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'Out of pipe' dewatering of thickened tailings during deposition

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Abstract

One of the challenges and opportunities in managing the deposition of surface deposited thickened tailings is the potential for a change in the rheological properties after they exit the pipe during deposition. As tailings flow away from the deposition point, for a slow enough flow, there may be sufficient time for water loss due to "bleeding" and possibly capillary action by underlying desiccated tailings. This was studied using single and multilayer tests in a flume, in which tailings were deposited at a variety of flow rates. Changes in the rheological properties were evaluated by fitting the lubrication theory equations (Henriquez and Simms 2009; Liu and Mei, 1989) to equilibrium profiles. The rheological properties of the tailings were characterised using slump tests and a vane rheometer. The geometry of the flows was visualised using high speed cameras. The water flux out of the flowing tailings into underlying desiccated tailings was tracked using tensiometers installed in the bottom layer. Preliminary results indicate that the yield stress can substantially increase while the tailings are still flowing by both settling and capillary action into underlying desiccated tailings.

1 Introduction

The flow of thickened tailings away from the deposition point and the consequent geometry of the stack have important consequences for the management of these facilities. The overall slope determines the footprint, controls susceptibility to erosion and is a factor in geotechnical stability, as well as having implications for cover design. This flow also controls densification by desiccation and oxidation during deposition, as the thickness of individual layers deposited in a cyclic deposition scheme regulates the rate of drying (Fisseha et al., 2009; Simms et al., 2007): thin layers dry more quickly than thick ones. The state of practice in controlling the geometry is more or less reactive rather than proactive: tailings flows are either left to sort themselves out, or deposition is managed in an ad hoc manner either by moving deposition points or through the placement of temporary barriers (Shuttleworth et al., 2005). While this approach can certainly achieve some management objectives, there is a lot to be gained from a better understanding of thickened tailings flows. Anticipating the final slope of the impoundment is difficult. Experience has shown that the final overall angle achieved is significantly less than measured in small-scale flume tests (Oxenford and Lord 2006; Engman et al., 2004). Henriquez and Simms (2009) showed that one possible explanation is the scale-dependency of non-Newtonian overland flows, which they showed arises out of lubrication theory. McPhail (1995) advanced a scaling technique based on energy dissipation of velocity head of the material as it comes out of the pipe.

Broad correlations suggest the final angle is a function of the degree of process dewatering of the tailings, material properties, the scale of deposition, the deposition plan (cyclic versus continuous) and climate. Multiple theories and associated predictive methods have been put forward to explain thickened tailings stack geometry (Fitton et al., 2008; Henriquez and Simms, 2009; Kwak et al., 2005; McPhail, 1995) Pirouz and Williams, 2007). The variety of theories reflects the alternate states of the tailings: laminar or turbulent, supercritical or subcritical, spreading or channelised flow. For example, tailings may be observed to exit the pipe as a supercritical flow, which undergoes a hydraulic jump close to the deposition point, and subsequently converts into a spreading subcritical flow. At the same mine, on the same stack but later in the deposition process, the flow does not undergo a hydraulic jump, and rather channelises, only spreading out near the bottom of the stack (for example, Figure 1).

The current paper investigates the influence of changes in rheological properties as the tailings are flowing. Even tailings prepared to a paste consistency (> 70% solids for gold tailings) exhibit hindered settling at a rate sufficient to result in a significant increase in yield stress during field deposition. Further, fresh tailings deposited over desiccated tailings may also be dewatered during deposition due to the capillary action of the underlying layer. Though such behaviour adds to the complexity of surface deposition, it is possible that operators may want to take advantage of this ‘out of pipe’ dewatering to maximise deposition angle. End of pipe flocculation systems provided by a number of suppliers and such as the one publicly advertised by Suncor would entirely rely on “out of pipe dewatering” to generate yield stress.

This paper presents some preliminary results on the change in rheological properties during deposition for laboratory scale flume tests. These tests are interpreted by using the lubrication theory equations, which have shown good skill in fitting single and multilayer flows of highly thickened tailings deposited at the laboratory (Simms, 2007; Henriquez and Simms, 2009). Though the best fit yield stress will be an average value, due to the variability in water content of the tailings, it at least gives some quantified index of the change in the rheological properties.

