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Structural changes of viscoelastic solutions of zwitterionic and anionic surfactant mixtures under the influence of simple salt

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Abstract
The paper presents the effects of sodium chloride on the rheological properties of aqueous solutions of cocamidopropyl betaine (CAPB) and sodium dodecylbenzene sulfonate (SDBS) mixtures. Studies were carried out in the CAPB/SDBS molar ratio range of 0.9 to 3.5, at sodium chloride concentrations varying from 0.03 M to 0.75 M. Continuous and oscillatory flow measurements showed that the impact of sodium chloride concentration on shear viscosity and relaxation time was closely linked to the CAPB/SDBS molar ratio. The maximum shear viscosity and the longest Maxwell relaxation time were obtained at the CAPB/SDBS molar ratio of 2. Based on CryoTEM images, it was determined that the shear viscosity and relaxation time peaks identified at a certain concentration of sodium chloride could be attributed to the transition of the entangled wormlike micellar network into branched wormlike micelles. Changes in the micellar microstructure accompanying modifications of the CAPB/SDBS molar ratio and sodium chloride concentration were accounted for on the basis of the packing parameter.

Keywords
wormlike micelles, surfactant solutions, CryoTEM, Maxwell model

1. INTRODUCTION

Cocamidopropyl betaine (CAPB) is a zwitterionic surfactant widely used in the production of cosmetics and household chemicals to achieve specific rheological properties required in shampoos, body cleansing gels or liquid soaps. The surfactant is produced by a number of manufacturers and available on the market in the form of aqueous solutions (CAPB concentration ranges from 30% to 50%). CAPB solutions offered by commercial companies also contain sodium chloride at concentrations between 2% and 6%.

In aqueous solutions, CAPB exhibits synergism with anionic surfactants (e.g. sodium dodecyl sulfate SDS, SDBS), leading to the formation of fluids with viscoelastic properties (Różańska, 2015; Różańska and Różański, 2019). Viscoelastic characteristics are typically observed in surfactant solutions in which wormlike micelles or branched wormlike micelles have been formed. Only a few surfactants are known to form wormlike micelles spontaneously in aqueous solutions. Typical examples include cationic surfactants with aliphatic chains of ca. 16 carbons (e.g. cetyltrimethylammonium bromide or cetylpyridinium bromide). The transition from spherical to wormlike micelles can be induced through the addition of simple salts (NaCl, KCl) (Parker and Fieber, 2013), hydrotropes (Fieber et al., 2021) and co-surfactants (Fieber et al., 2021). In cosmetics and household chemicals, the formation of wormlike micelles is achieved by using appropriately selected surfactant mixtures (cationic/anionic surfactants, ionic/non-ionic surfactants, cationic surfactant/sodium salicylate, and zwitterionic/anionic surfactants) (Bao et al., 2021; Lutz-Bueno et al., 2016; Schubert et al., 2003; Shibaev et al., 2020; Yang, 2002).

The increase in micelle length observed after the addition of simple salts to anionic surfactant solutions is due to the screening of the electrostatic repulsions between the charged head-groups (Pandya et al., 2021; Schubert et al., 2003). Reports in the literature show that an addition of sodium chloride also has a strong impact on the length of micelles forming in mixtures of cationic and anionic surfactants (Schubert et al., 2003) or zwitterionic and anionic surfactants (Jamadagni et al., 2021; López-Díaz and Castillo, 2010; Pandya et al., 2021).

López-Díaz and Castillo (2010) analysed the effect of sodium chloride on the properties of a mixture of zwitterionic surfactant N-tetradecyl-N,N-dimethyl-3-ammonio-1-propanesulfonate and anionic surfactant sodium dodecyl sulphate (López-Díaz and Castillo, 2010). These authors showed that the effect of sodium chloride on rheological properties strongly depends on the molar ratio of surfactants in the solution. The peak relaxation time and zero shear viscosity were also observed in the case of viscoelastic solutions of anionic surfactants with the addition of simple salts (Dreiss, 2007; Parker and Fieber, 2013). Its occurrence is associated with the transition from wormlike micelles to a branched network. Jamadagni et al. (2021) analysed the effect of pH and salt on the properties of mixtures of anionic sodium dodecyl sulphate (SDS) and zwitterionic lauramidopropyl betaine (LAPB). The effect of pH on the zero viscosity of SDS/LAPB solutions in the presence of NaCl was particularly strong at a large excess of LAPB.

As previously mentioned, commercially available CAPB solutions contain significant amounts of sodium chloride. The role of this salt in the formation of viscoelastic solutions of CAPB mixtures with anionic surfactants is not fully understood. The aim of the studies presented in this paper was to determine the effects of simple salts on the rheological properties of solutions of a cocamidopropyl betaine and sodium dodecylbenzene sulfonate mixture. The studies were oriented towards determining the relationship between the molar ratio of the surfactants in the solution and the concentration of sodium chloride. In addition, based on the images taken with a polarized light microscope and CryoTEM, the observed changes in the rheological properties of the CAPB/SDBS mixture were linked to alterations in the microstructure of the solution.

