical preparations [162].

Mixed esterification of trialkanolamines with fatty acids and sugar acids, optional alkoxylation of the esters, and quaternization of the (alkoxylated) esters gives environmentally friendly surfactants, useful in body care and hair treatments [163].

New sorbitol ester quaternary compounds are prepared by treating trialkanolamines with a mixture of fatty acids, dicarboxylic acids, and sorbitol. Optionally the mixture is alkoxylated and finally quaternized. The resulting cationic surfactants are useful in shampoos and other cosmetic applications [164].

D. Industrial Use

The functionality of cationic surfactants as surface activity, substantivity, antimicrobial and antistatic activity is of value in many industrial applications. Thus, the traditional alkyl quaternaries have become indispensable additives in biocidal formulations [165], manufacture of organoclays and nanocomposites, fertilizer production, ore flotation, textile finishing, fiber processing, pigment dispersants, textile finishing, and fiber processing, to name a few. Many of the conventional cationic surfactants used for these functions, even if completely biodegradable with time, do not biodegrade as rapidly as could be desired and are thus not considered as readily biodegradable. Due to the beneficial environmental behavior, esterquats have

received attention also for several industrial applications in recent years. Today the quaternized triethanolamine esters can be prepared as solvent-free fluids with a very low odor and with a good thermal stability. As a result, many of the environmental and safety concerns from the plant sites, distributors, and formulation companies will also be circumvented.

1. Paper Softening

For more than two decades distearyldimethylammonium chloride has been used as a paper softener in the production of tissue paper. In the early 1990s the use of this compound was regarded as a risk for the environment. Esterquats were discovered as good substitutes since they are readily biodegradable and they show a good effectiveness and ease of formulation [166]. Furthermore the costs are comparable to the traditional systems. Esterquats can be fine-tuned in order to obtain the desired performance. Long (partially hydrogenated) alkyl chains offer the best softening while shorter chains like coco or unsaturated chains like oleic offer less softening but better rewetting. Softening increases with chain length and degree of saturation while rewetting shows an opposite relation. Formulations for paper softening are rather liquid at room temperature and contain no flammable solvent [166].

Both quaternized triethanolamine fatty acid esters [167,168] and methyldiethanolamine fatty acid esters [169–174] have found new industrial uses in the paper softening area. Quaternized triethanolamine fatty acid esters are described for use as softeners or debonders for the manufacture of soft paper tissues and paper towels. These new softeners/debonders are claimed to exhibit premium water absorbency and give an improved softness to the paper [68,168,175,176].

2. Other Industrial Use

As shown in the literature, esterquats have also received attention for other industrial applications. However, for many processes, their hydrolytic instability may be a limiting factor for their use as substitutes for the common cationic surfactants employed. Examples of successful applications are mentioned below.

A method for enhancing the effectiveness of agricultural chemicals with quaternary ammonium compounds containing one or more carboxylic acid ester or amide groups is reported [177].

Other industrial uses for esterquats reported in the literature are as frictional resistance reducers for aqueous media [178] and as antistatic agents for thermoplastic polymers, especially polyvinyl chloride [179].

Quaternized fatty acid triethanolamine esters are useful in leather dubbing compositions giving good softness and hydrophobicity [180,181].

Ethanolamine-based esterquats are used in automatic car wash facilities to accelerate drying [182].

The quaternary ammonium salt of an alkoxylated ester amine is used as a deinking agent for recycled wastepaper [183].

It has been shown recently in the patent application literature that organoclays based on specific types of esterquats can be effective for use in preparations of nanocomposites [184,185].

Alkylolamine-based esterquats hydrophobize clays for their use as viscosity promoters in drilling emulsions [186] and improve the oil wettability of finely divided solids used as fluid loss additive for drilling fluids [187]. Detergent mixtures for tertiary recovery of crude oil contain alkyl oligoglycosides and esterquats [188]. Esterquats derived from TEA, MDEA, and DMAPD are claimed for use as collectors in mineral flotation [189].

A method for gas hydrate inhibiting with quaternary ammonium compounds has been developed by Klomp et al. [190,191]. New legislation caused a change to esterquats and good results have been obtained. Today huge amounts of up to 30% of methanol are used in the gas exploration industry to prevent gas hydrates. Small amounts of esterquat have a similar effect and offer the possibility to explore deeper gas fields. Buijs et al. developed a process to manufacture these esterquats [192].

Quaternary fatty acid amino alcohol esters of methylethanolisopropanolamine with fatty acids have also gained interest for multiple industrial uses, e.g., antistatic compounds, paper deinking, printing inks, ore flotation, asphalt emulsifiers, corrosion inhibition agents, pesticide emulsion agents, car drying aid sprays, and drilling fluid additives [89].

For many processes the hydrolytic instability for the esterquats in water solutions is a limiting factor for using them as substitutes for the traditional cationic surfactants employed. In some applications the hydrolytic instability is an advantage. An example where use is made of spontaneous decomposition into substances that are nontoxic is betaine esters which exhibit high

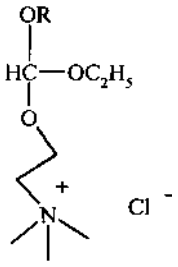

FIG. 20 *ortho*-Esterquat.

microbiocidal effects and therefore are recommended for application in time-limited antisepsis and disinfection [44].

3. Ortho-Esterquats

Another type of esterquats in the family of cleavable surfactants makes use of *ortho*-ester linkages. It has been demonstrated recently in the literature that not only nonionic [193] but also cationic surfactants with *ortho*-ester links can be prepared [194]. The *ortho*-ester amine is prepared from a fatty alcohol, a short-chain *ortho*-ester, and dimethylaminoethanol (Fig. 20).

The resulting *ortho*-ester amine is quaternized with methyl chloride. The main application areas for these novel *ortho*-ester cationic surfactants are seen in fields where high-pH formulations are used, since the *ortho*-ester link shows a good hydrolytic stability at higher pH and decomposes at lower pH.

ACKNOWLEDGMENT

With thanks to Götz (G.) Krüger who contributed to the first edition.

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12
Gemini Surfactants

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I. INTRODUCTION

Gemini or dimeric surfactants (Fig. 1) are new types of amphiphilic molecules that have attracted attention from various industrial and academic research groups. These surfactants are made up of two *amphiphilic moieties* connected at the level of the head groups, or very close to the head groups, by a *spacer group*, which can be hydrophobic or hydrophilic, flexible or rigid [1–3]. The gemini surfactants behave mainly as normal surfactants, with similar sequences of phases and aggregates structures, but they also show some interesting differences. They exhibit some unusual physicochemical properties that might prove useful for technical applications in the future. The current interest in such surfactants arises from three essential properties: (1) gemini surfactants are characterized by critical micelle concentrations (CMC) that are one to two orders of magnitude lower than for the corresponding conventional (monomeric) surfactants [1,4]; (2) gemini surfactants are much more efficient than the corresponding conventional (monomeric) surfactants at decreasing the surface tension of water [5–8]; (3) aqueous solutions of some gemini surfactants with short spacers can have remarkable rheological properties (viscoelasticity, gelification, shear thickening) at relatively low surfactant concentration whereas the solution of the corresponding monomer remains low viscous [9]. In addition to those properties, gemini surfactants appear to have better solubilizing, wetting, foaming, and lime soap dispersing properties than conventional surfactants [10–13]. Besides, the Krafft temperatures of gemini surfactants with hydrophilic spacers are generally very low [10–12,14,15], giving these surfactants the capacity to be used in cold water. These properties are commonly used to evaluate

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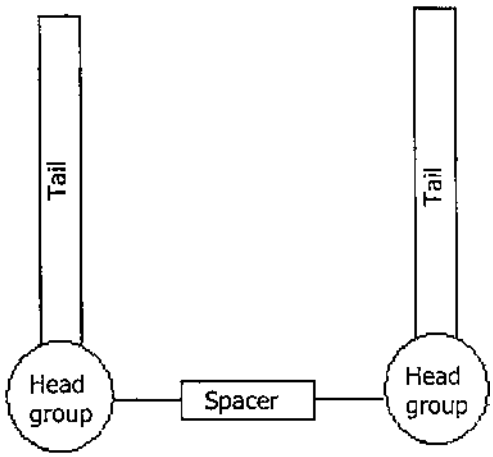

FIG. 1 Schematic representation of a gemini surfactant.

surfactant performance and are important for applications such as cleaning and stabilization of dispersed systems.

The first reports on gemini surfactants concerned bisquaternary ammonium halide surfactants. Their biological activity in aqueous solution was studied [13,16,17], and micellar solutions of these surfactants were used to catalyze chemical reactions [18]. Most studies, however, reported on the surface tension of the aqueous solutions of gemini surfactants for CMC determinations and an assessment of their capacity in reducing the surface tension of water [3,5–8]. These studies did not raise much interest among surfactant scientists in spite of the much lower CMC and stronger biological activity found for gemini surfactants compared with the corresponding monomeric conventional surfactants. It was only in the early 1990s, following the synthesis of gemini surfactants in a great variety of chemical structures, that more systematic studies revealed that such surfactants possess properties that make them superior to conventional surfactants [14]. Thus, their values of C_{20}, the surfactant concentration where the surface tension is decreased by 20 mN/m, are much lower for equal or lower values of γ_{CMC} (surface tension at the CMC) [14]. The idea underlying the study of gemini surfactants is that linking surfactants two by two may provide a new way to control the shape of their assemblies and thus some of their properties [19].

The vast majority of work on gemini surfactants has been made with symmetrical gemini surfactants, i.e., containing identical polar head groups and identical hydrophobic tails. These are true gemini surfactants and they

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can also be regarded as a kind of dimeric surfactants. Several reviews on gemini surfactants have recently been published [14,20–25].

It is well known from research on structure–property relationships that surfactants with an asymmetrical geometry may give interesting characteristics in terms of self-assembly into aggregates and packing at interfaces. For instance, fine tuning of the internal curvature of microemulsions in order to obtain systems with very large solubilization capacity can be made by designing surfactants with different lengths of the two hydrophobic tails or with asymmetrical branching of one tail [26–29]. Nature's own surfactants, the polar lipids, are usually asymmetrical if they are branched or double tailed. Diglycerides and phospholipids are typical examples [30]. Studies on asymmetrical gemini surfactants are still scarce. Recent studies have been made on gemini surfactants in which the polar head groups are chemically different. Gemini surfactants with nonidentical "halves" have been referred to as *hetero-gemini* [31,32]. By using a surfactant with such a chemical structure, one may expect to get the best out of two attractive concepts: (1) gemini surfactants and (2) a 1:1 molar combination of two different surfactants built into the same molecule. This novel geometry in the molecule may allow a new way to control the adsorption and shape of surfactant assemblies and may provide properties that are often obtained by mixed surfactants at equimolar ratio.

The alkanediyl-α,ω-bis(alkyldimethylammonium bromide) or bisquaternary ammonium bromides have been by far the most investigated gemini surfactants because their synthesis and purification are relatively easy. These surfactants are designated by the abbreviation *m-s-m*, $2Br^-$, *s* and *m* being the carbon numbers of the alkanediyl group (spacer) and of the alkyl chain of the amphiphilic moieties. These surfactants are formally the dimers of the quaternary dimethylammonium bromide surfactants with two unequal alkyl chains of carbon numbers *m* and *s*/2. The symbolism used above for symmetrical dimeric surfactants can be easily extended to asymmetrical dimeric surfactants (*m-s-m′*, $2Br^-$) and to surfactant oligomers (*m-s-m-s-m*, $3Br^-$ for a trimeric surfactant, for instance).

This chapter refers to symmetrical (dimeric) and asymmetrical gemini surfactants. Throughout the chapter, "conventional surfactants" and "monomeric surfactants" are given the same meaning.

The next section discusses chemical structures, synthesis, and purification of gemini surfactants. Section III reviews the behavior of gemini surfactants in solutions below the CMC. Section IV deals with their behavior at interfaces. The fifth section reviews micelle formation and solubilization. Section VI deals with micelle properties. Microstructure of aqueous solution of gemini surfactants, rheology of these solutions, and mixed micellization are considered in the following three sections. Section X deals with the phase behavior of

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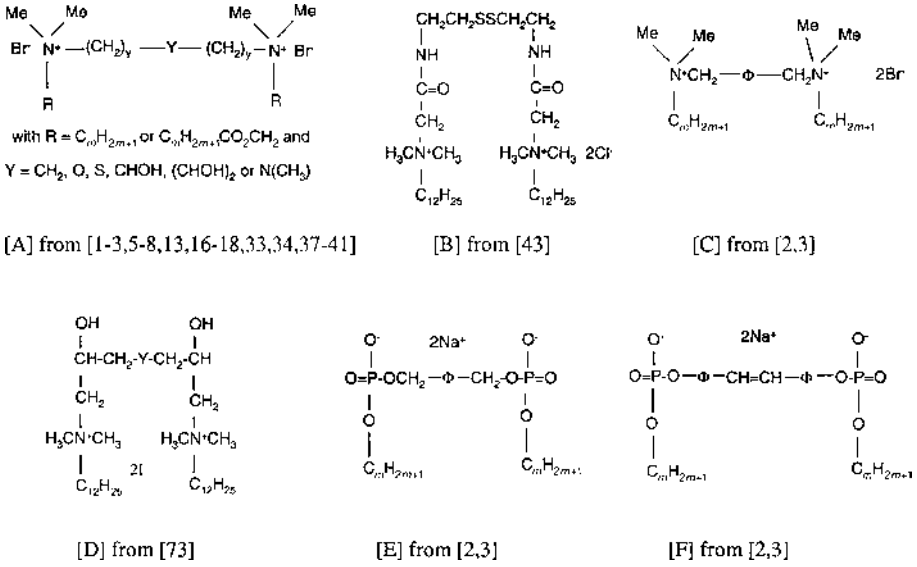
gemini surfactant–water mixtures. A last section briefly discusses potential applications of gemini surfactants.

II. CHEMICAL STRUCTURES, SYNTHESIS, AND PURIFICATION OF GEMINI SURFACTANTS

Gemini surfactants with a great variety of chemical structures have been obtained by acting on the nature of the head group and spacer group, as illustrated in Fig. 1. The head group can be anionic, cationic, nonionic, or zwitterionic while the spacer group is hydrophilic or hydrophobic, rigid or flexible [1–3,5–13,15–18,33–53]. Gemini surfactants with nonidentical head groups have been recently synthesized [31,54–60]. The hydrophobic moieties are generally normal alkyl chains, C_mH_{2m+1}. However, gemini surfactants with mixed fluorinated-hydrogenated alkyl chains, $C_8F_{17}C_4H_8$ for instance, have been synthesized [61].

Examples of chemical structures for gemini surfactants are given in Fig. 2. Surfactants [A]–[D] are cationic, [E]–[I] and [L] are anionic, [J] can be made zwitterionic, [K] is a nonionic sugar-based gemini surfactant, and [N] is a surfactant with one positive head group and one negative head group. [A], [B], [D], [G]–[J,] and [L] have a flexible spacer, whereas [C], [E], and [F] have a rigid



[A] from [1-3,5-8,13,16-18,33,34,37-41] [B] from [43] [C] from [2,3]

[D] from [73] [E] from [2,3] [F] from [2,3]

FIG. 2 Examples of gemini surfactants.

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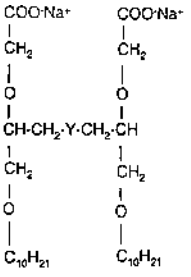
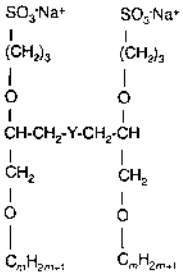
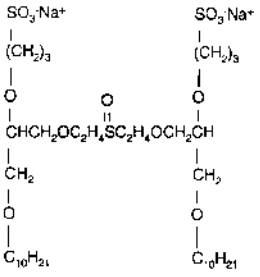


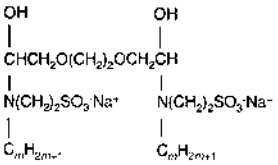
[G] from [45]



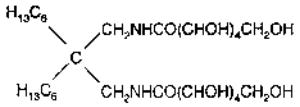
[H] from [46]



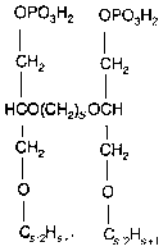
[I] from [47]



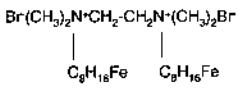
[J] from [48]



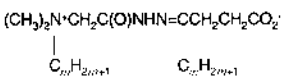
[K] from [51]



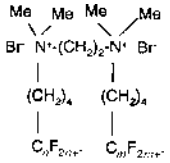
[L] from [52]



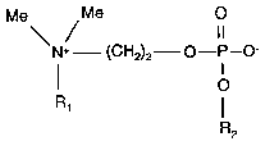
[M] from [53]



[N] from [54]

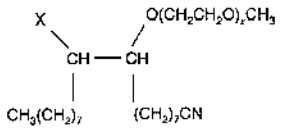


[O] from [61]



$R_1 = C_nH_{2n+1}$ and $R_2 = C_mH_{2m+1}$

[P] from [59]



X = OH or OSO_3Na

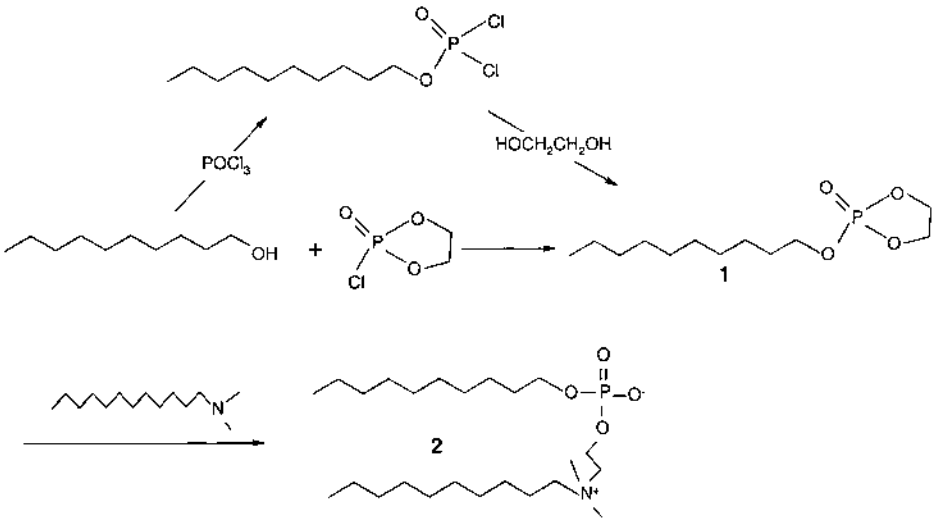
$x = 8, 12, 16$

[Q] from [31]

spacer. In [A]–[C], [E], [F], [L]–[O] the spacer is hydrophobic whereas it is hydrophilic in [D] and [G]–[J] where Y = O or $O(CH_2CH_2O)_x$. [M] and [N] are functional gemini surfactants: the electrical charge of [M] can be acted upon electrochemically and [N] is cleavable. [O] is a gemini surfactant with mixed hydrocarbon/fluorocarbon chains. [P] is a gemini surfactant with one anionic and one cationic head group separated by two methylene groups, the two alkyl chains may be symmetrical or asymmetrical. These surfactants will be denoted m,m', m and m' being the carbon numbers of the chains bound to the phosphate and trimethylammonium head groups, respectively. [Q] is a nonionic gemini surfactant when X = OH and an anionic gemini when X = SO_4Na.

Due to lack of space, only three examples of synthesis of gemini surfactants are given. Surfactant [A] and its homologs (R = $C_{12}H_{25}$ and Y = $-(CH_2)_s-$) were obtained via the single-step reaction of dodecyldimethylamine with the corresponding α,ω-dibromoalkane (molar ratio 2.1/1) in dry ethanol under reflux for 48 h [1]. Other solvents can be used, such as ethyl acetate, acetone, methyl cyanide, etc., depending on the surfactant synthesized [1–3,5–8,13,16–18,33–35,37–42].

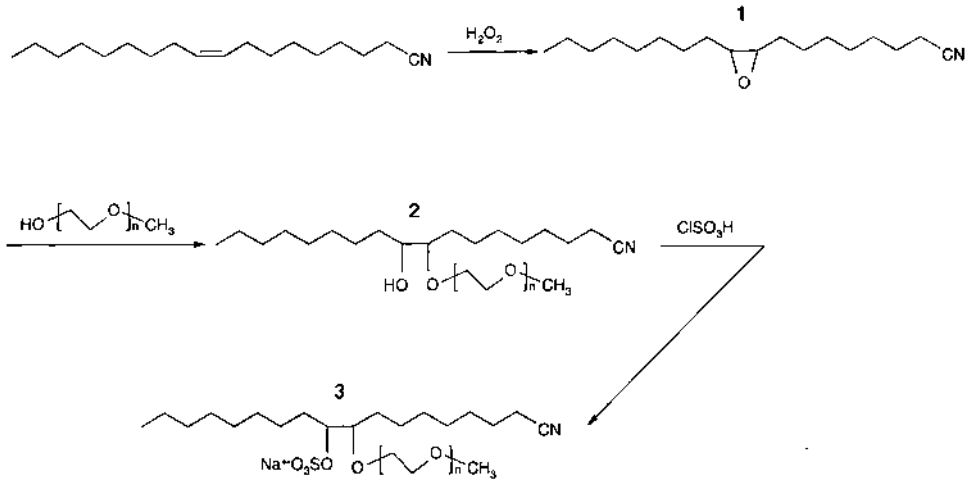
The phosphate-quaternary ammonium hetero-gemini surfactant [P] of Fig. 2 was synthesized by a surprisingly simple two-step, one-pot reaction, shown in Scheme 1 [58]. A fatty alcohol was reacted with the cyclic ethylene chlorophosphate to yield the intermediate 1, which was subsequently ring-opened by an alkyldimethylamine to form the desired gemini surfactant 2. A



SCHEME 1 Synthesis of surfactants [P] [59].

large series of surfactants of this type has been prepared with hydrocarbon chains containing 8–18 carbon atoms. The synthesis is attractive and versatile in that the two main building blocks, the fatty alcohol and the alkyldimethylamine, are readily available. The method therefore allows easy access to all types of surfactants with identical or different hydrocarbon tails. The cyclic ethylene chlorophosphate is somewhat expensive, but the use of this starting material may be circumvented by preparing the intermediate 1 by reacting the fatty alcohol with phosphoryl chloride followed by addition of ethylene glycol and a tertiary amine, as is also shown in Scheme 1. Contrary to the gemini surfactant [A] of Fig. 2, compound [P] is counterion free, i.e., the zwitterionic surfactant is in the form of an inner salt.

Compound [Q] of Fig. 2 is a gemini surfactant with different polar head groups, one hydroxyl group or sulfate and one methyl-capped poly(ethylene glycol). The published synthesis is outlined in Scheme 2 [31]. A fatty nitrile derived from oleic acid was used as starting material. Epoxidation with hydrogen peroxide over a tungstic acid catalyst yielded the epoxide 1, which was ring-opened by methyl-capped poly(ethylene glycol) to yield the nonionic gemini surfactant 2. Compound [Q] with the corresponding sulfate 3, was obtained by treatment of 2 with chlorosulfonic acid [60]. The synthesis strategy lends itself to production in large scale (in which case chlorosulfonic acid would probably be replaced by SO_3). Analogous products with other anionic groups than sulfate can probably be synthesized from the intermediate 2 by employing the synthesis routes discussed above. The synthesis strategy shown in Scheme 2 can in principle be used on all unsaturated



SCHEME 2 Synthesis of surfactants [Q] [31].

lipophilic starting materials. In practice there may not be many alternatives to oleic acid derivatives for large-scale preparation. An analog to the nonionic surfactant 2 has recently been synthesized from methyl oleate [62]. For most surfactant applications esters of fatty acids are less suitable than the corresponding nitriles; however, because of their sensitivity to alkaline hydrolysis.

The real difficulty when dealing with gemini surfactants lies in the purification of the raw surfactants. The purification of the crude gemini surfactants is essential, particularly in studies of adsorption and behavior at interfaces. The purification procedures are somewhat easier for the quaternary ammonium gemini surfactants. Sophisticated procedures must often be used. Indeed, one or more reaction steps that leads to gemini surfactants usually involves the two ends of some intermediate compound. This reaction rarely reaches full completion. It results in the formation of a mixture of mono- and difunctionalized compounds. Their separation is usually achieved through chromatography.

III. STATE OF GEMINI SURFACTANTS IN THE PREMICELLAR RANGE OF CONCENTRATION

Many papers discussed the state of ionic gemini surfactants at concentration below the CMC. Several situations were considered. First, the gemini may be completely disssociated, and give rise to one gemini ion and two counterions, or not completely dissociated, with partial binding of one counterion to the gemini ion. The binding equilibrium obeys the mass action law and the binding is expected to increase with the surfactant concentration. Second, depending on the conformation of the spacer group of the surfactant gemini, its two alkyl chains may or may not interact. Third, premicellar aggregation may take place, giving rise to small aggregates of gemini ions of low aggregation number. Some surface tension data have been interpreted on the basis that in the premicellar range, one bromide ion of gemini surfactants [A] binds to the surfactant ion [7,8,13,43], thereby reducing its charge. This effect would be similar to what has been assumed for the closely related bolaform surfactants alkanediyl-α,ω-bis(trimethylammonium bromide) [63,64]. However, potentiometric studies using surfactant-specific electrodes for 12-*s*-12 surfactants [A] did not reveal any ion pairing [1]. Indeed, for these surfactants the linear variation of the electromotive force (emf) with ln C (C = surfactant concentration) below CMC yielded an emf change close to 30 mV for a concentration change by a factor 10, a value close to that expected for divalent-univalent (2:1) electrolytes. However, conductivity measurements suggested that ion pairing takes place in submicellar solutions of 8-*s*-8, $2Br^-$ and 10-*s*-10, $2Br^-$ surfactants which are characterized by high CMC values which favor ion pairing [35,65].

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Another issue concerns a possible premicellar association of gemini surfactants into dimers and larger oligomers for surfactants [A] with $CH_2CHOHCH_2$ or $(CH_2CHOH)_2$ spacers [37,38] and surfactants [C], [E], and [F] with a hydrophobic rigid spacer [3], at $m \geq 14$. The decrease of the surface tension lowering effect of these surfactants and the increase of their CMC with increasing m, for $m \geq 14$–16, were explained on this basis [2,3,37,38]. Besides some surfactants [A] with R = C_mH_{2m+1} [66] or $C_mH_{2m+1}OC(O)CH_2$ [7,42] and with a polymethylene or other spacer groups did not show this abnormal behavior up to $m = 16$. Thus, premicellization appears to depend on the gemini surfactant nature. It is also favored by long polymethylene spacer as shown in a recent study [65].

IV. BEHAVIOR AT INTERFACES

Extensive surface tension measurements have been performed on aqueous solutions of gemini surfactants with the purpose of investigating their behavior at the air–solution interface (measurement of surface area a occupied by one surfactant molecule at the interface) and determining CMCs. The surface areas a were obtained from the slope of the variation of the surface tension γ with ln C (C = surfactant concentration) using the Gibbs expression of the surface excess concentration Γ:

$$\Gamma = -\frac{1}{nRT}\frac{d\gamma}{d\ln C} \tag{1}$$

where R is the gas constant and T the absolute temperature. The constant n takes the values 2 for univalent-univalent monomeric ionic surfactants and 3 for divalent-univalent ionic gemini surfactant, in the absence of a swamping electrolyte. The surface area occupied by one surfactant at the interface, a, is then obtained as $(N_A\Gamma)^{-1}$, N_A being Avogadro's number. The value $n = 2$ was used for ionic gemini surfactants in several studies [6–8,43], on the assumption that one of the two charged head groups is neutralized by a bound counterion. Several other studies used the values $n = 3$ [3,67–71]. At any rate, the value used for n does not affect the qualitative conclusions inferred from the a values for a series of homologous surfactants. This problem does not arise in the presence of a swamping electrolyte, then $n = 1$.

The effectiveness of gemini surfactants in lowering the surface tension of water is close to that of the corresponding monomeric surfactant. Indeed, the values of the surface tension at the CMC, γ_{CMC}, are close for monomeric and gemini surfactants, as illustrated by the results shown in Fig. 3 for 12-3-12, $2Br^-$ [4] and its corresponding monomeric surfactant, dodecyltrimethylammonium bromide (DTAB) [72]. However, the former are always more efficient surface-active agents than the latter because their CMCs

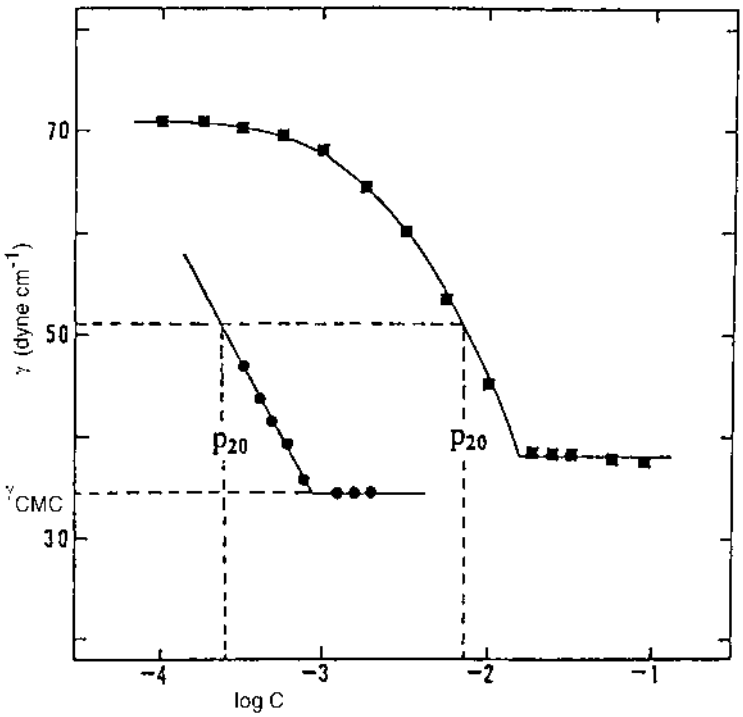

FIG. 3 Surface tension vs. concentration of the gemini surfactant 12-3-12, $2Br^-$ (●) and of dodecyltrimethylammonium bromide (■). (Adapted from data in Refs. 4 and 72.)

are much lower. Thus, the values of the surfactant concentration C_{20} for which γ is lowered by 20 mN/m are much lower for gemini than for monomeric surfactants. This result is very important for the utilization of gemini surfactants.

The behavior of gemini surfactants at the air-solution interface has been extensively investigated and some important results are summarized as follows:

1. Surface activity is favored by flexible spacers such as polymethylene or polyoxyethylene chains. Bulky and/or rigid aromatic spacers result in larger values of γ_{CMC} [3,37]. Bulky and/or rigid aromatic groups in the hydrocarbon tails near the spacer also have an unfavorable effect on surface tension lowering [73]. An effect of the aging of the solution on the measured surface tension has been reported for surfactants with rigid spacers [2,3]. This

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effect is probably in relation with the high Krafft temperature of these surfactants [74].

2. The alkyl chain carbon number m of the gemini surfactant has generally a small effect on a as long as, say, $m < 12$–14 [6,8,75]. However, for some cationic gemini surfactants an effect sets in at higher values of m and results in larger values of γ_{CMC} and a [2,3,7,37,38,76]. Premicellar association, self-coiling of the alkyl chains, and a peculiar configuration of the surfactant with its two alkyl chains lying more or less flat on the interface have been proposed to explain this behavior [2,3,37,38]. Premicellar association appears to be at the origin of the observed behavior [65].

3. For flexible spacers, of the $-(CH_2)_iY(CH_2)_i-$ type, the value of a depends on the nature of the chemical group Y. Thus, the value of a (in nm^2, in parentheses) increases in the order: -S- (0.84) < $-N(CH_3)-$ (1.08) < $-CH_2-$ (1.14) < -O- (1.28), for the gemini surfactants $[C_{12}H_{25}(CH_3)_2N^+, Br^-]_2[(CH_2)_2Y(CH_2)_2]$ [7,8].

4. Figure 4 shows the variation of a with the spacer carbon number s for the $[C_{12}H_{25}(CH_3)_2N^+, Br^-]_2(CH_2)_s$ series (hydrophobic polymethylene spacer [4]) and with the total number n_T of oxygen and carbon atoms separating the two head groups in anionic gemini which have a hydrophilic polyoxyethylene spacer (Y is O ($n_T = 9$), OCH_2CH_2O ($n_T = 12$), $O(CH_2CH_2O)_2$ ($n_T = 15$), and $O(CH_2CH_2O)_3$ ($n_T = 18$)) [45]. Focusing only on the qualitative features, a is observed to go through a maximum at $s = 10$–12 for the hydrophobic spacer series but not for the hydrophilic spacer series. A similar maximum in a at about the same value of s appears to occur for the bolaform surfactants $[(CH_3)_3N^+, Br^-]_2(CH_2)_s$ [77]. For the bolaform and the 12-s-12 surfactants this maximum was explained in terms of a change of location of the polymethylene chain as s increased. At $s < 10$, the chain has little flexibility and lies flat with a fairly linear conformation in the air–solution interface. This is supported by X-ray scattering studies of the lamellar and hexagonal phases in the water/12-s-12, $2Br^-$ surfactant mixtures [78] and by the rapid initial increase of a with s in Fig. 4. At $s > 10$ the chain is too hydrophobic to remain in contact with water and moves to the air side of the interface, adopting a wicket-like or looped conformation in doing so [4,64,77], which results in an overall decrease of a. This effect may be enhanced by a change of orientation of the alkyl chains with respect to the interface as s increases, at large s values. The absence of a maximum for gemini surfactants having a hydrophilic spacer supports this explanation. The maximum observed for gemini surfactants with a hydrophobic spacer has been accounted for theoretically [79,80]. The spacer conformational entropy and the attractive and repulsive interactions between surfactant molecules appear to be the dominant factors in determining the variation of a with s.

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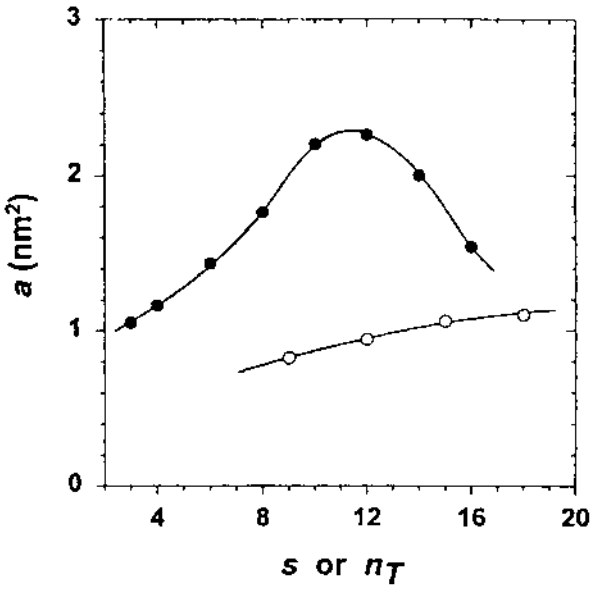

FIG. 4 Variation of the surface area per gemini surfactant at the air–water interface for the 12-*s*-12 series (●, from Ref. 4) and for $[C_{10}H_{21}OCH_2CH(OCH_2CO_2^-, Na^+)(CH_2)]_2O(CH_2CH_2O)_x$ series (○, from Ref. 45) vs. the spacer carbon number *s* or the total number of atoms n_T between charged groups at 25°C.

5. The values of the surface area *a* per surfactant [Q] with X = OH and a number *x* of ethylene oxide units equal to 7, 12, and 16, have been found to be 43, 50, and 55 Å^2, respectively, from surface tension data [31]. Note that for these surfactants $n = 1$ in Eq. (1). These values are lower than for a nonionic surfactant with a single hydrophobic chain and a polyoxyethylene head group even though surfactants [Q] contain two hydrophobic chains [81]. For instance, the values of *a* for $C_{12}E_8$ and $C_{10}E_8$ are 63 Å^2 and 70 Å^2, respectively. This suggests that the monolayer formed by gemini surfactants [Q] is relatively closely packed. For surfactants [Q] with X = SO_4Na, the surface tension at the CMC (γ_{CMC}) increases with the polyoxyethylene chain length, a phenomenon that is also observed with C_mE_x surfactants [82]. The value of *a* calculated from the surface tension data with $n = 2$ increases with the number of oxyethylene units, as expected. The surfactant with $x = 7$ appears to be the most effective one, with the lowest values of the CMC and γ_{CMC}. The variation of γ_{CMC} with the number of oxyethylene units *x* is often attributed to steric crowding of the nonionic head groups, which naturally increases with *x*.

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6. The Gibbs equation was used with $n = 1$ for the analysis of the surface tension data for surfactants [P]. Indeed, these surfactants are counterion free and therefore considered as neutral molecules. The surface areas per molecule have been obtained to be around 30 $Å^2$ [59]. These values are much lower than one would expect for a surface monolayer. They are also significantly lower than the values of a measured for equimolecular mixtures of two oppositely charged surfactants. The unrealistically low values of a obtained for gemini surfactants [P] may be due to some kind of surface aggregation [59], which remains to be clarified.

Dynamic surface tension (DST) studies of the cationic surfactants [A] with Y ≡ CHOH showed that their adsorption at the air–solution interface is controlled by diffusion [83]. On the contrary, for gemini surfactants [Q] (Fig. 5), the results suggest that at the beginning (short times) the adsorption is essentially diffusion controlled. However, close to equilibrium (long times) the DST decays are not consistent with a diffusion-controlled adsorption mechanism [31,60].

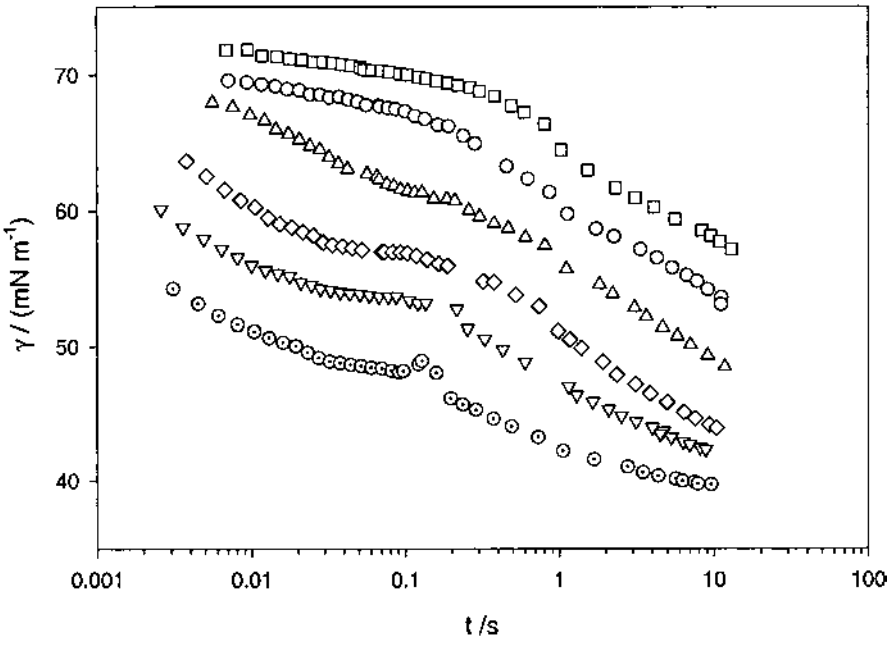

FIG. 5 Dynamic surface tension γ_t vs. time for gemini [Q] with X = SO_4Na and $x = 12$ (from Ref. 60). From top to bottom: 0.032, 0.064, 0.12, 0.207, 0.252, and 0.393 wt %.

The adsorption of gemini cationic surfactants [A], 12-*s*-12, $2Br^-$ on solid surfaces has been investigated. The surfactant 12-2-12, $2Br^-$ was less adsorbed than its corresponding monomer, DTAB, on silica [84] and titanium dioxide [85], when the adsorption was expressed in moles of adsorbed dodecyl chain per gram of solid. A similar conclusion was reached for the adsorption of DTAB and 12-2-12, $2Br^-$ on laponite clay [86]. No explanation was provided for these results. The maximum amount of 12-*s*-12, $2Br^-$ gemini surfactant adsorbed on silica was shown to decrease very much as the spacer carbon number was increased from 2 to 10 [87].

Adsorption of surfactants [Q] with X = OH and various values of x at silica surfaces have been investigated by optical reflectometry [31] (Fig. 6). The adsorbed amount of each surfactant on hydrophilic silica was about twice that on hydrophobic silica. The adsorbed amount depends little on x in the case of hydrophobic silica but decreases upon increasing x for hydrophilic silica, showing the effect of steric hindrance from the relatively larger head group. It was concluded that surfactants [Q] are better packed at solid–liquid interfaces than conventional surfactants.

Surfactants [Q] with X = SO_4Na show a significant decrease of the adsorbed amount on hydrophilic silica with increasing number of oxyethylene units [60] (Fig. 6). On both hydrophilic and hydrophobic silica, *a*

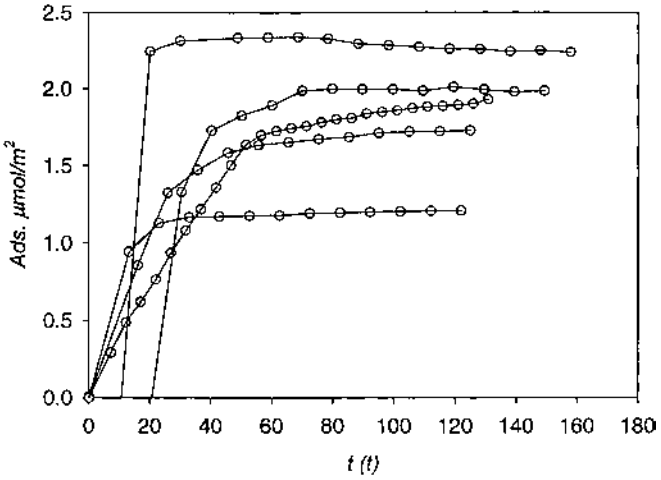

FIG. 6 Amount of adsorbed gemini surfactant [Q], on the hydrophilic silica surface (from Refs. 31 and 60). From top to bottom surfactant (X = OH, x = 12), (X = OH, x = 16), (X = SO_4Na, x = 8), (X = SO_4Na, x = 12), (X = SO_4Na, x = 16), respectively.

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increases with the polyoxyethylene chain length. This result indicates that packing at the solid–liquid interface is improved when the poly(oxyethylene) molecular weight decreases. This is a well-known phenomenon for monodisperse poly(ethylene glycol)monoalkylethers such as C_mE_x. Thus, the anionic character of the surfactants, introduced via the sulfate group, is of minor importance for adsorption. It should be pointed out that surfactants [Q] seem to pack better with X = OH than with X = SO_4Na at the air–water and solid–water interfaces. The sulfate group seems to decrease the ability of the surfactant to align tightly in a monolayer.

The adsorbed amount of surfactants [P] is higher at the surface of hydrophilic silica than on hydrophobic silica. The adsorbed amount for the pair 10,12 and 12,10 is higher than for 14,8 and 8,14 on both hydrophilic and hydrophobic silica. This might be due to the effect of the relatively larger difference between the lengths of the two alkyl chains of the latter surfactant pair. This asymmetry may be unfavorable for efficient packing at planar surfaces [59].

V. MICELLE FORMATION AND SOLUBILIZATION

A. Critical Micelle Concentration and Micelle Ionization Degree

The CMCs of gemini surfactants are much smaller than those of the corresponding monomeric surfactants by one order of magnitude or more. That is one reason for the current interest in gemini surfactants. Thus, the CMCs of 12-2-12, $2Br^-$ and of DTAB are 0.81 mM and 15 mM, respectively [1]. Such a large difference may seem surprising because these two surfactants have nearly the same hydrophilic–lipophilic balance (HLB) number. However, it is well explained in terms of the free energy change upon micellization. Indeed, for monomeric and gemini ionic surfactants the relationships between the free energy of micellization per alkyl chain, ΔG°_M, the CMC in moles of alkyl chain per liter, and the fraction α of charges of micellized surfactant not neutralized by bound counterions are, respectively [88]:

$$\Delta G^\circ_M = RT(2-\alpha)\ln \text{CMC} \tag{2a}$$

and

$$\Delta G^\circ_M t = RT(1.5-\alpha)\ln \text{CMC} \tag{2b}$$

These equations yield equal values of ΔG°_M for DTAB and 12-2-12, $2Br^-$, within the experimental error. The low CMC values of gemini surfactants arise simply because two alkyl chains are transferred at a time from water to the micelle pseudophase.

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For surfactants [A], Fig. 1, with the flexible hydrophobic spacer -$(CH_2)_2$ $Y(CH_2)_2$- the CMC depends little on the chemical nature of Y. Thus, for the $[C_{12}H_{25}(CH_3)_2N^+, Br^-]_2$ $[(CH_2)_2Y(CH_2)_2]$ surfactants, the CMCs have been found to be [8]: 1.2, 1.1, 1.0, and 0.84 mM for Y ≡ -$N(CH_3)$-, -O-, -CH_2-, and -S-, respectively.

For surfactants [G] with a polyoxyethylene spacer, the CMC increases from 0.084 to 0.37 mM as the number x of oxyethylene groups increases from 0 to 3 [45], whereas for conventional surfactants the CMC decreases upon intercalation of oxyethylene groups between the alkyl chain and the charged group [89].

The CMC of the nonionic gemini surfactants [K] where C_6H_{13} is substituted by C_mH_{2m+1} [51,75] are much lower than those of ionic gemini surfactants with the same alkyl chain carbon number m, just as for conventional surfactants.

The variation of CMC with m has been determined for several series of gemini surfactants. Figure 7 shows the variation of CMC with m for the

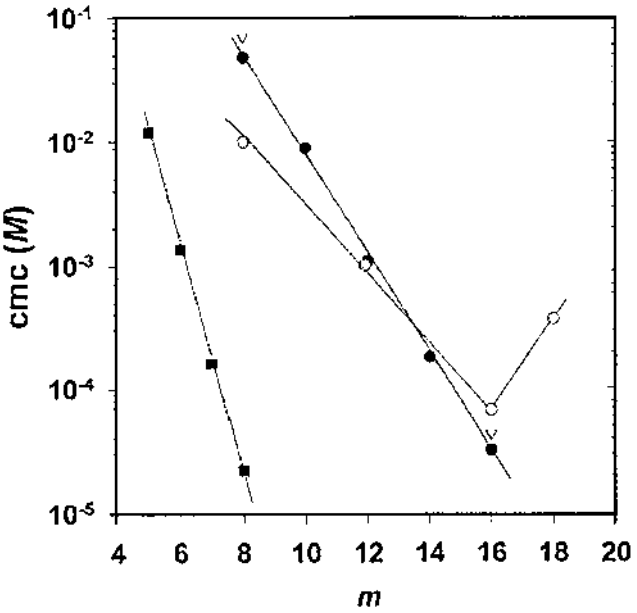

FIG. 7 Variation of the CMC of gemini surfactants with the alkyl chain carbon number m for the $(CH_2)_5$-1,5-bis[$C_mH_{2m+1}N^+(CH_3)_2$,Br^-] series (●, from Ref. 8); the $(CH_2)_6$-1,6-bis[$C_mH_{2m+1}N^+(CH_3)_2$,Br^-] series (∇, from Refs. 1 and 35); the surfactant [C] series (○, from Ref. 3); and the sugar surfactant [K] where C_mH_{2m+1} substitutes C_6H_{13} (■, from Ref. 75).

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cationic surfactants [A] with Y ≡ -$(CH_2)_3$-, and -$(CH_2)_4$-, for surfactants [C], and for the gemini sugar surfactants [K], in a semilogarithmic representation. The results for the first two series (flexible hydrophobic spacer) are nearly coincident and show a linear variation of ln CMC with m, as for the corresponding monomeric surfactants. The use of Eq. (2b) yields the value of the free energy of transfer from water to the micellar pseudophase per mole of CH_2 group, $\Delta G^{\circ}_{M}(CH_2) = -3.2 \pm 0.3$ kJ/mol, a value close to that for alkyltrimethylammonium bromides [88]. The plot for surfactants [K] is also linear and yields nearly the same value of $\Delta G^{\circ}_{M}(CH_2)$. Lastly, linear plots in the range $m = 10$–16 have been also reported for surfactants [A] with R = $C_mH_{2m+1}OC(O)CH_2$ [90] and also for several series of anionic gemini surfactants (disodium sulfonate with a polyoxyethylene spacer) [91]. The results for surfactants [C] (rigid hydrophobic spacer) are very different. The plot shows a linear behavior, with a slope smaller than for the other series at $m \leq 16$, and a minimum in CMC at $m = 16$ which was attributed to alkyl chain self-coiling and premicellar aggregation [3]. Similar increases of CMC upon increasing m or departures from linearity of the ln CMC vs. m plots observed with other series of gemini surfactants [37,38] and for a series of surfactants with three sodium sulfonate head groups and three alkyl chains [76] were also attributed to premicellization. Note, however, that the CMCs measured by surface tension were found to be very different from those obtained by other methods [3,76]. There appears to be a problem at this level which requires additional studies.

Figure 8 shows that the CMC goes through a maximum upon increasing spacer carbon number at about $s = 5$–6, irrespective of the value of m, for three series of surfactants [A] with hydrophobic polymethylene spacers [1,92]. This maximum has been attributed to changes of spacer conformation and its resulting effect on head group hydration [92] and alkyl chain orientation [1] and to a change of location of the spacer from the micelle surface to the micelle interior [1]. This change occurs when ln CMC starts decreasing nearly linearly at $s > 10$–12, i.e., when the spacer becomes hydrophobic enough to reside in the micelle interior. The fact that for surfactants with a hydrophilic polyoxyethylene spacer the CMC increases with the total number of atoms of the spacer (Fig. 8) supports this last explanation. Recent Monte Carlo simulations of gemini surfactant solutions have accounted for the maximum in the variation of the CMC with the spacer carbon number [93].

The CMC values of surfactants [Q] with X = OH depends little on the length of the polyoxyethylene chain. The CMC values were found to be 0.1, 0.2, and 0.4 mM for surfactants with $x = 7$, 12, and 16, respectively [31]. The CMC values for the nonionic surfactants [Q] with X = OH are only slightly lower than those of surfactants [Q] with X = SO_4Na [31,60]. Hence, the large

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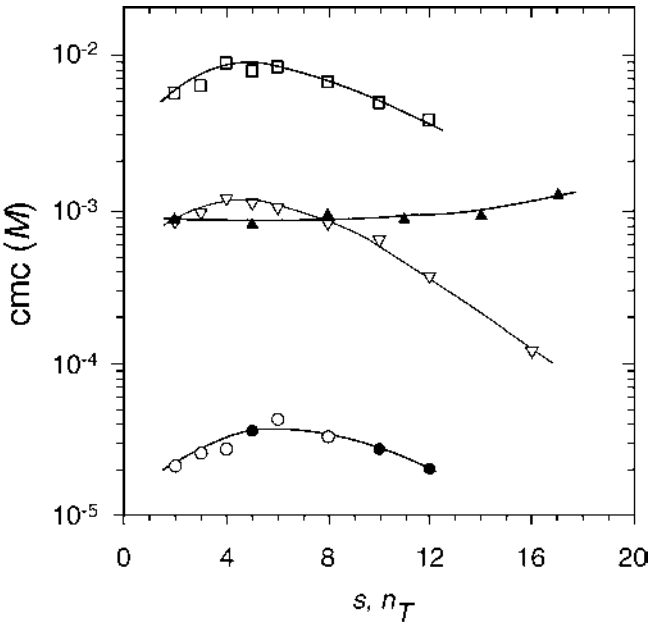

FIG. 8 Dependence of the CMC on the spacer carbon number s for the surfactant series 10-s-10 (□, from Ref. 36), 12-s-12 (∇, from Ref. 1), and 16-s-16 (○, from Ref. 1; ●, from Ref. 108). The symbols (▲, from Ref. 113) show the results for the surfactants 12-$CH_2CH_2(OCH_2CH_2)_x$-12 with a poly(ethylene oxide) spacer. n_T is the total number of oxygen and carbon atoms in this spacer.

differences normally observed between ionic and nonionic homologs for single-tail surfactants are absent in this case. The CMC of the 1:1 mixture of the anionic surfactant sodium decyl sulfate and of the nonionic surfactant octa(ethylene glycol)monodecyl ether, that mimics the gemini surfactant [Q] with X = SO_4Na and $x = 7$, was found to be larger than the CMC of this surfactant. Thus surfactants [Q] have superior properties than the mixture of the two surfactant moieties constituting them.

For surfactants [P], the CMC values of surfactant have been determined from equilibrium surface tension measurements [58,59]. A small difference was found between surfactant m,m' and surfactant m',m.

The existence of two CMCs has been reported in studies of cationic gemini surfactants by electrical conductivity [5,33,35], with the plots showing two breaks, for solutions of 8-3-8, $2Br^-$ and 8-6-8, $2Br^-$, for instance. The low concentration break was initially attributed to the formation of micelles [1]. It

was later shown that micelles are present only at concentrations above the second break [35]. The first change of slope is due to ion pairing between counterions and gemini surfactant ions favored by the high CMC values of these two surfactants [65]. The results suggest that this effect becomes significant only in the range between about CMC/2 and CMC.

There have been instances where the CMC was not detected when using specific methods for some surfactants. For instance, the CMC of 14-2-14, $2Br^-$ was not detected by dynamic surface tension [94], but clearly seen by fluorescence probing and conductivity [66]. No explanation was given for these differences.

Additions of β-cyclodextrin increased the CMC of bisquaternary ammonium surfactants [95]. Addition of β-cyclodextrin to nonionic gemini surfactant [Q] where X = OH causes a gradual change in the size and form of the aggregates. Rod-shaped aggregates form upon increasing cyclodextrin content. More and more rods form whereas the micellar aggregates break up [96,97].

Data concerning ionization degrees (α) of ionic gemini surfactant micelles are scarce. The few reported values were obtained from the variation of electrical conductivity, K, with surfactant concentration, taking $\alpha = (dK/dC)_{C>CMC}/(dK/dC)_{C<CMC}$ [1,35]. For the 12-s-12, $2Br^-$ series α increased with s in a sigmoidal manner from about 0.20 at $s = 2$ up to the large value of 0.67 at $s = 16$. This method of determining α has been discussed and shown to involve large errors [98]. The values of α have been redetermined from the same conductivity data analyzed by using a more accurate method. The range of variation of α with s for the 12-s-12, $2Br^-$ surfactants was much reduced, from 0.16 for $s = 2$ to 0.31 (instead of 0.62 [1]) for $s = 12$ [98]. Additional work using potentiometry or the change of CMC with concentration of added salt should be performed for more precise determinations of the ionization of gemini surfactant micelles.

B. Thermodynamics of Micellization

In most instances the values of the free energy of micellization ΔG°_M reported for gemini surfactants were obtained by inserting the CMC value into Eq. (2a) with or without the correcting α term [6–8,13,42], whereas Eq. (2b) should have been used. This resulted in errors difficult to evaluate since the values of α were not accurately known. The enthalpies of micellization, ΔH°_M, of the gemini surfactants $[C_mH_{2m+1}CO_2CH_2N^+(CH_3)_2, Cl^-]_2(CH_2)_2$ and 12-s-12, $2Br^-$ were determined calorimetrically [42,90,98,99]. These data have been used together with the values of ΔG°_M calculated from the reported CMCs using Eq. (2b), to obtain the entropies of micellization, ΔS°_M. The results indicate that the micellization of the investigated surfactants is entropy driven.

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The free-energy change upon micellization of gemini surfactants, expressed in per mole of CH_2, is close to that for conventional surfactants.

Volume changes upon micellization, ΔV_M^0, have been measured for cationic gemini surfactants. For the short-chain gemini surfactant 8-6-8, $2Br^-$, ΔV_M^0 was found to be about twice that for the corresponding monomeric surfactant [35]. A later study of surfactants [A] with $R \equiv C_mH_{2m+1}CO_2CH_2$ and no chemical group Y concluded on the basis of the ΔV_M^0 and ΔH_M° values that the two alkyl chains are partially associated in the premicellar range of concentration [90]. However the data involved measurements performed at concentrations below 1 mM where the errors are large. Besides, the comparison of the partial molal volumes of the monomeric and gemini surfactants neglected the important contribution of the hydrogen atom. It does not appear that at the present time thermodynamic measurements accurate enough can be performed in order to decide whether the alkyl chains are associated below the CMC. The ΔG_M° results in Fig. 7 do not support such a conclusion.

C. Solubilization

Devinsky et al. [36] studied in detail the solubilization of *trans*-azobenzene, a typical aromatic molecule, by micellar solutions of gemini surfactants $[C_mH_{2m+1}N^+(CH_3)_2, Br^-]_2(CH_2)_s$. The solubilizing capacity S_c, calculated from their data and expressed in moles of solubilized *trans*-azobenzene per mole of surfactant, increased nearly linearly with m at $s = 6$, a result similar to that for conventional surfactants, reflecting the nearly linear increase of volume of hydrophobic pseudo–phase with m. The results in Fig. 9 show the effect of the spacer carbon number, at $m = 10$. The solubilizing capacity is a maximum at an s value around 6, close to that where the CMC vs. s plot goes through a maximum. This result was interpreted in terms of spacer flexibility and micelle structure [36].

Dam et al. [94] reported that the solubilizing capacity of the gemini surfactants $[C_mH_{2m+1}N^+(CH_3)_2, Br^-]_2(CH_2)_s$ for toluene and *n*-hexane is larger than for the corresponding monomeric surfactants.

Esumi et al. showed that in the adsorbed state on silica [84], titanium dioxide [85], and laponite clay [86], the gemini surfactant 12-2-12, $2Br^-$ has a lower solubilizing power per mole of dodecyl chain than its corresponding monomer, DTAB, for 2-naphthol.

The solubilization of decanol and toluene in micellar solutions of surfactant [Q] with X = OH was investigated by small-angle neutron scattering (SANS). The micelles were modeled as spheres (for toluene solubilization) and cylinders (for decanol solubilization) in order to fit the SANS data. A growth of the micelle dimensions was thus evidenced upon addition of toluene and decanol [100].

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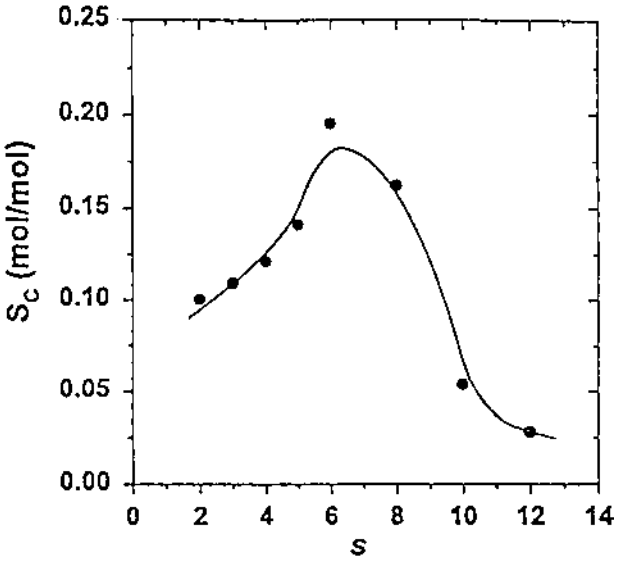

FIG. 9 Solubilizing capacity of *trans*-azobenzene by micellar solutions of 10-*s*-10, $2Br^-$ surfactants as a function of the spacer carbon number (from Ref. 36).

VI. PROPERTIES OF MICELLES OF GEMINI SURFACTANTS

A. Micelle Size and Shape

Time-resolved fluorescence quenching (TRFQ) [101,102] and SANS [97,100,103,104] have been used to characterize the size and aggregation numbers (N) of gemini surfactant micelles. The most complete set of aggregation numbers, N, have been obtained for the $[C_{12}H_{25}N^+(CH_3)_2, Br^-]_2(CH_2)_s$ surfactants [101,102]. Figure 10 shows that the N vs. concentration plots for the different surfactants converge to the same N value at low concentration (CMC). This value is close to that for the maximum spherical micelle formed by the corresponding monomeric surfactants with $m = 12$, indicating that the 12-*s*-12, $2Br^-$ surfactant micelles are nearly spherical at concentrations close to the CMC. As s is decreased, the increase of N with concentration becomes steeper, indicating an increased tendency to micelle growth and a change of micelle shape. It is shown in Section VII that for 12-2-12, $2Br^-$ and 12-3-12, $2Br^-$ micellar growth results in thread-like micelles. Very similar results were obtained in SANS studies of $[C_{10}H_{21}N^+(CH_3)_2, Br^-]_2(CH_2)_s$ [103] and $[C_{16}H_{33}N^+(CH_3)_2, Br^-]_2(CH_2)_s$ [104] surfactants. The aggregation number was shown to increase linearly with the square root of

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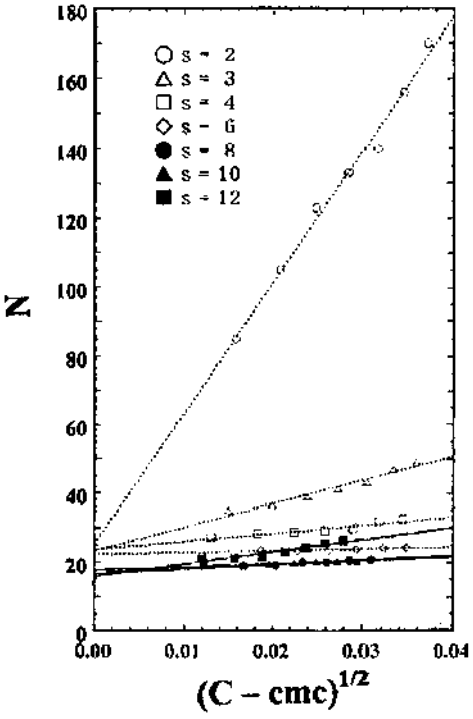

FIG. 10 Variation of the micelle aggregation number with the square root of the concentration of micellized surfactant for the 10-*s*-10, $2Br^-$ surfactants at 23°C (from Ref. 103b).

the concentration of $[C_{10}H_{21}N^+(CH_3)_2, Br^-]_2(CH_2)_s$ [103], as for conventional surfactants [105,106]. The analysis of the data in Ref. 103 in terms of the ladder model for micellar growth [105] yielded values of ΔG°_{SC}, free-energy difference between N_0 gemini surfactants packed in a part of a cylindrical micelle and in the maximum spherical micelle of aggregation number N_0. ΔG°_{SC} became less negative as s increased, as expected from the results.

Substitution of chloride counterions for the bromide counterions in cationic gemini surfactants 12-*s*-12 resulted in a significant decrease of N, as for conventional surfactants [101,102].

SANS studies [51,75] of the dichained-diglucamide sugar surfactants [K] (Fig. 1) where C_mH_{2m+1} substitutes C_6H_{13} showed that these surfactants form elongated micelles even at fairly low concentration for $m = 5$–7 and disk-like micelles for $m = 8$. Temperature had little effect on the micelle size.

A growth in micelle size, and consequently an increase in aggregation number, with the surfactant concentration was inferred from SANS study of the nonionic surfactant [Q], X = OH with $x = 12$ and 16 in D_2O [100]. The size of the micelles formed by surfactant with $x = 12$ was close to that for the surfactant with $x = 16$, i.e., with an aggregation number of 95 at 5 wt % and 116 at 10 wt %. The results also indicated that the micelles remained spherical with only a slight size polydispersity that did not vary significantly upon surfactant concentration.

For the ionic surfactant [Q] with X = SO_4Na the SANS data indicated narrowly polydisperse spherical micelles at low surfactant concentrations (below 2 wt %) and prolate ellipsoidal micelles at higher concentration. The apparent micellar surface charge was found to be low and did not change significantly with concentration. This could be due to screening of charged head groups by the poly(ethylene glycol) chain leading to weaker electrostatic repulsion between micelles [100].

SANS was also used to investigate the structure of micelles formed by the zwitterionic surfactant [P] 14,8 in D_2O solutions. The results were best fitted using a model of long cylindrical micelles. Note that the surfactant [P] 14,8 has been found to form entangled thread-like micelles. Studies using cryo-transmission electron microscopy indicate the presence of aggregates 40–50 nm long. Similar observations were made with dicationic gemini surfactant 12-2-12. Surfactant [P] 14,8 also showed a very high viscoelasticity compared to its homologs with a longer spacer. It is worth pointing out that in both surfactants [P] 14,8 and 12-2-12 the spacer is very short, made up of two methylene groups.

B. Micelle Dynamics

The kinetics of surfactant exchange between gemini surfactant micelles and intermicellar solution was investigated. Gemini surfactants with short alkyl chains, 8-6-8, $2Br^-$ and 8-3-8, $2Br^-$, were found to behave similarly to their monomeric counterparts [35]. Gemini surfactants associate to, and dissociate from, their micelles in a single step (the two chains at a time). The association reaction is nearly diffusion controlled, whereas the rate of dissociation (exit) depends strongly on the surfactant hydrophobicity.

A pressure jump study showed a distinctly different behavior for the longer chain surfactants 12-*s*-12, $2Br^-$ [107]. The association reaction of a surfactant to a micelle was found to be significantly slower than for diffusion-controlled processes, by a factor close to 100 in the case of 12-2-12, $2Br^-$. The results also indicated that the process of micelle formation/break-up proceeds via step-wise entry/exit of one surfactant at a time into/from its micelles. The results showed that the residence time of a 12-*s*-12 gemini surfactant in its micelle as

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well as the lifetime of 12-*s*-12 micelles are much longer than for the corresponding monomeric surfactants [107].

Rheological investigations of fairly concentrated solutions of 12-2-12, $2Br^-$ thread-like micelles yielded values of the time for the break-up of a worm-like micelle into to daughter micelles in the range 0.1–10 s [9].

