Experimental studies of rheological properties of stowing pulps

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Abstract. One of the promising directions in mining industry is improvement of effectiveness in transportation of processed products. Current development, which requires minimization of tailings’ volumes, leads to increase of solids (tailings) concentration in a flow of stowing pulps. It, consequently, leads to additional pressure losses in a pipeline. As a result, it becomes necessary to create higher head in order to overcome flow friction. One of the first steps to estimate optimum parameters of hydraulic transport operation is analysis of rheological properties of transported material.

Results of laboratory studies, which were taken to determine a correlation between viscosities of stowing pulps based on mill tailings and solids concentration in the pulps flow, are shown in this paper. Rheological curves were plotted to determine dynamic viscosities and shear strengths of pulps with different concentration of solids, based on experimental results. These results were obtained using rotational viscometer VT 550. It was determined that with the increase of pulp’s density, its viscosity and shear strength increase with some initial shear stress, showing properties of non-Newtonian fluid. An attempt to estimate functional correlation between rheological parameters of filling pulp’s flow and concentration of inert filler, using the regression analysis method, was taken as a research problem in this paper. Hydraulic fluid compositions with change in concentration from 10 to 38% volume (from 20 to 60% mass) were taken in these experiments. Reliability of the derived mathematical model was determined using the least square method. Obtained results show that derived regression describes experimental studies by 88%.

1. Introduction

Hydraulic transport is one of the main elements of technological processes at mining enterprises. It is widely used for transportation of hydraulic fluid compositions of mineral resources and for utilization of mill tailings into mine’s goaf [1]. Hydraulic transportation of mill tailings is a complex of factors, correlation of which is based on the physics of the movement of stratified two-phase flow. Theoretical correlations [2-6] describe this process in general terms, and determination of a field of application is one of the main purposes of experimental studies.

The most important characteristics, which influence the process of pipeline transportation, are solids concentration in pulp’s flow and its viscosity. The values of these characteristics determine all other hydraulic-mechanical and rheological parameters of the flow [7-10]. Analysis of rheological parameters of stowing pulp allows estimating its transportability in industrial pipelines. With consideration of obtained data, it is possible to correct parameters of stowing material: change in the amount of carrier liquid in the pulp, injection of special additives, which allows improving strength properties and uniformity of concrete block [11-13].
2. Materials and methods

Stowing pulp should have a complex of essential rheological parameters in accordance with requirements of its exploitation in actual mine conditions. Therefore, the research aim is to determine rational parameters of pipeline transportation of stowing pulps based on mill tailings to improve effectiveness of stowing operations in mining enterprises.

Research objects are stowing pulps, constituting of slime pulp based on ground tailings treatment together with clay inclusions and water as a carrier matter. Grain-size of solid particles prevails in the range of 0.001 to 0.1 mm.

Aims of experimental studies:

- It was revealed during preliminary theoretical studies that pulp’s viscosity is, generally, proportional to solids concentration – tailings, without definition of a function type and formula. Therefore, the first important aim of the experimental studies is to determine the type of functional correlation between viscosity and solids concentration.
- It is necessary to consider during experimental studies of correlation determination between viscosity and solids concentration that viscosity is an indirect parameter and may be obtained from known values of shear strength and velocity gradient.
- Together such parameters as shear strength, gradient of shear velocity, and viscosity are rheological characteristics of the pulp and, consequently, their determination is the second aim of experimental studies. It is important, because energy characteristics of the hydraulic transportation process in the form of head losses, which can be measured during experimental studies, depend on rheological parameters of the flow.

Rheological parameters of transported material are, generally, described using correlation between shear strength and velocity gradient, called the rheological curve.

3. Results of the experimental studies of rheological properties

Research of rheological parameters of stowing pulps based on mill tailings was carried out using the results obtained by the rotational viscometer VT 550. Equipment specifications are shown in Table 1.

| Table 1. Rotational viscometer VT 550 specifications |
|-------------------------------------------------|
| Viscosity range, mPa·s² | 2 - 100 000 |
| Shear strength, Pa | 1 - 105 |
| Yield strength | 10 - 105 |
| Shear velocity, s⁻¹ | 0.6 - 3×10⁻⁴ |
| Rotation rate, rpm | 0.5 - 800 |
| Accuracy, % | ± 1 |
| Torque range, N·sm | 0.01 - 2 (up to 800 rpm) |

Dependences of shear strength on velocity gradient of blends with different concentrations were determined during the experiment.

