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EXPERIMENTAL EVALUATION OF THE ADHESION PROPERTIES AND DISTINCTIVE FEATURES OF THE SPREADING OF AN ELECTRORHEOLOGICAL LIQUID UNDER ELECTRIC ACTION

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A study is made of the action of a constant electric field on the process of spreading of a droplet of an electrorheological liquid. It has been revealed that the effective viscosity, the surface tension, and the equilibrium contact angle of the electrorheological-liquid droplet and the adhesion properties of the liquid depend on the electric-field strength, all other things being equal. During the series of experiments, the influence of surfactants as part of the electrorheological liquids on the value of the contact angle and the rate of spreading of the electrorheological-liquid droplet on the substrate has been evaluated. The experimental-theoretical investigations carried out can be employed in developing the concept of using electrorheological liquids as film coatings and in other technologies.

Despite the considerable advances made in developing and studying applied aspects of the electrorheological effect, the shortage and fragmentary character of data on the physics and mechanics of the phenomenon are acutely felt at present. There is no rational explanation for the already found regularities of the manifestation of the electrorheological effect under different conditions, and the role of the influence of both external and internal factors characterizing the relationship between the hydromechanical and rheological parameters and the microstructural properties of an electrorheological liquid has not been evaluated in full measure [1].

In [2, 3], devoted to investigations of the spreading and the surface tension and determination of the contact angles of a bounded volume of an electrorheological liquid which has been placed on the electrode substrate, we have given experimental data on these parameters in variation of the concentration of the solid phase of the suspension, the strength of the electric field, and other factors. Based on these basic data, it became possible to determine the adhesion properties of the electrorheological liquid in relation to different materials, which is significant in developing film structures from an electrorheological liquid. For this purpose, we created an experimental setup containing an electrode substrate, a voltage source, a dynamometric device, and a set of specimens from different materials.

To the electrode substrate, we applied a layer of an electrorheological liquid and placed the test specimen on it. To monitor the constancy of the thickness of the suspension film upon placement of the specimen on it we employed a KM-6 cathetometer with a limiting error of reading of the microscope gratitude of ± 0.0015 mm. The thickness of the electrorheological-liquid film was 0.02 mm. Using the dynamometric system, we evaluated the adhesion of the suspension film to the specimen surface by the value of the breaking load without applying an electric field to the electrode substrate.

Analogously we carried out measurements in the case of action of an electric field on the film of the electrorheological liquid. We varied the composition of the suspension, the electric-field strength, and the specimen material. The measurement results are given in Figs. 1 and 2. From the experimental data obtained we have drawn the following conclusions:

1. The value of the breaking load changes from the specimen surface in modification of the composition of the electrorheological liquid (in particular, the concentration of the dispersed phase). For example, for a twofold increase in the concentration we observe a more than fivefold increase in the breaking load (Fig. 1).

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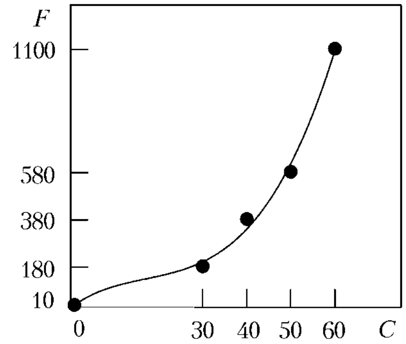

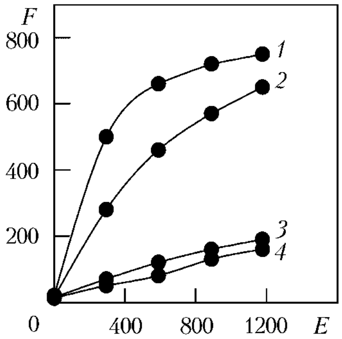

Fig. 1. Influence of the concentration of the dispersed phase on the specific breaking loads of an asbestos-cement specimen in the case of employment of the film of electrorheological liquid in the electric field of strength $E = 1.3 \cdot 10^2$ V/mm. F, gf/cm^2; C, %.

Fig. 2. Influence of the electric field on the specific breaking loads in the case of employment of a 50% suspension of diatomite in transformer oil: 1) asbestos cement; 2) textolite; 3) rigid-vinyl plastic; 4) acrylic plastic. E, V/mm; F, gf/cm^2.

