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Spread is better: An investigation of the mini-slump test

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ABSTRACT

In the rapidly evolving application of surface deposition of high density, thickened tailings (paste), a key design parameter is the yield stress. A method widely used in industry to obtain quick and easy measurements of the yield stress is the slump test. This paper investigates current techniques for interpreting the cylindrical slump (or mini-slump) test. The lifting process of the cylindrical mould was taken into account in numerical simulations using a computational fluid dynamics (CFD) approach. Simulations with different mould lifting velocities were carried out to understand the influence of mould lifting velocity. Therefore, the influence of plastic viscosity and yield stress on mini-slump test results was studied using a mould lifting velocity of 0.01 m/s, which is representative of rates used in laboratory tests. The predicted slump and spread from mini-slump test simulations for three different scenarios ($v_{\text{lifting}} = 0.002$ m/s, $v_{\text{lifting}} = 0.01$ m/s, and without mould lifting process, i.e. instantaneous disappearance of the mould) were compared to those from laboratory experiments on kaolin. The rheological properties of the kaolin were measured using a vane viscometer and the data used directly in the modelling study. The results suggest that the lifting speed of the mould has a significant influence on the mini-slump test result, which must therefore be taken into account in both numerical simulations and laboratory tests. It was found that the variation of mould lifting velocity had a greater influence on slump than spread, indicating that spread is a more appropriate measurement for determining the yield stress in a mini-slump test. This was particularly true for relatively low yield stresses (e.g. 60 Pa or less), which are values typical of most thickened tailings deposits currently operating internationally.

1. Introduction

The slump test was originally developed for the determination of the "workability" or consistency of fresh concrete, and has been used in many fields as a result of its simplicity of operation and acceptable accuracy. In slump testing, a conical or cylindrical mould is carefully filled with the material to be tested, and then the mould is raised vertically at a constant velocity. The slump, which is defined as the difference between the height of the mould and the height of the slumped material after flow stops, is measured. An alternative measure is a comparison of the final, spread diameter of the material with that of the cylinder. The slump (or spread) can be used to estimate the yield stress of the tested material (Kokado et al., 2000; Pashias et al., 1996;Roussel et al., 2005). Furthermore, to approximate the plastic viscosity of the tested material, partial or complete slump time is sometimes also measured and recorded (Bouvet et al., 2010; EFNARC, 2005; Ferraris and de Larrard, 1998; Tregger et al., 2008), although this is relatively uncommon.

Since Tanigawa and co-workers (Tanigawa and Mori, 1989; Tanigawa et al., 1990) simulated the slump test with their CFD codes, much work on simulation of both conical or cylindrical slump tests, based on single phase fluid flow, has been reported. Christensen (1991) used finite element method (FEM) based CFD codes to simulate the Abrams' cone slump test. He concluded that the final slump height was governed solely by the Bingham yield stress, while the plastic viscosity only influenced the slump time to reach an equilibrium condition.

Roussel and Coussot (2005) carried out simulations of both the ASTM cone and paste cone slump test with the commercial CFD code FLOW-3D. Good agreement between model and experimental results was reported. However, in their simulations, the mould lifting process was not taken into account, meaning that the mould 'disappeared' at the commencement of iteration. To remove inertial effects, a relatively large plastic viscosity was used in their work, i.e. plastic viscosity = 300 Pa s for the ASTM cone and plastic viscosity = 10 Pa s for the paste cone (Roussel, 2006). This "artificial" plastic viscosity may indeed enable the model and the experimental results to coincide, but it is preferable to use actual, measured values of viscosity for comparisons of model versus experimental data as the increased viscosity may result in some

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information, such as flow time, from the simulations being irrelevant. Furthermore, as shown in this paper, viscosity does indeed affect the predicted slump height and spread, so artificially increasing the viscosity is not advisable.

Thrane (2007) simulated the ASTM cone slump test with the mould lifting velocity taken into account and found that the lifting velocity of the cone influenced the time to reach equilibrium, and if not accounted for, incorrect interpretation of physical properties of the tested paste may result. However, poor agreement between simulation and experimental results was obtained. To make the predicted and experimental spread results comparable, applied plastic viscosity or yield stress in the simulation, which should have been determined by experiment, had to be changed. No cogent reasons for the clear disparity of results between simulation and experimental results were given.

Tregger et al. (2008) used a FEM based, commercially available CFD code to simulate the mini-slump test and found the final spread was underestimated. They argued that this discrepancy should mainly be attributed to the coarse mesh used. The mould lifting process was not simulated in their work.