Figure 1 Thickened tailings running off the stack initially as a channelised flow (top right). Photo courtesy Vincent Martin

2 Theory

Simms (2007) and Henriquez and Simms (2009) previously employed lubrication theory to simulate steady profiles and transient flows of multilayer deposits in flumes and in unbounded ‘pour’ tests of thickened tailings. Lubrication theory of various forms has been previously applied to model lava and mudflows (Cousset and Proust, 1996). We follow the form of the theory derived by Liu and Mei (1989). Several assumptions were used in order to simplify the momentum and continuity equations, such as: very small thickness to length ratios, homogeneous fluid and a very small velocity such that the ratio of inertia to viscous forces will vanish from the equations. Considering that on an inclined bed the flow is not driven by the pressure gradient but by the volume body force of gravity the momentum equation in the direction of the flow is as below:

$$\rho \sin\theta - \frac{\partial p}{\partial x} + \frac{\partial \tau}{\partial z} = 0 \qquad (1)$$

Where p is the pressure, ρ is the density and θ is the angle of declined surface.

The hydrostatic pressure distribution equals to:

$$p = \rho g(h - z)\cos\theta \tag{2}$$

Where *h* is the height of the free surface and is measured perpendicular to *x*.

Solving for τ, the stress depends on *z*:

$$\tau = \rho g(h - z)\cos\theta(\tan\theta - \frac{\partial h}{\partial x}) \tag{3}$$

When the bed stress exceeds the yield stress, fluid flow starts. Assuming a flat bed and putting z = 0 the following expression can be gained for a steady state profile of a Bingham fluid:

$$\tau_y(x - x_0) = \frac{\rho g}{2}(h^2 - h_0^2) \tag{4}$$

An equation for the profile on an inclined surface can be similarly derived (Yuhi and Mei, 2004):

$$h' - h_0' + \ln(1 - h') = x' - x_0' \tag{5}$$

where: $h = h'(\frac{\tau_y}{\rho g \sin\theta})$ and $x = x' \cot\theta(\frac{\tau_y}{\rho g \sin\theta})$.

3 Methodology

Tests were conducted on gold tailings. The geotechnical properties and particle size distribution of the tailings are shown in Table 1, and Figure 2 respectively. These tailings have a somewhat coarser grind than tailings obtained earlier from the same mine that were used in Henriquez and Simms (2009). The D_{50} value was twice that of the recent tailings sample.

The tailings are shipped from the mine at a geotechnical gravimetric water content (GWC) of 40%, corresponding to a solid content of 70%, but undergo settling during transport and arrive with a layer of bleed water on top, and the settled tailings have a GWC of 25%. Therefore, the bleed water was mixed back in to bring the tailings back up to the pumping water content by mixing. The predominant dissolved species in the bleed water were calcium, magnesium and sulfate. The electric conductivity of the pore-water was ~4 mS/cm.

Table 1 Properties of tested tailings

Property	**Value**
Specific gravity	2.9
D_{10}, D_{50}, D_{60} (microns)	3, 100, 150
Cu (D_{60}/D_{10})	27.5
Liquid limit (%)	20
Plastic limit (%)	19
Hydraulic conductivity (m/s)	2 x 10^{-7}

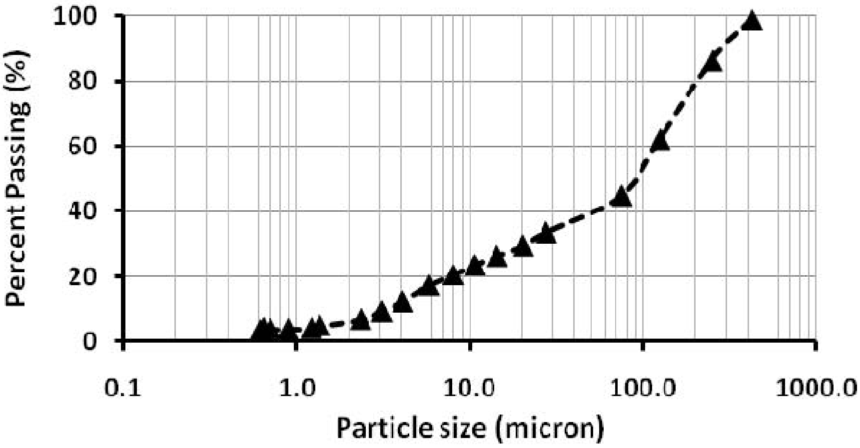

Figure 2 Particle size distribution of gold tailings from hydrometer and sieve analyses