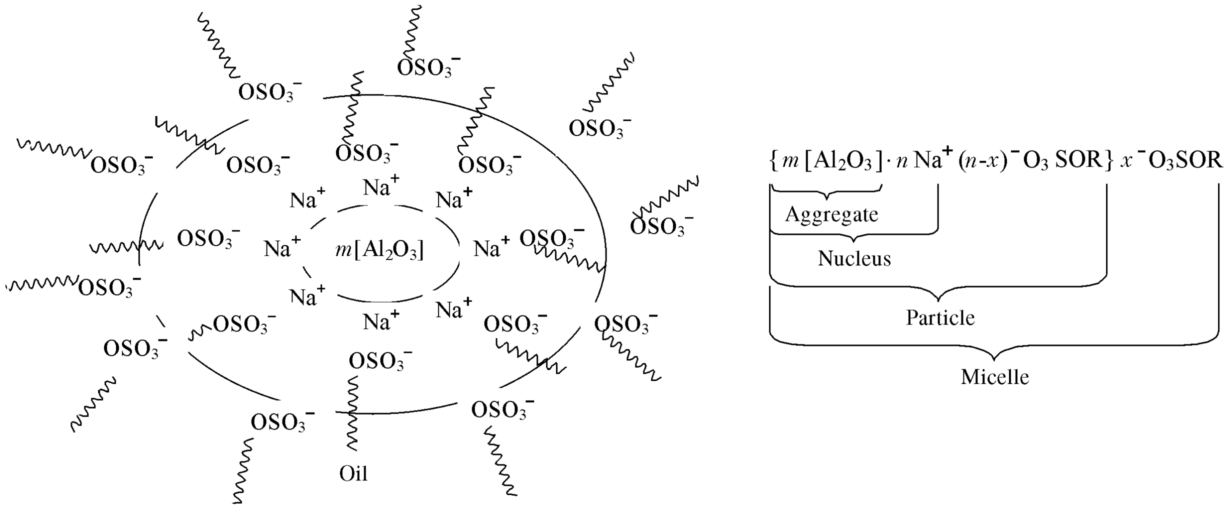

Fig. 3. Structure of an electroneutral micelle.

2. The increase in the field strength E leads to a rapid rise in the breaking load (adhesion) at the beginning of loading but after $E \sim 500$ V/mm we observe saturation (the curve becomes mildly sloping). There is a certain interval of the electric-field strength, specific for each formula of the electrorheological liquid and ensuring the highest value of the adhesion (Fig. 2).

3. The surface properties of the material (roughness, porosity, presence of coatings, etc.) also influence the adhesion in the case of action of an electric field on the electrorheological liquid. For example, among the test kinds of dielectric materials, the greatest breaking load was exhibited by the asbestos-cement specimen (Fig. 2).

Electrorheological liquids usually consist of a solid phase and a dispersion medium. To improve their aggregation stability one introduces, as a rule, a third component, i.e., a surfactant, into the system. Stabilization of the suspensions with a surfactant is ensured due to the adsorption of the latter on the particles of the solid phase for a certain orientation of the surfactant molecules, which usually causes a decrease in the surface tension and an increase in the entropy. Depending on the type of surfactant (ionic, nonionic), the suspension particles acquire the corresponding charge or adsorption-solvate layers occur on their surface, which must have an effect on the behavior of the particles in the electric field.

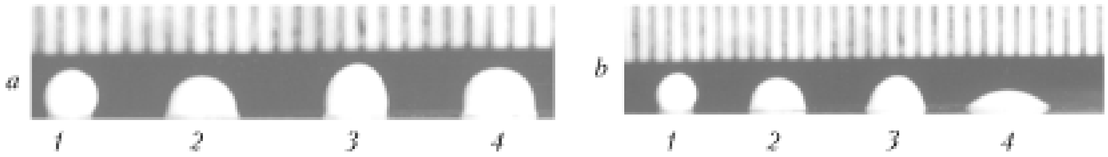

Fig. 4. Dependences of the contact angle on the type of surfactant in the electrorheological liquid: a) E = 1088 V/mm [1) without a surfactant, θ_1 = 115°; 2) oleic acid, θ_2 = 77°; 3) Armac-D, θ_3 = 95°; 4) Armeen-D, θ_4 = 81°]; b) E = 0 [1) without a surfactant, θ_1 = 114°; 2) oleic acid, θ_2 = 76°; 3) Armac-D, θ_3 = 73°; 4) Armeen-D, θ_4 = 32°].