C. Micropolarity and Microviscosity of Gemini Surfactant Micelles

The micropolarity and the microviscosity of the micelles of the $[C_mH_{2m+1}N^+(CH_3)_2, Br^-]_2(CH_2)_s$ surfactants have been systematically investigated as a function of *m* and *s* using the fluorescent probes pyrene (micropolarity) and diphenylhexatriene or dipyrenylpropane (microviscosity) [108–110]. The results for the 12-*s*-12, $2Br^-$ series have been compared to those for the series of the corresponding monomeric surfactants $C_{12}H_{25}(C_{s/2}H_{s+1})N^+(CH_3)_2$, Br^-. Figure 11 shows that the micropolarity is nearly the same for monomeric and gemini surfactant micelles at a given *s* value, except at $s = 2$. This result was explained on the basis of the similar compositions of the

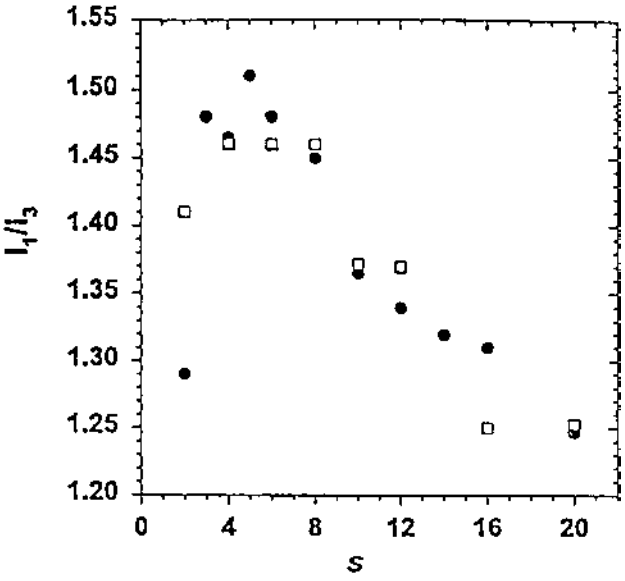

FIG. 11 Micropolarity (pyrene fluorescence intensity ratio I_1/I_3 [110]) for micelles of the gemini surfactants 12-*s*-12, $2Br^-$ (●) and for the corresponding monomeric surfactants $C_{12}H_{25}(C_{s/2}H_{s+1})N^+(CH_3)_2\ Br^-$) (□) as a function of the spacer carbon number *s*.

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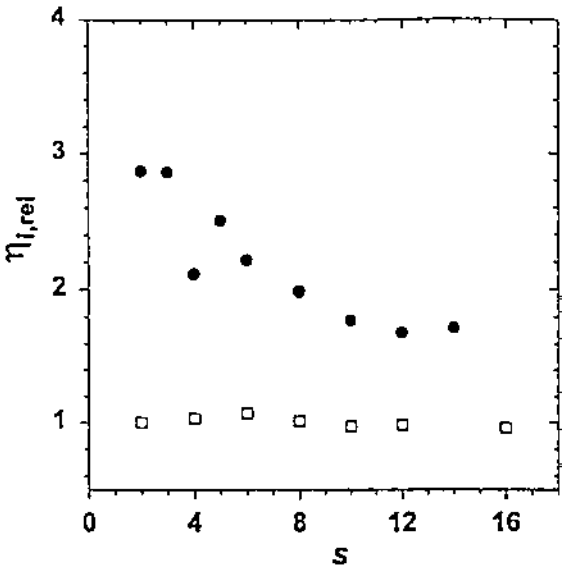

FIG. 12 Microviscosity (product of the fluorescence lifetime by the intensity ratio $I_{monomer}/I_{excimer}$ of dipyrenylpropane [110]) for micelles of the gemini surfactants 12-*s*-12, $2Br^-$ (●) and for their corresponding monomeric surfactants $C_{12}H_{25}(C_{s/2}H_{s+1})N^+(CH_3)_2\ Br^-$) (□), relative to that in DTAB micelles, as a function of the carbon number *s*.

micelle palisade layers, site of solubilization of pyrene, for monomeric and gemini surfactants [110]. Figure 12 shows that the microviscosities of gemini surfactant micelles are always larger than for the corresponding monomeric surfactants, with a fairly steep change of microviscosity at $s > 3$. A similar behavior was reported for the 16-*s*-16 surfactants [108]. These results were interpreted in terms of probe motion in the micelles [110]. In gemini surfactant micelles with short spacers this motion is more hindered because the chains cannot move independently and are tethered to the head groups which are chemically bonded two by two.

VII. MICROSTRUCTURE OF AQUEOUS SOLUTIONS OF GEMINI SURFACTANTS

Transmission electron microscopy at cryogenic temperature (cryo-TEM) was extensively used to investigate the microstructure of aqueous solutions of gemini surfactants mainly of the *m-s-m*, $2Br^-$ type [101,111–114]. In these

studies the specimen are prepared by rapid vitrification of thin samples of solution from a selected temperature. The resolution of the cryo-TEM technique has dramatically improved in the past 5 years owing to the digital recording of the images. This permits imaging at very low electron exposure to select the appropriate area of the specimen and recording of the images at much higher magnification than what was possible with photographic films.

The electron micrographs of a 20-mM 12-2-12 solution showed entangled thread-like micelles several micrometers long [101,111,114] (see Fig. 13C).

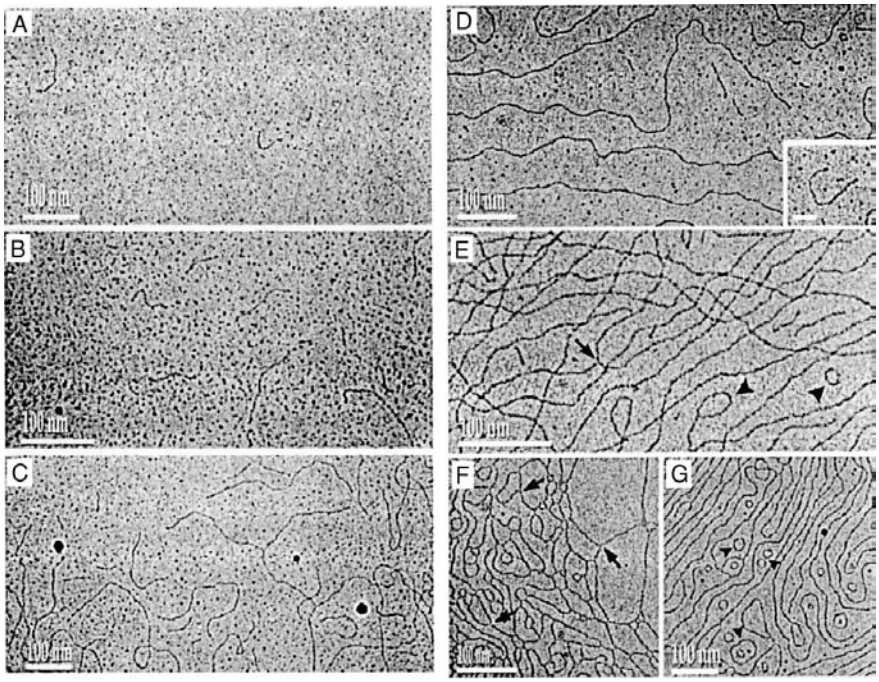

FIG. 13 Cryo-TEM images of 12-2-12, $2Br^-$ solutions at 25°C. (A) 0.26 wt %: the dark dots are spherical micelles; a few short cylindrical micelles are observed. (B) 0.50 wt %: longer cylindrical micelles in larger number than in A. (C) 0.62 wt % and (D) 0.74 wt %: the density of spheroidal micelles has significantly decreased and the length of the elongated micelles has much increased. The inset in (D) shows that the endcaps have a larger diameter than the cylindrical part of the micelles. (E) 1 wt %: very few spheroidal micelles and end caps are still present. Existence of branching points (arrows) and closed rings (arrowheads). (F) 1.5 wt %: network of branched (arrows) cylindrical micelles. (G) 1.5 wt %: many closed ring micelles in addition to normal branching points (from Ref. 114).

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Shorter but still elongated micelles were also seen in the micrographs of a 110-mM 12-3-12 solution, whereas only spheroidal micelles were visualized in a 30-mM solution of this surfactant [101,111]. Recall that the micelles of DTAB, which can be considered as the monomer of 12-2-12, and 12-3-12, remain spherical even at fairly high concentration. The micrographs of 5–7 wt % solutions of 12-4-12, 12-8-12, and 12-12-12 showed only densely packed spheroidal micelles [101]. The change of microstructure with the spacer carbon number s is in agreement with the results concerning the aggregation numbers of the 12-s-12, $2Br^-$ surfactant micelles [101]. The micrographs for 12-16-12 and 12-20-12 revealed vesicles, often doubly lamellar for 12-20-12 [5]. Note that the quaternary ammonium surfactants with two unequal alkyl chains, 12–8 and 12–10, which are the corresponding monomers of 12-16-12 and 12-20-12, also formed vesicles at higher concentration. The 12-s-12, $2Br^-$ surfactant series thus shows the unusual sequence of structures upon increasing s:

Elongated micelles → spheroidal micelles → vesicles

Cryo-TEM was used for a detailed investigation of the growth of 12-2-12, $2Br^-$ micelles [114] (Fig. 13). The micrographs showed spherical micelles at 0.26 wt %. Worm-like micelles appeared at 0.5 wt %, coexisting with spherical micelles. As the concentration was increased from 0.26 to 1 wt %, the fraction of material under the form of worm-like micelles increased and the number of spherical micelles per unit volume decreased rapidly. At 1 wt % branched thread-like micelles as well as closed-ring cylindrical micelles were observed. At 1.5 wt % the micrograph showed a network of connected cylindrical and closed-ring micelles with few isolated spherical and closed-ring micelles [114]. The improved cryo-TEM resolution revealed that the diameter of the endcaps of the worm-like micelles is larger than the diameter of the cylindrical part of the micelles, in agreement with theoretical predictions [114].

The cryo-TEM investigation of the 16-s-16, $2Br^-$ series revealed a mixture of vesicles, bilayers, membrane fragments, and thread-like micelles for 16-3-16, worm-like micelles for 16-4-16, still slightly elongated micelles for 16-6-16, and spheroidal micelles for 16-8-16 [101]. CTAB, which can be considered as the monomer of 16-3-16, forms elongated micelles only at high concentration. The sequence of structures of 16-s-16, $2Br^-$ micelles upon increasing s is vesicles + elongated micelles → elongated micelles → spheroidal micelles.

The microstructure in solutions of the asymmetrical geminis m-s-m', $2Br^-$ was systematically investigated by various techniques [55,57]. For small values of $m + m'$ or large values of $m - m'$ only spherical or worm-like micelles were formed. For large values of $m + m'$ or small values of $m - m'$ lamellar and tubular structures were observed (Fig. 14).

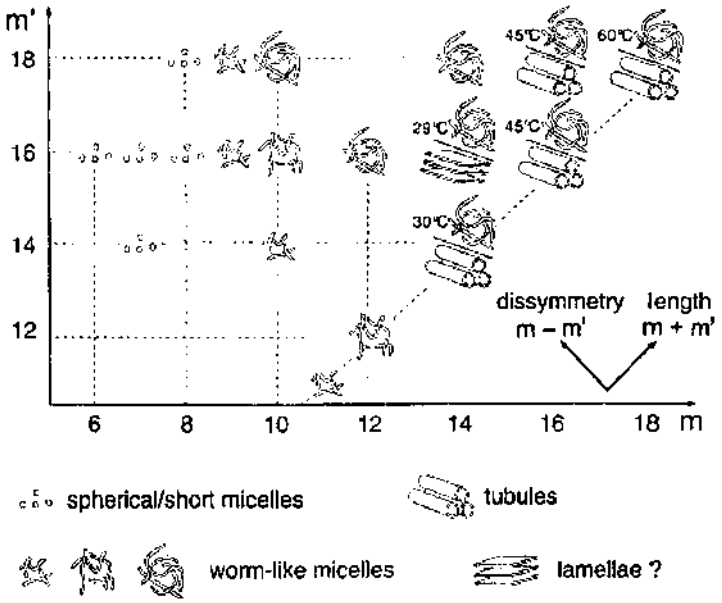

FIG. 14 Phases observed in aqueous solutions of surfactants *m*-2-*m*′, $2Br^-$ as a function of *m* and *m*′. The concentrations of the investigated solutions were between 0.1 and 10 wt %. Transition temperatures are indicated whenever a phase transition was observed. The different types of worm-like micelles differ by their overlap concentrations: lower than 0.5 wt % for the longest micelles, between 0.5 and 2 wt %, and between 2 and 10 wt % (from Ref. 55).

Molecular dynamics simulations of gemini surfactants in aqueous solutions accounted for the change of micelle shape from spheroidal to elongated upon decreasing spacer carbon number [115]. They also predicted the formation of branched thread-like micelles. Oligomeric surfactants are capable of forming such structures because the different alkyl chains of such a surfactant can take different relative orientations in the micelles.

VIII. RHEOLOGY OF AQUEOUS SOLUTIONS OF GEMINI SURFACTANTS

All of the reported studies concerned aqueous solutions of 12-2-12, $2Br^-$ [9,116–118]. The rheological behavior of this surfactant in the absence of added salt is illustrated in Fig. 15. The steep and very large increase of the zero shear viscosity η with the surfactant volume fraction Φ at above Φ^* was

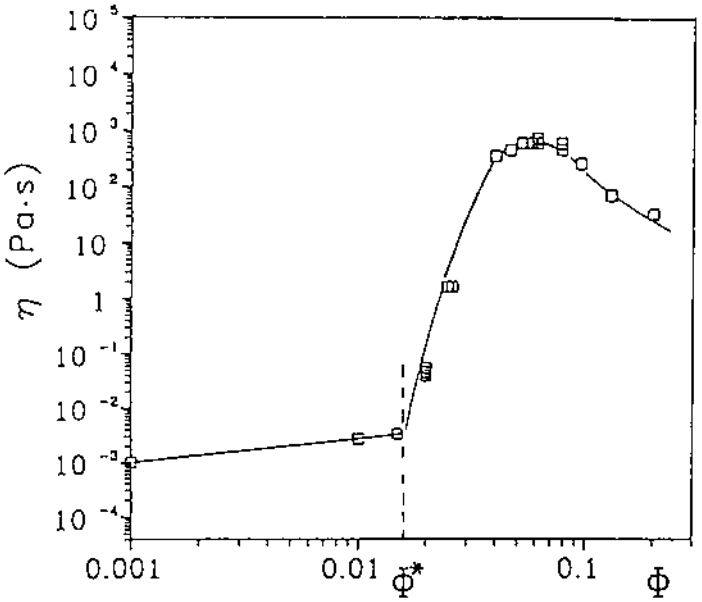

FIG. 15 Variation of the zero shear viscosity of solutions of 12-2-12, $2Br^-$ with the surfactant volume fraction Φ at 20°C. (Reproduced from Ref. 9.)

interpreted as the onset of fast micellar growth and of the semidilute regime [9]. Above Φ^* the thread-like micelles are entangled. The maximum in the η vs. Φ plot was attributed [9] to a true decrease of micelle length associated to an increase of micelle ionization degree with the surfactant concentration for cylindrical micelles [119,120] and, in turn, a decrease of magnitude of the free-energy difference ΔG°_{SC} (see Section VI.A). Molecular dynamic simulations suggested an alternative explanation in terms of the formation of branched thread-like micelles [115]. Theoretical calculations showed that the zero shear viscosity of systems of branched micelles may be lower than that of entangled linear micelles [121].

The linear and nonlinear viscoelastic properties of 12-2-12, $2Br^-$ solutions in the presence of salt depend on the electrostatic interactions between micelles [116]. These long-range interactions result in the occurrence of a pronounced correlation peak in the SANS spectra of the solutions [117].

Salt-free dilute solutions of 12-2-12, $2Br^-$ (surfactant volume fraction below 1%) show shear-induced structuration (micelle growth) resulting in an increase of viscosity, as illustrated in Fig. 16 [118].

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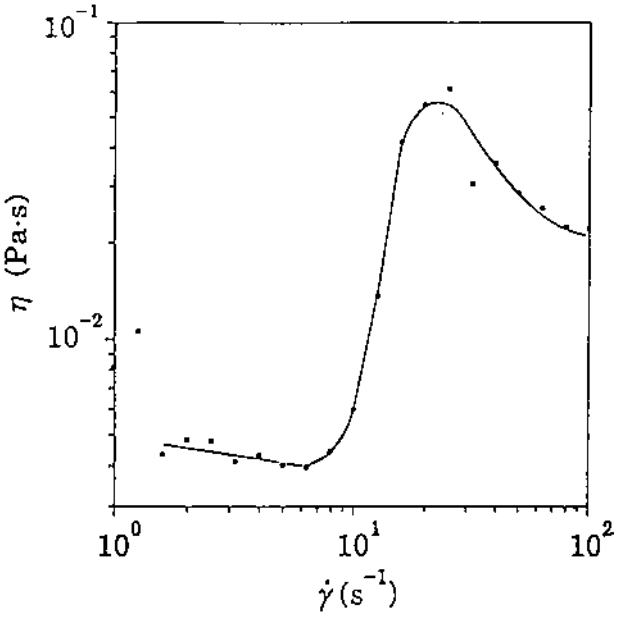

FIG. 16 Variation of the viscosity of a 0.8% solution of 12-2-12, $2Br^-$ with the shear rate at 20°C (from Ref. 118).

IX. MIXED MICELLIZATION

Rosen et al. [122–124] investigated possible synergism in surface activity and micelle formation in mixtures of gemini surfactants and a variety of conventional surfactants, anionic, cationic, nonionic, and zwitterionic, by means of surface tension. Indeed, the existence of synergism would render even more attractive the use of gemini surfactants in formulating commercial detergents. The results were found to depend much on the nature of the gemini surfactant. With didecyldiphenylether disodium sulfonates (DADS, a structurally complex gemini surfactant) [122,125], synergism was evidenced in surface activity with all types of conventional surfactants, but synergism was weaker in the case of mixed micelle formation. Synergism was observed in surface tension reduction efficiency and effectiveness, as well as in mixed-micelle formation in mixtures of gemini surfactants [H] (see Fig. 2) and the zwitterionic surfactant dimethyltetradecaneamineoxide [123]. Synergism did not occur for micelle formation in mixtures of [H] (Fig. 2) and C_mEO_x (EO = ethyleneoxide) nonionic surfactants [123]. However, such synergism

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was observed in mixtures of C_mEO_x with a gemini di(sodium alkyl sulfate) surfactant having a short polyoxyethylene spacer [126]. Strong synergism, both in surface activity and in micelle formation, were reported to occur in mixtures of the cationic gemini surfactants $[C_mH_{2m+1}\ N^+(CH_3)_2, Br^-]_2(CH_2CHOH)_2$ with alkyl sulfate, ethoxysulfate, and sulfonate surfactants [124].

A dynamic surface tension study of gemini surfactant/conventional surfactant mixtures revealed a diffusion-controlled formation of the mixed surfactant adsorbed layer [127].

A cryo-TEM study revealed that the thread-like micelles formed by 12-2-12, $2Br^-$ are transformed into spheroidal micelles upon addition of DTAB, already at a DTAB mole fraction of 0.3 [111]. A SANS study concluded to a rather uniform DTAB distribution in the thread-like micelles and no detectable accumulation of DTAB in their hemispheric endcaps [128]. The same conclusions were reached in a study of mixtures of 16-*s*-16, $2Br^-$ surfactants and CTAB, which can be considered as their corresponding monomer [109].

In a similar way, a SANS study showed that the zwitterionic [P] 14,8 forms thread-like micelles. Upon addition of a conventional ionic surfactant (SDS or DTAB) to a solution of this surfactant, the thread-like micelles break up and mixed micelles of spheroidal shape form [100].

Addition of the spherical micelle-forming surfactants DTAB and 12-10-12, $2Br^-$ to vesicular suspensions of 12-20-12, $2Br^-$ was found to result in the progressive transformation of the vesicles into mixed spheroidal micelles (Fig. 17) [129]. No intermediate structures, such as bilayer membrane fragments and/or giant thread-like micelles usually appearing during such a transformation, were observed [129].

The formation of cross-linked micelles has been postulated upon addition of the gemini anionic surfactant [F] (see Fig. 2) with $m = 12$ and a hydrophobic rigid spacer to a CTAB solution [130]. Large particles were also present at mole ratio [gemini surfactant]/[CTAB] = 0.05–0.07. However, additions of the gemini disulfate surfactant with a hydrophilic spacer $[C_{10}H_{21}C(H)OSO_3^-Na^+]_2(CH_2(OCH_2CH_2)_2CH_2)$ to a CTAB solution under experimental conditions identical to those in Ref. 130 were found to result in the simple growth of the CTAB micelles and, at the highest content of gemini surfactant, in the presence of membrane fragments [131]. These disagreeing results call for more work on these systems.

Measurements of micelle aggregation numbers in mixtures of gemini and conventional surfactant have been reported [109,126,131,132]. In the case of the systems anionic gemini surfactant/$C_{12}E_5$ and $C_{12}E_8$, which show synergism in micelle formation, the plot of the total micelle aggregation number vs composition shows a minimum at about an equimolar composition [126].

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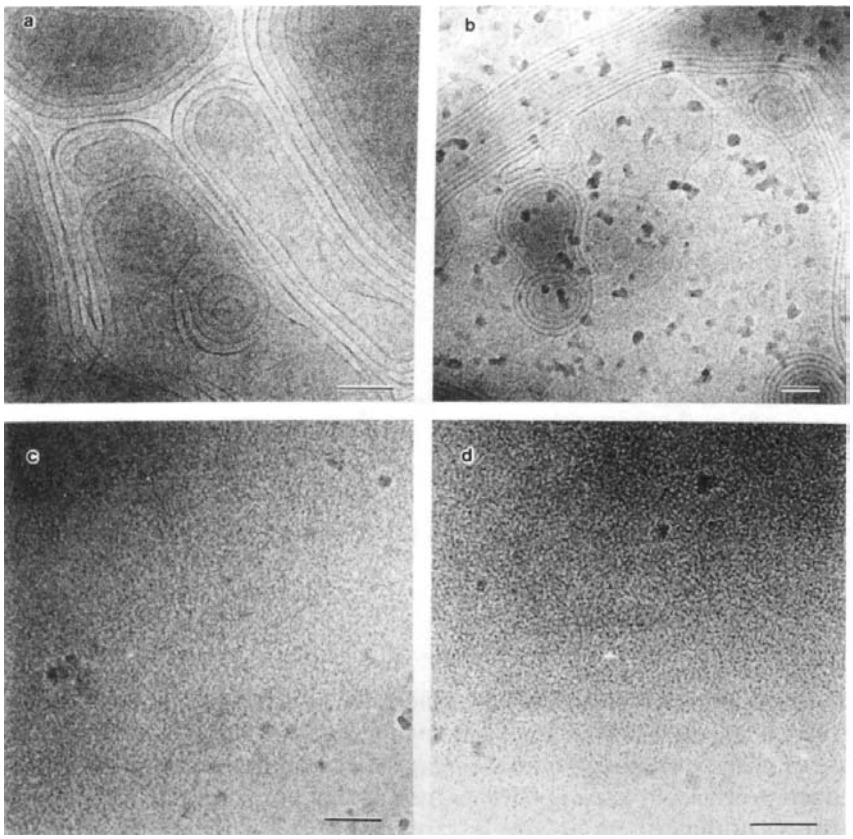

FIG. 17 Cryo-transmission electron micrographs of mixtures of 12-20-12, $2Br^-$ and 12-10-12, $2Br^-$ in water showing the progressive disruption of the large multilamellar vesicles of 12-20-12, $2Br^-$ and their transformation in mixed spheroidal micelles when increasing the amount of 12-10-12, $2Br^-$ in the system: (a) 0.44 wt %; (b) 1.32 wt %; (c) 2.56 wt %: (d) 4.40 wt %. The transformation is almost complete at 2.56 wt %. Concentration of 12-20-12, $2Br^-$: 1.4 wt %. Bar = 100 nm. (From Ref. 129.)

X. PHASE BEHAVIOR

The lyotropic mesophases in the 12-*s*-12, $2Br^-$-water mixtures occurred in a concentration range which narrowed as the spacer carbon number increased and completely disappeared for $s = 10$ and 12 [78]. For these two surfactants the micellar range extends to concentrations as high as 90%, a behavior similar to that for the corresponding monomeric surfactants, $C_{12}H_{25}$ $(C_{s/2}H_{s+1})N^+(CH_3)_2$ Br^- with $s/2 = 5$ and 6 [133]. This may

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be of interest in the use of these surfactants. Lyotropic mesophases are again observed for $s \geq 16$ with the texture of the conventional lamellar and cylindrical phases. Figure 18 represents the phase diagram of the 12-8-12, $2Br^-$–water mixtures. In the cylindrical phase the alkyl chains are located inside the cylinders. The octanediyl spacers lie nearly flat and almost fully extended on the core–water interface in both the lamellar and cylindrical (hexagonal) phases [78]. No thermotropism was observed with the pure 12-*s*-12, $2Br^-$ surfactants, contrary to the corresponding monomers (a behavior attributed to geometrical constraints on the head group arrangement associated to the presence of the spacer) [78]. A study of 16-*s*-16, $2Br^-$ surfactants evidenced intermediate and/or bicontinuous cubic phases, in addition to lamellar and hexagonal phases [134].

The effect of the alkyl chain carbon number *m* was found to be relatively unimportant for the *m*-6-*m*, $2Br^-$ series with $m = 8$, 10, and 12, as can be seen on the phase diagrams of these systems in Fig. 19 [135].

One study compared the phase diagrams of the gemini surfactant sodium-1,2-bis(*N*-dodecanoyl β-alanate)-*N*-ethane, to that of the corresponding monomeric surfactant, sodium *N*-dodecanoyl-*N*-methyl β-alanate [136]. The differences were relatively unimportant. This comparison demands to be extended to other pairs of gemini and conventional surfactants.

Upon additions of KBr the aqueous solutions of 12-2-12, $2Br^-$ first showed the presence of thread-like micelles, then that of a lamellar phase before the system separated into a salt-rich dilute surfactant phase and a

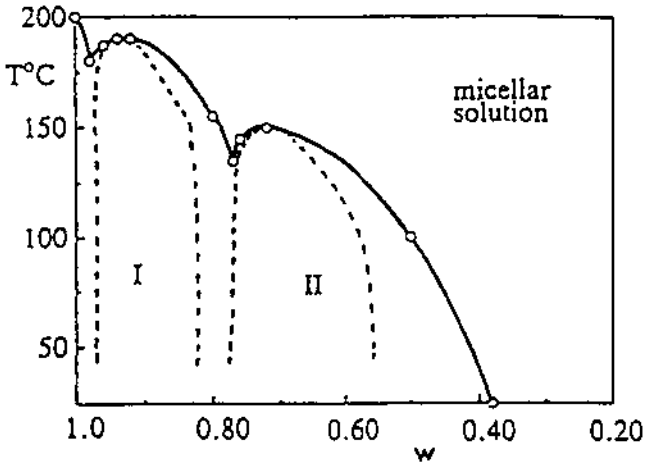

FIG. 18 Phase diagram of the 12-8-12, $2Br^-$/water mixture. (I), lamellar range; (II), hexagonal range. *w*, surfactant weight fraction. (Reproduced from Ref. 78.)

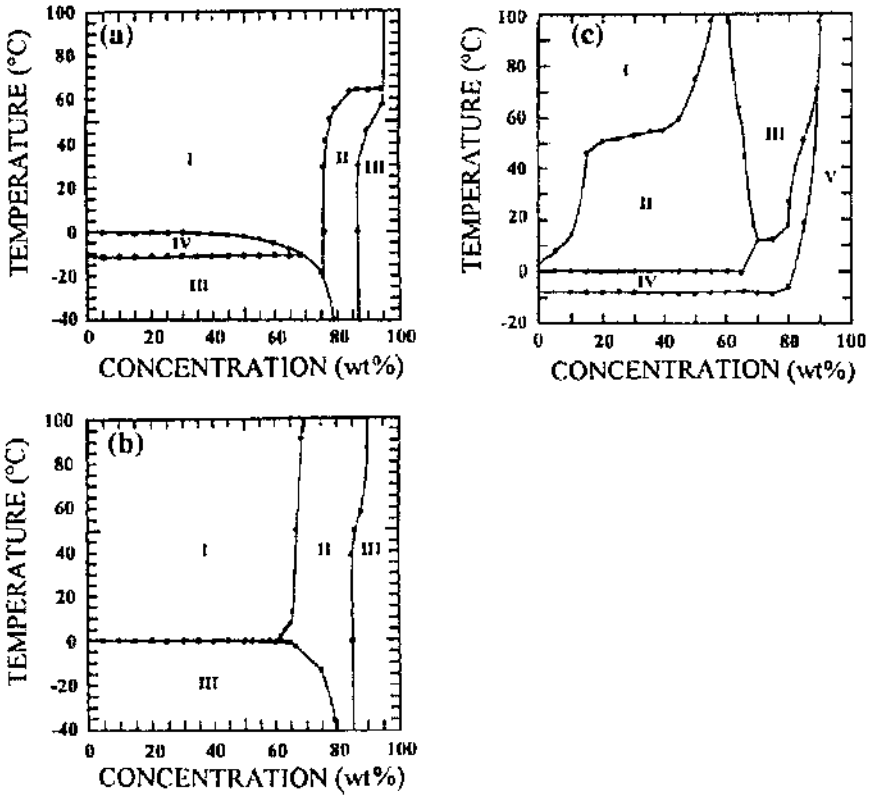

FIG. 19 Binary phase diagrams of mixtures of water with surfactants 8-6-8 (a), 10-6-10 (b), and 12-6-12 (c). Region I: homogeneous and transparent one-phase solution; region II: homogeneous and transparent viscous one-phase solution; region III: coagel phase; region IV: coagel + transparent gel; region V: hydrated crystal aqueous solution. (Reproduced from Ref. 135 with permission of Springer-Verlag.)

salt-poor lamellar phase [137]. The latter was shown to contain highly curved defects, which have been identified as water-filled holes crossing the lamellae.

The gemini surfactant $(CH_2)_6$-1,6-bis[$NCPhPhO(CH_2)_5N^+(CH_3)_2$, Br^-] forms no cylindrical phases but gives rise to two lamellar phases at appropriate temperature and concentration [138].

The gemini sugar surfactants [K] (Fig. 2) with the alkyl chains C_5H_{11} and C_6H_{13} showed the phase sequence hydrated crystals → lamellar (L_α) → cubic (V_1) → hexagonal (H_1) → micellar (L_1) with decreasing surfactant concentration, similarly to conventional surfactants [51,75]. However, the surfac-

tant with the heptyl chain showed an upper consolute solution temperature [75]—a rather unusual behavior for a nonionic surfactant.

Mixtures of surfactant [B] (Fig. 2) and water were found to form lamellar and hexagonal phases [43].

Gemini cationic surfactants with arginine head groups were recently synthesized and found to give rise to a hexagonal liquid crystalline phase at low concentration and temperature [139].

XI. POTENTIAL APPLICATIONS OF GEMINI SURFACTANTS

To the best of our knowledge, the commercial use of gemini surfactants in general is still in its infancy. There is, however, considerable interest on the part of companies in evaluation of geminis for different applications, as can be judged from the patenting activity. Their strong tendency to self-associate at very low concentration and their ability to pack at interfaces make gemini surfactants interesting candidates for applications where ease of micelle formation and efficiency in reducing surface tension and adsorbing at interfaces are important. In addition, the interesting rheological properties exhibited by some gemini surfactants triggers an interest in some areas. It is likely that the commercial impact of gemini surfactants will depend more on the ease of preparation, i.e. the cost of the synthesis, than on the physicochemical properties. Some of the geminis discussed in this chapter, in particular compounds [P] and [Q] of Fig. 2, are based on readily available starting materials and on relatively straight-forward synthesis routes.

As this chapter shows gemini surfactants possess properties that may make them interesting candidates for practical applications. Many of the gemini surfactants hitherto investigated have been made by elaborate syntheses that cannot realistically be scaled up. This is fine for research purposes, but for the concept of gemini surfactants in general, to be successful, it is imperative that the synthesis route is straight-forward. Apparently this can be achieved since the company Sasol (formally Condea, located in Marl, Germany) is already marketing formulations (Ceralution®) based on anionic dimeric surfactants and that can be used as dispersants or emulsifiers, for foam production, etc [140,141].

XII. CONCLUDING REMARKS

This chapter focused on the physicochemistry of gemini surfactants. Several interesting properties have been shown to result from their peculiar structure. In the field of applications the most interesting properties are doubtless the

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much lower CMC values, the stronger efficiency at decreasing surface tension of water and the interfacial tension of oil–solution interfaces, and the stronger adsorption at solid–solution interfaces than for the corresponding conventional surfactants. Also, these surfactants are capable of giving rise to linear and branched thread-like micelles as well as closed ring micelles at fairly low concentration. These structures bring about interesting rheological properties. At the present time the use of oligomeric surfactants is restricted to gemini surfactants in formulations for specialized uses. This makes sense as most of the improvement of properties is obtained in going from the monomeric to the gemini surfactant. Changing the length, nature (hydrophilic, hydrophobic), and flexibility of the spacer then offers the possibility to modulate very efficiently the properties of solutions of gemini surfactants. The enormous variety in the structures of gemini surfactants that can be synthesized will no doubt result in the synthesis of low-cost gemini surfactants with improved properties and in their increased uses. New regulations that are enacted in the developed world in relation with toxicity and ecology of surfactants may accelerate a move toward an increased use of gemini surfactants.

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α-Sulfomonocarboxylic Esters

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I. INTRODUCTION

From both economic and ecological points of view, substances derived from esters of monocarboxylic acids sulfonated in the α position form an interesting class of surfactants [1]. The general formula of these α-sulfomonocarboxylic esters, also called α-sulfo fatty acid esters or, in short, α-ester sulfonates, is R_1-CH(SO_3Me)-COO-R_2 (with R_1 and R_2 = alkyl groups, Me = alkali metal).

Ester sulfonates will become more and more interesting in the future because the raw materials for their preparation are fatty acid esters which can be prepared from oils and rats, and thus from renewable resources. They can be used as possible substitutes for surfactants based on petrochemicals. Even today renewable resources play a dominant role as raw materials for surfactants, but only because of the great contribution made by soaps to the production of surfactants. If the soaps are left out of consideration as "native surfactants," petrochemistry holds 65–70% of the production of "synthetic surfactants" [2]. But for the future a further increase in the use of renewable raw materials is expected to occur in surfactant production [3]. The main reason for this development is the superior digestibility in the environment of products produced from natural materials. The future importance of the renewable raw materials becomes evident from the fact that even now new plants are cultivated or plants are modified to obtain an improved yield. A new type of sunflower has been cultivated to obtain a higher proportion of monounsaturated oleic acid compared with doubly unsaturated linoleic acid [4].

In addition, the α-ester sulfonates are less important today. In the Federal Republic of Germany, for example, the total production of surfactants was

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about 700,000 t/a in 1993. For a more detailed analysis of different types of surfactants, use must be made of data collected before the unification of Germany. In 1988 the consumption of surfactants in detergents was about 227,500 t/a, the consumption of anionic surfactants was about 116,000 t/a, and of α-sulfo fatty acid esters less than 1000 t/a [5] (values refer to German detergent law).

However, it could be expected that the share of the latter group will rise to the same extent as the rising importance of environmental digestibility. It is very possible that in the future the C_{16}/C_{18} ester sulfonates will partly replace the alkylbenzenesulfonates produced from petrochemical raw material [6,7]. N. R. Smith [8] expects the α-sulfomethyl esters to be an alternative to ethylene-based surfactants. An increase in the production of surfactants based on ethylene is problematic because in industrial countries ethylene production occurs at 95% of capacity and more.

Compared with the fatty alcohol sulfates, which are also oleochemically produced anionic surfactants, the ester sulfonates have the advantage that their raw materials are on a low and therefore cost-effective level of rat refinement. The ester sulfonates are produced directly from the fatty acid esters by sulfonation, whereas the fatty alcohols, which are the source materials of the fatty alcohol sulfates, have to be formed by the catalytic high-pressure hydrogenation of fatty acids esters [9]. The fatty acid esters are obtained directly from the rats and oils by transesterification of the triglycerides with alcohols [10].

In addition to the good biodegradability of products made from native sources, the ester sulfonates have the great advantage of being insensitive to hard water. In this respect they are superior to the linear alkylbenzenesulfonates (LAS). Wool detergents based on ester sulfonates do not need sequestering agents or ion exchangers for water softening [11].

In spite of all their merits, ester sulfonates have not been used to a great extent as yet [12]. The reason is that a practicable process for producing α-sulfo fatty acid esters with good qualities is difficult because of the formation of by-products with worse properties (e.g., the disalts of the α-sulfo fatty acids).

II. TECHNICAL SYNTHESIS

A. Raw Materials

The starting substances for the production of α-ester sulfonates are the triglycerides of animal and vegetable rats and oils. The transesterification

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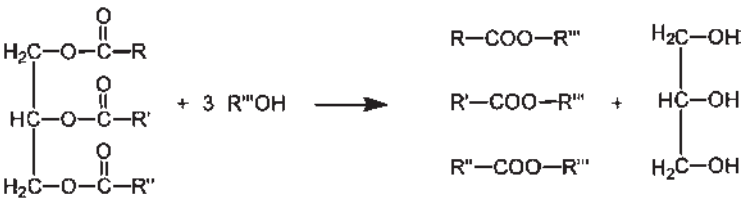
of the glycerides with alcohol leads directly to fatty acid alkyl esters and glycerin [7].



The α-sulfo fatty acid esters are obtained by α-sulfonation of the fatty acid esters. In basic media they form the corresponding salts.

The position of the hydrophilic group determines the properties of the molecule as is the case with other surfactants. If the group is in the middle of the molecule, the surfactant has good wetting properties but bad wash properties [13]. The wash properties improve when the hydrophilic group goes to the end of the molecule. For this reason the methyl esters are mainly interesting for detergents.

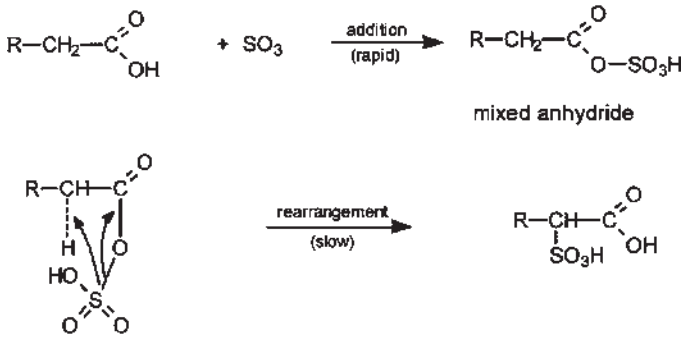
B. Reaction Mechanism

The beginning of systematic investigations concerning α-ester sulfonates was marked by the papers of F. Günther in the 1930s about the sulfonation of fatty acids [14] and the esterification of the sulfo fatty acids [15] and their salts [16]. In the 1950s and 1960s, the sulfo fatty acids and their derivatives, including the ester sulfonates, were studied in detail in the Eastern Regional Research Laboratory of the V.S. Department of Agriculture [17–31]. These first investigations for preparing ester sulfonates were laboratory methods whereby the purified α-sulfo fatty acids or their monosalts were esterified with the corresponding alcohols [19–30]. The sulfonation of fatty acid esters was not discussed in the first publications, although in some patents for the

sulfonation of fatty acids their esters were also named in a list of initial products capable of being sulfonated (see, e.g., Ref. 32). The problem of direct sulfonation is that it can only be achieved with strong sulfonation agents and under strong conditions because the hydrogen in the α position is only weakly activated by the neighboring ester group. The strong conditions led to many side reactions, so that the products were too dark in color [33].

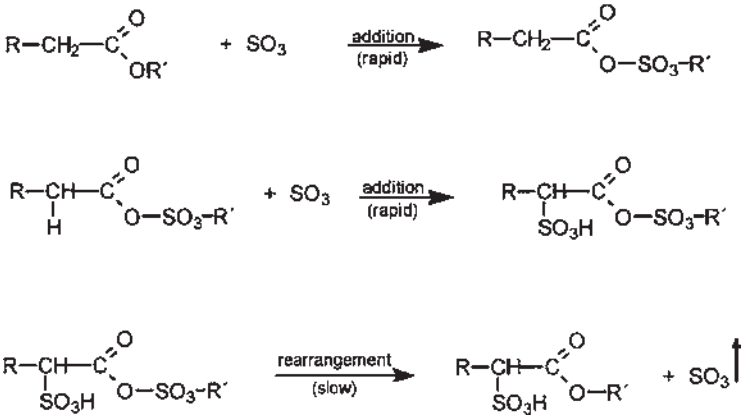
For technical applications, the production of ester sulfonates from the (purified) sulfo fatty acids involves too much effort, especially because the relevant fatty acid esters can be produced directly from the triglycerides of fats and oils by transesterification. The only possible way to produce ester sulfonates is the sulfonation of fatty acid esters.

In order to introduce an SO_3 group into long-chain fatty acids, direct sulfonation with sulfur trioxide bad been suggested in 1962 [29], similar to the Hell-Volhard-Zelinskii reaction of the α-bromation studied by Watson [34]. Ten years previously de Boer had reviewed this mechanism, among others, for lower aliphatic sulfocarboxylic acids [35]. The sulfonation process was proposed as a two-step mechanism. The first step is the rapid addition of the SO_3 into the O-H binding of the COOH group to form a mixed anhydride and the second step is the slow rearrangement of the mixed anhydride to form the α-sulfo fatty acid.



Smith and Stirton applied this mechanism to the sulfonation of long-chain fatty acid esters [31]. Instead of forming the well-defined mixed anhydride during the reaction of fatty acids with SO_3 the acid esters form a complex less defined in structure and composition. In this complex the α hydrogen is activated, so that a second molecule of SO_3 can react. These two addition

steps are fast. The final step is again a slow rearrangement of the intermediate with a loss of one molecule of SO_3.



Besides this reaction scheme, two slightly different mechanisms were published in the 1970s. Stein et al. [12,33] assumed an addition of the SO_3 molecule with the free electron pair of the carbonyl oxygen of the ester group. The adduct increases the activation of the α-hydrogen atom and a rearrangement occurs, whereby the α-H is substituted by the SO_3^- group forming a C-S bond. Simultaneously the carbonyl group is reformed. The first step, the addition, is very fast, and the second step, the rearrangement, is slow.

Nagayarna et al. [36] studied α sulfonation using nuclear magnetic resonance (NMR). They reported the presence of two intermediates. The first intermediate is the adduct of SO_3 to the carbonyl oxygen formed at low temperatures. In contrast to the mechanism of Stein et al., they did not propose a rearrangement of this intermediate but a second addition of SO_3 to the activated α hydrogen to give the second intermediate. The reaction of the intermediate with sodium hydroxide can lead to the disodium salt if the neutralization is immediate or to the sodium α-sulfo fatty acid ester if the neutralization is delayed.

Schmid et al. studied in detail the sulfonation reaction of fatty acid methyl esters with sulfur trioxide [37]. They measured the time dependency of the products formed during ester sulfonation. These measurements together with a mass balance confirmed the existence of an intermediate with two SO_3 groups in the molecule. To decide the way in which the intermediate is formed the measured time dependency of the products was compared with the complex kinetics of different mechanisms. Only the following two-step

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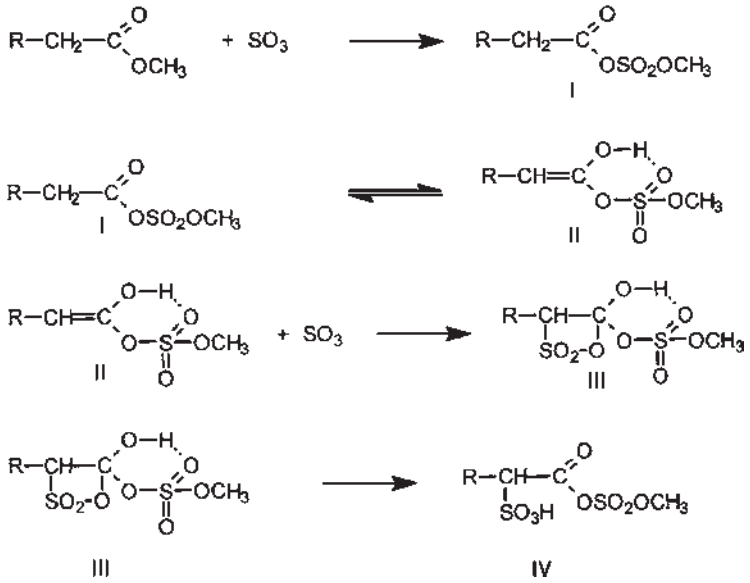
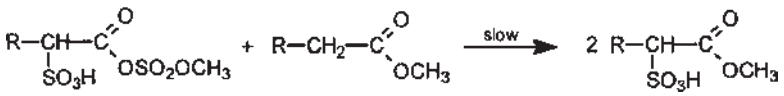
mechanism allowed a calculation of the measured data with a variation of the velocity constants in the kinetic differential equations.
First step:

Intermediates of the first step:



Second step:



In the first step an SO_3 molecule is inserted into the ester binding and a mixed anhydride of the sulfuric acid (I) is formed. The anhydride is in a very fast equilibrium with its cyclic enol form (II), whose double bonding is attacked by a second molecule of sulfur trioxide in a fast electrophilic

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addition (III and IV). In the second, slower step, the α-sulfonated anhydride is rearranged into the ester sulfonate and releases one molecule of SO_3 which in turn sulfonates a new molecule of the fatty acid ester. The real sulfonation agent of the acid ester is not the sulfur trioxide but the initially formed sulfonated anhydride. In their detailed analysis of the different steps and intermediates of the sulfonation reaction, Schmid et al. showed that the mechanism presented by Smith and Stirton [31] is the correct one.

Neutralization leads to the salt of the α-sulfo fatty acid ester, but only if the neutralization step is delayed. If the neutralization is immediate the α-sulfonated anhydride forms a disalt of the α-sulfo fatty acid as a by-product [38]. Production of the disalt is also affected by the ratio between SO_3 and the ester. A high surplus of SO_3 would shorten the reaction time, but the amount of disalt in the end product would increase. For 90°C and 30 min an optimal SO_3/ester ratio is 1.2:1 [37].

Most of the technically produced α-sulfo fatty esters are prepared from unbranched saturated fatty acid esters that are derived from C_8–C_{22} carboxylic acids and C_1–C_3 alcohols. In particular, the C_{12} (lauric), C_{14} (myristic), C_{16} (palmitic), and C_{18} (stearic) acids are interesting because the ester sulfonates with these carbon chains have the best properties for surfactant applications. Triglycerides with the needed number of carbons are available in coconut oil (~48% C_{12}, 17% C_{14}), palm kernel oil (~50% C_{12}, 17% C_{14}), palm oil (~46% C_{16}), and tallow (~26% C_{16}, 23% C_{18}) [3,8]. Unsaturated esters normally contained in natural oils and tallow (e.g., tallow contains about 43% of oleic oil) cause an undesirable color of the ester sulfonates. Therefore, the esters must be distilled or hydrogenated before sulfonation so that their iodine number is less than 0.5 [38].

Besides these normal technical products, many other different types of α-sulfo fatty acid esters have been described in the literature. For example, Weil et al. prepared α-sulfopalmitates and stearates with higher alcohols [19] and also monoesters of polyhydric alcohol [39] and of hexitols and sucrose [40] for their special properties. In addition to the sodium salt, Stirton et al. used other cations, such as Li, NH_4, K, Mg, and Ca, to study the relationship between structure and surfactant properties [30].

C. Sulfonating Agents

Different sulfonating agents have been used for the α sulfonation of fatty acids and their esters: stabilized liquid SO_3, sulfur trioxide vapor, chlorosulfonic acid, and dioxane–sulfur trioxide complex. Stirton tried all of them and preferred liquid SO_3. The other agents are used for special applications [29].

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Stein et al. used gaseous SO_3 mixed with an inert gas (preferably 90–95 vol % air) because of its commercial availability and quality [33,41]. Chlorosulfonic acid, which was used by Günther and Hetzer [14] and Bert et al. [42], does not have any advantage because the reaction needs higher temperatures leading to dark-colored products and higher costs, and the reaction supplies the corrosive by-product HCl. Ishiguro reported that the dioxan–sulfur trioxide complex gives lighter colored products [43]. Today generally gaseous SO_3 is used because of economic factors [38].

In the literature a number of different techniques for the preparation of α-sulfo fatty acid esters can be found. There is equipment for small-scale and commercial scale sulfonation. Stirton et al. added liquid sulfur trioxide dropwise to the fatty acids dispersed or dissolved in chloroform, carbon tetrachloride, or tetrachoroethylene [44]. The molar ratio of SO_3/fatty acid was 1.5–1.7 and the reaction temperature was increased to 65°C in the final stage of sulfonation. The yield was 75–85% of the dark-colored α-sulfonated acid. Esterification of the acid was carried out either with α-sulfonic acid alone, in which case the free sulfonic acid served as its own catalyst, or with the monosodium salt and a mineral catalyst.

Stein et al. used fatty acid esters and vaporized SO_3 diluted with air [41,45]. The apparatus was a cascade-type reactor with five vessels. In each vessel a batch sulfonation took place at different temperatures starting with 50°C and ending with 85°C. The amount of SO_3 added to each vessel could be controlled individually so that a lighter colored product is obtained. The final molar ratio of SO_3 to fatty acid ester was 1:3, and the SO_3 was diluted to 5 vol % in air.

The thin-film reactor for the continuous sulfonation of fatty acid esters was introduced by the Witco Technical Center in Oakland, New Jersey [46]. Hurlbert et al. designed this type of reactor for small-scale sulfonation with SO_3 [47,48]. The reaction partners could fill the reactor through three inlets. One was for the carrier gas (air or nitrogen), one for the liquified ester that is picked up from the carrier gas, and the last for the vaporized SO_3. The ester and the SO_3 reacted in a turbulent liquid film. Details of this reactor are given by Kapur et al. [46].

D. Technical Equipment

Today thin-film reactors are used not only for preparing ester sulfonates but for the sulfonation of alkylbenzenes or for the sulfonation of long-chain alcohols. The principle of this technique is that both reactants are fed to the equipment in a concurrent stream. Sulfur trioxide reacts with the organic component to form sulfonic acid, which continues through the reactor and is finally removed from the residual inert gas using a cyclone-type separator.

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The reaction is therefore characterized as a "single-pass," short-reaction-time process. Different systems are used to form the film and to generate turbulence by the mixing of the two reactants during sulfonation. The best-known systems are the Stepan [49], Allied Chemical Corporation [50], and Chemithon reactors [51]. The reactor heads of the three systems are illustrated by Kapur et al. [46]. Lion Corporation modified these reactors in order to improve the reaction conditions. A dry-air stream is introduced between the diluted SO_3 gas stream and the organic thin film so that the diffusion of the surfactant agent could be better controlled and a mild sulfonation reaction achieved [38].

E. Bleaching and Neutralization

Even if the fatty acid esters have been sulfonated under optimal conditions the ester sulfonates are dark-colored [12,33], so that the sulfonated product has to be bleached. The second pretreatment is the neutralization of the acid product to obtain the salt of the α-sulfo fatty acid ester. Different techniques have been published in the literature. Kapur et al. suggested bleaching with 3–4 wt % NaOCl (15 wt % solution) after neutralization with a 30% aqueous solution of sodium hydroxide. This technique is for small-scale sulfonation [46].

For the production of ester sulfonates on a technical scale, Stein et al. studied the bleaching and neutralization conditions in great detail [12,33, 52,53]. They had the best results when they bleached the sulfonated product with hydrogen peroxide before neutralization. The success of bleaching depends on the following variables: (1) quantity of bleach, (2) concentration of the peroxide, (3) bleaching temperature, and (4) bleaching time. The optimal quantity of H_2O_2 depends on the quality of the fatty ester. It varies from 1.5% to 3.5% of the sulfonated product. The concentration and amount of H_2O_2 plays a particular role in the bleaching step. There is a connection between the bleaching effect and the concentration of sulfuric acid, which is formed by a reaction of the excess SO_3 in the sulfonated product with the water in the hydrogen peroxide. If the concentration of the sulfuric acid is too high the color is bad; if the concentration is too low hydrolytic cleavage of the ester occurs. Stein and Baumann tested the conditions for bleaching α-sulfonated palm kernel ethyl ester. The best bleaching effect was obtained with 40% H_2O_2, which corresponds to a 68% sulfuric acid concentration (reaction conditions: bleaching time = 2 h; temperature = 60°C; H_2O_2 quantity = 3 wt % of sulfonated product). Under these conditions, 10% of the ester was hydrolyzed.

The best temperature range for good bleaching is 60–80°C. It is very important to control this temperature during the reaction and to remove the

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considerable heat of reaction by efficient cooling. The bleaching time at a temperature of 60°C was between 10 min and 1 h. In the case of insufficient bleaching with hydrogen peroxide due to the poor quality of the starting materials, the addition of 0.5 wt % sodium hypochloride (basis weight of sulfonated product) was effective when added to the neutral ester sulfonate as a 13% aqueous solution at 50°C [52].

After bleaching, the α-sulfonated ester has to be neutralized with sodium hydroxide or some other aqueous base to obtain the salt. Hydrolysis of the ester groups is avoided if the temperature does not exceed 45°C and the pH is between 7.5 and 9. Neutralization is thus performed in a continuous process to ensure pH control and effective heat removal [33]. The concentration of the NaOH solution has to be calculated so that a slurry is obtained that has a low viscosity to facilitate further processing. For example, neutralization can produce a 40% aqueous slurry of sodium palm kernel methyl ester α-sulfonate or a 25% aqueous slurry of sodium tallow methyl ester α-sulfonate [33].

In Japan, the Lion Corporation carried out a follow-up treatment of dark-colored products by simultaneous reesterification and bleaching before the neutralization [38]. Even with mild sulfonation and neutralization the products were dark brown and contained about 20% hydrolyzed products. They were bleached with H_2O_2 and reesterified with methanol, which was used as the solvent. The conditions of this follow-up treatment were as follows: temperature range 80–100°C, amount of H_2O_2 1–3%. The addition of methanol was not only for reesterification but to reduce the slurry viscosity in the next step. If the viscosity was high in the neutralization process, disodium salts were formed because of insufficient mixing. Using methanol, neutralization could be performed even with concentrated slurries without cleavage of the ester group. The methanol in the neutralized product was vaporized and recovered in a recovery unit and could be reused.

A simple yet highly effective nonbleach, two-step process had been described for purifying palm $C_{16–18}$ potassium methyl ester sulfonates [54]. In the first step, water is added to the impure surfactant mixture. The temperature of the system is maintained above the Krafft point of the surfactant, so that the surfactant and associated impurities are completely solubilized. Once completely dissolved, the surfactant mixture is allowed to cool, and the potassium-neutralized methyl ester sulfonate precipitates out selectively. In the second step, the purified surfactant is recovered by gravity or pressure filtration or by centrifugation, followed by drying.

The process significantly improves $C_{16–18}$ methyl ester sulfonates' analytical purity and color without raising safety or environmental concerns. It also allows for the purification of products derived from lower grade methyl esters, resolves odor issues, and does not require use of substantial amounts of solvent such as methanol.

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III. PHYSICOCHEMICAL PROPERTIES

Because of their preferential use as detergents, the main interest in the physicochemical properties of the salts of α-sulfo fatty acid esters is related to their behavior in aqueous solution and at interfaces. In principle, these are surface-active properties of general interest like micelle formation, solubility, and adsorption, and those of interest for special applications like detergency, foaming, and stability in hard water.

A. Critical Micelle Concentration and Aggregation Number

For all surface-active substances the critical micelle concentration (CMC) is of great interest. This property has therefore been measured since the beginning of investigations with ester sulfonates in the 1950s and 1960s. The CMC values of the α-sulfo fatty acid esters are in the same region as those of other surfactants with the same carbon chain length [22,26,27]. Stirton et al. [28,30,55] summarized the CMC values of a great number of different types of ester sulfonates (Table 1). The CMC was determined by dye titration in a pinacyanole chloride solution [56]. Table 1 shows that the CMC decreases with an increase in the numbers of carbon atoms and is a function of the position of the hydrophilic part in the molecule. The more symmetrical molecules, like the pelargonates or heptyl α-sulfolaurate, have the highest values in their particular group of isomers.

Stirton et al. also studied the influence of the structure of the ester group on CMC. They found that for α-sulfopalmitates and α-sulfostearates the esters of secondary alcohols, like isopropyl, isobutyl, and secondary butyl esters, have higher CMC values than the esters of primary alcohols [30].

Bistline and Stirton compared the CMC values of ester sulfonates with cyclic ester groups [55]. The phenyl esters have higher values than benzyl and cyclohexyl esters. The influence of the structure of the ester group decreases with increasing chain length of the hydrophobic fatty acid group. For example, the cyclic esters of α-sulfostearic acid have nearly the same CMC values.

At the end of the 1960s, Subba Rao et al. examined the influence of the interface on the CMC values [57]. They found a decrease in the CMC at the oil–water interface compared with the air–water interface. The CMC decreased by about 10% in the presence of heptane and by about 30–40% in the presence of benzene. The solubilization of the hydrocarbon in the micelle interior results in an increase in the micelle size and a slight change in the curvature of the micelle surface. The electrical potential and hence the electrical work of micellization per micelle-forming ion will therefore be decreased. Furthermore, the effect of decreasing the surface free energy in the hydrocarbon chain of the surfactant on micellization also increases. Both

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TABLE 1 Critical Micelle Concentration of Different Sodium α-Sulfo Fatty Acid Alkyl Esters

C_mH_{2m+1} $CH(SO_3Na)COOC_nH_{2n+1}$	m	n	C Atom $m + n + 2$	CMC (mmol/L)	Ref.
Na decyl α-sulfobutyrate	2	10	14	9.6	28
Na amyl α-sulfopelargonate	7	5	14	15.6	28
Na ethyl α-sulfolaurate	10	2	14	7.8	28
Na dodecyl α-sulfopropionate	1	12	15	3.2	28
Na hexyl α-sulfopelargonate	7	6	15	6.9	28
Na propyl α-sulfolaurate	10	3	15	5.3	28
Na methyl α-sulfomyristate	12	1	15	2.8	28
Na dodecyl α-sulfobutyrate	2	12	16	1.9	28
Na heptyl α-sulfopelargonate	7	7	16	4.5	28
Na butyl α-sulfolaurate	10	4	16	2.8	28
Na ethyl α-sulfomyristate	12	2	16	1.9	28
Na tetradecyl α-sulfopropionate	1	14	17	0.77	28
Na octyl α-sulfopelargonate	7	8	17	2.1	28
Na amyl α-sulfolaurate	10	5	17	1.7	28
Na propyl α-sulfomyristate	12	3	17	1.1	28
Na methyl α-sulfopalmitate	14	1	17	0.4	28
				0.37	30
Na tetradecyl α-sulfobutyrate	2	14	18	0.45	28
Na nonyl α-sulfopelargonate	7	9	18	1.2	28
Na hexyl α-sulfolaurate	10	6	18	0.87	28
Na ethyl α-sulfopalmitate	14	2	18	0.34	28
				0.31	30
Na decyl α-sulfopelargonate	7	10	19	0.49	28
Na heptyl α-sulfolaurate	10	7	19	0.5	28
Na amyl α-sulfomyristate	12	5	19	0.34	28
Na propyl α-sulfopalmitate	14	3	19	0.26	28
				0.24	30
Na methyl α-sulfostearate	16	1	19	0.08	28
				0.16	30
Na butyl α-sulfopalmitate	14	4	20	0.16	30
Na ethyl α-sulfostearate	16	2	20	0.13	30
Na amyl α-sulfopalmitate	14	5	21	0.13	55
Na propyl α-sulfostearate	16	3	21	0.07	55
				0.072	30
Na butyl α-sulfostearate	16	4	22	0.06	30
Na amyl α-sulfostearate	16	5	23	0.07	55

Source: Expanded from Ref. 28.

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factors tend to decrease the CMC. This effect is greater for benzene than for *n*-heptane because it is readily water soluble. By increasing the ionic strength from 0.01 to 0.04 M, the CMC values were considerably lowered as a result of decreased electrical energy per micelle-forming ion.

The contribution of a CH_2 group in the hydrophobic chain to the free energy of micellization can be calculated from the CMC values of a series of sodium α-sulfo fatty acid methyl esters [58]. The CMC values were determined from different measurements (conductivity, surface tension, solubilization of a dye, and solubility). In the presence of an electrolyte with a constant concentration the CMC decreases by a factor of 3.16 when the hydrophobic chain is increased for one CH_2 group (Fig. 1). This is the same value that has been found for nonionic surfactants like alkylhexaglycol ether. The change of the free energy of micellization is about 2.85 kJ/mol in this case. The electrolyte suppresses the electrical part of the energy of micellization, so that the anionic surfactant behaves like a nonionic. Without electrolyte the change of the free energy is much lower, only about 1.65 kJ/mol, which means that the CMC decreases by a factor of 1.95 for each additional CH_2 group (Fig. 1) [59].

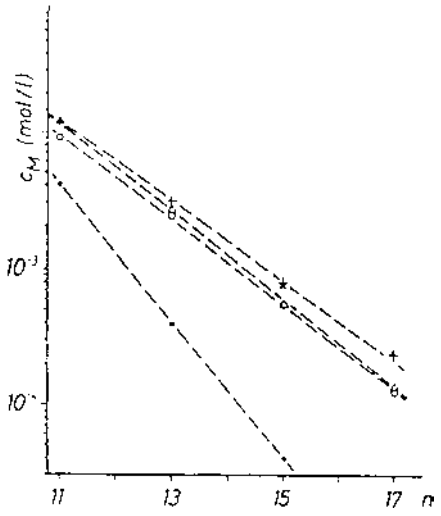

FIG. 1 Critical micelle concentration as a function of the number of carbon atoms in the hydrophobic rest of sodium α-sulfo fatty acid methyl esters. Methods: ○, surface tension; +, conductivity; △, solubilization of a dye, ×, solubility (all without electrolyte); ●, surface tension with a constant electrolyte concentration of 5×10^{-2} mol/L. (From Ref. 58.)

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Compared with sodium *n*-alkyl sulfates, the ester sulfonates with the same number of carbon atoms in the hydrophobic chain have lower CMC values because the methyl group also contributes to the micellization.

When fatty acid esters are sulfonated, the corresponding disodium salt of the α-sulfo fatty acids is also formed. Therefore, it is interesting to compare the properties of these two classes of surfactant. Long-chain disalts have much higher CMC values than the α-ester sulfonates [59]. The CMC also corresponds to the chain length of the hydrophobic portion, but the CMC decreases by a factor of 1.5 with each additional CH_2 group only. The reason is that the disalts have two polar groups. During micelle formation in ionic surfactants, work must be performed to counter the electrical repulsion of the polar end groups. This work is only partially reduced by the outer layer of the electrical double layer, which consists of counterions. This electrical repulsion is greater for disalts than for α-ester sulfonates [59]. Because there are never chain length–pure surfactants in technical applications, the CMC of mixtures of different ester sulfonates is important. Fabry and Giesen showed that the CMC value of C_{16} α-methyl ester sulfonate is lower than the value of a C_{16}/C_{18} α-ester sulfonate. There is the same tendency for C_{16} α-disalt and C_{16}/C_{18} α-disalt. For the C_{16}/C_{18} mixtures the ester group has no influence on the CMC. The methyl ester has nearly the same values as the ethyl and the *i*-propyl ester [60].

Okane et al. measured the CMC values of α-sulfonated fatty acid higher alcohol esters. These molecules can be regarded as double-chain amphiphiles, but the CMC values are about three to six orders of magnitude larger than expected for double-chain amphiphiles that can spontaneously form vesicles in water [61].

Fujiwara et al. used the CMC values of sodium and calcium salts to calculate the energetic parameters of the micellization [62]. The cohesive energy change in micelle formation of the α-sulfonated fatty acid methyl esters, calculated from the dependency of the CMC on the numbers of C atoms, is equivalent to that of typical ionic surfactants (Na ester sulfonates, 1.1 kT; Ca ester sulfonates, 0.93 kT; Na dodecyl sulfate, 1.1 kT). The degree of dissociation for the counterions bound to the micelle can be calculated from the dependency of the CMC on the concentration of the counterions. The values of the ester sulfonates are also in the same range as for other typical ionic surfactants (Na ester sulfonates, 0.61; Ca ester sulfonates, 0.70; Na dodecyl sulfate, 0.66).

From light scattering measurements Fujiwara et al. determined the molecular mass of the micelles, which gives the aggregation number [62]. The sodium salts of α-sulfomyristic acid methyl ester and α-sulfopalmitic acid methyl ester have nearly the same values (81 or 85 in 0.01 N $NaNO_3$), but the aggregation number of the sulfostearate is slightly greater (106 in 0.01 N $NaNO_3$). There is also a dependency of the number on the concentration of coexisting electrolytes. The aggregation number increases with increasing

concentration (Na methyl α-sulfomyristate: 81 in 0.01 N $NaNO_3$, 95 in 0.1 N $NaNO_3$, and 119 in 0.4 N $NaNO_3$). The calcium salt of the sulfomyristate has larger values [96 in pure water, 132 in 0.003 N $Ca(NO_3)_2$, and 124 in 0.01 N $Ca(NO_3)_2$].

The same measurements also provide values of the second virial coefficient, which corresponds to the repulsive energy between micelles. The coefficient of the Na methyl α-sulfomyristate decreases from 7.30×10^{-3} to 3.05×10^{-4} mL/g with increasing concentration of the electrolyte. The second virial coefficient of the calcium salt is small and changes to a negative value in 0.01 N $Ca(NO_3)_2$. The CMC values of the Na salts of α-sulfonatomyristic acid methyl, ethyl, and propyl esters in water are determined from the plot of differential conductivity $(\partial\kappa/\partial C)_{T,P}$ vs. square root of concentration in mM $(\sqrt{C})$ [63,64]. The logarithmic CMC values at different counterion concentrations are plotted against logarithmic concentrations of counterion (Na^+) at discrete temperatures (Corrin-Harkins relation). The slope of this plot corresponds to the degree of counterion binding (β). With these two parameters (CMC and β) the standard Gibbs energy change on micelle formation (ΔG_m°) as well as the enthalpy change on micelle formation (ΔH_m°) and the entropy change (ΔS_m°) can be calculated. The absolute value of negative ΔG_m° increases in the order propyl < ethyl < methyl ester, in parallel with the increasing order of β. This tendency reflects the increasing hydrophobicity of the side chain, indicating that the larger alkyl group near the head group leads to less coulombic repulsion between head groups.

Roberts derived a quantitative structure–property relationship, based on the octanol/water partition coefficient (log *P*), for anionic surfactant micellization potential, quantified as pCMC, the negative logarithm of the critical micelle concentration [65]. The micellization potential of anionic surfactants covering a diverse range of structures is found to be well modeled by a combination of two parameters, π_h and *L*, the former being the log *P* fragment value for the hydrophobe (simply defined as the whole molecule minus the negatively charged fundamental fragment) and the latter being the length, in C-C single-bond units, of the hydrophobe. Besides other anionic surfactants this concept is also used for ester sulfonates.

B. Solubility and Krafft Point

The solubility of several salts of alkyl esters of α-sulfopalmitic acid and α-sulfostearic acid was measured by Stirton et al. [30]. The aqueous solubility of the α-sulfopalmitates is better than the solubility of the α-sulfostearates and it also increases with increasing molecular weight of the alcohol. The same dependency is found in organic solvents, such as chloroform ethanol, petroleum ether, diethyl ether, and mineral oil. They also showed that esters of

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secondary and branched chain alcohols are more soluble than esters of normal primary alcohols.