3.1 Rheological properties

The rheology of the tailings was characterised using slump tests and an Anton Paar Physica MCR301 Model Rheometer with a vane fixture. Tailings were prepared at geotechnical gravimetric water contents ranging from 25–50%. Yield stress was extrapolated from the slump tests using the method of Palshias et al. (1996) using different cylinder heights, by which slump height is related to yield stress through the following equation:

$$\tau_y' = \frac{1}{2} - \frac{1}{2}\sqrt{s'} \qquad (6)$$

Where τ_y' and s' are dimensionless yield stress and slump height. The yield stress was then calculated by multiplying the dimensionless yield stress by the unit weight and height of the cylinder. The dimensions of the cylinders are shown in Table 2. The rheometer was used to obtain both conventional flow curves and stress growth plots at various strain rates.

Table 2 Dimension of the used cylinders

Cylinder	Height (cm)	Diameter (cm)
1	19.1	15.4
2	7.9	4.8
3	6	4.8

3.2 Flume test

The flume used in this study was made up of acrylic side walls with the height of 30 cm and total length and width of 243 and 15.2 cm. Before and during each test the tailings were thoroughly mixed using a paint mixer and were then pumped through a tube with the diameter of 73 mm. The tailings were pumped at constant flow rates between 0.4 to 8 litres per minute (LPM). The geometry of the flows was visualised using high speed cameras, Model IN250 from High Speed Imaging. In multilayer testing, the older layer was left to dry for several days to generate a significant matric suction. The water flux between the two layers was tracked by tensiometers installed in the underlying older layers, and by sampling the fresh layer for water content after it had stopped moving. Run-out and the depth at different locations (every 5 cm) was measured after the flow came to rest. The variability in yield stress was evaluated by best-fitting Equation (4) or (5) to the flume profiles. While the actual yield stress probably varies within these layers, this at least gives an indication of the change in the rheological properties as the tailings flow.

3.3 Pour tests

These sets of tests were also conducted on a flat surface, while a certain volume of tailings were poured through the funnel allowing it to flow radially resulting in roughly axis-symmetric deposits. Layers are deposited after the previous layer has stopped settling but before desiccation occurs (~32% GWC for this material). Topography is visualised by dropping plumb lines from an overlying grid. A selection of these results is presented, to illustrate an interesting aspect of flow behaviour.

Both the flume and the pouring tests were performed at room temperature (21–24°C).

4 Results

4.1 Rheological properties

Yield stresses obtained from slump tests are given in Figure 3, while examples of the flow curve and stress growth curves obtained for 38% geotechnical GWC (70% solids) using the rheometer are shown in Figures 4 and 5. The dynamic yield stress is usually evaluated by best fitting the flow curve excluding the data below a shear rate of 100 S^{-1}. For this material, the dynamic yield stress is much greater than the yield stress evaluated from the slump test (30 Pa for 38% GWC). In fact, the shear stress measured at the lowest shear rate by the rheometer gives the best agreement with the yield stress extrapolated from the slump test. Unfortunately, data at low shear rates are usually discounted because of errors that arise at this level of shear stress. Nevertheless, it must be stressed that the yield stress of interest is the yield stress that characterises where the material stops flowing, and therefore it should not be surprising that the slump yield stress lies significantly below the dynamic yield stress.

