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Influence of Electrolyte on Interfacial and Rheological Properties and Shear Stability of Highly Concentrated W/O Emulsions[1]

K. Kovalchuk[a], I. Masalova[a], and A. Ya. Malkin[b]

[a] *Material Science and Technology Group, Engineering Faculty, Cape Peninsula University of Technology (CPUT), Cape Town, P.O. Box 8000, Republic of South Africa*

[b] *Russian Academy of Sciences, Institute of Petrochemical Synthesis, Moscow, 119991 Russia*

e-mail: masalovai@cput.ac.za, alex_malkin@mig.phys.msu.ru

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Abstract—The effect of the electrolyte concentration on the interfacial interactions, rheological properties and emulsion shear stability was investigated. The increase of the electrolyte concentration leads to the growth of storage modulus and the yield stress of emulsions and enhances the emulsion stability to shearing, while interfacial tension decreases. The observed effects were attributed to the interfacial interaction of a surfactant and an electrolyte that was confirmed by the IR-analysis. The interaction between an electrolyte and a surfactant provides a stable interface.

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1. INTRODUCTION

Highly concentrated emulsion (HCE) is a mixture of two incompatible liquids, with volume concentration of the dispersed phase exceeding the limit of the closest packing of spherical droplets, φ*. This limit is equal to app. 0.74 for monodisperse droplets and is somewhat higher for polydisperse particles. The packing above this limit is possible due to the compression of spherical droplets and their transformation into polyhedrons. The wide interest to HCE is dictated by both, their practical importance and fundamental problems of the physics of these systems. The physical nature of HCE was examined in several fundamental publications [1–3]. The general concept of these studies was based on treating the osmotic pressure as the driving force of the droplet compression. This force is balanced by the excess surface energy stored due to the increase of the surface area in the droplet transformation from spheres to polyhedrons. The formation of such structure leads to the solid-like behaviour of HCE in the low stress domain. This solid-like behaviour is demonstrated as the frequency independence of storage (elastic) modulus in a wide frequency range [4–8] at small amplitudes. As a consequence of this conception, a possibility of scaling of elastic modulus by Laplace pressure exists.

HCE are non-linear visco-plastic media with clearly expressed yield stress [3, 7, 9–11]. Also, the non-linear behaviour of HCE was experimentally observed in measuring a flow curve at shear stresses beyond the yield stress threshold [7, 8, 12–15] or measuring elastic modulus as a function of amplitude of deformations in large-amplitude oscillation sweep [8, 12, 16, 17].

The objects of this work are highly concentrated water-in-oil emulsions, containing the oversaturated ammonium nitrate (AN) solution as an aqueous phase. Besides the usual origin of instability, these emulsions can lose their applied properties due to the crystallization of the dispersed phase.

One of the important components of an emulsion is an electrolyte, which is possibly not an inert part of a system but an active agent interacting with a surfactant and therefore influencing the character and properties of the interfacial layer.

The effect of an electrolyte on emulsion properties was described in several publications. The increase in rheological properties [18–20] and improvement of physical emulsion (HCE) stability [18, 21–23] were reported. These investigations were carried out with the use of low molecular weight, polymeric surfactant and proteins. The variety of electrolytes used in these studies was not very wide (KCl, K_2SO_4, $MgCl_2$, $MgSO_4$, $AlCl_3$). The data concerning the influence of the electrolyte concentration on the interfacial tension are contradictory: some authors reported about the decrease [18, 21] of the interfacial tension with electrolyte addition while others observed rising interfacial tension [19]. However, it should be mentioned that different surfactants were used for emulsion stabilization.

It is known that the family of the poly(isobutylene) succinic anhydride (Pibsa) derivatives can be used as effective surfactants for stabilization of liquid explosives which are HCE of the W/O type [21]. Several publications were devoted to the investigation of their

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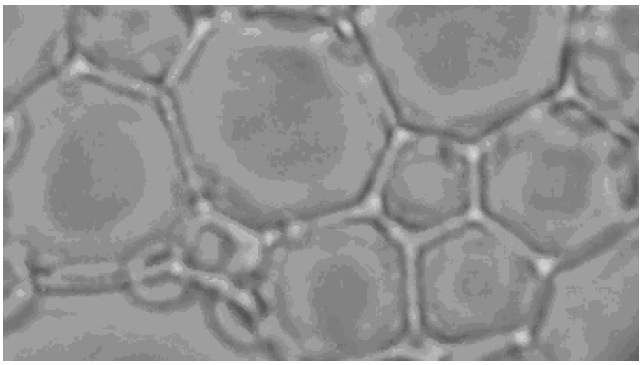

Fig. 1. Microscopic image depicting the emulsion with the average droplet size 8 μm (×500).

monolayers [24, 25] and their interactions with the aqueous phase (AN solution) [21, 26–28] but the electrolyte effect was not understood.

