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Sugar-based anionic surfactants: synthesis and micelle formation of sodium methyl 2-acylamido-2-deoxy-6-*O*-sulfo-D-glucopyranosides

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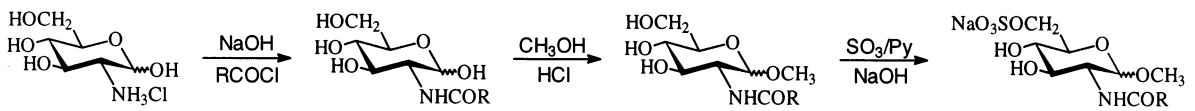
Abstract

The following sequence of reactions has been employed to synthesize the title anionic surfactants:



where $R = C_7H_{15}$; $C_{11}H_{23}$; and $C_{15}H_{31}$, respectively, and Py refers to pyridine. Aggregation of the surfactants synthesized (predominantly α anomers) in water was studied at 40 °C by conductivity measurements. Increasing the chain length of R decreases the critical micelle concentration (CMC) and the degree of counter-ion dissociation. The dependence of the Gibbs free energy of micellization and CMC on the length of R is similar to other ionic surfactants, but the head-group, i.e., the sulfated sugar moiety is less hydrophilic than the structurally related group $-(OCH_2-CH_2)_2-OSO_3^-Na^+$, most probably because of intermolecular H-bonding in the micellar pseudo-phase

Keywords: Sugar-based surfactants; Sugar sulfates; Sodium methyl 2-acylamido-2-deoxy-6-*O*-sulfo-D-glucopyranosides; Aqueous micelles

1. Introduction

A sugar-based surfactant carries a hydrophobic moiety (usually a long chain alkyl group) and a hydrophilic carbohydrate head-group (e.g., glucose, sucrose, etc.). These surfactants have generated much interest because they are biodegradable, mild to the skin, and are derived from renewable sources.[1] 2-Amino-2-deoxy-D-glucopyranose (hereafter called 2-amino-D-glucose) is widely present in nature, e.g., as the building block of chitin, the second most abundant natural polymer after cellulose.[2] It is also a main component of peptidoglycan, the backbone of the cell wall of numerous bacteria. This amino sugar is an interesting starting material for synthesis of sugar-based surfactants because it carries two different functional groups, namely NH_2 and OH, which can be specifically derivatized.[3]

The 2-amino-D-glucose-based surfactants that have been previously synthesized include the following: (1) nonionic, with the 2-amino group present either as a free base or derivatized as amide; (2) cationic, with the 2-amino

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group converted into ammonium ion or quaternary ammonium ion; and (3) anionic, carrying carboxylate and sulfonate head-ions.[4–9] The latter surfactant is a mixture of anomers, and there is no information on its micellar properties.[9] To our knowledge, there has been no report on methyl 2-acylamido-2-deoxy-6-*O*-sulfo-D-glucopyranoside surfactants. In the present work, we synthesized a series of surfactants of known anomeric composition, with increasing hydrophobic character (acyl group = octanoyl, dodecanoyl and hexadecanoyl), and studied their aggregation in water. Our results show that the relationship between micellar parameters and the chain length of the acyl group is similar to that observed for other ionic surfactants; the sulfated sugar moiety is less hydrophilic than the structurally related group $-(OCH_2-CH_2)_2-OSO_3^-Na^+$.

2. Experimental

Materials.—Commercial solvents and reagents (Aldrich Chemical Co. and E. Merck Chemical Co.) were purified by standard procedures.[10] Acyl chlorides were prepared by reacting the purified carboxylic acid with excess thionyl chloride, followed by fractional distillation.

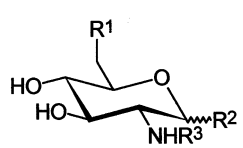
Chromatography.—The eluents (eluent A, 60:25:4; eluent B, 40:20:1) employed in TLC and flash-column chromatography were mixtures of $CHCl_3$–MeOH–water. TLC plates were sprayed with solutions of either 1:1:10 anisaldehyde–H_2SO_4–EtOH or 1% ninhydrin in acetone, and were developed by heating.