2. MATERIALS AND METHODS

2.1. Materials

Zwitterionic cocamidopropyl betaine (CAPB) was purchased from PCC Exol (Poland), the commercial name is Rokamina K30, and contained 30% of active matter and a maximum 6% of NaCl. Anionic sodium dodecylbenzenesulfonate (SDBS) surfactant was purchased from Aldrich. Its average molecular weight was 348.48 g/mol. The following procedure was used to purify cocamidopropyl betaine (CAPB) from NaCl. The water was evaporated from the original CAPB product at 60 degrees Celsius and then the resulting dry mass was dissolved in chloroform. The solution thus obtained was filtered through paper to separate NaCl crystals. Chloroform was evaporated from the obtained filtrate, and then the dry mass was redissolved in water. All aqueous surfactant solutions were prepared in the same manner. First, in a small amount of distilled water, the appropriate amount of CAPB and SDBS were dissolved. A certain amount of NaCl (Chempur, Poland) was added to the CAPB solution. Thus, the prepared pre-test portions were mixed together, always by adding SDBS solution to CAPB/NaCl solution. The samples were supplemented with distilled water until the desired concentration of solutions. CAPB/SDBS solutions with different molar ratios (from 0.9 to 3.5) were used in the tests, while the total concentration of surfactants was constant and amounted to 0.151 M. Surfactant solutions were stirred at elevated temperature (50 °C) using a magnetic stirrer for 4 hours and left for 24 hours. Air bubbles in the solutions were not observed.

2.2. Rheological measurements

Rheological measurements were performed using a rotational rheometer Physica MCR 501 produced by Anton Paar (Austria) with cone-plate (cone diameter was 60 mm, the gap 0.253 mm and cone inclination angle 2°) and plate-plate geometrics (plate diameter 50 mm). The measuring device was equipped with a temperature controlling unit (Peltier plate) that provided very good temperature control over an extended period of time. Frequency sweep measurements were performed in the linear viscoelastic regime of the samples, as determined previously by the dynamic strain sweep measurements (frequency 1 Hz). All rheological tests were performed at a stabilized temperature of 20 ± 0.1 °C.

The mechanical spectra were determined in two independent tests, and the viscosity curves in three independent tests. The differences between the determined storage modulus plateau values did not exceed 4%, while the differences between zero viscosity values did not exceed 6%.

2.3. Cryo transmission electron microscopy Cryo-TEM and polarization microscopy

Cryogenic transmission electron microscopy (CryoTEM) investigations were performed with a Glacios 200kV instrument (Thermo Fisher Scientific). Before taking pictures, 5 µl of sample solution was frozen in liquid ethane using a Vitrobot Mark IV (Thermo Fisher). Then, they were applied to Quantifoil R2/2 Cu mesh 200 TEM grids. The frozen grids were imaged using an electron microscope under cryogenic conditions using EPU 2.11 single particle analysis software.

Polarisation microscopy observation was carried out on a Nikon LabopHot-2 microscope connected with the camera (Japan) at 20 °C.

3. RESULTS AND DISCUSSION

3.1. Zero shear viscosity

Figure 1a shows the viscosity curves obtained for aqueous CAPB/SDBS solutions at different component molar ratios without added salt. All the solutions are fluids characterized by a relatively low viscosity (maximum value: 0.071 Pa·s). The viscosity of the solutions increases along with rising CAPB/SDBS molar ratios in the range of 0.9 to 2.2, after which it decreases slightly. Fig. 1b shows the viscosity curves obtained for four selected CAPB/SDBS solutions in a 0.09 M NaCl solution. The addition of sodium chloride was found to induce rapid changes in the rheological properties. In CAPB/SDBS solutions with added NaCl, both the zero shear viscosity range (η_0) and the shear thinning range can be identified. Fig. 2 shows a comparison of the relationship of zero shear viscosity determined for CAPB/SDBS solutions in distilled water and with added salt (0.1 M). A relatively small amount of NaCl caused a sharp increase in zero shear viscosity by up to several orders of magnitude. Also, data in Fig. 2 show that the impact of salt on zero shear viscosity is strongly dependent on the CAPB/SDBS molar ratio.