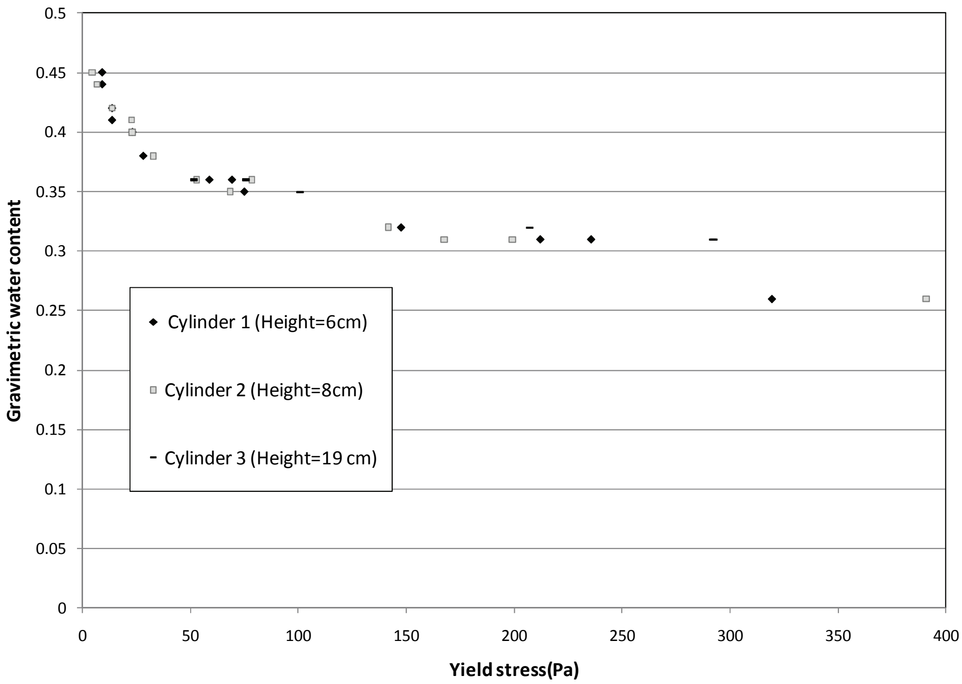

Figure 3 Yield stress from slump test using the method of Palshias et al. (1996)

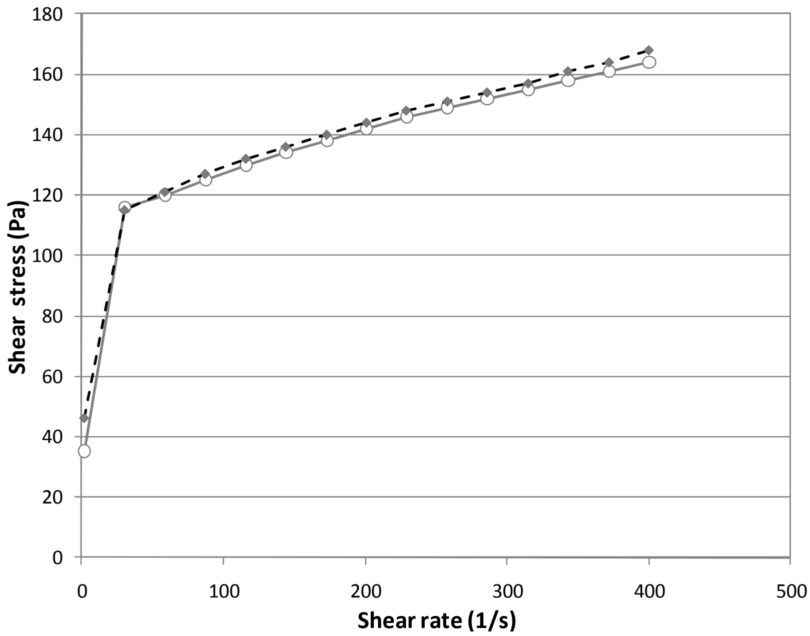

Figure 4 Two flow curves at 38% gravimetric water content, measured with vane geometry

The rheological behaviour of the tailings was also investigated using the stress growth technique, in which a low and constant shear rate was exerted on the tailings and shear stress as a function of time was measured. In this type of test, typically an elastic region is apparent where there is a linear relationship between strain and shear stress, and the yield stress demarks the change from elastic to viscoplastic behaviour. However, for this material, it is not clear where the elastic region ends, if indeed such a region exists at all (Figure 5). Further investigation on defining the yield stress of this material is underway employing oscillatory rheometry.

