VISCOELASTIC BEHAVIOR OF ELECTRORHEOLOGICAL SUSPENSIONS

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The dependence of viscoelastic properties (modulus of elasticity G' and loss modulus G") of electrorheological suspensions on applied electric field is determined experimentally.

Electrorheological suspensions (ER-suspensions) based on a dielectric dispersed phase and activated silica are weakly conductive, and behave like typical pseudoplastic systems under the action of an electric field [1, 2]. This is most obvious in the range of low and moderate shear velocities with growth in electric field intensity E. One then finds not only an increase in the region of anomolous-viscous flow, but also growth in the initial shear stresses (τ_0, the yield point), which undoubtedly indicates the existence of a structural framework in the system. The appearance of these effects becomes more marked with increase in the concentration of the solid phase C. At certain values of C and E saturation of the dependence $\tau_0(C, E)$ is reached. The processes of forming the structural framework of the system, first in the form of chains, fibers, dendrite formations, then rigid bridges of solid phase dielectric particles coated by conductive layers of activator, are characterized by greatly differing formation and decomposition times (response times). These depend on the relationships between various parameters — suspension composition, mechanical loading characteristics, and electric field intensity. The pattern of structure formation in dilute suspensions has been recorded by cine and still photography [3].

Unfortunately, the effect of electrical fields on viscoelastic behavior of suspensions has been studied mainly by static methods [1, 2]. However, the majority of devices, primarily hydraulic, which use concentrated suspensions (vibrators, dampers, pumps, etc.) [4] operate under dynamic conditions, created by time variable mechanical effects and impulsive or acoustic fields. Thus, in order to study factors which affect the speed of such devices it is necessary to study elastic and relaxation characteristics of electrorheological suspensions under such dynamic conditions. In particular, the mechanical behavior of ER-suspensions periodically perturbed can be characterized by a modulus of elasticity (G') and loss modulus (G"), the latter defining mechanical losses in the system: dissipation of mechanical energy. The moduli G' and G" are components of the complex dynamic modulus $G^* = G' + iG''$. By performing experiments with low amplitude damping where the linear relationship between stress and deformation is preserved, one can evaluate the viscoelastic properties of ER-suspensions with unchanged structural deformation. The reaction to the external stimulus is determined by the mobility of the structural elements which develop in the electric field, i.e., the system relaxation characteristics.

The goal of the present study is to investigate the viscoelastic properties and features of structures formed in ER-suspensions under the action of an electric field as a function of the intensity of the field and content of dispersed phase.

The object of study was an ER-suspension based on diatomite and transformer oil (activator, water; surface active material, oleic acid) with moderate and high concentrations of the solid phase (10-60% by mass).

The studies were performed on a dynamic testing device — a mechanical spectrometer [5] with working chamber in the form of coaxial cylinders operating with forced sinusoidal low amplitude oscillations. A diagram of the device is shown in Fig. 1. The drive coil 1 is mounted on a light but rigid frame 2, suspended on beryllium bronze tension members in the homogeneous field of permanent magnet 3. The ends of the tension members are rigidly attached to springs 4 and 5, mounted on a fixed insert. Mirror 6 is attached to the upper part of the framework, while its lower end is attached to hollow tube 7, which ends in a clamp,

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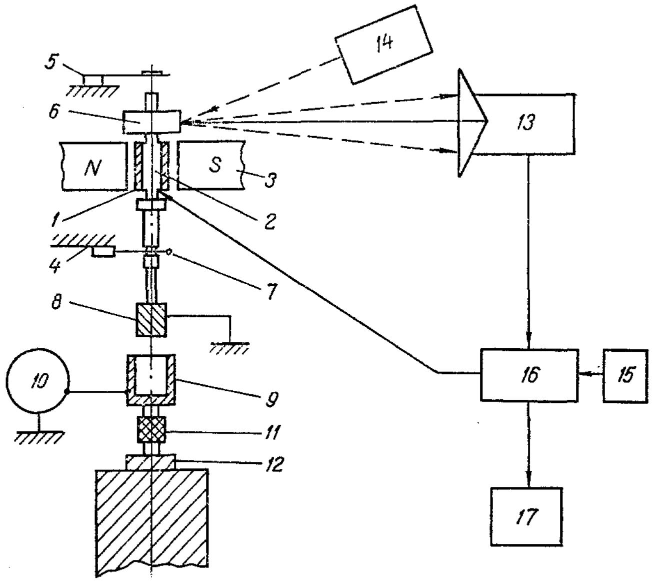