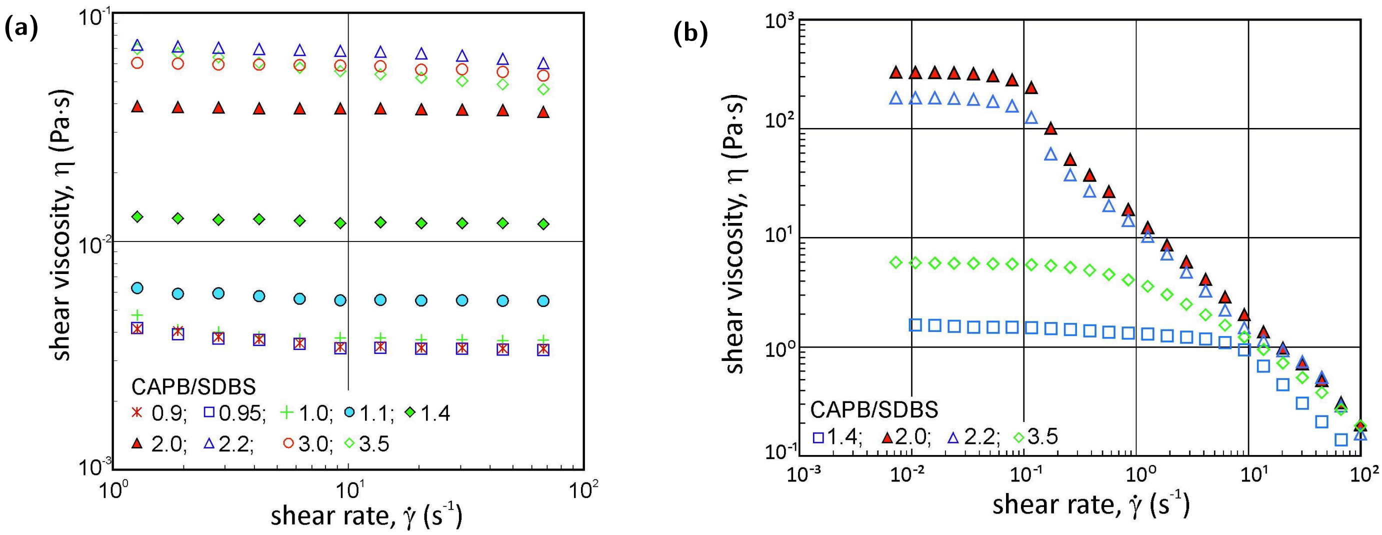

Figure 1. Viscosity curves of CAPB/SDBS solutions without salt addition (a) and with the addition of salt (NaCl concentration 0.09 M) (b).

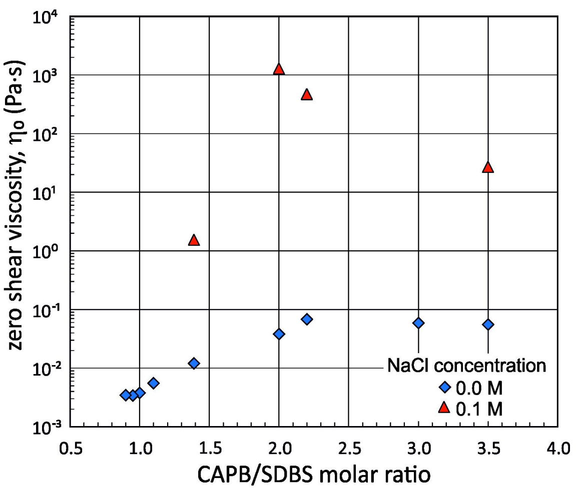

Figure 2. Dependence of zero shear viscosity on the CAPB/SDBS molar ratio for solutions in distilled water and with the addition of NaCl (0.1 M).

There is a similarity to solutions of other surfactants. Lutz-Bueno et al. (2016) showed that the concentration of the counterion in solutions of cationic surfactant/sodium salicylate mixtures also increased the zero shear viscosity, although the relative changes in η_0 were much smaller than in the case of CAPB/SDBS solutions.

The relationship between zero shear viscosity and salt concentration in CAPB/SDBS solutions with different molar ratios is illustrated in Fig. 3. All CAPB/SDBS solutions reveal a zero shear viscosity peak. The NaCl concentration at which the zero shear viscosity peak is observed ($\eta_{0,\text{max}}$) rises with increasing CAPB/SDBS molar ratios. The maximum values of zero shear viscosity are also strongly dependent on the molar ratio of the CAPB/SDBS mixture. The values of zero shear viscosity $\eta_{0,\text{max}}$ rise along with increasing molar ratios of surfactants, reaching the maximum value for the CAPB/SDBS ratio of 2.0, after which they decrease (Table 1). The data in Fig. 3 also point towards a slightly different relationship between zero shear viscosity and salt concentration in the solution with the CAPB/SDBS molar ratio of 3.5. In this case, a zero shear viscosity peak at the NaCl concentration of 0.18 M is noted as well. Nevertheless, at salt concentrations greater than 0.18 M, zero shear viscosity only slightly declines, after which it begins to rise.

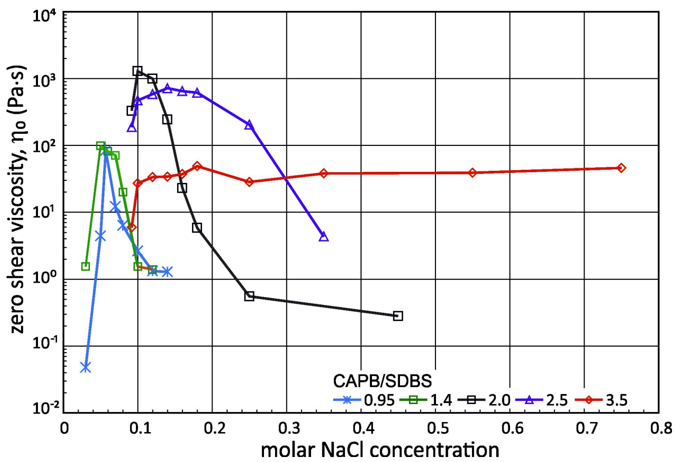

Figure 3. Dependence on the zero shear viscosity vs NaCl concentration for solutions with different CAPB/SDBS molar ratios.