A comparison of the solubility of different sodium α-sulfo fatty acid methyl esters and sodium *n*-alkyl sulfates shows the influence of the hydrophobic and hydrophilic group of the surfactants on this property. An increase in the chain length of the hydrophobic portion increases the hydrophobic tendency of this part of the molecule and leads to a lower aqueous solubility. This means that the Krafft point will be shifted to a higher temperature. Sodium methyl α-sulfolaurate and sulfomyristate have Krafft points below 0°C; the Krafft points of the palmitate and the stearate are 13°C and 19.5°C, respectively. But the hydrophobic chain also has an effect on the solubility. Compared with alkyl sulfates with the same number of C atoms in the hydrophobic chain the methyl ester sulfonates have lower Krafft points. The higher solubility results from the greater hydrophilic tendency of the hydrophilic portion. The methyl ester group in the α-ester sulfonates can also be regarded as a short-chain side group [59]. It is known that branching in the hydrophobic chain leads to a lowering of the Krafft point [13].

For the disodium salts of the α-sulfo fatty acids it was found that the Krafft points are higher than those of the α-ester sulfonates. Because the CMC is also higher for the disalts they are more soluble than ester sulfonates at low temperatures but less soluble at higher temperatures [59].

Mixtures of two neighboring homologous ester sulfonates and two neighboring disalts (e.g., mixtures of C_{16} and C_{18}) have different effects on the solubility compared with the pure components. Suitable mixtures of ester sulfonates are more soluble in water than their pure components. However, the disalts behave in the opposite way (Figs. 2 and 3) [59].

Sodium α-sulfonated fatty acid esters of long-chain alcohols have a structural effect on the Krafft point different from that of amphiphiles with short alkyl chains [61]. In a series of homologs with the same total carbon number, the Krafft points are highest when the hydrophilic alkyl chain lengths in the α-sulfonated fatty acid and the alcohol are fairly long and equal. In this case, the packing of the molecules becomes close and tight.

The Krafft point, i.e., the aqueous solubility, also depends greatly on the type of counterion [30,61,62]. For example, potassium salts have higher Krafft points than sodium or ammonium salts. Bivalent cations, like calcium and magnesium, raise the Krafft point. The rise is smaller for ester sulfonates than for alkyl sulfates [62].

C. Phase Behavior

The phase behavior of α-ester sulfonates has been studied in detail with methyl laurate and methyl palmitate [59]. In both cases, at higher temper-

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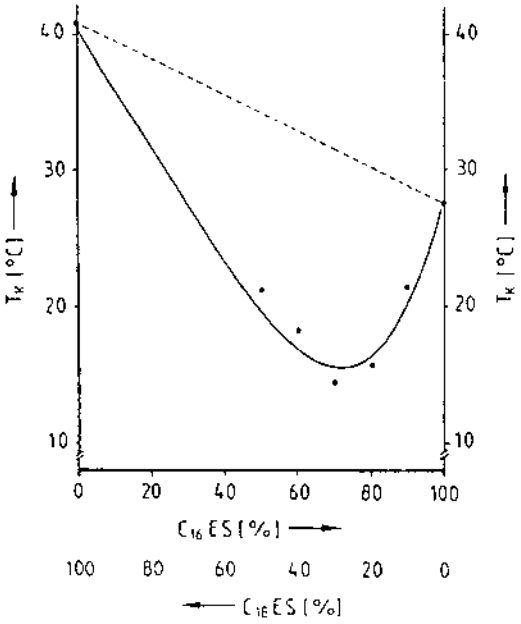

FIG. 2 Krafft points T_K of aqueous surfactant solutions vs. mixing ratio of C_{16}/C_{18} α-ester sulfonates. (From Ref. 59.)

atures, as the surfactant concentration increases there is a transition from an isotropic solution to a hexagonal liquid crystalline phase and, finally, at high surfactant concentrations, to a lamellar liquid crystal (Fig. 4). The crystalline/liquid-crystalline phase transition occurs at even higher temperatures as the chain length increases. On the other hand, chain length has practically no influence on the transition temperature from isotropic solution to hexagonal liquid crystal and from the hexagonal to the lamellar phase.

The liquid crystalline phases differ in their rheological behavior. The highest viscosities are in the hexagonal phase. They are l00-fold higher than in the isotropic phase and even in the lamellar phase. The difference in the viscosities of the two liquid crystalline phases is due to their different structures. The lamellar phase consists of macroscopically extended areas of surfactant double layers, with a layer of water between them. The water layer facilitates sliding processes without disturbing the crystal arrangement and is thus responsible for the relatively low viscosity. The hexagonal phase is made up of hexagonally arranged rod micelles. At high shear rates it often displays plastic flow behavior.

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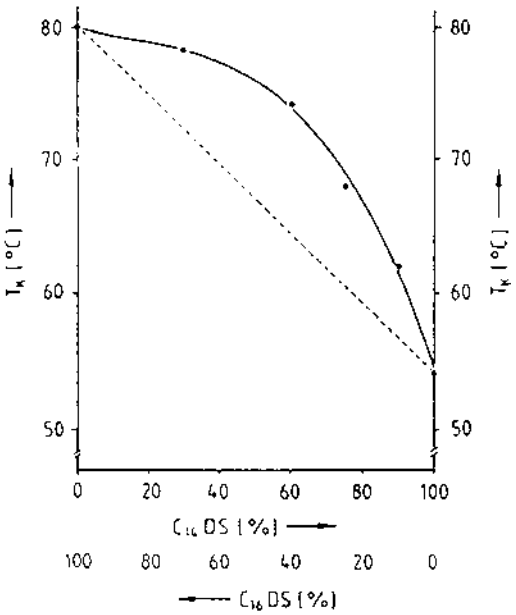

FIG. 3 Krafft points T_K of aqueous surfactant solutions vs. mixing ratio of C_{14}/C_{16} disalt. (From Ref. 59.)

Fujiwara et al. studied the phase diagram of the α-sulfonated palmitic acid methyl ester sodium salt (SFMe)–water system by measuring the phase transition temperatures (T_c) and the X-ray diffraction patterns for each solid phase of the ester sulfonate at various water contents [66]. The following phases could be recognized in the developed phase diagram:

One anhydrous solid phase
Three distinct hydrated solid phases (SFMe·$2H_2O$, SFMe·$5H_2O$, and SFMe·$10H_2O$)
Liquid crystalline phases, a micellar phase, and a monomer phase

From the analysis of the T_c changes due to the water contents of each solid phase according to the Flory-Huggins-Scott equation, it was found that the hydrated ester sulfonate solids form eutectic mixtures with each other. When the dry and wet solids were left in an atmosphere with ordinary relative humidity and temperature, the water content of the solid converged into the water content corresponding to that of the SFMe·$2H_2O$. Analysis of the phase diagrams and crystal structures determined by X-ray measurements gives an idea of the arrangement of the surfactant molecules.

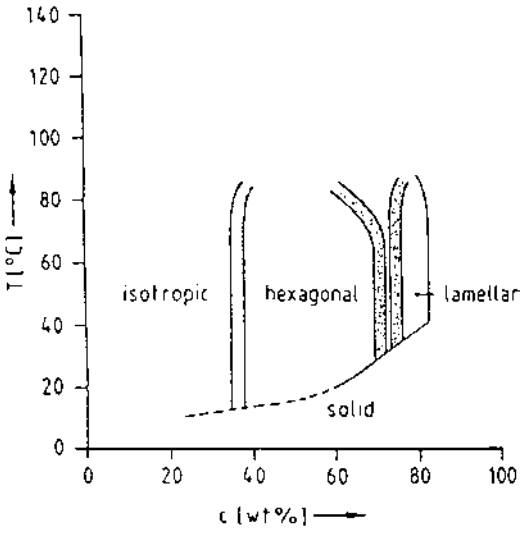

FIG. 4 Phase diagram of the binary system water/C_{12} α-ester sulfonate. (From Ref. 59.)

This information is necessary to understand the fundamental nature of the α-sulfonated fatty acid esters and their characteristic behavior, such as the low Krafft points, the hard-water tolerance, and the large heat of transition [67].

Crystal structures of sodium, potassium, and cesium salts of α-sulfonated fatty acid methyl ester were analyzed by X-ray methods to characterize physicochemical properties of the solid state in relation to counterions [68]. The crystal contains racemic molecules with the stereogenic β-carbon atom. The crystals have a bilayer structure with the interdigitated alkyl chain of anions, whereas the cations and water molecules are intercalated between the layers. These crystals have different thermal stability indicated by the decrease in melting temperature in the order potassium, cesium, and sodium salts. The crystals of sodium, potassium, and cesium salts contain two, one, and one water molecule, respectively. The space group is *Pbca* for all of these crystals having the same type of crystal packing of anions regardless of the different cations. The crystal packing of the potassium salts is not significantly affected by the alkyl chain length, except for the difference in the *c* dimension. The energetic difference of the crystal structures was analyzed by molecular mechanics calculations using X-ray coordinates. The thermal stability of the crystal is related to the crystal structure, especially to the packing of cations and sulfonato groups between the

layers. The potassium ion contributes more to the thermal stabilization of the crystal than the sodium and cesium ions because of more effective contact with the sulfonato groups by less coordination with the water molecule and by acquired electrostatic potential. The close packing of ionic layers observed in the crystals of potassium salts causes dense packing of the alkyl chains, which stabilizes the crystal packing.

Phase diagrams of aqueous mixtures of Na methyl α-sulfopalmitate and nonionic surfactants have been measured between 20°C and 40°C and the percentage area of the isotropic region has been determined [69]. Three polyoxyethylene (20) sorbitan monoesters (POESE) with different hydrophobic chain lengths [laurate (POESE 12), stearate (POESE 18:0), and oleate (POESE 18:1)] and nonylphenolethoxylated alcohol (NPEO) with different ethoxylate, hydrophilic lengths [9.5 (NPEO 95), 12 (NPEO 120), and 40 (NPEO 400)] were used as nonionic surfactants. The isotropic region increased with the temperature and the incorporation of a nonionic surfactant increased the solubilizing efficiency of the ester sulfonate. A mixture of Na methyl α-sulfopalmitate and POESE 12 exhibited the largest isotropic region. These results confirm the rule that the solubility of a surfactant with a high Krafft temperature can be increased by mixing with a surfactant with a lower Krafft temperature.

D. Surface and Interfacial Tension

The surface and interfacial tension of a great number of ester sulfonates has been measured by Stirton et al. [26–28,30]. The values of the surface tension of 0.2% solutions at 25°C are in the range from 25 to 50 mN/m and from 2 to 20 mN/m for the interfacial tension. In the group with the same number of C atoms the pelargonates and laurates have the lowest values. Among the esters of the same α-sulfo fatty acid, the surface and interfacial tension decreases with increasing molecular weight of the alcohols. Surface tension values also depend on the cation. For the alkali salts the values decrease from lithium to sodium to potassium.

The values of surface and interfacial tension can also be used to calculate the geometrical and energetic parameters of adsorption at the interface. These calculations have been done for the air–water and oil–water (*n*-heptane–water and benzene–water) interfaces with the values of ester sulfonates with different structures: Na hexyl α-sulfopelargonate and Na heptyl α-sulfopelargonate have nearly the same chain length in the α-sulfo fatty acid group, whereas Na methyl α-sulfomyristate and Na methyl α-sulfopalmitate have the hydrophobic group at the side [57]. The methyl esters of a homologous series of α-sulfo fatty acids from lauric acid to stearic acid have been used to analyze the surface tension at the air–water interface [58].

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The concentrations of two neighboring surfactants of a homologous series, which give rise to the same interfacial tension value, decrease with increasing numbers of C atoms in the hydrophobic chain. Traube's rule predicts a decrease by a factor of 3 per CH_2 group for constant electrolyte concentration. This factor corresponds to the energy contribution of one CH_2 group for the transition from the bulk phase to the interface, in the same way as the factor of the CMC corresponds to the transfer to the micelles. Subba Rao et al. found that the concentrations decrease by a factor of about 3.7 per CH_2 group. This gives an energy amount of about 3.2 kJ/mol [57]. The homologous series of α-sulfo fatty acid methyl esters yielded a factor of 3.1 for constant ionic strength and a factor of 2.01 without electrolyte (Fig. 5) [58]. These values agree very well with the factors found for the change of the CMC. This means that the energy contribution per CH_2 group is the same for transfer to the interface and for micellization.

The Gibbs equation allows the amount of surfactant adsorbed at the interface to be calculated from the interfacial tension values measured with different concentrations of surfactant, but at constant counterion concen-

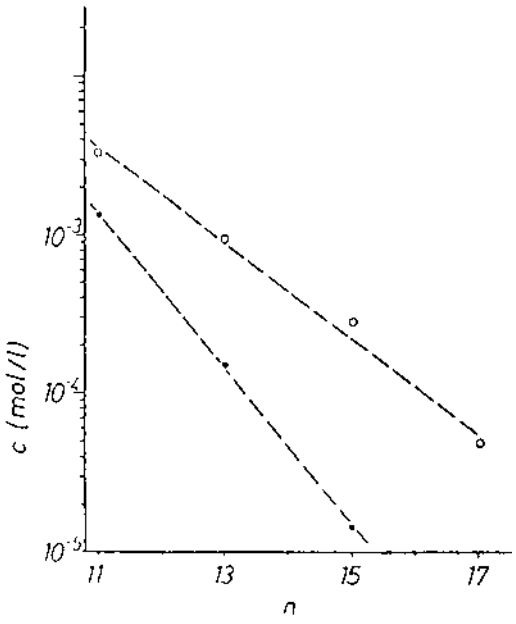

FIG. 5 Concentration giving a surface tension of 45 dynes/cm as a function of the number of carbon atoms in the hydrophobic rest (○, without electrolyte; ●, with a constant electrolyte concentration of 5×10^{-2} mol/L). (From Ref. 59.)

tration. The amount adsorbed can be converted to the area of a surfactant molecule. The co-areas at the air–water interface are in the range of 4.4–5.9 nm^2/molecule [57,58]. A comparison of these values with those from molecular models indicates that all four surfactants are oriented normally to the interface with the carbon chain outstretched and closely packed. The co-areas at the oil–water interface are greater (heptane–water, 4.9–6.6 nm^2/molecule; benzene–water, 5.9–7.5 nm^2/molecule). This relatively small increase of about 10% for the heptane–water and about 30% for the benzene–water interface means that the orientation at the oil–water interface is the same as at the air–water interface, but the α-sulfo fatty acid ester films are more expanded [57].

The electrolyte concentration also has an effect on the co-areas. An increase in the ionic strength from 0.01 to 0.04 M causes a considerable decrease in the interfacial tension [57].

For long-chain alcohol esters it is interesting to see that the interfacial tension between a 0.01 wt % aqueous solution and octane or xylene has a minimum for ester sulfonates with a total of 22 carbon atoms in the fatty acid chain and the ester chain [61]. The balance in length between the two chains has only a poor effect. Thus, α-sulfonated fatty acid esters with a total number of 22–26 carbon atoms in the molecule have excellent interfacial activities. To attain the same magnitude in the interfacial tension between linear alkylsulfonates (LAS) solution and octane, the required concentration of LAS is 0.1 wt %. This is 10 times the concentration needed for α-sulfonated fatty acid esters [61].

E. Stability to Hydrolysis

Esters of α-sulfonated fatty acids are surprisingly resistant to hydrolysis in hot acid or alkaline solutions [20,27,30]. The bulky sulfo group in the neighborhood of the carboxylate linkage retards attack on this place. The steric effect of the sulfo group was shown by Stirton et al. They measured the rate constant for a first-order acid-catalyzed hydrolysis of sodium di-(2-ethylhexyl)sulfosuccinate. This molecule has two neighboring carboxyl groups, one with an adjacent sulfo group. Under special conditions this molecule is hydrolyzed stepwise, first at the linkage unprotected by the sulfo group and then less rapidly at the ester linkage adjacent to the sulfo group. The rate constant of this second slower reaction is about 20% less than the constant of the first reaction. Under the same conditions the sodium alkyl α-sulfopelargonates have similar rate constants [27]. The rate constant for the acid-catalyzed hydrolysis and for the alkaline hydrolysis of α-sulfostearates generally decreases with increasing molecular weight of the primary alcohol and is significantly less for esters of secondary alcohols. The energy of activation can be calculated from the temperature dependency of the rate constant of the

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alkaline hydrolysis. For sodium methyl α-sulfopalmitate and -stearate the values are about 70 kJ/mol [30]. Stein and Baumann studied the hydrolysis under washing conditions [33]. The hydrolysis rate of the palm kernel methyl ester α-sulfonate is very slow in the pH range of 3–9.5, even at 80°C.

F. Stability in Hard Water

The solubility of numerous ionic surfactants in water is strongly reduced in the presence of divalent cations. Stability in hard water is thus an important fact for surfactants used as detergents. Their stability can be measured as the amount of divalent cations at which the formation of a poorly soluble surfactant salt leads to permanent turbidity. The values given in the literature can only be compared with difficulty because there are differences in temperature, in surfactant concentration, and in the type of divalent cations used for the measurements. For example, sometimes only Ca^{2+} ions are used (calcium stability) [26–30], and sometimes a mixture of calcium and magnesium (Ca/Mg = 5:1) is used (sensitivity to water hardness) [59]. In principle, the less symmetrical α-sulfo fatty acid esters, with different chain lengths of the acid and ester portion, have greater calcium stability [30] and a branching in the ester chain lowers the stability [28]. Especially the esters of higher alcohols have an extremely high sensitivity to calcium ions [61]. Referring to the conditions of normal tap water (1–5 mmol/L Me^{2+}), the methyl esters of α-sulfonated fatty acids have very good stability conditions. At 60°C a 1 g/L surfactant solution remains clear up to a Me^{2+} concentration of about 25 mmol/L [59]. The disalts, in contrast, are very sensitive to water hardness.

Fujiwara et al. studied the precipitation phase boundary diagrams of the sodium salts of α-sulfonated myristic and palmitic acid methyl esters in the presence of calcium ions [62]. The time dependency of the precipitation showed that the calcium salts have an extremely slow crystallization rate at room temperatures. This is the reason for the good hardness tolerance of the α-sulfonated fatty acid methyl esters.

G. Wetting Time

If a piece of cotton material is dipped in a surfactant solution the liquid can penetrate into the fabric and displace the air, so that the test material will sink. The time between immersion and sinking is the wetting time. Regarding the α-sulfonated fatty acid esters, there is not a good correlation between the structure and the wetting time. In general, the esters of 15–17 carbon atoms are the best wetting agents in distilled and hard water, particularly if they have the hydrophilic group at or near the middle of the molecule [26,28,60]. In the series of sodium *n*-alkyl α-sulfopelargonates, for example, the heptyl ester is the most efficient wetting agent [27]. A comparison between α-sulfopalmitates

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and -stearates shows that palmitates have better wetting properties than stearates [30]. Branching of the ester group, by the use of either a branched alcohol or a normal secondary alcohol, improves the wetting properties [27].

H. Foaming Properties

As with the wetting time, the foam height can only be correlated to the structure of the molecule with difficulty. This is especially true for technical products. In principle, the higher alkyl ester sulfonates have lower foams, which disintegrate faster than the methyl ester, perhaps because of the higher content of weak-foaming disodium salt [60]. The α-sulfopelargonates have good foaming properties in soft water, except for the very short esters. In hard water only the pelargonates with fewer than 9 C atoms in the ester group are good foaming agents [27]. In the series of α-sulfopalmitates and -stearates the esters with 17–20 C atoms have the best foaming properties and the foam height of the alkyl α-sulfostearates decreases with increasing molecular weight [30].

I. Lime Soap Dispersion Power

The ability to disperse the calcium soap formed from a given amount of sodium oleate has been studied for a number of α-sulfo fatty acid esters with 14–22 carbon atoms [28,30]. In principle, the lime soap dispersion property increases with the number of C atoms and the dissymmetry of the molecule. Esters with 14 C atoms have no dispersion power, and in the case of esters with 15–17 carbon atoms the least symmetrical are the better lime soap–dispersing agents. However, this property depends not only on the symmetry but on the chain length of the fatty acid group. For example, methyl and ethyl α-sulfomyristate have better dispersing power than dodecyl propionate and butyrate. The esters with 18 and more carbon atoms are about equal in lime soap dispersion power. Isobutyl α-sulfopalmitate is the most effective agent under the test conditions.

J. Detergency

Detergency is measured as the increase in reflectance after washing of soiled fabric in a surfactant solution. The conditions of the washing process can differ, so that the assessments of the detergency of the α-sulfo fatty acid esters are not the same in the literature. The reflectance values measured by Stirton et al. suggested that the detergency of unsymmetrical ester sulfonates is in the same range as the detergency of alkyl sulfates [28,30]. However, detailed investigations of a series of sodium α-sulfo fatty acid methyl esters and sodium *n*-alkyl sulfates with different synthetic and natural materials showed

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that the ester sulfonates are not as good as the alkyl sulfates with a comparable number of carbon atoms in the hydrophobic chain [58]. This behavior can be explained by the better solubility and the stronger hydrophilic power of the hydrophilic group of the fatty acid esters. Both properties reduce the adsorption of the surfactant on soil particles and textile fibers and thus also the detergency. It is interesting to see that graphite is not a good model for the hydrophobic pigment soil. There is no difference between the adsorption of ester sulfonates and alkyl sulfates on graphite. A plot of the logarithm of the amount adsorbed in equilibrium against the number of carbon atoms in the hydrophobic chain gives the same line for both surfactant classes (Fig. 6). An increase in the number of C atoms in the hydrophobic chain increases the van der Waals forces and thus the attraction to the hydrophobic solid surface. In contrast to graphite, the adsorption on kaolin gives different lines for the two surfactant classes, with the line for the ester sulfonate being below the line for the alkyl sulfate (Fig. 7). This lower adsorption of the sodium α-sulfo fatty methyl esters on kaolin is in accord with their somewhat worse detergency.

In principle, the soil removal for the α-ester sulfonates increases appreciably in soft water as chain length increases. In hard water the results for C_{16} and C_{18} ester sulfonates are nearly the same with and without zeolite A, a builder for complexing Ca^{2+} ions (Fig. 8) [59].

From the practical point of view, it is important to study the detergency of technical surfactants. Ester sulfonates produced from technical starting materials have fatty acid groups of different chain lengths. Optimal washing properties are reached in the case of the methyl ester sulfonates with

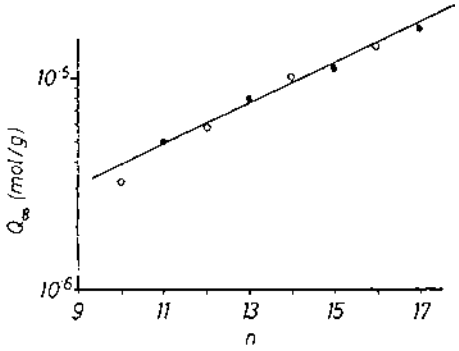

FIG. 6 Amount adsorbed in equilibrium on graphite as a function of the chain length of the adsorptive. ○, $C_nH_{2n+1}OSO_3Na$; ●, $C_{n-1}H_{2(n-1)+1}CH(SO_3Na)COOCH_3$. (From Ref. 58.)

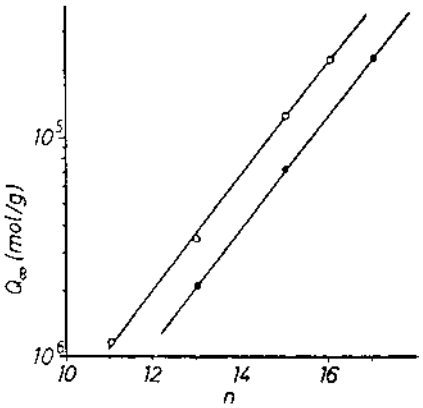

FIG. 7 Amount adsorbed in equilibrium on kaolin as a function of the chain length of the adsorptive. ○, $C_nH_{2n+1}OSO_3Na$; ●, $C_{n-1}H_{2(n-1)+1}CH(SO_3Na)COOCH_3$. (From Ref. 58.)

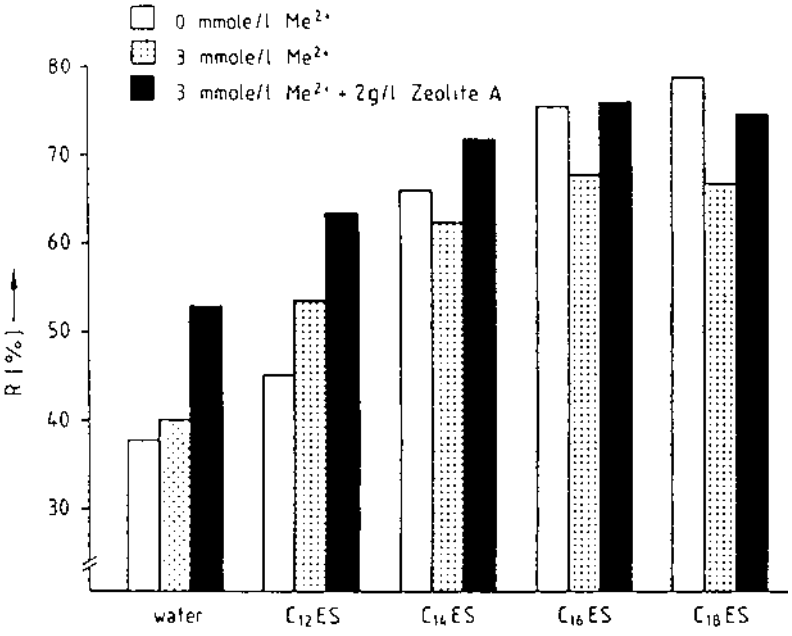

FIG. 8 Effect of chain length of α-ester sulfonates and water hardness on detergency R for fabrics soiled with clay/sebum (T = 60°C; 1 g/L surfactant). (From Ref. 59.)

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C_{16}–C_{18} fatty acids. This distribution is best realized with palm kernel methyl ester sulfonate (average chain length about $C1_{3.1}$) and tallow methyl ester sulfonate (average chain length about $C_{17.6}$) [33]. Compared with LAS the tallow methyl ester sulfonate possesses better detergency in soft and hard water. In soft water LAS is a little better than palm kernel methyl ester sulfonate, but in hard water the detergency of LAS decreases strongly whereas the detergency of the ester sulfonates is nearly independent of water hardness. If different washing conditions (light- and heavy-duty detergent formulations) are taken into account tallow methyl ester sulfonate is the best detergent, but palm kernel methyl ester sulfonate has better foaming properties [33].

The influence on detergency of mixing ester sulfonates with different chain lengths has been studied with sodium methyl α-sulfopalmitate (C_{16} ester sulfonate) and sodium methyl α-sulfostearate (C_{18} ester sulfonate) [59]. At 20°C a mixture of 70% C_{16} ester sulfonate and 30% C_{18} ester sulfonate has better detergency than the individual surfactants. At this temperature the amount of surfactant used (5 g/L) is only fully dissolved in this mixture. The two individual surfactants are only partially dissolved. The higher remission value of the C_{16} ester sulfonate compared with C_{18} ester sulfonate is due to the

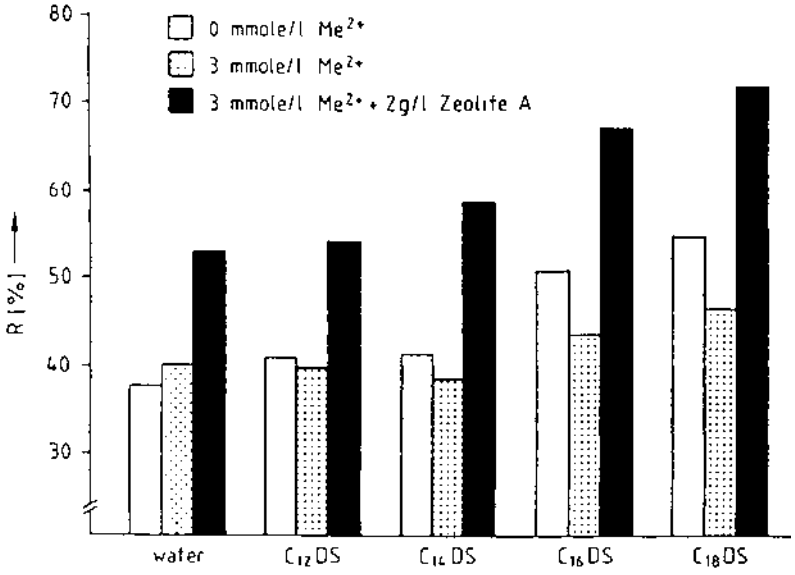

FIG. 9 Effect of chain length of disalt and water hardness on detergency R for fabrics soiled with clay/sebum ($T = 60°C$; 1 g/L surfactant). (From Ref. 59.)

higher solubility of the shorter chain surfactant. Although this behavior can be explained by the solubility, the differences in remission between the fully dissolved mixture and the pure components are remarkably small. Some of the undissolved surfactants probably dissolve during the washing process, since the wash liquor loses surfactant due to adsorption on fabric and removed soil particles.

The disodium salts of the α-sulfo fatty acids, which are also formed during sulfonation, have worse washing properties than the α-sulfo fatty acid esters, especially in hard water [59]. Figure 9 shows the soil removal of disalts with different chain lengths. In demineralized water and in hard water the remission values are worse than those of the α-ester sulfonates with the same chain length (compare Figs. 8 and 9). The disalts are less soluble in water and have a lower interfacial activity. The great sensitivity of the disalts to water

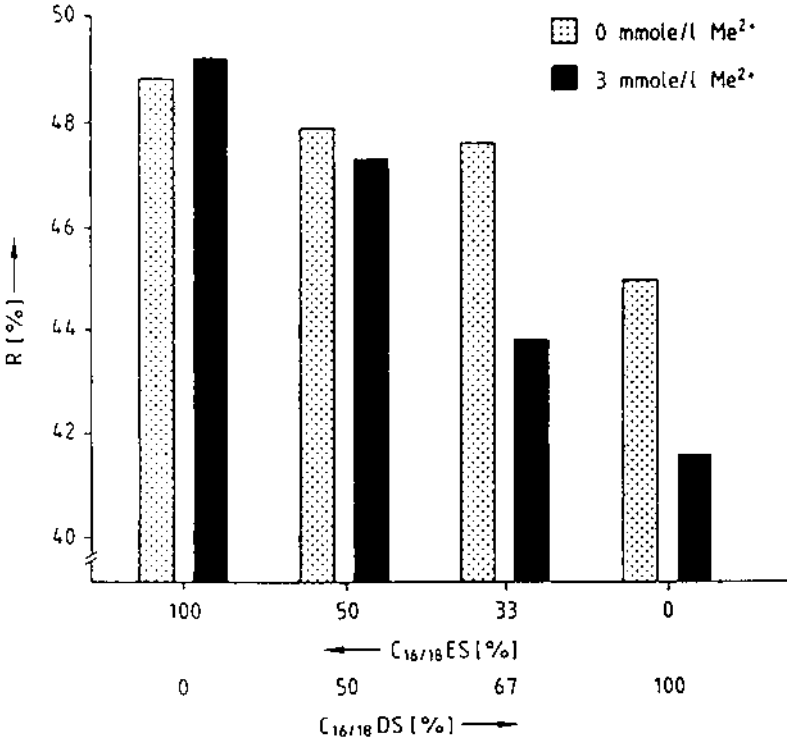

FIG. 10 Effect of the mixing ratio tallow α-ester sulfonate/tallow disalt and water hardness on detergency R for fabrics soiled with mineral oil (T = 60°C; 1 g/L surfactant). (From Ref. 59.)

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hardness is demonstrated by the increasing remission value in the presence of zeolite A. Part of the washing efficiency can be traced to the washing effect of the builder itself, as is shown by comparing the remission values in surfactant-free solutions (water in Figs. 8 and 9).

In mixtures of ester sulfonates and disalts the remission decreases as the content of disalts increases (Fig. 10). But small amounts of disalts do not have a strong negative effect on the detergency of the α-sulfo fatty acid esters [59].

IV. APPLICATIONS

The applications of α-sulfo fatty acid esters are widely spread as for other surfactants. They can be used in detergents, cleansers, and cosmetic products as well as in the building industry and for the production of synthetic materials and agrochemicals. The main properties for these applications are surface activity, wetting ability, hard water stability, lime soap dispersion power, and good human and environmental safety profiles.

A. Detergents

Powder and liquid detergents can be used in washing machines. The α-sulfo fatty acid esters are used in both product types, but their solubility in water has to be taken into account. In the United States, sodium α-sulfomethyl laurate is mainly used in liquid detergents, whereas in Europe, where powder detergents are widely distributed, α-sulfomethyl tallowate is more important [70].

In nearly all detergents a combination of different surfactants is used to optimize the properties. For example, the detergency of α-sulfonated fatty acid methyl esters and LAS is affected by water hardness in different ways. In soft water the detergency of LAS is good, but it decreases dramatically with increasing water hardness. On the other band, the ester sulfonates clean especially well in hard water but not so well in soft water. A mixture of the two surfactants ensures good detergency under both conditions. If an alcohol ethoxylate is added, the performance gets better. Therefore, the surfactant formulation of a heavy-duty liquid detergent may be 10% alkylbenzenesulfonic acid, 11.4% $C_{12–15}$ alcohol ethoxylate, and 11.4% α-sulfonated $C_{13.6}$ fatty acid methyl ester [70]. The viscosity of this formulation mixture is good even without alcohol or xylene sulfonate.

Because of the excellent hard water stability α-sulfonated fatty acid esters are suitable for the development of a phosphate-free detergent. The low sensitivity to water hardness is also the reason that the ester sulfonates, especially α-sulfomethyl tallow ester, have good washing properties in

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heavy-duty detergents even at low concentrations. In light-duty detergents the detergency is good for wool, especially at low concentrations [38].

When α-sulfo fatty acid esters are used as the major active component in detergents they can cause problems because of their foaming properties. In European horizontal drum-type automatic washers they produce too much foam, and in the rinse cycle of the American and Japanese pulsator-type washers the foam cannot be completely rinsed out [38]. The problem of inefficient rinsing can be solved by the addition of soap [71] or sulfonated unsaturated fatty acid esters [72]. For European applications, special foam inhibitors are needed.

Another property of the α-sulfo fatty acid esters, which is interesting for detergent formulations, is their lime soap dispersion power. Tallow soaps are unsuitable as detergents because of their inactivation due to the formation of lime soap in hard water. This lime soap tends to accumulate on fabrics and washing machine components, so that the absorbency of the fabrics and their permeability to air and the efficiency of the washing machines is reduced. Ester sulfonates are not only used to replace soaps as the active washing component in detergents but are also used in combination with soaps. In soap-based detergent formulations they work as a lime soap dispersion agent. The typical soap micelle with the hydrophobic part on the surface is changed by bivalent cations to an inverted phase with the hydrophobic part outside, which leads to separation of water-insoluble lime soap paste. In the presence of the lime soap dispersion agent the inversion of the micelles is prevented, possibly through formation of a mixed micelle in which the proper curvature is maintained by the bulky hydrophiles of the lime soap dispersion agent [73]. Calcium soaps stabilized by a surface adsorption of the dispersion agent could not be found [74].

Detailed studies with soap-based detergent formulations showed that the lime soap dispersion agents not only prevent the precipitation of lime soap curds in the washing and rinsing cycles but also improve the detergency of soap. Detergency can be further enhanced by the addition of small quantities of certain builders, like sodium tripolyphosphate, sodium silicate, sodium diglycolate, and sodium citrate. The quantities of the builders needed for the improvement are much below the level required to remove all of the calcium and magnesium ions in hard water [75].

A special application of α-sulfo fatty acid esters is for highly concentrated hard surface cleaners which are used after dilution in a pail of water. Normally hydrotropes are needed to increase the solubility of the surfactants in water and assure clear, homogeneous, and storage-stable products. If the LAS, which are typical surfactants in hard surface cleaners, are replaced by ester sulfonates, the hydrotrope can be deleted from the formula [70].

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A great number of detergent compositions using α-sulfo fatty acid esters are given in the patent literature. The α-ester sulfonates are major or minor components, besides other surfactants and builders [76–84]. Some examples of laundry and dishwashing detergents are given below.

A powdered soap–based laundry detergent contains 44% tallow soap, 18% sodium salt of α-sulfonated 1:1 methyl stearate–methyl palmitate mixture, 9% sodium silicate, 10% Na_2SO_4, 2.5% ethoxylated cocoethanolamide, 1.4% cellulose, 0.2% fluorescent whitener, 0.7% enzyme, 0.5% perfume, and 5% water [85].

A liquid detergent for dishes, vegetables, and fruit comprises the sodium salt of α-sulfo coconut acid ethyl ester (20%), an alkylamine oxide (5%), citric acid (0.5%), ethanol (50%), and water [86].

A soap-based powder can be produced in combination with ester sulfonates. Thirty-five percent of a sodium soap mixture (5% lauric acid, 5% myristic acid, 52% palmitic acid, 21% stearic acid, 12% oleic acid, and 5% linoleic acid) is mixed with 15% sodium α-sulfo palm oil fatty acid methyl ester, 3% lauric acid ethoxylate, 5% sodium silicate, 17% sodium carbonate, 20% $Na_2SO_4 \cdot 10H_2O$, and 5% water [87].

A phosphate-free detergent with excellent detergency and improved foaming and rinsing properties consists of 10% sodium α-sulfo hardened beef tallow fatty acid methyl ester, 10% sodium dodecyl sulfate, 5% α-sulfomyristic acid disodium salt, 10% zeolite, 10% sodium silicate, 10% sodium carbonate, 10% cellulose, 40% Flauber's salt, and 4% water [88].

A heavy granular detergent can be produced by mixing a detergent composition with powdered or granular sodium carbonate. A typical detergent comprises 8% sodium α-sulfo hardened palm oil fatty acid methyl ester, 2% di-Na α-sulfopalmitate, 10% Na coconut oil alcohol sulfate, 2% polyethylene glycol, 10% zeolite, 4% Na citrate, 3% water, 50% Na sulfate, and 10% granular Na carbonate [89].

For an enzyme-containing detergent the enzyme is added to a detergent composition with esters and disalts of α-sulfo fatty acids. The detergent granular comprises 7% sodium α-sulfo hardened palm oil fatty acid methyl ester, 5% disodium salt of α-sulfo hardened palm oil fatty acid, 10% sodium α-olefin ($C_{14–18}$) sulfonate, 10% zeolite, 5% sodium carbonate, 5% water, and 55% sodium sulfate [90].

The addition of an ester sulfonate of an unsaturated fatty acid improves the rinsing properties in washing tests. A mixture of 50% sodium methyl α-sulfostearate and 50% sodium salt of sulfonated methyl oleate (30:70 monosulfonate/polysulfonate ratio) was used [91].

A detergent imparting better flexibility to cotton cloth is produced by adding 1% sodium α-sulfo hardened tallow fatty acid methyl ester and 9%

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disodium α-sulfo hardened palm oil fatty acid to a mixture of 5% sodium *n*-dodecylbenzenesulfonate, 5% α-C_{16}-olefin sulfonate, 3% dimethyldistearylammonium chloride, 15% zeolite, 10% sodium silicate, 10% sodium carbonate, 2% soap, 35% $Na_2SO_4 \cdot 7H_2O$, and 5% water [92].

A liquid kitchen detergent especially for dishwashing is made of 20% alkyl ether sulfate, 6% α-sulfo fatty acid ethyl ester salt (from coconut oil), 4% dimethyllaurylamineoxide, 2% sodium octenyl succinate, and 68% water [93].

Alkali metal alkanesulfonates containing an average of 11–21 carbon atoms are used as viscosity regulators for highly concentrated α-sulfo fatty acid ester salt solutions (more than 30% surfactant), so that the detergent is flowable and pumpable [94].

B. Cosmetics

Generally speaking, up to now the importance of α-sulfo fatty acid esters in cosmetic products has been low [1, p. 367]. In the future they may become more interesting because of their mildness. α-Sulfomethyl laurate and most other ester sulfonates are mild to the skin; also, they are not human skin sensitizers or primary skin irritants. Tests have shown that α-sulfomethyl laurate is mild enough to be in bath products, such as bubble bath [70]. Three patents for different applications are given to show how ester sulfonates can be used in cosmetics.

Sodium α-sulfomethyl myristate is the major component of a clear, antiseptic, liquid cleanser especially for use on the skin. A disinfectant such as fluorophene, bithionol, *p*-chloro-*m*-xylenol, or hexachlorophene is added, along with a high-quality animal, vegetable, mineral, or synthetic oil and an alkyl ether of polyethylene glycol [95].

Sodium α-sulfomethyl myristate is used together with the sodium salt of hardened beef tallow fatty acid to produce a soap with little skin irritation [96].

Shampoos for application to hair as well as skin comprise α-sulfo fatty acid ester salts, fatty acid dialkanolamides, and citric acid. For example, a shampoo that consists of 15% sodium α-sulfoethyl myristate, 3% lauric acid diethanolamide, 0.5% citric acid, and 81.5% water is very effective even in hard water and only slightly irritating to the skin [97].

C. Agrochemical Additives

If agrochemicals are prepared as granules, surfactants can be used to support disintegration and spreading of the granules. Because of their good biodegradability and low phytotoxicity α-sulfo fatty acid esters are

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well suited as agrochemical additives. It was shown that the ratio of bentonite, which was used together with talc as the carrier and binder, and is more expensive than talc, could be decreased if α-sulfo fatty acid esters were used instead of LAS [38]. The spreading properties of the ester sulfonates are good, especially in bard water, so that it can be expected that they may be developed not only as additives for formulations but as spreading agents in the near future [38]. Agrochemical granules with sodium methyl α-sulfomyristate show better disintegrating properties than granules containing sodium lignin sulfonates [98]. An example of pesticide granules containing ester sulfonates is given in the patent literature: 7% chloromethoxynyl, 18% bentonite, 2% Toxanone GR-30, 2% Sanex P-252 (a binder), 0.05% sodium methyl a-sulfolaurate, and 70.95% calcium carbonate are mixed with water, pressed through a screen (pore diameter = 0.9 mm), and dried to give 14- to 32-mesh granules [99].

D. Additives for Synthetic Materials

There are same applications for α-sulfo fatty acid esters in the production and processing of synthetic materials or natural rubber. Emulsifiers are needed for the emulsion polymerization, antistatic agents improve the properties of polymers, and wetting agents are needed as parting components for elastomers.

An example of an emulsifier for the polymerization of ethylenically unsaturated monomers is a 22:88 mixture of disodium α-sulfolaurate and sodium methyl α-sulfolaurate. The emulsion is stable for much longer than an emulsion with *n*-dodecylbenzenesulfonate as the emulsifier [100]. Ester sulfonates are also used as emulsifiers in the continuous manufacture of vinyl chloride polymers [101].

Polymer films can be made antistatic with α-sulfonated fatty acid salts and esters [102]. For example, an antistatic additive for polypropylene manufacture can be prepared from potassium methyl α-sulfopalmitate, styrene oligomer, and 2-propanol [103]. The treatment of synthetic fibers and fabrics with α-sulfocarboxylic esters makes the material antistatic and imparts smoothness and softness to the fibers. The antistatic agents can be applied from mineral oil emulsions or from aqueous solutions and are easily removed by washing [104].

Amine salts of α-sulfonated fatty acids and esters are also used as antistatic agents. Mixtures of alkyl α-sulfo fatty acid ester diethanolamine salts and hexadecyl stearate or butyl stearate are coated onto nylon yarn after fiber formation and before stretching [105]. Polypropylene can be made antistatic with an amine salt of α-sulfolauric acid [$C_{10}H_{21}CH(SO_3Na)$-$COO^{-}\cdot{}^{+}NH(CH_2CH(OH)CH_3)_3$] [106]. Pieces of natural and synthetic rub-

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ber tend to be self-bonding. If the material is immersed in a wetting agent a film is formed on the surface and parting can occur without breakage. Good wetting agents for rubber are the 1,2-propanediamine salt [107] and the *N*-methyl-l,3-propanediamine salt [108] of methyl α-sulfo palm oil fatty acid ester. The ammonium salt is not useful because of poor wetting.

E. Additives for Road and Building Materials

Salts of α-sulfo fatty acid esters can work as emulsifying agents for the preparation of asphalt emulsions and asphalt-latex emulsions. The ester sulfonates improve the storage stability of the emulsions [109,110]. In the manufacture of lightweight gypsum products air bubbles have to be mixed into the slurries. The use of salts of sulfonated $C_{10–18}$ fatty acid alkyl esters as foaming agents produces uniformly distributed fine bubbles [111]. Salts of $C_{10–16}$ fatty acid alkyl ester sulfonates can also be added to cement mixtures to prevent slump loss of the mixtures [112].

V. ANALYTICAL METHODS

A. Separation from Detergent Mixtures

The analytical methods for α-sulfo fatty acid esters reported in the literature deal with the determination of the surfactants in different matrices like detergents or product mixtures from the fabrication. The methyl esters of α-sulfo fatty acids can be separated from a mixture of different surfactants together with sulfonated surfactants by adsorption on an anionic exchanger resin such as Dowex 1X2 or 1X8. Desorption from the exchanger resin is successful with sodium hydroxide (2%) in a 1:1 mixture of isopropanol and water [113].

For a further separation of the sulfonated surfactants the latter are heated for 4 h with 2 N HCl. The methyl ester sulfonates are split into methanol and α-sulfo fatty acids, which form disodium salts after neutralization with NaOH. The product mixture from acid hydrolysis can be separated by extraction with petroleum ether. For example, the fatty alcohols formed from fatty alcohol sulfoacetates are soluble in the petroleum ether phase whereas the disalts of the ester sulfonates remain in the water phase. The saponification of the α-sulfo fatty acid esters with 2 N alcoholic potash lye leads to an extensive decomposition of the fatty acids [113].

B. Gravimetric and Volumetric Methods

Gravimetric and volumetric methods are practicable for the quantitative determination of the α-sulfo fatty acid esters. Using gravimetric methods

the surfactant is precipitated with *p*-toluidine or barium chloride [113]. The volumetric determination method is two-phase titration. In this technique different titrants and indicators are used. For the analysis of α-sulfo fatty acid esters the quaternary ammonium surfactant hyamine 1622 (*p*,*t*-octylphenoxyethyldimethylammonium chloride) is used as the titrant [114]. The indicator depends on the pH value of the titration solution. Titration with a phenol red indicator is carried out at a pH of about 9, methylene blue is used in acid medium [114], and a mixed indicator of a cationic (dimidium bromide) and an anionic (disulfine blue VN150) dye can be used in an acidic and basic medium [113].

The amount of the ester sulfonates, besides the mono- and disalt of the α-sulfo fatty acid, can be calculated by two titrations, one in the acid and one in the basic range. In the basic range both sulfonates and carbocylate functionalities are negatively charged and titrated with the cationic surfactant hyamine. In acid medium the RCOOH group is protonated and no longer available for the titration. Since hyamine-methylene blue (acid conditions) titrates only sulfonate and hyamine-phenol red (basic conditions) determines both sulfonates and carbocylates, subtractions of the titration value with phenol red from the double value of the titration with methylene blue yields only the α-sulfo fatty acid ester. This is the only species of the three that has merely the sulfonate function [114]. Instead of using an indicator, an ion-sensitive electrode can be used. An aqueous solution is titrated potentiometrically against 0.04 N hyamine 1622 solution using a nitrate ion–selective electrode and a silver/silver chloride reference electrode [114].

C. Chromatographic Methods

Besides the calculation of the different sulfonated species, it is also possible to determine them directly by chromatographic methods. Separation of the ester sulfonate and the disodium salt is achieved by thin-layer chromatography on silica gel plates. With a solvent mixture of acetone and tetrahydrofuran (90:10 v/v), the disodium salt stays at the start whereas the ester sulfonate has an R_f value of 0.2. With the more polar solvent 0.1 N H_2SO_4 + methanol + chloroform, the ester sulfonate and the disalt have R_f values of 0.36 and 0.14. For visualization, the plate is sprayed with pinacryptol yellow. In UV light (254 and 366 nm) the ester sulfonate is detected by its yellow color. Semiquantitative results can be obtained by using standard samples of known amounts of ester sulfonate and a visual comparison [115].

Another chromatographic method is pyrolysis/gas–liquid chromatography. The sample is mixed with P_2O_5 and heated to 400°C. This technique yields the chain length distribution of the fatty acids initially used [115].

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Finally, ion chromatography can be used to determine the α-sulfo fatty acid esters. The chromatographic column is a nonpolar polystyrene/divinylbenzene column and the ion pair reagent is 0.005 M ammonia. In order to reduce the elution time, acetonitrile is added as a modifier with increasing concentration. This gradient technique makes it possible to simultaneously separate ester sulfonates and disalts by chain length. Determination is achieved by standards with defined chain length [115].

A new technique for the determination of anionic surfactants in mixtures is the on-line coupling of high-performance liquid chromatography (HPLC) separation and ion pair formation with fluorescent counterions [116]. Extraction of the ion pair formed by the addition of a cationic dye to the HPLC column effluent is performed on line by the further addition of an immiscible apolar organic solvent and the application of a continuously operating phase separator. A fluorescence detector is used for detection purposes. In contrast to conventional HPLC detectors, such as conductivity or refractive index detectors, this system performs well under gradient elution conditions. Separation is performed with a reversed-phase column and a mobile phase of two components. Component A is an aqueous mixture of hypochloric acid and trisodium citrate dihydrate and component B also contains acetonitrile. For the mobile phase gradient the amount of component B is increased from 20% to 100% in 20 min. 1-Cyano-[2-(2-trimethylammonio)ethyl]-benz(f) isoindole (CTBI) is used as a fluorescent cationic dye, added for ion pair formation. As an example, the separation and detection of the sodium salts of α-sulfomethyl palmitate and α-sulfomethyl stearate have been shown, besides the disodium salts of the corresponding fatty acids [116].

D. Spectroscopic Methods

The identification of α-sulfo fatty acid esters can also be performed by spectroscopic methods. The IR spectrum of sodium α-sulfomethyl palmitate shows characteristic absorption bands of the alkyl chain at 3.42 μm (2924 cm^{-1}) and 3.5 μm (2857 cm^{-1}) (CH stretching), at 6.85 μm (1460 cm^{-1}) (CH deformation), and at 13.95 μm (717 cm^{-1}) (δCH out of plane). The CO stretching mode of the ester appears at 5.8 μm (1724 cm^{-1}), and the stretching modes of the sulfonate group appear at 8.25 μm (1212 cm^{-1}), 9.5 μm (1053 cm^{-1}), and 11.8 μm (848 cm^{-1}) [113].

In the NMR spectrum of sodium α-sulfomethyl palmitate the protons of the different methyl groups can be distinguished [113]:

0.9 ppm	CH_3 group at the end of the alkyl chain
1.3 ppm	CH_2 groups in the neighborhood of other CH_2 groups
~2 ppm	CH_2 group in the neighborhood of the $CH(SO_3^-)$ group

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3.8 ppm CH group in the neighborhood of the carboxylic and sulfo groups together with the ester group

VI. ENVIRONMENTAL PROPERTIES

Since the α-sulfo fatty acid esters became more interesting in the 1960s and 1970s, investigations into the biological and environmental behavior of these surfactants were also carried out [117–120]. All of these studies show that the ester sulfonates have good to excellent properties concerning their use in cosmetics and detergents and concerning biodegradation.

More detailed investigations into biodegradation have been performed since the mid-1980s. The methyl esters of the α-sulfo fatty acids with an alkyl chain length of 12–18, which are mainly used in commercial products, have a high primary and ultimate biodegradability [121–123]. Primary biodegradation can be measured as the loss of methylene blue active substance (MBAS) and the ultimate biodegradation as the removal of the dissolved organic carbon (DOC). The test conditions are defined in different standards, like the MBAS loss in the OECD screening test [121], or the Japanese Industrial Standards [123,124], the shake culture method of the Japanese Industrial Standards [123,124], the river die-away test [123,124], or the MITI test [123,124]. A modified OECD confirmatory test system provides very practical results using a sewage treatment model plant [121]. It is shown by a model test using a radiolabeled C_{18} ester sulfonate that the very high elimination of surfactant-derived organic carbon in sewage plant simulation tests is due to the ultimate biodegradation of the compound. Thus, elimination without degradation, e.g., due to adsorption on the activated sludge, is of no importance [111]. Investigations with ^{14}C-labeled substances can also be used to identify the biodegradation pathways of the α-sulfo fatty acid methyl esters [122,124]. Microbial attack on the surfactant molecule starts with ω-oxidation to form a carboxyl group. Degradation continues with β oxidation, removing two carbon atoms at a time, to form a temporary intermediate, the monomethyl α-sulfosuccinate. The next steps are the loss of the sulfo and ester groups. Desulfonation is assumed to take place prior to the scission of the methyl ester bond since this bond is chemically very stable on account of the α-sulfo substitution. Ultimately, the final metabolism of desulfonated carboxylic intermediates may proceed quickly and quantitatively, leading to a high degree of mineralization and biomass production. These investigations with labeled molecules and a test for recalcitrant metabolites indicate that no problematic intermediates are formed [121].

The acute toxicity of ester sulfonates is mainly related to the length of the carbon chain of the fatty acid. The acute fish toxicity of tallow-based ester sulfonates is relatively high (LC_0 = 0.4–0.9 mg/L) compared with coconut-

based ester sulfonates ($LC_0 \sim 46$ mg/L) [121]. In spite of this relatively high fish toxicity of the long-chain ester sulfonates both acute and long-term toxic effects can be excluded for normal environmental conditions. For example, the sum of all anionic surfactants in German rivers is stable on a level far below 0.1 mg/L. In addition, the primary degradation of the ester sulfonates is so fast that an accumulation of acute toxicity is not expected [121].

In a continuous model river test system it can be shown that after passage through a sewage treatment plant ester sulfonates have no significant influence on the qualitative and quantitative composition of the biocenosis of a receiving water [121]. All of the investigations into the environmental rate of α-sulfo fatty acid esters demonstrate that aquatic toxicity is alleviated by their fast ultimate biodegradability, which allows them to be classified as environmentally compatible.

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14

Methyl Ester Ethoxylates

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I. INTRODUCTION

More than 2 million metric tons of ethylene oxide–derived surfactants is consumed worldwide each year [1]. It is produced by more than 150 different ethoxylators located in almost every developed country in the world.

The high consumption figure of ethylene oxide–derived surfactants is due to several factors: the surfactants are relatively easy to manufacture, they are relatively inexpensive, and they can be derived from a variety of hydrophobic feedstocks, including oleochemical- and petrochemical-based alcohols, and petrochemical-based alkylphenols and alkylamines. Because their hydrophobe and hydrophile chain lengths can be varied significantly, they fit a wide range of applications.

Historically, ethylene oxide–derived surfactants have been produced from hydrophobic feedstocks which contain an "active," or labile, hydrogen, a hydrogen that is connected to a heteroatom such as oxygen or nitrogen. For alcohols, this active hydrogen atom is readily removed with base to form a reactive anion which then reacts quickly and efficiently with ethylene oxide to form the ethoxylate. For amines, the active hydrogen atom is easily rearranged from the nitrogen to the oxygen during reaction with ethylene oxide to form the ethoxylate.

In 1989, the concept of ethoxylating methyl esters, which do not carry a labile hydrogen, was introduced by Hoechts [2] and Henkel [3]. Hoechst demonstrated the ethoxylation of esters was chemically feasible using catalysts based on alkali and alkaline earth metals (e.g., sodium hydroxide, sodium methoxide, barium hydroxide, etc.). Henkel demonstrated the feasibility of using calcined hydrotalcite (aluminum-magnesium hydroxycarbonates) for the reaction. Reactivities and conversions with these catalysts, however, were found to be too low for commercial application.

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In 1990, Vista Chemical Company (now Sasol North America Inc.) developed a commercially viable process based on more complex alkoxylation catalysts (activated calcium and aluminum alkoxides) that effectively and efficiently achieved the ethoxylation of esters [4]. Soon after, Lion demonstrated that magnesium oxide–based catalysts also worked well [5]. These discoveries opened the door to ester alkoxylate development and have led to a flurry of research directed at understanding and utilizing these materials, most notably methyl ester ethoxylates [6–23].

Henkel has also demonstrated that acceptable reactivities and conversions can be achieved with hydrotalcite when cocatalysts such as ethylene glycol, fatty acids, standard alkali catalysts, etc., are used [24,25].

It is important to note that methyl ester ethoxylates have been produced, primarily for the textile industry, for several years. They have been manufactured by condensing fatty acids with monomethyl-capped polyethylene glycol. This reaction, however, is more complex and more costly than direct ethoxylation [26].

Methyl ester ethoxylates are similar in structure to conventional alchol ethoxylates, but the structural differences that do exist have an important impact on their performance. As shown in Fig. 1, methyl ester ethoxylates contain an ester linkage at the hydrophobe–hydrophile boundary of the molecule in place of the ether linkage in alcohol ethoxylates. This ester linkage sterically constrains the molecule, which reduces the tendency of the surfactant to micellize and leads to a higher critical micelle concentration

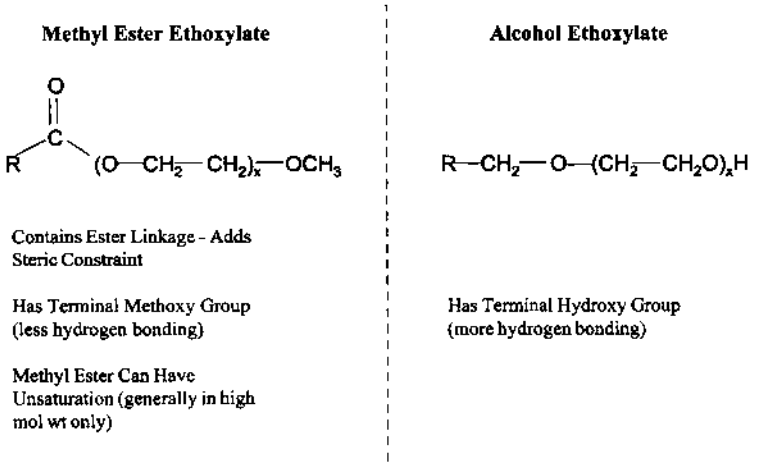

FIG. 1 Methyl ester ethoxylates vs. alcohol ethoxylates: differences in molecular structure.

(CMC). Methyl ester ethoxylates also carry a terminal methoxy group in place of a terminal hydroxyl group. This reduces the hydrogen bonding of the surfactant, which in turn reduces water solubility and the tendency to form aqueous gels.

Also, unlike most alcohols, methyl esters can have a significant level of unsaturation. The degree of unsaturation varies depending on the oleochemical source of the feedstock, and the carbon chain length. In general, the higher the carbon chain length, the higher the degree of unsaturation. The impact of unsaturation on performance is addressed later in this chapter.

Another important characteristic of methyl ester ethoxylate structure is the distribution of the ethoxymers (the relative concentration of unethoxylated feedstock, of 1-mol ethoxymer, of 2-mol ethoxymer, etc.). As discussed later in this chapter, the ethoxymer distribution of methyl ester ethoxylates, like that of their alcohol ethoxylate counterparts, can vary depending on the catalysts used to prepare them.

Large quantities of methyl esters are currently produced from oleochemical sources (Fig. 2). Their major use is as intermediates in the production of fatty alcohols. They can also be produced through esterification of fatty acids with methanol. It is safe to assume that commercial quantities of methyl esters could be made readily available as ethoxylation feedstocks for methyl ester ethoxylates.

This chapter first examines the ethoxylation of esters and the composition of methyl ester ethoxylates. Important aspects related to the formulation of

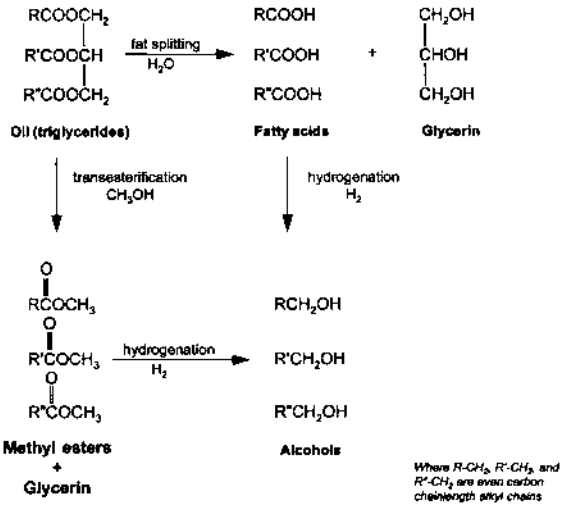

FIG. 2 Major oleochemical routes for making alcohols.

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liquid detergents with methyl ester ethoxylates are then discussed, followed by a review of the performance properties of methyl ester ethoxylates, and a brief discussion of the use of methyl ester ethoxylates in household and industrial detergents. The ethoxylation of other types of esters, the propoxylation of esters, and the impact of unsaturation on performance are also briefly discussed.

II. ETHOXYLATION OF ESTERS

Ethoxylation of methyl esters using conventional hydroxide catalysts (NaOH, KOH, etc,) does not proceed efficiently because of the absence of an active hydrogen. As shown in the chromatograrm of the resulting ethoxylate (Fig. 3A), conversion is poor, and the product contains a broad distribution, of ethoxymers as well as significant concentration of unethoxylated methyl esters.

In contrast, ethoxylation of methyl esters with a more complex catalyst system (activated calcium and aluminum alkolide [27]) is significantly more successful in achieving efficient ethoxylation, reducing the level of unethoxylated methyl ester, and yielding a more "peaked" distribution of ethoxymers (Fig. 3B).

These proprietary catalysts are more expensive because they must be manufactured rather than simply purchased. Certain catalysts must also be removed from the finished ethoxylate via filtration in order to obtain a clear, transparent ethoxylate. On the other hand, complex catalysts can be significantly more reactive than hydroxide catalysts so that the ethoxylation reaction proceeds in less time, with less catalyst, and at lower temperatures. Ethoxylation with complex catalysts is accomplished via conventional ethoxylation equipment and procedures.

The mechanism of the ethoxylation of esters with these complex catalysts is not well understood. It is thought to involve a transesterification which effectively inserts ethylene oxide into the ester linkage between the carbonyl carbon and the methoxy oxygen [9,15,18]. This mechanism is illustrated in Fig. 4. As shown, the active catalyst (calcium and aluminum alkoxyethoxylate) first reacts with ethylene oxide to form the ethoxylated version of the metal alkoxythoxylate. This molecule then transesterifies with methyl ester to form the alkyl ester ethoxylate and a metal-coordinated methoxide ion. Addition of more ethylene oxide (step 2) produces progressively more highly ethoxylated versions of the metal-coordinated methoxide ions, which then transesterify with the ester (step 3) to form methyl ester ethoxylate, the alkyl ester ethoxylate, and the metal-coordinated methoxide. Steps 2 and 3 occur continuously with the addition of more ethylene oxide until excess methyl

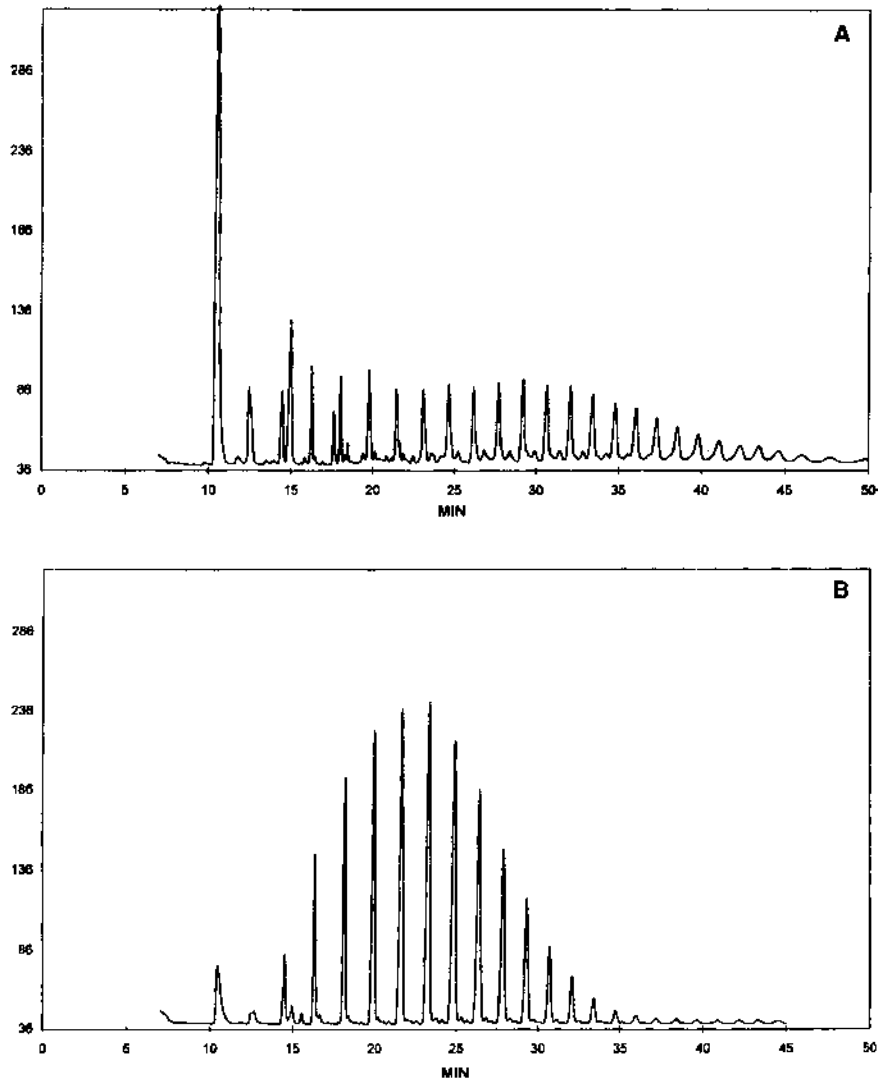

FIG. 3 (A) Ethylene oxide distribution (via supercritical liquid chromatography) of C_{14} methyl ester ethoxylate obtained with conventional (NaOH) catalyst. (B) Ethylene oxide distribution (via supercritical liquid chromatography) of C_{14} methyl ester ethoxylate obtained with Ca/Al-alkoxide catalyst. (From Ref. 27.) (C) Ethylene oxide distribution (via supercritical liquid chromatography) of C_{14} alcohol ethoxylate obtained with conventional (NaOH) catalyst. (D) Ethylene oxide distribution (via supercritical liquid chromatography) of C_{14} alcohol ethoxylate obtained with Ca/Al-alkoxide catalyst. (From Ref. 27.)

