EFFECT OF THE DISPERSION OF COAL ON THE ELASTICITY
AND STRENGTH OF ITS SUSPENSIONS

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Study of the rheological properties of highly concentrated finely dispersed suspensions of coal in water is of interest in connection with the planning and construction of pilot plants for transport and combustion of coal suspensions [1-3]. Direct combustion of the suspensions eliminates dehydration of the finely dispersed coal, huge amounts of which collect at wet-beneficiation plants and hydraulic mines. Such coal suspensions are highly plastic Schwedoff-Bingham bodies [4]; the present author studied [5] the elastic properties and mechanical strengths of coal suspensions at low rates of displacement and the effect of volume concentration of coal on these properties.

The present paper deals with the effect of the dispersion of coal on the strength and elasticity of suspensions, decreasing due to slow displacement. Obiakor [6], who studied the rheological properties of coal suspensions, gives only general information on the abnormalities of these properties and the way the latter correspond to those of Bingham viscoelastic bodies. The investigations were performed on suspensions on different samples of beneficiated G coal with an ash constant $A_c$ of 6.9% and density $p_t = 1410$ kg/m$^3$. Coal samples with different degrees of dispersion were obtained by dry crushing. The degree of dispersion of the coal was determined by the specific surface area of the coal in cm$^2$/cm$^3$ by the air-conductivity method in a Tovarov apparatus and by wet screening of samples on 0.25, 0.088, and 0.040-mm sieves.

The experimental data revealed that the specific surface $A$ is related to the residue $R_{0.040}$% on a 0.040-mm sieve by the following equation:

$$A = 14.4 \left[ \frac{1.5}{\log_{10} \left( \frac{100}{R_{0.040}} \right)} \right] (\text{cm}^2/\text{cm}^3) \cdot 10^3$$

The values of $A$ in the coal specimens were between 4900 and 18,000 cm$^2$/cm$^3$, corresponding to a change in $R_{0.040}$ from 75 to 5%. Below we give the results of experiments on suspensions at a volumetric concentration of coal of 40%, corresponding to 50% moisture content of the suspension; this was taken as the initial value in the pilot plants for burning the suspensions.

The elasticity and creep were studied in a rotary viscosimeter by the method of constant shear stress ($\tau = \text{const}$). This method was first used for studying the elastic properties of dispersed systems by Schwedoff [7].

The SNS-2 viscosimeter was adapted for this work by adding a second dial for recording the angle of rotation of the upper head of the thread (dynamometer), a mirror, screen, and light source. The light beam was reflected by the mirror, fixed on the inner cylinder of the viscosimeter, on to the screen. This made it possible to measure very accurately small shear deformations, which were determined from the formula

$$\varepsilon = \frac{2r_2^2}{r_2^2 - r_1^2} \phi,$$

where $r_1$ and $r_2$ are the radii of the inner and outer cylinders of the viscosimeter, $r_1 = 2.0$ cm, $r_2 = 3.0$ cm, $\phi = \Delta h/R$ is the angle of rotation of the cylinder in rad ($\Delta h$ is the distance travelled by the reflected light to the screen in centimeters, and $R$ is the distance between the axis of the apparatus and the screen in centimeters).

The value of the applied shear stress was determined by the formula

$$\tau = k\phi,$$

Fig. 1. 1) \( \tau = 12.9 \text{ N/m}^2 \); 2) \( \tau = 25.9 \text{ N/m}^2 \); \( t_1 \) is the moment of relief (stress removed).

where \( k \) is the constant (rigidity) of the thread and \( \varphi \) is the angle of torsion of the thread.

