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Method-dependent variation of yield stress in a thickened gold tailings explained using a structure based viscosity model

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ABSTRACT

Mine tailings may be sufficiently dewatered prior to deposition such that they exhibit a yield stress and therefore they will form gently sloped deposits, which result in a number of advantages from an engineering perspective. Predicting the slope and the shape of these deposits at the field scale remains challenging, and is probably the key technical unknown holding back more general adoption of thickened tailings disposal in the mining industry. Methods for estimating the slope are very sensitive to rheological data, in particular the yield stress. This paper presents data from rheometry on a gold tailings that presents yield stress values in the range of 18–125 Pa. A rheometer with a vane fixture was used in a number of techniques, including controlled increments in strain rate to generate a flow curve, stress relaxation, stress growth and creep techniques. A controlled stress technique was used to simulate the stress history that the material would experience in the field as the tailings slow to a rest. The measured yield stress varied substantially (18–125 Pa) depending on the measurement method. This result is explained using a structure based viscosity model, modified from work created by others working on clays. Ageing and shear rate appear to be significant factors that influence the rheology, though the mechanism for ageing may be partly due to gravity driven particle settling, as opposed to or in addition to the buildup of a network structure.

1. Introduction

Dewatering tailings using operations such as tank thickening, in-line thickening, or filtration, is an increasingly common practice, which is done to realize several possible benefits, including greater water recovery and reuse, minimization of waste volume, and minimizing reliance on containment structures (dams or dyke). The last advantage can be realized if the tailings are sufficiently dewatered to the point where they become a non-Newtonian fluid and exhibit a yield stress, which allows them to be deposited in a gently sloped stack. As the stack does not require confinement by dams, this deposition method avoids the type of catastrophic failures (Recently in Minas Geiras Brazil, October 2015, Mount Polley in British Columbia, Canada July 2014) that unfortunately occur with some regularity (ICOLD, 2001). Increasing density comes with increased cost, and whether a given density is economically viable depends on site-specific requirements such as transport distance, topography, rate of mining, and cost and availability of land and water.

The slope of mature deposits (after a few years of operation) ranges between 1.5% and 5%. Predicting this slope remains challenging. This is in part due to complex flow behavior during deposition. Tailings may transit from some symmetrical spreading or slumping types flow, to flowing in channels formed by erosion of previously deposited tailings by the tailings stream itself (Mizani et al., 2013; Simms et al., 2011). The most commonly used predictive methods in assume that the self-eroding behavior of channels will limit the slope of large deposits (Fitton et al., 2008; McPhail, 2008). Both methods imply strong dependence of slope on (i) the rheology and (ii) the flow rate at deposition. Sensitivity to yield stress is high, and therefore uncertainty in this parameter is problematic.

Various methods for measuring the yield stress have been developed, with more data available from concentrated suspensions than for high density tailings (Keentok, 1982; Magnin and Piau, 1987; Dzuy and Boger, 1983; Gawu and Fourie, 2004). Some methods rely on rheometers using various fixtures, while others are simpler, such as the slump test (Pashias et al., 1996). While there is no universally accepted method for measuring yield stress, some are more popular than others (i.e. vane method). The vane fixture has shown to have certain advantages for concentrated suspensions, including elimination off wall slip and minimization

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of the particle size effect (Gawu and Fourie, 2004; Liddell and Boger, 1996). Moreover, sample disturbance during vane intrusion is minimized. For instance, Yoon and Mohtar (2013) showed that large strains (sample disturbance) occurring in bentonite suspensions during cone placement resulted in underestimation of yield stress values compared to measurements using a vane geometry.

A common issue encountered in yield stress fluids is variability in the results when different techniques are employed. Variation in the results are often associated with the time scale of the technique, definition of yield stress and the principle inherited in each method (Cheng, 1986; Nguyen and Boger, 1992; Nguyen et al., 2006). Nguyen et al. (2006) compared the yield stress values obtained on TiO_2 suspensions, from 6 different laboratories, each using several techniques, and observed that while there exists a variation between different techniques, larger variations were observed among different laboratories. Considering the time-dependency and shear dependency behavior of the tested suspension, Nguyen et al. (2006) proposed that the variations in yield stress was likely due to differences in sample preparation.