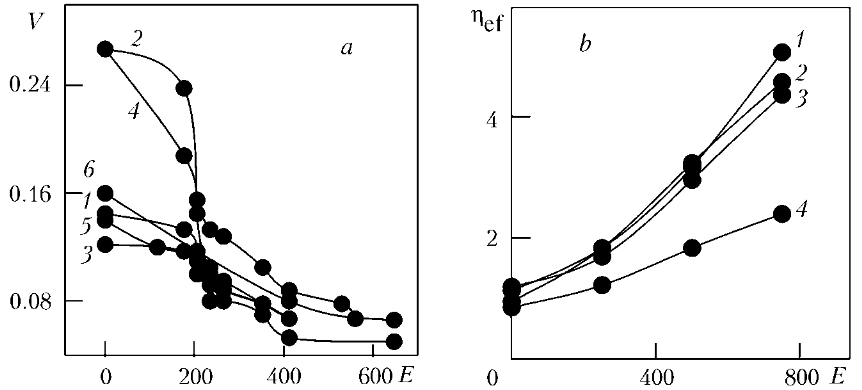

Fig. 5. Influence of the surfactant on the rate of spreading of a droplet of the electrorheological liquid (suspension of Al_2O_3 in the liquid PMS-100) (a) and of the electric field on the effective viscosity of the electrorheological liquid in the case of employment of different surfactants (b) [1) 1-octyl sulfate; 2) Armac-D; 3) OS-20; 4) Armeen-D; 5) without a surfactant; 6) oleic acid]. V, mm/s; η_{ef}, Pa·sec; E, V/mm.

In this work, we have investigated both ionic surfactants — cation-active (Armac-D ($C_{14}H_{29}NH_2 \cdot CH_3COOH$)) and anion-active (Na laurate ($C_{11}H_{23}COONa$), 1-octyl sulfate ($C_8H_{17}SO_4Na$)) — and nonionic surfactants — Armeen-D ($C_{14}H_{29}BH_2$) and OS-20 (monoalkyl polyethylene-glycol esters based on primary fatty alcohols). The surfactant additives were introduced into a 50% suspension of Al_2O_3 in a PMS-100 (polymethylsiloxane oil) liquid.

The suspension effect is shown in Fig. 3, where the structure of an electroneutral micelle (particle of the dispersed phase in the heterogeneous disperse system together with an electric double layer) is given using Al_2O_3 in the PMS as an example. In this case, 1-octyl sulfate ($C_8H_{17}SO_4Na$) acts as the detergent.

During the series of experiments, we evaluated the influence of the surfactant as part of the electrorheological liquid on the value of the contact angle θ in exposure of the suspension to the electric field. The photographs of the droplets (placed on the electrode substrate) of the electrorheological liquid with different surfactants give a clear idea of the influence of the latter on their shape. We successively placed droplets of an electrorheological liquid (50% suspension of Al_2O_3 in the liquid PMS-100) on a horizontally oriented electrode substrate with applied electric field E = 1088 V/mm. The time of exposure of the electrorheological liquid to the electric field up to the instant of photographing was 90 sec (Fig. 4a). It is seen that the largest contact angle is formed in a surfactant-free droplet. The remaining droplets have different but smaller contact angles whose value is determined by the physicochemical properties of the surfactant (the droplet of the suspension with the surfactant (oleic acid) has the smallest contact angle, while the droplet of the suspension with the cation-active Armac-D has the largest contact angle). The surfactants also influence the character of spreading of the electrorheological-liquid droplets during the prescribed period (15 sec) after the disconnection of the electric field (Fig. 4b).

Figure 5a gives results of the experiments on studying the influence of the nature of a surfactant on the rate of spreading of an electrorheological-liquid droplet on an inclined (at an angle of 45°) substrate exposed to an electric field.