Apparatus.—Melting points were determined with an Electrothermal model IA 6304 apparatus and are uncorrected. Microanalyses were carried out at the Microanalyses Laboratory of this Institute. FTIR spectra were recorded with a Nicolet FTIR 510 spectrophotometer. NMR spectra were recorded with Varian Innova-300 and Bruker DRX-500 spectrometers. Peak attribution was confirmed by COSY experiments. Critical micelle concentrations (CMC) were determined with a PC-interfaced Fisher Accumet 50 pH meter/conductimeter provided with a Digimed model DM-C1 micro-conductivity cell and Schott model Titronic T200 programmed burette. A home-developed software package was used both for programmed dilution of the concentrated surfactant solution and for acquisition of conductivity data. Water was determined by Karl–Fisher titration with a Schott model 1200 titration controller and PT 1400 electrode. Gas chromatographic analysis was carried out on a Shimadzu model GC 17A-2 apparatus, equipped with FID detector and Supelcowax 10 capillary column (Supelco, USA).

Synthesis.—Compounds **1a**, **1b**, and **1c** (2-acylamido-2-deoxy-D-glucopyranoses) were prepared by reacting the appropriate acyl chlorides with 2-amino-D-glucose under vigorous stirring, initially at −10 °C for 1 h, then at rt for an additional 2 h.[11] The solids obtained were washed with water until free of Cl^-, dried, washed with anhyd ethyl ether, recrystallized from absolute EtOH, and dried under reduced pressure.

The following results were obtained (Fig. 1):

Compound **1a**: White solid; yield, 48%; mp (dec) 202–203 °C, lit. 215 °C;[11] IR (KBr, cm^{-1}), 1643 ($\nu_{C=O}$, secondary amide, α anomer), 1621 ($\nu_{C=O}$, secondary amide, β anomer) and 1556 ($\delta_{N-H} + \nu_{C-NH}$, secondary amide). The absence of a band at ca. 1740 indicated no O-acylation. The ^1H NMR spec-



	R1	R2	R3
1a	OH		$C_7H_{15}CO-$
1b	OH		$C_{11}H_{23}CO-$
1c	OH		$C_{15}H_{31}CO-$
2a	OH	OCH_3	$C_7H_{15}CO-$
2b	OH	OCH_3	$C_{11}H_{23}CO-$
2c	OH	OCH_3	$C_{15}H_{31}CO-$
3a	$-OSO_3Na$	OCH_3	$C_7H_{15}CO-$
3b	$-OSO_3Na$	OCH_3	$C_{11}H_{23}CO-$
3c	$-OSO_3Na$	OCH_3	$C_{15}H_{31}CO-$

Fig. 1. Structures of the compounds synthesized.

trum (DMSO-d_6, Table 1) showed peaks due to α and β anomers, 72:28.

Compound **1b**: White solid; yield, 52%; mp (dec) 194–195 °C, lit. 208–209 °C;[11] α:β anomers, 74:26. The IR band frequencies and ^{1}H NMR chemical shifts were identical to those of compound **1a**.

Compound **1c**: White solid; yield, 71%; mp (dec) 195–196 °C, lit. 202–203 °C;[11] α:β anomers, 65:35. The IR band frequencies and ^{1}H NMR chemical shifts were identical to those of compound **1a**.

Compounds **2a**, **2b**, and **2c** (methyl 2-acylamido-2-deoxy-D-glucopyranosides) were prepared by refluxing a solution of compound **1** in anhyd methanolic HCl (final [acid] = 1.5%) for the appropriate time (12, 24, and 36 h, for compounds **1a**, **1b**, and **1c**, respectively). The alcoholic solution was neutralized with solid $CaCO_3$, the suspension was filtered, and the solution was evaporated to 10% of its original volume and added to cold water. The precipitate was filtered, washed with water and dried.

