RHEOLOGICAL PROPERTIES OF CLAY SOLUTIONS

V. M. Dobrychenko, L. L. Povkh, and A. E. Éidel'man

UDC 532.584

Empirical relationships are obtained between the parameters of the Bingham–Shvedov model and the concentration of the solid phase in a clay solution.

Clay solutions, which are the main washing liquids in well drilling, display essentially non-Newtonian properties. The determining effect in the clay–water system is the formation of a coagulation structure of individual crystals of the clay mineral and the bound water [1]. During the flow of a structured clay solution the state of the coagulation structure depends on the shear velocity, so that the shear stresses vary nonlinearly. The study of non-Newtonian systems has led to the appearance of different rheological models [2] which are used to calculate the laminar movement in simple devices.

The possibility of applying the Bingham–Shvedov model

$$\tau = \tau_0 + \mu_p \frac{dU}{dr} \tag{1}$$

for the description of the movement of clay solutions which are close in rheological properties to industrial washing liquids is examined in the present report on the basis of experimental measurements. Principal attention was paid to movement with small shear velocities which exist in pipes of large diameter in well drilling [3].

Clay solutions with a coarsely and a finely dispersed solid phase with a weight concentration of 2.0–34% were the subject of the study. Four series of measurements were conducted: the first and second for Al'met'evsk bentonite of two grades, the third for Konstantinovsk clay powder, and the fourth for coarsely dispersed Khvalynsk lump clay.

The experiments were conducted on a capillary viscosimeter having tubes with diameter D = 3.9 and 6.23 mm and length L = 425D and 360D, respectively. The diameter of the capillaries was determined by volumetric means and was determined more accurately through calibration. The flow curves obtained were plotted in the consistent coordinates [2]

$$\tau_R = \frac{\Delta PD}{4L}, \tag{2}$$

$$\gamma_{\text{equ}} = \frac{8U_0}{D}. \tag{3}$$

The equivalent shear velocities γ_{equ} were varied in the range from 25 to $2.5 \cdot 10^3$ sec^{-1}.

In the measurements corrections were introduced for entrance effects and the kinetic energy of the emerging jet, which were taken into account by the coefficient α in the expression for the determination of the pressure drop

Donetsk State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 28, No. 3, pp. 399–402, March, 1975. Original article submitted July 10, 1974.

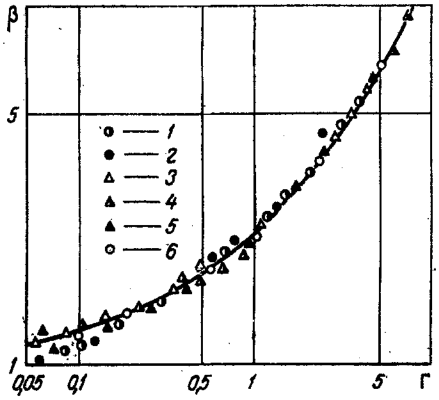

Fig. 1. Comparison of the experimental data with the flow curve of a Bingham lamina: 1) η = 3.9%; 2) 4.55; 3) 8.45; 4) 11.0; 5) 9.4; 6) 15.0%.

$$\Delta P = \Delta P_i - \frac{\rho U_0^2}{2\alpha}. \tag{4}$$

The effect of other corrections can be neglected since their size does not exceed the limits of the measurement error [2]. The calibration of the instrument was conducted on water and showed that the value of the coefficient α = 0.5 is suitable for the entire range of laminar movement. Upon the transition to turbulent movement α increases to 1.

The results of the measurements showed the essentially non-Newtonian behavior of the clay solutions studied. During their movement with small shear velocities their shear stresses τ_R at the wall are considerable greater than τ_R for water, with this divergence becoming larger with an increase in the concentration of the disperse phase. The measurements performed on both tubes of the capillary viscosimeter with the movement of the same clay solution gave close results. This indicates the absence or the insignificant magnitude of the slippage effect [4]. With an increase in velocity the pressure looses in clay solutions approach in magnitude to those for water, disruption of the stream stability occurs, and the flow becomes turbulent.

Let us see how the results of the experiments agree with the Bingham-Shvedov model. The solution of Eq. (1) for a round tube, the Buckingham equation [4], has the following appearance in dimensionless form:

$$\Gamma = \beta\left(1 - \frac{4}{3\beta} + \frac{1}{3\beta^4}\right), \tag{5}$$

where $\Gamma = \gamma_{equ}\,\mu_p/\tau_0$ and $\beta = \tau_R/\tau_0$. The solid line in Fig. 1, which is in point of fact the flow curve of a Bingham lamina in the coordinates Γ, β, corresponds to Eq. (5).

The deviation of the majority of the experimental points corresponding to the various clay solutions from the calculated curve does not exceed the experimental error. For some of them at values of $\Gamma < 0.1$ the value of β is somewhat lower than follows from the Bingham-Shvedov model. This deviation does not exceed 15% in the studies of shear velocities and therefore there is no need to complicate the rheological model.

In applying the results obtained to a flow calculation one must estimate what value the parameter Γ can take in tubes of large diameter. For example, in a tube 94 mm in diameter at velocities of from 0.4 to 2.5 m/sec it varies in the range of 0.1-0.6 for the systems studied. Consequently, the approximation of solutions by the model (1) leads to an insignificant error in a calculation of the flow in this tube.