This work is devoted to the investigation of the effect of the electrolyte concentration on interfacial and rheological properties of HCE. The aim of the present study is to look closely at the structure and interaction at the interface. This will enable better understanding of factors governing the behaviour of emulsions of this type.

2. MATERIALS AND METHODS

Materials

The objects of this work were HCE used as "liquid explosives". They are emulsions of the water-in-oil type. One can find the details of the composition of these emulsions in earlier publications [6, 10, 29]. In short, the concentration of the disperse phase is 90–96 wt %. This phase in the standard technological recipes is a super-cooled aqueous solution of AN. Water comprises < 20% by mass of this phase. So, the salt concentration φ exceeds 80%.

A typical view of compressed droplets forming the internal aqueous phase is shown in Fig. 1. It is evident that the droplets really have a polyhedron shape. The equilibrium temperature of dissolving for such concentration is app. 65°C. For the preparation of these super-cooled solutions, the granulated AN was added to the distillate water at a temperature of 80°C.

Experiments were performed at room temperature. It means that an aqueous phase is a super-cooled (over-saturated) solution. These solutions are thermodynamically unstable but kinetically they do not change over several weeks. This means that it is possible to perform different experiments with these materials, treating them as quasi-stable.

The size of dispersed particles is spread in the range from 2 to app. 40 μm. The upper boundary of sizes is determined by the requirement of the kinetic stability of super-cooled solutions. It was proven [10] that only smaller droplets can be kinetically stable during necessary time.

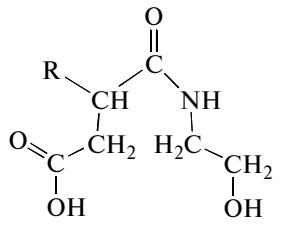

Fig. 2. Chemical structure of Pibsa-MEA surfactant head group (R—polyisobutylene).

The oil phase is a solution of a surfactant in hydrocarbon oil. Mosspar-H oil (produced and supplied by Lake International Technologies, Republic of South Africa) was used for the emulsion preparation. This oil comprises mainly *iso*-paraffins (80–90%, where *n*-paraffins and cycloparaffins constitute a part of 10–15%) and aromatics (< 0.1%). Oil density is 792 kg/m^3 at 20°C.

The surfactant used in preparing emulsions was based on organic derivatives of polyisobutylene succinic anhydride (acronym is Pibsa), especially on alkanolamine derivatives. The following material was used. Pibsa-MEA is Pibsa of molecular weight 1048, reacted approx. 1 : 1 with monoethanolamine to an uncondensed amide/acid head group. The tail group is polyisobutylene. Molecular weight of 1048 corresponds to 19 repeat units in the chain. The hydrophilic-lipophile balance of surfactant is low (between 2 and 4). The structure of the Pibsa-MEA surfactant head group is shown in Fig. 2.

Emulsions with different concentrations of AN in the aqueous phase were used to investigate the effect of the salt concentration on properties of emulsions.

2.2. Methods

2.2.1. FT-IR analysis. The FT-IR studies were conducted with use of a Perkin Elmer Spectrum 100 FT-IR Spectrometer. The spectra of the emulsions and solutions were recorded at room temperature using Attenuated Total Reflectance (ATR) accessory. The ATR cell was equipped with a Germanium (Ge) crystal. The range of measurements was from 4000 to 500 cm^{-1}. The wavelength accuracy is 0.1 cm^{-1} at resolution 4 cm^{-1}. A thin film of each sample was put directly on the Ge crystal for measurement. No other sample preparation was used. Experiments were performed in the temperature range 25–30°C.

2.2.2. The measurements of interfacial tension. Interfacial tension between the oil phase with the surfactant and aqueous phases with the AN was measured with the use of Krüss K100 tensiometer (Germany). The principle of operation of the K100 is straightforward. About 15 cm^3 AN solution is placed in a clean