The observation of the samples also reveals that at higher salt concentrations the solutions with the CAPB/SDBS molar ratios of ≤ 2.0 become turbid (photos shown in Fig. 4). The sodium chloride concentration at which turbidity is observed in the solutions increases along with rising CAPB/SDBS molar ratios. At molar ratios higher than 2.0, CAPB/SDBS solutions are clear even at very high NaCl concentrations. In addi-

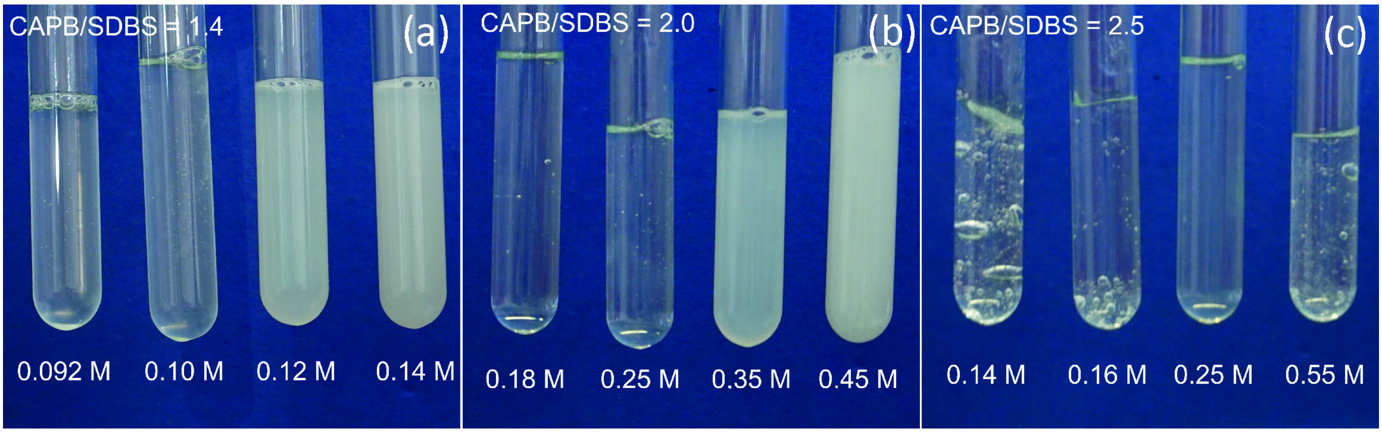

Figure 4. Influence of NaCl concentration on the image of samples of CAPB/SDBS solutions with a molar ratio of surfactants of 1.4 (a), 2.0 (b) and 2.5 (c).

tion, the salt concentration at which turbidity of the solutions was observed was found to increase with rising CAPB/SDBS molar ratios (Table 1).

Table 1. NaCl concentration at which the CAPB/SDBS solutions become cloudy.

CAPB/SDBS ratio	NaCl concentration [M]
0.95	0.08
1.4	0.12
2.0	0.35
2.5	clear
3.5	clear

3.2. Oscillatory flow

Figure 5 presents examples of mechanical spectra obtained for different molar ratios of CAPB/SDBS solutions. The curves showing the relationship of the storage modulus G' and the loss modulus G'' with the oscillation frequency ω were described with the Maxwell model:

$$G'(\omega) = G_0 \cdot \frac{\omega^2 \cdot \lambda_M^2}{1 + \omega^2 \cdot \lambda_M^2} \tag{1}$$

$$G''(\omega) = G_0 \cdot \frac{\omega \cdot \lambda_M}{1 + \omega^2 \cdot \lambda_M^2} \tag{2}$$

where: G_0 is the elastic modulus extrapolated to infinite frequency (plateau modulus), and λ_M is the Maxwell relaxation time of the system.

The comparison in Fig. 5 demonstrates that the Maxwell model can be used to describe the curves $G' = f(\omega)$ and $G'' = f(\omega)$ in CAPB/SDBS solutions with the molar ratios of 1.4 to 2.5. However, the model is not suitable for CAPB/SDBS solutions with the molar ratio of 3.5. Cates (1987) proposed a model according to which the dynamics of wormlike micelles is dependent on two relaxation times: the reptation time λ_r and the breaking time λ_b. The concept of reptation time is derived from the theory put forth by de Gennes to describe the dynamics of entangled polymers

