THE EFFECT OF SOLID COMPONENTS ON THE RHEOLOGICAL PROPERTIES OF COPPER ORE TAILINGS

Maciej Gruszczyński[1], Jan Błotnicki, Stanisław Czaban, Tomasz Tymiński

[1] *Wrocław University of Environmental and Life Sciences, Institute of Environmental Engineering; maciej.gruszczynski@upwr.edu.pl*

During the thickening process of mining tailings the amount of water is reduced. This causes a change in the rheological properties. In mining Tailing Storage Facility "TSF" in which coarse particles are used to construct the body of the dam, it is important to separate the biggest particles from the tailing stream. The segregation process on the TSF beaches is natural-gravitational or artificial – in the hydrocyclones. After the hydrocyclones and thickening processes, two streams of tailings leave thickening stations – thickened coarse tailings and thickened fine tailings. The size distribution and the concentration of the streams depend on the technology used in the segregation and the thickening processes of the slurries. While designing and optimising the processes of the thickening and transferring thickened tailings it's essential to have valid rheological description of the flow. This paper presents the results of the rheological tests of thickened flotation copper ore tailings as a function of concentration and particle size distribution. The main objective of the experiments was to select the rheological model which will be optimal for the rheological data. The assumptions for building empirical models have been chosen so that they would be simple to use.

KEY WORDS: rheological models, tailings, slurry, thickening, particle size composition, yield stress, plastic viscosity.

NOTATION

a, b, c, d	Empirical parameter, result of approximation (-)
c_s	Mass concentration of solid phase (%)
$d_{90,50,10}$	Particle size indicators, particle diameter corresponding to 90%, 50% or 10% cumulative undersize particle size distribution (μm)
i=1	Lower limit of summation (-)
m_m	Mixture mass (g)
m_s	Solids mass (g)
m_w	Water mass (g)
$MAPE$	Mean Absolute Percentage Error (%)
n	Upper sum limit, number of measuring points (-)
R^2	Coefficient of determination (-)
TSF	Tailings Storage Facility
$\hat{y}_n$	Value of the dependent variable using the selected model (-)
$\bar{y}$	Mean of the observed data (-)
y_n	Value of measured variable (-)

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$\dot{\gamma}$	Shear rate (s^{-1})
η_B	Viscosity of Bingham model (Pa·s)
τ	Shear stress (a)
τ_0	Yield stress (Pa)

1. INTRODUCTION

The technology for storing thickened mining waste is increasingly used in the mining industry (Jewell, 2010; DFAT, 2016). Tailings of non-ferrous metal ores are thickened and used as backfill or injected into voids for exploitation in underground mines (Belem and Benzaazoua, 2008). The largest particles of tailings are usually used as the construction material of the dam body of TSF (ICOLD, 2001; DFAT, 2016). For this purpose, the tailings stream from ore enrichment plant should be segregated into sand and silt fractions. Segregation and thickening of the tailings stream causes a drastic change in rheological properties. The frictional head losses depend on the rheological characteristics of the medium, which makes it necessary to describe rheological parameters as a function of concentration to optimise and design transport systems (Chandel et al, 2009; Assefa and Klaushal, 2015). The granulometric composition has a very significant effect on the rheological characteristics of the mixture (Dames et al, 2001; Chandel et al, 2009; Geisenhansluecke, 2009; Bentz et al, 2012; Schippa, 2018; Desriviers, 2019). The Bingham model is the most commonly used rheological model describing the flow of thickened tailings (Darby, 1992; Pomykała et al, 2012; Zengeni, 2016) after flotation of non-ferrous ores. An empirical description of rheological parameters, i.e. yield stress and viscosity in the Bingham model as a function of the mass concentration of the solid phase (Zengeni, 2016) and particle size composition will facilitate and accelerate the design process of thickened tailings transport installations.

2. RESEARCH METHODOLOGY

2.1 MATERIAL FOR TESTING

Samples for testing were taken from copper ore flotation TSF. The material was taken from two different storage areas. The first group of samples was taken from the beach of TSF so that it would contain the right hand side of particle size composition curve. The second group of samples was taken from the central part so that it would contain the left part of the curve of tailings reaching the TSF (Czaban et al, 2017). The different composition of samples taken is caused by the process of natural segregation occurring during the deposition on the beach of TSF. The particle specific density was determined from the first and the second region and was the same – 2800 kg·m^{-3}.

Samples taken from area I contain 97% sand fraction and 3% silty fraction, while samples taken from area II contain 5% sand, 81% silty fraction and 14% clay. Samples from region I were called sand tailings and from the area II silty tailings (Figure 1).