The following results were obtained:

Compound **2a**: Yellowish solid; yield, 69%; R_f 0.54 (eluent A); IR (KBr, cm^{-1}), 1644 ($\nu_{C=O}$, secondary amide, α anomer), 1621 ($\nu_{C=O}$, secondary amide, β anomer) and 1555 ($\delta_{N-H} + \nu_{C-NH}$, secondary amide). The absence of a band at ca. 1740 cm^{-1} indicated no O-acylation. The ^{1}H NMR spectrum (DMSO-d_6, Table 1) showed peaks due to α and β anomers (83:17).

Compound **2b**: Yellowish solid; yield, 90%; R_f 0.58 (eluent A); α:β anomers, 85:15. The IR band frequencies and ^{1}H NMR chemical shifts were identical to those of compound **2a**.

Compound **2c**: Yellowish solid; yield, 87%; R_f 0.63 (eluent A); α:β anomers, 79:12. The IR band frequencies and ^{1}H NMR chemical shifts were identical to those of compound **2a**.

Sodium methyl 2-acylamido-2-deoxy-6-O-sulfo-D-glucopyranosides.—To a cold solution (−10 °C) of compound **2** (74.6 mmol) in 200 mL of Py were slowly added 89.6 mmol of SO_3·Py complex. The solution was stirred for 30 min at −10 °C, followed by 24 h at rt. Cold water (1 L) was added, and the pH of the solution was adjusted to pH 8 with aq NaOH. Water was evaporated and the residue was suspended in 100 mL of abs EtOH. The solvent was removed, and the process was repeated twice in order to eliminate traces of Py. The solid was extracted with anhyd MeOH, and the solvent was evaporated.

The residue was purified with flash-column chromatography using eluent A and a material–silica gel ratio of 1:100. After solvent evaporation, the surfactant was dissolved in the minimum amount of water, the aq solution filtered through a 0.22-μm membrane, and the product was dried by lyophilization.

The following results were obtained:

Compound **3a**: White solid; yield, 56%; R_f 0.19 (eluent A), mp (dec) 172–174 °C, IR (KBr, cm^{-1}), 1646 ($\nu_{C=O}$, secondary amide, α anomer); 1555 ($\delta_{N-H} + \nu_{C-NH}$, secondary amide) 1231 ($\nu_{as,S=O}$ of SO_4); 821 (ν_{C-O-SO_2}, primary, equatorial position). Table 1 shows ^{1}H and ^{13}C NMR spectral analysis of compound **3a**. The product obtained was a mixture of α and β anomers (82:18) and contained water that was not removed by extensive lyophilization or drying under reduced pressure over P_2O_5. Its concentration (8.35%) was determined by the Karl–Fisher titration. Anal. Calcd for $C_{15}H_{28}NNaO_9S + 8.35\%$ H_2O: C, 39.18; H, 6.97; N, 3.05. Found: C, 38.78; H, 6.67; N, 3.15.

Compound **3b**: White solid; yield, 53%; R_f 0.26 (eluent A); mp (dec) 174–175 °C; α:β anomers, 85:15. The IR band frequencies, ^{1}H and ^{13}C NMR chemical shifts were identical to those of compound **3a**. Anal. Calcd for $C_{19}H_{36}NNaO_9S + 8.61\%$ H_2O: C, 43.67; H, 7.91; N, 2.68. Found: C, 43.29; H, 7.58; N, 2.71.

Compound **3c**: The ^{1}H NMR spectrum of the product purified with column chromatography by using eluent A showed the presence of ca. 10% of disulfated products. These were eliminated by repeated purifications with column chromatography by using eluent B. The pure product is a white solid; yield 40%; R_f 0.26 (eluent A); mp (dec) 163–165 °C; α:β anomers, 79:21. The IR band frequencies, and ^{1}H and ^{13}C NMR chemical shifts were identical to those of compound **3a**. Anal. Calcd for $C_{23}H_{44}NNaO_9S + 7.25\%$ H_2O: C, 48.01; H, 8.52; N, 2.43. Found: C, 47.74; H, 8.28; N, 2.53.