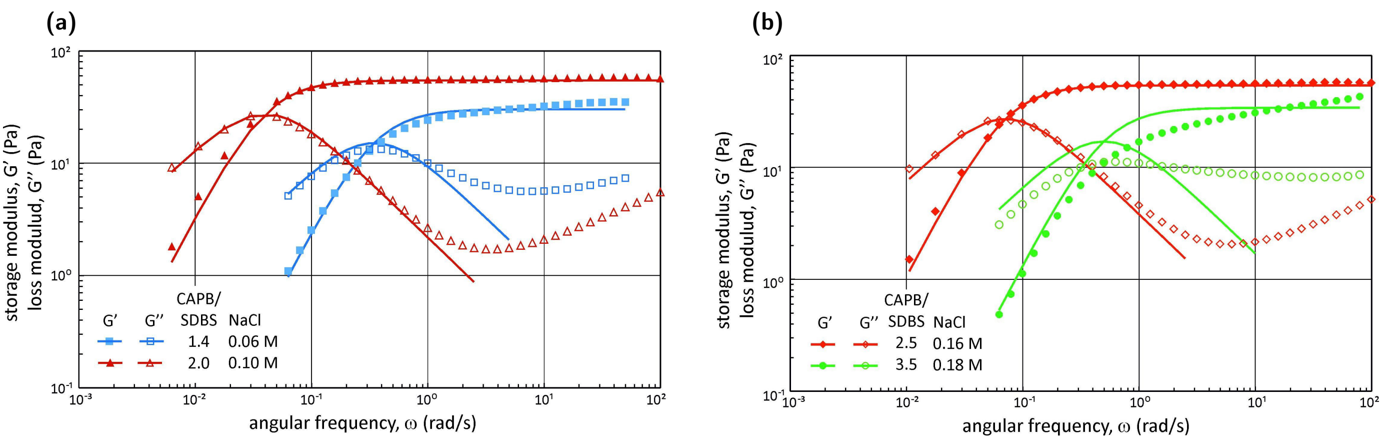

Figure 5. Exemplary mechanical spectra for solutions with different CAPB/SDBS molar ratios and NaCl concentrations (CAPB/SDBS = 1.4; CAPB/SDBS = 2.0 (a) and CAPB/SDBS = 2.5; CAPB/SDBS = 3.5 (b)).

(de Gennes, 1979). The reptation time λ_r is the time during which a wormlike micelle diffuses through a hypothetical tube formed by the entanglements from other wormlike micelles. The breaking time refers to the average time needed to break a micelle into two smaller micelles. According to the model put forth by Cates, if $\lambda_r > \lambda_b$, the description of the dynamics of wormlike surfactant solutions will be the same as in polymers (such surfactant solutions are also called "dead" polymers" (Chu et al., 2013)). Where $\lambda_r < \lambda_b$, the mechanical spectra of surfactant solutions can be described with the single-relaxation-time Maxwell model, and the relationship between the Maxwell relaxation time, the reptation time and the breaking time is accounted for by the equation:

$$\lambda_M = \sqrt{\lambda_r \cdot \lambda_b} \tag{3}$$

Single-relaxation-time Maxwell fluids include CAPB/SDBS solutions with the component molar ratios of 1.4 to 2.5. Hence, based on the Cates' model, it follows that the solutions contain wormlike micelles for which $\lambda_r < \lambda_b$. In this case, based on the experimentally determined values of the plateau storage modulus G_0, it is possible to determine the mesh size ξ of the micellar network.

$$\xi = \left(\frac{k_B T}{G_0}\right)^{1/3} \tag{4}$$

where k_B is the Boltzmann's constant and T is the temperature.

The local minimum of G'' in the high frequency region is related to the micellar contour length L according to the following relation (Granek and Cates, 1992):

$$\frac{G_0}{G''_{\min}} \approx \frac{L}{l_e} \tag{5}$$

where: l_e is the entanglement length, i.e., the contour length of the section of wormlike micelles between two entanglement points. The ratio L/l_e defines the average number of entanglements per micelle.

Table 2 summarizes the Maxwell model parameters, mean mesh sizes, and L/l_e ratios. The qualitative changes in these parameters accompanying increases in the NaCl concentration are consistent with the Maxwellian relaxation time. The reptation time and shear viscosity reach their maximum values at the same NaCl concentration. The breaking time values decrease along with increasing salt concentrations. The mesh size ξ is the largest in the solutions with the CAPB/SDBS ratio of 1.4; at the same time, these solutions were found to have the smallest L/l_e ratio. The highest values of λ_r and L/l_e were obtained for the solution with the CAPB/SDBS molar ratio of 2, which indirectly indicates that, in this case, the emerging wormlike micelles had the greatest contour length. Another characteristic feature is that increasing proportions of CAPB in the surfactant mixture are accompanied by the maximum Maxwellian relaxation time, reptation time and L/l_e ratio occurring at gradually rising

Table 2. Parameters of the Maxwell model and the micellar network for CAPB/SDBS solutions with different surfactant molar ratios.