2.2 PREPARATION OF SAMPLES FOR TESTS

Eleven samples were prepared by mixing sand and silty tailings in various proportions as given in Table 1 (Olhero and Ferreira, 2004). The 100-0 ratio means that the sample has 100% silty tailings and 0% sand tailings (Figure 1). The cited ratio is the appropriate proportion of the mass. Each prepared sample was diluted with tap water at 20°C to obtain about 12 different concentrations of mass solid phase; the mass concentration was defined as:

$$c_s = \frac{m_s}{m_m} = \frac{m_s}{m_s + m_w} \tag{1}$$

Table 1

Preparation of a sample with different particle size composition with three particle size indicators

Content by mass		**Particle size indicators**		
Silt	Sand	d10	d50	d90
(%)	(%)	(μm)	(μm)	(μm)
100	0	1,3	8,9	34,8
90	10	0,8	8,5	42,4
80	20	1,7	10,3	113,4
70	30	2,2	13,8	173,2
60	40	1,6	13,3	204,8
50	50	1,4	15,3	256,3
40	60	1,3	24,9	290,0
30	70	1,9	50,4	358,3
20	80	4,2	165,4	388,1
10	90	16,8	206,6	394,3
0	100	119,3	242,0	433,7

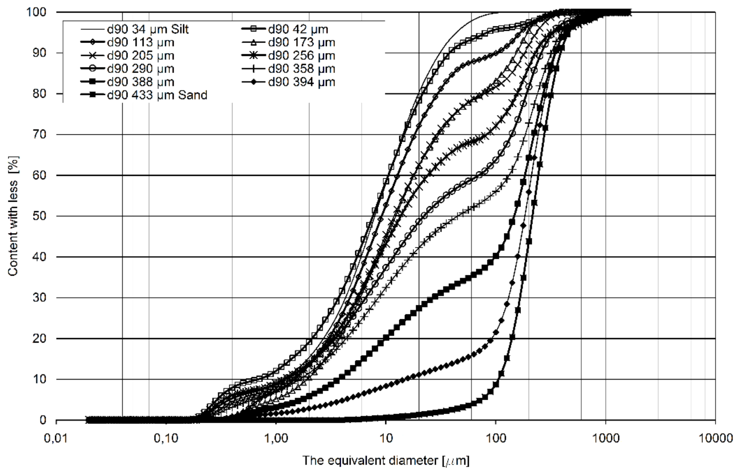

Figure 1. Particle size composition curves of samples from region one and two. Particle size composition curves of mixed samples from Table 1

2.3 RHEOLOGICAL STUDIES

Rheological measurements on the prepared samples were carried out using the Brookfield co-axial rheometer model R/S Plus CC (Coaxial Cylinder) in shear rate control mode. The measuring system formed a cylindrical spindle type CC3-45, which allowed measurements of the viscosity ranging from 0,005 to 1512 Pa·s and measuring cylinder to which a 100 ml sample was placed. The design of the rheometer allowed the measurement of torque ranging from 0,05 to 50 mNm. The maximum rotational speed of the device was 1000 rpm which corresponded to the maximum available shear rate 1000 s^{-1}. The R/S Plus rheometer has dedicated Rheo2000 software designed to enable the creation of measurement procedures and the analysis of collected data, including the determination of basic rheological models (Bingham, Casson, Ostwald-De Waele, Herschel-Bulkley).

The first sample for each particle composition was prepared at a concentration by mass about 60%, which was placed in the rheometer and the rheological tests were carried out. The sample was then removed from the measuring cylinder, mixed and about 15 ml was taken to determine the mass concentration and then about 15 ml of tap water was added. The sample was then mixed thoroughly and placed back in the measuring cylinder. The procedure was repeated about ten times. Viscosity measurements could not be made for a content above 60% of the sand fraction because the viscometer rotor did not have sufficiently high torque to break the yield stress.

2.4 MEASUREMENT OF PARTICLE COMPOSITION

The particle size distribution was measured using the Mastersizer 2000 instrument. The samples were prepared and dispersed in distilled water. The data was subjected to computer analysis using Malvern software. The measuring range of the instrument is from 0,02 to 2000 µm. The particle size distribution of the samples was characterised by characteristic diameters d_{10}, d_{50} and d_{90}.The results of particle size distribution measurements are presented in Table 1 and Figure 1.