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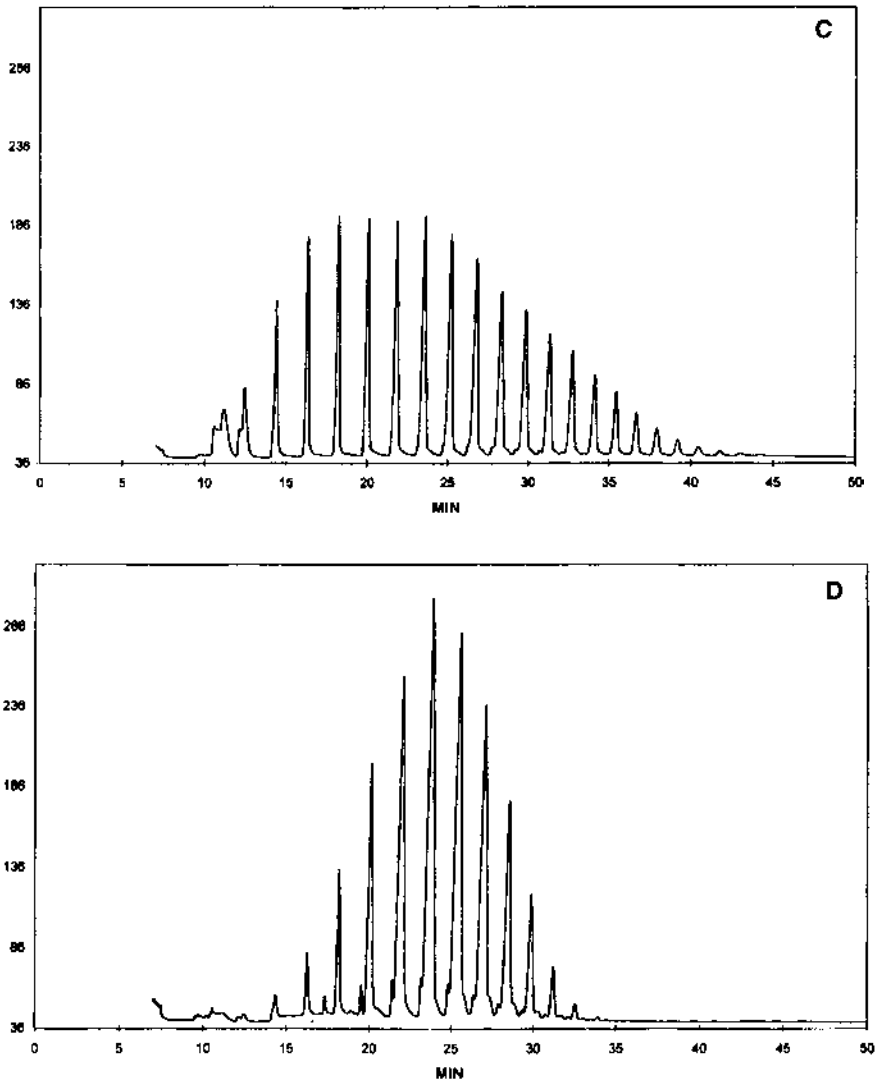

FIG. 3 (Continued)

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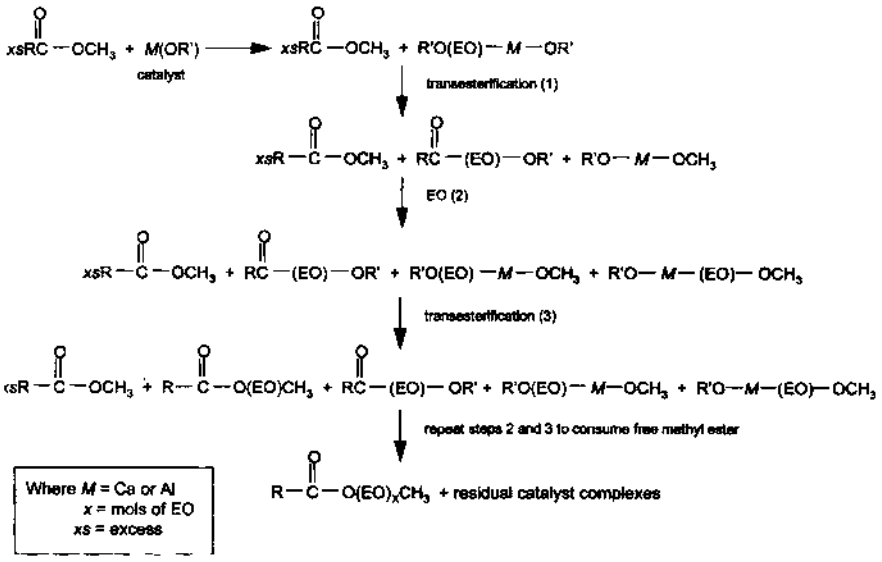

FIG. 4 Proposed mechanism for the alkoxylation of methyl ester ethoxylates.

ester is consumed. This results in a distribution of methyl ester ethoxylates containing a small concentration of residual catalyst complexes.

Few studies have yet been published which investigate this ethoxylation mechanism in detail. Hama, however, has investigated the impact of catalyst structure on catalyst activity and product composition for magnesium oxide–based catalysts [12].

Variations in methyl ester purity or composition (unsaturation, carbon chain length distribution, etc.) do not appear to influence the ethoxylation reaction or overall ethoxylate quality. The purity of the methyl ester, however, does appear to impact color. A yellow-tinted methyl ester logically yields a yellow-tinted ethoxylate.

III. COMPOSITION OF METHYL ESTER ETHOXYLATES

Ethoxylates can be prepared from any methyl ester. Normally, methyl esters are derived from oleochemical sources, and the carbon chain length distribution and the level unsaturation can vary significantly depending on the specific feedstock used and the quality of the distillation process employed.

The distribution of methyl ester ethoxymers (the relative concentrations of unethoxylated feedstock, of 1-mol ethoxylate, of 2-mol ethoxylate, etc.)

depends on the catalyst and conditions used. A calcium/aluminum alkoxide catalyst [16] yields ethoxymer distributions which fall between what is typically considered conventional or "broad" (the ethylene oxide chain distribution of alcohol ethoxylates produced with conventional alkali hydroxide catalysts) and what is considered "peaked" or "narrow range" (the ethylene oxide chain distribution of alcohol ethoxylates produced with calcium and aluminum alkoxide catalysts). Figure 3A–D illustrates ethoxymer distributions in C_{14} linear, primary alcohol ethoxylate, and C_{14} methyl ester ethoxylate produced with a conventional sodium hydroxide catalyst and with a calcium/aluminum alkoxide catalyst. As shown, sodium hydroxide effectively ethoxylates the alcohol but is relatively less effective in the ethoxylation of the methyl ester. In contrast, the complex catalyst can effectively ethoxylate

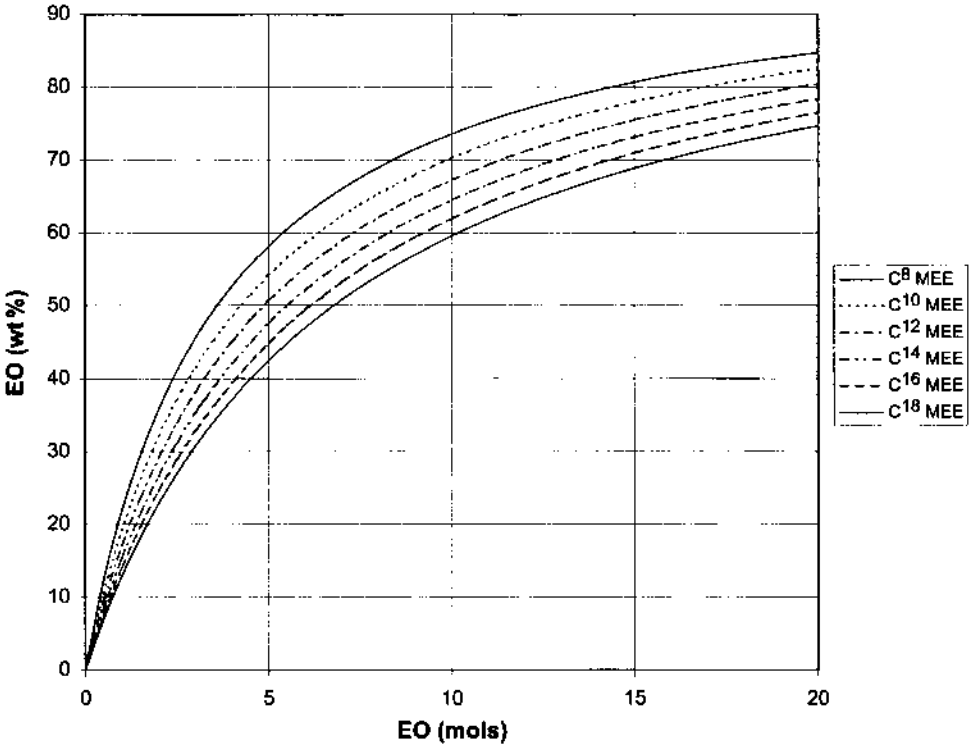

FIG. 5 Relationship between moles EO and wt % EO for C_8, C_{10}, C_{12}, C_{14}, C_{16}, and C_{18} methyl ester ethoxylate:

$$\text{Wt \%} = \frac{(\text{mols EO})(44) \times 100}{[(\text{mols EO})(44) + (\text{mol wt of ME})]}$$

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either feedstock, although the degree of peaking achieved with the methyl ester is less than that achieved with fatty alcohol.

Hama has demonstrated that magnesium oxide catalysts can be used to produced both broad and peaked methyl ester ethoxylates [13]. The impact of peaking the ethoxymer distribution of methyl ester ethoxylates has also been studied by Hama [13]. He demonstrated that increased peaking reduces the tendency of the ethoxylate to form gels, reduces inverse cloud point (which is noteworthy since the opposite trend is observed with alcohol ethoxylates), improves wetting performance, and reduces foaming. The degree of peaking was also found to affect surface tension reduction. While a broad distribution yields low surface tension over a relatively broad range of ethylene oxide levels, a peaked methyl ester ethoxylate can provide even lower surface tension values, but if the ethylene oxide content is optimized.

Another feature that differentiates methyl ester ethoxylates from alcohol ethoxylates in unsaturatinon. Methyl esters, particularly those in the tallow range, are relatively highly unsaturated, generally more than 50%. Alcohols, in contrast, are typically fully saturated. The impact of unsaturation on performance can be significantly, and is addressed in the last section of this chapter.

As with all ethoxylates, the relationship between mols of and weight-percent of ethylene oxide is nonlinear for methyl ester ethoxylates. This relationship is also slightly different from that for the corresponding alcohol ethoxylate because of the difference in molecular weight between the feedstocks. The relationship between mols and weight-percent ethylene oxide for various methyl ester, ethoxylates is shown in Fig. 5.

IV. FORMULATES DETERGENTS WITH METHYL ESTER ETHOXYLATES

A. Water Solubility

The relationship between water solubility and the degree of ethoxylation (polyethylene oxide chain length) is well understood for alcohol ethoxylates. When the degree of ethoxylation is expressed as average weight percent, an alcohol ethoxylate is generally water soluble if the ethylene oxide content averages more than 50%. At an average ethylene oxide content of 50%, alcohol ethoxylates are generally considered borderline water soluble.

Methyl ester ethoxylates, however, are inherently less water soluble than their alcohol ethoxylate counterparts because they contain a terminal methoxy group in place of the more hydrophilic hydroxyl group. Consequently, it takes a higher degree of ethoxylation for methyl ester ethoxylates to achieve water solubility. Although it is difficult to determine the precise ethoxylation level needed to achieve water solubility, studies suggest that methyl ester

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ethoxylates require at least 55 wt % of ethylene oxide to achieve borderline water solubility. Addition of more ethylene oxide to the polyethylene oxide chain logically increases water solubility. Each mole of ethylene oxide has less of an impact on solubility than the alcohol ethoxylates, as illustrated in Fig. 6.

Figure 6 compares the inverse cloud point temperatures (temperature at which 1% aqueous ethoxylate solutions cloud,as temperature is increased) as a function of average ethylene oxide content for $C_{12–16}$ alcohol ethoxylates and $C_{12–16}$ methyl ester ethoxylates. Methyl ester ethoxylates generally give inverse cloud point temperatures that are roughly 10°C lower than those of their alcohol ethoxylate counterparts. Although the desired inverse cloud point temperature can be obtained by adding additional ethylene oxide to the methyl ester, the amount of ethylene oxide required depends on the target inverse cloud point. For example, to achieve a cloud point of about 45°C, a

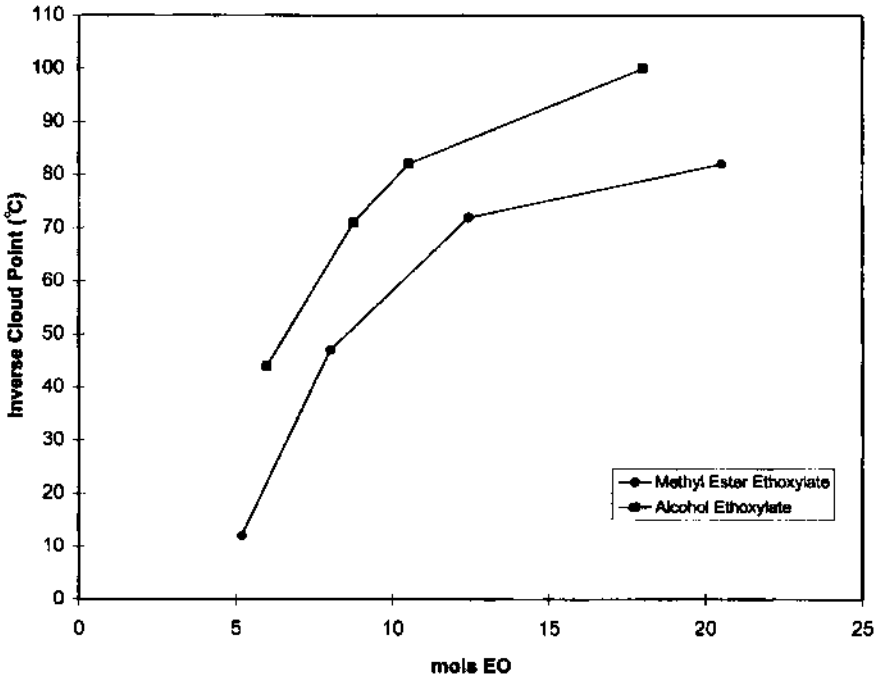

FIG. 6 Water solubility (inverse cloud point temperature) as a function of EO content (moles) for $C_{12–16}$ alcohol and methyl ester ethoxylates made with Ca/Al-alkoxide catalyst. (Cloud point temperature = temperature at which 1% aqueous solution turns cloudy upon slow heating; $C_{12–16}$ alcohol ethoxylate is described in Table 1; distribution of methyl ester = 9% C_8, 8% C_{10}, 46% C_{12}, 18% C_{14}, 9% C_{16}, and 10% C_{18}.) (From Ref. 27.)

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$C_{12–16}$ methyl ester ethoxylate requires about two additional moles of ethylene oxide compared to a $C_{12–16}$ linear alcohol ethoxylate. To obtain an inverse cloud point of 80°C, approximately eight additional moles of ethylene oxide would be needed.

In practice, inverse cloud point temperature is used more as a quality control measure rather than as a solubility requirement. Although methyl ester ethoxylates are less water soluble than their alcohol ethoxylate counterparts, they can achieve comparable formulatability characteristics at somewhat higher ethylene oxide levels.

Water solubility is affected by carbon chain length. A shorter carbon chain length results in greater water solubility (higher inverse cloud point temperatures) unless the level of ethylene oxide is unusually high [14,16]. At high ethylene oxide levels, the impact of carbon chain length is effectively nullified because solubility is almost entirely controlled by the long polyethylene oxide chain.

B. Viscosity/Gel Formation

Alcohol ethoxylates tend to form gels in the preparation of aqueous solutions. These gels readily form as ethoxylate concentration, average ethylene oxide content, and ionic strength are increased and as temperature is decreased. To destroy them can require substantial mechanical mixing and sometimes heat.

Methyl ester ethoxylates have been shown to have a significantly reduced tendency to form gels [9,16]. For example, the viscosity behavior of a commonly used 7-mol lauryl-range ethoxylate (based on a modified oxo-type $C_{12–15}$ alcohol) is illustrated in Fig. 7. Gross viscosity was examined as a function of concentration and ionic strength (sodium chloride concentration) at 10, 25, and 40°C. As illustrated, gels (shown in black in Fig. 7) form readily, particularly at room temperature and below.

Figure 8 shows the gross viscosity behavior for a comparable methyl ester ethoxylate. The lesser tendency of methyl ester ethoxylate to form highly viscous solutions and gels is related to structural difference between the two ethoxylates. Methyl ester ethoxylates lack a terminal hydroxyl group which can participate in forming more structured liquids via hydrogen bonding. Methyl ester ethoxylates also have an ester linkage which increases steric constraint and reduces the ability of the surfactant to form complex structures in solution.

For formulating liquid products, absence of gel formation is an advantage. Since methyl ester ethoxylates do not normally require passing through a gel stage, they dissolve more rapidly. Methyl ester ethoxylates may also be useful in reducing the gelling of aqueous solution of other ethoxylates, such as alcohol ethoxylates and alcohol ether sulfates.

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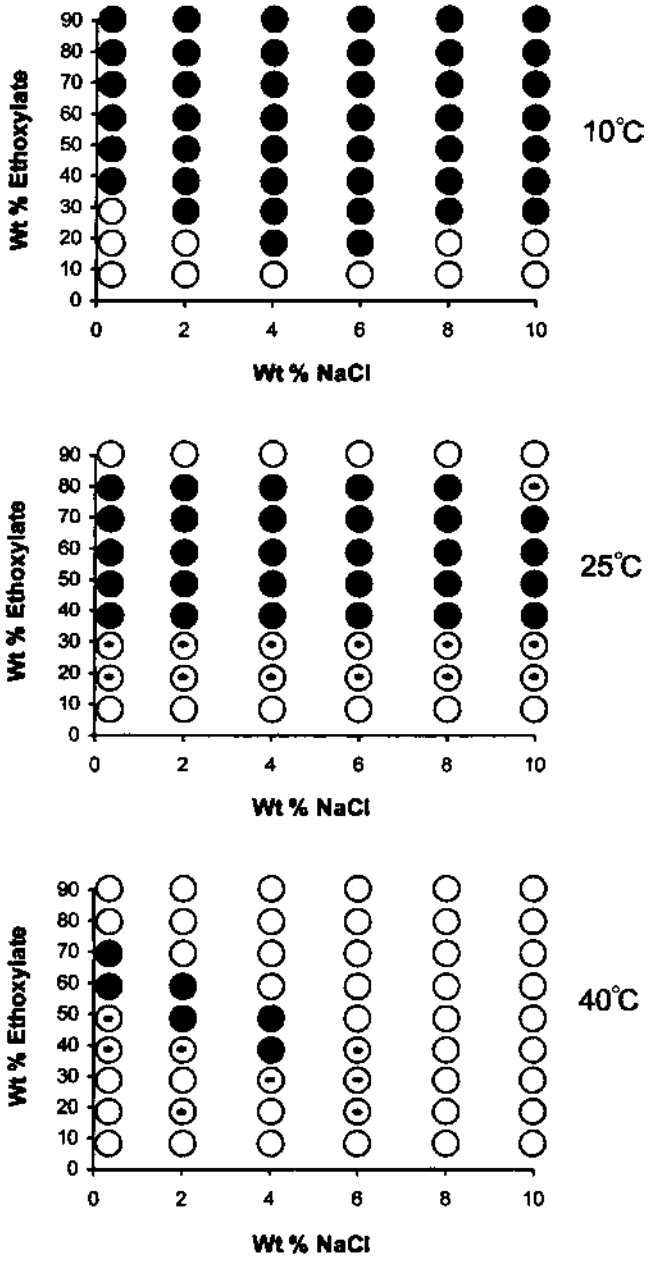

FIG. 7 Gel boundary diagram for C_{12-15} 7-mol modified-oxo-type alcohol ethoxylate at 10, 25, 40°C. ○, low-viscosity liquid; ⊙, high-viscosity liquid; ●, gel.

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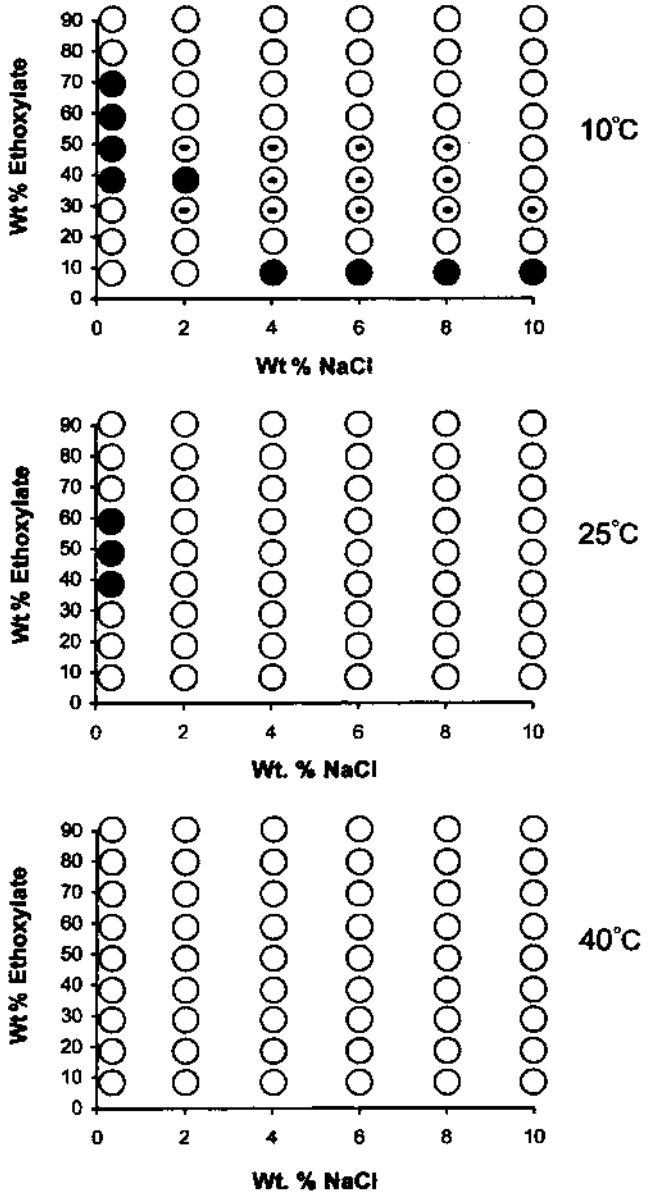

FIG. 8 Gel boundary diagrams for $C_{12–16}$ 7.5-mol average methyl ester ethoxylate prepared using Ca/Al-alkoxide catalyst at 10, 25, and 40°C. (Distribution of methyl ester = 9% C_8, 8% C_{10}, 46% C_{12}, 18% C_{14}, 9% C_{16}, and 10% C_{18}. ○, low-viscosity liquid; ⊙, high-viscosity liquid; ●, gel. (From Ref. 27.)

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Even at a lessened tendency to gel formation, methyl ester ethoxylates are influenced by the same compositional factors as other ethoxylates. As shown in Figs. 9 and 10, increasing carbon chain length and ethylene oxide content increases their tendency to form gels.

C. Chemical Stability

The presence of an ester linkage makes methyl ester ethoxylates susceptible to base hydrolysis unlike their alcohol ethoxylate counterparts. Studies reported elsewhere concluded that aqueous solutions of methyl ester ethoxy-

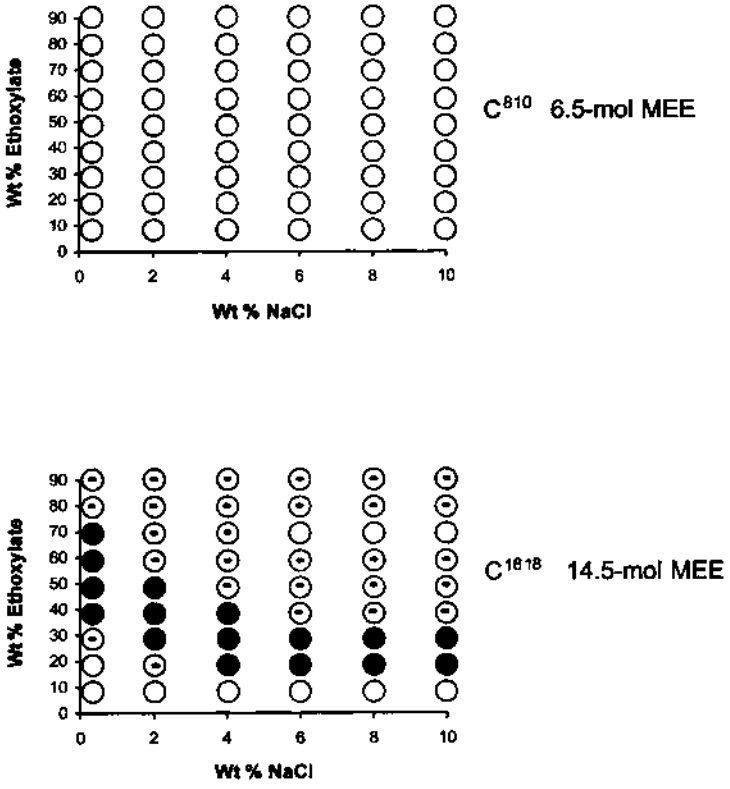

FIG. 9 Gel boundary diagrams for $C_{8–10}$ and $C_{12–16}$ methyl ester ethoxylates prepared using Ca/Al-alkoxide catalyst at 25°C. (Distribution of $C_{8–10}$ methyl ester = 4% C_6, 53% C_8, and 43% C_{10}; distribution of $C_{12–16}$ methyl ester = 57% C_{12}, 23% C_{14}, 12% C_{16}, and 8% C_{18}.) ○, low-viscosity liquid; ⊙, high-viscosity liquid; ●, gel. (From Ref. 27.)

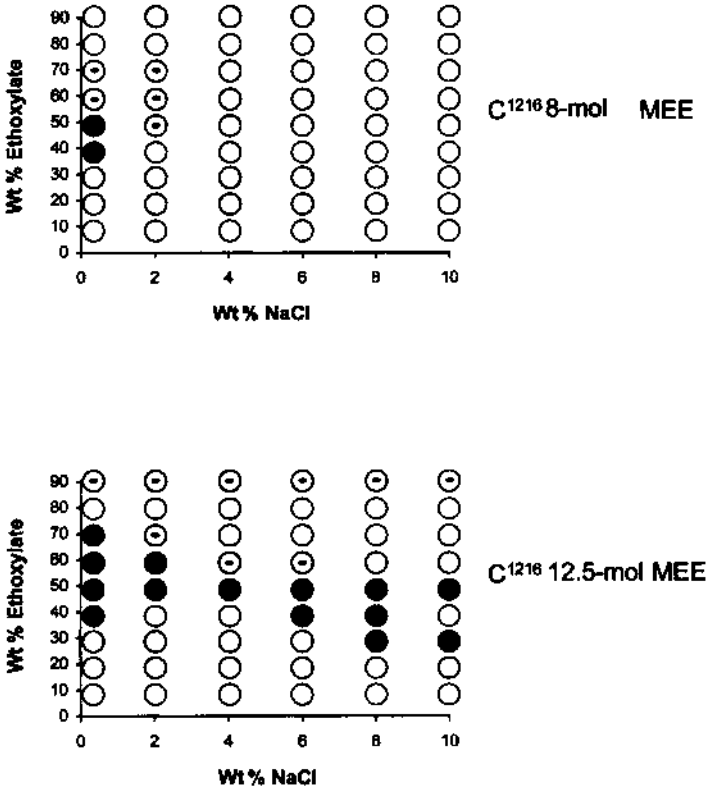

FIG. 10 Gel boundary diagrams for $C_{12–16}$ 8-mol and 12.5-mol methyl ester ethoxylates prepared using Ca/Al-alkoxide catalyst at 25°C. (Distribution of $C_{12–16}$ methyl ester = 57% C_{12}, 23% C_{14}, 12% C_{16}, and 8% C_{18}.) ○, low-viscosity liquid; ⊙, high-viscosity liquid; ●, gel. (From Ref. 27.)

lates degraded with time and temperature pH > 9 [9,15]. Studies examining the potential for hydrolysis occurring when methyl ester ethoxylates are included in powder formulations containing alkaline ingredients have yet to be reported.

D. Odor

As expected, methyl ester ethoxylates smell "different" from thier conventional alcohol ethoxylate counterparts. Methyl ester ethoxylates made with short-chain ($C_{8–10}$) feedstocks have a clear advantage over conventional

alcohol ethoxylates in both the level and the offensiveness of the odor. With short-chain ethoxylates, odor is generally determined by the level and odor of the unethoxylated feedstock. Short-chain ($C_{8–10}$) methyl ester is significantly less pungent than short-chain alcohol.

The opposite trend is true to a lesser degree with tallow range ethoxylates. In general, ethoxylates of tallow range alcohol have essentially no odor, while tallow range methyl ethoxylates have a slight "methyl ester" odor.

The level of odor in the ethoxylates depends on carbon chain length and the degree of ethoxylation. As with alcohol ethoxylates, longer carbon chain lengths and higher ethylene oxide levels result in an overall reduction of odor level.

V. PERFORMANCE

A. Surface Properties

Methyl ester ethoxylates and their alcohol ethoxylate counterparts have similar surface properties. Gibbs' plot for pure C_{14} 7-mol (no other ethoxymers except the 7-mol homolog) methyl ester ethoxylate is compared to its pure C_{14} 7-mol alcohol ethoxylate counterpart in Fig. 11. The methyl ethoxylate shows a higher CMC and a lower surface tension at the CMC than its alcohol ethoxylate equivalent. This increase in CMC is presumably due to the presence of the ester moiety which adds rigidity and steric constraint to the methyl ester ethoxylate molecule. This would likely reduce the tendency of a molecule to micellize, leading to a slightly higher CMC.

The slightly lower surface tension of the methyl ester ethoxylate at and beyond the CMC is thought to be related to the presence of the terminal methoxy group on the ethylene oxide chain. In comparison to a terminal hydroxyl group, a terminal methoxy group is less hydrophilic. The resulting lower water solubility effectively drives more of the surfactant to the air/water interface, resulting in a lower surface tension.

At concentrations below the CMC, a longer carbon chain length yields a more efficient methyl ester ethoxylate surfactant [16]. At concentrations above the CMC, all carbon chain lengths are effective in lowering the surface tension once the ethylene oxide content is sufficiently optimized. Results also show that a methyl ester ethoxylate with a broader carbon chain length distribution is less surface active than one based on a more narrow-cut methyl ester.

The optimal level of ethylene oxide will vary depending on carbon chain length. In general, a lower degree of ethoxylation yields better surface properties, down to the limit where water solubility is no longer obtained.

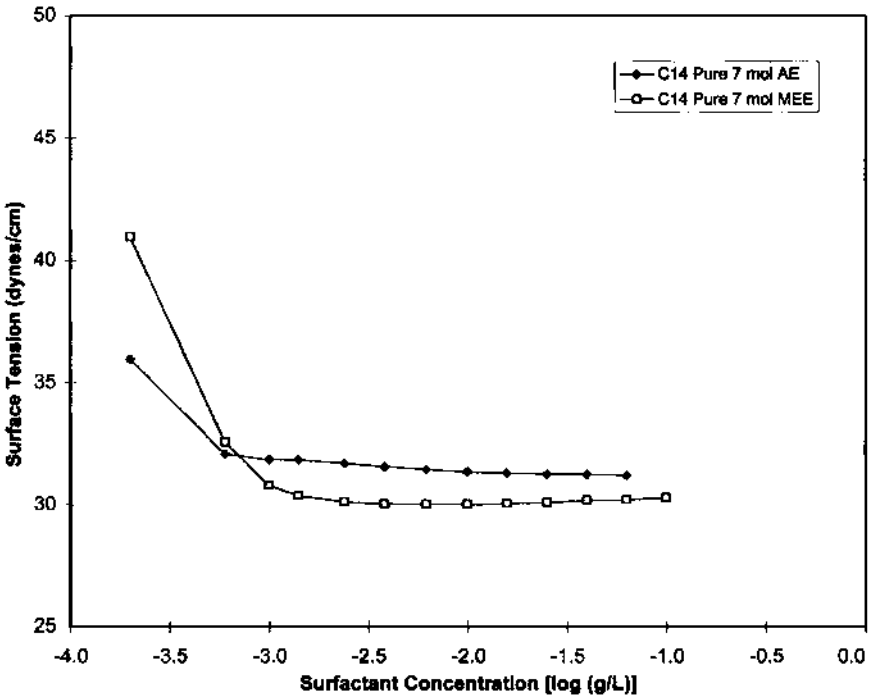

FIG. 11 Gibbs' plot for C_{14} pure (ethoxylates are pure 7-mol ethoxylates; there are no other homologs) 7-mol methyl ester and alcohol ethoxylates.

There is also a difference in dynamic surface properties between methyl ester ethoxylates and alcohol ethoxylates. As shown in Fig. 12 for pure 7-mol homologs, the methyl ester ethoxylate maintains a lower surface tension than its alcohol ethoxylate counterpart as measurements become more "dynamic" (bubble rate of bubble tensiometer is increased). This suggests that methyl ester ethoxylate is more effective in lowering surface tension (can achieve the same surface tension reduction with a lower surfactant concentration at the interface) and/or it diffuses through aqueous solution at a faster rate.

The impact of molecular structure on the ability of methyl ester ethoxylates to lower interfacial tension has been examined elsewhere [14]. These studies show that the relative performance of methyl ester and alcohol ethoxylates and the impact of ethylene oxide content and distribution depend strongly on the composition of the soil used to determine the interfacial tension.

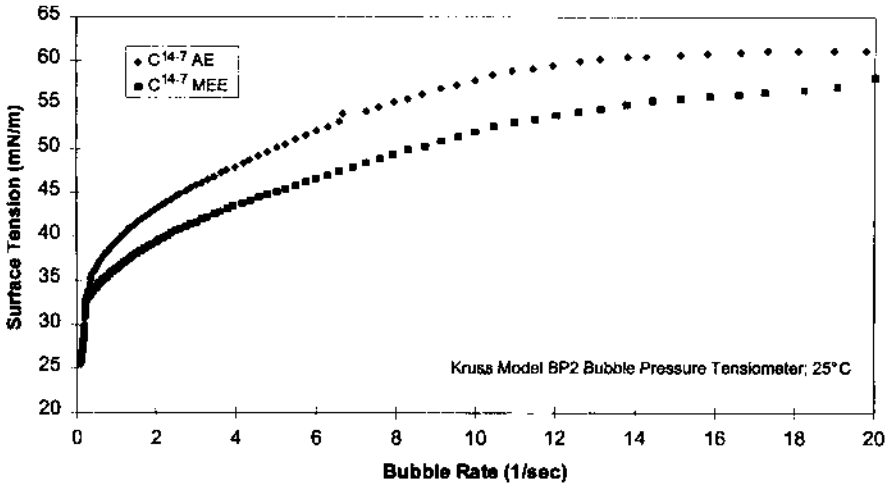

FIG. 12 Surface tension (nM/m) vs. bubble rate for C_{14} pure 7-mol methyl ester and alcohol ethoxylates. (Ethoxylates are pure 7-mol ethoxylates; there are no other homologs.)

B. Soil Removal from Fabric

Based on the surface property data discussed earlier, methyl ester ethoxylates would be expected to perform similarly to alcohol ethoxylates, which is indeed the case. As shown in Fig. 13, methyl ester ethoxylates are comparable to alcohol ethoxylates, as well as other commonly used surfactants (see Table 1), in their ability to remove soil from fabric. Compositional variables affect the performance of methyl ester ethoxylates and alcohol ethoxylates. Lauryl range and tallow range methyl ester ethoxylates provide the best detergency, while optimal ethylene oxide content appears to depend on soil/cloth-type (Fig. 14). Interaction with other surfactants also affects detergency performance. As shown in Fig. 15, methyl ester ethoxylates act synergistically with alcohol ethoxylates, while the opposite can be observed with alcohol sulfate and alcohol ether sulfate.

C. Soil Removal from Hard Surfaces

Studies [28] have shown that linear alcohol ethoxylates made with short-chain alcohols are effective as hard-surface cleaners. A shorter chain hydrophobe is thought to confer greater solvency on the surfactant, which assists

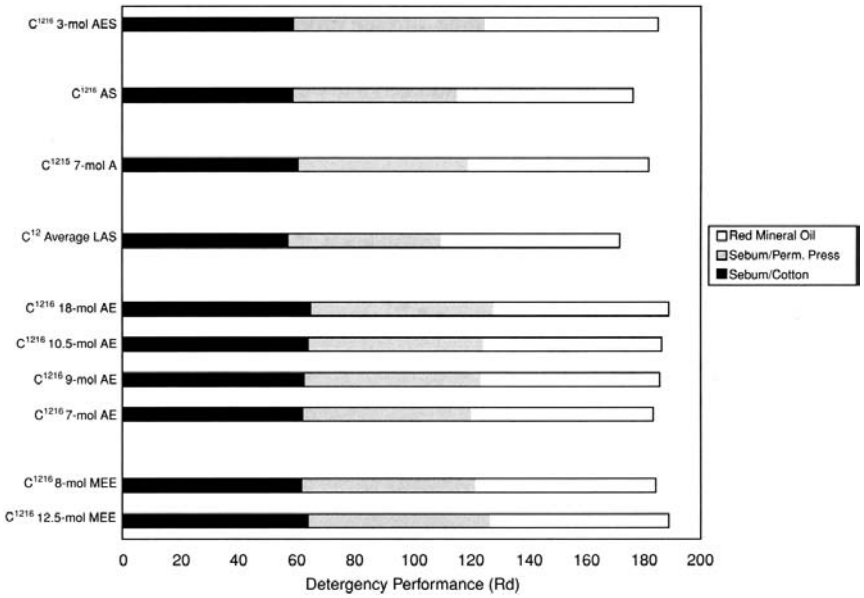

FIG. 13 Fabric detergency performance of methyl ester ethoxylate vs. conventional surfactants. (Conditions, test method, and protocol described elsewhere [15], descriptions of reference surfactants are given in Table 1; distribution for $C_{12–16}$ methyl ester = 57% C_{12}, 23% C_{14}, 12% C_{16}, and 8% C_{18}; MEEs prepared using calcium/aluminum alkoxide catalyst. (From Ref. 27.)

TABLE 1 Reference Surfactants Used in MEE Assessment Studies

Abbreviation	Description
$C_{12–16}$ 3-mol AES	$C_{12–16}$[a] 3-mol average sodium alcohol ether sulfate
$C_{12–16}$ AS	$C_{12–16}$[a] sodium alcohol sulfate
$C_{12–15}$ 7-mol AE	$C_{12–15}$[b] 7-mol average alcohol ethoxylate; alcohol "modified-oxo" type
C_{12} Average LAS	C_{12} average sodium linear alkylbenzenesulfonate (low 2-phenyl type)
$C_{12–16}$ 7-, 9-, 10.5-, and 18-mol AE	$C_{12–16}$[a] alcohol ethoxylates

[a] Typical distribution of alcohol (linear, primary) = 68% C_{12}, 25% C_{14}, and 7% C_{16}.
[b] Typical distribution of alcohol = 20% C_{12}, 30% C_{13}, 30% C_{14}, and 20% C_{16}.

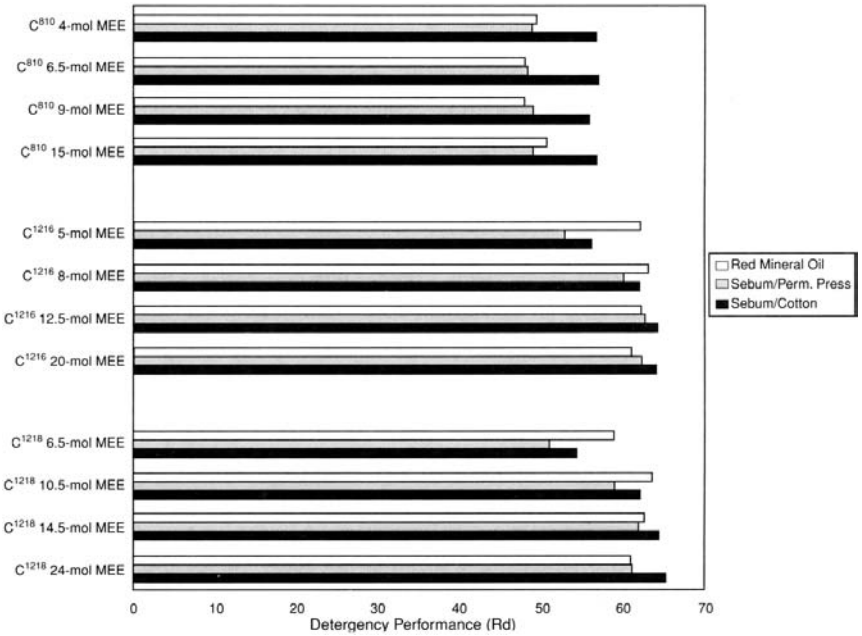

FIG. 14 Fabric detergency performance of methyl ester ethoxylates as a function of carbon chain length and EO content. (From Ref. 15.)

in the removal of solid, greasy soils. An intermediate amount of ethylene oxide was also found to be generally best for hard-surface cleaning.

Previous studies [15,16] have shown that the same phenomenon is observed with methyl ester ethoxylates. Figure 16 indicates that, compared to conventional surfactants commonly used in hard-surface cleaners, methyl ester ethoxylates are highly effective. These results suggest that the increased solvency produced by reducing carbon chain length is magnified in some way with methyl ester ethoxylates. Whether or not the terminal hydroxyl group and/or presence of the ester linkage produces this magnification is unknown.

Another way to demonstrate the impact of solvency on soil removal is to observe the change in soil weight upon immersion in aqueous surfactant solutions. Figure 17 shows how soil (lard) weight changes when immersed in 3% solutions of various methyl ester ethoxylates. Short-chain (C_{8-10}) low-mol ethoxylates cause an increase in weight because they are effective in penetrating the soil during the immersion period. With higher carbon chain length and higher ethylene oxide–containing methyl ester ethoxylates, soil weight is observed to decrease because the rate of soil removal (liquefaction, solubilization, emulsification) exceeds the rate of soil penetration.

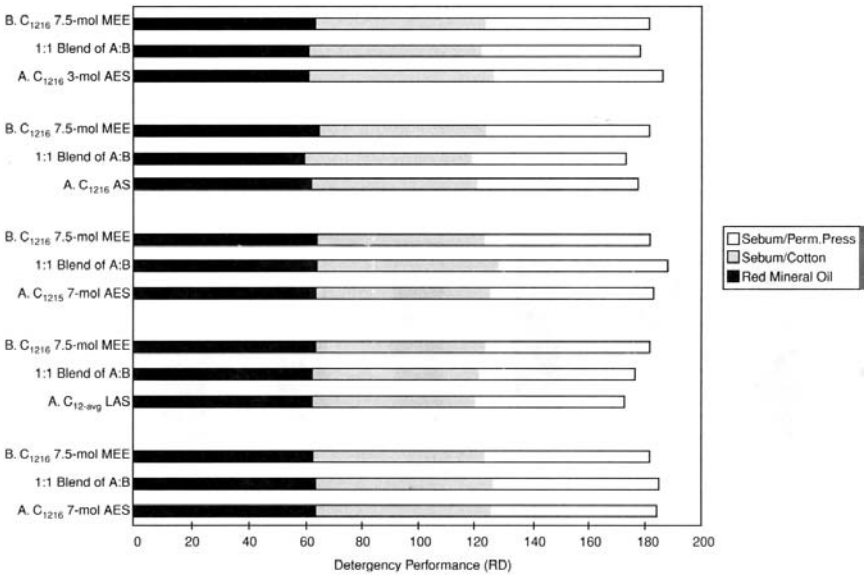

FIG. 15 Fabric detergency performance of $C_{12–16}$ 7.5-mole methyl ester in 1:1 blends with other surfactants. (From Ref. 15.)

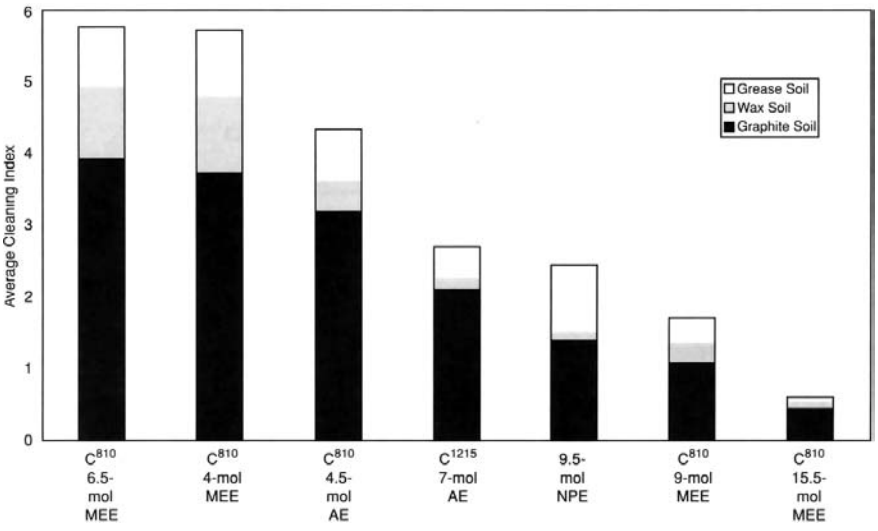

FIG. 16 Hard-surface cleaning performance of methyl ester ethoxylates vs. other surfactants. (From Ref. 15.)

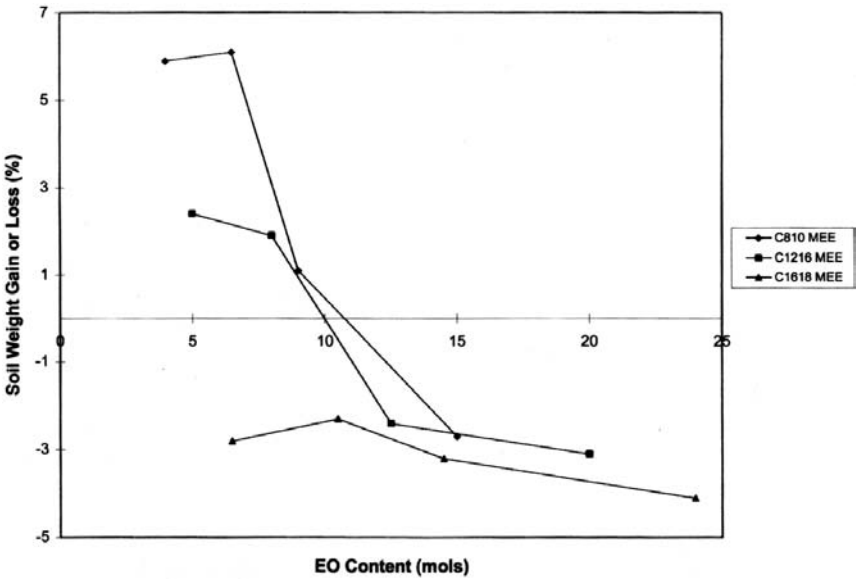

FIG. 17 Change in soil weight when soiled plates are dipped in aqueous solutions of methyl ester ethoxylates (1618 methyl ester = 31% C_{16} and 68% C_{18}). (From Ref. 15.)

Although short-chain ethoxylates are excellent surfactants for hard-surface cleaning, their performance is concentration dependent. With both alcohol ethoxylates and methyl ester ethoxylates, a shorter chain length improves hard-surface cleaning, particularly on greasy soils, but only at relatively high (>1% surfactant) concentrations. At lower concentrations, performance is dictated less by solvency properties and more by surface properties. Consequently, a longer carbon chain length provides improved performance at low concentrations. The selection of the optimal performing ethoxylate therefore depends on the use concentration as well as on soil and on substrate.

D. Foam Performance

Methyl ester ethoxylates are moderate foamers. They produce less foam than their alcohol ethoxylate counterparts (Fig. 18) because they are sterically more constrained and because of the absence of a terminal hydroxyl group on the ethylene oxide chain.

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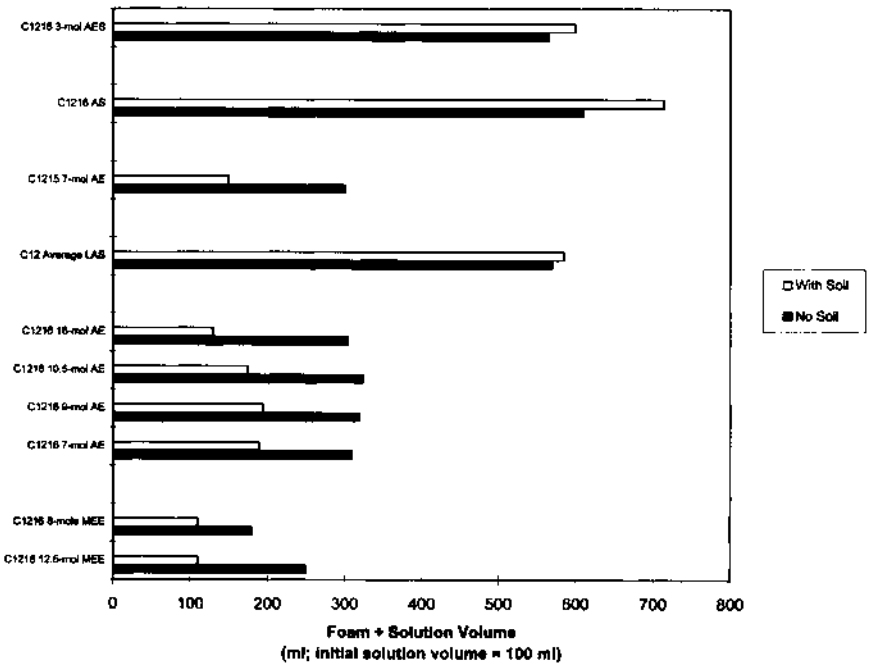

FIG. 18 Comparison of flash foaming of methyl ester ethoxylates vs. conventional surfactants (100 ppm surfactant solutions; soil = 15% Crisco shortening, 15% olive oil, 15% instant mashed potato flakes, 30% milk, 25% water; test method (Schlag Foam Generation) and protocol are described elsewhere [15]).

Ethoxylate structure has a significant impact of foaming. As shown in Figure 19, increasing carbon chain length and ethylene oxide content results in higher foaming, which presumably correlates with the ability to lower surface tension. Hama has also shown that short-chain methyl ester ethoxylates, based on C_8 and C_{10} methyl esters, produce unstable foams [14].

The ability of methyl ester ethoxylates to produce foam appears to be sensitive to the presence of greasy soil. As shown in Figs. 18 and 19, the addition of this soil significantly reduces foaming.

VI. APPLICATION OF METHYL ESTER ETHOXYLATES

Methyl ester ethoxylates are relatively new, and are now just being introduced into the market. In general, they can be considered to be interchangeable with alcohol ethoxylates except in terms of their pH stability, which limits

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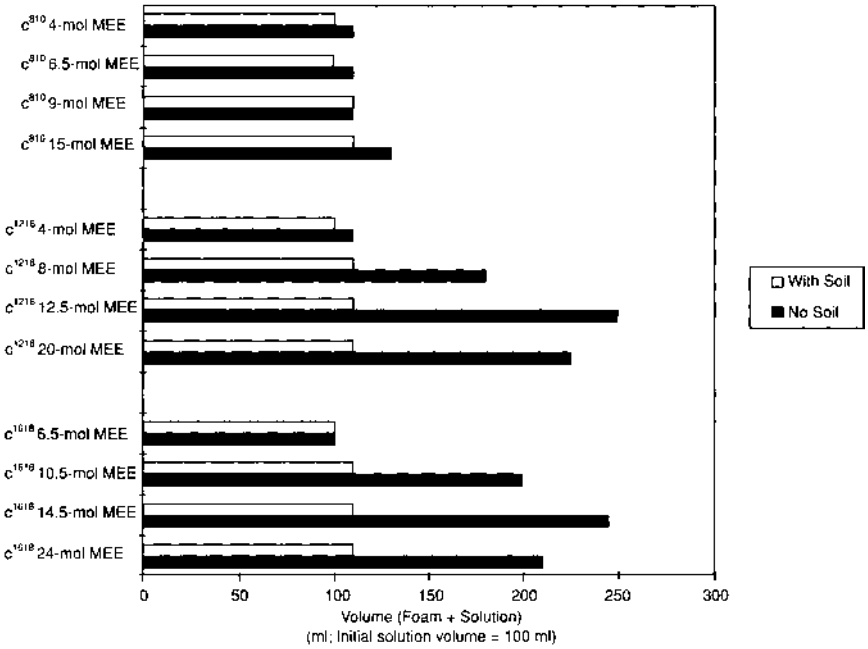

FIG. 19 Comparison of flash foaming of methyl ester ethoxylates as a function of carbon chain length and EO content (100 ppm surfactant solutions; soil = 15% Crisco shortening, 15% olive oil, 15% instant mashed potato flakes, 30% milk, 25% water; test method (Schlag Foam Generation) and protocol are described elsewhere [15]).

their incorporation into aqueous formulations to a pH < 9. The following sections discuss the pros and cons for formulating methyl ester ethoxylates in detergents.

A. Laundry Powders

Methyl ester ethoxylates are good detergents, comparable with alcohol ethoxylates. They also appear to perform synergistically with other surfactants, which should be examined closely when developing finished formulations. They also foam less, making them a little more compatible for "controlled-foam" detergents. However, studies have yet to be published which discuss the ability of methyl ester ethoxylate to be processed into detergent powders. Methyl ester ethoxylates hydrolyze at high pH (>9).

Information regarding stability during processing (spray drying, agglomeration, etc.) and during storage is not yet available.

B. Laundry Liquids

Methyl ester ethoxylates should formulate well into liquids and provide acceptable stability provided pH remains less than 9. Methyl ester ethoxylates should be easier to handle than their alcohol ethoxylate counterparts because of their reduced tendency to gel formation.

C. Hard-Surface Cleaners

Short-chain methyl ester ethoxylates appear to be outstanding detergents for removing solid soils from hard surfaces, but only when surfactant use concentration is significant ($>1\%$). At lower use concentrations, higher carbon chain length methyl ester ethoxylates are more effective.

Short-chain methyl ester ethoxylates also have an odor advantage over conventional alcohol ethoxylates, which can be important, particularly in household products. Formulation pH must be controlled to prevent hydrolysis of the methyl ester ethoxylates.

D. Dishwashing Detergents

Since methyl ester ethoxylates are moderate foamers, and undergo significant hydrolysis at a pH greater than 9, they will not likely be used as the main surfactant in either hand or machine dish detergents. However, because of their ability to remove solid soil, methyl ester ethoxylates may find use not as a foam stabilizers or foam-generating surfactants but for enhancement of soil removal properties.

VII. ETHOXYLATION OF OTHER ESTERS

Other esters (triglycerides, alkyl esters, fatty-fatty diesters, etc.) are also reasonable ethoxylation feedstocks [6], and are currently under study.

VIII. PROPOXYLATION OF METHYL ESTERS

Propoxylation, butoxylation, etc., of methyl ester ethoxylates is chemically straightforward. Propoxylation of methyl esters is discussed in detail elsewhere [17].

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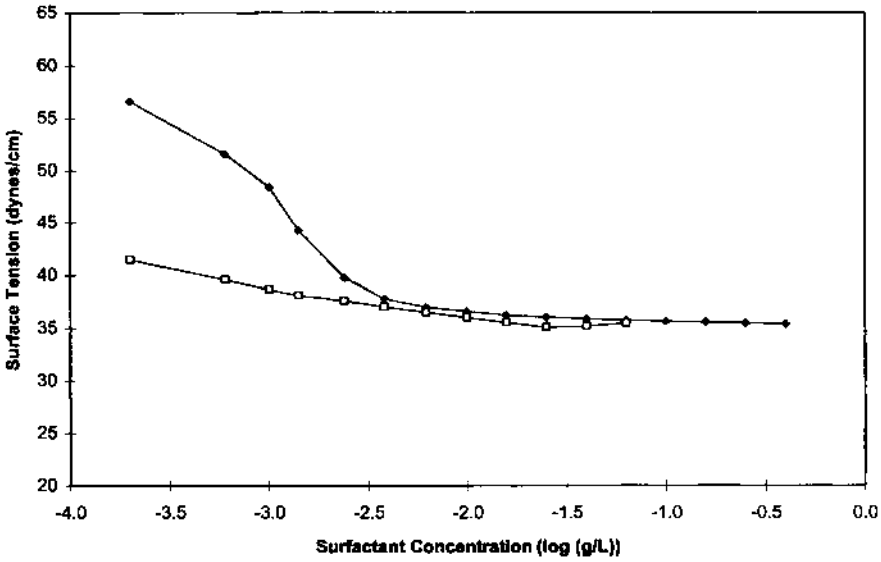

FIG. 20 Gibbs' plots of hydrogenated methyl tallowate ethoxylate (14.5 mol) vs. $C_{16/18}$ 14.5-mol MEE. [-◆-$C_{16/18}$ 14.5-mol MEE; -□-$C_{16/18}$ 14.5-mol MEE (hydrogenated methyl ester).] (From Ref. 15.)

IX. IMPACT OF UNSATURATION

The impact of unsaturation stems from the increase in rigidity caused by the presence of one or more double bonds to the alkyl chain. Although studies so far show that unsaturation has a relatively low impact on water solubility and viscosity, it has been reported to lower melting points by about 5–10°C [16]. Studies also show (Fig. 20) that unsaturation affects surface properties. Gibbs' plots of 14.5-mole ethoxylates produced from hydrogenated and nonhydrogenated $C_{16–18}$ methyl ester show that unsaturation appears to increase surface tension below the CMC. This suggests that unsaturation reduces the hydrophobic character of the methyl ester chain.

ACKNOWLEDGMENT

From *Detergency of Specialty Surfactants*, F.E. Friedli, ed., Marcel Dekker, Inc., 2001.

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15
Polymerizable Surfactants

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I. INTRODUCTION

A. What are Polymerizable Surfactants?

One would expect the term polymerizable surfactants to include amphiphilic molecules containing somewhere in their structure a polymerizable group such as styrenic, acrylic or methacrylic, vinylic, maleic, crotonic, or allylic. These groups may be located in different places such as the end or head of the hydrophilic sequence, the end of the hydrophobic moiety, between the two, or finally somewhere along the surfactant structure as pendant (side) groups.

On the other hand, as an extension of the term, one can find a group that can participate in a polymerization process, as, for instance, as initiator. It has been proposed this group be named *inisurfs* or *transurfs* (transfer agents) in a radical polymerization process. By analogy, it has been proposed that the polymerizable surfactants be named *surfmers*.

From polymerizable surfactants one can obtain polymeric surfactants. However, because a book of this series has been devoted to polymeric surfactants [1], we will not cover them in this chapter.

B. Why Use Polymerizable Surfactants?

Above a certain concentration, surfactants are known to produce a few kinds of organized structures, e.g., micelles (either spherical or lamellar), or more complex structures such as vesicles. Some years ago, the stabilization of such objects, attracted considerable attention because they can serve as a model for biological membranes and can also be used in drug delivery systems. Several good reviews have been devoted to this topic [2–8]. However, the stabilization of vesicles was achieved but this was not the case for micelles. The main reason

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for this seems to be the dynamics of micelles, which exchange their molecules with the continuous phase very rapidly. In contrasts, vesicles are much more stable, thus allowing enough time for polymerization to occur without noticeable exchange of the individual molecules [9–12]. Then, when attempts are carried out to polymerize micelles (with a diameter of, say, 10 nm), one generally obtains particles with much large diameter (e.g., 200 nm).

Some good explanations have been recently published [13]. The explanation has been set for a high-reactivity styrenic surfmer with a low critical micelle concentration (CMC). It rests on the comparison of the average lifetime of a micelle (T_M; which is $> 10^{-2}$ s) with the time of addition of a styrenic monomer, which is around 10^{-3} s, so that during the life of a micelle, once it is activated photochemically, all the monomer constituting the micelle should be consumed (i.e., 20–100 units). On the other hand, because the molecular weight of the polymer obtained is very high (in between 0.8 and 4×10^6 Da) it is clear that the polymer particles from a fully converted micelle are fed with monomer coming from nonactivated micelles. Such a mechanism is similar to that observed in emulsion polymerization, and even more so microemulsion polymerization [14]. If the reactivity of the surfmer is much smaller (e.g., allyl compounds), the time T_M is too short for consuming all of the monomers present in the micelle, so that the micelle disappears and the oligomeric radical returns in the continuous phase. On the other hand, if the CMC of the surfmer is high, the initiation of the polymer should take place in the continuous phase. In both cases it cannot result in keeping the shape and the size of the micelles.

The second major use of polymerizable surfactants is their application as stabilizer in polymerization in dispersed media, chiefly in emulsion polymerization, but also in dispersion polymerization.

In emulsion polymerization as well as dispersion polymerization, use of reactive surfactants, i.e., surfactants that can be covalently linked to the surface of the particles, is expected to bring certain advantages. First of all, one can expect an improvement of the latex stability. Because the surfactants are simply adsorbed onto the surface of particles, in conventional emulsion polymerization they can desorb under certain circumstances, so causing a lack of stability. This is the case when the latexes are submitted to high shear. It is also the case when the latex is frozen. In both cases, flocculation takes place.

A second kind of benefits is expected in the case of film-forming latexes. In conventional emulsion, the surfactants are not firmly attached to the particle and thus are able to migrate toward the surface of the films. It may result in defects of adhesion if the film is expected to protect the surface of a substrate, as for the various kind of paints. In addition, it is known that during the

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process of coalescence, phase separation takes place. Then some domains containing residual water are formed. These domains also contain a high concentration of surfactants. They may be trapped in the polymer. Some may migrate toward the surface of the film but some will remain trapped. If the film is exposed to water or even to high levels of humidity, the diffusion of water through the polymer film toward these trapped domains make them swell; this is the main cause of water rebound of the film, which again is detrimental to the protection of the substrate against corrosion. This is because if the domain swells enough a percolation system may occur, causing the film to become permeable to water.

A third kind of benefit takes place if it is intended that the latex will release material upon flocculation. Then it may be expected that, if the surfactant is covalently linked to the surface of the polymer particles, a smaller amount of it will be rejected in the water phase. Therefore, water remaining after the flocculation process will be less polluted.

II. EMULSION POLYMERIZATION USING POLYMERIZABLE SURFACTANTS

A. Introduction

Emulsion polymerization involves the polymerization of a set of monomers, usually with low water solubility (mostly styrene, methyl methacrylate, acrylic esters, vinylic esters), which are emulsified in small droplets (a few to several hundred micrometers) through the use of surfactants. Such surfactants are water soluble at the temperature of polymerization (5–90 °C). Polymerization is initiated using water-soluble initiators such as peroxydisulfates or water-soluble azo compounds. There is also the inverse emulsion polymerization with water-soluble monomers, surfactants (chiefly nonionics), and either water-soluble or oil-soluble initiators, the continuous medium being organic non-water-soluble products (such as hydrocarbons). In a normal emulsion polymerization, there is often a small amount of water-soluble, functional monomers (such as acrylic acid). These functional monomers are needed for applications of emulsion polymerization to the synthesis of film-forming latexes because of their interaction with other components. The main uses of film-forming latexes are paints, adhesives, paper coatings, textile sizing, non-woven textile, glass fibers, binders, and so forth. Another important field of application of lattices are the synthetic elastomers, such as styrene-butadiene-rubber (SBR), and nitride-butadiene-rubber (NBR), polychloroprene rubber, as well as some important plastics such as acrylonitrile-butadiene-styrene

(ABS) and polyvinyl chloride (PVC). In the emulsion polymerization, reactive surfactants can be used as inisurfs when they can replace both the initiator and the surfactants, as transurfs when they may be used to control the molecular weight, and finally as surfmers when they are used as comonomers which are polymerizable.

B. Inisurfs

Inisurf molecules are composed of at least three different parts: the radical generating group, a hydrophobic part, and a hydrophilic part. Inisurfs can be subdivided into azo and peroxy compounds with regard to the chemical nature of the radical generating group. Both types of inisurf are known. It is noteworthy that most of the papers dealing with peroxy inisurfs are published in Russian scientific papers. For more detailed information concerning publications in Russian journals, see the papers mentioned in Ref. 15.

Both types of inisurf may be monomeric or polymeric in terms of the number of radical-generating groups per molecule. Another way to subdivide inisurfs is based on the symmetry of the groups attached to the radical-generating group. Symmetrical inisurfs have the same structural groups on both sides of the azo or peroxy group, i.e., two surface-active radicals with the same structure are produced after decomposition [15]. Nonsymmetrical inisurfs have only one surface-active group attached to the radical-generating group. Consequently, after decomposition they form one surface-active and one non-surface-active radical for instance a tertiary butyl or hydroxyl radical [16].

A third method to subdivide surface-active initiators is based on the chemical nature of the hydrophobic and hydrophilic groups. The hydrophilic group may be anionic or cationic, or an oxyethylene chain of an appropriate chain length. Hydrocarbon chains (alkyl, alkylphenol) or propylene oxide chains are used as hydropobic molecule components. Oxyethylene chains are also used as hydrophobic groups if they are in the neighborhood of ionic groups.

One advantage of inisurfs is the possibility of reducing the ingredients of an emulsion polymerization to the monomer, water, and initiator. The accessory content of the final latex can be considerably decreased in this way.

Problems exist with the chemical and structural purity of the inisurfs, especially from the colloidal point of view. One must always bear in mind that impurities are present in most systems investigated. Nevertheless, the results obtained clearly show the pecularities of inisurfs compared to conventional initiators for emulsion polymerizations such as water-soluble peroxides or azobisisobutyronitrile (AIBN). Inisurfs behave like surfactants,

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e.g., they form micelles and are adsorbed at surfaces. So they are characterized by a CMC in solution and an area per molecule in the adsorbed state. This surface activity is the most important physical property of inisurfs, strongly influencing their polymerization behavior. For instance, the decomposition behavior of inisurfs is highly dependent on whether their concentration is above or below the CMC [17]. The ability of these initiators to form micelles or to adsorb leads to a much higher primary radical recombination due to an enhanced cage effect. Several authors estimated radical efficiency values, f, in the range of 10^{-2}–10^{-4}, which are much lower than those for conventional initiators. Such low values were found (for azo in [18], for peroxy inisurfs [19]) in the structure of the inisurf. However, it is possible to realize high overall polymerization rates with inisurfs using emulsion polymerization.

Recently, new surface-active initiators have been synthesised and tested in emulsion polymerizations in the framework of a European network. The inisurfs known before the start of the network have one main drawback: their susceptibility to hydrolysis due to the presence of ester linkages (R_1-CO-OR_2 or R_3-OSO_3^- or both). Another drawback is that their preparation requires a multistep synthesis. Considerable progress has been made in overcoming these drawbacks.

The general structures of new surface active initiators are given in Table 1 (A1 and A2). With both Inisurfs it is possible to carry out emulsion polymerizations without additional stabilizers up to more than 50% solid contents. In particular, structure A2 fulfills all of the demands with respect to chemical stability against hydrolysis and ease of preparation (one-step synthesis via a modified Ritter reaction). Structure A1 has still ester bonds, but a sulfonate instead of a sulfate hydrophilic group. The synthesis occurs via a two-step procedure where by the first step is the preparation of the corresponding bis(phenyl alkyl)-2,2′-azobisisobutyrates (Pinner reaction) and the second step is the sulfonation of the phenyl ring.