Recently Bouvet et al. (2010) conducted mini-conical slump flow test simulations with the commercial code COMSOL. Again the lifting process was neglected. In their work, the yield stress τ_y (20 Pa and 1 Pa for paste Nos. 1 and 2, respectively) used in the simulations was obtained from Eq. (1) for the mini-cone slump test proposed by (Kokado et al., 2000).

$$\tau_y = \frac{225\rho g V^2}{4\pi^2 D^5} \tag{1}$$

where ρ is the density of paste, g is the gravitational acceleration, V is the volume of the tested material and D is the final spread.

However, Eq. (1) does not account for any inertial effects that may influence the spread of low yield stress paste in a mini-slump test. Therefore, the yield stress in their work was more likely underestimated. Moreover, these yield stresses were used to determine the Bingham viscosities by forcing agreement of flow time between the Marsh-conical test and simulations. The plastic viscosity may therefore be overestimated.

In thickened tailings disposal operations, the yield stress of the tailings in most cases ranges from 20 Pa to 50 Pa (Williams et al., 2008), for which the inertial effects caused by the mould lifting process would be non-negligible. Furthermore, the mould used for the mini-slump test in the tailings industry is typically cylindrical. However, from previous work, little effort has been made to simulate the mini-slump test with the cylindrical mould lifting process taken into account. Given the lack of information in this regard, an investigation of the influence of mould lifting velocity on the mini-slump test was considered crucial.

In the present work, our focus was to assess the influence of lifting velocity of mini-cylindrical mould on the slump, spread, and flow time of paste with a relatively low yield stress (from about 20 Pa to 60 Pa) in a mini-slump test.

The following section describes the experimental work, followed by a description and validation of the numerical model used in the simulation. Thereafter a series of simulations were conducted to investigate the influence of lifting velocity of the mould, yield stress and plastic viscosity on the mini-slump test.

2. Experimental procedure

2.1. Materials and sample preparation

Paste materials of different moisture content were prepared by mixing kaolin clay with fresh water at a constant rotational speed for 20 min, resulting in a smooth, homogeneous mixture.

2.2. Measurement techniques

The yield stresses of paste materials were measured using a Viscotester 550 from Thermo HAAKE. This viscometer has a six-bladed vane attached to its torsion head, allowing measurement of yield stress below 1 kPa at a controlled rotational speed. The vane employed throughout this work had a height of 16 mm and a diameter of 22 mm.

The cylindrical mould used in the mini-slump test in the present work was made from PVC pipe with a wall thickness of 5 mm. The inner diameter and height of the mould were both 79 mm and the inside walls were smooth.

2.3. Experimental procedure

The yield stress measurement was carried out at a constant rotational speed of 0.1 rpm (Boger, 1985). The largest shear stress value recorded within 100 s was reported as the yield stress of the tested material. The plastic viscosity was given by the slope of the steady state flow curve which was obtained by the CR mode (Controlled Rate) in RheoWin software from Thermo HAAKE. Each steady state flow curve was composed of 100 data points, linearly distributed within a shear rate range from 0 to 40 s^{-1}. More precisely, the range of shear rate (from 0 to 40 s^{-1}) was evenly divided with 100 points. Then the shear rate of the vane increased from 0 to 40 s^{-1} stepwise and fixed at each shear rate point long enough that the measured shear stress remained unchanged, and then recorded. The 100 shear rate points and their corresponding unchanged shear stress composed the steady state flow curve. Since the data point in the steady state flow curve was measured at its equilibrium, the result has no time effect. Hence the steady state measurement has the highest reproducibility.

There is no standard experimental procedure for the mini-slump test using a cylindrical mould. In the present case, paste samples were poured into the cylindrical mould to overfill it. Then a spatula was used to smooth the top surface, and care was taken to lift the mould vertically, slowly and evenly. As the top surface of slumped material was usually not even, the middle point of the top surface was taken as the reference point to measure the slump. The slump height of each sample was measured four times and the mean value was reported as the final slump. The diameter of the slumped sample was measured twice in two perpendicular directions and the mean value was reported as the spread. Both slump and spread were measured to the nearest 0.02 mm with a vernier calliper. Density and moisture content were also measured at the time of testing.

To reduce the time effect, yield stress measurement and mini-slump test were conducted at virtually the same time.

3. Simulation

3.1. Numerical model

The computational fluid dynamics (CFD) software package – ANSYS FLUENT – was used to perform the simulations in this work. It is a commercially available CFD code and uses the Finite-volume method (FVM) to solve the governing equations for a fluid.

3.1.1. Continuity and momentum equations for incompressible flow

For the mini-slump test, the fluid (paste in this work) is assumed to be incompressible. Thus the continuity and momentum equations can be simplified as:

$$\nabla \cdot (\vec{v}) = 0 \tag{2}$$

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho \nabla \cdot (\vec{v}\,\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} \tag{3}$$