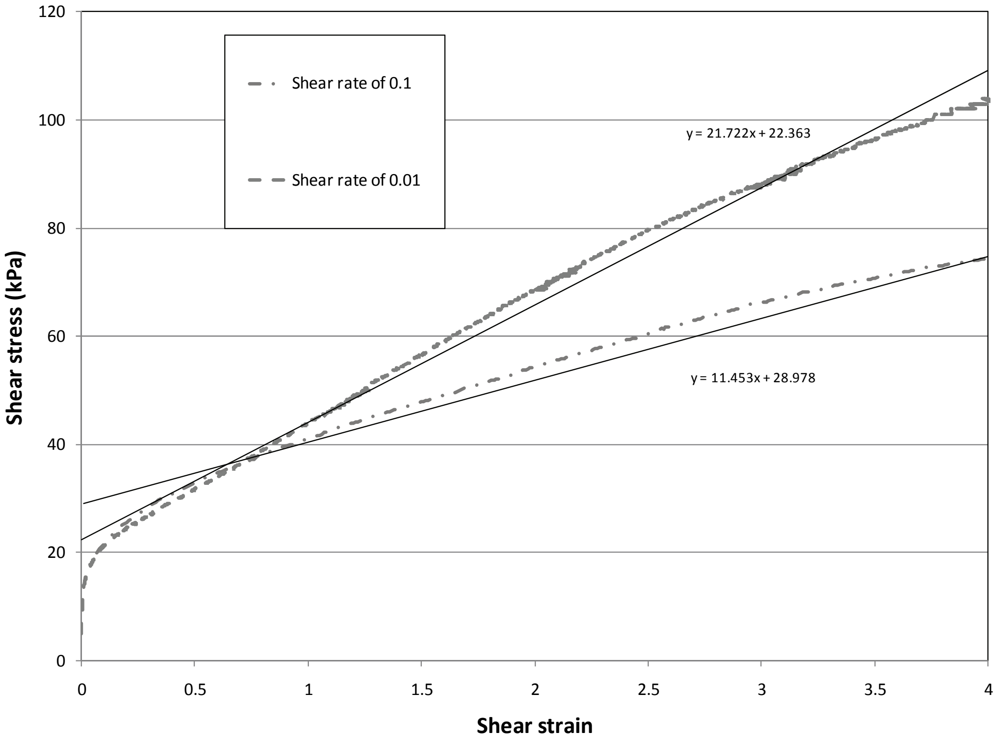

Figure 5 Stress growth at constant strain, 38% gravimetric water content

4.2 Flume tests

Figure 6 shows the equilibrium profiles for the tailings deposited at different speeds, while Figures 7 and 8 show best fits for Equation (4) for the fastest and slowest deposition flow rates. Generally no difference in profiles was observed for tailings deposited at 1.6 LPM or higher, for this specific volume of material. The test with a flow rate of 1.6 LPM is best-fit with a yield stress of 30 Pa, which corresponds to the yield stress extrapolated from the slump test, while the test with the slowest flow rate, 0.4 LPM, was best-fit to a yield stress of 40 Pa. For the slowest test, the water content after the cessation of the flow at different locations was measured. The result showed that the water content at the toe of the deposition was the highest (42.8%) and the lowest at the deposition point at the bottom of the tailings with the water content of 37.2%. This is due to two factors, i) the flow unrolls like a carpet, the freshest tailings flowing over the older tailings to the toe, and ii) bleed water drains toward the toe in the flume tests (vertical drain).

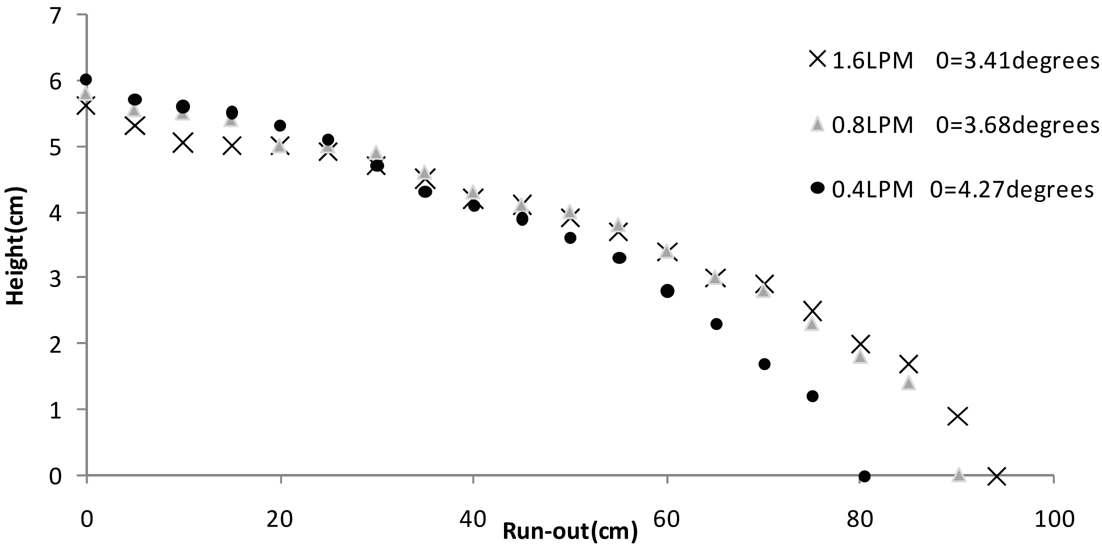

Figure 6 Four single layer flows at 38% gravimetric water content at different deposition rates