There is another important difference between the two types of surfactant. The phenylalkylsulfonates (A1) represent simple dimeric surfactants, whereas the A2 compounds are examples of a new class of surfactants, the gemini surfactants. Both types of surfactants and consequently both types of inisurfs differ considerably in their properties. The gemini inisurfs are able to stabilize a much larger surface area per molecule than conventional and simple dimeric surfactants. Consequently, the gemini inisurfs should lead in an emulsion polymerization to smaller particle sizes than the other inisurfs.

As the decomposition product of the gemini inisurfs is a conventional surface-active radical with the ability to stabilize only a smaller surface area, the particle size distribution should be broad or bimodal if a certain number of

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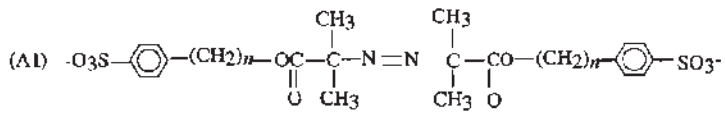
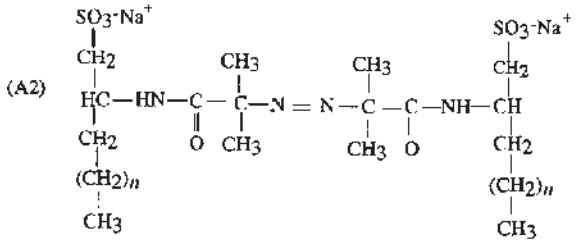
TABLE 1 Anionic and Nonionic Inisurfs

Anionic Inisurfs

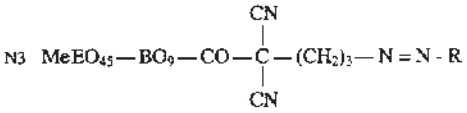
(A1) 

Bis[2-(4′-sulfophenyl)alkyl]-2,2′-azodiisobutyrate ammonium salts ($n = 1, 2, 3$)

(A2) 

2,2′-Azobis(*N*-2′-methylpropanoyl-2-aminoalkyl-1-sulfonate)s ($n = 4, 12, 14$)

Nonionic Inisurfs

N3 

R = *t*-butyl or -C-NH-$(CH_2CH_2OH)_3$

particles are generated not by chains started with inisurf radicals but by chain transfer radicals (desorbed radicals). In that case, the smaller particle fraction is derived from the chain transfer radicals and is stabilized by inisurf molecules or their primary recombination products.

Figure 1 demonstrates these effects by means of the particle size distribution of polystyrene latexes prepared with both types of inisurf. The polymerizations are carried out at 90°C with 100 g of water, 10 g of styrene, and 0.25 g of 2,2′-azobis(N-2′-methylpropanoyl-2-amino-decyl-1-sulfonate) as gemini inisurf (Fig. 1a) and 1.292 g of bis(2-phenyl ethyl)-2,2′-azodiisobutyrate (Fig. 1b) as conventional surface-active initiator, respectively.

Beside the synthesis of new inisurf structures, a second topic was the search for possibilities to increase their efficiency in heterophase polymerizations. In order to achieve that goal, methoxyoligo(ethylenye oxide-*block*-butylene

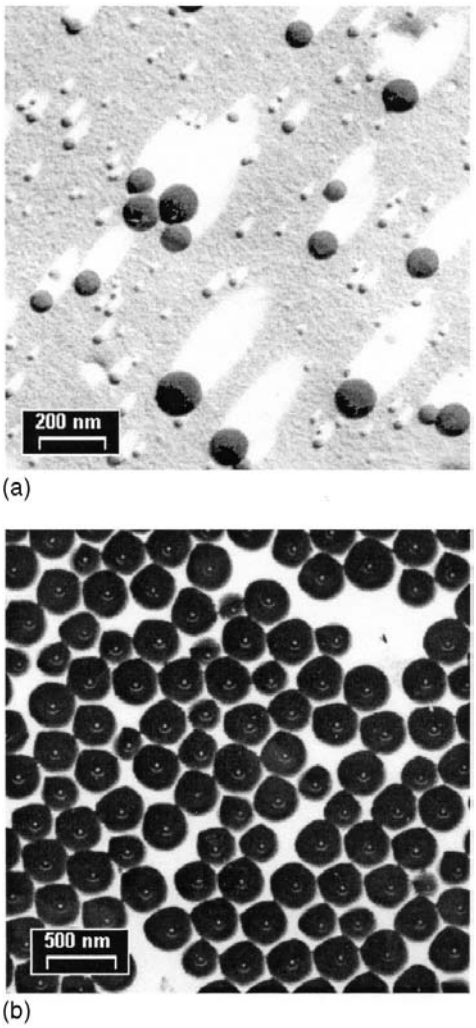


FIG. 1 Inisurfs. (a) Gemini inisurf; (b) conventional surface active initiation.

oxide) surfactants were esterified with 4-(*tert*-butylazo)-4-cyanopentanoic acid to attach the azoinitiator fragment to the hydrophobic part of the block oligomer (N3). In the case of this asymmetrical inisurf, the radical generating group is located inside the micelles and particles, respectively. Although this type of inisurf could initiate the *ab initio* emulsion polymerization of styrene and stabilize the resultant latex, kinetic studies revealed a

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disappointingly low initiator efficiency and, consequently, a low incorporation yield as well. The reason for this could be that the primary radical recombination is very fast in case of this asymmetrical inisurfs, too. Only when the small *tert*-butyl radicals leave the particles immediately after generation does initiation by the remaining surface-active radicals would become possible.

Another way to increase the radical efficiency as well as the incorporation yield could be to increase the hydrophilicity of the smaller, highly mobile radicals of the asymmetrical inisurfs. Unfortunately, all synthetic efforts in this direction have not been successful. One must conclude that with respect to inisurfs as reactive surfactants the main drawback of very low radical efficiency still exists.

C. Transurfs

Some transfer activity is displayed by many common surfactants. For instance, when emulsion polymerization of styrene is initiated photochemically using biacetyl in the presence of sodium dodecyl sulfate (SDS) as emulsifier, the resulting latex is slightly charged (3 mC/m^2) with strong acid groups. Some other surfactants show more transfer activity, e.g., transurfs I and II of Table 2.

Only one study has been carried out with a aurfactant carrying a typical transfer agent thiol group. Fitch and Fifield [20] reported the synthesis of transurf III with a CMC of 6.1×10^{-2} mol/L at 24°C. This surfactant was used both in polystyrene latex synthesis at concentrations lower than the CMC and in seeded polymerization experiments. Monodisperse particles about 400 nm in diameter were obtained in latex synthesis initiated with azocyanovaleric acid. In contrast to latex prepared in the presence of SDS, these latexes are not sensitive to coagulation upon ion exchange. A very surprising result is that the particle size seems to be practically insensitive to the amount of the transurf. Seeded experiments have been carried out with a large seed latex (700 nm) prepared without emulsifier and carrying a small charge density (3.4 mC/m^2). The seed was first reacted with the transurf and

TABLE 2 Reactive Surfactants with Transfer Capability

I	$C_{11}H_{23}—CH{=}CH—CH_2SO_3Na$
II	$C_{11}H_{23}—C(OH){=}CH—CH_2SO_3Na$
III	$HSC_{10}H_{22}—SO_3Na$

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then swollen with styrene and a solution of AIBN in dichloroethane. Polymerization at 55°C resulted in a particle size of 740 nm with a higher charge density (53 mC/m^2). Then the yield of surface location of the transurf can be estimated to be 60%.

Another thiol transurf was recently studied by Vidal et al [21]. It was prepared from bromoundecanol used first to initiate the ring opening polymerization of ethylene oxide, and second to change the bromine for a thiol group after hydrolysis of a thiazolium salt. The length of the hydrophilic sequence was varied from 17 to 90 units of ethylene oxide. These transurfs were used in the emulsion polymerization of styrene, mainly in batch but also in seeded semibatch process. The kinetics of monomer conversion, as well as molecular weight, particle size, and their distribution, were studied. Very broad molecular weight distributions, were observed while monodisperse particles were formed. Smaller particles were obtained using the longer hydrophilic sequences. The incorporation yield of the transurf in the latex particles, as measured from the comparison of Nuclear magnetic resonance (NMR) signal of polystyrene and polyethylene oxide was around 25%. Decoupling the surfactant function from the transfer function showed that the stability of the particles is better when both functions are incorporated in the same molecules.

The thiol equivalent of macromonomer of polyethylene oxide (PEO) was also studied as an inifer system where initiation reaction results from a redox system with the thiol-polyethylene oxide and *t*-butyl hydroperoxide [22], while the thiol keeps its transfer capability.

Although most of the PEO segments remain in the water phase, a polystyrene latex is obtained and is sterically stabilized by grafted PEO segments. The efficiency of the stabilization chiefly depends on the grafting density. Side reactions in the water phase strongly limit the incorporation of these PEO segments at the end of the polystyrene chains, which remain limited to less than 25% in the best cases. On the other hand, the molecular weight inside the particles is limited by other side transfer reactions [23,24].

It is important to increase the capture efficiency of the oligoradicals produced in the water phase. It seems that two conditions should be fulfilled. The first condition would be better control of the nucleation steps. This difficulty might be avoided by using a seed polymerization protocol. It is rather easy to produce a seed with a well-controlled size and surface coverage using conventional surfactants. The second condition would be better knowledge of the consumption of the thiol-ended PEO. Some preliminary trials show that coulometric titration might be a convenient method for that purpose, work is in progress in that direction. The actual thiol concentration and the *t*-BuOOH consumption throughout

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the process might indicate the best protocol for the introduction of this reactive PEO.

Nonionic transurfs have been synthetized through functionalization of methoxyoligo(ethylene oxide–*block*–butylene oxide) precursors. One has thiol-ended functionality. When used in styrene emulsion polymerization carried out in two steps (seed and feed), it gives a rather high incorporation yield (up to 79%) after washing with water. However, upon washing with ethanol, the residual incorporation yield decreases down to 18%. The transfer constant of this kind of product is quite high, around 15–20 [25], so that the surfactant is quite reactive in the water phase. Most of it remains as oligomers after termination in the water phase. It is more or less strongly adsorbed onto the particles but is desorbed upon washing with ethanol.

To ensure a more gradual incorporation of transurf in batch experiments, the transfer activity needs to be moderated. To this end, allyl sulfide–type transfer agents working with a transfer-fragmentation mechanism [26] appear the most promising, as their transfer constant has been reported to be close to one, meaning that they will be active throughout the polymerization and thereby allow in addition an effective control of molecular weight.

As a first approach, a transurf prepared by esterification of the precursor surfactant with 2-phenyl-2-propenylmercaptopropionic acid has been tested. This transurf compound shows a very good incorporation in the batch emulsion polymerization of styrene, as determined by gradient polymer elution chromatography and NMR spectroscopy.

The synthesis of another transurf agent was carried out according to the following scheme [27]. Dimers (or trimers) of methyl methacrylate are first produced through a radical mechanism in the presence of a powerful cobalt derivative transfer agent (CoBF), Then, after hydrolysis of the ester groups with lithine, these carboxylate dimers were esterified by condensation onto a surface-active long alkyl chain sulfate. This transurf has been used in the *ab initio* emulsion polymerization of MMA at 70°C, where it was compared with SDS [28]. It was expected to work through an addition-fragmentation mechanism shown in the second scheme. Then the surface-active alkyl sulfate moiety should be located at the end of each polymer molecule. It was found that the rate was lowered and the average diameter nearly doubled compared to the SDS experiments (control). In addition, the molecular weight distribution was very broad but had a lower M_n than the SDS experiment. Unfortunately, due to the formation of many water-soluble oligomers, the consumption of transurf could not be obtained accurately. However, it was estimated theoretically that only a very small amount of transurf would be consumed, and a method to increase the incorporation of transurf into the particles is to keep the ratio of monomer to transurf as low as

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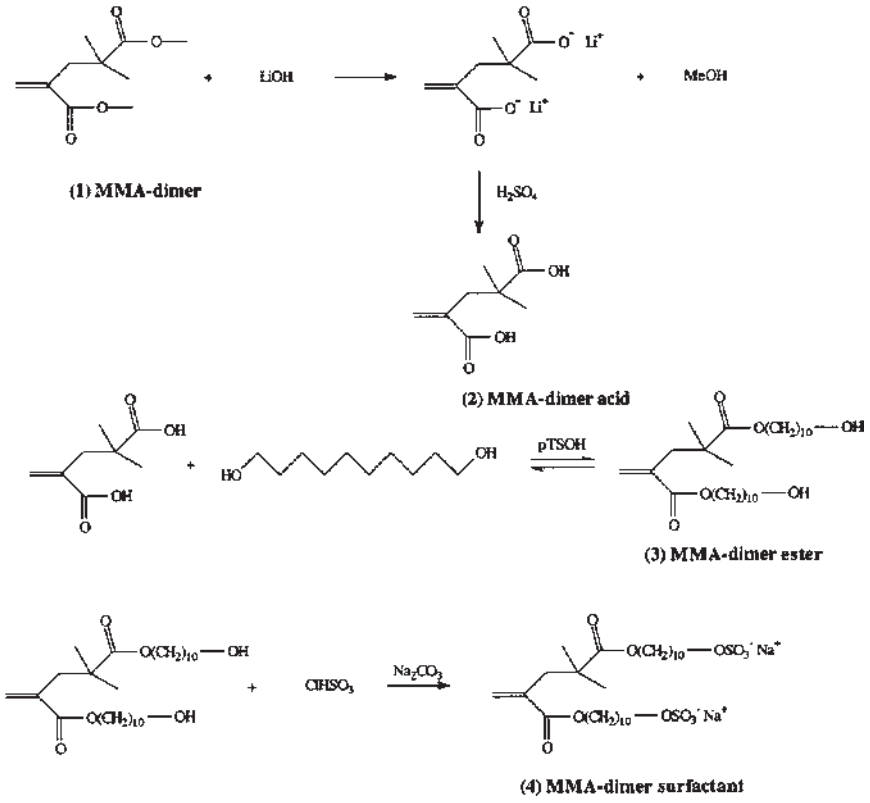
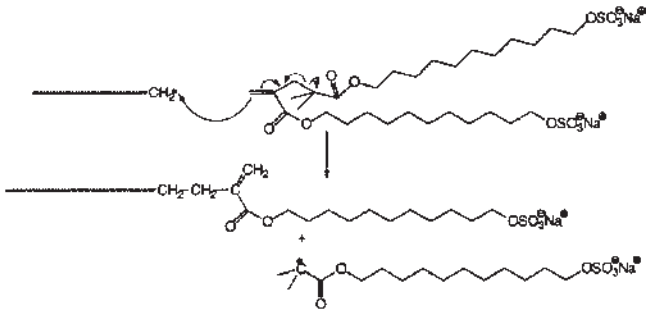
possible. The best way to achieve this is to carry the experiments out under starved-feed conditions.



The addition fragmentation mechanism is as follows:



The new radical carrying the surface active moiety will polymerize the hydrophobic monomers, and the chain end will have a sulfonate end group.

The addition fragmentation mechanism has attracted strong interest because it is the basis for a new way to control radical polymerization. The corresponding system is reversible addition fragmentation transfer (RAFT). This strong interest arises from the fact that, at variance to the other ways of obtaining a controlled radical polymerization, such as the nitroxide or the ATRP (atom transfer radical polymerization), it can be adapted to all kinds of commercial monomers, including the vinylics. The first publication about this process appeared in the open literature in 1998 [29], whereas its first applications in emulsion polymerization were published in 2000 [30]. The RAFT agents are most often derived from thioester compounds or xanthates. The group of Monteiro prepared two different RAFT agents with surface-active properties that they named SURRAFT. Their structures are as follows:

$$EtO - C(=S)S - C(CH_2)_2CONH - CH(CH_2SO_3Na) - C_6H_{13} \quad \text{and}$$

$$EtO - C(=S)S - C(CH_3) - (CH_2)_9O\ SO_3Na$$

Work is in progress in his laboratory to apply these compounds in emulsion polymerizations, but this work has not yet been published.

D. Ionic Surfmers

The oldest report we know dealing with the polymerization of a molecule nowadays termed a surfmer is the work of Bistline et al. [31]. They obtained surface-active polymers with a mean degree of polymerization of about 10 by polymerization of allylic esters of sodium salts of α-sulfostearic acid and α-sulfopalmitic acid.

The early work of Greene [32–34] used as surfmer sodium 9- and 10-acrylamidostearate (Na-AAS). They prepared a styrene-butadiene latex with a small amount of Na-AAS in batch at 70°C and obtained 134-nm-diameter particles with low surface coverage. This latex was later covered with various amounts of Na-AAS (calculated so that the final surface coverage would be 20–100%), equilibrated, and heated for an additional hour at 70°C in the presence of potassium persulfate for in situ polymerization of the surfmer. A part of the surfmer was removed after ion-exchange resin treatment, either as nonpolymerized monomer or water-soluble polymer. The latex surface coverage by immobilized surfmer polymer was varied from 20% to 80%; the yield of immobilization was almost 100% for low coverage but decreased to about 70% when high coverage was used. Up to 60% coverage, no difference could be found between monomer and polymer units for occupancy of the latex surface; above 60%, interference between the polymer chains occurred so that some parts of the surface still accessible to small-monomer molecules were

forbidden for further polymer segments. The latex covered with polymerized surfmer at high coverage was shown to display better mechanical stability than nonpolymerized surfmer at the same coverage [31]. The same is true for electrolyte stability [32]. These latexes were used to check some quantitative features of the DLVO theory.

A styrenic surfactant has been prepared and used by Tsaur and Fitch [35], namely, the styrene sodium dodecylsulfonate ether (SSDSE), with a CMC of 2×10^{-3} mol/L at room temperature. Styrene polymerization has been carried out both at 20°C using a photoinitiator (biacetyl) and at 65°C using KPS. In the first case, the stabilization is not good enough and SDS must be added in concentrations larger than that of SSDSE in order to obtain monodisperse particles in the range 140–260 nm with a surface charge density between 1.9 and 6.5 mC/m^2. When KPS is used as initiator, a good control of particle size is obtained between 150 and 400 nm (log D_n being proportional to log [SSDSE]) with excellent size uniformity ($D_w/D_n < 1.05$ [D_w is the weight average diameter of the particles]), the surface charge density being 4.0–14.0 mC/m^2. The main interest in that surfmer seems to be for surface functionalization of seeded particles. A polystyrene seed latex of 180–200 nm was used and copolymerization of SSDSE with styrene was carried out in the presence of water-soluble initiator. Monodisperse particles with no water-soluble polymer formation were obtained when [SSDSE] < CMC; the surface yield of SSDSE was between 10% and 60%, so that the surface charge density was well controlled between 10 and 100 mC/m^2 with a narrow charge distribution, as judged by electrophoresis experiments. When [SSDSE] was larger than CMC, polyelectrolyte was formed which could be separated from the latex upon several cycles of centrifugation and redispersion. It was concluded that this technique is quite useful for controlling the charge density of the latex particles.

In both studies of Greene [32] and Tsaur and Fitch [35], rather small amounts of polymerizable surfactants have been engaged, so that the surfmer was mainly adsorbed onto the surface of the seed. However, in both cases part of the polymerization process occurred in the water phase.

A comprehensive study of the behavior of another kind of polymerizable surfactant was published by the Lehigh group [36]. The surfmer sodium alkylallylsulfosuccinate (SAAS) is commercially available. Its behavior has been compared with its hydrogenated nonpolymerizable analog (H-SAAS). From its copolymerization behavior with vinyl acetate in homogeneous medium, the following reactivity ratios were determined: $R_{VA} = 0.36$, $R_{SAAS} = 0.48$. In addition, SAAS was proven to be an efficient transfer agent with a transfer constant of $C_T = 0.011$ whereas H-SAAS shows no transfer ability. It was observed that using SAAS the polymerization kinetics were slower than when using H-SAAS. Modeling showed that it is due mainly

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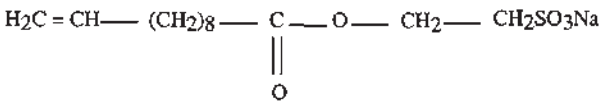
to the transfer events, which cause a partial desorption of the radicals; a secondary cause was the reactivity in copolymerization.

It was also observed that oligocopolymers of SAAS and vinyl acetate are found in the water phase in amounts increasing with the concentration of the surfmer and with the concentration of initiator. The incorporation of SAAS at the surface of polymer particles increases with the amount of the surfmer but decreases with increasing initiator concentration (for constant [SAAS]). The polymerization rate decreases when [SAAS] increases while the particle size decreases. The H-SAAS has the expected effect of a normal surfactant, decreasing the size and increasing the rate due to the higher number of particles with increasing concentration of surfactant. In the presence of H-SAAS, the initiator concentration has no effect on the size of the particles. In contrast, in the case of SAAS, the size increases with the concentration of the initiator. These results may be explained by termination reactions in the water phase, producing water-soluble oligomers of low molecular weight that do not participate in the nucleation of particles.

A set of smart experiments, involving competitive growth of two latex particles of different sizes, were carried out using either SAAS or H-SAAS. The normal behavior of growth with decreasing difference in the size of the two families of particles was observed with H-SAAS. In contrast, in the case of SAAS, the growth of the small particles was smaller and that of the big particles was correspondingly higher, with the effect enhanced by increasing SAAS concentration. In addition, the polymerization rate was decreased in the presence of SAAS. The explanation lies in the more important retardation of the polymerization process due to the low reactivity of the SAAS in polymerization and its good ability to copolymerize with vinyl acetate; its high transfer constant gives an additional explanation to the retardation effect, causing an enhanced exit rate for the radical and more efficient termination in the water phase. All of these results demonstrate the active part played by the surfmer in the polymerization process. However, it may be expected that some of these unusual results are due to the choice of the allyl function as the polymerizable function.

Chen and Chang [37] have used surfmer with a vinylic end group in the hydrophobic part (compound I in Table 3). The CMC at the polymerization temperature was 3.8×10^{-2} mol/L. Polystyrene latexes were prepared in the presence of KPS resulting in monodisperse particles in the range of 100–180 nm in diameter, increasing with solid contents, but with formation of coagulum at high solid contents. The number of particles increases as $[\text{surfmer}]^{1}$ and $[\text{KPS}]^{0.5}$ and is slightly sensitive to the ionic strength, passing through a maximum. The nucleation is considered to take place in a rather short period of time because the particles are somewhat monodisperse, and to follow a homogeneous mechanism. This is because the concentration of

TABLE 3 Ionic Surfmer Structures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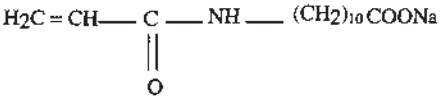
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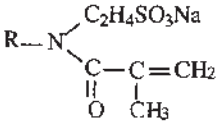
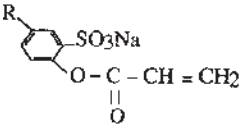
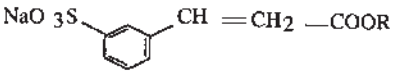
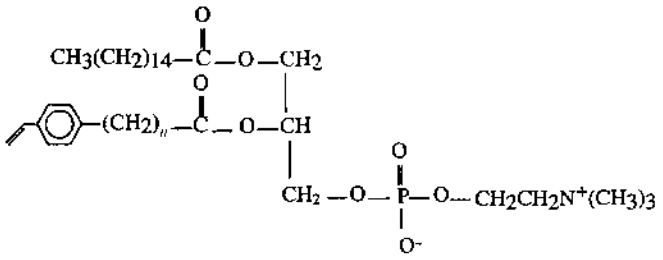

R = $C_{10}H_{21}$, $C_{12}H_{25}$ III


R = $C_{10}H_{21}$, $C_{12}H_{25}$ IV


R = $C_{10}H_{21}$ V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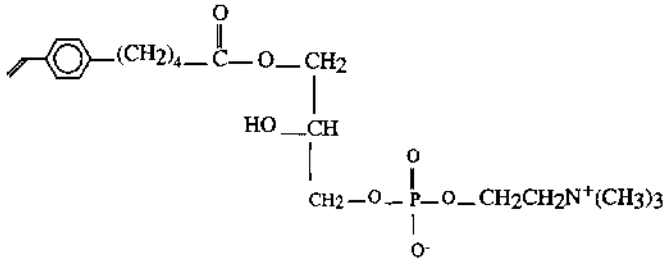
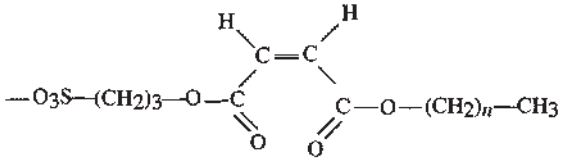
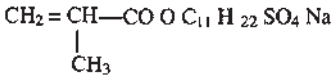

VII

TABLE 3 Continued



VIII



IX

surfmer was under the CMC, except possibly at high ionic strength where, due to the sensitivity of the CMC to the ionic strength, micelles are present; then both micellar and homogeneous nucleation can take place. That surfmer can be compared with sulfopropyl methacrylate (SPM), an ionogenic monomer used by Juang and Krieger [38] to prepare monodisperse polystyrene latexes. In that case; the absence of surfactant properties makes the nucleation strongly dependent on their ionic strength, with nucleation taking place in a homogeneous medium with aggregation, the stabilization being purely electrostatic. The number of particles is proportional to $[SPM]^2$ and $[KPS]^1$. So it appears that introduction of surfactant properties to the monomers used for stabilizing the particles causes a drastic change in the nucleation mechanism.

A carboxylate surfmer (II in Table 3) has been studied by Guillaume et al. [39] for the purpose of preparing latexes carrying only carboxylic surface groups. Sodium acrylamidoundecanoate (SAU) has been used, with a CMC at 25°C of 5×10^{-3} mol/L. It has been utilized in copolymerization with styrene (S) and butylacrylate (B), initiated at 70°C by an azocarboxy compound. The reactivity ratios with S and B were measured (S) or estimated (B) from the Q, e scheme; the partition coefficients of SAU and the comonomer between water and organic phases were also measured, so that a simulation of the copolymerization process was obtained that shows an S shape for the conversion of SAU, indicating that most of that surfmer is polymerized only at the end of the polymerization process. This results in poor stability at ionic strength greater than 10^{-2} N, most of the SAU being used as adsorbed emulsifier during the process. Polyelectrolyte is formed in the later stages, causing flocculation, so that the particle number N_p goes through a maximum with increasing conversion. Before the maximum, N_p varies as $[SAU]^1$ as in the case of surfmer I. The surface yield in COO^- is limited to 20–30%, a part of the COO group being buried inside the particles (10–50%) mostly when solid contents are high (30%). The remaining part is in the water phase as polyelectrolyte or residual monomer.

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According to Krieger [38], seeded polystyrene latexes prepared with KPS and SPM were used to study its coverage by SAU. The surface yield of carboxylic groups was limited to the range 25–35%.

A Russian team [40] described the use of a few new surfmers, one being cationic, namely, *N*-decylaceto-2-methyl-5 vinylpyridinium bromide, and the others being anionic, namely, decyl (or dodecyl), sodium ethylsulfonate, methacrylamides (III in Table 3), decyl (or dodecyl)-phenyl (Na or K sulfonate) acrylate (IV in Table 3), and decyl ester of sodium (or K or NH_4^+) sulfocinnamic acid (V in Table 3). These surfmers were used for emulsion polymerization of styrene, butylacrylate, or chloroprene in the presence of KPS or AIBN without any other surfactants. It should be noted that consumption of these surfactants takes place early in the polymerization process, which is faster than in the case where SDS is used as surfactant. No emulsifier is left in the water phase, and the latexes are highly stable with regard to electrolyte, temperature, and redispersion.

Phospholipidic compounds carrying polymerizable groups such as VI and VII in Table 3 have been shown [41] to allow the preparation of stable monodisperse polystyrene latexes, with diameters in the range of 200–300 nm, carrying a phospholipid layer on their surface with yields higher than 75%.

Most of the reactive surfactants already used for emulsion polymerization have their reactive group at the end of the hydrophobic part of the surfactant. This seems to be obvious because the main polymerization process takes place in the latex particle on which that hydrophobic part is, at least, adsorbed if not anchored. Demonstration of the rightness of this choice has recently been done by Sherrington [42] who showed that the other choice (end of the hydrophilic chain) with an acrylated end group led to worse stability, as compared with the equivalent bearing an ethyl ester group.

One of the drawbacks of the surfmers with allylic, acrylic, and vinylic polymerizable groups is their tendency to produce water-soluble polyelectrolytes when used in too large amounts, i.e., above their CMC. This problem may be overcome by using maleic derivatives, which can copolymerize but are unable to homopolymerize at normal temperatures because their ceiling temperature is very low. Surfmer VIII of Table 3 can be prepared easily by first reacting maleic anhydride with a fatty alcohol, the resulting hemiester being further reacted with propanesultone [17]. A series of such surfmers have been prepared [16] with an alkyl chain length from 12–18 carbon atoms and CMC from 1 to 0.1 mmol/L. These surfmers can be very efficiently bound to the latex particle surface when used in emulsion polymerization of styrene. The surface tension of the latex serum can be kept very high (above 70 mN/m) after the polymerization even if amounts greater than 100 times the CMC are used. Due to the fact that the maleic surfmers are only able to copolymerize, the surfactant is expected to be bound covalently to the polymer chains.

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Recently, this kind of surfmer was studied in more detail [43] in the copolymerization of styrene, butylacrylate, and acrylic acid (49:49:2) in semicontinuous (seeded or nonseeded) protocols at 30% or 50% solid contents recipes, on the basis of kinetics (both overall and instantaneous whole conversion), evaluation of the surface tension, and amount of coagulum produced. The reactivity ratios with the comonomer have also been measured for the reaction that took place in water phase, and a two-phase titration technique has been developed to analyze the conversion of the surfmers. The behavior of these surfactants was compared to that of a methacrylic compound and a crotonic compounds (IX and X of Table 3).

On the basis of the reactions described it can be concluded that the maleate surfmer is the most interesting surfmer of the three investigated for the styrene-butylacrylate-acrylic acid system from the point of view of reactivity/copolymerization behavior. The methacrylate surfmer is too reactive, and the crotonate surfmer is not reactive enough. In case of the maleate, it seems possible to reach relatively high conversions in the absence of homopolymerization in the aqueous phase, which can lead to premature emulsion instability. It was found that a high instantaneous conversion throughout the reaction can lead to significant burying of surfactant in the particle interior. A strong dependence of the maleate surfmer conversion on the particle diameter was found, and although high conversions are reached for small particles up to 100 nm in diameter, above this value the maleate conversion decreases steadily with diameter. This is in agreement with a reaction at the particle surface. It is also concluded that although the maleate surfmer may be the best of the three investigated surfmers for the present system, the ideal surfmer behavior cannot be obtained. The ideal situation would be a moderately reactive surfmer with low conversions during the reaction, and high conversion at the end of the reaction brought about by a change in reactivity of the surfmer or of the main monomers [44]. From that definition of the ideal situation and observations that have been made, several strategies have been proposed to optimize surfmer use, i.e., to achieve both high surface coverage and high surfmer conversion.

In one example, a mixture of vinyl esters was added during the final discontinuous stage of an S-BA emulsion copolymerization carried out in a semibatch reactor using a maleate surfmer. In the absence of vinyl esters, the final conversion of the surfmer was 52%, whereas with vinyl esters the surfmer conversion increased from 52% to 80% in the last batch stage [44].

In some systems the main monomer reactivity decreases automatically due to strong composition drift. For example, in systems where one of the main monomers is very unreactive, this monomer will not be incorporated to the same degree as the more reactive monomers, and even in monomer-starved

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semicontinuous reactions a considerable portion will be left over at the end of the feeding period, when the more reactive monomers have been depleted. Then the unreactive surfmer, which has not reacted considerably up to that point, can start to copolymerize.

An example of this behavior is the emulsion terpolymerization of MMA/BA/VA:vinyl acetate (50:35:15 wt/wt/wt) using a maleate surfmer [VIII in Table 3]. VA:vinyl acetate is by far the least reactive monomer and accumulates in some extent in the reactor during the semicontinuous operation. At the end of the addition period, the surfmer conversion was about 60%, and during the final discontinuous stage complete conversion of the surfmer was achieved.

A second strategy that was proposed consisted of offering a larger surface area for the adsorption of the surfmer and its further reaction at the end of the process. Another experiment was proposed in which at the end of the polymerization a new crop of seed particles would be introduced together with a small amount of monomer, just to swell these particles. It was observed that conversion of the surfmer was increased from 52% to nearly 100% [44].

The very simple maleate surfmer, which is the precursor of the maleate surfmer (just the neutralized hemiester of a fatty alcohol), also gave very good results [45]. It was used to prepare seeds of polystyrene latex with small particle size (100 nm) which were grown up to 200 nm with a shell of film-forming copolymers. Use of a convenient addition profile, with a first addition at the beginning of the feed and then a continuous feed of the surfmer together with a separate continuous feed of the comonomers, allows one to reach a high incorporation yield of about 75% [46]. These simple surfmers confer to the latexes a remarkable stability; later it was shown that the corresponding hemiamides, prepared upon reaction of fatty amines with maleic anhydride, confer to the latexes an even better stability and are less sensitive to hydrolysis at high temperature [47]. Simple hemiesters (C_{12} chain) have been used in the synthesis of all acrylic latexes prepared in a power-feed reactor allowing progressive modification of the composition of the latex particles from the core to the shell, and useful in the formulation of wood stain varnishes as well as printing inks and metal coatings. The films from these latexes show improved properties in terms of blocking, weatherability, and wet adhesion [48]. The origin of the improvement of the blocking properties lies in the fact that in the coalescence process of the particles the development of the cohesive energy is more rapid with these films than in similar latexes using SDS as conventional surfactant [46]. Another application of these hemiesters was recently patented [49]. This patent deals with the polymerization of chloroprene to produce adhesives with lower water uptake than products prepared using the conventional collophane surfactants.

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A Japanese company [50] studied a series of allylic surfactants such as 1-nonylphenoxy-2-polyoxyethylene-3-allyloxy propane and their sulfate and phosphate derivatives, along with their use in the emulsion polymerization of acrylic ester copolymers. Their major interest lies on improvement of their foaming properties. The same company put on the market another series of methallyl surfactants of the same nature [51].

A few promising results were obtained using cationic and zwitterionic derivatives of the hemiester cited above. Their synthesis involves first the reaction of an hemiester (or an hemiamide) with an alkyl chain of 12–20 carbon atoms with diethyl(chloroethyl)amine. The resulting tertiary amine is then quaternarized using ethyl iodide, allylbromide, hydrochloric acid, or sulfuric acid to give cationic surfactants, or reacted with propanesultone to give zwitterionic surfactants. Both syntheses produce monodisperse particles of polystyrene, with the cationic one leading to small particles [52]. A series of surfmers derived from the hemiamides and the hemiesters of maleic anhydride have been studied and characterized, as have the analogous compounds derived from succinic anhydride [53,54]. These surfactants are reported in Table 4 along with a number of other cationic surfactants from other studies [55,56]. In [55], the hemiesters were reacted in the presence of catalysts (DCC, DMAP) with α-ω-bromo-alkanol at low temperature, and then with pyridine. It results in quaternarized pyridinium diesters with (4, 5 in Table 4) or without (6 in Table 4) reactive double bonds, depending on the nature of the initial hemiester (maleic or succinic). In [56], two series of surfmers are described: one of the head type, where a vinylbenzyldimethylamine is quaternarized with a long-chain alkyl halide (7 in Table 4),while in the series named tail type a vinylbenzyl (or a methacryloyl) alkylbromide is quaternarized with trimethylamine (8 in Table 4).

Both the head-type surfmers and the tail-type compounds were used as adsorbants on colloidal silica particles before spontaneous polymerization (without initiators) upon increasing the temperature, to produce colloidal nanocomposites [56].

The other cationic and zwitterionic maleic surfmers and similar compounds derived from succinic anhydride instead of maleic anhydride have been engaged in emulsion polymerization of styrene or copolymerization of styrene and butyl acrylate, and compared with the same kind of latex using SDS as surfactant [52,57]. All surfactants can produce stable latexes with high conversion. In the case of cationic surfmers, small polystyrene particle size (30–50 nm) can be obtained, depending on the counterion (Br^- and SO_4^- being the best, as compared with Cl^-), and the latexes can resist moderate addition of $MgSO_4^{2-}$ but not the freeze-thaw test. In the case of zwitterionic surfmers, the particle size is much larger (300 nm). In the case of film-forming copolymers, whatever the surfactant type is, rather high polymerization rates can be

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TABLE 4 New Cationic Reactive Surfactants

N°	Formula	CMC (mmol/L)
1	$C_{12}H_{25}OCH=CHCOO\text{-}(CH_2)_2N^{\circ}(C_2H_5)_2\ C_2H_5I^-$	0.041
2	$C_{16}H_{33}OCH=CHCOO\text{-}(CH_2)_2N^+(C_2H_5)_2\ C_2H_5Br^-$	0.006
3	$C_{16}H_{33}OCH=CHCOO\text{-}(CH_2)_2N^+(C_2H_5)_2\ C_3H_6SO_3^-$	0.007
4	$C_6H_{13}OCH=CHCOO\text{-}(CH_2)_6N^+(C_5H_5)\ Br^-$	3.6
5	$C_{12}H_{25}OCH=CHCOO\text{-}(CH_2)_2N^+(C_5H_5)\ Br^-$	0.32
6	$C_{12}H_{25}O\ CH_2CH_2COO\text{-}(CH_2)_2N^+(C_5H_5)\ Br^-$	0.11
7	$CH_2=CH(C_6H_4CH_2N^+(CH_3)_2C_{16}H_{33}Cl^-$	
8	$CH_2=CH(C_6H_4\text{-}C_{10}H_{20}N^+(CH_3)_3\ Cl^-$	

reached with high conversion and particle size in the range 100–180 nm. However, some of them (the C_{16} derivative of the zwitterionic compound, for instance) confer to the latex a surprising stability with resistance to electrolyte addition and even to freeze-thaw test. No essential difference was observed for stability tests using nonreactive succinic or reactive maleic surfactants [57]. However, again, differences appear with the films from latexes using the two classes of surfactants [59]. Without doubts the water rebound of the films is smallest in the case of reactive surfactants, as shown in Figs. 2 and 3.

The cationic derivatives containing pyridinium moieties were also engaged in styrene emulsion polymerizations [58]. It appears that the maleic surfmers are able to give higher polymerization rates than the succinic surfactants. Particle sizes range from 100 to 200 nm, while the best results in terms of coagulum production are obtained from the longer initial chains of the hemiesters. However the succinic derivatives lead to better resistance vs. electrolytes addition. On the other hand, long alkyl sequences in between the ester group and the pyridinium end lead to immediate flocculation in the same tests of electrolyte addition.

Further studies also deal with the use of the dodecyl moiety of the allylic compound SAAS (already studied by Urquiola [36] in the semibatch polymerization of butyl acrylate. Such surfactant was reported to behave like SDS, with the fraction of chemically incorporated surfactant burried inside the particles increasing with the size of the particles [60]. A study of the stability of these latexes was recently reported, showing the influence of the shear rate during the polymerization, as well as the critical coagulation concentration (CCC) in the presence of electrolytes [61].

Recently, Nagai et al. [62] functionnalized polystyrene microspheres with a series of activated esters surfmers; obtained from condensation of un-

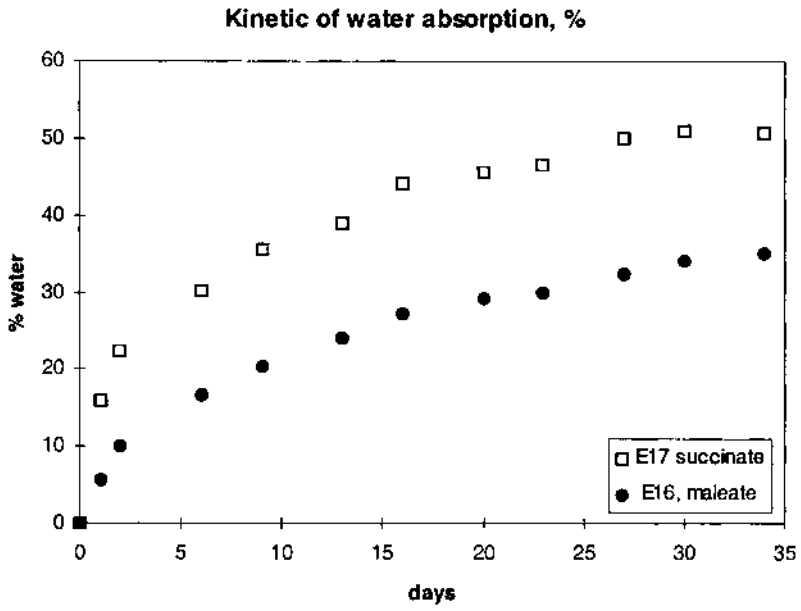

FIG. 2 Kinetics of water absorption of films from latexes prepared using zwitterionic surfactants: succinic (open squares) and maleic (filled circles). (From Ref. 59.)

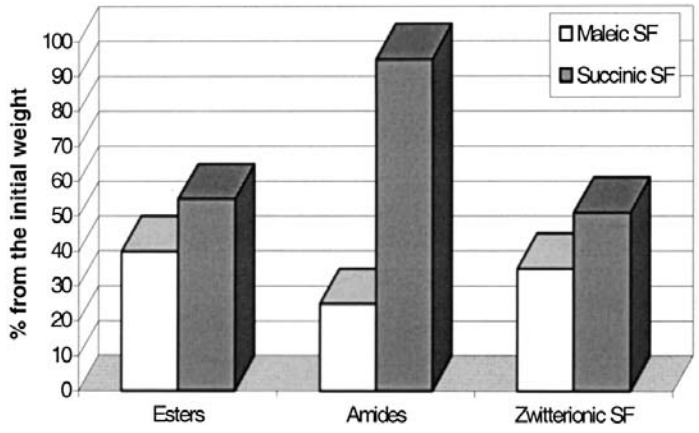

FIG. 3 Comparison of the warze uptake of films prepared using the three series of surfactants (hemiesters, hemiamides, zwitterionics). (From Ref. 59.)

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saturated carboxylic acids (methacrylic, vinylbenzoic, acrylamidoundecanoic,decene-1-yl) onto hydroxyphenyldimethylsulfonium methyl sulfate. That technique lead to a high density of reactive groups at the surface of the cationic latexes that could find uses in biotechnology.

Some derivatives of isophthalic acid, polymerizable or not, have been engaged in emulsion polymerization of various usual monomers [styrene, methyl methacrylate (MMA), butyl acrylate (BA)] in comparison with SDS [63]. Their synthesis involves the condensation of *p*-phenolisophthalic diester on either a long-chain hydrocarbon or an alkylstyrene before hydrolysis of the esters groups.Both potassium salts of these compounds are efficient stabilizers, allowing the production of small-particle (40–80 nm) latexes with high conversion, and good stability. The styrenic surfmer is able to copolymerize in good yields and imparts to the latex an improved stabilization.

The acylation of alcohol-containing monomers, such as hydroxyethyl acrylates and methacrylates or vinylbenzyl alcohol, with maleic, or succinic, or sulfosuccinic anhydride, allows easy preparation of bifunctional polymerizable surfactants [64]. Some among these compounds, listed in Table 5, have been engaged in batch polymerization of styrene as well as in core-shell copolymerization of styrene and butyl acrylate. Stable latexes have been obtained in both cases, with only low floc production. A high conversion of the surfmers was most often reached, with little burying. However, these latexes do not show a noticeable resistance to the addition of electrolytes and cannot withstand freezing tests; these features are not so surprising because their stabilization is only electrostatic and in no way steric. It can be noted, however, that their water rebound is somewhat limited, unless their water

TABLE 5 New Anionics Polymerizable Surfactants

Name	Formula	CMC (m/L)	γ (mN/m)
BAM	$CH_2=CHCOO(CH_2)_4OCOCH=CHCOOH$	0.040	33
MAPM	$CH_2=CH(CH_3)COOCH_2CH(CH_3)OCOCH=CHCOOH$	0.035	45
MAEM	$CH_2=CH(CH_3)COO(CH_2)_2OCOCH=CHCOOH$	0.220	32
VBM	$CH_2=CHC_6H_4CH_2OCOCH=CHCOOH$	0.008	46
VBS	$CH_2=CHC_6H_4CH_2OCOCH_2CH_2COOH$	0.002	45
MAS	$CH_2=CH\ (CH_2)_2OCOCH_2CH_2COOH$	0.054	55
BAS	$CH_2=CH\ (CH_2)_4OCOCH_2CH_2COOH$	0.016	52
VBSS	$CH_2=CHC_6H_4CH_2OCOCH_2CHSO_3COOH$	0.0092	56
MAESS	$CH_2CH_2SO_3\ COO\ CH_2CH_2OCOCH=CH\ COOH$	No CMC	

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solubility is so high that they do not show a well-characterized CMC (case of MASS).

E. Nonionic Surfmers

In the field of nonionic surfactants, the pionering work has been done by the group of Ottewill, using a methacrylic macromonomer of polyethylene glycol [65], now available commercially. This nonionic stabilizer has been used with charged latexes from persulfate initiator as well as noncharged latexes from an organic redox system, and in combination with nonionic nonreactive surfactant. The reactive surfactant seems to be preferentially located on the surface of the latexes, where it may tend to replace the nonreactive nonionic one, which was then burried inside the latexes, causing a depression of the glass transition temperature. The noncharged latexes exhibit excellent stability vs. electrolytes; later they were shown to resist freeze-thawing experiments [66]. In a much more recent paper [67], the same authors have studied the effect of addition of the same macromonomers on a surfactant-free latex initiated with potassium persulfate, at different times of the polymerization. It was known that the basic system (surfactant-free latex) leads to monodisperse particles. The addition of the macromonomers at this initial stage of the polymerization process led to the formation of a second population of larger particles. The balance between the two population is shifted toward the smaller particles when the addition of the macromonomer takes place later in the process; if the addition is carried out when most of the monomer has been consumed, only one population of particles is observed again. However, the behavior of the latex vs. electrolytes or vs. a test of freeze thawing shows that at least a part of the macromonomers has been grafted because the latex show an excellent stability in both cases. If the addition takes place at intermediate steps, intermediate electrosteric stability can be observed.

From the initial work of the Ottewill group, ICI has developed two industrial processes. The one named NIAD (nonionic aqueous dispersion) is actually an emulsion process using either a noncharged redox initiator (hydrogen peroxide + ascorbic acid) or a water-soluble azo initiator [68a,68b]. The reactive surfactant can be the methacrylic macromonomer of polyethylene glycol or a triallyl derivative of pentaerithrol containing a block copolymer of butylene oxide (2 units) and ethylene oxide (35 units). In the latter case, due to the low reactivity of the allyl group with styrene derivatives, the system cannot be used with such monomers. But using the macromonomer, the system lead to stable latexes only if the solubility of the monomer is limited (it fails, for instance, with methyl methacrylate). On the other hand, rather high concentration of macromonomer must be used (at least 3%) in

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order to get stable latexes. Another parameter is the polymerization temperature which should be low enough to not reach the cloud point of the reactive surfactant (or precursor).

The second process developed by ICI, named Aquersymer [69], is actually a dispersion polymerization process, using as a continuous medium a mixture of alcohol (methanol, ethanol) and water; the medium is a solvent of the monomer, but the polymer is not soluble. The stabilization is provided by the macromonomer of polyoxyethylene; it may be used as a preformed copolymer or, preferably, produced in situ. Particle size in the range 100–450 nm can be produced at solid contents up to 40–50%.

Important parameters are the composition of the alcohol–water system [between 60–40 (vol/vol) and 30–70 (vol/vol)] and the length of the polyoxyethylene sequence. Most of the usual monomers can be used, with the exception of MMA if it is used alone (it can be used as a comonomer when the T_g of the resulting copolymer remains lower than 40°C). The latex displays good stability as well as good film properties.

The Australian branch of ICI has also developed another kind of technology based on allylic reactive surfactants wherein a preformed polymer (such as an alkyd or an epoxy resin) is dissolved in a suitable monomer mixture that is polymerized in the presence of the reactive surfactant and water. Because organic initiator are used, the process is actually a suspension process [70].

A group at Procter and Gamble [71] have used diblock copolymers of ethylene oxide and propylene oxide, functionalized by a vinylbenzyl chain end, located at the end of the hydrophobic block in the emulsion polymerization of styrene. Good stability vs. electrolyte addition have been observed even if the latex were cleaned with ethanol, when nonionic initiators were used. At variance, if potassium persulfate was used, the latex displays poor stability.

Another estimate of the incorporation yield of a styrenic surfmer of polyethylene oxide in batch copolymerization with styrene has been published recently. The polyethylene oxide absorbance can be estimated (using NMR) in the latex produced [72]. The incorporation yield was shown to be between 7–42%, most of the surfactant remaining in the serum. Latex stabillity involves a long enough polyoxyethylene sequence (around 50 units). At variance with saccharide surfactants [73], copolymerization of the styrene with a more hydrophilic monome such as methyl methacrylate tends to reduce the incorporation yield.

The same problem of incorporation is also under examination with block copolymer of ethylene oxide and butylene oxide, already quoted above for inisurfs and transurfs, but functionalized with various polymerizable groups such as acrylic, methacrylic, and styrenic. These surfactants are produced by ring-opening anionic polymerization of butylene oxide, initiated by the

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monomethyl ether of polyoxyethylene. The polymerization, which is a living one, can be killed in the same reactor by an acid chloride (acrylics) or vinylbenzyl chloride (styrenic). Latex with high solid contents can be produced that display an excellent stability vs. freeze thawing and electrolytes, provided a correct protocol is adopted for the introduction of the nonionic surfmers. However, flocculation can follow an inadequate protocol [74].

A Japanese group [75] has carried out cationic ring-opening block copolymerization of 2-methyl-2-oxazoline (hydrophilic sequence) and 2-butyl-2-oxazoline (hydrophobic sequence) initiated by vinyl iodoacetate. This is a living polymerization, so that the two sequences were produced in two steps. The vinyliodoacetate initiator provides the polymerizable group, and it is possible to begin the polymerization either by the hydrophilic sequence or by the hydrophobic sequence. In both cases the initiation reaction seems to be faster than the propagation reaction, so that the length of each sequence can be well controlled by adjusting the ratio of oxazoline monomers to initiator. It appears that the rates of vinyl acetate polymerization were faster when the hydrophobic sequence was involved in the first step of the synthesis of the polymerizable surfactant. Correspondingly, the size of the particle was smaller (e.g., 90 nm in diameter instead of 220 nm when using similar amounts with similar structure) but with the reverse order in the two sequences (hydrophilic and then hydrophobic).

The group of Pichot [73,76–80] prepared some macromonomers and reactive surfactants with hydrophilic part different from polyethylene oxide sequences. They further applied such compounds to surface functionalization of seed latex of polystyrene. A first compound was a macromonomer of polyvinyl alcohol prepared from aldol group transfer polymerization [76,77], whereas a second series dealt with saccharidic monomers [78,79] containing a polymerizable group (styrenic or methacrylic), a hydrophobic spacer (hydrocarbon chain), and a saccharidic moiety (dissaccharide, CHMA) or maltobionamide (LIMA). These studies were quite complete, including determination of the reactivity ratios of the macromonomers with styrene [76,78], the surface activity of the reactive surfactants [77,79], and the characterization of the stabilizer at the surface of the seeded latex particles, which is studied by various methods such as NMR in deuterated dimethylsulfoxide (showing only the hydrophilic sequence) after elimination of the serum by centrifugation, electron spectroscopy for chemical analysis (ESCA) and X-ray analysis and finally electrophoretic mobility [73,77–80]. In addition, some analysis of the serum by NMR after redissolution in deuterated dimethylformamide allowed estimation of the yield of the incorporation of the stabilizer at the surface (or inside) of the particles [80], which in the case of LIMA was estimated at 50–70%.

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Styrenic surfmers have been prepared recently [81] with the following strategy: potassium vinylbenzyl alcoholate was used to initiate the ring-opening polymerization of first butylene oxide and then ethylene oxide. The resulting living block copolymer was either killed with diluted methanolic solution of hydrogen chloride, thus producing a nonionic surfactant, or used for ring opening of propanesultone, so giving an anionic sulfonated surfactant. It was then possible to control the length of the hydrophobic and hydrophilic sequences, and consequently control the HLB balance. Most of the yields of the polymerization were almost quantitative, with quite narrow molecular weight distributions, as can be expected from this kind of living polymerization of course, the CMCs are dependent on the structure of the copolymers, and are in between 4 and 180 $\times$ 10^{-6} mol/L. Of course, the anionic surfmers are more water soluble than the corresponding nonionic surfmers. Similar nonreactive surfactants were obtained using methylbenzyl derivative as initiator instead of the vinylbenzyl compounds.

These styrenic surfmers have been engaged in the seeded copolymerization of a 1:1 mixture of MMA and BA [82]. The styrenic block copolymer surfactants, either nonionic or anionic (with sulfonated chain end groups), allow the preparation of stable core-shell particles, with a core of PMMA and a film-forming shell of copolymer PMMA-PBuA, giving stable latexes with very small amounts of coagulum with up to 40% solids content. The stability of these latexes depends on their structure, and the best results have been obtained with a rather short hydrophobic butylene oxide chain and a moderate hydrophilic sequence of around 35 ethylene oxide units. The best latex stabilization has been obtained using surfmers, even in compared with an efficient industrial surfactant like NP30. Depending on their HLB balance, some of these surfactants confer to the latexes an outstanding stability. These interesting surfmers have somewhat high CMCs of around 0.2 mmol.L^{-1}. Similar but nonpolymerizable structures (a methyl group replacing the vinyl) also give good results, but the latexes derived from these nonreactive surfactants do not resist shear testing. However, they can resist ethanol testing and even freeze-thawing testing, showing that they are strongly adsorbed onto the particle surface. More data on the structure of the surface of the particles and on ways of incorporating the surfmers have been obtained [83] through analysis of the surfactants desorption by ultrafiltration, as well as of the conformation of the surfactants at the particle surface by NMR with suppression of the signal from water, with addition of about 10% deuterated water in the serum. From the ultrafiltration technique it can be shown that, using a replacement factor of at least 200, it is possible to recover most of the surfmer as copolymers, the composition of these copolymers being poor in butyl acrylate; most of the recovered materials are copolymers of MMA and surfmers, and the amount is less and less important. In the case of the non-

reactive MB surfactants, all of the surfactant is recovered after a replacement factor of 5. The rather special technique of NMR analysis of the hydrophilic surfactant located on the particle surface can demonstrate that, in the case of the surfmers, about 95% of the surfmer is not in the serum, whereas this amount decreases to 85% for the MB surfactants. Furthermore, it can be shown that only part of the polyethylene oxide sequence is mobile in the serum, showing a narrow signal, whereas the other part remains adsorbed onto the surface and is much less mobile, giving a broad signal.

Surprisingly, the morphology of the particles from the nonpolymerizable surfactants is more regular than that from the polymerizable surfactants. The latter reveal some protuberances, and the aged films formed from them seem weaker in ultimate mechanical properties. It is suggested that the high reactivity of the styrenic surfmer is capable of fixing them irreversibly onto the surface but does not allow the coverage to reach a regular equilibrium, so that some parts of the particle surface are not well protected, giving rise to limited local floculation and agglomeration of a small number of particles.

The more interesting property of the films from polymerizable surfactants is undoubtedly their behavior in the presence of water. The fact that the reactive surfactants remain more fixed to the surface of the particles largely limits their migration toward the surface, which is then more hydrophobic as shown by contact angle measurements. In addition, the water uptake of these films is much lower. After dipping these films in water, their weight gain is reduced to less than 60% rather than 90% for the nonreactive surfactants. Consequently, their dimensional stability is much higher. Halter-shaped film samples, dipped during one month into water, are keeping about their length when they have been obtained from latexes using surfmers, whereas they show a 50% elongation when nonreactive surfactants have been used. Another set of polymerizable surfactants have been prepared [84] using, as in the work of Schechtman [71], the reverse strategy: the hydrophilic sequence of polyethylene oxide is prepared with 37 units, followed by a rather short sequence (10 units) of polypropylene oxide; the living block copolymer was then killed with a reactive chloride carrying the polymerizable or an equivalent group, or used to open the ring of maleic anhydride to give a maleic surfmer.

This second set of nonionic surfmers was engaged in core-shell emulsion copolymerization of 1:1 tyrene-butyl acrylate, in comparison with a commercial nonionic surfactant NP30 [85]. High conversions were obtained in all cases, with limited amounts of floc at solid contents of 35%. To reach the targeted size of 240 nm, the amount of surfactant must be adjusted. Too much surfactant causes nucleation of new particles without decreasing the amount of floc, whereas in the reverse case limited flocculation is observed (slightly larger particles) and more floc is produced.

The methacrylic surfmer (Mac) was fully incorporated during the emulsion polymerization process but partially buried inside the particles (28%). The latex is then stable even against freeze-thawing tests. In the case of the commercial surfactant, as well as in the case of the nonpolymerizable surfactant (Iso) with a structure very similar to that of the surfmers, and also in the case of the maleic surfmer, all of the surfactant can be extracted with acetone and then is not incorporated. The allylic surfmer (All) causes the formation of acetone-extractable oligomers, probably because it behaves also as a transfer agent. It is partially incorporated in the high copolymer mass and does not provide stability against the freeze-thawing test. The same conclusion is valid in the case of the vinylic surfmer (VA). It also produces acetone-extractable oligomers, but for reasons of reactivity in copolymerization rather than for transfer activity. Upon replacement of the styrene with methyl methacrylate with the vinylic surfmer (VA), a more stable latex is obtained (stable to freeze-thaw cycles), and the surfmer is fully incorporated due to better reactivity of MMA with the vinylic surfmer (VA) in comparison with styrene. However, in the same way, some surfmer (28%) is buried in the latex particles. The balance of the different surfactant locations are reported in Table 6, as well as the weight–average molecular weight of the main polymer and of the acetone extract obtained in two cases.

We can assume that the theory defining an "ideal" surfmer as moderately reactive at the beginning of the process and highly reactive only at the very end of the polymerization is not so realistic because a low-reactivity surfmer gives a latex with low surfmer incorporation. On the other hand, using a high-reactivity surfmer produces a latex with almost 100% surfmer incorporation but with some of it burried in the latex particles. In replacing a conventional surfactant by a reactive one (surfmer), colloidal stability are improved, such as freeze–thaw cycles and addition of organic solvent (e.g., acetone). However, because it is reactive, it will react all along the polymerization process, and a part of it will be buried in the latex particles (in

TABLE 6 Balances for Surfactants %

		acetone extract		high polymer fraction		
Surfactant	Nonreacted	Free	Polymer	MW	Free	MW
Iso	16	84	0		0	164000
Mac	15	0	0		85	174000
Hem	11	89	0		0	162000
All	12	27	40	45000	21	121000
VA	(12)	21	54	66000	13	145000

this chapter around 30%). Unfortunately, there is no way to avoid this phenomenon. In order to synthesize a similar latex (particle size and distribution, solid contents, amount of flocculation) with a surfmer rather than with a conventional surfactant, latex producers will have to adjust the amount and the reactivity of the surfmer vs. monomers in the emulsion polymerization process.

In a recent study, Tuncel and Serpen [86] used a macromonomer of a very short polyoxyethylene chain ($n = 3$) and an ethyl methacrylate polymerizable group, which was applied to emulsion copolymerization of styrene and methacrylic acid. The effects of concentrations of reactants on the particle size and on the polymerization rate were studied in detail, but no data concerning the stability of the latexes have been reported.

The synthesis of two sets of nonionic surfmer derived from maleic hemiesters has been described recently [87]. The first set is composed with amidoesters resulting from reaction of the activated form of the acidic group reacted with an amine, whether primary, secondary, or tertiary, whereas the second set is obtained more simply from condensation of the hemiester with glycidol under acidic or basic conditions. Some data about these surfmers are reported in Table 7. Both sets have been successfully engaged in emulsion polymerizations: either batch polymerization of styrene, or seeded core-shell copolymerization of styrene and butyl acrylate in a semibatch process. High conversions were obtained in all cases resulting in monodisperse stable latexes with limited amounts of floc at 20% solid contents. Characterization of the latexes by different methods permits the conclusion that the surfmers have been incorporated with a high yield. However, tests of stability were disappointing: the latexes are floculated, as well upon freezing as upon addition of electrolyte, which means that the surfmers do not provide them with the expected steric stabilization but rather keep an electrostatic stabilization

TABLE 7 Nonionic Amidoesters and Diesters

Ref.	Formula	CMC (mmol/L)	γ (mN/m)
12M	$C_{12}H_{25}O\text{-}COCH=CHONH(CH_2CH_2OH$	0.031	28.2
12D	$C_{12}H_{25}OCOCH=CHON(CH_2CH_2OH)_2$	0.048	30.4
12T	$C_{12}H_{25}O\text{-}COCH=CHONHC(CH_2CH_2OH)_3$	0.059	34.9
16M	$C_{16}H_{33}O\text{-}\ COCH=CHONH(CH_2CH_2OH$	0.047	26.8
16D	$C_{16}H_{33}O\text{-}\ COCH=CHON(CH_2CH_2OH)_2$	0.077	41.7
16T	$C_{16}H_{33}O\text{-}\ COCH=CHONHC(CH_2CH_2OH)_3$	0.088	42.7
16G1	$C_{16}H_{33}O\text{-}COCH=CHCOOCH_2CHOH\text{-}CH_2OH$	0.080	31.5
16G2	$C_{16}H_{33}O\text{-}COCH=CHCOO(CH_2CHOHCH_2O)_n$	0.159	40.6

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probably due to the sulfate groups of the initiator residues. It is suggested that this lack of steric stabilization results from the nonpolymeric character of the hydrophilic part of these surfactants.

Recently, the company Uniquema developed on a commercial scale a new surfactant named Maxemul 5011, with the reactive group in between a long hydrophobic alkyl chain and the hydrophilic nonionic part. The precise formula was not disclosed, nor was its preparation procedure. A few reports have been given at various meetings, and the first publication appeared recently [88]. High-solids (50%) latexes of film-forming copolymers MMA/BuA, with particle sizes in the range 150–180 nm, using 3% of the surfmer and KPS as initiator, which provide additional stabilization with anionic charges were obtained. Feeding partly with a mixture containing acrylic (or methacrylic) acid at the end of the polymerization confers further stabilization to the latex. The latexes are stable against addition of electrolytes, but not against the freeze-thawing tests. It is thought that the surfmer conversion can be measured, using high-performance liquid chromatography (HPLC), but no data are given. A phosphonic derivative of this surfmer has been mentioned at a meeting.

III. OTHER POLYMERIZATION PROCESSES

A. Introduction

Besides emulsion polymerization, all of the heterogeneous processes of polymerization use surfactants. The only exception is precipitation polymerization, such as of vinyl chloride, where the only active ingredients are the monomer and the initiator. These heterogeneous processes are suspension polymerization, dispersion polymerization, polymerization in mini- and microemulsion, and, finally, micellar polymerization. Among these processes only the suspension polymerization meet industrial importance, chiefly for vinyl chloride and styrenic compounds.

The suspension polymerization requires stabilization, which is generally provided by the so-called suspension agents. There agents may be inorganic, such as bentonite or tricalcium phosphate, or organic, such as water-soluble cellulosic polymers or polyvinyl alcohol. The latter is generally derived from polyvinyl acetate which is not fully hydrolyzed so that it has some surface activity, which is generally completed by additional grafting of the growing polymers. Conventional surfactants can be used with these systems in order to complete the control of stabilization and some other properties such as the porosity in the vinyl chloride polymerization (nonionic surfactants) or the broadness of the particle size distribution in the styrene polymerization (e.g., the association of sodium dodecyl benzenesulfonate with tricalcium

phosphate). However, up to now the surfactants used were not reactive. The only exception is the use of very small amounts of potassium persulfate in the polystyrene process stabilized with calcium triphosphate. In that case, as was recently demonstrated [89], oligomers of styrene can be produced that have surface activity due to their charged sulfate end group. The remainder of this chapter will focus on three processes: dispersion polymerization, polymerization in mini- and microemulsions, and micellar polymerization.

B. Use of Reactive Surfactants in Dispersion Polymerization

During the dispersion polymerization, the polymer precipitates from an initially homogeneous reaction mixture containing monomer, initiator, steric stabilizer, and solvents. Under favorable conditions, monodisperse polymer particles stabilized by a steric barrier of dissolved polymer are formed. The early work, mainly done in nonaqueous media such as aliphatic hydrocarbons, was thoroughly reviewed by Barrett [90]. Most of the studies dealt with polymer particles in the 0.1- to 2- μm size range.

More recently, several authors have investigated the dispersion polymerization of monomers (especially styrene [91,92] and methyl methacrylate [93,94] in polar media (mainly alcohol–water mixtures) using polymeric steric stabilizers soluble in such media, e.g., polyvinylpyrrolidone [95,96], polyacrylic acid [97,98], poly-(2-ethyl-2-oxazoline [99], or hydroxypropylcellulose) [100]; in order to examine the influence of several experimental parameters on the particle size and particle size distribution. The aim was to improve and to understand the conditions that yield large, monodisperse polymer particles. When one uses a precursor polymer that contains sites for chain transfer of radicals, such as polyacrylic acid, hydroxypropylcellulose, or polyvinylpyrrolidone, a graft copolymer can be produced in situ during dispersion polymerization. However, the effect of this grafting mechanism on particle formation is quite complicated and depends largely on the polymerization parameters. Moreover, competition is likely to occur between the adsorption of the graft copolymer and that of the precursor polymer. A few comprehensive studies on the preparation of monodisperse particles up to 12 μm have been reported [101,102], and a rather simple mechanistic model for predicting particle size has been proposed by Paine [103]. However, the mechanisms involved in dispersion polymerization remain poorly understood.

AB or ABA block copolymers are a second type of steric stabilizers that can be used in dispersion polymerization [104,105]. Poly(styrene-*b*-ethylene oxide) was recently used by Winnik and coworkers in the dispersion polymerization of styrene in methanol [106]. Provided that a selective solvent for the block copolymer is used as the continuous phase, these copolymers can be

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adsorbed onto the surface of the particles formed in order to achieve their stabilization. Unfortunately, for such systems, broad or bimodal distributions were often observed.

Another approach to achieving particle formation and subsequent stabilization is by the use of macromonomers. Macromonomers can be prereacted to form graft copolymers, which will be introduced in the reaction medium afterward. ICI used macromonomers to make preformed graft copolymer stabilizers. They synthesized a poly(12-hydroxystearic acid) macromonomer with a methacrylate end group. This macromonomer was copolymerized with methyl methacrylate to obtain a preformed comb–graft copolymer, which was successfully used as stabilizer in nonaqueous dispersions of methyl methacrylate [90]. Macromonomers can also be allowed to react in situ during the dispersion polymerization to form graft copolymers. This is a simple and flexible method for producing monodisperse micrometer-sized polymer particles. For instance, PEO macromonomers are commonly used in the ICI aqueous dispersion process, the "Aquersymer" process, in order to produce ion-free acrylic latexes with superior stability and film-forming properties compared to conventional charge stabilized latexes [68].