Table 1
^{1}H and ^{13}C NMR data of the surfactants synthesized and their precursors [a,b]

	H-1 ($J_{1,2}$)	H-2 ($J_{2,3}$)	H-3 ($J_{3,4}$)	H-4 ($J_{4,5}$)	H-5 ($J_{5,6'}$)	H-6 ($J_{5,6}$)	H-6′ ($J_{6,6'}$)	NH ($J_{2,NH}$)	OH-1 ($J_{1,OH}$)	OH-3 ($J_{3,OH}$)	OH-4 ($J_{4,OH}$)	OH-6 ($J_{6,OH}$)	OCH_3
^{1}H NMR data													
1a-α [c]	4.91	3.0–3.7	3.0–3.7	3.0–3.7	3.0–3.7	3.0–3.7	3.0–3.7	7.50	6.38	4.55	4.88	4.41	
	(3.7)	(nd)	(nd)	(nd)	(nd)	(nd)	(nd)	(7.9)	(3.8)	(5.5)	(5.4)	(5.4)	
2a-α [d]	4.52	3.62–3.67	3.29-3.32	3.12	3.41–3.48	3.62–3.67	3.41–3.48	7.65		4.69	4.99	4.53	3.23
	(3.4)	(nd)	(nd)	(9.2)	(nd)	(nd)	(nd)	(8.1)		(5.9)	(5.6)	(6.0)	
3a-α [e]	4.51	3.65	3.44	3.08	3.49	4.03	3.75	7.56		4.64	5.00		3.23
	(3.5)	(10.7)	(8.6)	(9.8)	(6.7)	(1.9)	(10.9)	(8.1)		(5.7)	(5.6)		

^{13}C NMR data [f]	C-1	C-2	C-3 [g]	C-4	C-5 [g]	C-6	OCH_3	C=O
3a-α	98.1	53.9	70.6	71.3	70.7	65.9	54.5	172.5
3a-β	101.9	55.0	71.0	75.0	71.0	65.9	55.6	172.3

[a] Spectra were recorded at 25 °C, for all solutions in DMSO-d_6. Chemical shifts are given in δ (ppm), relative to internal TMS. Spin–spin coupling constants (J) are given in Hz. The chemical shifts for the other members of the each series, namely, **1b**, **1c**, **2b**, **2c**, **3b**, and **3c** were within ± 0.01 ppm (^{1}H) and ± 0.1 ppm (^{13}C).

[b] The ^{1}H NMR spectra also contained the following signals, corresponding to the acyl group chain: 2.09, $-CH_2CH_2(CH_2)_nCH_3$; 1.47, $-CH_2CH_2(CH_2)_nCH_3$; 1.24, $-CH_2CH_2(CH_2)_nCH_3$; and 0.86, $-CH_2CH_2(CH_2)_nCH_3$.

[c] Signals from the β anomers: 7.63 ($J_{2,NH}$ 7.9 Hz, NH), 6.45 ($J_{1,OH}$ 6.3 Hz, OH-1), 4.77 ($J_{3,OH}$ 5.1 Hz, OH-3), 4.52 ($J_{1,2}$ 7.0 Hz, H-1), 4.43 ($J_{6,OH}$ 6.3 Hz, OH-6).

[d] Signals from the β anomers: 7.59 ($J_{2,NH}$ 9.0 Hz, NH), 4.17 ($J_{1,2}$ 8.0 Hz, H-1).

[e] Signals from the β anomers: 7.55 ($J_{2,NH}$ 8.9 Hz, NH), 4.99 ($J_{4,OH}$ 5.4 Hz, OH-4), 4.80 ($J_{3,OH}$ 5.5 Hz, OH-3), 4.19 ($J_{1,2}$ 8.4 Hz, H-1).