NaCl concentration [M]	G_0 [Pa]	λ_M [s]	λ_b [s]	λ_r [s]	ξ [nm]	L/l_e	η_0 [Pa·s]
			1.4				
0.05	20.00	6.30	2.49	16.10	58.70	0.284	126.00
0.06	27.00	3.20	0.86	11.70	53.11	0.207	86.40
0.07	25.00	3.20	1.49	6.80	54.49	0.331	80.00
			2.0				
0.092	53.10	6.70	0.64	69.90	42.39	11.10	355.80
0.1	54.60	25.00	0.60	1036.10	42.00	31.70	1365.00
0.14	57.80	17.50	0.56	551.20	41.21	30.70	1011.50
0.16	51.00	5.00	0.53	47.70	42.97	8.60	255.00
0.25	49.50	0.50	0.26	1.00	43.40	3.40	24.75
			2.5				
0.092	27.80	6.30	2.42	16.60	52.60	5.60	175.10
0.1	41.00	12.60	1.84	86.70	46.21	10.00	516.60
0.14	51.50	15.90	1.01	250.20	42.83	20.40	818.90
0.16	53.90	14.10	0.53	375.60	42.18	26.20	760.00
0.25	55.70	4.00	0.35	46.00	41.72	11.10	222.80
0.35	68.00	0.10	0.02	0.10	39.04	2.40	6.80

salt concentrations. What these data show is that the effect of sodium chloride concentration on the parameters of the micellar network is closely linked to the CAPB/SDBS molar ratio.

3.3. Images of the micellar microstructure

The presence of the zero shear viscosity peak, the turbidity of the solutions, and the parameters of the micellar network obtained in oscillation tests provide evidence for changes in the micellar microstructure occurring along with increasing CAPB/SDBS molar ratios and salt concentrations. For turbid CAPB/SDBS solutions, polarized light microscopy images were obtained (Fig. 6), demonstrating that the turbidity seen in the solutions can be attributed to the formation of bilayer (vesicular or lamellar) structures. Nonetheless, observations of the samples show that structures of this type emerge at NaCl concentrations exceeding the salt levels at which the zero shear viscosity peak was observed.

The occurrence of the zero shear viscosity peak, the relaxation time peak, and the reptation time pek can be explained based on the CryoTEM images shown in Fig. 7 for a solution with the CAPB/SDBS molar ratio of 2.5 and three different salt concentrations. At a salt concentration of 0.12 M, the image presents an entangled network of wormlike micelles. An increase in salt concentration to 0.18 M induces the transition of the wormlike entangled network into the branched network. According to Lequeux (1992), the formation of the branched wormlike micellar network is responsible for the observed decrease in shear viscosity of the solution. Based on the analysis carried out by this author, the formation of branches eases the diffusion of micellar chains by sliding along the micellar contour, thereby serving as stress relaxation points. The zero shear viscosity peak caused by the transformation of the wormlike entangled network into a branched network has been observed in many other solutions of surfactant mixtures (for example, cationic/anionic surfactants (Lutz-Bueno et al., 2016), cationic surfactant/sodium salicylate (Bao et al., 2021; Shibaev et al., 2020). The image in Fig. 7c shows that at high salt concentrations (0.35 M) the branched network disintegrates, with a large number of short micelles identifiable in the images. Consequently, a marked decrease in shear viscosity in the solutions with the CAPB/SDBS ratio of 2.5 is attributable to the formation of short wormlike micelles. The image in Figure 8 also reveals a large number of short micelles emerging when the CAPB/SDBS ratio increases to 3.5. In this case, a small zero shear viscosity peak is seen, following which shear viscosity stabilizes at a constant level. As mentioned above, the

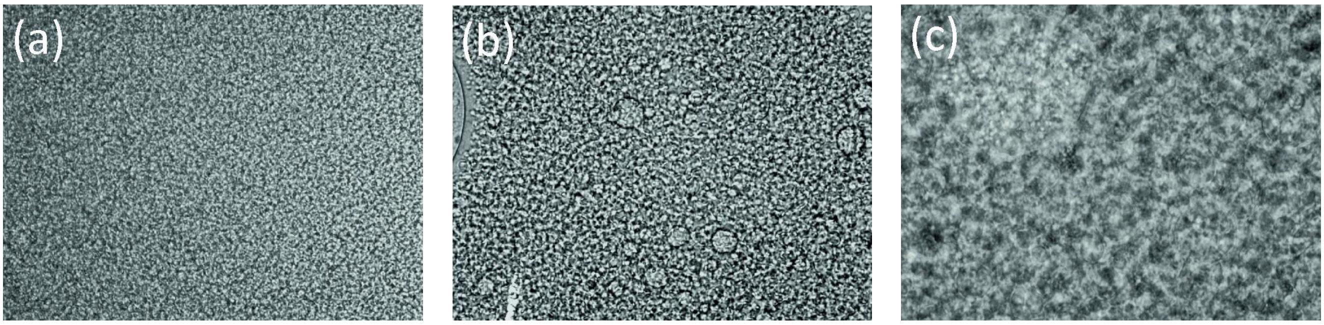

Figure 6. Polarizing microscope images for CAPB/SDBS solutions with molar ratios: (a) 0.95 (0.18 M NaCl), (b) 1.39 (0.35 M NaCl), (c) 2.0 (0.35 M NaCl).