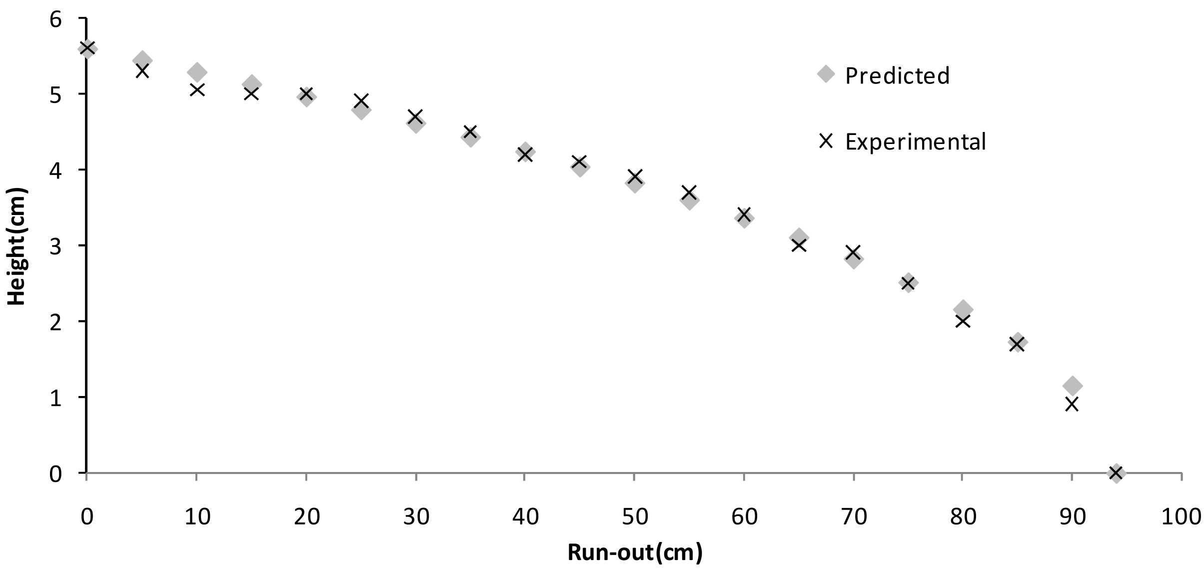

Figure 7 A single layer flow at 38% GWC with the deposition rate of 1.6 LPM, all fitted with Equation (4) employing a 30 Pa yield stress