As can be seen in Figure 1 with increase of inert filler (solids) in stowing pulps shear strength increases non-linear and velocity gradient is rising with some initial shear strength. Curves obtained from the experiments (Figure 1) show that stowing pulp under study behaves as non-Newtonian fluid when flows in viscometer gap, and Shvedoff-Bingham model corresponds to it:

\[ \tau = \tau_0 + \mu \frac{dv}{dr} = \tau_0 + \mu \gamma, \]

where \( \tau \) – total shearing stress on the pipe wall, Pa;
\( \tau_0 \) – initial (static) stress, Pa;
\( \frac{dv}{dr} \) – gradient of shear velocity, 1/s;
\( \mu \) – dynamic viscosity of hydraulic blend, Pa·s.
Figure 1. Dependence of shear strength \(\tau\) on velocity gradient \(dv/dr\) for stowing pulp with volume concentration \(c_v = 10\% - 38\%\).

Viscosity of a hydraulic blend is determined as a slope of rheological curve (Figure 1). When viscosities are determined, for each concentration dependence of pulp viscosity on its concentration is plotted (Figure 2).

This dependence is shown as a following model [14]:

\[
\mu = \mu_0 e^{kc_v}.
\]

where \(\mu_0\) – dynamic viscosity coefficient of clean water, Pa \(\cdot\) s; 
\(k\) – proportionality factor; 
\(c_v\) – volume concentration of stowing pulp;
To determine model's coefficients $\mu_0$ and $k$, regression analysis method [3] was used. To do so, it is necessary to take the logarithm of both parts of the equation (2) to derive the linear function:

$$\ln(\mu) = \ln(\mu_0) + kc_v.$$  \hspace{1cm} (3)

Elements of the equation are marked as $\ln(\mu) = y$, $\ln(\mu_0) = a$, $b = k$, $c_v = x$; therefore, the function is the following:

$$y = a + bx.$$  \hspace{1cm} (4)

To determine coefficients $a$ and $b$ in equation (4), the system of the equation was composed:

$$\left\{ \begin{array}{l}
\left( \sum_{i=1}^{n} x_i \right) a + \left( \sum_{i=1}^{n} x_i^2 \right) b = \sum_{i=1}^{n} x_i y_i \\
na + \left( \sum_{i=1}^{n} x_i \right) b = \sum_{i=1}^{n} y_i \end{array} \right.$$  \hspace{1cm} (5)

By solving this system, values of the coefficients were determined: $a = -5.53$ and $b = 8.87$.

Found values were put in the equation (4): $y'' = -5.53 + 8.87x$.  \hspace{1cm} (6)

To determine the degree of adequacy of curve plotted using empirical values, the coefficient of determination was found:

$$R^2 = 1 - \frac{s_{sd}}{S_{td}},$$  \hspace{1cm} (7)

where $s_{sd}$ – sum of squared deviations of theoretical values of the function from empirical values, $S_{td}$ – total sum of deviations.

$$s_{sd} = \sum_{i=1}^{11} (y''_i - y_i)^2 = 0.84848,$$

$$S_{td} = \sum_{i=1}^{11} (y_i - y')^2 = 6.75099,$$

where $y'$ – arithmetic mean value of the function (3).

$$y' = \frac{\sum_{i=1}^{n} y_i}{n}.$$

The following equation was obtained by putting the values of the sum of squared deviations in the equation (7):

$$R^2 = 1 - \frac{0.84848}{6.75099} = 0.88.$$

Therefore, the coefficient of determination shows that obtained regression describes experimental studies by 88%.
The equation of regression was obtained using the least square method:

\[ \ln(\mu) = -5.53 + 8.87c_v, \quad (8) \]

This will take the following form for real values of parameters and factors:

\[ \mu = e^{-5.53} \cdot e^{8.87c_v} = 0.00396 \cdot e^{8.87c_v}. \quad (9) \]

4. Conclusions

During laboratory experiments of rheological parameters of stowing pulp determination, it was obtained that shear strength is increasing with rise in solids concentration of the pulp. Based on experimental data, the functional dependence of pulp’s viscosity on volume concentration was obtained, and the form of the equation is the following: \( \mu = 0.00396 \cdot e^{8.87c_v}. \) The degree of adequacy of the mathematical model to experimental studies on the viscometer is 88%.

Obtained parameters of the viscosity should be compared to the values calculated during experimental studies on a full-sized pipeline testing unit, as well as with theoretical values. Convergence of experimental and theoretical values can be used to make a conclusion on the degree of adequacy of the mathematical model to the real conditions of the pipeline transportation of stowing material.

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