3. ANALYSIS OF MEASUREMENT RESULTS

The results of rheological measurements were described by the two-parameter Bingham model (Mezger, 2000):

$$\tau = \tau_o + \eta_B \dot{\gamma} \tag{2}$$

Sixty-five tailings flow curves for various concentrations and for different granulometric compositions were analysed in terms of the dependence of the Bingham model parameters on the solids mass concentration c_s (Fleischmann, 2014; Huebner et al, 2012) and the granulometric composition represented by the particle size indicator d_{90}. The relationship between concentration and viscosity and also concentration and yield stress of Bingham model was described by the use of exponential equations (Barnes et al, 2014):

$$\eta_B = a \cdot {c_s}^b \tag{3}$$

$$\tau_o = c \cdot {c_s}^d \tag{4}$$

The method of minimising the residual sum of squared deviations was used to estimate the parameters a, b, c, and d and are given in Table 2. The parameter a for the whole set of measurement results did not differ much from the value of 20,6 and this value was taken as a constant regardless of the granulometric composition. In estimating the parameter b, it was the assumed that the parameter increases as the sand fraction increases. The parameter c for the whole set of measurement results was calculated as 11600 and this value was also assumed constant regardless of the granulometric composition. In the analysis it was assumed that the parameter d increases as the sand fraction increases.

Table 2

Results of approximation of empirical parameters as a function of granulometric composition

Particle size indicators	**Content of fractions**		**Approximation parameter by viscosity**		**Approximation parameter by yield stress**	
d_{90}	Silt	Sand	a	b	c	d
(μm)	(%)	(%)	(-)	(-)	(-)	(-)
34,8	100	0	20,6	7,83	11600	7,05
42,4	90	10		8,34		7,71
113,4	80	20		9,66		9,24
173,2	70	30		11,1		10,8
204,8	60	40		12,1		11,5
256,3	50	50		14,3		13,3
290,0	40	60		15,4		14,6

Then, after analysing several mathematical models, the simplest solution was chosen so as not to reduce significantly the accuracy of the modelling results. The parameter b is described by the function:

$$b = 0{,}0284 d_{90} + 6{,}70 \tag{5}$$

After substituting Equation 5 into Equation 3 the plastic viscosity is given by:

$$\eta_B = 20{,}6 \cdot c_s^{(0{,}0284 d_{90} + 6{,}70)} \tag{6}$$

Then, the same mathematical function as for them viscosity description was selected to describe yield stress. The parameter d is described by:

$$d = 0{,}0278 d_{90} + 6{,}16 \tag{7}$$

After substituting Equation 7 into Equation 4 the yield stress parameter is given by:

$$\tau_o = 11600 \cdot c_s^{0{,}0278\, d_{90} + 6{,}16} \tag{8}$$

Figure 2 presents the results of measurements and the results of the models with the Bingham Plastic model containing plastic viscosity (Equation 6) and yield stress (Equation 8).

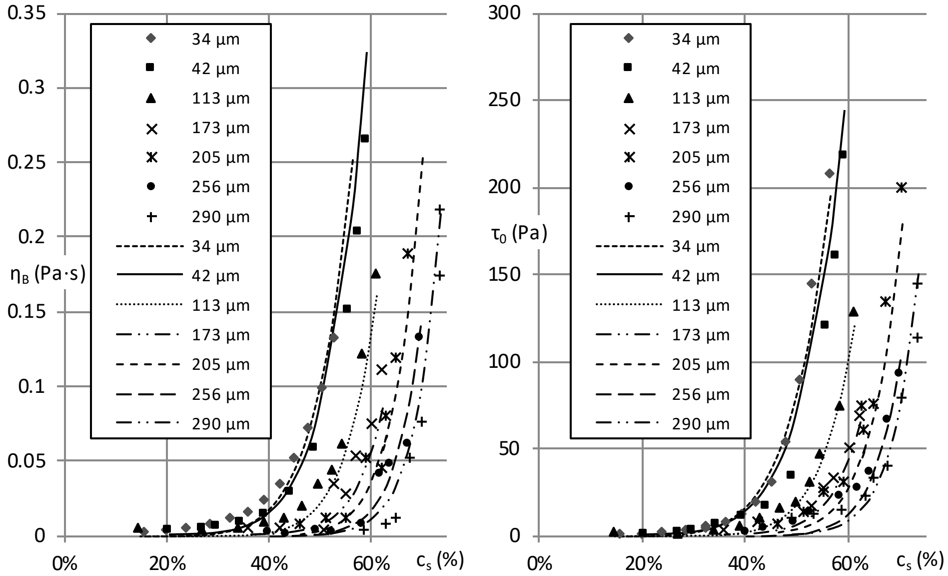

Figure 2. The plastic viscosity model (6) and the yield stress model (8) with marked measuring points for the seven granulometric compositions

Figure 3 presents the surface of solution for the models (6) and (8). The figure shows three axes: on the X axis the mass concentrations of the solid phase were determined (%), on the Y-axis the plastic viscosity in the Bingham model was determined (Pa·s) as well as yield stress (Pa), on the Z-axis the particle size indicators d_{90} (µm).