Fig. 1. Diagram of experimental device for determination of viscoelastic properties of ER-suspensions.

in which the upper end of the inner cylinder 8 is held. The outer cylinder 9, to which a high voltage is applied from high voltage source 10, is held in a fixed clamp. It is rigidly connected by dielectric coupling 11 to the dilatometric compensator 12, which eliminates undesirable normal stresses. As ac current of specified amplitude and frequency passing through coil 1 creates a torsional moment which is applied to cylinder 8. Forced torsional oscillations of the cylinder are recoded by rotation angle sensor 13, based on a low inertial optoelectronic device with highly collimated light source 14. Oscillation frequencies over the range 0.01-1 Hz are created by low-frequency generator 15. Signals from sensor 13 and generator 15 are applied to analog circuit 16, which ensures the specified amplitude of angular oscillation or perturbing moment. This unit also processes the data it receives with the aid of counter system 17, giving values of the phase difference δ between the perturbing moment and the angular oscillations of the specimen, the amplitude of the angular oscillations, the absolute value of the complex torsion moment [M*] and its real M' and imaginary M'' components. The moduli G' and G'' are determined from the expressions:

$$G' = \frac{M'}{\Theta A} - \frac{K_e}{A} + \frac{I\omega^2}{2}; \quad G'' = \frac{M''}{\Theta A} - \frac{K_v}{A}\,\omega,$$

where Θ is the maximum angle of rotation of the inner cylinder; I is the main central moment of inertia of the system; ω is the circular frequency; K_e and K_v are the elastic and viscous constants of the device; and A is the specimen form coefficient. In the experiments with imposition of the electric field the high voltage potential from the source was applied to the outer cylinder of the device, rigidly attached to the fixed clamp by the dielectric coupling. The data obtained permit calculation of not only the values of $|G^*|$, G', and G'', but also an important rheological characteristic of the system – the absolute value of the complex dynamic viscosity $|\eta^*| = |G^*|/i\omega$.

Figure 2 shows results of measurements of viscoelastic characteristics of ER-suspensions in the form of graphs of the logarithms of G' and G'' vs electric field intensity. The shaded symbols correspond to voltage increase; the light ones, to voltage reduction. It is evident that the slope of the curves varies with change in content of the solid phase C. For low C (10%) the functions log G'(E) and G''(E) show practically no change; for C = 20% they increase smoothly, with the tangent of the slope angle of the G'(E) line being 0.1. It should be noted that electrical field application to an object with high concentration of solid phase has a most abrupt effect on the dependence G'(E), with slope equal to 0.5, while dissipative losses for this system change insignificantly. As is well known [6], the modulus of elasticity of a system is extremely sensitive to formation of a spatial structural framework, the nodes of which have sufficiently high rigidity. On this basis it can be proposed that under the action of an electric field there develop within the system structural framework elements and rigid bridges extending along the electric field intensity vector. (For

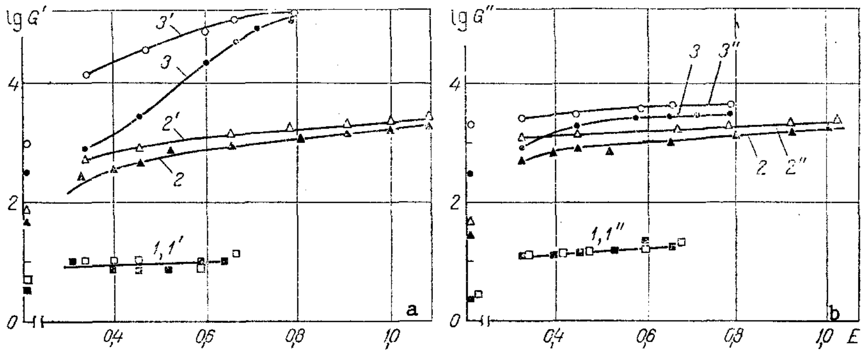

Fig. 2. Logarithms of modulus of elasticity G' (a) and loss modulus G'' (b) of ER-suspensions with various content of dispersed phase (diatomite) vs electric field intensity E, kV/mm. Curves 1, 2, 3 (diatomite content 10, 20, 60% mass) obtained with E increase; curves 1', 2', 3', with E decrease.