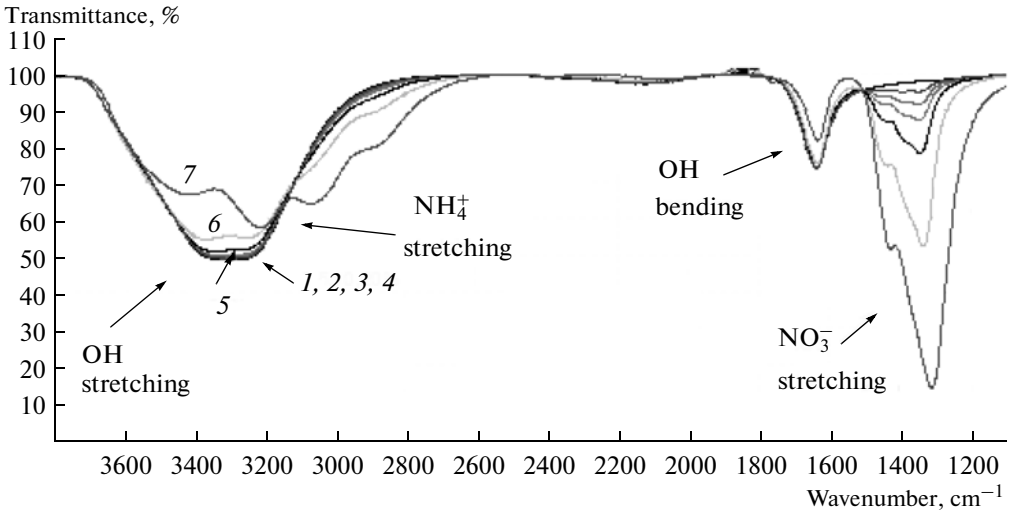

Fig. 3. FT-IR spectra of aqueous solutions with different AN concentrations: *1*—0, *3*—10, *4*—20, *5*—30, *6*—40, *7*—60%.

70 mm diameter glass dish. A hydrophilic platinum (Wilhelmy) plate is suspended vertically from a sensitive force transducer with its lower edge penetrating the surface of the AN solution. About 50 cm^3 of the oil phase is added, so that the plate is wholly submerged. The interfacial tension is given by following equation:

$$\gamma = F/L\cos\theta, \quad (1)$$

where F [mN] is the vertical force acting on the plate, after a correction has been made for the plate buoyancy, L[m] is the wetted plate length, θ is the contact angle. Since the plate is hydrophilic, the contact angle is taken as zero.

2.2.3. Emulsion preparation. The Hobart N50 mixer was used to manufacture the samples under study. The hot (80°C) AN solution was slowly added to the oil phase at low mixing speed. After the emulsion was formed the samples with different droplet sizes were taken at different mixing times.

2.2.4. Rheological analysis. All rheological studies were made with a rotational stress rheometer MCR 300 (Paar Physica). The geometry of the measuring unit was plate-and-plate with a sandblasted surface (the plate diameter was 50 mm). The experiments were made in the following regimes of deformation:

• Oscillatory measurements for measuring the strain amplitude dependencies of the (storage and loss) components of dynamic modules; the frequency (1 Hz) was kept constant in the amplitude sweep test. Strain was controlled between 0.01 and 200%.

• Steady state flow measuring flow curves (shear stress versus shear rate).

Experiments were performed in the temperature range 25–30°C.

2.2.5. Droplet size measurements. Measuring the size of dispersed particles was carried out with the Mastersizer-2000 device (Malvern Instruments Co). The measurement procedure is based on sample dispersion under software control and the measurement of angle dependence of the intensity of scattering of a collimated He-Ne laser beam. Particle size in the range from 0.26 to 1500 μm can be measured; this range is much wider than sizes of the real samples used in this work. The size distribution calculations are based on the rigorous Mie theory and using the standard software applied to the instrument. Each emulsion sample (a small quantity of the sample was taken) was dispersed in the large volume of oil to reach a very diluted concentration of water droplets in oil and to avoid agglomerates formation. The average value D_{32} was used as a measure of droplet size in the investigation.

Table 1. The variation of IR frequencies with the AN concentration in solution

C, %	ν(N–H), cm^{-1}	ν(N–O), cm^{-1}
0	–	–
5	–	1348
10	–	1347
20	–	1347
30	3273	1344
40	3241	1335
60	3207	1311

3. RESULTS AND DISCUSSION

3.1. FTIR analysis

The effect of salt content on the structure of solutions was investigated by IR spectroscopy. The results are present in Table 1.

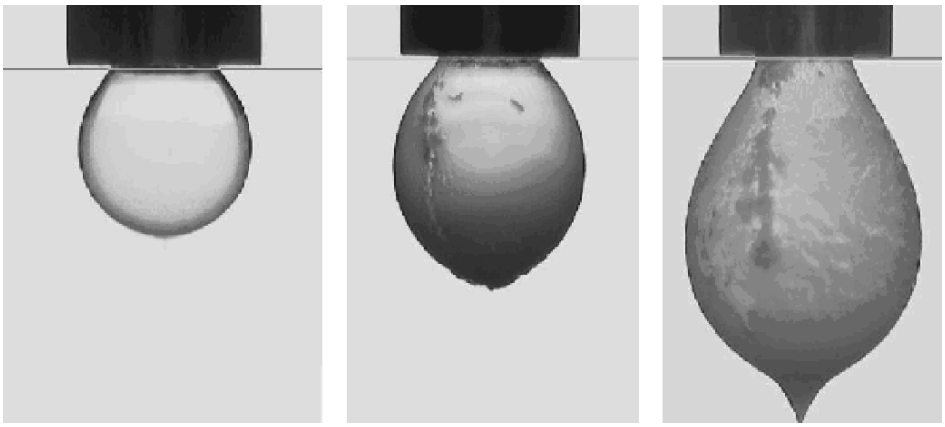

Fig. 4. Interfacial film growth without AN salt in an aqueous phase: *1*—after 30 min, *2*—7, *3*—19 h.