We plotted from the experimental data the time dependence of \( \varepsilon \) at \( \gamma = \text{const} \) and \( A = 15,000 \text{ cm}^2/\text{cm}^3 \) (Fig. 1) and then determined the arbitrary-instantaneous \( \varepsilon_0 \) and delayed \( \varepsilon_2 \) elastic shear deformations and the creep rate \( \varepsilon_1 = d\varepsilon/dt \), equal (taking into account the scale) to the gradient \( \alpha \) of the stationary-state line with respect to the \( t \) axis. The \( \varepsilon_0 \) and \( \varepsilon_2 \) values were determined at the moment of load relief \( t_1 \) because, for coal suspensions, the arbitrary-instantaneous deformations under load \( \varepsilon_0 \) and at load relief \( \varepsilon_2 \) do not coincide (\( \varepsilon_0 > \varepsilon_2 \)); it is only at maximum strength of the suspension (due to prolonged creep) the \( \varepsilon_0 = \varepsilon_2 \). This constitutes the marked difference between coal suspensions and Rebinder's dispersed systems [8], where \( \varepsilon_0 = \varepsilon_2 \) in all cases.

We also determined from the \( \varepsilon(t) \) curves the lag time \( \varepsilon \) of elastic deformation as the period in which delayed deformation reached \( 1/2 \) of its total value (see Fig. 1). This was due to the fact that, as shown by the experiments, the development of delayed deformation in time corresponded to the Kelvin equation \( \varepsilon = \varepsilon_H (1-e^{-t/\varepsilon}) \), where \( \varepsilon_H \) is the total deformation at \( t = \infty \).

The moduli of elasticity were determined from the formulas: \( E_1 = \tau / \varepsilon_0 \) and \( E_2 = \tau / \varepsilon_2 \), where \( E_1 \) and \( E_2 \) are the moduli of arbitrary instantaneous and delayed elasticity, respectively. The creep viscosity \( \eta_1 \) was determined from the formula \( \eta_1 = (\tau - \tau_0) / \varepsilon_2 \) where \( \tau_0 \) is the elastic limit below which creep was absent and only elastic deformation was observed.

The experiments revealed that \( E_1 \) and \( E_2 \) are independent of the applied shear stress; this shows that Hooke's law holds true for the elasticity of coal suspensions. The scatter of the experimental data was characterized by the following variation coefficients: for \( E_1 25-35\% \), \( E_2 40-50\% \), and \( \eta_1 60\% \) or more.

Figure 2 plots the averaged \( E_1 \) and \( E_2 \) values and elasticities of the suspension \( \lambda = E_1/(E_1 + E_2) \) versus the specific surface of the coal \( A \) in the suspension; owing to the scatter of the experimental data, a quantitative relationship between \( \eta_2 \) and \( A \) was not observed. The approximate values of \( \eta_1 \) (in thous. N-sec/m^2) at different values of \( A \) (in thous. cm^2/cm^3) were 15-60 at \( A = 7.3 \), 30-100 at \( A = 15 \), and 50-100 or more at \( A = 18 \). Note that Rebinder [8], who studied the creep of clay suspensions, gives only the order of magnitude of the \( \eta_1 \) values.

The strengths of coal suspensions were studied at \( \dot{\varepsilon} = \text{const} \) in the same viscometer. In the factory model, the speed of the outer cylinder is \( n = 0.2 \text{ rpm} \), corresponding to a mean rate of shear in the gap: \( \dot{\varepsilon} = 2\pi n/(2\pi 21n) = 0.075 \text{ 1/sec} \). Figure 3 is a plot of \( \tau \) versus \( t \) at \( \dot{\varepsilon} = \text{const} = 0.075 \text{ 1/sec} \).

In the experiments we used threads (dynamometers) of different rigidities and therefore studied the effect of the rigidity on the \( \tau(t) \) curve; little effect was observed in the rigidity range \( 0.39 \cdot 10^3-2.70 \cdot 10^3 \text{ N-m/rad} \). Mikhailov's hypothesis [9] that the maxima (i.e., \( \tau_m \)) on the curves are determined not by the properties of the suspensions but by the rigidity was therefore not confirmed for coal suspensions.

We determined from the \( \tau(t) \) curves the \( \tau_1 \) values, characterizing the mechanical strength of the undisturbed structure of the suspension, and the \( \tau_2 \) values corresponding to equilibrium shear stress in the current characterizing the mechanical strength of the disturbed structure of the suspension. Figure 4 shows the effect of the specific surface