Recently the Japanese group of Kobayashi [107,108] discovered that the use of macromonomers of polyoxazoline allows control over the particle size of polymethyl methacrylate, with much less stabilizer than using high molecular weight polymer of the same structure. Typically, 0.2–0.8% of macromonomers can be used instead of 5–30% of high polymer to give monodisperse ($D_w/D_n < 1.03$) particles of 1–4 μm in diameter. In a study by Kawaguchi et al. [109], styrenic macromonomers of polyethylene oxide showed good stabilization efficiency. The authors have developed a mechanistic model based on some adaptation of the model of Paine [103] that allows prediction of the final particle size.

A more systematic study has been carried out by Lacroix-Desmazes [110] in which a set of hydrophilic macromonomers of polyoxyethylene are compared to a variety of polymerizable groups with the corresponding amphiphilic products having an hydrophobic chain end. Whatever the nature of macromonomer (styrenic, methacrylic, maleic), it has been observed that better performances (in term of particle size monodispersity, coagulum formation, and incorporation yield) were obtained with macromonomers than with their amphiphilic analogs. However, the incorporation yield is rather limited. The macromonomer stabilizers lead to a good fit with the Kawaguchi model involving a very rapid particles nucleation, which may be checked, but do not account for the change in solvency of the medium due to conversion of the monomer [111]. The reasons for the better performances of the macromonomers than of the true surfactants is not clear. It should probably be related to the reactivity of the stabilizer in the solution. The

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parameters having some effects on both the kinetics of polymerization and the incorporation yield of the polyoxyethylene chain have been studied by the same authors [112]. More important are the nature of the polymerizable group and the polarity of the reaction medium (i.e., amount of water in the ethanol–water mixture). Finally it has been shown that using the dynamic swelling method first proposed by Okubo et al. [96], it is possible to increase the incorporation yield to more than 80%. The big latex particles (>2 μm) produced are stable, depending chiefly on the grafting density of the macromonomer. When the length of the chain is about 50 monomer units, the latex is resistant to freeze-thawing experiments provided the area covered by each molecule of grafted macromonomer does not exceed 6 nm^2.

Transfer agents equivalent to macromonomer, i.e., thiol-ended polyoxyethylene, are also able to stabilize dispersion polymerization of styrene with a limited amount of material [113]. Recently, it has been shown that it was possible to stabilize vinyl acetate dispersion polymerization in supercritical CO_2 using perfluoroalkyl polymerizable surfactant [114].

C. Microemulsion Polymerization

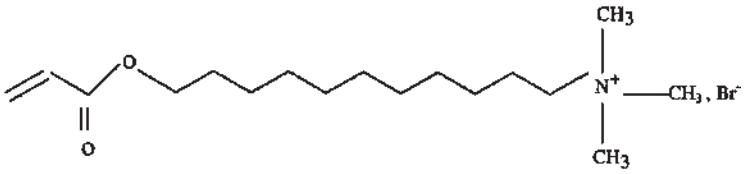
This polymerization mode, though not yet finding industrial appplications, should be useful for producing particles smaller than in the conventional emulsion polymerization. This would allow for improved properties in some applications such, as better gloss in paints.

The basic feature is that in these systems nucleation can take place directly inside very small monomer droplets. The smaller size of the droplets in comparison with the conventional emulsions, usually results from the use of cosurfactants in addition to the conventional surfactants, although in some cases a special surfactant can be used alone, e.g., cetyltrimethylammonium bromide (CTAB). The more popular cosurfactants, used in combination with conventional surfactant such as SDS, are low molecular weight alcohols such as pentanol and hexanol. The combination has been shown to form a rather strong film at the interface between oil and water [115]. Due to that feature the system is considered as thermodynamically stable. However, the small size of the droplets means a very high interface area, so that huge amounts of surfactants and cosurfactants are needed. Another difficulty for the polymerization of styrene in microemulsion is due to the character of precipitant of the cosurfactant. Then, generally the attempts for such a polymerization result in getting latex particles much larger than the initial size of the droplets. Actually it is now considered that the entry of radicals from the water phase in conventional emulsion polymerization is slow down because of the strength of the film of the surfactant–cosurfactant system. For that reason, only a few droplets can be initiated to produce polymer particles; owing to the Ostwald

ripening phenomenon, the small microemulsion particles lose their monomer for feeding the particle of polymer already nucleated. On the other hand, the nucleation process is a long process. For these reasons, the particle size distribution in these systems is quite broad.

Using just one surfactant without cosurfactant, it has been possible to prepare latex particles as small as about 20 nm in diameter [116]. They have used CTAB, or a mixture of anionic and nonionic surfactants. These systems have been more thoroughly studied as shown in a recent review by Antonietti [117]. This author [118] and later Vu [119] were able to develop a predictive model for styrene microemulsion polymerization with crosslinker, initiated by AIBN. This model shows that the size of the droplets is dependent on the ratio between the weight fraction of monomer and the total amount of monomer plus surfactant. This model is based on simple geometrical considerations, the monomer mixture being the core of a particle surrounded by a shell of surfactant.

Reports are few regarding the use of polymerizable surfactants to produce nanolatexes. All are quite recents papers. The first one to appear [120] was based on a polymerizable product, similar to CTAB, namely, 11-(acryloyloxy)undecyltrimethylammonium bromide (AUTMAB)



The polymerization was carried out with γ irradiation on transparent mixtures of styrene–water–surfactant. Using a weight ratio between surfactant and monomer of 4, polymer particles of 20.7 nm in diameter were obtained. However, the duration of the polymerization was much longer than in the case of CTAB. In addition to the copolymer particles, a large amount of AUTMAB was just homopolymerized. The particle size distribution was rather broad.

More recently,the same authors [121] compared the behavior of AUTMAB with another surfmer in which the polymerizable group is near the hydrophilic part of the surfmer. In that case, the particle size remained that of the initial microemulsion, but they were linked together by a few polymer chains, so that the final product was similar to a gel.

Two other investigations employed polymerizable cosurfactants. In one case [122], high-solid nanolatexes with size between 22 and 60 nm and solid

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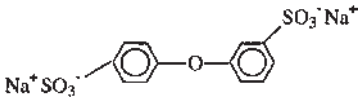
contents up to 42% were based on the use of acrylamide as cosurfactant and Dowfax 2 A-1 as surfactant. This surfactant is an anionic (Dowfax) with the following structure:



The products were polymers of methyl methacrylate, butyl acrylate, or their copolymer. The amount of surfactant was about 9% of the monomers and for the cosurfactant the feature was only 1%. When the same surfactant was used with pentanol as cosurfactant or with no cosurfactant, the particle size distribution was much broader, even bimodal. The latexes were shown to be stable vs. electrolyte (aluminum sulfate), and also for several freeze–thaw cycles. These features were attributed more to the nature of the surfactant than to the use of polymerizable cosurfactant.

The last investigation [123] suggested the use of hydroxypropyl methacrylate and similar polymerizable products as cosurfactant. Polymerization of styrene with 100% conversion was achieved at room temperature using either an oil-soluble photoinitiator or a water-soluble redox system (H_2O_2–ascorbic acid). The resulting latex had a particle size around 20 nm. The composition of the copolymer is similar to that of the mixture of monomer when using a redox system, where the radicals are produced in the water phase, while a two-step polymerization giving rise to a block copolymer is produced when using the oil-soluble initiator. In the later case, styrene (inside the core of the particles) is polymerized first. The ratio between the monomer and surfactants remains low but the cosurfactant becomes incorporated in the latex, so that the cleaning process of the latex necessitated by the use of large amounts of surfactant can be simplified. No data were given in that paper about the particles size distribution.

More recently, Favero et al. [124] replaced SDS with the simple maleic surfmer A3 (Table 1) and kept the réactive costabilizer HPMA, as well as the initiator redox system, to polymerize styrene microemulsions. They get latexes with small particles of 20–30 nm. containing all of the monomer and HMPA, but only a part of the surfmer; which was not fully converted.

D. Miniemulsion Polymerization

In these systems also, the surfactant(s) is combined with a costabilizer to stabilize the small droplets. However, the monomer droplets are larger than

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in the microemulsions (in the range of 100–500 nm in diameter). The amount of surfactant and costabilizer needed is not that large as compared with microemulsions. Correspondingly, the miniemulsions are no more thermodynamically stable and are not transparent, so that they cream after a certain time (shelf life). This time may be 30 min to more than a month. There are two kinds of costabilizers: long-chain hydrocarbons (typically hexadecane) or long-chain alcohol (typically cetyl alcohol). Most probably, these two kinds of costabilizers do not working with the same mechanism. Cetyl alcohol is probably a real cosurfactant, like pentanol in the case of microemulsion, that acts by forming a more or less strong film with the surfactant. For instance, it may be suggested that the long chain of cetyl alcohol and SDS can be organized like a pseudocrystalline compound, with orientation of the alcohol group of cetyl alcohol and of the polar head of SDS, toward the water phase. Hexadecane has no polar group, and although it may reinforce the van der Waals interaction of the long hydrocarbon chain of SDS, it mainly acts as a hydrophobe preventing Ostwald ripening and then stabilizing the monomer droplets against diffusion. It may also be considered that cetyl alcohol with its long hydrocarbon chain acts as a hydrophobe.

Whatever the mechanism of droplets stabilization is, the behavior of the miniemulsion polymerization is similar to that of microemulsion in that the nucleation process can also be quite long. For that reason, it often leads to broad particle size distribution. However; it is known that the hexadecane system tends to give narrower distribution and in many cases allows retention of the size of the initial monomer droplets.

Until recently, there was only one report about the use of reactive costabilizers in miniemulsion polymerization [125]. In that study, dodecyl methacrylate (DMA) and stearyl methacrylate (SMA) were been used as cosurfactants with SDS and compared with cetyl alcohol (CA) and hexadecane (HD). It has been shown that DMA behaves like CA, whereas SMA displays a behavior similar to HD in terms of droplet size stability as well as in the particle size distribution of latexes. However, the distribution obtained using these reactive hydrophobes is in both cases somewhat narrower than for the model compounds. More recently, the same team published a study where in the polymerization of styrene in miniemulsions stabilized using DMA or SMA, small quantities of acrylic acid or methacrylic acid were added [126]. The authors were chiefly interested in the nucleation mechanism. Surprisingly, the addition of these hydrophilic monomers tends to favor nucleation within the droplets more than homogeneous nucleation, which is the dominating mechanism in the absence of these water-soluble monomers. The explanation lies in the fact that the styrene-carboxylic co-oligomers, because they are much more hydrophilic, are more reluctant to nucleate new particles.

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On the other hand, the capture of these oligomers, which are charged, provides to the particles an electrosteric stabilization and tends to repel the new charged entering oligoradicals.

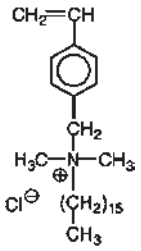
A few anionic surfmers from those reported in Table 5, have been tested in miniemulsions of styrene and methyl methacrylate. Two of them, now commercially available (MAEM, MAES, Aldrich) as well as ABM, are capable of stabilizing monomer miniemulsion droplets but tend to flocculate upon polymerization. The polymerization was successful in the case of ABM, when, to prepare the miniemulsion, one uses a mixture of SDS and ABM 1:3. Better results have been obtained in the case of VBSS, the CMC of which is close to that of SDS. Using VBSS as a polymerizable surfactant [127], in the presence of hexadecane, it is rather easy to obtain stable miniemulsions of either styrene or methyl methacrylate, with diameter of droplets in the range 100–250 nm. Upon polymerization with either AIBN or KPS, the size of the polymer particles remains near that of the initial droplets with high conversion of the monomers. It appears that 50–75% of the surfactant remains fixed on the surface of the polymer particles. Large differences of latex stability vs. addition of electrolytes or freeze-thawing test are observed, depending on the initiator used in the copolymerization. When using KPS, the stability is much better than when AIBN is used. It seems that, in addition to the electrostatic stabilization due to the anionic sulfonated surfactant, there is a steric stabilization when KPS initiates the polymerization. Then there is a rather large difference between the particle diameter as measured by dynamic light scattering and by electron microscopy. This difference shows that there is a hydrophilic layer around the particles with a thickness of several nanometers. From the particles obtained upon polymerization of the miniemulsion droplets it was possible to carry out a second step of growth, using a nonionic polymerizable block copolymer surfactant, so that the solid contents of the latex increases from 20% to 30% and the particle size from 215 to 283 nm by transmission electron microscopy and 342 nm by light scattering, which involves a shell of 30 nm thickness, which is expected to be covered by a layer of both the hydrophilic part of the surfactant and some oligomers containing VBSS and styrene units.

E. Micellar Emulsion Polymerizations

In micellar polymerization, all of the monomer that swells a micelle is polymerized from the same radical. In the case of emulsion polymerization, the radical is expected to come from the water phase, where it should polymerize the water-soluble monomers. So it will produce block copolymers, with segments of water-soluble monomer units, followed by a hydro-

phobic segment of the monomer swelling one micelle. If it returns in the water phase, it will continue to polymerize the water-soluble monomer; then it may enter another micelle, and so on. A multiblock copolymer results, with an alternation of hydrophilic and hydrophobic segments. The hydrophilic segments present a random distribution, but the hydrophobic ones should have a quasi-monodistribution because the swollen micelles are expected to be of the same size.

This topic has been studied thoroughly by the Candau et al. [128] in an attempt to produce associative thickeners. They have prepared and used styrenic cationic surfmers named N16:



In order to study the mchanism of micellar polymerization, they used a variety of initiators and inhibitors having different water solubilities. It was concluded that most of the time the radicals are produced in the water phase and have to enter the micelles before the polymerization can take place. The authors have studied three systems: in the first, a hydrophobic acrylamido monomer swelling SDS micelles was copolymerized with acrylamide; in the second, they used their styrenic cationic surfmer N16; and in the last, they used mixed micelles of N16 and a similar but nonpolymerizable surfactant B16.

In the first system, the hydrophobic monomer included in the SDS micelle is polymerized in the same polymer chain, but most of the SDS is relarged in the serum; in the second system, the hydrophilic part of the surfmer remains associated with the main polymer chain (Fig. 4). In contrast, if the surfmer is mixed with a nonpolymerizable surfactant, the surfmer units are randomly distributed in the polyacrylamide polymer (Fig. 5). Surprisingly, the thickening efficiency of that last system is a thousand times higher than the former. it is suggested that the difference is due to the intramolecular nature of the hydrophobic interactions, when the micelles contain the surfmer only.

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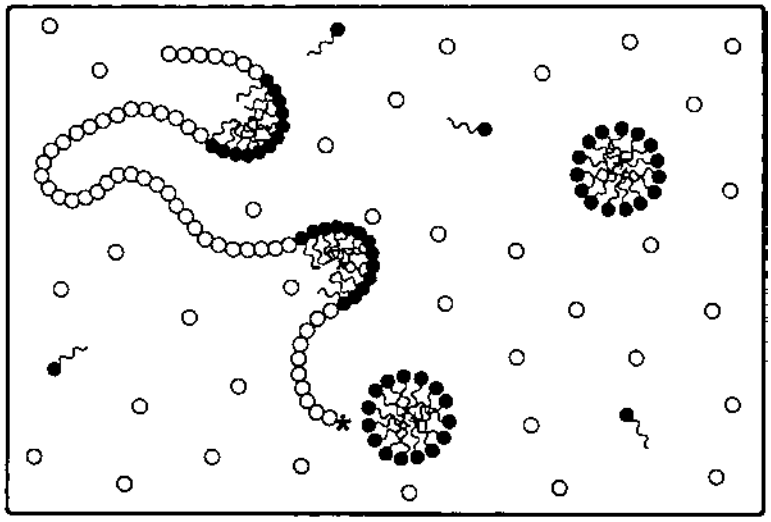

FIG. 4 Schematic representation of the copolymerization process II: acrylamide (o) and polymerizable surfactant (●〰). (From Ref. 128.)

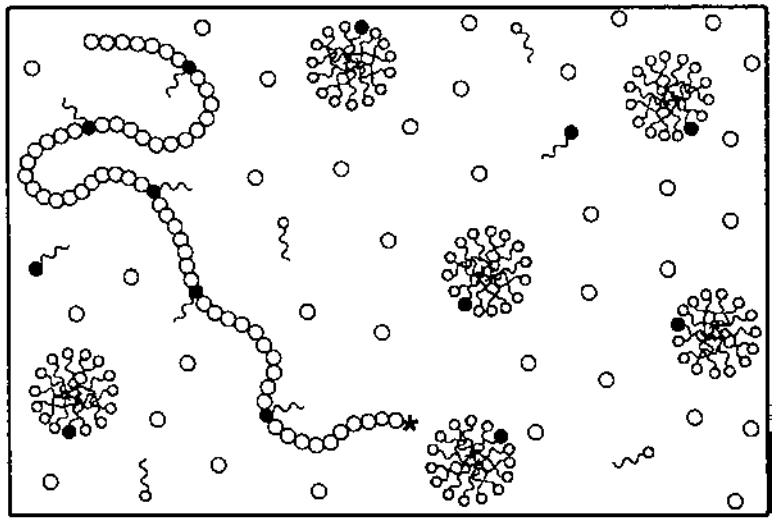

FIG. 5 Schematic representation of the copolymerization process III: acrylamide (o) and a mixture of polymerizable (surfmer) and nonpolymerizable surfactants (black points for the polymerizable group of the surfmer). (From Ref. 128.)

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IV. CONCLUSIONS, PERSPECTIVES, AND OTHER ALTERNATIVES

This second edition of the chapter is an extension of the earlier edition of 1998 [129], itself following several earlier reviews [130–133].

The main property that a reactive surfactant is expected to show is to be reactive enough in the emulsion polymerization process to remain covalently linked to the particle surface from which it cannot be desorbed, as for the conventionnal surfactants. In order to meet this requirement, particularly in terms of the applications of a polymer colloid, it is important that the reactive surfactant be, at the end of the polymerization process, located and grafted onto the surface of the colloid. That means that it cannot be lost in the serum surrounding this colloid. It must not be adsorbed, and it must not be buried inside.

Two important conclusions can be drawn: (1) The reactivity of this surfactant should be well fitted to the reactivity of the other monomers engaged. Although, it has to be copolymerized with the other monomers, it must not be too reactive, which could cause it to react very fast in the water phase and end up in the serum. Possibly, it will form high molecular weight polymers able to cause bridging flocculation of the colloids. (2) If a highly reactive surfactant reacts within the particles or on the surface, there is a high probability that it will be buried inside. The need for a moderate reactivity has been considered as a general rule of the reactive surfactant canal [44, 133]. For instance, it has been shown that transurfs with highly reactive thiol groups, are much too reactive, and are chiefly lost in the water phase [24]. However, good results in terms of stability of the latexes vs. addition of electrolytes or resistance to freeze-thawing tests, have been obtained with rather reactive surfmers, such as styrenic [82] or methacrylic [85], even if they can be partially buried.

The second conclusion is related to the process used. It is clear that a seed-and-feed strategy is better than *ab initio* batch polymerization. Of course such a strategy provides the conditions in which high solid contents latex can be produced. Also provides the conditions for having the surface protected when it is growing. A certain percent coverage is needed for stabilization of the particles. It is important that a convenient amount of surfactant be grafted onto the surface permanently. Indeed, such conditions were fulfilled in the early work by Greene et al. [32] because the reactive surface has been allowed to polymerize onto the seed latex, which was not growing. It has been clearly demonstrated that a high yield of grafting can be achieved (almost 100%) when the surface is not yet saturated by the reactive surfactant (if the coverage is limited to 70%). That means that it should be better to have two independant feeding system: one for the monomers and one for the surfactants. Possibly

also a third independant system would be needed for a programmed introduction of initiator.

Up to now, except for ICI, the industry did not apply too much polymerizable surfactants. Some people prefer to use ionogenic monomers such as acrylic, itaconic, or methacrylic acid, as well as styrene sulfonate or related compounds. Anyway, interest in polymerizable surfactants seems to be growing, and a few patents have recently been published [134].

The second alternative for polymerizable surfactants is polymeric surfactants. The subject has been recently reviewed by Lachewsky [8]. Even more recently the same authors [135] compared polymerizable surfactant and their homopolymers (polysoaps) and showed that good results can be obtained from them. The same conclusion has been shown valid for the homopolymer of one of the first commercially available allylic surfmers [136]. Recently, core-shell particles have been prepared using an inisurfmer, containing both a polymerizable moiety and a peroxydic group. This compound has been used to cover a seed polymer particle and initiate, from the peroxide group, the polymerization of a shell of another polymer [137].

The use of block copolymer surfactants was already quite popular [1] for stabilization of both emulsion and dispersion polymers, but usually these products were nonionic (noncharged). A renewable interest now seems to be paid to block copolymer carrying charges for stabilizing high-solid-content emulsion polymer [138]. This topic was reviewed by Guyot and Tauer [139].

Finally, it is interesting to note that the first mention of a reactive polymeric surfactant was published by Tauer and Zimmermann [140]. Their research involved sulfonated polybutadiene, containing enough double bonds after the sulfonation process to be grafted to a growing polymer in an emulsion polymerization. A further improvement in the stabilization of these latexes was obtained using as starting material the block copolymer poly(ethylene-oxide-*block*-polybutadiene before the sulfonation. Then properties of steric stabilization were added to the simple electrosteric stabilization [141]. In this kind of compound, both the lengths of each block and the degree of sulfonation can be varied so as to finely tune the stabilization properties.

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Polymeric Surfactants

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I. INTRODUCTION

Many industrial formulations consist of dispersions of the solid–liquid (suspensions) or liquid–liquid (emulsions) types. The stabilization of these dispersions against flocculation and/or coalescence requires the presence of an energy barrier between the particles or droplets that prevent their close approach where the van der Waals attraction is large. Two general mechanisms of stabilization can be applied. The first, referred to as electrostatic stabilization, is based on charge separation and formation of electrical double layers [1]. The double layer is characterized by a surface charge that is compensated by unequal distribution of counter and coions. When two particles or droplets approach to a distance of separation h that is smaller than twice the double layer thickness, repulsion occurs since the double layers cannot be fully developed. The magnitude of repulsion depends on the surface (or ζ) potential and electrolyte concentration and valency. At low electrolyte concentrations, the double layers are extended and the repulsive energy at intermediate distances becomes larger than the van der Waals attraction, producing an energy barrier that prevents approach of the particles or droplets. This picture forms the basis of the theory of colloid stability developed independently by Deryaguin and Landau [2] and Verwey and Overbeek [3] more than 50 years ago (DLVO theory). The production of charge on particle or droplet surfaces can be due to the presence of ionogenic groups or by adsorption of ionic surfactants. Unfortunately, this stabilization mechanism is seldom sufficient in practice since most practical industrial formulations contain high amounts of electrolyte. In addition, ionic surfactants may not be strongly adsorbed on the particle surface and on close approach desorption may take place. An alternative approach is to use nonionic surfactants of the ethoxylate type that may tolerate high electrolyte concentrations. However, as with ionic surfactants such molecules are seldom strongly adsorbed on the particle surface. The most effective procedure for

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stabilization of dispersions is to use surface active polymers (to be referred as polymeric surfactants) which not only adsorb very strongly on the particle or droplet surface but also can be applied in the presence of high electrolyte concentrations and at high temperatures. This forms the second mechanism of stabilization that is usually referred to as steric stabilization [4]. The polymeric surfactant molecule can be specifically designed to have a strong "anchor" chain and a "stabilizing" chain that extends from the surface giving a layer thickness δ that is several nanometers thick. When two particles or droplets approach to a distance of separation h that is smaller than 2δ, the stabilizing chains may undergo overlap and/or become compressed. The chains will also lose configurational entropy in the overlap region. When these chains are in good solvent conditions, such overlap is unfavorable and this leads to strong repulsion that increases very sharply with decrease of h when $h < 2\delta$.

This chapter will start with a short account of the general classification and description of polymeric surfactants. This is followed by a summary on their solutions properties. The adsorption and conformation of polymeric surfactants at the solid–liquid interface will be discussed at a fundamental level and some experimental results will be presented to illustrate the prediction of the theories. The interaction energies between particles or droplets containing adsorbed polymeric surfactants will be briefly described. The final section will give some applications of polymeric surfactants in suspensions, emulsions, and multiple emulsions.

II. GENERAL CLASSIFICATION AND DESCRIPTION OF POLYMERIC SURFACTANTS

The simplest type of a polymeric surfactant is a homopolymer, which is formed from the same repeating units: poly(ethylene oxide) (PEO); poly (vinylpyrrolidone) (PVP). Homopolymers have little surface activity at the oil/water (o/w) interface. However, homopolymers may adsorb significantly at the solid–liquid (S/L) interface. Even if the adsorption energy per monomer segment is small (fraction of kT, where k is the Boltzmann constant and T is the absolute temperature), the total adsorption energy per molecule may be sufficient (several segments are adsorbed at the surface) to overcome the unfavorable entropy loss of the molecule at the S/L interface. Homopolymers may also adsorb at the solid surface by some specific interaction, e.g., hydrogen bonding (e.g., adsorption of PEO or PVP on silica). In general, homopolymers are not the most suitable emulsifiers or dispersants.

A small variant is to use polymers that contain specific groups that have high affinity to the surface, e.g., partially hydrolyzed poly(vinyl acetate) (PVAc)—technically referred to as poly(vinyl alcohol) (PVA). Commercially

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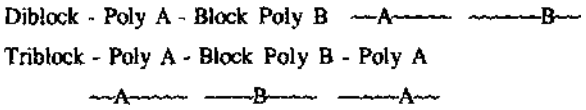
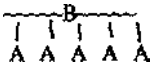
available PVA molecules contain 4–12% acetate groups. The acetate groups give the molecule its amphipathic character; on a hydrophobic surface (such as polystyrene) the polymer adsorbs with preferential attachment of the acetate groups on the surface, leaving the more hydrophilic vinyl alcohol segments dangling in the aqueous medium. Partially hydrolyzed PVA molecules exhibit surface activity at the o/w interface.

Polymeric surfactants of the block (A-B or A-B-A) or graft (BA_n) type are essential materials for the preparation of many systems, e.g., dyestuffs, paper coatings, inks, agrochemicals, pharmaceuticals, personal care products, ceramics, and detergents. A block copolymer is a linear arrangement of blocks of varying composition [5]:



A graft copolymer is a nonlinear array of one B block on which several A polymers are grafted:



Block copolymers have gained considerable importance in the last three decades. Their special chemical structure (different A and B chains) yields unusual physical properties. Block copolymers frequently exhibit phase separation, i.e., one block type in a continuous matrix of the second block type. The fact that block copolymers are able to participate in different types of phases give them special properties, i.e., colloidal and mechanical, surface activity, surface elasticity, and impact modification.

Two types of investigations are essential to unravel the behavior of block and graft copolymers: (1) properties in a solvent in which both the A and B blocks are soluble, thus giving information on their conformation; (2) properties in a solvent that is a nonsolvent for one of the blocks but a good solvent for the other block.

Block copolymers exhibit surface activity since one of the blocks is soluble in one phase and the other is miscible in the other phase, e.g., A-B block, A hydrophilic, B hydrophobic:

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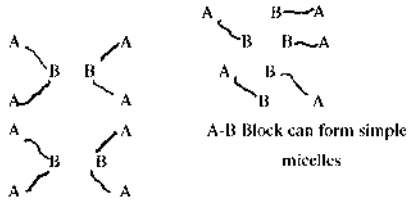
Since block copolymers are amphiphilic, they aggregate in solution to form micelles:



A-B-A Block copolymer may form micelles with smaller aggregation number

Graft copolymers also aggregate in solution to form micelles, again with small aggregation numbers. A dimer may be the form of aggregation.

Most block and graft copolymers have low critical micelle concentrations (CMCs) and in many cases it is not easy to measure the CMC for these block and graft copolymers. The aggregation process is also affected by temperature and solvency of the medium for the A chains. One of the most useful methods to follow the aggregation of block and graft copolymers is time-average light scattering. By measuring the intensity as a function of concentration one can extrapolate the results to zero concentration and obtain the molecular weight of the micelle. This allows one to obtain the aggregation number from a knowledge of the molecular weight of the monomer.

Several examples of block and graft copolymer may be quoted: Triblock polymeric surfactants, e.g., Pluronics (BASF) or Synperonic PE (ICI); two poly-A blocks of PEO and one poly-B block of polypropylene oxide (PPO); several chain lengths of PEO and PPO are available. Triblocks of PPO-PEO-PPO (inverse Pluronics) are also available. Polymeric triblock surfactants can be applied as emulsifiers and dispersants. The hydrophobic PPO chain resides at the hydrophobic surface, leaving the two PEO chains dangling in aqueous solution (providing steric stabilization).

The above triblocks are not the most efficient emulsifiers or dispersants, the PPO chain is not sufficiently hydrophobic to provide a strong "anchor" to a hydrophobic surface or to an oil droplet. The reason for the surface activity of the PEO-PPO-PEO triblock at the o/w interface is probably due to "rejection" anchoring; the PPO chain is not soluble in water or most oils.

Several other di- and triblock copolymers have been synthesized: diblocks of polystyrene-block-polyvinyl alcohol; triblocks of polymethyl methacrylate-block polyethylene oxide-polymethyl methacrylate; diblocks of polystyrene-polyethylene oxide; and triblocks of polyethylene oxide-polystyrene-polyethylene oxide.

An alternative (and perhaps more efficient) polymeric surfactant is the amphipathic graft copolymer consisting of a polymeric backbone B (poly-

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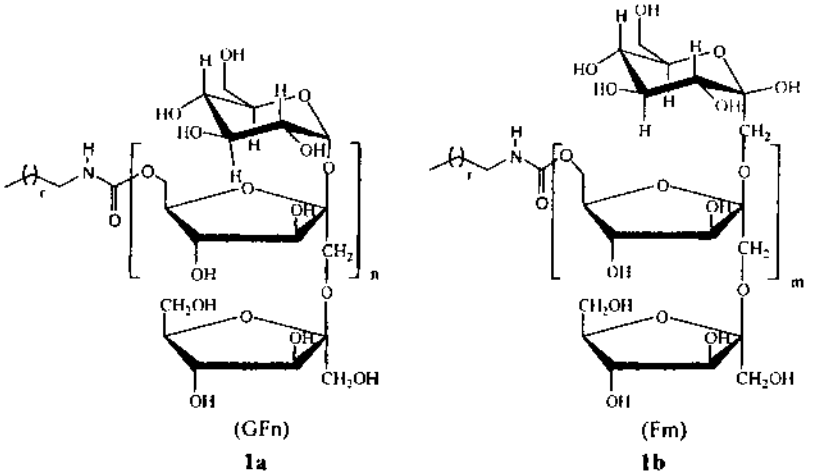
styrene or polymethyl methacrylate) and several A chains (“teeth”) such as polyethylene oxide. The graft copolymer is referred to as a “comb” stabilizer; the polymer forms a “brush” at the solid–liquid interface. The copolymer is usually prepared by grafting a macromonomer such as methoxy polyethylene oxide methacrylate with polymethyl methacrylate. In most cases, some polymethacrylic acid is incorporated with the polymethyl methacrylate backbone; this leads to reduction of the glass transition of the backbone, which makes the chain more flexible for adsorption at the solid–liquid interface. Typical commercially available graft copolymers are Atlox 4913 and Hypermer CG-6 supplied by ICI.

The “grafting into technique has also been used to synthesize polystyrene-polyethylene oxide graft copolymers. These molecules are not commercially available.

Recently, a novel graft copolymer based on a naturally occurring polysaccharide, namely inulin (polyfructose), has been synthesized [6]. Inulin is a polydisperse polysaccharide consisting mainly, if not exclusively, of β(2→1) fructosyl fructose units (F_m) with normally, but not necessarily, one glucopyranose unit at the reducing end (GF_n) [7,8]. To produce the amphipathic graft copolymer, the chains were modified by introduction of alkyl groups (C_4–C_{18}) on the polyfructose backbone through isocyanates. The structure of the molecule (inulin carbamate) is illustrated below.



Structure of inulin carbamates.

In the above structure, the alkyl groups represent the B chains (that are randomly distributed on the sugar backbone on primary hydroxyl functions as well as on the secondary ones) which become strongly adsorbed on a

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hydrophobic solid such as carbon black, polystyrene, or an oil droplet. The sugar chain forms the stabilizing chain as this is highly water soluble. These graft copolymers are surface active and they lower the surface tension of water and the interfacial tension at the o/w interface. They will also adsorb on hydrophobic surfaces with the alkyl groups strongly attached (multipoint anchoring), leaving the polyfructose chains dangling in solution and probably forming large loops. As we will see later, these graft copolymers can produce highly stable suspensions and emulsions, particularly at high electrolyte concentrations.

III. SOLUTION PROPERTIES OF POLYMERIC SURFACTANTS

To understand the solution behavior of polymeric surfactants of the block and graft type, it is essential to consider the solution properties of the simpler homopolymers. The solution behavior of homopolymers was considered in the thermodynamic treatment of Flory and Huggins [9].

The Flory-Huggins theory considers the free energy of mixing of pure polymer with pure solvent, ΔG_{mix}, in terms of two contributions: enthalpy of mixing, ΔH_{mix}, and entropy of mixing ΔS_{mix},

$$\Delta G_{\text{mix}} = \Delta H_{\text{mix}} - T\,\Delta S_{\text{mix}} \tag{1}$$

Assuming that the polymer chain adopts a configuration on a lattice (provided by the solvent molecules) and considering that the mixing is "random," ΔS_{mix} is given by

$$\Delta G_{\text{mix}} = -k[n_1 \ln\ \phi_1 + n_2 \ln\ \phi_2] \tag{2}$$

where k is the Boltzmann constant, n_1 is the number of solvent molecules with a volume fraction ϕ_1 and n_2 is the number of polymer molecules with a volume fraction ϕ_2.

The enthalpy of mixing, ΔH_{mix}, is given by the expression:

$$\Delta H_{\text{mix}} = n_1 \phi_2 \chi kT \tag{3}$$

where χ is a dimensionless interaction parameter and χkT expresses the difference in energy of a solvent molecule in pure solvent compared to its immersion in pure polymer. χ is usually referred to as the Flory-Huggins interaction parameter.

Combining Eqs. (1)–(3), one obtains

$$\Delta G_{\text{mix}} = kT[n_1\ \ln\ \phi_1 + n_2\ \ln\ \phi_2 + n_1\ \chi\ \phi_2] \tag{4}$$

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The mixing of a pure solvent with a polymer solution creates an osmotic pressure, π, which can be expressed in terms of the polymer concentration c_2 and the volume fraction of the polymer:

$$\frac{\pi}{c_2} = RT\left[\left(\frac{1}{M_2}\right) + \left(\frac{v_2^2}{V_1}\right)\left(\frac{1}{2} - \chi\right)c_2 + \cdots\right] \tag{5}$$

where v_2 is the partial specific volume of the polymer ($v_2 = V_2/M_2$) and V_1 is the molar volume of the solvent.

The second term in Eq. [5] is the second virial coefficient:

$$\frac{\pi}{c_2} = RT\left[\left(\frac{1}{M_2}\right) + B_2 c_2 + \cdots\right] \tag{6}$$

$$B_2 = \left(\frac{v_2^2}{V_1}\right)\left(\frac{1}{2} - \chi\right) \tag{7}$$

Note that $B_2 = 0$ when $\chi = 1/2$. The polymer behaves as ideal in mixing with the solvent. Flory called this condition the θ point. In a θ condition, the polymer chains in solution have no attraction or repulsion or they adopt their unperturbed dimensions. When $\chi < 1/2$, B_2 is positive. Mixing is nonideal leading to positive deviation (repulsion). This occurs when the polymer chains are in "good" solvent conditions. When $\chi > 1/2$, B_2 is negative; mixing is nonideal leading to negative deviation (attraction). This occurs when the polymer chains are in "poor" solvent conditions (precipitation of the polymer may occur under these conditions).

Since the polymer solvency depends on temperature, one can also define a θ-temperature at which $\chi = 1/2$.

The function $[(1/2) - \chi]$ can also be expressed in terms of two mixing parameters, an enthalpy parameter κ_1 and an entropy parameter ψ_1:

$$\left(\frac{1}{2} - \chi\right) = \kappa_1 - \psi_1 \tag{8}$$

The θ temperature can also be expressed in terms of κ_1 and ψ_1:

$$\theta = \frac{\kappa_1 T}{\psi_1} \tag{9}$$

Alternatively, one can write,

$$\left(\frac{1}{2} - \chi\right) = \psi_1\left(1 - \frac{\theta}{T}\right) \tag{10}$$

Several experimental results cannot be accounted for by the Flory-Huggins theory. e.g., dependence of χ on polymer concentration and phase separation of many polymer solutions (e.g., PEO) on heating.

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The solution properties of copolymers are much more complicated. The two copolymer components A and B behave differently in different solvents. When the two components A and B are both soluble in the same solvent, they exhibit similar solution properties, e.g., a nonpolar copolymer in a nonpolar solvent.

With branched polymers consisting of high monomer density (e.g., star branched polymers), the θ temperature depends on the length of the arms and is in general lower than that of a linear polymer with the same molecular weight. Another complication arises from specific interaction with the solvent, e.g., hydrogen bonding between polymer and solvent molecules (such as with PEO and PVA in water). Aggregation in solution (lack of complete dissolution) may also present a problem in determining the solution properties of block and graft copolymers.

One of the most useful parameters for characterising the conformation of a polymer in solution is the root mean square (rms) end-to-end length $\langle r^2 \rangle^{1/2}$, which represents a configuration character r as the distance from one end group to the other of a polymer chain molecule. Another useful parameter is the radius of gyration $\langle s^2 \rangle^{1/2}$, which is a measure of the effective size of a polymer molecule. It is the rms distance of the elements of the chain from its center of gravity.

For linear polymers,

$$\langle s^2 \rangle^{1/2} = \frac{\left[\langle r^2 \rangle^{1/2} \right]}{6^{1/2}} \tag{11}$$

The radius of gyration of a polymer molecule in solution can be determined from light scattering measurements. Dilute solutions of copolymers in solvents that are good for both components exhibit similar behavior to homopolymer chains. In selective solvents, whereby the medium is a good solvent for one component A and a poor solvent for the second component B, one part of the amphipathic block or graft copolymer will separate as a distinct phase while the other stays in solution. The insoluble portion of the amphipathic copolymer will aggregate reversibly to form micelles. It is believed that the micelles of block and graft copolymers are spherical. The CMC of block and graft copolymers is usually very low.

Several methods may be applied to obtain the micellar size and shape of block and graft copolymers: light scattering, small-angle X-ray scattering, and small-angle neutron scattering.

Dynamic light scattering (photon correlation spectroscopy, PCS) can also be applied to obtain the hydrodynamic radius of the micelle. By measuring the intensity fluctuation of scattered light by the micelles (when these undergo Brownian diffusion), one can obtain the diffusion coefficient of the micelles D,

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from which the hydrodynamic radius R can be obtained using the Stokes-Einstein equation;

$$D = \frac{kT}{6\pi\eta R} \tag{12}$$

where η is the viscosity of the medium.

IV. ADSORPTION AND CONFORMATION OF POLYMERIC SURFACTANTS AT INTERFACES

Understanding the adsorption and conformation of polymeric surfactants at interfaces is key to knowing how these molecules act as stabilizers. Most basic ideas on adsorption and conformation of polymers have been developed for the solid–liquid interface [10]. The same concepts may be applied to the liquid–liquid interface, with some modification whereby some parts of the molecule may reside within the oil phase rather than simply staying at the interface. Such modification does not alter the basic concepts, particularly when one deals with stabilization by these molecules.

The process of polymer adsorption involves a number of various interactions that must be separately considered. Three main interactions must be taken into account, namely, the interaction of the solvent molecules with the surface (or oil in the case of o/w emulsions) which need to be displaced for the polymer segments to adsorb, the interaction between the chains and the solvent and the interaction between the polymer and the surface. Apart from knowing these interactions, one of the most fundamental considerations is the conformation of the polymer molecule at the interface. These molecules adopt various conformations, depending on their structure. The simplest case to consider is that of a homopolymer consisting of identical segments, e.g., poly(ethylene oxide), which shows a sequence of loops, trains, and tails, as is illustrated in Fig. 1a. It should be mentioned at this stage that for such a polymer to adsorb, the reduction in entropy of the chain as it approaches the interface must be compensated by an energy of adsorption between the segments and the surface. In other words, the chain segments must have a minimal adsorption energy, χ^s, otherwise no adsorption occurs. With polymers that are highly water soluble, such as poly(ethylene oxide) (PEO), the interaction energy with the surface may be too small for adsorption to occur, and if this takes place the whole molecule may not be strongly adsorbed to the surface. For this reason, many commercially available polymers that are described as hompolymers, such as poly(vinyl alcohol) (PVA), contain some hydrophobic groups or short blocks (vinyl acetate in the case of PVA) that ensured their adsorption to hydrophobic surfaces. This is illustrated in

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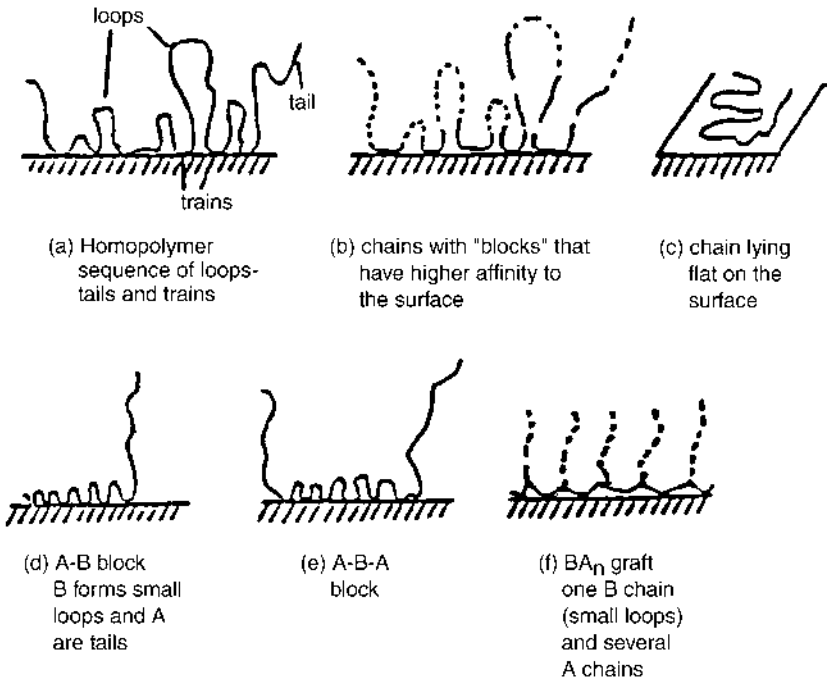

FIG. 1 Various conformations of polymeric surfactants adsorbed on a plane surface. (a) Random conformation of loops-trains-tails (hompolymer); (b) preferential adsorption of "short blocks"; (c) chain lying flat on the surface; (d) AB block copolymer with loop-train configuration of B and long tail of A; (e) ABA block as in d; (f) BA_n graft with backbone B forming small loops and several tails of A ("teeth").

Fig. 1b. Clearly, if all the segments have a high affinity to the surface, the whole molecule may lie flat on the surface, as illustrated in Fig. 1c. This situation is rarely the case because the molecule will have very low solubility in the continuous medium.

The most favorable structures for polymeric surfactants are those represented in Fig. 1(d–f), referred to as block and graft copolymers. The molecules shown in Fig. 1d is an A-B block, consisting of a B chain that has a high affinity for the surface (or soluble in the oil phase), referred to as the "anchoring" chain, and an A chain that has very low affinity for the surface and is strongly solvated by the medium. As will be discussed in the section on stabilization, this is the most convenient structure because the forces that ensure strong adsorption are opposite of those that ensure stability. A variance on the structure shown in Fig. 1d is the A-B-A block copolymer shown in Fig. 1e. In this case, the anchor chain B contains two stabilizing

chains (tails). Another variance is that shown in Fig. 1f, which is described as a graft copolymer ("comb" type structure) with one B chain and several A chains (tails or "teeth").

It is clear from the above description of polymer configurations that for full characterization of the process of adsorption it is necessary to know the following parameters, namely, the amount of polymer adsorbed per unit area of the surface, Γ (mole m^{-2} or mg m^{-2}); the fraction of segments in close contact with the surface, p and the distribution of polymer segments, $\rho(z)$, from the surface toward the bulk solution. It is essential to know how far the segments extend into solution, i.e., the adsorbed clayer thickness δ. It is important to know how these parameters change with polymer overage (concentration), the structure of the polymer, and its molecular weight. It is also essential to know how these parameters change with the environment such as solvency of the medium for the chains and temperature.

Several theories exist that describe the process of polymer adsorption, which have been developed using either statistical mechanical approach or quasi-lattice models. In the statistical mechanical approach, the polymer is considered to consist of three types of structures with different energy states: trains, loops, and tails [11,12]. The structures close to the surface (trains) are adsorbed with an internal partition function determined by short-range forces between the segment and surface (assigned an adsorption energy per segment χ^s). The segments in loops and tails are considered to have an internal partition function equivalent to that of segments in bulk solution, and these are assigned a segment–solvent interaction parameter χ (Flory-Huggins interaction parameter). By equating the chemical potential of the macromolecule in the adsorbed state and in bulk solution, the adsorption isotherm can be determined. In the earlier theories, the case of an isolated chain on the surface (low coverage) was considered; however, but later the theories were modified to take into account the lateral interaction between the chains, i.e., at high coverage.

The quasi-lattice model was developed by Roe [13] and by Scheutjens and Fleer [14,15]. The basis procedure was to describe all chain conformations as step-weighted random walks on a quasi-crystalline lattice that extends in parallel layers away from the surface. This is illustrated in Fig. 2, which shows a possible conformation of a polymer molecule at a surface. The partition function was written in terms of number of chain configurations, which were treated as connected sequences of segments. In each layer, random mixing (Bragg-William or mean field approximation) between segments and solvent molecules was assumed. Each step in the random walk was assigned a weighting factor p_i that was considered to consist of three contributions, namely, the adsorption energy χ^s, the configurational entropy of mixing, and the segment–solvent interaction parameter χ.

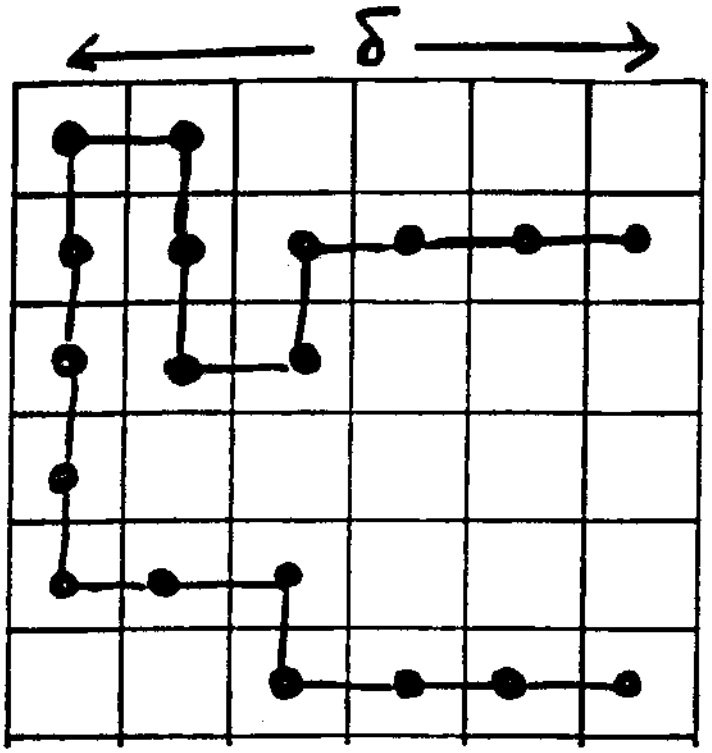

FIG. 2 Possible conformation of a polymer molecule at an interface.

The above theories gave a number of predictions for polymeric surfactant adsorption. Figure 3 shows typical adsorption isotherms plotted as surface coverage θ (in equivalent monolayers) vs. polymer volume fraction ϕ in bulk solution (ϕ was taken to vary between 0 and 10^{-3}, which is the normal experimental range). The results in Fig. 3 show the effect of increasing the chain length r and effect of solvency [using two values for the Flory-Huggins interaction parameter, i.e., $\chi = 0$ (athermal solvent) and $\chi = 0.5$ (θ solvent)]. As the number of segments in the chain increases from low (with few segments) to high (large number of segments) values, the adsorption isotherm changes from a Langmuirian type (characteristic for surfactant adsorption) to a high-affinity type. In the latter case, the first addition of polymer chains to the solution results in their virtually complete adsorption. The adsorption isotherms for chains with $r = 100$ and above are typical of those obtained experimentally for most polymers that are not too polydisperse, i.e, showing a steep rise followed by a nearly horizontal pseudo-

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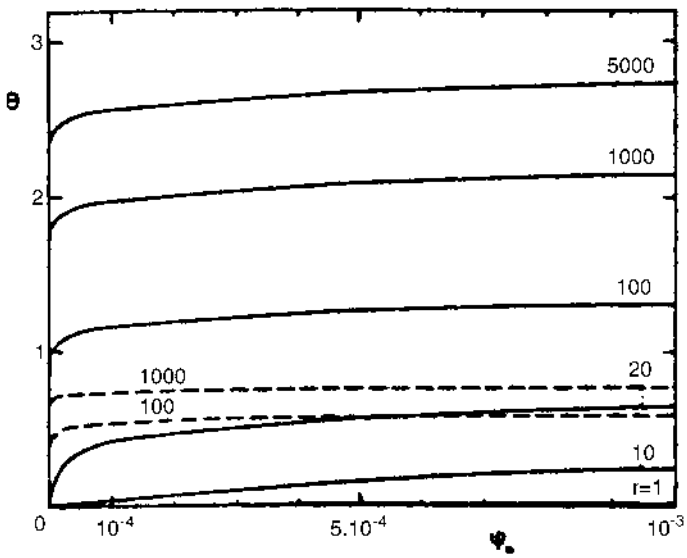

FIG. 3 Adsorption isotherms for oligomers and polymers in the dilute region. ___, $\chi = 0.5$; ---, $\chi = 0$; $\chi_s = 1$. Hexagonal lattice.

plateau (which only increases few percentage points per decade of ϕ). Adsorption in this case is described as being irreversible," i.e., the equilibrium between adsorbed and free polymer is shifted toward the surface. This explains the strong anchoring of the polymer chains to the surface. As the solvency of the medium for the chains decreases, the amount of polymer adsorbed increases. This is clearly illustrated in Fig. 7 when comparing the results obtained when $\chi = 0$ (very good solvent) with those obtained using a poor solvent with $\chi = 0.5$. In good solvents (dashed lines in Fig. 3), θ is much smaller and levels off for long chains to attain an adsorption plateau that is essentially independent of molecular weight. This explains the "weaker" adsorption of homopolymers that are highly solvated by the medium. It is now clear from these theories why block and graft copolymers are preferred for stabilization of dispersions. The poor solubility of the anchor chain B in the medium and its strong affinity to the surface ensures the strong adsorption of the molecule. In contrast, the high solubility of the stabilizing chain A ensures effective steric stabilization. Another prediction from the theories is that the higher the molecular weight of the polymer, the higher the amount of adsorption, when the latter is expressed in mg/m^2.

Some general features of the adsorption isotherms over a wide concentration range can be illustrated by using logarithmic scales for both θ and

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$\phi_\bullet$ which highlight the behavior in extremely dilute solutions. Such presentation [16] is shown in Fig. 4. These results show a linear Henry region followed by a pseudoplateau region. A transition concentration, $\phi_\bullet^{1c}$, can be defined by extrapolation of the two linear parts. $\phi_\bullet^{c}$ decreases exponentially with increasing chain length and when $r = 50$, $\phi_\bullet^{c}$ is so small (10^{-12}) that it does not appear within the scale shown in Fig. 4. With $r = 1000$, $\phi_\bullet^{c}$ reaches the ridiculously low value of 10^{-235}. The region below $\phi_\bullet^{c}$ is the Henry region where the adsorbed polymer molecules behaves essentially as isolated molecules. The representation in Fig. 8 also answers the question of reversibility vs. irreversibility for polymer adsorption. When $r > 50$, the pseudoplateau region extends down to very low concentration ($\phi_\bullet^{c} = 10^{-12}$), and this explains why one cannot easily detect any desorption upon dilution. Clearly, if such extremely low concentration can be reached, desorption of the polymer may take place. Thus, the lack of desorption (sometimes referred to as irreversible adsorption) is due to the fact that the equilibrium between adsorbed and free polymer is shifted far in favor of the surface because of the high possible number of possible attachments per chain.

Another point that emerges from Scheutjens and Fleer's theory [17] is the difference in shape between experimental and theoretical adsorption iso-

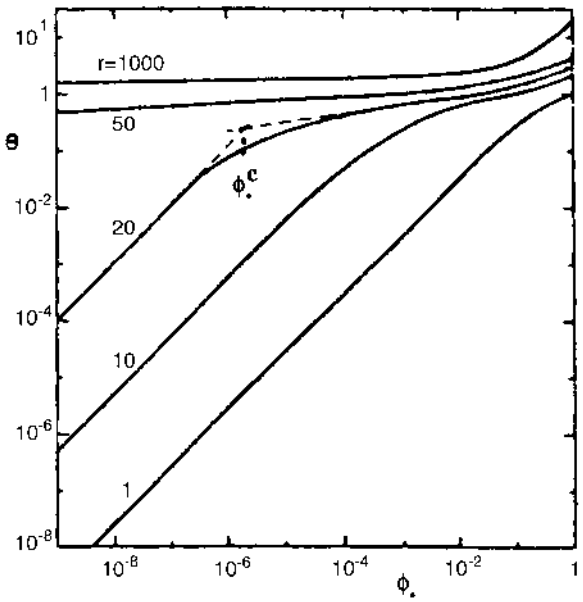

FIG. 4 Log-log presentation of adsorption isotherms of various r values, $\chi_s = 1$; $\chi = 0.5$. Hexagonal lattice.

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therms in the low-concentration region. The experimental isotherms are usually rounded, whereas those predicted from theory are flat. This is accounted for in terms of the molecular weight distribution (polydispersity) that is encountered in many practical systems. This effect has been explained by Fleer et al. [17]. With polydisperse polymer fractions, the larger molecules adsorb preferentially over the smaller ones. At low polymer concentrations, nearly all molecular weights are adsorbed, leaving only a small fraction of polymer with the lowest molecular weight in solution. As the polymer concentration is increased, the higher molecular weight fractions displace the lower ones on the surface, which are now released in solution, thus shifting the molecular weight distribution of the polymer in bulk solution to lower values. This process continues with further increase in polymer concentration leading to a fractionation process whereby the higher molecular weight fractions are adsorbed at the expense of the lower fractions, which are released in the bulk. However, in very concentrated solutions, monomers adsorb preferentially with respect to polymers and short chains with respect to larger ones. This is due to the fact that in this region the conformational entropy term dominates the free energy, disfavoring the adsorption of long chains.

The bound fraction, p, is high at low polymer concentrations ($\phi_\bullet < \phi_\bullet^c$) approaching unity, and it is relatively independent of molecular weight when $r > 20$. p also increases with increase of the adsorption energy, χ^s, but it decreases with increase in surface coverage and increase of the molecular weight of the polymer.

The structure of the adsorbed layer is described in terms of the segment density distribution, $\rho(z)$. As an illustration, Fig. 5 shows some calculations by Scheutjens and Fleer [17] for loops and tails with $r = 1000$, $\phi_\bullet = 10^{-6}$, and $\chi = 0.5$. In this example, 38% of the segments are in trains, 55.5% in loops, and 6.5% in tails. This theory demonstrates the importance of tails which dominate the total distribution in the outer region of the adsorbed layer. As we will discuss in the next section on experimental techniques for characterization of the adsorption and conformation of polymers at the solid–liquid interface, determination of the segment density distribution is not easy and usually assigns a value for the adsorbed layer thickness δ. This increases with increase of the molecular weight of the polymer and increase of solvency of the medium for the chains.

The segment density distribution of block copolymers gives a different pattern, since the hydrophilic block (the buoy) extends away from the surface into bulk solution, whereas the lyophobic anchor block provides firm attachment to the surface. This is illustrated in Fig. 6, which shows the theoretical adsorption and hydrodynamic layer thickness behavior of an AB block copolymer according to Schuetjens and Fleer's theory [17].

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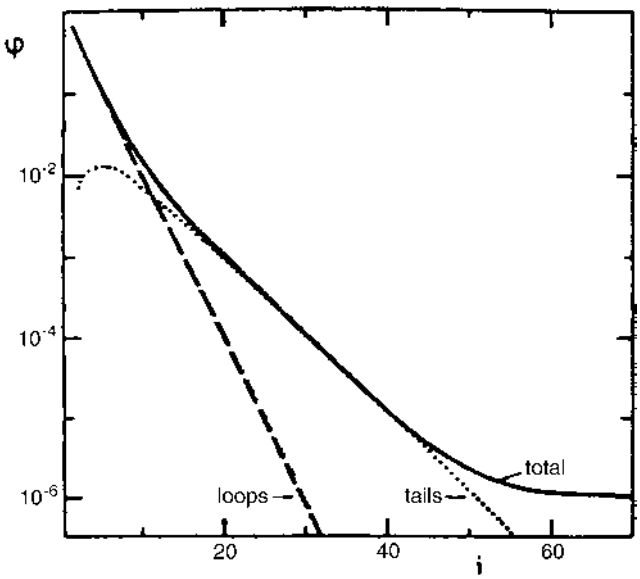

FIG. 5 Loop, tail, and total segment concentration profiles according to Scheutjens and Fleer's theory [17]. $\chi = 0.5$, $\chi_g = 1$, $r = 1000$, $\phi_\bullet = 10^{-6}$.

In general, the adsorbed amounts are higher than is the case for homopolymers and the adsorbed layer more extended and more dense. Maximal levels of adsorption are achieved when around 10% of segments are anchors. In principle, these materials are better steric stabilizers than hompolymers.

Chain architecture also plays a role in determining the adsorption characteristics of block copolymers. For example, for an A-B-A triblock the relative position of the anchor and buoy blocks becomes important. This is illustrated below in the experimental section on polymer adsorption.

V. EXPERIMENTAL METHODS FOR MEASUREMENT OF ADSORPTION PARAMETERS FOR POLYMERIC SURFACTANTS

A. Amount of Polymer Adsorbed Γ—The Adsorption Isotherms

The determination of the adsorption isotherms, i.e., Γ, as a function of equilibrium concentration in solution C_2 is fairly well established. Basically

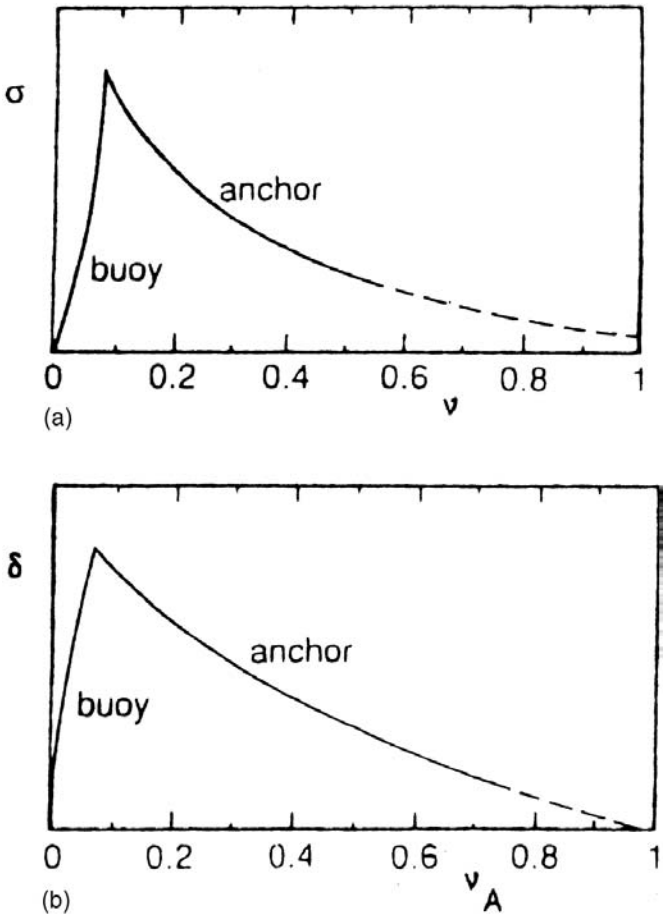

FIG. 6 Prediction of Scheutjens and Fleer's theory for adsorption (surface density σ) (a) and adsorbed layer thickness δ (b) of diblock copolymers vs. fraction of anchor segment ν_A.

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one determines the change in polymer concentration, ΔC, in bulk solution before and after equilibration with the solid particles of mass m and specific surface area A_s:

$$\Gamma = \frac{\Delta C\ V}{mA_s} \tag{13}$$

where V is the volume of the solution in liters.

It is essential to develop analytical techniques that are capable of measuring low concentrations (ppm) in order to establish the initially steeply rising part of the isotherm. Although simple in principle, it requires some care to establish reliable isotherms. This has to do with the problem of irreversibility and adsorption/desorption kinetics. The attainment of equilibrium is studying polymer adsorption represent a problem, due to the low diffusion coefficient of polymer molecules in solution and the finite time taken for a polymer molecule to adopt its steady-state conformation. Thus, long equilibration times (hours to days) are needed. This is particularly the case at high coverage and when the polymer is polydisperse. The smaller molecules, which have higher diffusion coefficients, will adsorb first and are gradually replaced by preferentially adsorbed larger molecules.

As an illustration, Fig. 7 shows the adsorption isotherms at 25°C for PVA (containing 12% acetate) [18]. The polymer was fractionated using preparative gel permeation chromatography [18] or by a sequential precipitation technique using acetone [19]. The fractions were characterized for their molecular weight using ultracentrifugation and later by intrinsic viscosity measurements. The intrinsic viscosity [η] could be related to the weight average molecular weight of the polymer (determined using ultracentrifugation) using the Mark-Houwink relationship:

$$[\eta] = KM^{\alpha} \tag{14}$$

where K and α were established from knowledge of [η] and M.

The latter values could also be used to calculate the molecular dimensions (radius of gyration) and the polymer–solvent interaction parameter χ was also determined. The polystyrene latex used for the adsorption measurements was a model system prepared using surfactant-free polymerization and the particles were fairly monodisperse. Hence, the specific surface area of the particles could be estimated from simple geometry using electron microscopy.

Figure 7 shows the high-affinity isotherms for the polymers and the increase in adsorption of the polymer with an increase in molecular weight. Similar isotherms are expected for the adsorption of the polymer on oil droplets. However, in the latter case it is not possible to obtain the full isotherm since to produce the emulsion one requires a minimum of polymer.

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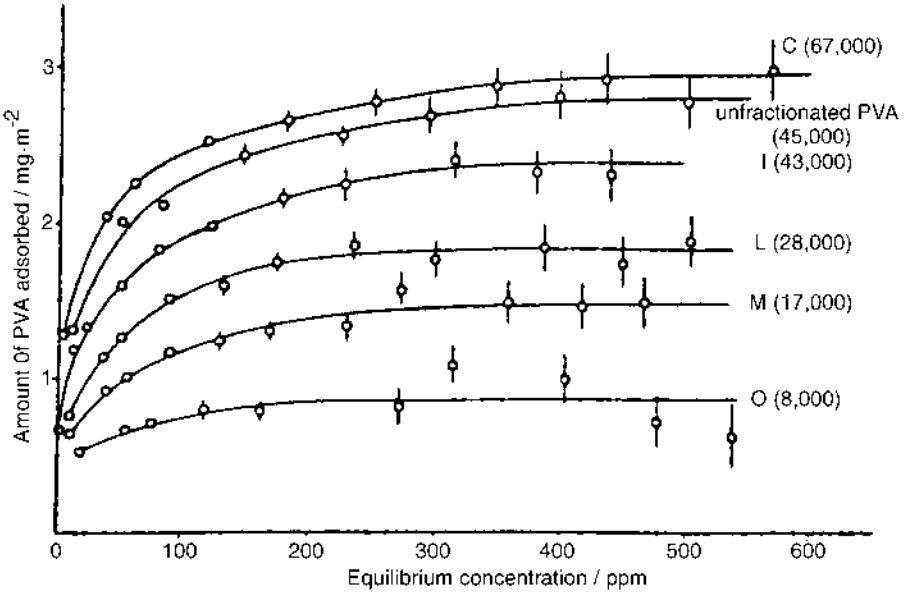

FIG. 7 Adsorption isotherms of polyvinyl alcohol on polystyrene latex at 25°C [18].

In addition, the surface area of the emulsion has to be determined at each point from the droplet size distribution.

To study the effect of solvency on adsorption, measurements were carried out as a function of temperature [19] and addition of electrolyte (KCl or Na_2SO_4) [20]. Increasing temperature and/or addition of electrolyte reduces the solvency of the medium for the PVA chains (due to break down of the hydrogen bonds between the vinyl alcohol units and water). Figure 8 shows the adsorption isotherms for PVA with $M = 65000$ as a function of temperature. This shows systematic increase of adsorption with increase of temperature, i.e., with reduction of solvency (increase in the value of the χ parameter), as expected from theory. The results obtained in the presence of electrolyte are shown in Figs. 9 and 10. In both cases, addition of electrolyte increases adsorption of PVA, again as a result of the reduction of solvency of the medium for the chains.

The above polymer (PVA) is a "blocky" copolymer (containing short vinyl acetate blocks) and hence it does not represent the case for adsorption of homopolymers. The latter case is exemplified by PEO [21] as is illustrated in Fig. 11 for adsorption on polystyrene latex using three different molecular

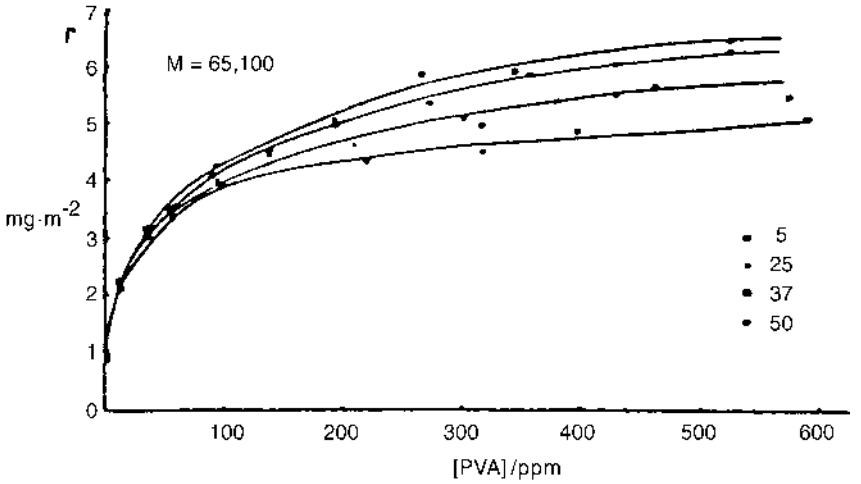

FIG. 8 Adsorption isotherms for PVA (M = 65,000) on polystyrene latex at various temperatures.