Another approach to estimate this is to simulate deposition in the laboratory and back-calculate yield stress analytically from experiments on bench scale flows. Early studies focused on relating the slope in a flume test to the material's rheology (Sofra and Boger, 2001; Kwak et al., 2005); however these ignored the fact that the slope of even bench scale deposits varies with the size of the deposit. More recently, data from laboratory flume have been fitted by equations derived from lubrication theory, which implicitly handles scale dependency. Several researchers have developed equations for the profiles of static deposits of a Bingham fluid using lubrication theory to reduce the Navier-Stokes equation (e.g., Yuhi and Mei, 2004). These equations have been successfully applied to bench scale deposits for hard rock tailings and finer-grained tailings from overburden (Simms, 2007; Henriquez and Simms, 2009; Mizani et al., 2013). Mizani et al. (2013), however, showed that the yield stress back-calculated from such methods may be dependent on deposition time, as the tailings begin to settle even as they flow. This settling behavior leads to consideration that the apparent yield stress of the material is dependent on shear history and ageing, as explored by Coussot et al. (2002a,b) for clays.

This paper presents measurements of the yield stress of a high density gold tailings using a number of different techniques. As will be shown, the variation in rheology measured by the different techniques can be explained by shearing and ageing phenomena, and can be modelled using a structure based viscosity model, similar to the model proposed by Coussot et al. (2002a).

2. Materials and methods

2.1. Materials

Gold mine tailings were shipped from a gold mine with process water to the laboratory. The specific gravity of solid phase is 2.9 (ASTM D854, 2000). The particle size distribution was determined by the combination of sieve (mechanical technique) and hydrometer analyses results based on ASTM D 422-63 (2002) and is shown in Fig. 1.

Geotechnical parameters Liquid Limit (LL), and Plastic Limit (PL) were 22.5%, 20% respectively (ASTM D4318, 2000). Mineralogical composition was: Silicates 80%, Pyrite 11%, Calcite 5%, and Ankerite 4%. Chemical analysis of tailings liquid phase showed the concentration of important dissolved ionic species: Sodium (394 mg/L), Arsenic (95.3 mg/L), Copper (126 mg/L) Magnesium (2010 mg/L) Calcium (7030 mg/L), iron (31,100 mg/L), (Al-Tarhouni, 2008).

The tailings were transported from the gold mine in 20 L pails at C_s (solid concentration) = 72%. Which is equivalent to C_v (solids by volume) = 47%. Due to agitation during transport, the tailings released water and formed a cake of about C_s = 80%, and homogenization was required to remix the tailings with the bleed water produced by settling in order to re-produce the tailings at higher water contents. Subsequent to remixing the tailings at higher water content, under quiescent conditions, the tailings inevitably settle to a solids content of 76% within 48 h. Data from two settling tests at two different initial heights are shown in Fig. 2. Investigations of behavior during bench-scale simulations of deposition show tailings release water even as they are flowing, and therefore could effect interpretation of rheometry (Mizani et al., 2013).

2.2. Methods

The rheology of the tailings was measured using (i) a rheometer with a vane fixture employing various controlled stress or strain paths, and (ii) using the slump test to measure yield stress. Each method is described as follows:

2.2.1. Slump test

Yield stress was extrapolated from the slump tests using the method of Pashias et al. (1996). The slump test is considered to offer reliable estimates of yield stress for values less than 200 Pa (Roussell and Coussot, 2005). The slump test has been shown by others to be a reliable method for yield stress measurement of

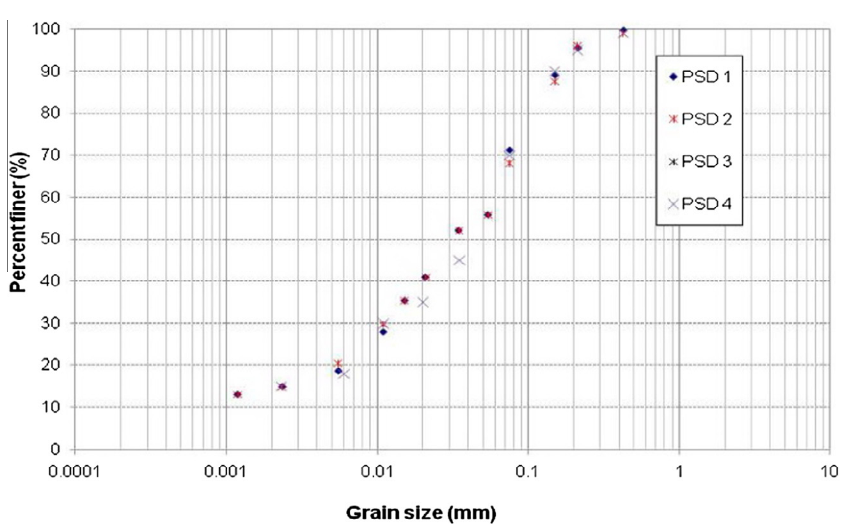

Fig. 1. Particle size distribution of gold tailings for different samples.