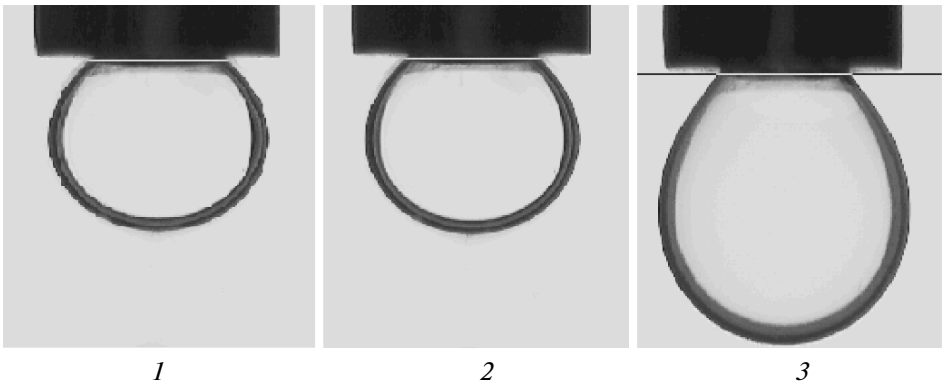

Fig. 5. Water-oil interface in presence of AN salt (5%) in an aqueous phase at different time: *1*—initial moment, *2*—after 10, *3*—20 h.

The intensity of the nitrate ion peak increases with increasing AN concentration. The peak in range from 3300 to 3200 cm^{-1} which assigned to NH covalent bond in ammonium ion begins to appear (can be distinguished and separated from OH stretching vibration peak in water molecule) at the salt concentration equal to 30% and shifts to the lower frequency value as well as NO stretching vibration peak (the values are given in Table 1). The spectra are shown in Fig. 3. The shift becomes more significant at 30% AN concentration followed by 40 and 60%. This effect can probably arise from more intensive interactions between NH_4^+ and NO_3^- ions when increasing their concentration in water. The strong evidences for direct cation-anion contacts at high AN concentration in an aqueous phase were reported in the literature: decrease in the coordination number forming a weakly defined hydration shell around the ammonium ion [30, 31] and hydration shell moves closer to the ammonium ion at higher AN concentration [30]. These support the obtained results.

The effect of AN concentration on the IR-spectra of emulsions was observed. It is important to mention that the effect of the salt on the stability of the interface was clearly observed even to the naked eye. This forced us to carry out more detailed investigation of the samples.

As the images (Figs. 4, 5) demonstrate, the ruff film starts to grow at the interface of the droplet after 30 min (Fig. 4) and continues to develop during the next 19 hours at least. The origin of this interfacial film is probably the surfactant coming out of solution or spontaneous emulsification (formation of micro droplets at the oil/water boundary) [18]. A similar film appears when the interface is formed away from the tensiometer in a small vial. Figure 5 shows very clear interface in the presence of electrolyte in the aqueous phase. The formation of a bright and shiny interface was also observed in [18] when the electrolyte is incorporated in the aqueous phase. This observation raises the possibility that AN salt stabilises the W/O interface due to the interaction with a surfactant [21, 26–28]. One of the interesting suggestions about the interac-

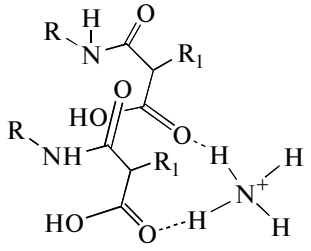

Fig. 6. Possible hydrogen bonds formation between two molecules of Pibsa-MEA head group and NH_4^+ ion ($R–CH_2–CH_2–OH$, R_1 —polyisobutylene).

tion between a surfactant and ammonium ion was advanced in [27]. The authors assumed that NH_4^+ and NO_3^- participate as the bridging component between the head groups. Based on this assumption we tried to express it schematically (Fig. 6).

We suppose that these interactions are quite possible and even the formation of a persistent membrane (uninterrupted monolayer), since the ions in such super concentrated solution (melt) are very close to each other due to the lack of water molecules and increased ion-ion interactions as discussed above. Moreover, the NH bond in AN was found to be sensitive to the AN concentration. Obtained results are given in Table 2.

From the above experimental data it is clear that along with the increasing AN concentration, the NH peak shifts to the lower frequency value in the emulsion state as well as in the solution state but a much stronger effect is observed in the case of an emulsion. If a pure solution is considered, the observed effect is related to the increased ion-ion interactions (as discussed above). But if an emulsion is considered, the larger shift can be attributed to the stronger surfactant-electrolyte interactions with increasing AN content.