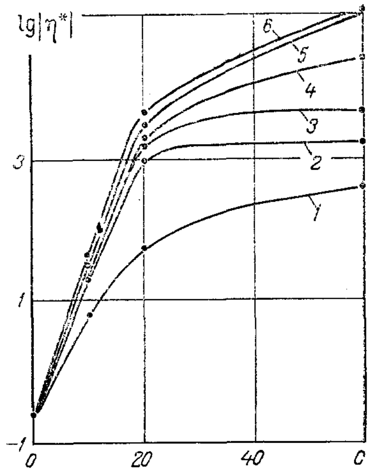

Fig. 3. Logarithm of absolute value of complex dynamic viscosity log |η*| of ER-suspension vs content of dispersed phase (diatomite) C (%) for various electric field intensities. Curves 1, 2, 3, 4, 5, 6, field intensity E, kV/mm: 0, 0.33, 0.5, 0.6, 0.8, 1.0.

A unique feature of high concentration suspensions is that the dissipative component of the complex modulus G'' dominates in the suspension response. This feature appears clearly in hydraulic devices [4], where shear stresses (working range $0 < \dot{\gamma} < 100$ sec^{-1}) compete with electrical ones, as a result of which loose structures are decomposed and reformed every second. This creates conditions equivalent to the action of small electric fields with a low periodic loading frequency (f ~ 1 Hz), i.e., similar to those modeled in the present study. Electrorheological suspensions then behave like media with a variable yield point, since upon preliminary action by an external electric field the initial shear stress τ_0(E) increases. Therefore, with increase in shear deformation the process of structure decomposition will dominate, producing a decisive effect on the dissipative component of the system or its viscosity.

It should be noted that for objects with a low concentration of the solid phase the functions G'(E) and G''(E) obtained in experiments with increase and decrease in E practically coincide, and moreover, return to their initial values $G_0' = \lim_{E\to 0} G'$ and $G_0'' = \lim_{E\to 0} G''$ corresponding to the initial state of the ER-suspension after removal of the voltage. For the specimen with high solid phase content the values of G_0' and G_0'' differ before and after application of the electric field. This indicates that the structure formed is of a relaxation nature, with lifetime after removal of electric field action being determined by the structural framework decay time. There can be no doubt that measurement of this characteristic is an important experimental problem of great practical value, since it should determine the working capabilities of the electrorheological liquid.

It is interesting to compare the relative change in the initial rheological parameters of the specimens, i.e., G_0' and G_0'', with change in solid phase concentration, with their values measured in an electric field of opposite polarity. It is evident from the functions G'(E) and G"(E) (Fig. 2) that the effect of the field depends significantly on the concentration of solid phase and increases with growth in C. This conclusion is illustrated clearly by the data of Fig. 3, which shows the log of the absolute value of the complex dynamic viscosity $|\eta^*|$ as a function of concentration C for various values of E. It is quite evident that without electric field action the value of $|\eta^*|$ increases monotonically with increase in C. However, depending on the electric field intensity, the rheological properties of such systems may change over a range of hundreds of thousands of times, with a significant role played by the concentration of the solid phase. In fact, from comparison of curves 1-6 (Fig. 3), it follows that the optimum electrorheological effect can be achieved only with consideration of both factors – the solid phase concentration and the value of the applied electric field. (At C = 20% this effect is significantly weaker than at C = 60%.)

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FLOW OF NON-NEWTONIAN LIQUID IN HELICAL CHANNELS WITH CONSTANT PITCH

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We carry out an approximate variational solution of a problem of laminar steady-state flow of a nonlinearly viscous liquid with a formed velocity profile in helical channels.

Helical channels formed by placing helical inserts from strips twisted into a helix or screw inserts in a tube (Fig. 1) are an effective means of increasing convective heat exchange in non-Newtonian media [1].

Independently of the form of the transverse cross section, a helical channel has a helical symmetry. To use the available single-parametric symmetry group, we introduce new independent variables r', φ', and z' related to the independent variables of the cylindrical coordinate system by r' = r, φ' = φ – (2π/S)z, z' = z. The introduction of the new independent variables gives, by making the transformation of variables,

$$\frac{\partial}{\partial r}=\frac{\partial}{\partial r'},\quad \frac{\partial}{\partial \varphi}=\frac{\partial}{\partial \varphi'},\quad \frac{\partial}{\partial z}=-\frac{2\pi}{S}\frac{\partial}{\partial \varphi'}+\frac{\partial}{\partial z'}. \tag{1}$$

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