[f] The spectra contained the following signals from the acylic chain: 35.4 (α anomer) and 35.9 (β anomer), $-CH_2CH_2(CH_2)_nCH_2CH_2CH_3$; 25.5, $-CH_2CH_2(CH_2)_nCH_2CH_2CH_3$; 28.7–29.6, $-CH_2CH_2(CH_2)_nCH_2CH_2CH_3$; 31.5, $-CH_2CH_2(CH_2)_nCH_2CH_2CH_3$; 22.3, $-CH_2CH_2(CH_2)_nCH_2CH_2CH_3$; and 14.1, $-CH_2CH_2(CH_2)_nCH_2CH_2CH_3$.

[g] Due to very close chemical shifts, the assignments for C-3 and C-5 are only tentative.

Determination of properties of aqueous surfactant solutions. The apparent Krafft temperature.—This was determined visually as the temperature at which 1% (w/v) aq surfactant solution became clear. Each solution was cooled until it became turbid then transferred to a thermostated bath whose temperature was raised at the rate of 1 °C/min.

Critical micelle concentration (CMC) and degree of micelle dissociation (α_{mic}).—Both properties were determined by measuring solution conductivity as a function of [surfactant] in the range 5×10^{-5}–5×10^{-2} M.

3. Results and discussion

Synthesis

2-Acylamido-2-deoxy-D-glucopyranoses.—We have attempted to synthesize compound **1b** by reacting dodecanoyl chloride with 2-amino-D-glucose in DMF, followed by extraction with *n*-butanol.[12] The very low yield obtained (8%) is probably due to limited solubility of **1b** in the alcohol employed. Although elimination of the extraction step has resulted in a better yield (40%), this method proved to be unsatisfactory, both for large-scale synthesis of this compound (0.56 mol), and for synthesis of **1a** (10% yield). The method published elsewhere[11] proved to be satisfactory, probably because the acyl chlorides used are insoluble in water and 2-amino-D-glucose is a strong nucleophile, i.e., the rate of aminolysis of the acyl chloride is faster than its rate of hydrolysis.

Mixtures of α and β anomers were obtained because 2-amino-D-glucose undergoes mutarotation, similar to D-glucose.[13] The presence of these anomers also explains the differences between the melting points that we observed and those reported elsewhere. For example, since the melting points of pure α and β anomers of 2-acetamido-2-deoxy-D-glucopyranoside are 205 °C and 182–183.5 °C, respectively,[14] the melting points of their mixtures are expected to depend on the relative concentration of each anomer.

Methyl 2-acylamido-2-deoxy-D-glucopyranosides.—Preliminary experiments on methylation of compounds **1b** and **1c** under conditions given elsewhere ([HCl] = 2.5%, reflux time = 24 h)[15] have indicated the occurrence of two acid-catalyzed side reactions: formation of esters (methyl dodecanoate, 15%, and/or methyl hexadecanoate, 24%), and polymerization to polyglycosides. Indeed, in the (industrial) acid-catalyzed production of alkylpolyglycosides, the polymer yield increases as a function of increasing reaction time and acid concentration.[16] In order to avoid these side reactions, the concentration of HCl was reduced to 1.5%, and the optimum reflux time for each starting material (12, 24 and 36 h for compounds **1a**, **1b**, and **1c**, respectively) was determined by following the reaction progress by TLC analysis. The reaction involves fast formation of methyl 2-acylamido-2-deoxy-D-glucofuranoside (kinetic product), followed by its slow conversion into the corresponding thermodynamic product, namely, the pyranoside.[3,17] No furanosides were detected by ^{1}H NMR spectroscopy, and the α:β anomer ratio was found to increase as a function of increasing [HCl], being ca. 91:9 at 2.5% HCl and ca. 80:20 at 1.5% HCl, respectively.