It is obvious that the presence of AN in the aqueous phase of an emulsion results in the interaction of Pibsa-MEA polar head group with AN due to the formation of hydrogen bonds and possible salt complex formation with the ammonium nitrate ions. Moreover, the changes in surfactant molecular conformation owing to the modification of the head groups and

Table 2. The variation of IR frequencies with AN concentrations

C, %	ν(N–H) in emulsion, cm^{-1}	ν(N–H) in solution, cm^{-1}	ν(N–H) shift, cm^{-1}
30	3264	3273	9
40	3226	3241	15

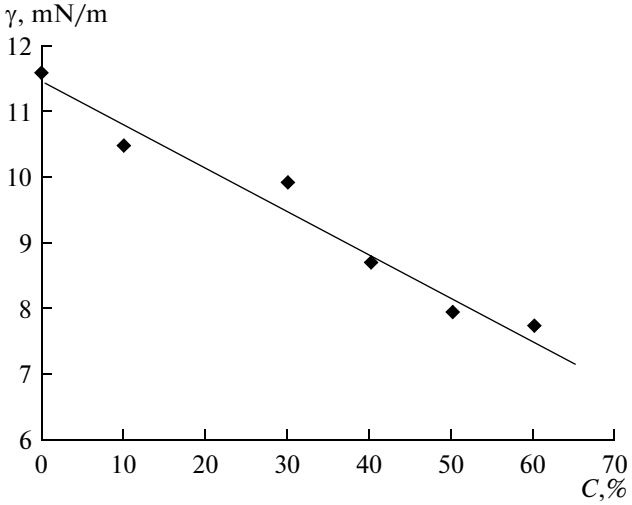

Fig. 7. Dependence of the interfacial tension of Pibsa-MEA surfactant (8 wt % in oil phase) at the W/O interface on the electrolyte concentration in the aqueous phase.

increased association of the salt ions or ion pairs with the head groups can influence the packing of acyl chains at the interface: due to electrostatic interactions between the head groups [26, 27] and due to the hydrogen bonding network [32]. Furthermore, the increasing of ions association around the head groups leads to their dehydration and increased lateral interactions between the surfactant chains [19]. Based on the above discussion, we assume that the orientation of adsorbed surfactant molecules at the interface depends on the strength of surfactant-electrolyte interactions and therefore on the electrolyte concentration in the aqueous phase. It is reasonable to assume that the increase in the AN concentration leads to the more stable and structured interface due to the hydrogen bonding network and electrostatic interactions between the head groups.

3.2. Interfacial Tension Measurements

The effect of AN concentration *c* on the interfacial tension was observed. The results are shown in Fig. 7. The linear decrease of interfacial tension with the increase in salt concentration in the aqueous phase can probably be attributed to the different packing behaviour of surfactant at the interface due to interactions of the Pibsa-MEA surfactant head group with the matter of a drop since no extra adsorption of the surfactant was found at the interface with increasing AN concentration in the aqueous phase (Fig. 8). From Fig. 8 one can see that the slope $d\gamma/d\ln c$ (*c* is the concentration of surfactant) for both AN concentrations is the same. This reflects about the same surfactant adsorption at the interface at both used AN concentrations.

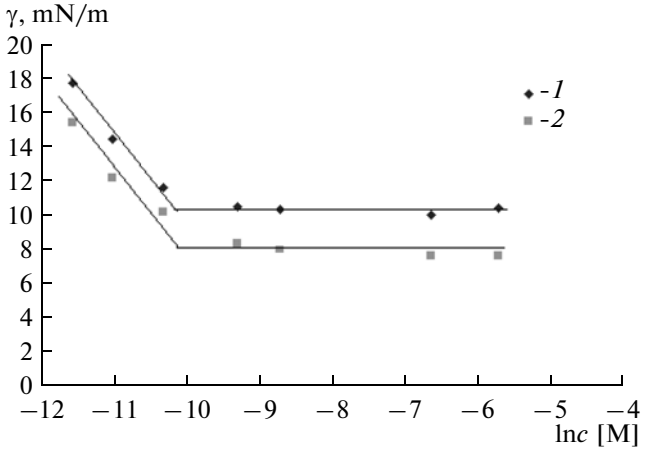

Fig. 8. Dependence of interfacial tension on surfactant concentration for systems with 10 (*1*) and 60% (*2*) of AN in aqueous phase.

The decrease in interfacial tension shown in Fig. 7 might also be influenced by the changes in structure of AN solution at the interface.

3.3. Emulsification

The evolution of droplet burst during the emulsification process was followed by taking samples from the evolving emulsion at different processing times, and analysing their size distribution.

All the emulsions were mixed for a long time to reach the limiting diameter value (D_{lim}); this is a minimal value of the size that does not change regardless of how long further deformation continues. Typical experimental results of droplet size evolution for emulsions with different AN content in aqueous phase are shown in Fig. 9.

As illustrated in Fig. 9, the droplet break-up is fast during the first 15 min. The droplet size reaches the limiting constant value D_{lim} after app. 40 min of mixing. The evolution of the average size in time fits the following equation:

$$D(t) = D_{lim} + e^{-(t/\theta)}(D_0 - D_{lim}), \qquad (2)$$

where, $D(t)$ are experimental values of D_{32}; D_0 is the initial droplet size; D_{lim} is the limiting D value and θ is the characteristic time of the emulsification process.