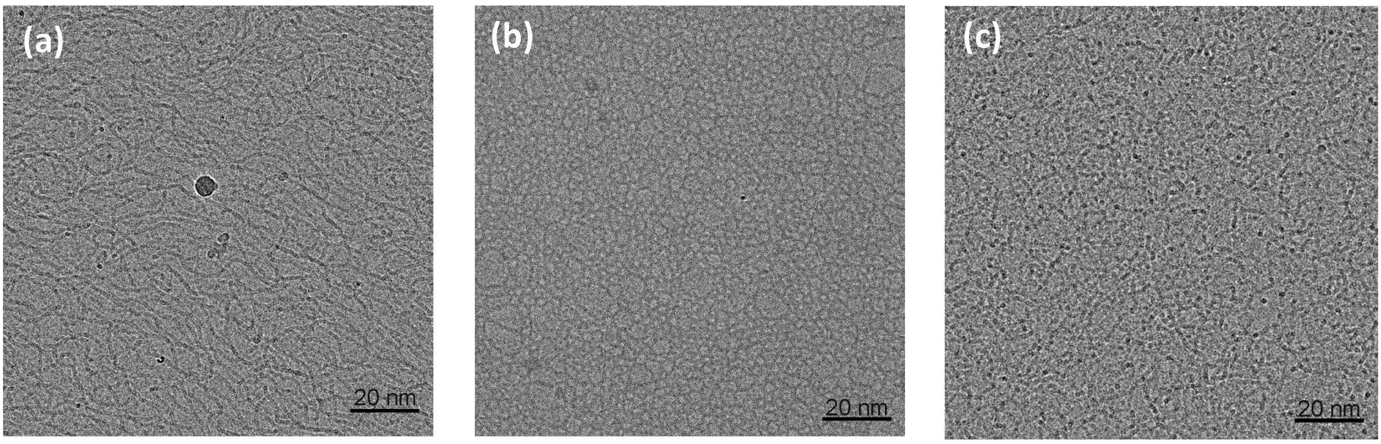

Figure 7. CryoTEM images for solutions with a molar ratio of CAPB/SDBS = 2.5 and a salt concentration of 0.12 M (a), 0.18 M (b) and 0.35 M (c).

mechanical spectra obtained for the CAPB/SDBS = 3.5 solutions cannot be described using Maxwell single-relaxation-time, which may indicate that, in this instance, the reptation time is either comparable to or greater than the breaking time. This explanation is aligned with the reptation model proposed by de Gennes (1979), who postulated a relationship between the reptation time and the length of the polymer chains.

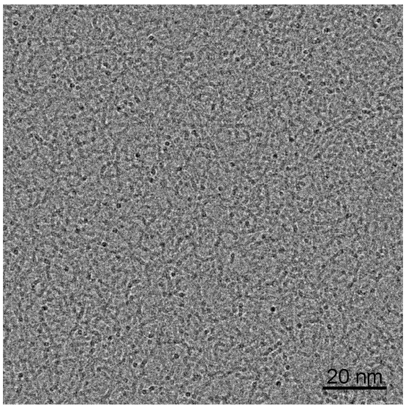

Figure 8. CryoTEM photo for a solution with a CAPB/SDBS ratio = 3.5 and a salt concentration of 0.35 M.

3.4. Mechanisms

According to Israelachvili et al. (1976), the relationship between the shape of the surfactant molecule and the type of micelles that will be formed in a solution can be determined by the so-called packing parameter p (Fig. 9):

$$p = \frac{V}{A_S L_S} \tag{6}$$

where: V – volume of the hydrophobic tail, A_S – the effective surface area occupied by the polar head on the micelle surface, L_S – length of the hydrophobic tail, defined as the maximum length of the stretched chain. If $p < 1/3$, spherical micelles will form in the solution, for $1/3 < p < 1/2$ wormlike micelles, $1/2 < p < 1$ vesicle micelles, $p \approx 1$ flat lamellar structure and $p > 1$ reverse micelles.

The effective surface area A_S may change through interactions between adjacent molecules or the addition of salt (Bao et al., 2021; Shibaev et al., 2020). Fig. 9 shows a schematic representation of the proposed mechanism underlying the interactions between sodium ions and CAPB/SDBS mixed micelles (a model of mixed micelles can be found in Różańska and Różański (2019)).

In micelles of this type, the value of the p parameter correlates with the relationship between the electrostatic attraction of part of the positively charged CAPB head and the negatively charged SDBS head, and the electrostatic repulsion between the negatively charged parts of the CAPB head. Introducing sodium ions into solutions screens the negatively charged part of the CAPB head, which reduces the effective surface area A_S, causing an increase in the p parameter and extending the length of micelles. In the case of small CAPB/SDBS molar ratios, sodium ions are able to penetrate the area between the negative parts of the CAPB