Sodium methyl 2-acylamido-2-deoxy-6-O-sulfo-D-glucopyranosides.—The method published elsewhere for sulfation of glucose[18] has been employed, with the following modification: we employed 20% excess of the sulfating agent (SO_3·pyridine), and the reaction mixture was stirred at −10 °C for 30 min and at room temperature for 24 h. The following evidence shows that the surfactants purified are free of disulfated contaminants: (1) ^{1}H NMR spectra (DMSO-d_6) showed the presence of OH-3 and OH-4 but not OH-6. The latter group is clearly observed (at 4.51 ppm) in the spectrum of compounds **2a**–**2c**; (2) the IR C–O–SO_3^- band at 821 cm^{-1} is characteristic of a sulfate group in the C-6 position (equatorial, primary position). This band shifts to 832 cm^{-1} when the group is present in the C-3 or C-4 position.[19]

As given in Section 2, these surfactants contain water that was not removed by extensive drying. Rather than heating the products, a procedure that may lead to side reactions (e.g., decomposition), we have accurately determined their water content by Karl–Fisher titration, and subsequently took this into account.

Table 2
Micellar properties of aqueous solutions of methyl 2-acylamido-2-deoxy-6-*O*-sulfo-D-glucopyranoside surfactants

Compound	Apparent T_{Krafft} (°C)	$10^3 \times$ CMC (mol/L) [a]	N_{agg} [b]	α [a]	ΔG°_{mic} (kJ/mol)
3a	<0	25	28	0.33	−33.5
3b	14.0	1.7	56	0.20	−48.6
3c	39.0	0.12	95	0.17	−62.3

[a] Measured at 40 °C.
[b] Calculated (see text for details).

Properties of the surfactant synthesized.— Table 2 shows the properties of sodium methyl 2-acylamido-2-deoxy-6-*O*-sulfo-D-glucopyranosides (**3a**, **3b** and **3c**, respectively), namely the apparent Krafft temperature, CMC, α_{mic}, the micellar aggregation number (N_{agg}), and Gibbs free energy of micelle formation (ΔG°_{mic}).

Although the apparent Krafft temperatures were measured at single solution composition (1%, w/v), those of the alkyl 2-amino-2-deoxy-β-D-glucopyranoside nonioinic surfactants were found to be independent of surfactant concentration,[5] i.e., the values reported here may not be far from the true Krafft temperatures.

The CMC and α_{mic} values were determined by measuring the dependence of solution conductance on [surfactant] at 40 °C, i.e., just above the apparent Krafft temperature of **3c** (Fig. 2). As shown below, plots of specific conductance versus [surfactant] exhibited two straight lines intersecting at the CMC. According to Evans, α_{mic} can be calculated from solution conductance by Eq. (1):[20]

$$1000S_2 = \frac{(N_{agg} - \beta_{mic})^2}{N_{agg}^{3/4}}(1000S_1 - \lambda_{Na}) + \alpha_{mic}\lambda_{Na} \quad (1)$$

where S_2, S_1, λ_{Na} and β_{mic} refer to the slope of the linear portion above the CMC, the slope of the linear portion below the CMC, the equivalent conductance of the surfactant counter ion (Na^+) at infinite dilution, and the number of counter ions attached to the micelle (i.e., $\beta_{mic} = 1 - \alpha_{mic}$), respectively. Eq. (1) is rather insensitive to N_{agg} employed, e.g., changing N_{agg} of **3b** by 50% resulted in a change of only 5% in α_{mic}. That is, reliable α_{mic} can be obtained from Eq. (1) by using N_{agg} calculated from the corresponding volumes of the micelles and the monomers, respectively.[21] The calculations were based on the usual assumption, i.e., ionic micelles are spherical-shaped at surfactant concentrations close to the CMC.[22,23] Calculated N_{agg} values were then used to calculate α_{mic} from Eq. (1).