From Fig. 9 and Table 3 it is seen that the increase in the AN concentration in the aqueous phase leads to higher D_{lim} values and longer characteristic time. Meanwhile, it is clearly seen that, generally speaking, the increase of the AN concentration results in more shear stable emulsions. However, all curves can be separated into two groups: emulsions with low AN concentration in aqueous phase (0–30%) and emulsions with high AN concentration in the aqueous phase (40–80%). This pronounced difference between 30 and 40% AN solutions can probably be attributed to the structural changes of AN solution.

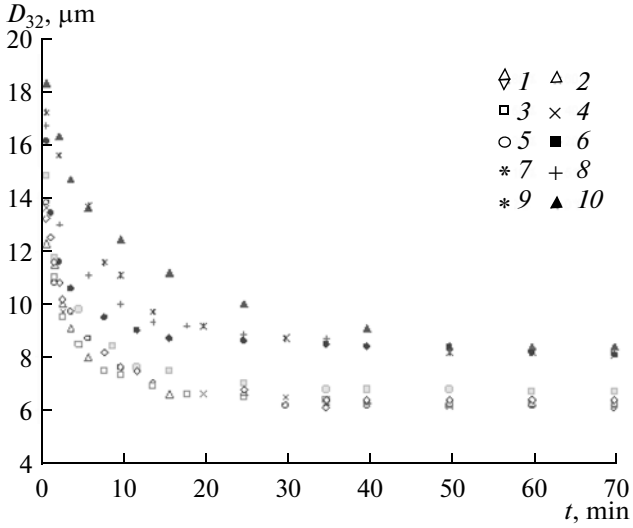

Fig. 9. Droplet size as a function of mixing time for emulsion with different concentration of AN in aqueous phase: *2*—2, *3*—5, *4*—10, *5*—20, *6*—30, *7*—40, *8*—50, *9*— 60, *10*—80%).

3.4. Rheological Investigation

Samples with the same droplet sizes (8 μm) were chosen for the rheological investigation in order to

Table 3. Limiting diameter of emulsion droplets contained different AN concentrations

AN concentration, %	D_0, μm	D_{lim}, μm	θ, min
0	14.8	6.4	4.2
2	14.0	6.3	4.3
5	14.0	6.3	4.5
10	14.5	6.3	4.5
20	14.5	6.3	5
30	15.5	6.8	5.1
40	15.7	8.2	5.1
50	16.0	8.2	7.5
60	17.8	8.2	8.5
80	18.0	8.4	12.8

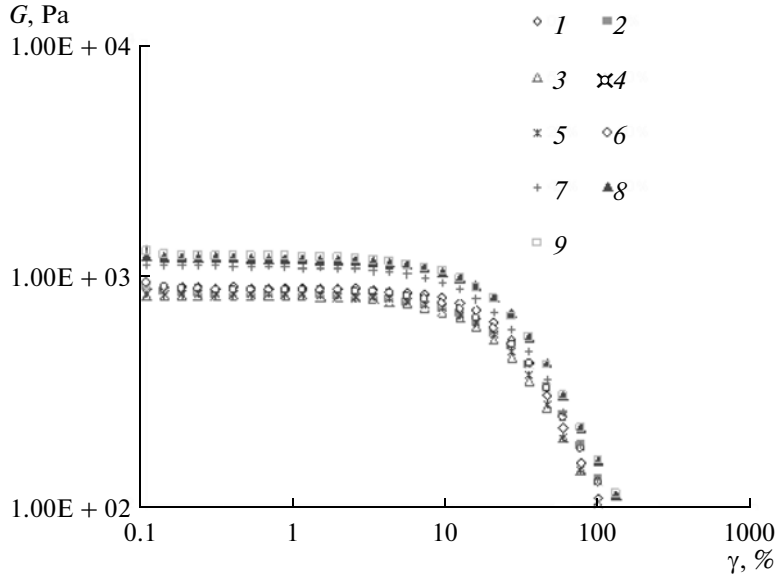

Fig. 10. Amplitude dependence of storage modulus for emulsions with different AN concentration: *1*—0, *2*—2, *3*—5, *4*—10, *5*—20, *6*—30, *7*—40, *8*—50, *9*—60%. $D_{32} = 8$ μm.

