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Estimation model for yield stress of fresh uncemented thickened tailings: Coupled effects of true solid density, bulk density, and solid concentration

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ABSTRACT

Yield stress is an important issue in the dewatering process of mineral waste tailings. However, very few studies focus on yield stress affected by the tailing properties of true solid density (T) and bulk density (B), which are the two most common properties used to evaluate a tailing. In the present study, an estimation model for yield stress of fresh uncemented thickened tailings (UTT) is proposed and verified based on rheological experimental results. As the model relates to the true solid density, bulk density, and solid concentration (C) of tailings, it is referred to as the TBC model. The change trend of yield stress with the variation of TBC properties is expressed by the first derivative of the TBC model. Results show that yield stress increases with true solid density and solid concentration, whereas the variation is reversed for bulk density. This study enhances our understanding of yield stress and helps predict the yield stress of thickened tailings according to their TBC properties.

1. Introduction

A growing number of underground mines currently use cemented paste backfill (CPB) in backfilling-excavated voids. Backfilled voids stabilize the ground to allow mining of adjacent voids and increase ore recovery while reducing surface waste disposal. CPB consists of mine tailings (MT), binder, and water; approximately 70 wt.% to 80 wt.% are solids (Benzaazoua et al., 2004; Kesimal et al., 2003, 2005; Klein and Simon, 2006; Orejarena and Fall, 2008). The solid components of CPB are mainly made up of uncemented thickened tailings (UTT) and deep cone/high-rate thickener (DCT/HRT), which are usually employed in the thickening process. The performance (i.e., the torque of the rake) of the thickener is significantly affected by the rheological performance of the tailings.

Yield stress is one of the rheological parameters that is of great importance in several suspensions, including food, pharmaceutical products, paintings, ceramics, and mineral suspensions (Alejo and Barrientos, 2009). The importance of yield stress in the field of mineral processing is principally related to the grinding (Ding et al., 2007; Klimpel, 1983) and thickening of concentrates or tailings.

The yield stress of mineral–water mixtures, including UTT, depends on the physical properties of the mixture (e.g., solid content, particle size distribution, and shape) and on the type and magnitude of interparticle forces (e.g., pH and ionic concentration of the pore fluid) (Crowder, 2004; Dabak and Yucel, 1987; Dzuy and Boger, 1983; Kwak et al., 2005; Simon and Grabinsky, 2013; Sofrá and Boger, 2002; Wildemuth and Williams, 1985). Despite the tremendous progress in the understanding of the yield stress of UTT in recent years, major technological challenges remain. One challenge is the understanding of yield stress of UTT, particularly the coupled effect of true solid density (T), bulk density (B), and solid concentration (C), which are the most commonly used and easily measured properties of UTT.

However, only a few studies have explored the coupled TBC processes that occur in yield stress. As mentioned above, most studies are focused on the concentration of solids, solid size, solid shape, and pH of slurry at the laboratory scale. However, these factors are difficult to test and are too complex for field workers. Hence, additional knowledge about the effects of TBC on yield stress must be acquired.

The purpose of this study is to establish an estimation model for yield stress of fresh UTTs affected by TBC properties. The model is called the TBC model. The study can help us understand the flow property of UTT as a major factor in knowing and predicting the thickening performance of tailings.

2. Materials and methods

2.1. Materials

The materials used in the experimental study were copper tailings from two different copper mines. These materials are referred to as 1#

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tailings and 2# tailings, which were respectively used to develop and validate the TBC model. Tap water was used as the mixing liquid.

Fig. 1 presents the particle size distribution (PSD) curves of the 1# tailings and 2# tailings. The PSD of both tailing samples (1# & 2#) was determined using a Malvern Laser Mastersizer 2000 (Malvern Instruments, Ltd., Worcestershire, UK), which measures particle size in the range of 0.02–2000 μm with an accuracy of ± 1%. From Fig. 1, it can be observed that particles finer than 74 μm account for 45 wt.% and 64.32 wt.% of the 1# tailings and 2# tailings, respectively. Particles finer than 20 μm are 35 wt.% and 29.8 wt.% of the total amount of tailings.

The physical and chemical properties of the 1# tailings and 2# tailings are given in Table 1. The true solid densities of the two tailings were calculated using Eq. (1) based on the specific gravity test results (Yesiller et al., 2014). The specific gravity (G_s) of the two tailings was determined using a water pycnometer as per method ASTM D854.

$$\rho_s = G_s \rho_w \tag{1}$$

where G_s is the specific gravity of dry tailing, ρ_s is the true solid density of dry tailing, and ρ_w is the density of water at 20 °C. It should be noted that the G_s is a dimensionless parameter due to the fact of same units are used for the densities.

The bulk densities of two tailings were determined as per standard GB/T 14684-2001 (6.14.2.3). A measuring cylinder was filled with a known mass of dry tailings and covered with a rubber flat surface. The cylinder was tapped until no change of volume of the tailings. The bulk densities of the two tailings were referred to the ratio of the mass of the tailings to the volume that it occupied in the cylinder (Abdullah and Geldart, 1999; Wong, 2002). The porosity (n) of the dry tailings was estimated using Eq. (2).

$$n = \left(1 - \frac{\rho}{\rho_s}\right) \times 100\% \tag{2}$$

where n is the porosity, ρ is the tailings bulk density, and ρ_s is the true solid density.