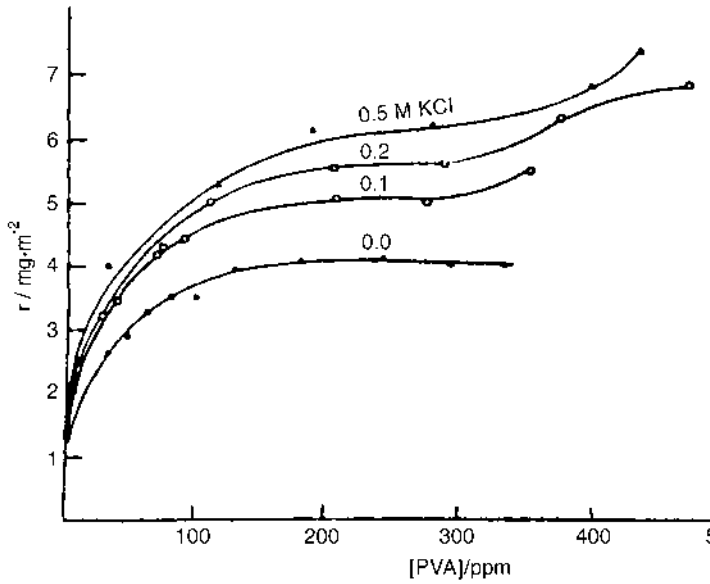

FIG. 9 Adsorption isotherms for PVA on polystyrene latex particles at various KCl concentrations.

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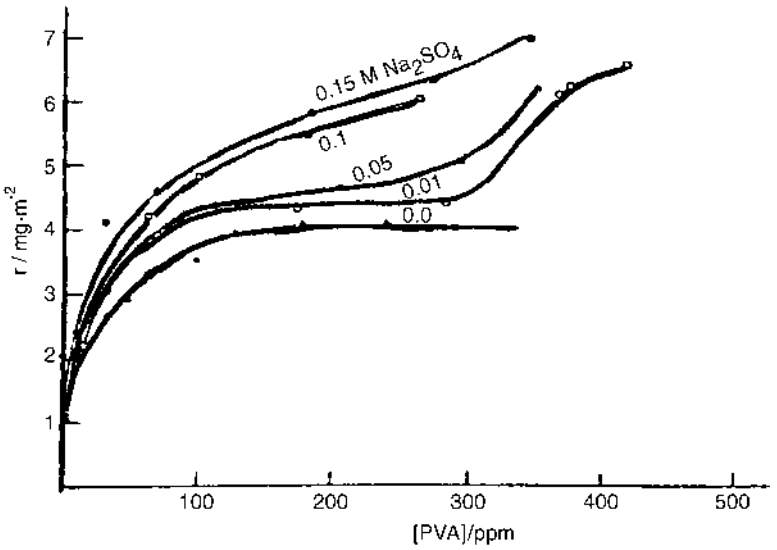

FIG. 10 Adsorption isotherms for PVA on polystyrene latex at various Na_2SO_4 concentrations.

weight PEOs. As with PVA, the isotherms are of the high-affinity type and the adsorbed amount increases with increase of the molecular weight of the polymer. However, the amount of adsorption is much lower than that obtained using PVA. This reflects the difference between the two polymers.

B. Polymer-Bound Fraction *p*

The bound fraction p represents the ratio of the number of segments in close contact with the surface (i.e., in trains) to the total number of segments in the polymer chain. The polymer bound fraction, p, can be directly determined using spectroscopic methods such as infrared (IR), electron spin resonance (ESR), and nuclear magnetic resonance (NMR). The IR method depends on measuring the shift in some absorption peak for a polymer and/or surface group [22–25]. The ESR and NMR methods depend on the reduction in the mobility of the segments that are in close contact with the surface (larger rotational correlation time for trains when compared to loops). By using a pulsed NMR technique one can estimate p. An indirect method for estimation of p is microcalorimetry. Basically one compares the enthalpy of adsorption per molecule with that per segment. The latter may be obtained by using small molecules of similar structure to a polymer segment. This can

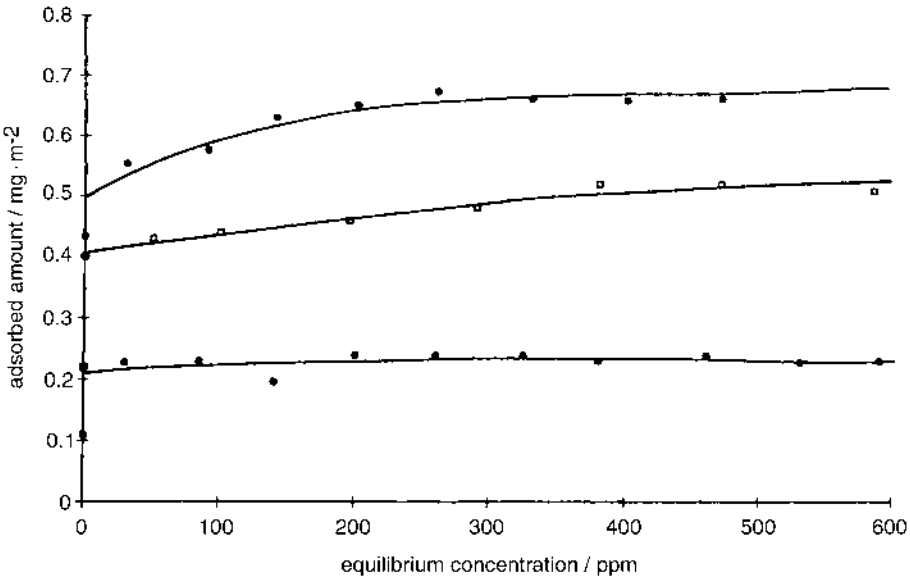

FIG. 11 Adsorption isotherms for PEO with various molecular weights on polystyrene latex. Molecular weight in order of decreasing adsorbed amounts are 930 K, 114 K, and 10.3 K.

be obtained from measurement of the heat of wetting of such a small molecule on the same surface.

Cohen Stuart et al. [26] compared the value of p obtained using IR, NMR, and microcalorimetry for PVP adsorption on silica. The p values obtained from IR agree rather poorly with the theoretical data, whereas the ESR and NMR agree well with each other and with theoretical predictions. The microcalorimetry also gave reasonable results, but only for relatively short polymer chains. Thus, it seems that ESR and NMR are the most reliable methods for estimation of polymer-b fraction.

C. Adsorbed Layer Thickness δ and Segment Density Distribution $\rho(z)$

Three direct methods can be applied for determination of adsorbed layer thickness: ellipsometry, attenuated total reflection (ATR), and neutron scattering. Both ellipsometry and ATR [27] depend on the difference between refractive indices between the substrate, the adsorbed layer, and the bulk solution and they require flat reflecting surface. Ellipsometry [27] is based on the principle that light undergoes a change in polarizability

when it is reflected at a flat surface (whether covered or uncovered with a polymer layer).

The above limitations when using ellipsometry or ATR are overcome by the application technique of neutron scattering, which can be applied to both flat surfaces and particulate dispersions. The basic principle of neutron scattering is to measure the scattering due to the adsorbed layer, when the scattering length density of the particle is matched to that of the medium (the so-called contrast matching method). Contrast matching of particles and medium can be achieved by changing the isotopic composition of the system (using deuterated particles and mixture of D_2O and H_2O) [28]. It was used for measurement of the adsorbed layer thickness of polymers, e.g., PVA or PEO on polystyrene latex [28]. Apart from obtaining δ, one can also determine the segment density distribution $\rho(z)$. This is illustrated in Fig. 12 which shows the normalized density distribution for PVA (M = 37,000) on PS latex.

The results shows a monotonic decay of $\rho(z)$ with distance z from the surface and several regions may be distinguished. Close to the surface ($0 < z < 3$ nm), the decay in $\rho(z)$ is rapid and assuming a thickness of 1.3 nm for the bound layer, p was calculated to be 0.1, which is in close agreement with the results obtained using NMR measurements. In the middle region, $\rho(z)$ shows a shallow maximum followed by a slow decay which extends to 18 nm, i.e., close to the hydrodynamic layer thickness δ_h of the polymer chain (see below). δ_h is determined by the longest tails and is about 2.5 times the radius of gyration in bulk solution (about 7.2 nm). This slow decay of $\rho(z)$ with z at long distances is in qualitative agreement with Schutjens and Fleers's theory [17]

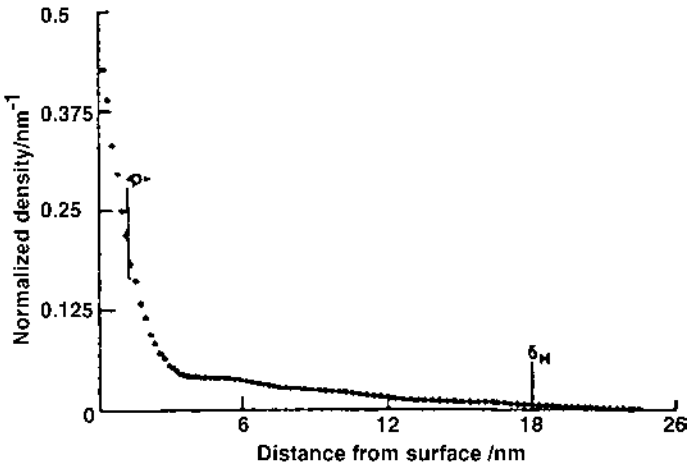

FIG. 12 Plot of $\rho(z)$ against z for PVA (M = 37,000) adsorbed on deuterated PS latex in D_2O/H_2O.

which predicts the presence of long tails. The shallow maximum at intermediate distances suggests that the observed segment density distribution is a summation of a fast monotonic decay due to loops and trains together with the segment density for tails which are a maximal density away from the surface. The latter maximum was clearly observed for a sample that had PEO grafted to a deuterated PS latex [29], where the configuration is represented by tails only.

The hydrodynamic thickness of block copolymers shows different behavior from that of homopolymers (or random copolymers). This is illustrated in Figs. 16 and 17 for an ABA block copolymer of PEO-PPO-PEO [21] which show the adsorbed amount (Fig. 13) and the hydrodynamic thickness (Fig. 14) vs. fraction of anchor segment. The theoretical (Scheutjens and Fleer) prediction of adsorbed amount and layer thickness versus fraction of anchor segment are shown in the inserts of Figs. 16 and 17. When there are two buoy blocks and a central anchor block, as in the above example, the A-B-A block shows similar behavior to that of an A-B block. However, if there are two anchor blocks and a central buoy block, surface precipitation of the polymer

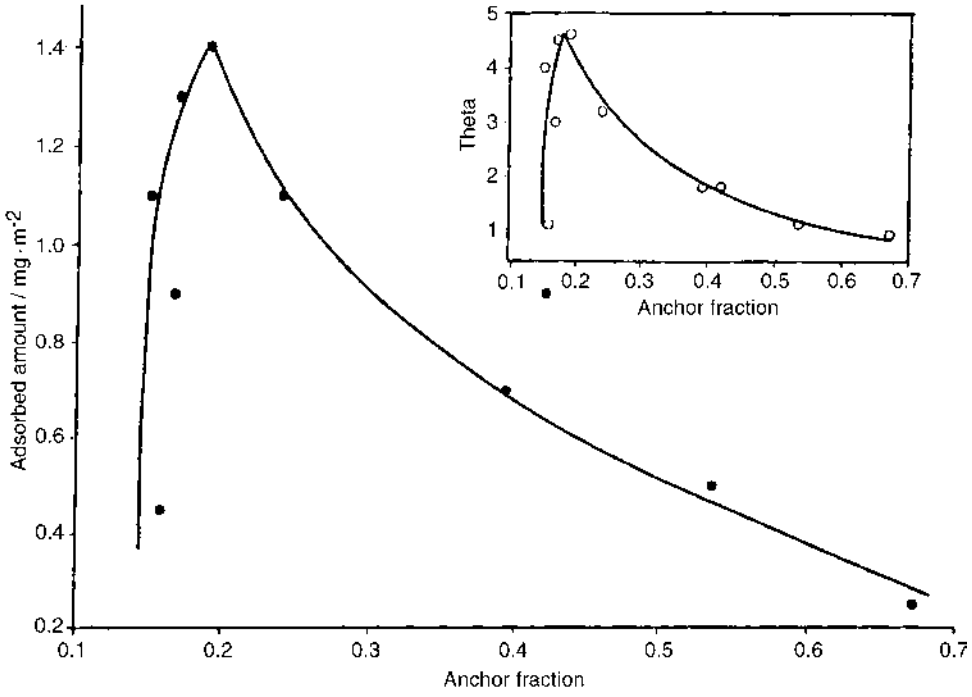

FIG. 13 Adsorbed amount vs. fraction of anchor segment ν_A for PEO-PPO-PEO block copolymer. Insert shows the theoretical predictions.

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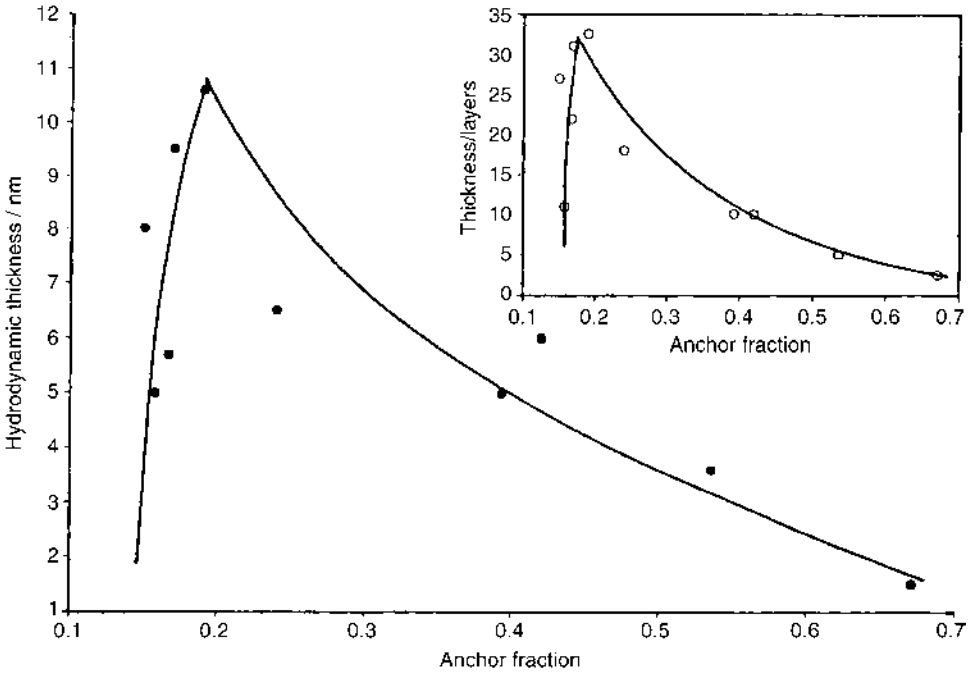

FIG. 14 Hydrodynamic thickness vs. fraction of anchor segment ν_A for PEO-PPO-PEO block copolymer. Insert shows theoretical predictions.

molecule at the particle surface is observed, and this is reflected in a continuous increase of adsorption with increase in polymer concentration as has been shown for an A-B-A block of PPO-PEO-PPO [21].

The above technique of neutron scattering gives clearly a quantitative picture of the adsorbed polymer layer. However, its application in practice is limited since one needs to prepare deuterated particles or polymers for the contrast matching procedure. The practical methods for determination of the adsorbed layer thickness are mostly based on hydrodynamic techniques and these are discussed below.

D. Hydrodynamic Thickness Determination

Several methods may be applied to determine the hydrodynamic thickness of adsorbed polymer layers of which viscosity, sedimentation coefficient (using an ultracentrifuge), and dynamic light scattering measurements are the most convenient. A less accurate method is from ζ potential measurements. These techniques are summarized below.

The viscosity method [29] depends on measuring the increase in the volume fraction of the particles as a result of the presence of an adsorbed layer of thickness δ_h. The volume fraction of the particles ϕ plus the contribution of the adsorbed layers is usually referred to as the effective volume fraction ϕ_{eff}. Assuming the particles behave as hard spheres, then the measured relative viscosity η_r is related to the effective volume fraction by the Einstein's equation, i.e.,

$$\eta_r = 1 + 2.5\phi_{eff} \tag{15}$$

ϕ_{eff} and ϕ are related from simple geometry by

$$\phi_{eff} = \phi\left[1 + \left(\frac{\delta_h}{R}\right)\right]^3 \tag{16}$$

where R is the particle radius. Thus, from a knowledge of η_r and ϕ, one can obtain δ_h using the above equations.

The sedimentation method depends on measuring the sedimentation coefficient (using an ultracentrifuge) of the particles S_0' (extrapolated to zero concentration) in the presence of the polymer layer [30]. Assuming the particles obey Stokes' law, S_0' is given by the expression:

$$S_0^{'} = \frac{(4/3)\pi R^3(\rho - \rho_s) + (4/3)\pi\left[(R + \delta_h)^3 - R^3\right](\rho_s^{ads} - \rho_s)}{6\pi\eta(R + \delta_h)} \tag{17}$$

where ρ and ρ_s are the mass density of the solid and solution phase, respectively, and ρ^{ads} is the average mass density of the adsorbed layer, which may be obtained from the average mass concentration of the polymer in the adsorbed layer.

In order to apply the above methods, one should use a dispersion with monodisperse particles with a radius that is not much larger than δ_h. Small model particles of polystyrene may be used.

A relatively simple sedimentation method for determination of δ_h is the slow-speed centrifugation applied by Garvey et al. [30]. Basically a stable monodisperse dispersion is slowly centrifuged at low g values ($< 50\ g$) to form a close-packed (hexagonal or cubic) lattice in the sediment. From a knowledge of ϕ and the packing fraction (0.74 for hexagonal packing), the distance of separation between the center of two particles R_δ may be obtained, i.e.,

$$R_\delta = R + \delta_h = \left(\frac{0.74\ V\rho_1 R_3}{W}\right) \tag{18}$$

where V is the sediment volume, ρ_1 is the density of the particles, and W is their weight.

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The most rapid technique for measuring δ_h is photon correlation spectroscopy (PCS) (sometime referred to as quasi-elastic light scattering), which allows one to obtain the diffusion coefficient of the particles with and without the adsorbed layer (D_δ and D, respectively). This is obtained from measurement of the intensity fluctuation of scattered light as the particles undergo Brownian diffusion [31]. When a light beam (e.g., monochromatic laser beam) passes through a dispersion, an oscillating dipole is induced in the particles, thus reradiating the light. Due to the random arrangement of the particles (which are separated by a distance comparable to the wavelength of the light beam, i.e., the light is coherent with the interparticle distance), the intensity of the scattered light will, at any instant, appear as random diffraction or "speckle" pattern. As the particles undergo Brownian motion, the random configuration of the speckle pattern changes. The intensity at any one point in the pattern will, therefore, fluctuate such that the time taken for an intensity maximum to become a minimum (i.e., the coherence time) corresponds approximately to the time required for a particle to move one wavelength. Using a photomultiplier of active area about the size of a diffraction maximum, i.e., approximately one coherence area, this intensity fluctuation can be measured. A digital correlator is used to measure the photocount or intensity correlation function of the scattered light. The photocount correlation function can be used to obtain the diffusion coefficient D of the particles. For monodisperse noninteracting particles (i.e., at sufficient dilution), the normalized correlation function $[g^{(1)}(\tau)]$ of the scattered electric field is given by the equation:

$$\left[g^{(1)}(\tau)\right] = \exp - (\Gamma\tau) \tag{19}$$

where τ is the correlation delay time and Γ is the decay rate or inverse coherence time. Γ is related to D by the equation:

$$\Gamma = DK^2 \tag{20}$$

where K is the magnitude of the scattering vector that is given by

$$K = \left(\frac{4n}{\lambda_o}\right)\sin\left(\frac{\theta}{2}\right) \tag{21}$$

where n is the refractive index of the solution, λ is the wavelength of light in vacuum, and θ is the scattering angle.

From D, the particle radius R is calculated using the Stokes-Einstein equation:

$$D = \frac{kT}{6\pi\eta R} \tag{22}$$

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where k is the Boltzmann constant and T is the absolute temperature. For a polymer coated-particle R is denoted R_δ which is equal to $R + \delta_h$. Thus, by measuring D_δ and D, one can obtain δ_h. It should be mentioned that the accuracy of the PCS method depends on the ratio of δ_δ/R, since δ_h is determined by difference. Since the accuracy of the measurement is $\pm$ 1%, δ_h should be at least 10% of the particle radius. This method can only be used with small particles and reasonably thick adsorbed layers.

Electrophoretic mobility, u, measurements can also be applied to measure δ_h [34]. From u, the ζ potential, i.e., the potential at the slipping (shear) plane of the particles, can be calculated. Adsorption of a polymer causes a shift in the shear plane from its value in the absence of a polymer layer (which is close to the Stern plane) to a value that depends on the thickness of the adsorbed layer. Thus, by measuring ζ in the presence (ζ_δ) and absence (ζ) of a polymer layer one can estimate δ_h. Assuming that the thickness of the Stern plane is Δ, then ζ_δ may be related to ζ (which may be assumed to be equal to the Stern potential ψ_d) by the equation:

$$\tan\ h\left(\frac{\psi_\delta}{4kT}\right) = \tan\ h\left(\frac{\zeta}{4kT}\right)\exp\ [-\kappa(\delta_h - \Delta)] \tag{23}$$

where κ is the Debye parameter that is related to electrolyte concentration and valency.

It should be mentioned that the value of δ_h calculated using the above simple equation shows a dependence on electrolyte concentration and hence the method cannot be used in a straightforward manner. Cohen-Stuart et al. [32] showed that the measured electrophoretic thickness δ_e approaches δ_h only at low electrolyte concentrations. Thus, to obtain δ_h from electrophoretic mobility measurements, results should be obtained at various electrolyte concentrations and δ_e should be plotted against the Debye length ($1/\kappa$) to obtain the limiting value at high ($1/\kappa$) (i.e., low electrolyte concentration) which now corresponds to δ_h.

VI. INTERACTION BETWEEN PARTICLES (DROPLETS) CONTAINING ADSORBED POLYMER LAYERS (STERIC STABILIZATION)

When two particles or droplets containing adsorbed polymer layers (with an adsorbed layer thickness δ) approach to a distance of separation h whereby these layers begin to overlap, i.e., when $h < 2\delta$, repulsion occurs as a result of two main effects [6]. The first repulsive force arises from the unfavorable mixing of the polymer layers when these are present in a good solvent (i.e., the chains are strongly solvated by the medium). The unfavorable mixing of

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polymer solutions in good solvent conditions was considered by Flory and Krigbaum [33] whose theory was applied to the present case of interparticle interaction. A schematic representation of the mixing of polymer layers on close approach is shown in Fig. 15, which shows the situation when two particles with polymer layers are forced to approach to a distance h that is less than 2δ forming an overlap region with a volume element dV. Before overlap, the chains have a volume fraction ϕ_2 and the solvent has a chemical potential μ_1^{α}. In the overlap region, the volume fraction of the chains is ϕ_2' which is higher the ϕ_2, and the solvent has a chemical potential μ_1^{β}, which is lower than μ_1^{α}. This is equivalent to an increase in the osmotic pressure in the overlap region. As a result, solvent diffuses from the bulk to the overlap region and the two particles or droplets are separated apart, i.e., this results in strong repulsion. The latter is referred to as mixing or osmotic repulsion.

Using the Flory-Krigbaum theory [33], one can calculate the free energy of mixing, G_{mix}, due to this unfavorable overlap, i.e.,

$$\frac{G_{\text{mix}}}{kT} = \frac{4\pi}{3V_1}\phi_2^2 N_{\text{av}}\left(\frac{1}{2} - \chi\right)\left(\delta - \frac{\text{h}}{2}\right)^2\left(3R + 2\delta + \frac{h}{2}\right) \tag{24}$$

where k is the Boltzmann constant, T is the absolute temperature, V_1 is the molar volume of the solvent, and N_{av} is the Avogadros's constant.

It is clear from Eq. (18) that when the Flory-Huggins interaction parameter, χ, is less than 0.5, i.e., the chains are in good solvent conditions, G_{mix} is positive and the interaction is repulsive, and it increases very rapidly with decreasing h, when the latter is lower than 2_{δ}. This explains why polymeric surfactants such as Hypermer CG6 (a graft copolymer of polymethyl methacrylate backbone and PEO side chains, produced by ICI) is ideal for

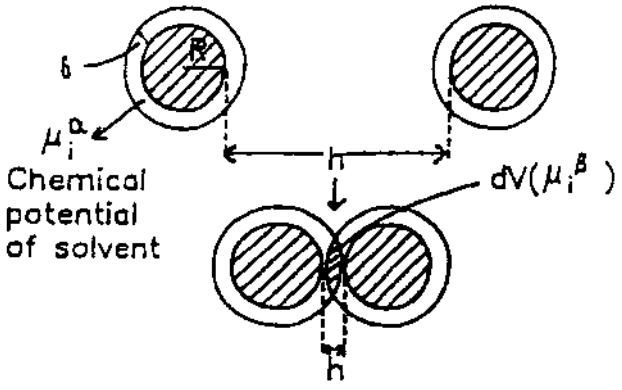

FIG. 15 Schematic representation of overlap of two polymer layers.

stabilizing dispersions in aqueous media. For stabilization of dispersions in nonaqueous media, such as w/o emulsions, the stabilizing chains have to be soluble in the oil phase (normally a hydrocarbon). In this case, poly(hydroxystearic acid) (PHS) chains are ideal. A polymeric surfactant such as Arlacel P135 (an ABA block copolymer of PHS-PEO-PHS produced by ICI) is an ideal w/o emulsifier.

Equation (18) also shows that when $\chi > 0.5$, i.e., when the solvency of the medium for the chains becomes poor, G_{mix} is negative and the interaction becomes attractive. The condition $\chi = 0.5$ is referred to as θ solvent, and this denotes the onset of change of repulsion to attraction. Thus, to ensure steric stabilization by the above mechanism one has to ensure that the chains are kept in better than a θ solvent.

The second repulsive force arises from the loss of configurational entropy when the chains overlap. This is illustrated schematically in Fig. 16, whereby the polymer chain is represented by a simple rod with one attachment point to the surface. When the two surfaces are separated at infinite distance, each chain will have a number of configurations, Ω_∞, that are determined by the volume of the hemisphere swept by the rod. When the two surfaces approach to a distance h that is smaller than the radius of the hemisphere swept by the rod, the volume available to the chains becomes smaller and this results in a reduction in the configurational entropy to a value Ω (that is less than Ω_∞). This results in strong repulsion. The effect is referred to as entropic, volume restriction or elastic repulsion and is given by the following expression [6]:

$$G_{el} = 2\nu \ln \frac{\Omega}{\Omega_\infty} \tag{25}$$

where ν is the number of polymer chains per unit area of the surface. It should be mentioned that G_{el} is always repulsive, becoming very high on considerable overlap of the polymer chains.

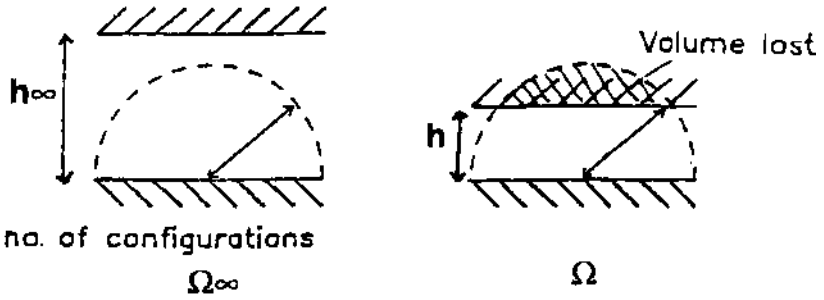

FIG. 16 Schematic representation of the entropic volume restriction or elastic interaction.

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Plots of G_{mix} and G_{el} vs. h are illustrated in Fig. 17, which shows that G_{mix} increases very rapidly with decrease of h as soon as h becomes smaller than 2δ (and $\chi < 0.5$). G_{el} also increases very rapidly with decrease of h on further overlap. Combination of G_{mix}, G_{el}, and G_A (the van der Waals attraction) results in the total $G_T - h$ curve shown in Fig. 20. This curve shows a minimum (G_{min}) at $h \sim 2\delta$, but when $h < 2\delta$, G_T increases very rapidly with further decrease in h. The depth of the minimum, G_{min}, depends on the adsorbed layer thickness. With increase of δ, G_{min} decreases and at sufficiently high values of δ (of the order of 5–10 nm), it reaches small values (fraction of kT units). This shows that with sterically stabilized dispersions, there is only weak attraction at relatively long distances of separation, which in most cases is overcome by Brownian diffusion. Thus, one can say that the net interaction is repulsive and this ensures the long-term stability of the dispersion.

From the above discussion one can summarize the main criteria for effective steric stabilization. First, there should be enough polymer to ensure complete coverage of the surface by the chains. This prevents any attraction between the bare patches or bridging by the polymer chains (which can adsorb simultaneously on more than one particle). Second, the chains must be strongly adsorbed ("anchored") to the surface. This prevents any displacement on close approach. In this respect, block and graft copolymers containing an anchoring chain [such as polystyrene or poly(methyl methacrylate) to hydrophobic surfaces] are the best stabilizers. In some cases strong adsorption may be achieved by a phenomenon referred to as *rejection anchoring*. If the B chain is insoluble in the medium (water or oil) it can adsorb by this rejection mechanism. This situation applies to PPO, which is insoluble in water and in

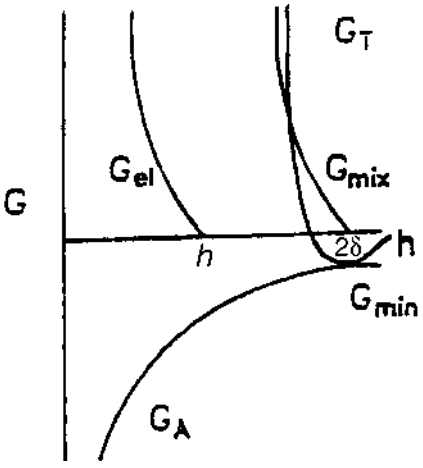

FIG. 17 Schematic representation of the variation of G_{mix}, G_{el}, G_A and G_T with h.

most oils. This explains the use of block copolymers of the PEO-PPO-PEO as emulsifiers.

The third criteria for effective steric stabilization is to ensure that the stabilizing chain A remains in good solvent conditions at all times and under all conditions. As discussed above, for systems where water is the continuous medium PEO is the most suitable A chain(s). The polymer chain is highly soluble in water and remains solvated up to high temperatures. It can also tolerate reasonable amounts of electrolyte. For dispersions, where the continuous medium is a hydrocarbon oil (e.g., w/o emulsions), poly(hydroxystearic acid) is the most suitable A chain(s).

The last criterion for effective steric stabilization is to have a sufficiently thick adsorbed layer to avoid any weak flocculation. This is particularly important for concentrated dispersions. As discussed above, a value of δ of the order of 5–10 nm is usually sufficient. Hence, the side PEO chains must have a molecular weight of the order of 1000–2000. With most graft copolymers, these side chains are extended and provide a sufficiently thick layer.

VII. USE OF POLYMERIC SURFACTANTS FOR STABILIZATION OF EMULSIONS

Polymeric surfactants are ideal for stabilization of both oil-in-water (o/w) and water-in-oil (w/o) emulsions against flocculation, Ostwald ripening, and coalescence. The stabilization against flocculation was discussed in detail in the previous section, which showed that by using A-B, A-B-A, or BA_n copolymers can overcome flocculation by proper choice of B (anchor chain) and A (stabilizing chains). In order to ensure absence of flocculation, the χ parameter should be maintained at a value less than 0.5 under all conditions of storage of the emulsion. Both PEO and polyfructose chains can be used for this purpose in water. With PEO, flocculation can also be maintained at moderate electrolyte concentrations. For much higher electrolyte concentrations, the PEO chains may undergo dehydration and χ may reach a value of 0.5 and higher, under which conditions strong flocculation (sometimes referred to as incipient flocculation) may occur. This problem may be overcome using polyfructose chains, as, for example, the case with inulin carbamates, which can tolerate much higher salt concentrations than PEO. To confirm the above hypothesis, we have recently investigated emulsion stability in the presence of high salt concentrations using inulin carbamate [34]. The o/w emulsions of Isopar M (an isoparaffinic oil) were prepared using 2% (based on the oil phase) Inutec surfactant LiC 0.1 (based on Inutec N25, with a degree of polymerization greater than 23 and containing an average of

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0.1 degree of substitution with C_{12} alkyl chains). This polymeric surfactant is commercially available (Orafti, Tienen, Belgium). These emulsions were prepared in water, 0.5, 1, and 2 mol dm^{-3} NaCl, and 0.5, 1, and 2 mol dm^{-3} $MgSO_4$. No emulsion containing NaCl showed a strong flocculation or coalescence up to 50°C for one-year storage. The same result was obtained with $MgSO_4$ up to 1 mol dm^{-3}. This stability in such high electrolyte concentrations were not observed with polymeric surfactants containing PEO as the stabilizing chain.

The difference in stabilization between inulin-based and PEO-based surfactants can be accounted for in terms of the effect on the χ parameter. With both inulin and PEO in water, the χ parameter is maintained below 0.5 up to 100°C. This is illustrated in Figs. 18–20, which show the variation of cloud point with PEO and Inulin concentrations.

However, in the presence of electrolyte, inulin and PEO show different behavior. With PEO, the cloud point falls below 60°C when the NaCl concentration exceeds 2 mol dm^{-3} NaCl and 0.5 mol dm^{-3} $MgSO_4$. With inulin, no cloud point could be measured up to 4 mol dm^{-3} NaCl or 1 mol dm^{-3} $MgSO_4$. This indicates that the inulin chain (polyfructose) retains its hydration to much higher temperatures and electrolyte concentrations than the PEO chains. This is probably the reason for the high stability obtained when using inulin carbamates as emulsion stabilizers.

Generally speaking, the cloud point is related to the χ parameter. When χ exceeds 0.5, dehydration of the chain takes place and the chain–chain interaction leads to cloudiness. The cloud point depends both on the polymer concentration as well as the molecular weight; with increase in the molecular weight and concentration, the cloud point decreases (Figs. 18 and 19). With PEO at 2 mol dm^{-3} the cloud point at 5% is about 60°C, and if the concentration in the polymer layer reaches, for example, 20%, the cloud point will be lower than 50°C. Thus, for emulsion stabilizers based on PEO,

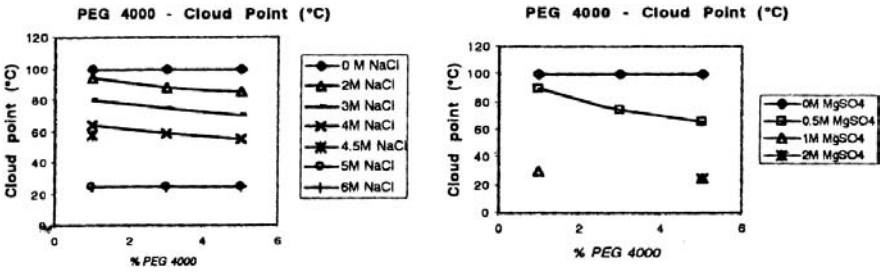

FIG. 18 Variation of cloud point with PEO (M = 4000) concentration in the presence and absence of NaCl and $MgSO_4$.

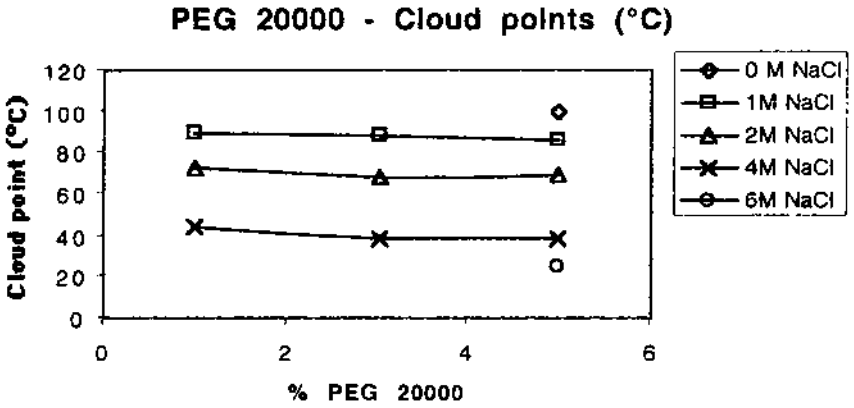

FIG. 19 Variation of cloud point with PEO (M = 20,000) in presence and absence of NaCl.

the stability against flocculation could not be maintained at 2 mol dm^{-3} NaCl. With $MgSO_4$, the situation is even worse, as shown in Fig. 18; at 5% PEO (M = 4000), the cloud point is lower than room temperature at 1 mol dm^{-3} $MgSO_4$. Hence, instability will be more serious with this electrolyte. However, for inulin based emulsifiers no cloud point was observed up to 4 mol dm^{-3} NaCl and a temperature of 100°C. One would expect stable emulsions at temperatures exceeding 50°C up to 4 mol dm^{-3} NaCl. With $MgSO_4$ stability could be maintained at high temperatures up to 1 mol dm^{-3}. Thus, these cloud point measurements give conclusive evidence of the unique behavior of polymeric surfactants based on inulin. The polyfructose chain remains hydrated up to high temperatures and in the presence of high electrolyte con-

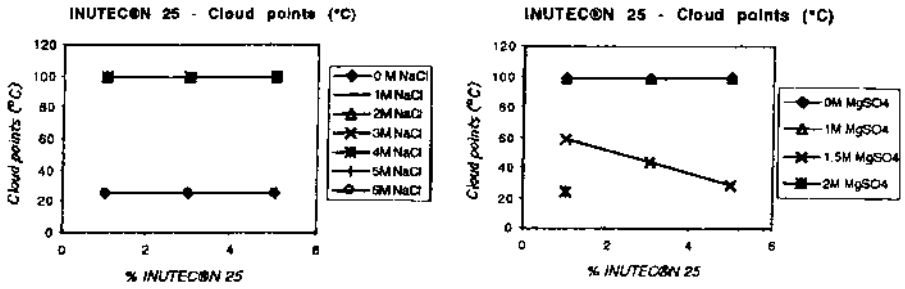

FIG. 20 Variation of cloud point of Inulin in the presence and absence of NaCl and $MgSO_4$.

centrations. Thus, by adequate design of the polymeric surfactant one can achieve very high stability for the emulsions.

Another polymeric surfactant that is very effective for stabilization of w/o emulsions is the A-B-A block of poly(hydroxystearic acid)–poly(ethylene oxide)–poly(hydroxy stearic acid) (PHS-PEO-PHS) (Arlacel P135 commercially available by Uniqema, Wilton, UK). Thus, this polymeric surfactant [35] is a polyester-polyether-polyester ABA block. The head group is B PEO, while the two tails are poly(12-hydroxystearic acid). The weight–average molecular weight M_w of the molecule is 6809 g mol^{-1}, whereas the number-average M_n is 3499 g mol^{-1} (i.e., the polymer is polydisperse with M_w/M_n = 1.94). It has a hydrophilic–lipohilic balance (HLB) of 5–6, which makes it suitable for a w/o emulsion. The molecule is soluble in hydrocarbon oils and produces lamellar liquid crystals even at low concentrations. X-ray diffraction measurements showed a thickness of 17.3 nm for the bilayer, which implies an adsorbed layer thickness at the w/o interface in the region of 9 nm. Surface pressure measurement at the o/w interface using a Langmuir trough showed that on compression of the molecule a surface pressure in the region of 50 mN m^{-1} could be obtained, indicating a very interfacial tension at the w/o interface. This makes this polymeric surfactant an ideal candidate for preparation of w/o emulsions. Indeed, w/o emulsions containing more than 80% water could be prepared and these emulsions were relatively fluid. The droplet size of the resulting emulsion was quite small (in the region of 200 nm), and these emulsions were very stable against any flocculation or coalescence. In addition, due to the small droplet size, creaming was insignificant.

VIII. POLYMERIC SURFACTANTS FOR STABILIZATION OF SUSPENSIONS

To illustrate the use of polymeric surfactants for stabilization of suspensions, two graft copolymers were used to investigate the stability of dispersions of polystyrene latex [36]. The two graft copolymers were based on poly(methyl methacrylate–methacrylic acid) backbone with methoxy-capped PEO side chains (M = 750). Two commercially available graft copolymers, Hypermer CG-6 and Atlox 4913 (both supplied by Uniqema, Wilton, UK), were used. The two copolymers are structurally the same except that Hypermer CG-6 contains higher proportion of methacrylic acid in the backbone. The adsorption isotherms of the graft copolymers were of the high affinity type (showing no desorption under practical conditions). The adsorption plateau value was higher for Atlox 4913 than for CG-6 (about 1.5 mg m^{-2} for Atlox 4913 and about 1.2 mg m^{-2} for CG-6. The higher adsorption with Atlox 4913 is due

to the higher surface density of PEO chains. Increase of temperature caused an increase in adsorption due to the reduction of solvency for the PEO chains.

The stability of the dispersions was investigated using rheological measurements. The storage modulus (which could be measured using oscillatory measurements) was followed as a function of temperature in the presence and absence of Na_2SO_4. The results are shown in Figs. 21 and 22 for Atlox 4913 and CG-6, respectively. In the absence of salt no flocculation was observed up to 65°C (the maximal temperature at which measurements were made). However, addition of Na_2SO_4 caused a reduction in the critical flocculation temperature (CFT). With Atlox 4913, the CFT is about 40°C in 0.1 mol dm^{-3} and about 30°C in 0.2 and 0.3 mol dm^{-3} Na_2SO_4. CG-6 gave higher CFT values when compared with Atlox 4913. This shows the importance of the molecular architecture of the polymeric surfactant on the stability of the dispersion.

Another graft copolymer that could be used for stabilization of suspensions is that based on polyfructose backbone on which several alkyl groups have been grafted (Inutec LiC 0.1), mentioned above for stabilization of emulsions. This polymeric surfactant was used to investigate the stability of polystyrene (PS) and polymethyl methacrylate (PMMA) suspensions in the presence of electrolytes [NaCl, $CaCl_2$, and $Al_2(SO_4)_3$] [37]. Polystyrene latex

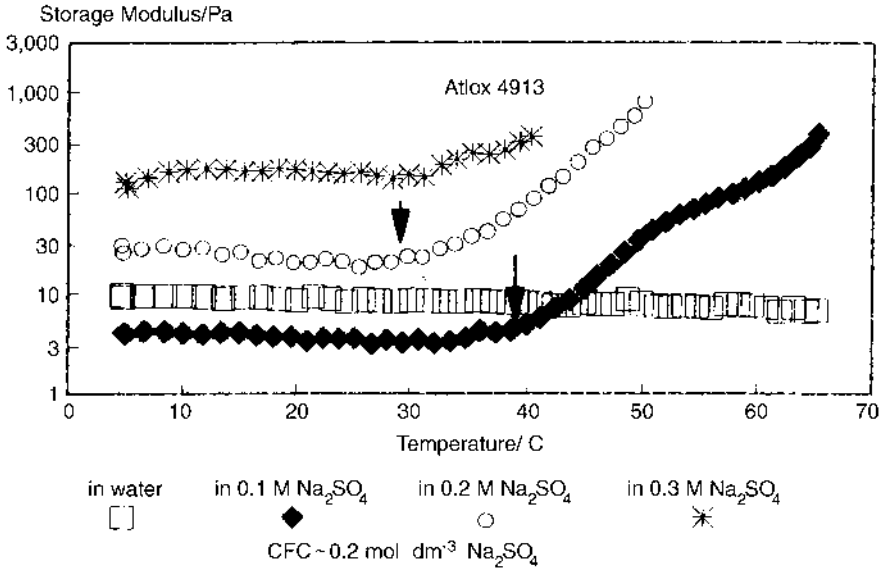

FIG. 21 CFT values for Atlox 4913.

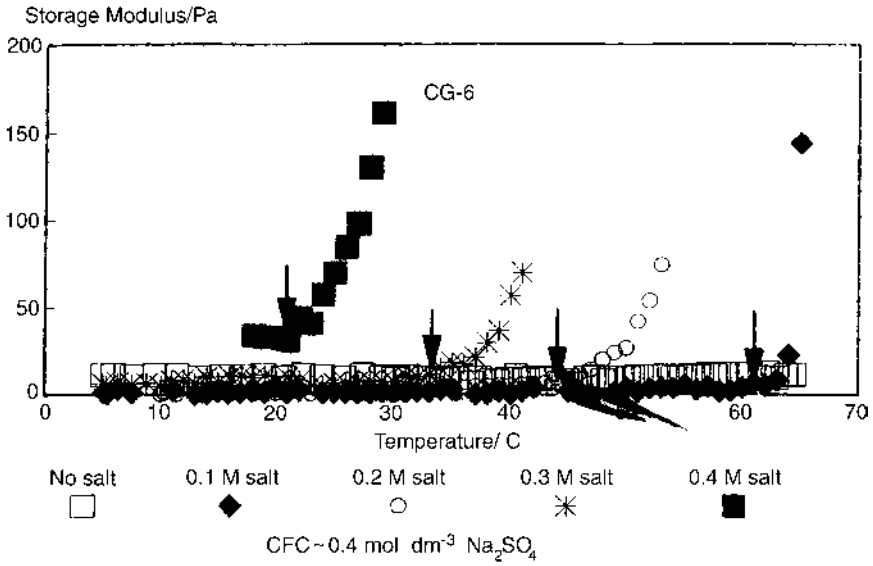

FIG. 22 CFT values for CG-6.

was prepared by emulsion polymerization without surfactant and was fairly monodisperse with a diameter of 210 nm. The PMMA latex was prepared by emulsion polymerization using sodium dodecyl sulfate as emulsifier. The latex had an average diameter of 61.8 nm and was fairly monodisperse. The critical coagulation concentration (CCC) was determined by gradually increasing the electrolyte concentration and observing floc formation using optical microscopy. Alternatively, the CCC was determined using turbidity measurements. The turbidity of the latex was determined as a function of the wavelength of light (400–600 nm). Log-log plots of turbidity (or % transmission) vs. wavelength gave straight lines from which the slope of the line n was calculated. By plotting n vs. electrolyte concentration, the CCC could be accurately determined (n remains constant up to the CCC, after which it shows a rapid decrease). The CCC values for 5% PS latex containing 0.25% Inutec surfactant are > 5.7 mol dm^{-3} for NaCl, > 4.37 mol dm^{-3} for $CaCl_2$ and > 0.5 mol dm^{-3} for $Al_2(SO_4)_3$. For 2.5% PMMA latex containing 0.5% Inutec surfactant, the CCC for CaI_2 was > 2.29 mol dm^{-3}. This clearly shows the considerable stabilization effect of the Inutec surfactant. A low surfactant concentration is sufficient for stabilization and a very high CCC value is obtained when compared with the latex without adsorbed polymer. This high stability in the presence of high electrolyte concentration is due to the polyfructose stabilizing chain, which remains highly hydrated at such

high electrolyte concentrations. This was explained in detail in the section on emulsions.

IX. POLYMERIC SURFACTANTS IN MULTIPLE EMULSIONS

The main criteria for the preparation of stable multiple emulsions are summarized as follows [38]. First, one needs two optimal emulsifiers, one with low and one with high HLB numbers. Emulsifier 1 (with low HLB number), which is used to prepare the primary w/o emulsion (for the case of w/o/w multiple emulsion), should prevent any flocculation or coalescence of the emulsion droplets. This emulsifier should ideally produce a viscoelastic film at the w/o interface that ensures the stability of the emulsions and prevents any transport of components from the internal droplets to the outer continuous medium during storage. Recent work in our laboratory [38] showed that Aralacel P135 satisfies these criteria. It produces a viscoelastic film and the w/o emulsions prepared using this polymeric surfactant are stable over a long period of time and at various temperatures. The secondary emulsifier, with the high HLB number, should also produce an effective barrier to prevent flocculation and coalescence of the resulting multiple emulsion drops. Again a polymeric surfactant, such as Synperonic PF 127 (an ABA block of PEO-PPO-PEO produced by ICI) is ideal in this case.

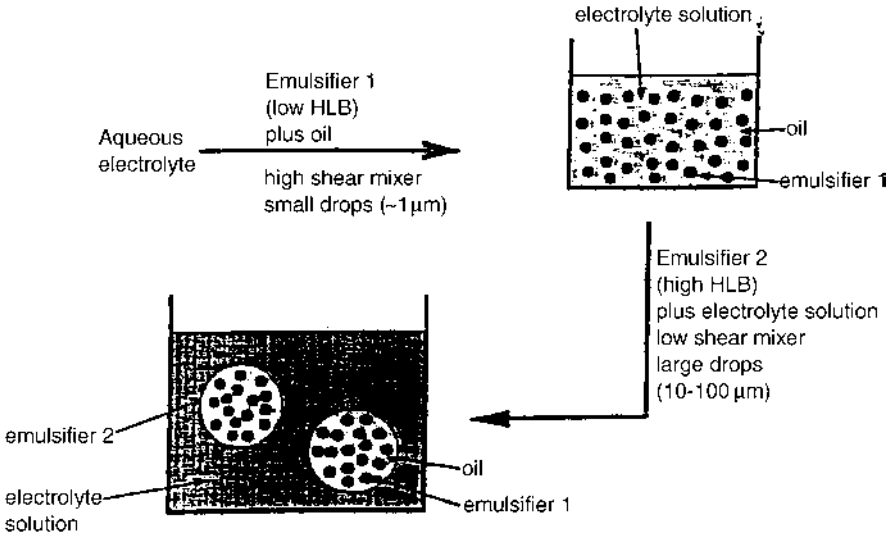

FIG. 23 Schematic representation of the preparation of w/o/w multiple emulsion.

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The second criterion for stabilization of the multiple emulsion on storage is to have an optimal osmotic balance between the internal (water droplets) and the external continuous medium. This can be achieved by the use of electrolytes or nonelectrolytes. Usually, one keeps the osmotic pressure in the external continuous medium slightly lower than that of the internal water droplets.

The multiple emulsion is prepared by a two stage process as is schematically illustrated in Fig. 23. The primary emulsion is prepared by adding the aqueous phase to an oil solution of the polymeric emulsifier 1 with low HLB number, e.g., Aralcel P135, using a high-speed stirrer. Using this polymeric emulsifier, primary water droplets that are smaller than 1 μm in diameter can be produced. The size of the droplets in the primary emulsion can be determined using photon correlation spectroscopy. This primary emulsion is then emulsified into aqueous solution of the high HLB polymeric surfactant

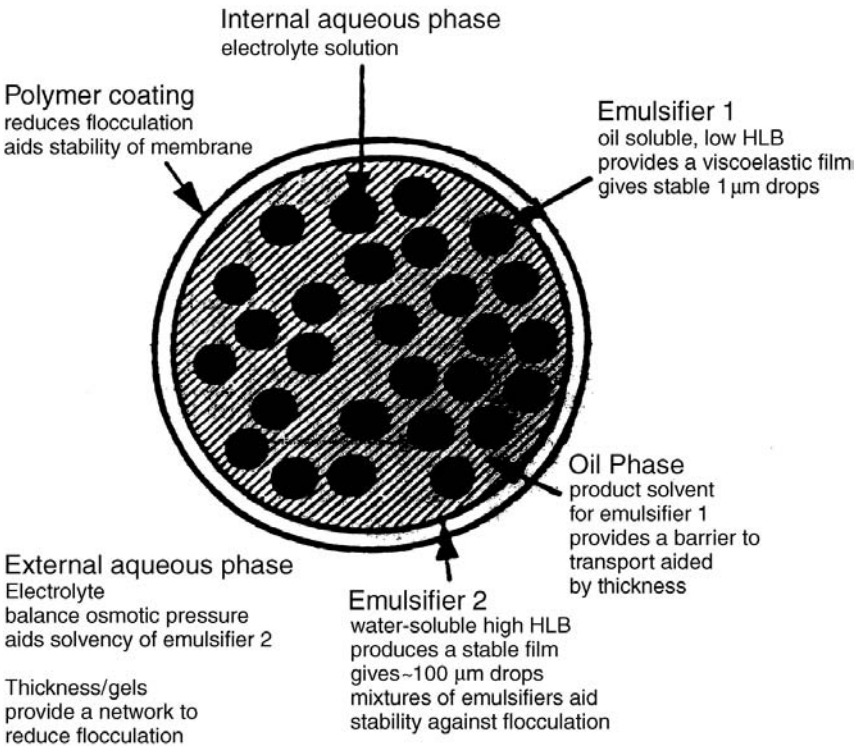

FIG. 24 Schematic representation of the multiple emulsion drop showing the role of the various components.

(Synperonic PEF 127) using a low-speed stirrer (paddle stirrer) to produce multiple emulsion drops of the order of 10–100 μm in diameter.

A schematic representation of the multiple emulsion drop is shown in Fig. 24 which illustrates the various components. In some cases a polymer coating (produced using, for example, polymethacrylic acid) may be used to ensure the long-term physical stability of the multiple emulsion. Using polymeric surfactants, multiple emulsions that are stable for more than one year could be produced [39]. By incorporating a gelling agent such as Carbopol in the aqueous continuous phase, creaming of the multiple emulsion could be prevented. This gelling agent also produced the right consistency (rheology) for application as a cream.

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17
Silicone Surfactants

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I. INTRODUCTION

The success of silicone surfactants is related to their special character, which differs in many respects from that of organic low molecular weight and polymeric surfactants. The reasons for these differences may be summarized by three points:

The physicochemistry of silicones gives access to unique features because silicones are soluble neither in water nor in organic oils, so that the silicone part in silicone surfactants contributes hydrophobic as well as oleophobic properties to the molecule.

The high flexibility of the silicone polymer chain, especially of the polydimethylsiloxane chain, enables the high molecular weight molecules to arrange in an optimum way at the interface between different phases in a relatively short time.

The chemistry of organo-modified silicones offers a great versatility for the synthesis of well-defined oligomeric or polymeric molecules in a flexible and tailor-made manner.

This chapter provides explanations as to why silicone-based surfactants show these properties. Additionally, important fields of application are described.

A. General Information

1. Preparation of Silicones

It was not until the 1940s that Müller and Rochow found a route to the direct synthesis of methychlorosilane that founded the basis for the success of silicones (Fig. 1) [1].

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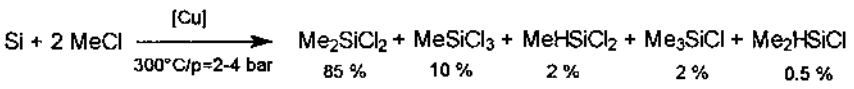

FIG. 1 Rochow synthesis.

Me_2SiC1_2 is purified by distillation and eventually hydrolyzed to generate silicones. This designation is misleading because the hydrolysis yields not the analog to acetone but a polymer. It is more correct to refer to polydimethylsiloxanes. By the end of the last decade 800,000 t/a of methylchlorosilanes was produced in a continuous technical process [2]. There are different ways to influence the process parameters that are regarded to be proprietary. Thus, the given amounts and distribution of side products (Fig. 1) are generalized numbers. $MeSiC1_3$ is the second largest fraction at a yield of 10–15% followed by $MeHSiC1_2$ and Me_3SiC1 [3]. Me_2HsiC1, which is required for α,ω-functionalized siloxanes, is found in the low-boiling fraction and has to be thoroughly fractionated to obtain a yield of 0.5%.

The first step toward the synthesis of oligomers is hydrolysis or methanolysis (Fig. 2) [4]. Water or methanol is mixed successively with Me_2SiC1_2 to obtain linear and cyclic products. The cyclic products contain 3–10 units of dimethylsiloxane (denoted as D_3–D_{10}), with D_4 and D_5 (m = 4–5) as main products.

Special focus must be given to the content of branching units in all sources of bifunctional moieties. When molecular weights are built up, even small

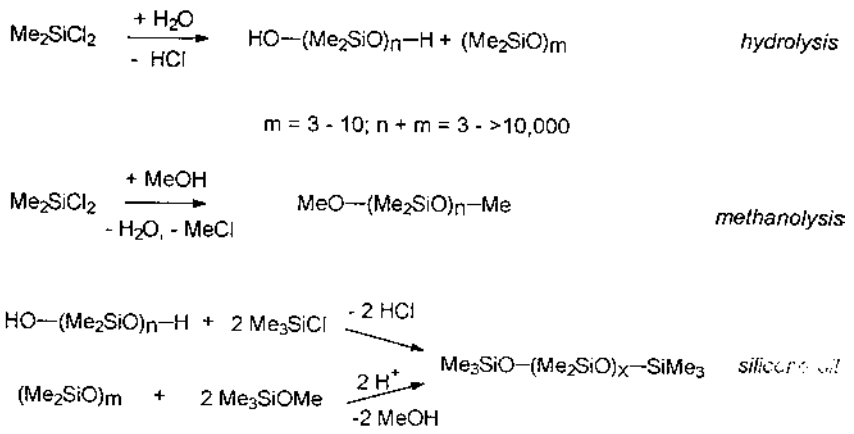

FIG. 2 Hydrolysis and methanolysis.

amounts can lead to a dramatic increase or cause gelling. So the content of branching units must not exceed 100 ppm, which is difficult to achieve as the boiling points of the methylchlorosilanes Me_2SiC1_2 and $MeSiC1_3$ differ by only 4°C.

2. Polycondensation

Cyclic products are converted by polymerization to polymers, whereas the molecular weight of linear diols can be increased by polycondensation. In both cases, siloxane bonds are cleaved and silanol groups condensed. Starting materials for the former products are D_4 or D_5. The smaller the ring size, the higher is its reactivity. In the latter, process, both acidic and basic catalysis are suitable, but acids are preferred such as H_2SO_4 and especially CF_3SO_3H or Lewis acids such as $FeC1_3$.

3. Equilibration

The process whereby bonds of a polymeric backbone are simultaneously cleaved and formed is denoted equilibration (Fig. 3). This reaction is limited to polymers whose backbone can be built up or cleaved by a reaction of low enthalpy. Another well-known example for an equilibration process is the transesterification of polyesters. Within silicone chemistry equilibration plays a key role as it enables the design of silicones with tailor-made molecular weights and patterns of functionalities. Via equilibration polymers, oligomers or monomers can be combined in any way and will give access to polymers whose structure (mean molecular weight, mean number of even different functionalities, pattern of functionalities) will only be determined by statis-

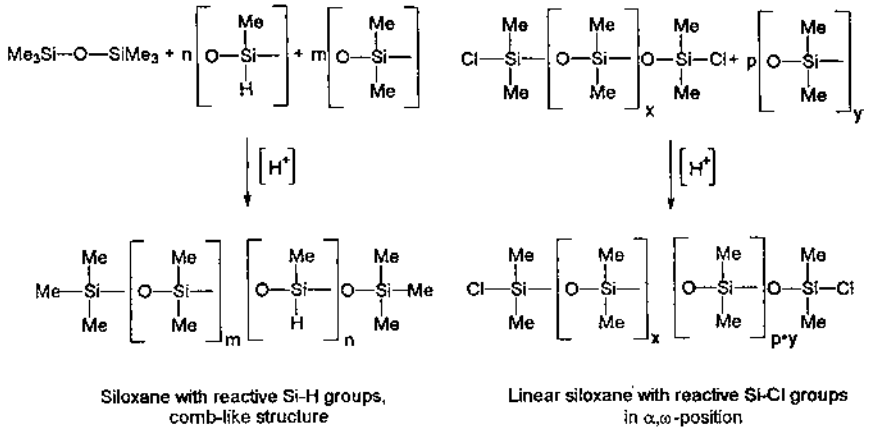

FIG. 3 Equilibration.

tical rules. In particular, the flexible but reproducible introduction of functional groups forms the basis of a variety of organo-modified silicones.

Figure 3 displays how functional moieties are introduced to give a comb-like structure and how molecular weight can be increased by addition of cyclic oligomers to a functionalized oligomer. These examples are by no means limiting. Combinations of end group and side group modification are possible, as well as the introduction of branching moieties $SiO_{4/2}$ or $MeSiO_{3/2}$.

Silicone oils show some outstanding properties such as high surface activity, high thermo- and UV resistance, and low toxicity. Pure oils are also known to be used as plasticizers for silicone elastomers, as heat-resistant oils in transformers, and as raw material for deaerators, defoamers, and release agents for rubbers and fibers.

B. Organofunctional Modification

Due to the flexible way of generating functional siloxanes, there are many different ways to modify polysiloxanes. If some of the methyl groups in the chain of a polydimethylsiloxane are substituted by other organic substituents (e.g., phenyl), products with different properties can be obtained depending on the proportion of dimethyl groups in the molecule. Figure 4 gives a general formula demonstrating organically modified polysiloxanes by substituting various organic groups for methyl moieties.

This generic structure describes the variety of organo-modified siloxanes. R and/or R′ represent various organic substituents, which can be aliphatic and/or aromatic, monomers or polymers. They can be attached to a linear, comb-like, or branched siloxane backbone via an SiC Bond ($z = 0$) or a $SiOC_1$ bond ($z = 1$). In this way it is possible to control solubility and compatibility. In general, the organically substituted silicones have relatively short siloxane chain lengths ($x + y = 10$–200). The organic substituents play a substantial role in the properties of such products.

1. Polyethers

(a) Production and General Information. Polyethers are the most important modifying group of siloxanes. The polymerization of alkylene oxides is

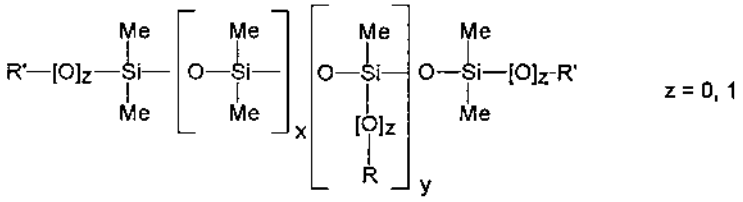

FIG. 4 Generic structure of organo-modified siloxanes.

accomplished by successive addition of compounds that contain acidic hydrogen atoms in the presence of catalysts (Fig. 5) [5]. Usually alkali salts such as KOH or KOMe [6] are utilized, but Lewis acids [7] and double-metal complex catalysts [8] can be used as well. Tetrahydrofuran (THF) undergoes polymerization with Lewis acids [9] or strong protic acids [10]. A reaction of x molecules of alkylene oxide with a starting molecule R(OH)x gives access to polyether monools, diols, triols, etc.

For polyethers in polysiloxanes, allyl or butyl alcohol (R′) is commonly used as a starting molecule. The most popular monomers for polyethers are ethylene oxide (EO), propylene oxide (PO), and mixtures thereof. The effect of their ratio can be described with the hydrophilic-lipophilic balance (HLB) concept, which will be discussed later [11]. The higher the PO content, the more hydrophobic is the corresponding polyether. Thus, by varying the composition of the polyethers, sometimes denoted as polyoxyalkylene, it is possible to adjust the polarity of the polydimethylsiloxane polyether copolymer. A macroscopic measure for the polarity of both polyethers and polyethersiloxanes is the cloud point of a 1% aq. solution. The higher it is, the more hydrophilic is the molecule. In this chapter we will denote these compounds as polyethersiloxanes. It is possible to design silicone surfactants that are suitable for aqueous and nonaqueous systems.

The hydrophobicity of PO is superseded by monomers such as butylene oxide and THF. All of these monomers can be combined statistically or in blocks of different molecular weights to give access to a large variety of polyethers.

When allyl alcohol is used as the starting molecule, one obstacle in the production of polyethers is the preservation of the terminal double bond. Reaction conditions must be carefully chosen to prevent isomerization because polyethers containing propenyl instead of allyl cannot be used for the modification of siloxanes [12].

(b) Reactions to Capped End Groups. Some applications, such as foam stabilizers in polyurethanes, require a polyether without hydroxyl group (Fig. 5, Z). The conversion of the hydroxyl group with MeCl gives methylated polyethers [13] (Z = Me). Other ways to introduce end groups also take

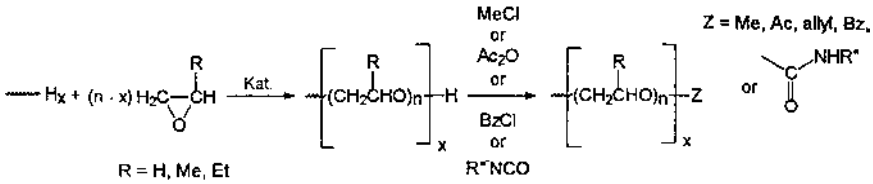

FIG. 5 Generation of polyethers started at acidic hydrogens.

advantage of chloro-containing groups, e.g., acetyl, benzyl, allyl, or butyl chloride. These capping groups are inert to thermal oxidative attack over a wide temperature range. End-group modifications are not limited to nonionic end groups; ionic groups are known as well.

2. Structural Variety of Siloxanes

As discussed previously, the ability to equilibrate siloxanes gives access to a wide range of structures. The introduction of organo modification can lead to terminal groups in α,ω-siloxanes (Fig. 6b), to comb-like structures (Fig. 6a) or to structures that resemble classical surfactants (Fig. 6d, e). Additionally, the

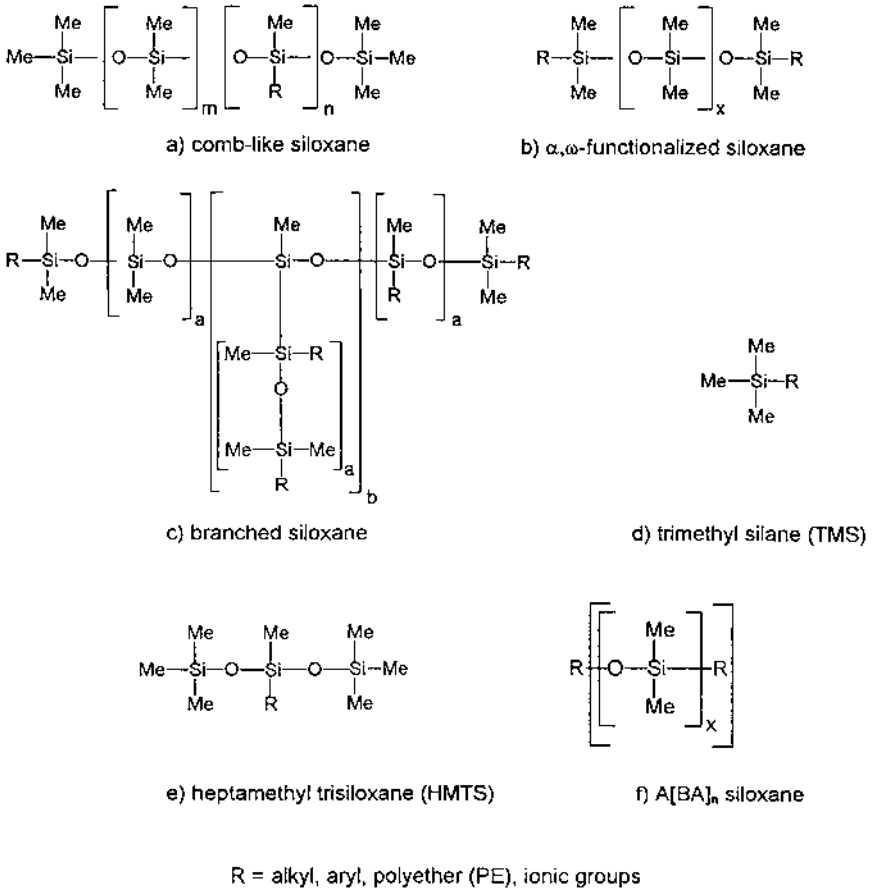

FIG. 6 Generic structures of siloxanes.

former structures can be combined to give oligomers that are substituted both in α, ω position and along the siloxane backbone.