The critical shear stress τ_0 and the plastic viscosity μ_p depend on the physicochemical properties of the clay mineral which is used as the disperse phase and on its volumetric concentration. The values of the rheological parameters for solutions prepared from different clay materials are shown in Fig. 2. For each of the parameters τ_0 and μ_p there exists a family of curves which can be described by the following equations:

$$\tau_0 = k_1\,(k_2\eta)^{3,0}, \tag{6}$$

$$\frac{\mu_p}{\mu} = \exp(k_2\eta), \tag{7}$$

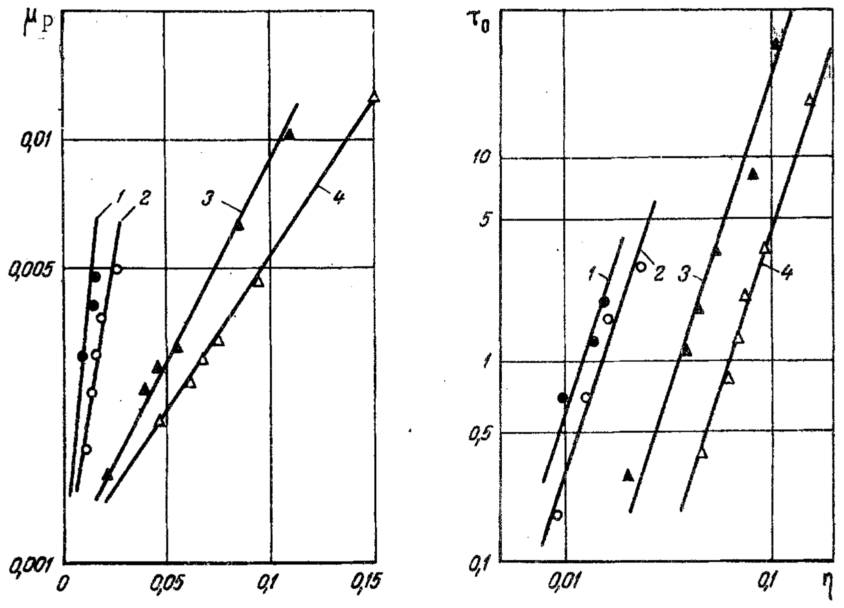

Fig. 2. Dependence of plastic viscosity μ_p (N·sec/m^2) and critical shear stress τ_0 (N/m^2) on volumetric concentration η of disperse phase: 1) bentonite, second series; 2) bentonite, first series; 3) clay powder; 4) lump clay.

where the coefficients k_1 and k_2, presented in Table 1, are constant for each type of clay. Taking notice of the close values of the coefficient k_1 for different clay minerals, one can conclude that the important parameter is the product $k_2\eta$, which takes into account the physical properties of the solid particles along with their concentration.

The results of the study of aqueous clay dispersions agree well with data obtained for dispersions of metal oxides and kaolin [5]. The exponent in Eq. (6) is constant and has the value 3.0 within the limits of the experimental error for all the indicated materials, which have different natures and granulometric compositions. The basis for the similar behavior of dispersions of different materials is the identical mechanisms of formation of the structure in such systems. The sizes of the particles in the clay solutions studied were determined from the experimental functions relating the critical shear stress τ_0 and the plastic viscosity μ_p with the average particle diameter of the solid phase which are presented in [5]. The values obtained are 0.1 μ for Al'met'evsk bentonite in the first series, 0.07 μ in the second series, 0.7 μ for Konstantinov clay powder, and 1.6 μ for Khvalynsk lump clay.

TABLE 1. Values of Coefficients in Eqs. (6) and (7)

Series No.	k_1, N/m^2	k_2
1	0,77	71,5
2	0,75	100
3	1,15	21,8
4	0,88	16,7

The average particle diameter can be used as a parameter determining the grade of the clay, its capacity for structure formation. Equations (6) and (7) allow one to select a clay mineral and to determine its concentration required to obtain a clay solution with the necessary rheological properties.

NOTATION

r, L, D, radial coordinate, length, and diameter of tube; U, U_0, average and flow-rate velocity; γ_{equ}, equivalent shear velocity; ΔP, pressure drop; τ_0, τ_R, critical shear stress and shear stress at wall; μ_p, plastic viscosity; ρ, density; η, volumetric concentration; k_1, k_2, α, coefficients.

LITERATURE CITED

1. P. F. Ovchinnikov, N. N. Kruglitskii, and N. V. Mikhailov, Rheology of Thixotropic Systems [in Russian], Naukova Dumka, Kiev (1972).
2. B. M. Smol'skii, Z. P. Shul'man, and V. M. Gorislavets, Rheodynamics and Heat Exchange of Nonlinearly Viscoplastic Materials [in Russian], Nauka i Tekhnika, Minsk (1970).
3. A. Kh. Mirzadzhanzade, A. A. Mirzoyan, G. M. Gevinyan, and M. K. Seid-rza, Hydraulics of Clay and Cement Solutions [in Russian], Nedra, Moscow (1966).
4. W. L. Wilkinson, Non-Newtonian Liquids [Russian translation], Mir, Moscow (1964).
5. D. G. Thomas, Am. Inst. Chem. Eng. J., 7, 431 (1961).