Three tailing samples were analyzed for the true solid density and bulk density determination to ensure the repeatability of the results. The data given in Table 1 represent an average value of these three test results. It also should be noted that the tailing samples were dried using oven at 105 ± 5 °C for 24 h before these physical properties determined as per standard ASTM D2216.

As shown in Table 1, the true solid densities of the two tailings are almost the same because both of them are copper tailings. The bulk density of the 1# tailings is smaller than that of the 2# tailings because of the fine particle size of the former (shown in Fig. 1). The specific surface areas of 1# and 2# tailings are 0.71 and 0.61 $m^2\ cm^{-3}$, respectively. The mineralogical analysis was done on micronized tailings using X-ray

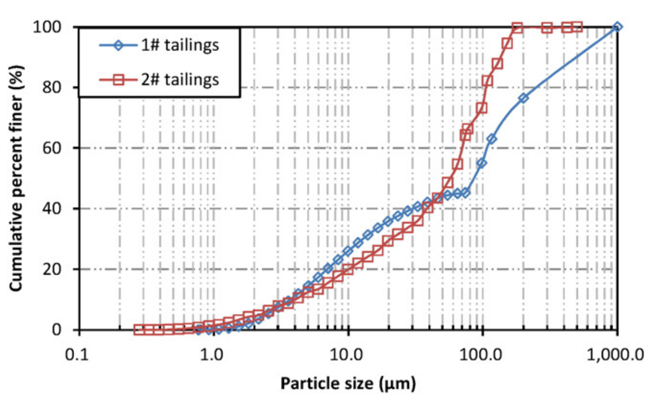

Fig. 1. Particle size distribution curve of 1# tailings and 2# tailings.

Table 1
Physical and chemical characterization of the 1# and 2# tailings.

Characteristics	1# tailings content %	2# tailings content %
Chemical composition		
SiO_2	73.25	64.69
Al_2O_3	13.04	6.19
S	2.38	0.39
MgO	0.33	1.40
CaO	0.15	9.16
K_2O	0.95	–
Na_2O	0.33	–
Loss-on-ignition (LOI)	6.85	16.53
Total	97.28	98.36
Physical properties		
True solid density (kg m^{-3})	2690	2660
Tightly packed bulk density (kg m^{-3})	1500	1600
Porosity (%)	44.24	39.74
Specific surface area ($m^2\ cm^{-3}$)	0.71	0.61

diffraction. The SiO_2 contents of 1# and 2# tailings are 73.25% and 64.69%, respectively. The variations in mineralogy of the two tailings are minor.

2.2. Specimen preparation and test

As shown in Fig. 2, 18 tailing specimens with different concentrations (1# tailings, 59 wt.% to 71 wt.%; 2# tailings, 67 wt.% to 76 wt.%) were prepared for this study. The specimen holders for rheological testing were cylindrical glass beakers, which featured with diameter of 75 mm and height of 115 mm. The height of the thickened tailings was about 100 mm. After pouring the thickened tailings into the beakers, the specimens were tamped 18 times using a glass rod (5 mm diameter). The purpose of this tamping is to remove air bubbles and to level the thickened tailings. After immersing the mixing rotor (V60_30_3tol) of the Brookfield R/S + Rheometer into the prepared tailing samples and fixing the beaker, the test mode was then set on the controlled shear rate (CSR). The shear rate and shear time were successively set as 1 to 120 s^{-1} and 120 s.

3. Results and discussion

3.1. Yield stress

Fig. 2(a) and (b) presents the shear rates at different solid concentrations of the 1# and 2# thickened tailings that affect shear stress. Shear rate and solid concentration obviously affect the shear stress of thickened tailings significantly. The shear stress of thickened tailings increases gradually with the increase in solid concentration. This phenomenon is mainly caused by the relatively high concentration of thickened tailings. This concentration results in a large force between the solid particle and the liquid.

Yield stress is obtained by the regression method based on the test results. The most widely used regression model for viscoelastic material flow are Bingham and Herschel–Bulkley (H–B) models (Barnes et al., 1989). Generally, the H–B model is more accurate than the Bingham model for the flow curve of widely shear rate (from zero to high shear rate). And the Bingham model is the special situation of H–B model when the flow index of H–B model is equal to 1. The Bingham model is usually used for prediction of pipeline transport as the relevant shear rate range is between 10–100 s^{-1}. However, it is possible that the corresponding transport shear rates were quite low (e.g., zero for pipeline start-up conditions), thus making the Bingham assumption is largely incorrect (Coussot, 1994; Henriquez and Simms, 2009). In the present test, the shear rates of two thickened tailings are 1–120 s^{-1}. Both the Bingham and H–B yield stress model are used to fit the experiment results (shear rate of 1–120 s^{-1}). The lowest correlation (R^2) of fit