The structures also differ from a polymeric point of view. Comb-like structures show a classical Gaussian curve in terms of both chain length and substitution pattern. However, if the modification density is too low, a certain fraction contains no modified groups, which can be proven by simple statistics in accordance with analytical methods. Therefore, a minimum of modifications is required to ensure that every molecule has at least one modification; otherwise a part of the product will be a silicone oil.

In α,ω-siloxanes, a uniform structure is synthesized that is denoted ABA. When a bifunctional polyether, e.g., a polyether diol, reacts with α,ω-siloxanes, polyether siloxanes with $A[BA]_n$, structure are obtained. Evidently there is no difference in the amount of modifications per molecule for the latter two structures. Trisiloxane copolymers based on HMTS differ insignificantly in their chain length.

3. Chemistry Based on Si-O-C Bonds as Compared to Si-C Bonds

There are two ways to modify a polysiloxane (Fig. 7). Substituents are attached via Si-C or Si-O-C linkages to the siloxane backbone. Condensation of chlorine-containing siloxanes (Cl) with compounds that contain acidic hydrogen atoms followed by the elimination of HCI is a well-established chemistry. The reaction proceeds rapidly even with secondary alcohols like polyethers with PO end groups. Because the Si-O-C linkage may be sensitive to hydrolysis (Fig. 4, $z = 1$) in acidic (pH < 4) or alkaline media (pH > 10) (yielding silicone oil and an organic residue), compounds based on Si-C linkages ($z = 0$) provide an alternative as they result in hydrolytically more stable products. SiC linkages are formed via the hydrosilylation reaction that

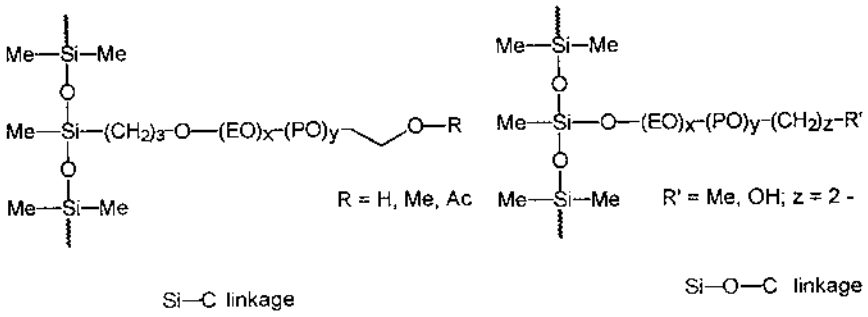

FIG. 7 General structure for polyether siloxanes (polydimethylsiloxane-polyoxyalkylene copolymers).

has been used on a technical scale for decades. A hydrogen-containing siloxane (SiH-siloxane) and a molecule containing a triple bond or a terminal double bond are brought to reaction. Transition metals such as platinum or rhodium are used as catalysts at treat rates of a few ppm, e.g., *cis*-platinum [$Cl_2Pt(NH_3)_2$] or hexachloroplatinum acid [$H_2(PtCl_6)$]. Typically, an excess of 30% of polyether is necessary for high yields and reaction rates and a low degree of side reactions.

4. Conversion of Epoxy Functional Polysiloxanes to Ionic and Nonionic Products

The hydrosilylation of allylglycidyl ether (AGE) to a siloxane proceeds readily (Fig. 8) [14]. The reactive epoxy group enables a variety of further modifications by attack of a nucleophile and subsequent ring opening. These conversions have been examined extensively [15].

The conversion of epoxy functional siloxanes with tertiary amines in the presence of acids leads to quaternary ammonium groups (Fig. 8) [16]. If a secondary amine is used instead, a subsequent step with monochloroacetic acid sodium salt gives a betaine [17]. Anionic surfactants can be generated by treating the epoxy with $NaHSO_3$ [18]. Analog products are available with Bunte salts [19].

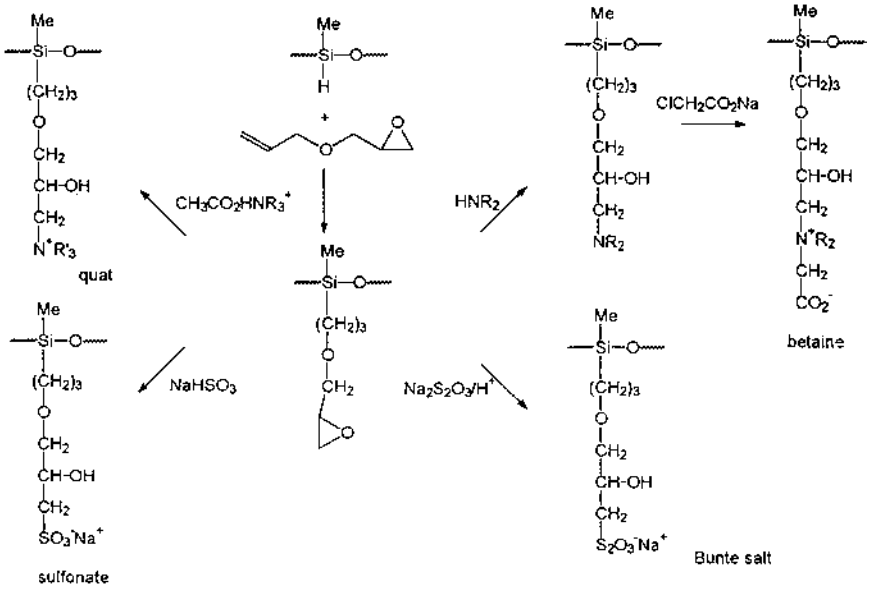

FIG. 8 Synthesis of ionic silicone surfactants from epoxy functional siloxanes.

5. Carbohydrate-Modified Siloxanes

This class of substances has been studied only in the last few years and thus it has not been thoroughly characterized. Commercial synthesis of carbohydrate-modified siloxanes turns out to be difficult because of the need for extensive use of protecting groups, hydrolysis of connecting bonds, or decomposition of the siloxane backbone under acidic reaction conditions. Only a few applications are known, e.g., for the modification of contact lenses [20,21] and the production of glass fibers [22]. A polyglycoside-modified siloxane has been developed that can be used as a water-in-oil (w/o) emulsifier in cosmetics [23].

Glycoside-modified silicones, obtained by the reaction of a polyether siloxane and a glycoside, contain an acetal linkage between the polyether and the glycoside [24]. Siloxane copolymers with polyhydroxyorganyl and polyether groups attached independently to the siloxane backbone exhibit special properties that cannot be achieved by simple mixtures of the corresponding siloxanes [25]. The polyhydroxyorganyl residue is introduced by the reaction of *N*-methyglucamine and an epoxy functional polyether siloxane copolymer (Fig. 9). These compounds possess thermally stable and nonhydrolyzable linkages between the sugar residue and the siloxane backbone. Such products can be used as polymeric o/w emulsifiers.

6. Protein-Modified Siloxanes

Protein-modified siloxanes have recently drawn commercial attention. One major advantage is the possibility of combining film formation and moisture retention properties of proteins with lubricity and spreadability of silicones. Amino acid–modified silicones are obtained by the reaction of an alkali salt of an amino acid and an organo-modified polysiloxane containing epoxy groups (Fig. 10) [26]. These new copolymers show promising potential for cosmetic applications.

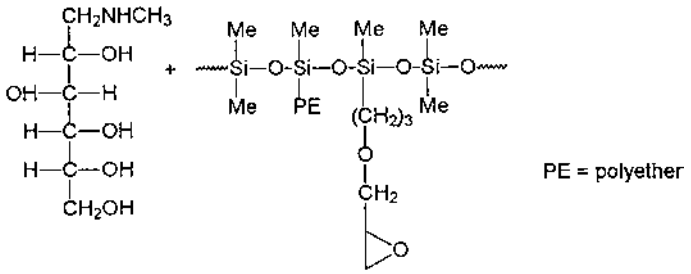

FIG. 9 Reaction of *N*-methylglucamine and an epoxy functional polyether siloxane copolymer.

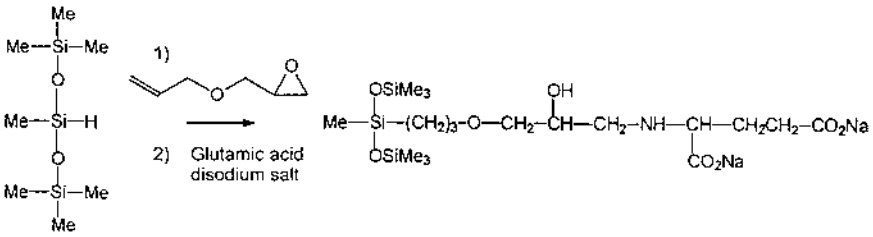

FIG. 10 Synthesis of protein-modified siloxanes.

The reaction is not limited to amino acids but can be extended to proteins in general [27,28]. For example, hydrolyzed wheat protein can be cross-linked with siloxane chains. These products are obtained by the reaction of epoxide or anhydride groups of organo-modified polysiloxanes with amino groups of the protein.

C. Physicochemical Properties

1. Characteristics of the Siloxane Backbone

Silicone oils are liquid even at molecular weights above 100,000 due to low intermolecular forces. As opposed to hydrocarbon-based polymers, the siloxane backbone is highly flexible resulting in low glass transition temperatures (T_g) [29]. Although polyethylene contains no "ligands" other than small hydrogen atoms, its glass transition temperature (148 K) is 2 K higher than that of an ordinary silicone oil (146 K) with methyl groups as substituents of the silicone atoms [30]. This may be explained by the low rotation barrier of the Si-O bond (0.8 kJ/mol) [31] resulting in a relatively high entropy contribution. Therefore, the siloxane backbone is much more flexible than that of ordinary hydrocarbons. Depending on the chemistry and the degree of modification, this conclusion can be extended to organo-modified siloxanes.

The unique character is confirmed by a closer look at bonding parameters. The difference of electronegativities of the Si-O bond is 1.76, according to Allred-Rochow. Nevertheless, this polar bond has little influence on the solubility of silicone oils. Evidently these bonds are shielded by methyl groups that are exposed exclusively at the surface.

The Si-O bond length is 0.165 nm compared with 0.140 nm of a C-C bond [30]. The Si-O-Si bond angle of 130 $\pm$ 10 degrees is much larger than the corresponding C-O-C bond angle of 110 degrees in dimethyl ether [1].

The surface tensions of silicone oils depend on molecular weight, increasing from 15.7 mN/m for hexamethyldisiloxane to about 22 mN/m for medium and high molecular weight oligomers and polymers [32]. This

is much lower than those for organic oils, which are usually in the range of 30–35 mN/m.

One outstanding feature of siloxanes and their organo-modified derivatives is their ability to reduce the surface tension of nonaqueous systems. Ordinary surfactants usually fail to influence the surface properties of organic bulk phases due to their inherent high surface tension.

Figure 11 shows typical curves for surface tensions of an organic surfactant and an organo-modified siloxane at different concentrations. The plots differ in the CMC, final surface tension, and curvature at lower concentration. The CMC of organo-modified siloxanes is reached at significantly lower concentrations than that of simple organic surfactants [33]. The curvatures inform about the behavior of the surfactants at the surface. Most plots that have an origin at the surface tension of pure water show a convex curvature and pass subsequently to a straight line. According to the Gibbs equation, a convex curvature indicates an increasing coverage of the surface with increasing surfactant concentration. However, a straight line as for the organo-modified siloxane implies that the adsorbing layer of the surfactant is compressed with increasing concentration, which indicates a high coverage of the surface at low concentrations. This clearly demonstrates the superior surface activity of silicone surfactants.

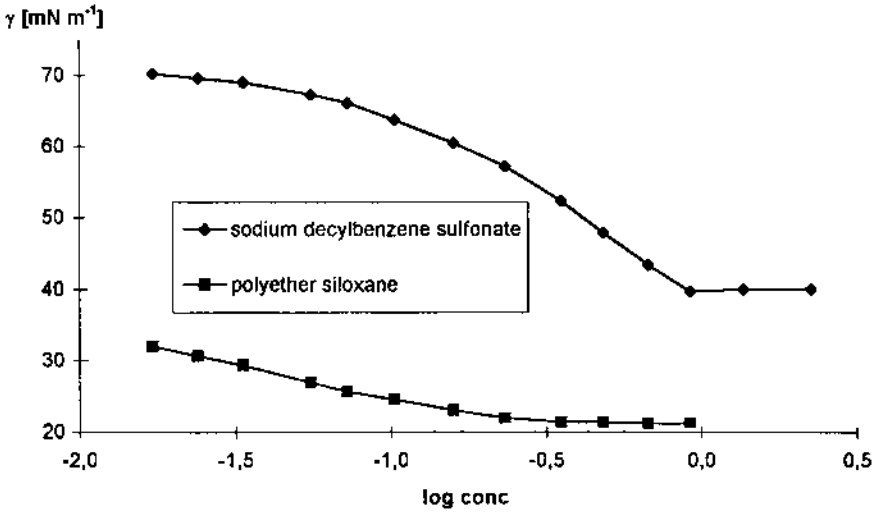

FIG. 11 Surface tension of a polyether siloxane and a typical organic surfactant, sodium decyl benzene sulfonate. (From Ref. 32.)

2. HLB and 3D-HLB Concepts Applied to Siloxanes

As pure silicone oils with $M_w > 700$ (corresponds to seven Me_2SiO units plus end groups) show no compatibility with other substances such as oils or water, they can be regarded as their own class of substances. Because the HLB concept [11] was originally developed for ethoxylated products such as fatty alcohol ethoxylates, it compares the ratio of the oil- and water-soluble portions of a surfactant molecule in order to predict their emulsification properties. Therefore, it is not applicable to siloxanes and its organo-modified derivatives. An expanded system denoted as three-dimensional HLB concept was recently introduced to consider oil, water, and siloxane solubilities in order to determine the emulsifying properties of silicone surfactants [34]. The standard HLB is now the hypotenuse of the triangle in the new system (Fig. 12). In the figure, the three sides represent the possible pairs of component types, i.e., oil/water (o/w), silicone/water (s/w), and oil/silicone (o/s). By substracting the sum of the weight percentages of the water- and oil-soluble segments from 100%, the percentage of the silicone-soluble part is obtained. A polyether siloxane (Table 1, B: siloxane content of about 32%, EO/PO ratio 75:25) is therefore analyzed to x and y values of 9.9 and 3.5, respectively. Thus, this compound should serve as s/w emulsifier.

Silicone surfactants decrease the surface tension of organic media where ordinary surfactants do not work [35]. Organo-modified silicones can be tuned to be soluble in water or oil, and thus to decrease surface tensions of organic and aqueous media. Their surface activity is used to realize wetting, spreading, leveling, detergency, defoaming, and emulsification in water and organic media. Examples are given in Table 1, e.g., polyether siloxane B is soluble in water well above 15 wt % at 25°C.

However, it has been known for several years that polyethersiloxanes such as D give excellent w/o emulsions. This characteristic is even enhanced if

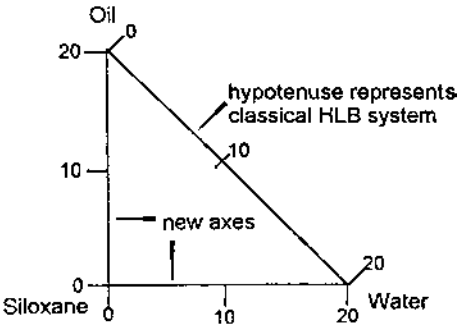

FIG. 12 3D-HLB concept.

TABLE 1 Physicochemical Properties of Polyether Siloxanes

Product	EO/PO in polyether (wt %)	HLB	3D-HLB (x/y)	Cloud point of 1% in water (°C)	Surface tension (mN/m)
A	100:0	19	13.6:0	90	28
B	75:25	18	9.9:3.5	65	28
C	35:65	14	3.5:6.2	30	27
D	20:80	11	2.7:10.7	10	—
E	80:20	—	11.7:2.9	45	23

Source: Ref. 36.

additional alkyl chains are attached to the siloxane backbone to give a terpolymer. In this regard the 3D-HLB concept is confirmed drawing on practical experience.

II. SURFACE-ACTIVE PRODUCTS FOR NON-WATER-BORNE APPLICATIONS

A. Polyurethane Foam Stabilization

1. General Information

One of the technically and commercially most interesting applications of silicone surfactants is their use in the production of polyurethane (PU) foams (Fig. 13). These foams are formed by the reaction of polyols and isocyanates. The finished foams typically have cell sizes in the millimeter range and below with densities mostly less than 50 kg/m^3, thus forming systems with very large surfaces. The process of foam formation is complex and consists of different phases, which require a variety of properties of the used surfactants. The flexibility of silicone chemistry, especially the broad variety of silicone polyether chemistry, is particularly suited to meet these different requirements.

The first step of foam production is the mixing of components, i.e., isocyanates are added to a mixture of polyol, catalyst, silicone surfactants, and water, as well as optional blowing agents, cross-linkers, modifiers, flame-retardant additives, colors, fillers, etc. Silicone surfactants help to disperse or emulsify incompatible materials.

The formation of gas bubbles in the liquid phase of the reaction mixture is governed by the presence of nucleation sites. The silicone surfactants allow the development of a large number of nucleation sites, which are needed in order to get a fine and regular distribution of foam cells. Thermodynamically, a small number of large bubbles would be more favorable because of the lower

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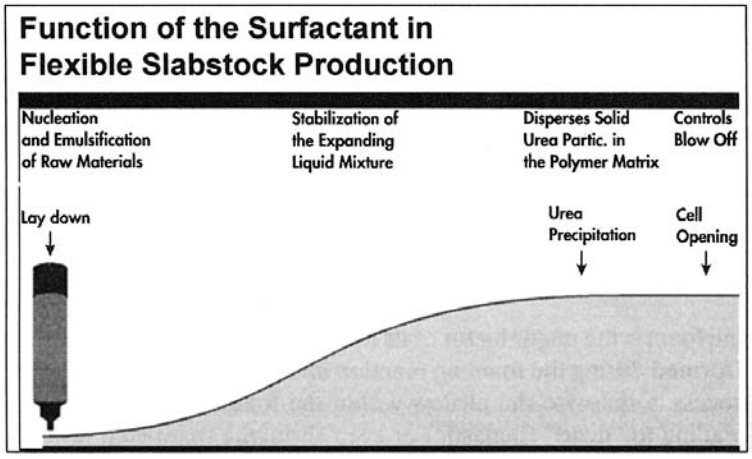

FIG. 13 Polyurethane foam production.

inner pressure of large bubbles. Nucleation is very often a critical step of foam formation and requires careful optimization for all of the different polyols, isocyanates, and blowing agents that are used commercially. The flexibility of adjusting the polarity, compatibility, and surface activity of silicone polyethers enables these requirements to be fulfilled, even if significant changes, such as the increased use of halogen-free blowing agents, e.g., pentane or pressurized carbon dioxide, take place in the industry.

During the expansion phase of the foam, the size of the gas bubbles increases due to diffusion of the blowing agent from the liquid to the gas phase. The energy needed for an enlargement of the gas bubbles is correlated to the surface tension and inversely correlated to the cell diameter. Any decrease in surface tension resulting from the action of a silicone surfactant leads to easier growth of gas bubbles and a more regular distribution of bubble sizes. An additional effect of silicone surfactants is seen in the decreased tendency of the gas bubbles to coalesce. Only the combination of sufficient nucleation sites together with bubble stabilization during the growth period ensures a fine and regular cell structure as is desired for flexible slabstock or rigid polyurethane foams [38].

Foams for insulation applications are rigid, with most of them having a high content of closed cells. In other applications the elastic property of a polyurethane foam is the major factor of its usefulness. Therefore, the gas bubbles (cells) formed during the foaming reaction have to open at the end of the foaming process. Otherwise the airflow within the foam would remain very restricted leading to "dead" (inelastic) or even shrinking foam with no

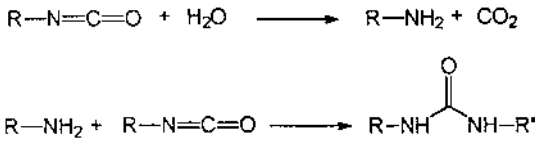

FIG. 14 Reactions of isocyanates.

resilience. As soon as the gas cells open (foam blow off) the polymeric structure has to stabilize the foam because there are no more gas bubbles with higher internal pressure counteracting the gravitational forces.

Cell opening is influenced by urea, which is formed by reaction of isocyanates and water via the amines (Fig. 14). The urea precipitates and forms crystalline domains that can grow to the dimension of cell walls, which are thereby destabilized, finally leading to cell opening. The size and effect of these urea hard segments within the PU phase has been the subject of intensive research [39–41]. The choice of silicone surfactants with high dispersing power influences the crystallization of the urea and delays the "antifoam" effect for a certain period. Thus, the blow-off is retained, which gives the foam more time to react chemically and prevents a collapse.

In some applications silicone polyethers are used as cell openers to achieve a desired content of open cells within the foam. Silicone polyethers with nonpolar polyethers can act in this way. Their solubility decreases during the course of urethane formation, finally giving the silicone polyethers a cell opening incompatibility. Aromatically substituted polyether side chains as a building a block in silicone polyether copolymers have recently been described for this application [42].

2. Utilization and Impact of Different Structures

(a) Standard Structures. It is obvious that all of the different requirements for control of polyurethane foam formation cannot be fulfilled by a single surfactant. However, in industrial formulations very often individual products can be identified. These products typically represent mixtures that contain different types of silicone polyethers. The synthesis of silicone polyethers itself yields a broad distribution of molecular individuals. By reacting a functional silicone oligomer, which shows a distribution of molecular weight, pattern and density functional groups, with one or several polyethers, which again have a distribution of molecular weight, overall polarity, and structure (block or random), a large variety of different molecules are produced. Molecules with quite different surfactant properties are formed. These mixtures might be a nightmare for the scientist in search of a simple structure-property relationship, but at the same time it may be

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a gift to those looking for a perfect additive for the control of foam production. Some general statements on structures and properties can nevertheless be made.

Figure 6a and c show typical structures of silicone surfactants for the production of polyurethane foam, i.e., comb-like and branched siloxanes. Siloxanes that are modified with polyether groups are important surfactants for rigid, ester, or flexible slabstock foams.

Si-C bonded silicone polyethers with only one or two different OH functional polyethers are used for rigid foams. They typically have a relatively high degree of modification (Fig. 6a, $m/n < 7$), which results in somewhat short polydimethylsiloxane segments between the pendant polyether groups. The content of closed cells is increased by chemical cross-linking of the OH functional polymers.

Silicone polyethers with end-capped polyethers are standard for the production of flexible foam. This type of foam requires a high number of open cells; thus, chemical cross-linking by the surfactant has to be avoided. The complex need for controlled cell sizes, high physical stabilization, and timely cell opening typically is met by products with a low degree of substitution (Fig. 3, $m/n > 7$), long silicone chains ($m + n > 40$), and often by using mixtures of two, three, or even more polyethers, which are attached to the same siloxane backbone.

The end capping of terminal OH groups can be accomplished by either an etherification or an esterification of the polyether (Fig. 5, Z = alkyl or acetyl). Clearly, esters are hydrolytically less stable than ethers. This may be important for some applications where premixes with water and amines are stored for a period of time.

A similar problem of hydrolytic stability has to be considered with Si-O-C-bonded silicone polyethers (Fig. 4, $z = 1$). In practice, however, problems are usually not encountered, even under the influence of amines and Lewis acids such as stannuous octoate, which is used as a catalyst in polyurethane foaming.

Inverse structures have been published for use in polyurethane foam formation [43]. Monofunctional siloxane chains are attached to a multifunctional polyether backbone. However, significant advantages over classical silicone surfactant structures could not demonstrated. A major drawback of this approach is the difficult synthesis of monofunctional siloxanes.

(b) Unmodified Silicones. Unmodified polydimethylsiloxanes certainly do not resemble classical surfactant structures (Fig. 2). However, if the mean chain length is chosen carefully and if the width of chain length distribution is limited properly, those silicones behave like surfactants below the CMC, i.e., they are compatible with the system, enrich at surfaces, and reduce surface tension. Because of these properties they can be used as cell regulators for the

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production of high-resilience foams. The desired cell structure in this case in not a very fine regular one but a more irregular one, leading to the desired high resilience. The use of highly reactive polyether polyols gives a very high chemical stabilization. Therefore, the surfactant mainly has to control cell growth, coalescence, and opening. Slightly modified silicone oils of rather low molecular weight can be used as well.

B. Additives in Fuels and Oils

1. Diesel Antifoams

The foaming of diesel fuel has drawn a certain attention in the last decade. Antifoams are usually one component of a package of diesel additive, which is used to adjust and improve the properties of the distillate from the refinery [44]. Antifoams prevent foam formation of the treated diesel fuel during pumping at refineries and service stations at treat rates between 5 and 15 ppm. They help to shorten substantially the filling time of fuel tanks and avoid splashing over.

When diesel fuel is delivered to filling stations, it may contain about 100 ppm water for two reasons. Moisture condenses into tanks when shipped overseas. In Scandinavia, diesel fuel is even stored above water in large vessels, and here concentrations between 200 and 1000 ppm are typical. Even a small water content increases the polarity of the fuel dramatically. Thus, specially designed antiforms are required to break the foam.

The first publication about diesel antifoams in 1966 described the use of polyether siloxanes [45]. At least 60% of the polyether, which is attached by Si-C linkages, is composed of EO or PO [46]. It was not until 20 years later that commercial interest was raised. Polyethersiloxanes were claimed in which at least 80% of the attached polyether is EO [47]. These antifoams are water-soluble and therefore partially incompatible with the hydrocarbon chains of the diesel fuel, which leads to their surface activity.

An innovation concerning the generic structure of polyethersiloxanes was given in the publication about cross-linked products [48] and their application as defoamers in diesel fuel [49]. Cross-linking was accomplished with divinylic compounds such as divinyltetramethyldisiloxane.

As in other applications, the diesel antifoam has to be incompatible with the foaming media and to be surface-active (see Section III.A of this chapter for a more detailed explanation). A deep understanding of diesel defoaming is difficult to achieve because the nature of the foaming substances is unclear. It is believed that foams occur in nonaqueous systems when components of the mixture are only partially soluble in the bulk. This would mean for diesel fuel that the alkyl chains at the upper limit (C_{24}–C_{26}) would cause the formation of foam. As slight modifications in the chemical structure of the antifoams result

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in significant loss of activity, one has to assume that a delicate balance between foaming compounds and antifoams, most probably in terms of compatibility and particle size distribution, has to be maintained.

The first generation of antifoams were found to lose their effectiveness in wet diesel fuel, which may be explained by the interaction of water with the EO units of the attached polyether. Provided that there is a certain water concentration in the fuel, it is likely that a water shell forms in the vicinity of the oxygen atoms (as part of the polyether) by forming hydrogen bonds. Thus, the delicate HLB is influenced and consequently the antifoam is less effective.

In addition to an ordinary polyether based on EO and PO, a phenol derivative such as eugenol can be grafted onto the siloxane backbone (Fig. 15) [50]. This leads to a major improvement of their performance in wet diesel fuel. It has not been possible to provide a completely satisfactory explanation for the effect of a polar ligand in combination with ordinary polyethers. Because the surface tension of diesel fuel remains unaffected by various antifoams, the particle size of the antifoam may be disturbed. Polar substituents on the siloxane backbone may be able to adjust the particle size of the antifoam such that its performance is regained.

Alkyne derivatives such as 1,4-butyne diol denoted as golpanol (Fig. 15) and its ethoxylated derivatives were introduced as an alternative polar ligand [51]. A further development was the conversion to esters by reacting the terminal hydroxy group with cyclic lactones such a ε-caprolactone [52]. Derivatives of golpanol are combined with ordinary polyethers based on EO and PO, giving alternative terpolymers. Optionally, alkyl groups and

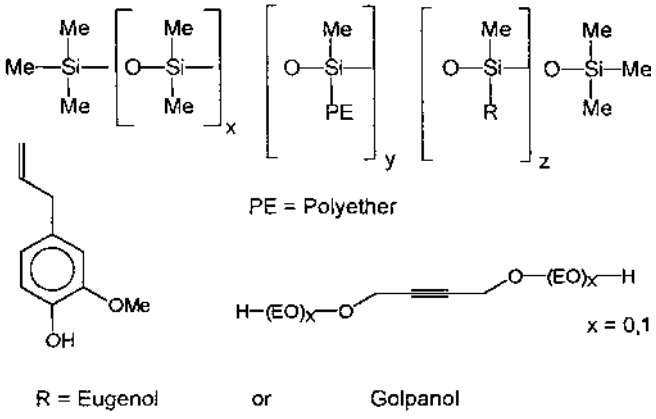

FIG. 15 Polysiloxane terpolymers as antifoams in diesel fuel.

alcohols may be attached [53]. Improved compatibility with hydrocarbon fuels is claimed by the introduction of phenyl derivatives such as α-methylstyrene to give terpolymers [54].

When the content of PO of the polyether is increased, the solubility of the corresponding polyether siloxanes in water is gradually shifted to insoluble compounds. They may serve to separate excessive quantities of gas such as butane from crude oil and to reduce foaming [55]. These foams, termed micro gas dispersions, contain gas bubbles that are less than 50 μm in size and also referred to as kugel foam. Since the gas bubbles move independently in the liquid, they are distinguished from other foams.

2. Dehazer in Oils and Fuels

The removal of water haze from distillate fuel is also accomplished by use of polyether siloxanes combined with simple halide salts such as $MgCl_2$ or $(Me)_4N^+Cl^-$ [56]. Thus, it may not be surprising that ionic groups, which are attached to the siloxane backbone, improve the demulsifying effect, e.g., a quaternary ammonium, an amine, a carboxylate, or a sulfonate group. Although it is widely known that the addition of salt or polar groups increases the polarity of the aqueous phase resulting in a better phase separation, this does not provide a complete understanding of the mechanism by which a demulsifier works.

Dehazers are used to diminish haze in organic liquids. Here siloxanes functionalized in α,ω position with polyethers (Fig. 6) can be mixed with copolymers of ethylene and unsaturated esters such as vinyl acetate, methylacrylate, etc. [57]. Because free acid groups tend to promote haze if moisture is present, completely esterified groups are preferred.

C. Surface-Modifying Additives for Coatings

Paints, varnishes, and printing inks are applied as thin layers on a variety of surfaces often denoted as substrates. Control of film formation is one major task in this industry where numerous problems can occur, such as foam formation, inadequate substrate wetting, crater formation, poor flow, and pigment floating. Due to their surface activity in the organic binders, silicones can reduce these problems already at treat rates of less than 1% on total formulation. The main effects that can be achieved are increased slip, improved mar and scratch resistance, defoaming/deaerating, substrate wetting, improved flow and leveling, and air release [58].

1. Silicone Oils or Dimethylpolysiloxanes

As mentioned above, silicone oils often behave in organic media like surfactants below the CMC. They significantly reduce the surface tension by enriching at the surface. This has led to applications where the addition of

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silicone oils, often types with rather low molecular weight, helps to form uniform and plain films on low-energy surfaces. Above their solubility limit, silicone oils do not form micelles but instead form macroscopic droplets of a separate phase with low surface tension. These droplets are extremely difficult to wet, where a special pattern of surface defects is desired. However, for most applications, the use of pure silicone oils proved to be somewhat risky because the gap between benefit and defect was very narrow.

2. (Poly)alkylene-Modified Polysiloxanes

Substitution of some of the methyl groups of polydimethylsiloxanes by alkyl or aryl groups gives products with somewhat better compatibility but still high surface activity. Figure 4 shows typical structures with z equals zero; R′ can be alkyl or arylalkyl.

Methylalkylpolysiloxanes are often used as deaerating agents, an application that requires a certain of incompatibility with the coating system. This dictates that no deaerator can be suitable for all systems: If too compatible, a substance does not deaerate; if too incompatible, surface defects will result. In practice, tailor-made methylalkylpolysiloxanes, methylalkylarypolysiloxanes, and methylarylpolysiloxanes are used, typically with 20–100 silicone units in the backbone skeleton. A special benefit compared to polydimethylsiloxanes is the easier overcoatability of these products. Moreover, the utilization of such (poly)alkylene-modified polysiloxanes often results—besides their deaerating effects—in a leveled surface with reduced coefficient of fiction.

3. Polyether Siloxanes

Although modification of silicones with alkyl or aryl groups can give an acceptable compatibility with binder systems, for optimum performance a higher degree of organic moieties is needed. With polyethersiloxanes, extremely active surfactants are available that tend to minimize detects or gloss reduction. Polyethersiloxanes with pendant, hydrophilic polyether side groups (EO content of 50% and higher) are among the most important flow and leveling additives.

The flow of material within the drying coating can form eddies having distinct edges, often in the form of regular hexagons known as Bénard cells (Fig. 16). Solvent-rich materials rises in the center of these cells, whereas material having a lower solvent concentration moves downward from the edges of the cells. As a result, the surface tension in the center of the eddies is lower than at the edges. Material flow occurs from the areas with lower surface tension to the areas with higher surface tension, forming valleys in the center of the eddies and mountains at the edges.

The change of surface tension due to evaporation of solvent can be most effectively controlled by the addition of silicone polyethers, which often have

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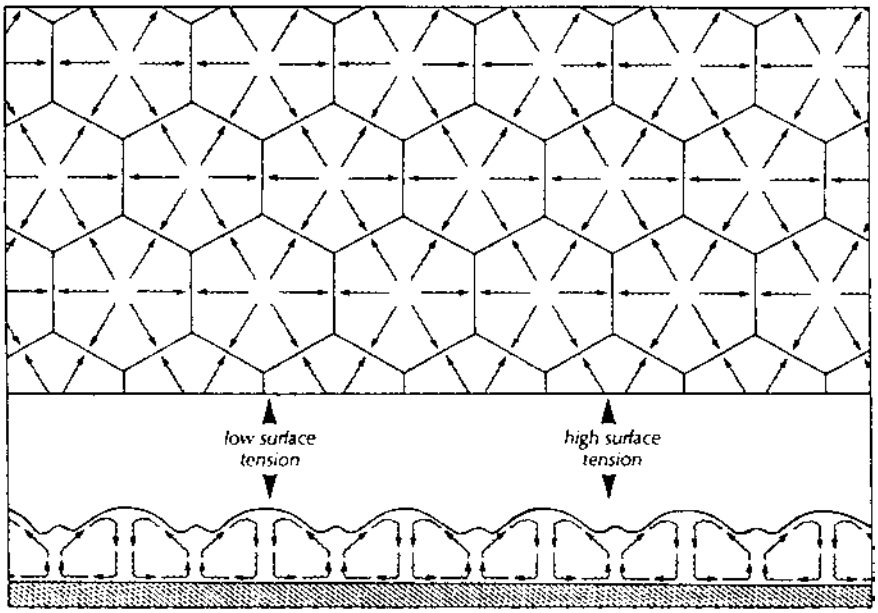

FIG. 16 Schematic illustration of Bénard cells.

a comb structure. By varying polarity, molecular weight, and number of polyether residues, the size of Bénard cells can be controlled, as well as the degree to which the surface of the dried coating mirrors the eddy currents of the drying process. In the automobile industry a specific marking of the coatings surface is even sometimes desired to hide irregularities of the body sheets. However, until now it not been possible to correlate any surfactant parameters exactly with the specific mode of action, and empirical findings still dominate the selection of flow additives.

Linear polyether siloxanes with ABA structure have demonstrated their superior ability to reduce the coefficient of friction of coatings and improve the mar and scratch resistance [59]. A chain of 20–60 dimethysiloxane units ensures the formation of a silicone oil like film on the surface even at a dosage level of 0.1%, whereas the polyether end groups guarantee a sufficient compatibility with the coating system. Slip properties of the polyether siloxane films for practical applications are even better than with pure silicone oil films, which tear under relatively low pressure due to their low intermolecular forces. The friction of coating surfaces can be reduced by a factor of 10 by the addition of only 0.1% of silicone polyethers.

Silicone polyethers with specific structures are being increasingly used as defoaming and wetting additives for water-borne coatings. As similar prod-

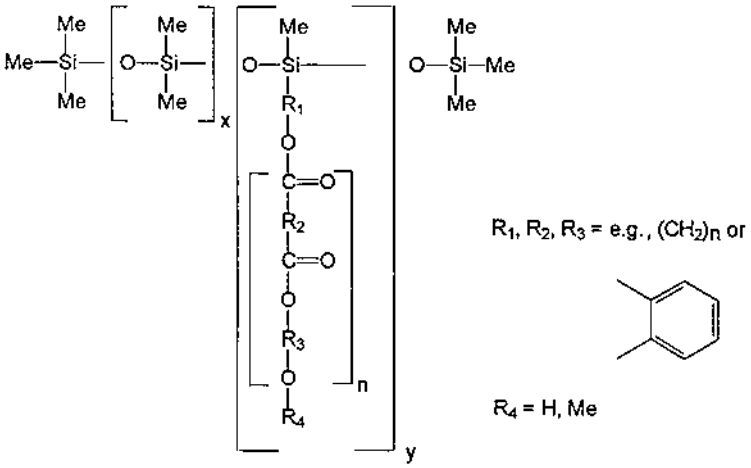

FIG. 17 Polyester-modified polysiloxanes.

ucts are also used in other water-borne systems, they are described in Section III of this chapter.

4. Polyester-Modified Polysiloxanes

Modification of polydimethylsiloxanes with polyester groups offers an additional opportunity to generate silicone copolymers with excellent compatibility while maintaining a very high level of surface activity. A special advantage of this type of modification can be detected in heat-curable coatings. (e.g., can coatings) because of the increased heat resistance up to temperatures of 250°C, for short times even up to 350°C [60]. Figure 17 shows a typical structure. In contrast, polyether siloxanes show significant decomposition effects at these temperatures.

The most common polyester-modified polysiloxanes [61] that are used in the coatings industry contain a polyester based on ε-caprolactone. It is polymerized on a hydroxy functional polydimethylsiloxane with 7–50 siloxane units and 1-8 hydorxyl groups. The structural diversity of the siloxane backbone is the same as described for the polyether-modified siloxanes.

III. SURFACE-ACTIVE PRODUCTS FOR WATER-BORNE APPLICATIONS

A. Antifoams

Foam is usually formed when liquids containing surfactants come into contact with air. Although foam is desirable in many industrial and house-

holds applications, it is undesirable in a large number of other applications, especially in a variety of water-borne systems. Thus, products are required that prevent foaming (denoted as antifoams) or destroy foam (denoted as defoamers).

1. Foam Formation

The mode of action of defoamers and antifoams can be understood on the basis of the theory of foaming, which is described extensively elsewhere [62–64]. The main factor of foam stabilization is the formation of a coherent surfactant layer that covers the air–liquid interfaces (Fig. 18).

2. Antifoaming Mechanisms

There are many contributions to account for antifoam mechanisms [65–67] but none of them is generally accepted for all systems. Yet, it is generally approved that antifoams have to meet at least the following requirements:

Insolubility in the foaming media in order to be surface active and to form discrete droplets of incompatible material

Low surface tension and spreading ability in order to enter the surfactant layer and to let hydrophobic particles interact with the surfactant layer

Provided that the interfacial tension of the antifoam and the liquid is sufficiently high (leading to incompatibility), the antifoam droplet migrates to the interface (Fig. 19) where it replaces foam-stabilizing surfactants in the foam lamella and spreads. The antifoam is dewetted, which leads to a destabilization of the foam lamella and eventually to a rupture of the foam bubbles.

Almost all antifoams contain hydrophobic particles that prohibit wetting of the surfactant's foam film due to their hydrophobic character. As the film thins through normal drainage, both surfaces of the lamella will come into contact with the particle and the film will adopt a certain contact angle

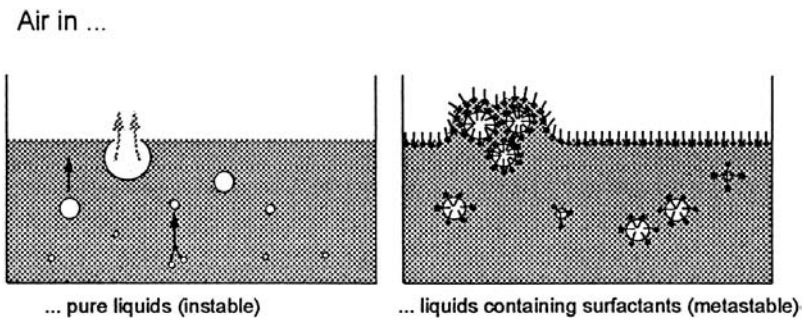

FIG. 18 Different characteristics of air in liquids.

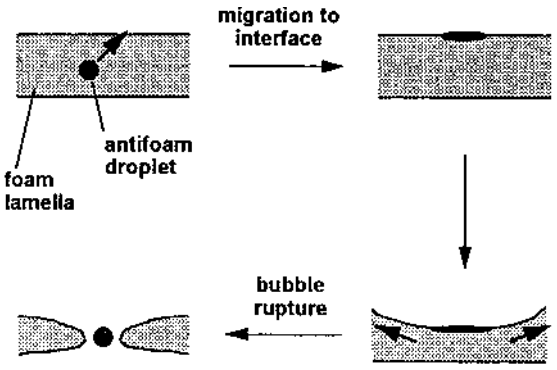

FIG. 19 Mechanism of defoaming.

[68]. The curvature results in a Laplace pressure ($p_{in} = p_{out} + 2\gamma/r$, where γ is the surface tension), which causes a flow of liquid away from the particle. If the resulting contact angle is greater than 90°C for spherical particles, the foam lamella gets thinner and finally the particle is dewetted and the foam lamella ruptures (Fig. 19). Irregularly shaped particles may lead to film rupture and foam breakdown at angles smaller than 90° [69]. In an alternative explanation, the oil drops with particles inside move to the plateau borders of the draining foam and do not work in the foam lamella [70].

The most important hydrophobic particles are hydrophobic silica, waxes, and metal soaps. Carriers are needed to transport the hydrophobic particles into the foam lamella and bring them into contact with the foam-stabilizing surfactant layer.

The mixed-type antifoams, i.e., those that combine carrier oil and hydrophobic particles, are more effective than the oil drops alone. This observation is consistent with industrial applications where antifoam formulations comprise hydrophobic oils (carrier oils) and finely dispersed solids, e.g., silica. The mixture is also more effective than the solid particles alone because the combination has a higher penetration depth into the solution. For high efficiency, the antifoam drops must have a minimal size because smaller drops are less likely to get trapped in the plateau borders.

Depending on the application and the surfactant causing the foam, the optimal structure of antifoams may vary. Thus combined expertise and experience are required to recommend the most effective antifoam.

3. Traditional Antifoams

Due to their low surface tension, silicone oils are extremely powerful base materials for foam-depressing compounds. Polydimethysiloxanes in a vis-

cosity range from 10^2 to 10^6 mPa filled with silica are applied as compounds or as emulsions, which consist of an active content from 5% to 50%. The latter provide the advantage that they are easily dispersible in the foaming media. Additionally, one can adjust the particle size of the antifoam during the emulsification in order to optimize the performance of the respective antifoam.

A variety of hydrophobic oils (polyethers, mineral and paraffin oils, derivatives of fatty acids or alcohols) are used as liquid components of antifoams. As the surface tension of these organic oils is in the range of 30 mN/m or even higher, and thus close to the surface tension of typical foaming liquids, these antifoams usually are not as effective as silicone oil–based defoamers.

4. Antifoams Based on Organo-Modified Siloxanes

Whereas organic oils do sometimes not perform effectively but usually show good compatibility, filled silicone oils are highly active but very incompatible and tend to separate from the bulk or induce faults such as craters in paints and inks. Antifoams based on organo-modified siloxanes can surpass traditional formulations in performance because they combine excellent activity with good compatibility (Fig. 20).

Silicone polyethers with a high content of PO in the polyether part are typically used. These copolymers have low surface tensions in the range of 21–25 mN/m. A high polyether content guarantees good compatibility with the foaming matrix. Both Si-C- and SiOC-bonded silicone polyethers are useful, the silicone backbone may be terminal substituted, or both at the same time. Organo-modified siloxane-based defoamers are utilized in a wide range of

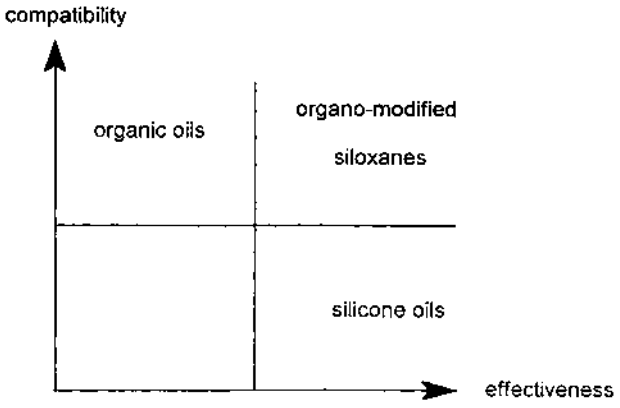

FIG. 20 Effectiveness vs. compatibility of different antifoams.

different industrial applications (polyvinyl chloride industry, polymer dispersions, detergents, paints and inks, etc.).

Stable macroemulsions with relatively large antifoam droplets can also be accomplished with polyether siloxanes. The optimal size of the droplets depends on the application and varies in the range from 1 to 40 μm.

Blends of different organosiloxanes, i.e., hydrophobic together with somewhat hydrophobic siloxanes, have also been claimed [71]. These blends can be used to produce highly concentrated antifoam emulsions that can be easily diluted. The stability of these systems can qualitatively be understood in view of the 3D-HLB system. The hydrophilic siloxane acts as an ideal emulsifying component for the hydrophobic siloxane, though synergistic effects between both components may be also observed.

Silicone polyethers of the $A[BA]_n$ type (A = polyether, B = siloxane; Fig. 6f) even allow the formulation of antifoams that are completely free of hydrophobic particles [72]. Compatibility of these antifoams is excellent, allowing their use in such sensitive applications as polyurethane dispersions, which are used as binders for floor coatings or automative coatings where even a very small number of craters on a large coated area enforces costly rework. The specific structure of the $A[BA]_n$ copolymers lets them enter and weaken the surfactant layer of foam lamellae very efficiently.

B. Emulsifiers in Cosmetic Applications

As the chemistry of silicone-based emulsifiers is extensively described earlier in this series only [73], a short survey covering the most important aspects will be given here. Depending on the kind and number of modifying groups, organo-modified siloxanes are surface active either in aqueous or in organic systems [74]. Thus, there are silicone-based emulsifiers for both systems. Commercially important emulsifiers are generally organo-modified silicones consisting of a comb-like structure (Fig. 3). Nonionic, organo-modified siloxanes such as polyether siloxanes (Fig. 7) are predominantly used to stabilize w/o emulsions, especially if the oil phase consists mainly of volatile cyclic siloxanes such as D_4 and D_5 [75]. Polyethersiloxanes with a relatively high molecular weight can be used in water-in-silicone oil emulsions [76]. To increase the stability of the emulsions, organic w/o emulsifiers such as derivatives of fatty acid esters may be added [77]. The solubility of polyether siloxanes. (Table 1) in water is determined by the content of EO. Yet the "silicone-specific" properties, i.e., contribution to compatibility, gloss, and handle in hair care products, are determined by the proportion of unmodified groups, i.e., dimethylsiloxane units.

Efforts to find more efficient w/o emulsifiers were successful when ternary copolymers, denoted as terpolymers, were found that comprise of a poly-

ether siloxane and additional alkyl chains, e.g., dodecyl and hexadecyl residues. Whereas the siloxane backbone possesses both hydrophobic and lipophobic properties, the polyether groups provide the necessary hydrophilic characteristics in the emulsifier molecule. Alkyl chains are important to achieve solubility and compatibility with the oil phase. It can be assumed that these molecules will arrange at the water–oil interface in a double comb–like manner, with the modifying groups sticking into the corresponding phase—the alkyl chain in the oil phase and the polyether in the aqueous phase (Fig. 21). These substances can stabilize emulsions very effectively, not only silicone fluids but also conventional mineral oils or even high portions of vegetable oils present in the oil phase.

Terpolymers play a key role in cosmetic formulations because corresponding emulsions show excellent features, e.g., fine-care properties, low concentration of emulsifiers (around 2%), and stability at temperatures below 0°C and above 50°C. In contrast, emulsions based on conventional organic emulsifiers, such as glycerol oleates, are not sufficiently stable and require additional oil-soluble waxes. These formulations show elevated viscosities and gel-like structures. Consequently, corresponding emulsions spread slowly and create a certain kind of stickiness when applied to the skin. Due to their low surface tension, emulsions based on terpolymers spread easily, immediately forming a continuous film. Once the water has evaporated, a uniform film is left on the skin. Thus light emulsions without additional stabilizing waxes were possible. Yet synergistic effects can also be achieved to improve emulsions stability by the addition of emulsifiers of low molecular weight, especially those based on polyglycerol esters of fatty acids.

If a cetyl group (C_{16}) instead of a dodecyl group is used, outstanding emulsifying properties of respective products were elucidated, e.g., the formation of emulsions that are stable at temperatures below −25°C and above 60°C [78], nonaqueous emulsions, multiple emulsions such as oil-in-water-in-oil (o/w/o) [79], and emulsions containing liposomes.

Clear correlations between chemical structure, molecular weight or polarity of the oil, and emulsion viscosity have not been obtained. Yet is has been shown that there are specific interactions of the emulsifier with the respective

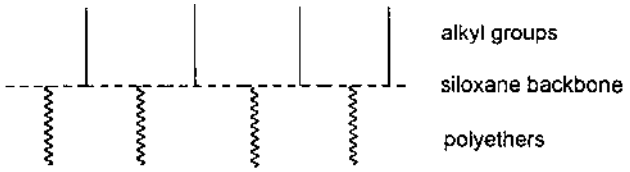

FIG. 21 Terpolymer with polyethers and alkyl groups as w/o emulsifier.

oil. Optimum stability is achieved as demonstrated in a plot of the concentration of the oil phase vs. the resulting viscosity of emulsion [80]. Only at the borderline of creamy and liquid emulsions is there a region of stability.

Terpolymers containing a cetyl group are also well suited for multiple emulsions, i.e., water-in-oil-in-water (w/o/w), because they do not migrate from one interface to the other [33]. They are adsorbed strongly at the interfaces due to their polymeric structure. In these systems, two interfaces have to be stabilized. One is between the inner oil phase and water phase, the other between the water phase and continuous oil phase. To prevent inhomegeneity and transformation into a two-phase system, terpolymers can thus be utilized. In contrast, at least two conventional emulsifiers with different HLB values are required to stablize such emulsions: one hyrophilic (HLB value $>$ 15) and one lipophilic emulsifier [81].

Cationic and amphoteric derivatives of ionic siloxanes (Fig. 8) combine a high gliding ability with antistatic properties, which are particularly interesting for textile applications and personal care. Silicone betaines and silicone quats are excellent additives in hair and skin care products such as hair rinses and conditioning shampoos where they improve the compatibility, gloss, and handle of hair. They are also good antistatics.

C. Wetting Agents

The application of aqueous formulations onto hydrophobic substrates such as polyolefins, other plastics, or waxy leaves is often problematic; the low surface energy of these substrates leads to poor wetting behavior or even dewetting phenomena such as crater formation and crawling [82].

Among the organo-modified silicones, which have been known for many years as surfactants with excellent surface activity [83,84], the trisiloxane surfactants (Fig. 22) occupy a specific position. Trisiloxane surfactants in aqueous systems do not exhibit high surface activity accompanied by low dynamic surface tension; in a number of applications they have been proven to possess outstanding wetting and spreading properties as well. Hence, they can serve as highly efficient wetting agents. If the siloxane part contains only one trimethylsilyl group, the compounds are called silane surfactants.

1. Trisiloxane Surfactants

Trisiloxanes can be regarded as the smallest comb-like polysiloxane carrying only one modifying group. The general structure of trisiloxane surfactants is shown above (Fig. 22).

The hydrophobic part of the molecule is the trisiloxane group, which does not exhibit the pronounced oleophobicity typical of siloxanes because of its lack of dimethylsiloxane groups. It is obtained by an equilibration reaction of

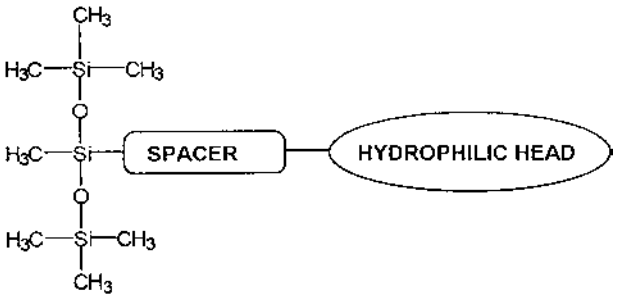

FIG. 22 Schematic structure of trisiloxane surfactants.

a siloxane containing solely SiH groups with an excess of hexamethyldisiloxane [36]. The hydrophilic moiety can be either ionic, e.g., an alkylsulfonate, phosphate, or ammonium alkylate (Fig. 8), or nonionic, e.g., an alcohol or a polyether group (Fig. 7). Because it is introduced mainly through conventional hydrosilylation reactions [85], the alkyl spacer is attached in most cases via a Si-C bond.

Trisiloxane surfactants reduce the surface tension in aqueous solution to approximately 22 mN/m, which is a value typical of polydimethylsiloxane. Moreover, if a polyether head group of a certain size or hydrophilicity is attached (Fig. 23), they exhibit outstanding wetting properties, a phenomenon often called superspreading [86]. Typically, a small drop (50 μL) of a diluted aqueous solution (0.1 wt %) of such a trisiloxane surfactant spreads on a hydrophobic surface such as a polypropylene sheet into a thin, wetting film of approximately 80 mm diameter within tens of seconds. This is about 20 times the area wetted by a 1 wt % solution of a conventional organic surfactant such as a nonylphenol ethoxylate.

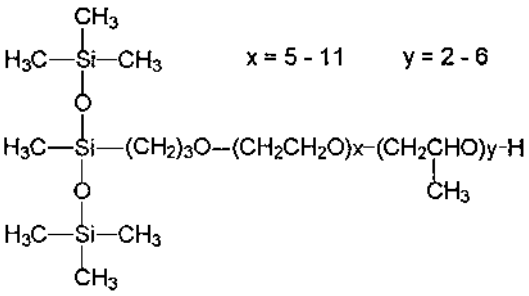

FIG. 23 Polyether trisiloxane copolymer A.

One major application of trisiloxane superspreading surfactants is therefore as adjuvants in a agriculture applications [87]. The superior coverage increases the contact area of the active ingredient with the plant; additionally, the low surface tension promotes stomatal infiltration and an accelerated uptake and translocation of the active ingredient into the plant. Subsequently, this leads to improved rainfastness.

The fast uptake of active ingredients in formulations containing a trisiloxane surfactant has been proven by experiments using radiolabeled glyphosate. Ten minutes after spraying formulations containing different surfactants on pea leaves, these were rinsed off to quantify the absorbed ^{14}C-glyphosate by scintillation counting. Results show that the trisiloxane surfactant leads to significantly higher uptake compared to a blend of conventional silicone surfactants and a traditional wetting agent (Fig. 24) [88]. Instead of a certain concentration, it was found that a fixed amount of trisiloxane surfactant per area is required to ensure uptake of active ingredients. This has the benefit of avoiding run-off at higher spray volumes [99]. Due to the low surface tension in aq. solutions, trisiloxane surfactants were suspected to decrease droplet size and thus to increase drift. In fact, they do not significantly influence the particle size and therefore, drift remains essentially unaffected [100].

Apart from agricultural applications, trisiloxane surfactants are used as additives in paints, polishes, textile auxiliaries, and other areas where wetting is critical.

One limitation concerning the application of trisiloxane surfactants is their hydrolysis in acidic or basic aqueous solutions. The degradation process leads to a cleavage of the Si-O bonds in the silocine backbone (Fig. 25). The

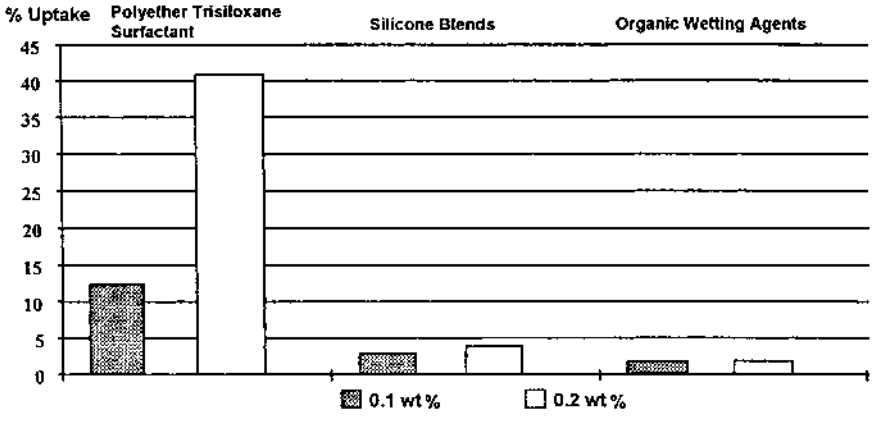

FIG. 24 Effect of surfactant on the uptake of ^{14}C-labeled glyphosate in pea leaves 10 min after treatment.

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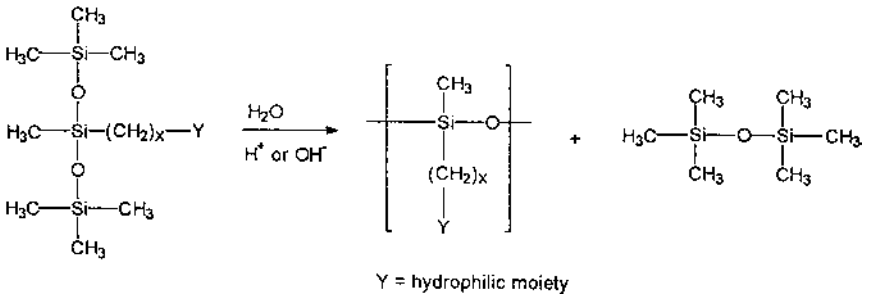

FIG. 25 Hydrolysis of trisiloxane surfactants in aqueous solution.

silanoles reequilibrate to form polysubstituted oligomers and hexamethyldisiloxane as decomposition products. The degradation is surprising with respect to the stability of other siloxanes under similar conditions.

Sometimes surfactants are required that are hydrolytically stable yet exhibit the same excellent wetting properties as the trisiloxane surfactants. Since the loss of surface activity in trisiloxanes is the result of a degradation of the siloxane backbone, attempts have been made to develop products that do not contain Si-O bonds within the structure but retain the surfactant properties of trisiloxanes; this led to the concept of trimethylsilane surfactants.

2. Trimethylsilane Surfactants

The first approach to obtain silicon-containing surfactants without Si-O bonds was made when carbosilanes were reacted with several α-olefins containing reactive moieties [89,90]. However, since the corresponding carbosilane precursors were synthesized via a Grignard reaction, these silane surfactants were difficult and costly to produce.

The availability of trimethylsilane in larger amounts and reproducible quality by the reduction of chlorotrimethylsilane to trimethylsilane with magnesium hydride [91] in a milling reactor provided a better method in silane surfactant chemistry [92]. By using trimethylsilane in hydrosilylation reactions with α, β-unsaturated compounds such as alkenols, allyl glycidyl ether, or alkenyl polyethers, a whole range of amphiphilic trimethylsilane compounds can be easily obtained (Fig. 8).

The silane alcohol can serve as an intermediate for further reactions with sulfamic acid to give sulfates or EO leading to anionic or nonionic silane surfactants (Fig. 26), respectively. Alternatively, the nonionic derivatives can be obtained by hydrosilylation of the trimethylsilane with an alkenol polyether (Fig. 26). The hydrosilylation reaction with allyl glycidyl ether (Fig. 8)

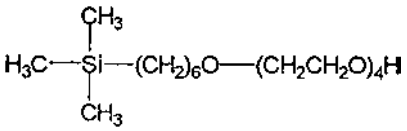

FIG. 26 Silane-based surfactant B.

leads to an epoxy intermediate that can be used to obtain cationic, zwitterionic, or anionic compounds by reaction with various nucleophiles.

A variety of nonionic silane surfactants have been synthesized differing in the length of the alkyl spacer (C_3 to C_{11}) and the degree of ethoxylation. Spreading tests of their aqueous solutions on polypropylene film have shown that the best wetting properties are obtained with a hexyl spacer groups and a polyether with on average four EO units (Fig. 26); the spreading is even comparable to trisiloxane surfactants, as discussed below.

To check its hydrolytic stability, dilute aqueous solutions of silane surfactant B (Fig. 26) were stored at pH values between 2 and 12. The spreading area on polypropylene was more or less constant over a period of more than 6 months, demonstrating the stability of the molecule. Even at temperatures of 50°C no significant hydrolysis takes place.

Yet is should be noted that the surfactant—despite its hydrolytic stability—was shown to be readily biodegradable (88% within 28 days, OECD closed-bottle test).

3. Comparison of Silane and Trisiloxane Surfactants

Several methods have been employed to study the effect of replacing the trisiloxane by a trimethylsilyl group on the surfactant properties. The results (Table 2) show that the silane surfactant B is comparable to the trisiloxane derivative A (Fig. 23) in terms of surface activity; the interfacial tensions are somewhat higher.

Low surface tension is not the only requirement for the superior wetting behavior of trisiloxane surfactants. It has been observed that aqueous solutions of superwetting trisiloxanes are slightly turbid; the presence of such a "dispersed surfactant-rich phase" has been reported to be necessary to exhibit superwetting [93]. However, the role of the lyotropic liquid crystalline phases and their dispersions in the spreading process is still under discussion [94–96].

Aqueous solutions of the optimized silane surfactant B are slightly turbid or opaque, too. Depending on temperature and concentration, several lyotropic liquid crystalline phases (L_1, L_3) separate. These do not spread on a hydrophobic substrate because of their high viscosity. Their aqueous dis-

TABLE 2 Comparison of the Surfactant Properties of a Nonionic Trisiloxane (A, Fig. 23) and Silane (B, Fig. 26)

Property	Trisiloxane surfactant A	Silane surfactant B
Static surface tension (drop volume) (0.05%)	22.0 mN/m	23.6 mN/m
CMC	0.05 wt %	0.05 wt %
Interfacial tension water/silicone oil (0.1 wt %) (without surfactant: 35 mN/m)	4.2 mN/m	10.5 mN/m
Interfacial tension water/decane (0.1 wt %) (without surfactant: 44 mN/m)	4.9 mN/m	11.4 mN/m

persions consist of vesicles as proven by video-enhanced contrast microscopy [97] and exhibit quite similar spreading properties as the trisiloxane superwetting surfactants.

In the case of superwetting trisiloxane surfactants the spreading area is not proportional to surfactant concentration; when the experiment is performed in controlled laboratory conditions at 50% relative humidity (Fig. 27A, filled circles) it usually decreases at concentrations above 0.1 wt %. This can be explained by the formation of viscous liquid crystalline

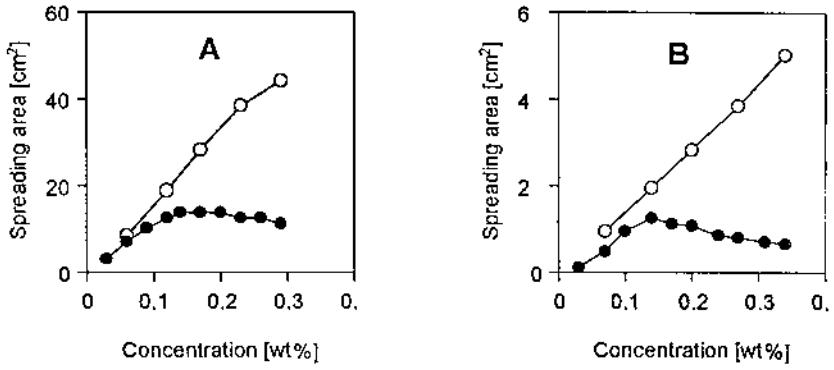

FIG. 27 Spreading area as a function of concentration at laboratory atmosphere: 50% relative humidity (●) and 100% relative humidity (○); nonionic trisiloxane (A, Fig. 23) and silane surfactant (B, Fig. 26).

phases on the surface of the droplet induced by evaporation. By performing the spreading experiment at 100% relative humidity, i.e., eliminating evaporation, the spreading area is exactly proportional to the amount of surfactant (Fig. 27A, open circles). Considering the size and number of surfactant molecules, in this case the final structure after the spreading process corresponds to a single bilayer [98].

Analogous spreading experiments using the trimethylsilane surfactant B revealed quite a similar behavior (Fig. 27B). Again, the spreading area decreases with increasing concentration above 0.1 wt % when the experiment is performed at laboratory atmosphere, whereas it is exactly proportional to the amount of surfactant when spreading is carried out at 100% relative humidity.

IV. SUMMARY

Due to the special properties of their hydrophobic building blocks, silicone surfactants are surface active in organic and water-borne media. Surface tensions as low as 22 mN/m can be achieved with silicone surfactants, which gives them unique properties in many applications. Silicone surfactants form a class of surfactants that is complementary to other classes of organic surfactants.

The chemistry of siloxanes is extremely flexible and allows the formation of different structural types with specific advantages for individual applications. One major factor is the equilibration reaction, which guarantees the controlled and reproducible design of siloxane backbones. The other important factor is the high degree of freedom for modifications; it is possible to introduce non-ionic or ionic groups, low or high molecular weight groups, hydrophilic or hydrophobic groups, individual groups, or mixtures of different groups.

However, a precise understanding of the mechanism of action of many silicone surfactant still requires investigation. The presence of many different components in the polymeric surfactants is certainly of value in many different industrial applications. At the same time it is still a challenge for scientists and technicians who look for stringent relationships between structure and property.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of Andreas Weier (polyurethane), Wolfgang Josten, and Stephan silber from Tego Chemie Service (coating), Michael Keup and Roland Sucker (antifoams), Burghard Grüning

(cosmetics), Stephan Stadtmüller and Joachim Venzmer (wetting agents), Geoffrey Hills (language consultant), and numerous other colleagues.

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