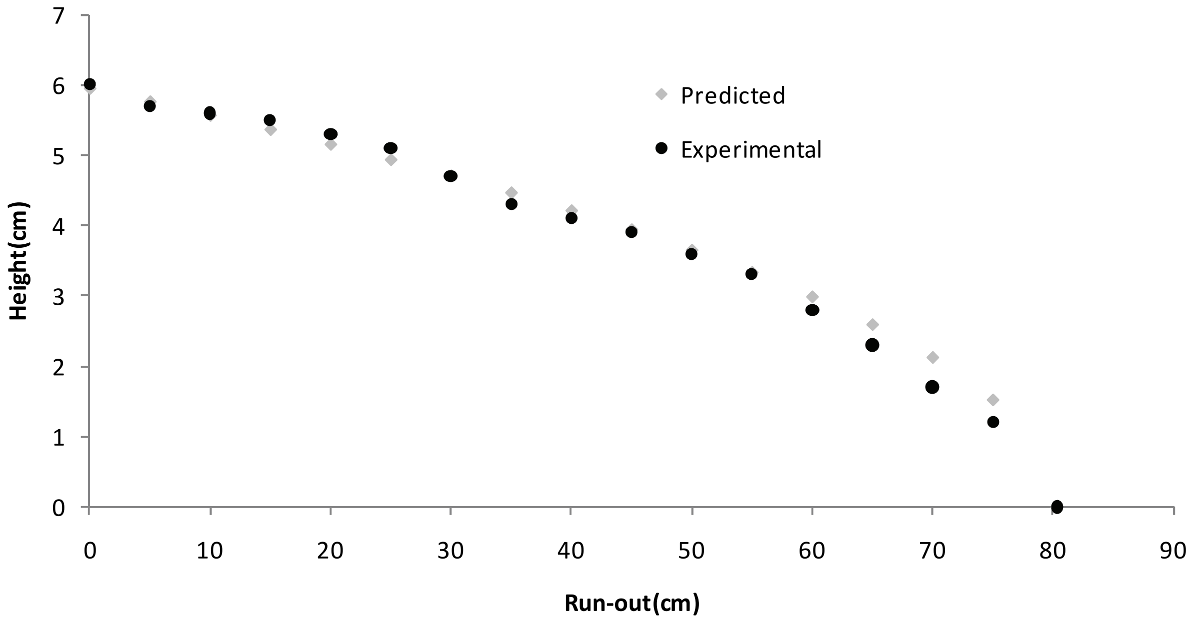

Figure 8 A single layer flow at 38% GWC with the deposition rate of 0.4 LPM, all fitted with Equation (4) with the best fit of 40 Pa yield stress

Results from a multilayer deposition are illustrated in Figure 9 and Figure 10. The evolution of suction in the older desiccated layer is shown in Figure 9. Tensiometers # 1 and #4 were installed at the toe and deposition point, and tensiometers # 2 and # 3 were located in between with tensiometer # 2 closest to the toe. There is a very dramatic dissipation of matric suctions as the flow passes over each tensiometer — remember, the flow takes 15 minutes (900 s) to be deposited — even the matric suction at the toe is completely dissipated before the flow stops.

The second layer is fitted with Equation (5). The angle in Equation (5), which represents the underlying topography, is obtained by fitting the original layer's topography with a linear profile to estimate the slope. The best fit for Equation (5), shown in Figure 8, is with a yield stress of 100 Pa, over three times the yield stress of a fresh layer deposited over a short time period.

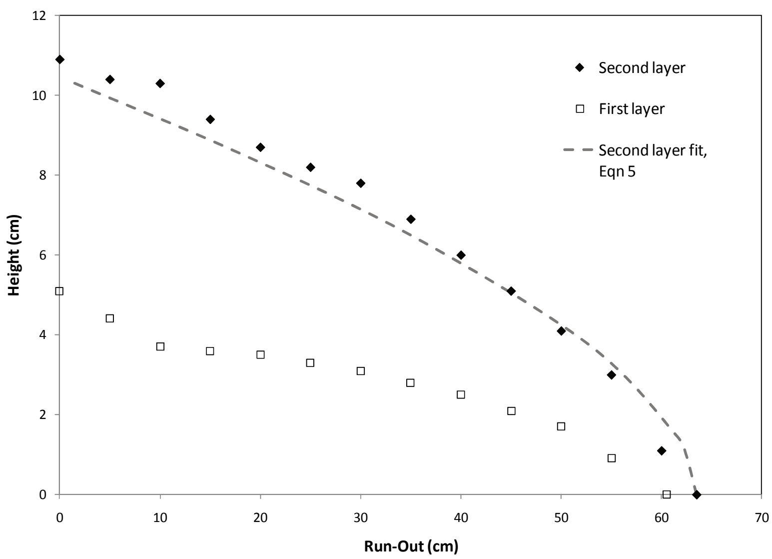

Figure 9 Deposition of second layer after the first layer is desiccated to a matric suction of 60 kPa by drying. Second layer is best fit to Equation (5), using a yield stress of 100 Pa