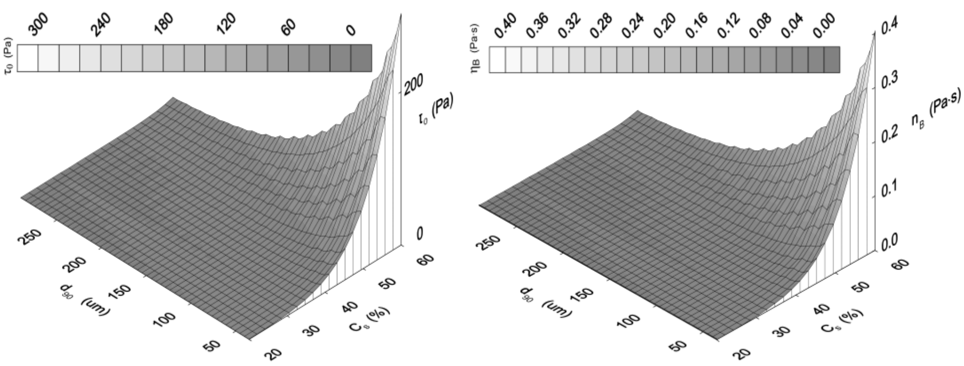

Figure 3. The surface of the solution for models (6) and (8)

Table 3 presents the assessment of matching the proposed models to the data collected during the measurements. In the first part of the table the assessment of the approximation with the model (3) and (6) is presented, whereas in the second part of the table with the model (4) and (8). MAPE parameter is defined as (9):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_n - \hat{y}_n}{y_n}\right| \cdot 100\% \tag{9}$$

The determination coefficient R^2 is defined as per Equation 10:

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_n - \bar{y})^2}{\sum_{i=1}^{n}(y_n - \bar{y})^2} \tag{10}$$

Table 3

Prediction accuracy parameters for model (3), (6) and (4), (8)

Particle size indicator	**Plastic viscosity by concentration**		**Plastic viscosity by concentration and d_{90}**		**Yield stress by concentration**		**Yield stress by concentration and d_{90}**	
(μm)	(-)	(%)	(-)	(%)	(-)	(%)	(-)	(%)
d_{90}	R^2	MAPE	R^2	MAPE	R^2	MAPE	R^2	MAPE
34,8	0,9953	50,96	0,9960	48,21	0,9945	38,11	0,9948	32,90
42,4	0,9988	41,74	0,9981	45,47	0,9943	40,38	0,9927	48,32
113,4	0,9984	43,82	0,9981	51,81	0,9968	40,76	0,9969	42,96
173,2	0,9797	70,89	0,9791	66,10	0,9959	34,78	0,9955	39,60
204,8	0,9813	32,30	0,9826	34,71	0,9914	25,36	0,9912	39,19
256,3	0,9752	44,90	0,9754	45,08	0,9911	52,23	0,9912	52,00
290,0	0,9839	70,71	0,9833	84,46	0,9853	39,61	0,9853	37,48

4. CONCLUSIONS

As can be seen from the results of the research presented above, it is possible to describe the plastic viscosity and yield stress in the Bingham Plastic model as a function of mass concentration of solid phase and particle composition. The chosen parameter describing the particle size distribution is the particle size indicator d_{90}. Rheological parameters could not be described using particle size indicators d_{10} and d_{50} due to the high complexity of mathematical functions, which would significantly hinder the use of the proposed formulae. The accuracy of the description oscillates around value MAPE 50%. This is not a high accuracy in the mapping of measurement results, but the proposed models can be very useful when planning the scope of rheological tests and while optimising the transfer installation of thickened non-ferrous flotation tailings (Durand et al, 2002). Accuracy of 25% is satisfactory in designing transport installations for thickened tailings (Zengeni, 2016). While designing the models, it was decided to use the simplest possible mathematical formulae so that even an unexperienced engineer could easily use the results of our work. The advantage of using the presented formulae is that the scope of rheological research can be more precisely planned. The proposed relationships will not replace research but will narrow the scope of the studies.

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