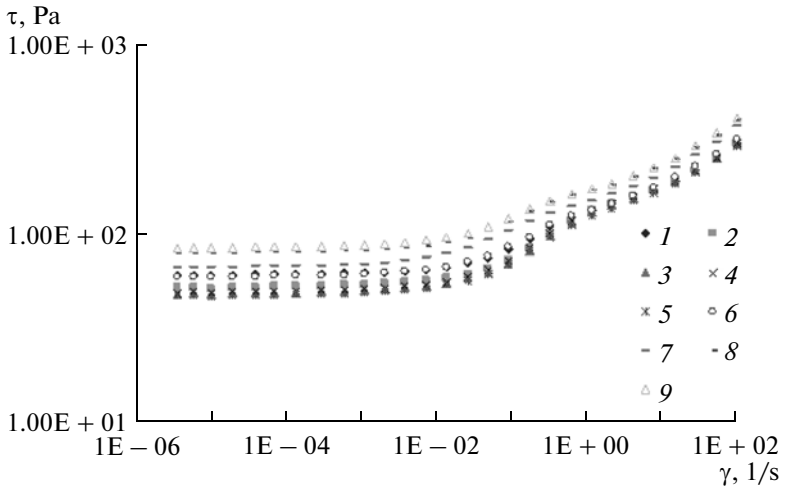

Fig. 11. Flow curves of emulsions with different AN concentration: *1*—0, *2*—2, *3*—5, *4*—10, *5*—20, *6*—30, *7*—40, *8*—50, *9*—60%. $D_{32} = 8$ μm.

exclude the effect of the droplet size and to separate the role of the AN in an aqueous phase. The main results of these studies are presented as the amplitude dependence of storage modules (Fig. 10) and flow curves (Fig. 11) for emulsions with different concentration of the AN in the internal phase droplets. The initial parts of flow curves—constant values of stress—give the yield stress values, τ_Y.

Figures 10 and 11 demonstrate that the storage modulus as well as the yield stress significantly increases along with the salt concentration, though the more pronounced effect is observed between 30 and 40% AN content. These results are in accordance with the structural changes at the interface as described above. Indeed, it was found that ion-ion interactions begin to dominate in the aqueous phase at high AN concentration [30] that probably results in a more shear-resistant microstructure of the material.

It is worth stressing that the elastic modulus as well as the yield stress have an opposite trend compared to the interfacial tension as a function of the AN concentration. This implies an important conclusion that it is not the interfacial tension that is responsible for the rise of the storage modulus and yield stress and cannot

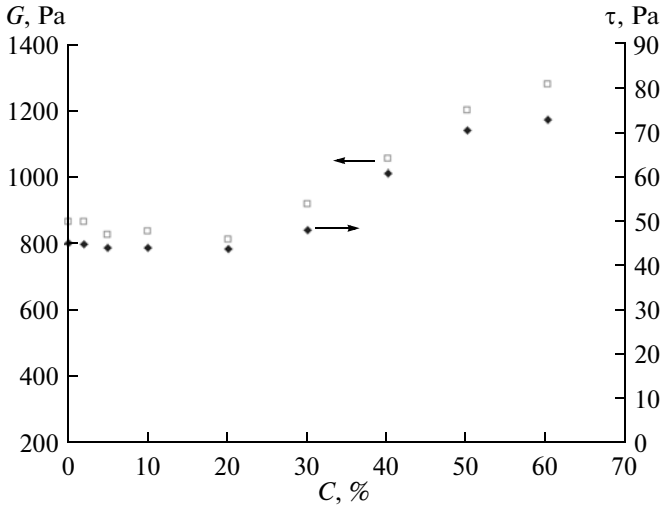

Fig. 12. Storage modulus G and yield stress τ as functions of AN concentration in the aqueous phase.

explain the experimental results presented in Fig. 12. It means that the additional sources of elasticity have to be taken into account as was discussed in [33]. It is reasonable to suppose that the electrolyte effect influencing the surfactant-electrolyte interactions and droplet-droplet interactions should be treated as this additional source of elasticity. The droplet interface becomes more stable and presumably rigid, which probably makes shearing more difficult due to interaction of salt with the surfactant head group. Similar observations were made in publications [19, 20]. In discussing the influence of electrolyte on shear stability of emulsions, it is necessary to take into account the effect of the double electrical layer, because electrostatic (Coulomb) forces are more long-distance acting. This seems especially important for highly-concentrated emulsions because the inter-droplet gap between neighbouring droplets is rather narrow.

The increase in the AN concentration results in the compression of the double electrical layer. Thus, this is the only force adding to the Laplace pressure, thereby increasing the stability of droplets. The role of electrostatic forces was also mentioned in [21, 34], though it is rather difficult to give the quantitative estimation of this effect.

4. CONCLUSIONS

The systematic experimental investigations of the role of the electrolyte in an aqueous phase in the W/O highly concentrated emulsions showed that the increase of the electrolyte concentration leads to the decrease of the interfacial tension but to the increase of shear stability of emulsions as well as to the increase of elastic modulus and the yield stress of emulsions. The IR-studies demonstrated the existence of the interaction between the hydrophilic end groups of a surfactant and an electrolyte. The strength of surfactant-electrolyte interactions increases with the addition of an electrolyte to the aqueous phase. The most pronounced changes in the effect of the electrolyte concentration occur in the range from 30 to 40% of the salt in an aqueous phase.