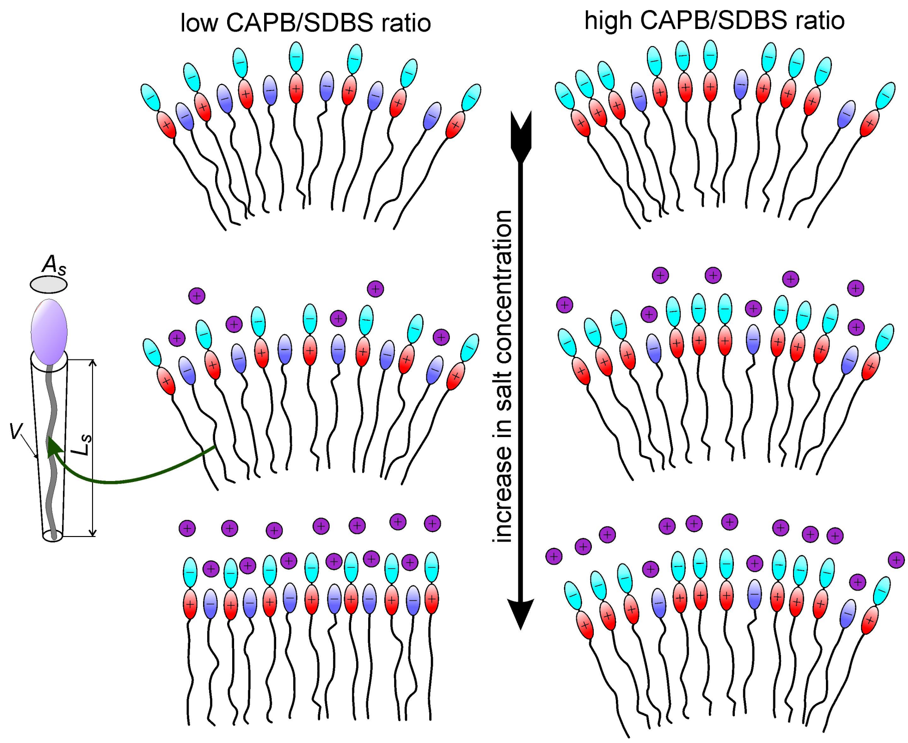

Figure 9. Proposed mechanism of NaCl influence on the shape of micelles formed in CAPB/NaCl solutions.

heads, which improves the effectiveness of screening and increases the p parameter even at low salt concentrations. The increase in the value of the p parameter along with increasing salt concentrations is responsible for the change in the shape of the resulting micelles. Above $p = 1/2$, long wormlike micelles are formed, which first develop into branched wormlike micelles, and when $p = 1$, further transform into bilayer structures. In cases involving high CAPB/SDBS molar ratios, the screening of negative charges on the micelle surface is mainly due to the adsorption of sodium ions in the Stern layer. In this case, the possible changes in the effective surface area A_S, and hence the parameter p, are considerably smaller. As a result, the CAPB/SDBS = 3.5 solution exhibits a relatively minor increase in viscosity accompanying a rise in the NaCl concentration, following which viscosity stabilizes at a constant level. In this instance, no turbidity was observed in the solutions even at very high NaCl concentrations, which may indicate that no bilayer structures were formed.

4. CONCLUSIONS

The rheological studies conducted for the purpose of this paper in continuous and oscillatory flows provide evidence that obtaining viscoelastic CAPB/SDBS solutions requires the presence of sodium ions in the solution. In solutions containing a CAPB/SDBS mixture with a low molar ratio, sodium chloride present in CAPB available commercially for technical applications (i.e. at concentrations ranging from 2% to 6%) is sufficient for the formation of a spatial micellar network. On the other hand, in solutions containing an excess of CAPB relative to SDBS, the formation of a micellar network is possible at relatively high salt concentrations. Appropriate adjustment of the CAPB/SDBS molar ratio and salt concentration may result in fluids containing either wormlike micelles, branched wormlike micelles or bilayer structures. In this way, it is possible to obtain fluids with diverse viscoelastic properties without having to modify the total surfactant concentration in the solution. The observed changes in the rheological properties of CAPB/SDBS solutions can be explained through reference to the packing parameter proposed by Israelachvili et al. (1976). At low CAPB/SDBS molar ratios, it is possible to screen the negative parts of the hydrophilic CAPB head with a greater amount of Na^+ ions compared to solutions containing a significant excess of CAPB. Screening of the negative charge in the CAPB molecule induces changes in the effective area occupied by the polar head on the surface of the micelles and, consequently, leads to changes in the value of the p parameter and the shape of the micelles. In summary, the results of research on the properties of viscoelastic solutions of mixtures of anionic and zwitterionic surfactants presented in the paper may be useful in the development of household chemistry products and cosmetics.

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SYMBOLS

A_S the effective surface area occupied by the polar head on the micelle surface, nm^2
G_0 plateau modulus, Pa
G' storage modulus, Pa
G'' loss modulus, Pa
L micellar contour length, nm
L_S length of the hydrophobic tail, nm
T temperature, K
V volume of the hydrophobic tail, nm^3
k_B Boltzmann constant, J/K
l_e entanglement length, nm
p packing parameter

Greek symbols

$\dot{\gamma}$ shear rate, s^{-1}
η shear viscosity, Pa·s
η_0 zero shear viscosity, Pa·s
λ_b breaking time, s
λ_M Maxwell relaxation time, s
λ_r reptation time, s
ξ mesh size, nm
ω angular frequency, rad/s

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