The Gibbs free energy of micellization (ΔG°_{mic}, Table 2) was calculated from Eq. (2):[22]

$$\Delta G^\circ_{mic} = (2 - \alpha_{mic})RT \ln \chi_{CMC} \quad (2)$$

where CMC is given on the mole fraction scale, χ. This free energy contains contributions for the transfer from bulk aqueous pseudo-phase to the micelle from the terminal CH_3 group, $\Delta G^\circ_{CH_3}$, the methylene groups of the alkyl chains, ($m\Delta G^\circ_{CH_2}$), where m refers to the number of methylene groups (6, 10, and 14 for **3a**, **3b**, and **3c**, respectively), and the head-group, i.e., the sulfated sugar moiety, $\Delta G^\circ_{head\text{-}group}$ (Eq. (3)):[23]

$$\Delta G^\circ_{mic} = \Delta G^\circ_{CH_3} + m\Delta G^\circ_{CH_2} + \Delta G^\circ_{head\text{-}group} \quad (3)$$

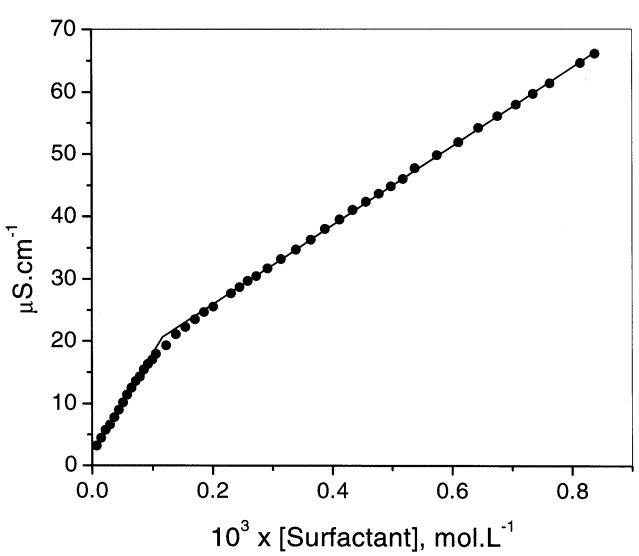


Fig. 2. Dependence of solution conductance on [surfactant] for **3c** at 40 °C.

Table 3
Available micellar properties of aqueous solutions of anionic surfactants related to **3a**–**3c**

Surfactant [Reference]	Structure	Apparent T_{Krafft}, °C	10^3 x CMC mol L^{-1}, (T °C)	A (Eq. 8)	B (Eq. 8)
4 [26]	R–C(=O)–NH–$(CH_2)_2OSO_3Na$	C_{12}: 14 C_{16}: 42	C_{12}: 10.1 (60) C_{16}: 0.55 (60)	1.6	-0.30
5 [26]	R–C(=O)–NH–$(CH_2)_3OSO_3Na$	C_{12}: 21 C_{16}: 47	C_{12}: 8.4 (60) C_{16}: 0.45 (60)	1.6	-0.30
6 [27]	R–C(=O)–NH–$(CH_2)_3SO_3Na$	C_{12}: <0 C_{16}: 44	C_{12}: 7.91 (60) C_{16}: 0.48 (60)	1.4	-0.29
7 [25]	RNH–C(=O)–CH_2OSO_3Na	C_{12}: 25.7 C_{16}: 47.1	C_{12}: 6.4 (50) C_{16}: 0.34 (50)	1.6	-0.32
8 [20]	$ROSO_3Na$	-	C_8: 136 (40) C_{12}: 8.65 (40) C_{16}: 0.58 (40)	1.5	-0.29
9 [28,29]	$R(OCH_2CH_2)_2OSO_3Na$	-	C_{12}: 3.1 (40) C_{16}: 0.23 (40)	1.0	-0.28

The dependence of ΔG°_{mic} on m is rigorously linear (correlation coefficient = 0.9996), the slope of this plot gives the Gibbs free energy of transfer–CH_2 group, $\Delta G^{\circ}_{CH_2} = -3.6 \pm 0.1$ kJ/mol.