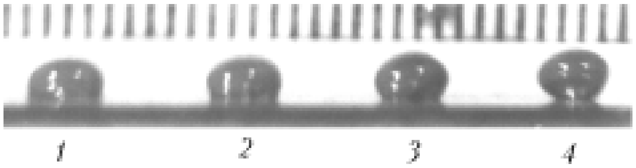

Fig. 6. Dependence of the contact angle of a droplet of the electrorheological liquid (suspension of diatomite in transformer oil) on the concentration of the dispersed phase (E = 1088 V/mm): 1) C = 30 and θ = 93.77, 2) 40 and 102.38, 3) 50 and 110.73, and 4) 60% and 119.63°. $R_1 > R_2 > R_3 > R_4$.

Whereas at $E = 0$ the rates of spreading of a droplet of the suspension with surfactant additives significantly differ, after E = 200 V/mm this difference is not so significant. When $E > 400$ V/mm, the spreading ceases for all the formulas of the electrorheological liquids. We also investigated the influence of the type of surfactant on the electrorheological properties of the liquid. The experiments were carried out on 50% electrorheological liquids representing suspensions of Al_2O_3 in PMS-100 oil. We used 1-octyl sulfate, Armac-D, OS-20, and Armeen-D as surfactants. In the case of absence of the electric field, the lowest viscosity was exhibited by the electrorheological liquids with Armeen-D and Armac-D as surfactants, while a somewhat higher viscosity was exhibited by the liquids containing 1-octyl sulfate and OS-20. Figure 5b shows the dependences of the viscosity of electrorheological liquids on the electric-field strength for a rate of shear of 15.4 1/sec. As is seen, the highest viscosity (in absolute value) is exhibited by the suspension in which we used 1-octyl sulfate. The preparation OS-20 and Armac-D yield similar values of the relative viscosity. The values for the electrorheological liquids with Armeen-D turned out to be the lowest.

Thus, the experimental data demonstrate that the effective viscosity η_{ef}, the surface tension σ, where $\sigma \sim \theta$, and the equilibrium contact angle θ_c of the electrorheological liquid depend on the electric-field strength E. When E = const, these quantities will have specific values. Let us give the dimensionless system of equations describing the kinetics of spreading of an electrorheological-liquid droplet on a solid horizontal surface [2]:

$$\frac{dR}{d\tau} = \frac{1}{R} (\sin \theta - \sin \theta_c(E))(\cos \theta_c(E) - \cos \theta)^{1/2} \ , \quad \frac{4}{R^3} = 3 \tan \frac{\theta}{2} + \tan^3 \frac{\theta}{2} \ . \tag{1}$$

We consider the influence of the electric-field strength E in the kinetics of spreading. It follows from the system of equations (1) that the functional dependence of the droplet radius R on the time τ is mainly influenced by the equilibrium contact angle and its dependence on the electric-field strength $\theta_c = \theta(E)$. In particular, in the region of obtuse contact angles $\theta = \pi/2$, we must not have spreading of the electrorheological-liquid droplet if the relation

$$\sin \theta \le \sin \theta_c \ . \tag{2}$$

holds. This theoretical calculation is confirmed experimentally. The results of experiments [2] have shown that, when E = 1000 V/mm, we obtain $\theta = 113^o$ and $\theta_c = 70.5^o$, and when E = 1500 V/mm we have $\theta = 117^o$ and $\theta_c = 76^o$ and the droplet is immobile. Substituting these data into inequality (2), we can assure ourselves that it holds.

Experimental-theoretical investigations whose results are partially given in Figs. 1–6 can be employed in studying the regularities of spreading of electrorheological suspensions with an open surface and in developing the concept of the use of electrorheological liquids as film coatings [2] and in the technology of use of lubricants with controlled characteristics, since they give an idea of the ways of selecting the components of electrorheological liquids.

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NOTATION

C, concentration of the dispersed phase of the electrorheological liquid; V, rate of spreading of a droplet; E, electric-field strength; F, specific breaking loads; R, droplet radius; η_{ef}, effective viscosity; σ, surface tension; θ, contact angle; θ_c, equilibrium contact angle; τ, time. Subscripts: ef, effective; c, constant.

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