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REFERENCES

1. Princen, H.N., *Langmuir*, 1986, vol. 2, p. 519.
2. Mason, T.G., Lacasse, M.-D., Grest, G.S., et al., *Phys. Rev. E: Stat. Phys., Plasmas, Fluids, Relat. Interdiscip. Top.*, 1997, vol. 56, p. 3150.
3. Mason, T.G., *Curr. Opin. Colloid Interface Sci.*, 1999, vol. 4, p. 231.
4. Pons, R., Erra, P., Solans, C., et al., *J. Phys. Chem.*, 1992, vol. 97, p. 2320.
5. Langenfeld, A., Schmitt, V., and Stebe, M.-J., *J. Colloid Interface Sci.*, 1999, vol. 218, p. 522.
6. Malkin, A.Ya., Masalova, I., Slatter, P., and Wilson, K., *Rheol. Acta*, 2004, vol. 43, p. 584.
7. Masalova, I., Taylor, M., Kharatiyan, E., and Malkin, A.Ya., *J. Rheol.* (N. Y.), 2005, vol. 49, p. 839.
8. Masalova, I. and Malkin, A.Ya., *Colloid J.*, 2007, vol. 69, p. 185.
9. Princen, H.M. and Kiss, A.D., *J. Colloid Interface Sci.*, 1989, vol. 128, p. 176.
10. Masalova, I., Malkin, A.Ya., Ferg, E., et al., *J. Rheol.* (N. Y.), 2006, vol. 50, p. 435.
11. Pal, R., *Food Hydrocolloids*, 2006, vol. 20, p. 997.
12. Otsubo, Y. and Prud'homme, R.K., *Rheol. Acta*, 1994, vol. 33, p. 29.
13. Barnes, H.A., *Colloids Surf., A*, 1994, vol. 91, p. 89.
14. Pal, R., *Ind. Eng. Chem.,* 1999, vol. 38, p. 5005.
15. Manka, S., Lapasin, R., Partal, P., and Gallegos, C., *Rheol. Acta*, 2001, vol. 40, p. 128.
16. Komatsu, H., Mitsui, T., and Onogi, S., *Trans. Soc. Rheol.*, 1973, vol. 17, p. 351.
17. Babak, V.G., Langenfeld, A., and Stebe, M.-J., *Prog. Colloid Polym. Sci.*, 2001, vol. 118, p. 216.
18. Aronson, M.P. and Petko, M.F.J., *Colloid Interface Sci.*, 1993, vol. 159, p. 134.
19. Solans, C., Pons, R., Zhu, S., et al., *Langmuir*, 1993, vol. 9, p. 1479.
20. Martinez, I., Riscardo, M.A., and Franco, J.M., *J. Food Eng.*, 2007, vol. 80, p. 1272.
21. Ganguly, S., Mohan, V.K., Bhasi, V.C.J., et al., *Colloids Surf.*, 1968, vol. 65, p. 245.
22. Kent, P. and Saunders, B.R.J., *Colloid Interface Sci.*, 2001, vol. 242, p. 437.
23. Park, C.I., Cho, W.-G., and Lee, S.J.J., *Rheol. Korea-Aust.*, 2003, vol. 15, p. 125.

24. Reynolds, P.A., Gilbert, E.P., and White, J.W., *J. Chem. Phys. B*, 2000, vol. 104, p. 7012.
25. Zank, J., Reynolds, P.A., Jackson, A.J., et al., *Physica B* (Amsterdam), 2006, vol. 776, p. 385.
26. Chattopadhyay, A.K., Ghaicha, L., Oh, S.G., and Shah, D.O., *J. Phys. Chem.,* 1992, vol. 96, p. 6509.
27. Ghaicha, L., Leblank, R.M., and Chattopadhyay, A.K., *Langmuir*, 1993, vol. 9, p. 288.
28. Maheshwari, R. and Dhathathreyan, A., *J. Colloid Interface Sci.*, 2004, vol. 275, p. 270.
29. Masalova, I., Malkin, A.Ya., Slatter, P., and Wilson, K., *J. Non-Newtonian Fluid Mech.*, 2003, vol. 112, p. 101.
30. Adya, A.K. and Neilson, G.W., *J. Chem. Soc., Faraday Trans.,* 1991, vol. 87, p. 279.
31. Walker, P.A.M., Lawrence, D.G., Neilson, G.W., and Cooper, J., *J. Chem. Soc., Faraday Trans.*, 1989, vol. 85, p. 1365.
32. Tikhonov, A.M., Patel, H., Garde, S., and Schlossman, M.L., *J. Phys. Chem. B*, 2006, vol. 110, p. 19093.
33. Foudazi, R., Masalova, I., and Malkin, A.Ya., *Colloid J.*, 2010, vol. 72, p. 74.
34. Babak, V.G. and Stebe, M.J., *J. Dispersion Sci. Technol.*, 2002, vol. 23, p. 1.