The relationship between the structure of hydrophilic and hydrophobic moieties of the surfactants synthesized and physicochemical properties of their aqueous solutions is a central point of the present work. In discussing our results, we consider data of related surfactants, e.g., those listed in Table 3, which includes the following compounds: sulfated and sulfonated ethanolamides and propanolamides of fatty acids, **4**–**6**; sulfated *N*-alkylamides of α-hydroxyacids, **7**; alkylsulfates, **8**; and sulfates of ethoxylated alcohols, **9**.

The following observations show that the relationship between the length of hydrophobic group of our sugar-based sulfates and their micellar properties are similar to those observed for surfactants listed in Table 3, and those reported elsewhere:[23,24] (i) The apparent Krafft temperatures of **3a**–**3c** increase as a function of increasing the hydrophobic chain length. Their values are similar to those of surfactants **4**–**7**, because in all compounds the hydrated surfactant crystals are probably stabilized by intermolecular H-bonding between the amide groups;[25] (ii) Increasing the length of the surfactant hydrophobic group leads to an increase of N_{agg}, and a decrease of CMC and α_{mic}; (iii) Our $\Delta G^{\circ}_{CH_2}$, −3.6 kJ/mol is in the same range of those which we calculated for surfactants **8**, −3.4 kJ/mol, and **9**, −3.7 kJ/mol, as well as other ionic and non-ionic surfactants, -3.1 ± 0.3 kJ/mol.[23]

Information about the head-group can be reached from the intercept of Eq. (3), which contains contributions from $\Delta G^{\circ}_{CH_3}$ and $\Delta G^{\circ}_{head\text{-}group}$. We calculated intercepts of −12, −2.8, and 0.1 kJ/mol, for surfactants **3** (**a**–**c**), **8**, and **9**, respectively. Since $\Delta G^{\circ}_{CH_3}$ is independent of the chain length of the surfactant,[23] its contribution is constant. That is, it appears that the sulfated glucose moiety is less hydrophilic than the head-group of **9**, namely $-(OCH_2–CH_2)_2–OSO_3^-Na^+$. This result is also corroborated from data of surfactants **4**–**7** (Table 3). Since their ΔG°_{mic} could not be calculated because their α_{mic} were not available, we have employed Eq. (4) which correlates log CMC with N instead of Eq. (3):[23,24]

$$\text{Log CMC} = A - BN \quad (4)$$

where the regression coefficients A and B are related to contributions of the head-group plus the terminal CH_3, and the methylene groups, respectively. Eq. (4) yielded 0.71 and −0.29, for A and B, respectively. Whereas the latter is in the range reported for surfactants **4**–**9**, as well as for other ionic surfactants,[23]

the former is smaller than the range of *A* shown in Table 3, 1.0–1.6, as well as that reported for other long-chain sulfates and sulfonates, 1.4 ± 0.2.[23] This, and the fact that CMC of compounds **3a**–**3c** are smaller than those of compounds **5**, **6** and **9** reflect the low hydrophilicity of interfacial sulfated sugar moiety most probably because of intermolecular H-bonding of the monomers in the micellar pseudo-phase (via the NHCO and OH groups).

4. Conclusions

Sodium methyl 2-acylamido-2-deoxy-6-*O*-sulfo-D-glucopyranosides have been synthesized by a scheme that led to N-acylation of 2-amino-D-glucose and sulfation of methyl 2-acylamido-2-deoxy-D-glucopyranosides with formation of surfactants that are predominantly composed of the α anomer. The CMC and α_{mic} values have shown that these surfactants are similar to sulfated ethanolamides and propanolamides of fatty acids, except that the head-group (sulfated acylamido sugar residue) are less hydrophilic than the structurally related group, $-(OCH_2-CH_2)_2-OSO_3^-Na^+$, due to intermolecular H-bonding.

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