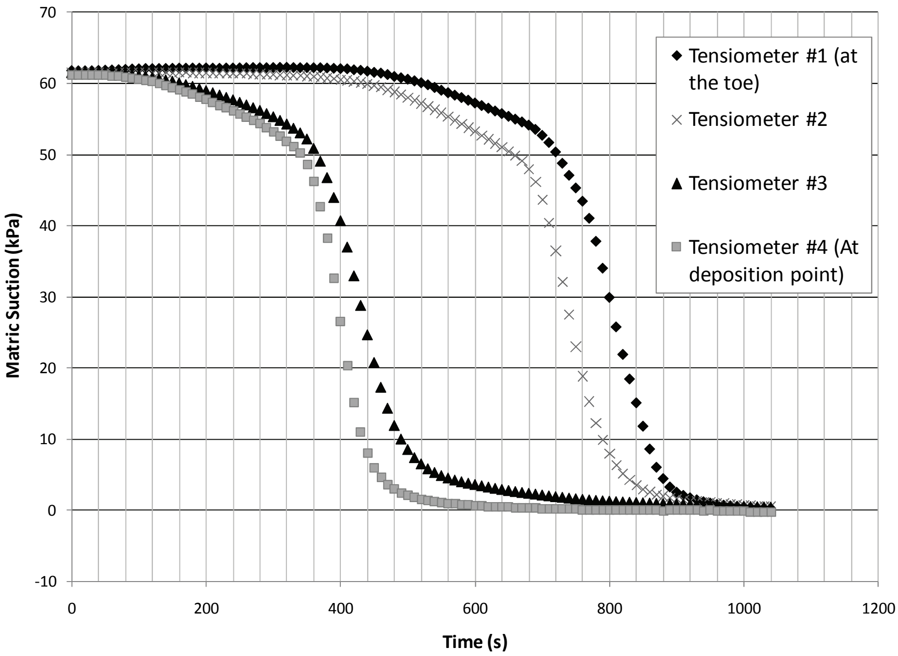

Figure 10 Evolution of matric suction in the older layer during deposition of the second layer over 900 s

4.3 Pour tests

Figure 11 illustrates an interesting result regarding the changing flow regime from layer to layer. These tests, all deposited using a consistent volume and at a constant flow rate, repeatedly show an unstable flow occurring at layer three, but then returning to a stable flow in layer four. The authors are continuing these tests to examine if there is a surface of parameters (flowrate, yield stress, density, average slope of previous layer) that define when this behaviour occurs. This information may be useful in helping operators maintain relatively stable flow behaviour and reduce the difficulty in managing impoundment geometry.

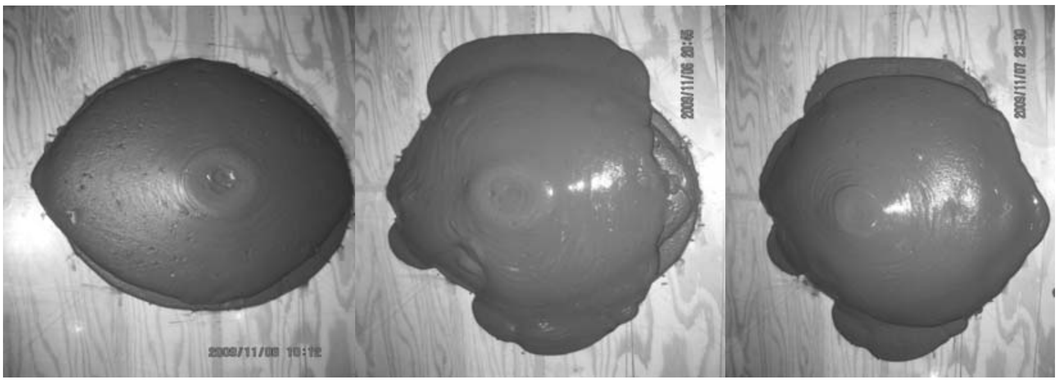

Figure 11 Multilayer pour test, moving from stable to unstable back to stable flow

5 Summary and conclusions

Preliminary tests have shown that both capillarity and the settling nature of even highly thickened tailings are sufficient to result in 'out of pipe' dewatering as the tailings flow. Significant increases in yield stress were detected for overland flow times of 12 minutes or more even without capillary action by the underlying layer. This shows that this effect is important to managing surface deposition, and may be potentially used as an advantage by engineers to control a stack's footprint.

For these tailings, the yield stress extrapolated from slump tests by the method of Palshias et al. (1996) agreed with the yield stress obtained by fitting the lubrication theory equations to the flume tests performed at normal rates of deposition. However, conventional interpretation of flow curves using a vane rheometer did not provide a good agreement with the yield stress derived from the slump test. This is in contrast to the finding of Henriquez and Simms (2009), where the slump test yield stress agreed the flow curve, but was somewhat higher than the yield stress obtained from the flume tests. The tailings used in the present study are a coarser grind that the tailings employed in Henriquez and Simms (2009).

Acknowledgements

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