Unsaturated flow and evaporation in multilayer deposits of gold paste tailings

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ABSTRACT
A series of small and large scale tests were undertaken to study unsaturated flow and evaporation from two-layer deposits of paste tailings. It is shown that the interlayer flow after addition of the second layer can be reasonably modelled using a 1-dimensional unsaturated flow code, without considering the effect of hysteresis on the water retention curve. Though significant cracking occurred during drying of the paste tailings, its effect on the rate of evaporation was minimal. In some of the tests, the accumulation of salt at the surface substantially suppressed the rate of evaporation.

RÉSUMÉ
Une série essais de petits et de grand échelle a été entreprise pour étudier l'écoulement et l'évaporation insaturés des dépôts de deux-couche des residus miniers en pâte. On lui montre que l'écoulement de couche intercalaire après l'addition de la deuxième couche peut être raisonnablement modelée utilisant un code insaturé à une dimension d'écoulement, sans considérer l'effet de l'hystérésis sur la courbe de conservation de l'eau. Bien que significatif la fissuration produite pendant le séchage des produits residus miniers en pâte, son effet sur le taux d'évaporation était minimale. Dans certains des essais, l'accumulation du sel sur la surface a sensiblement supprimé le taux d'évaporation.

1 INTRODUCTION

Deposition of tailings in thickened or "paste" form is often an economically viable alternative to conventional slurried deposition, especially when water recycling within an operation is desirable. The use of thickened tailings also avoids or reduces some of the risks of conventional disposal such as catastrophic dam failure and seepage from the tailings – thickened tailings do not necessarily require containment by dams, and there is no overlying head of water on top of the stack, which reduces the gradient driving seepage out of the impoundment.

The term "Paste" may be used to describe tailings thickened to the extent that no segregation of particle size occurs during transport and a relatively small amount of settling occur post-deposition (Cincilla *et al.* 1997). Paste deposition has been employed at a full-scale at the Bulyanhulu Gold Mine in Tanzania (Simms *et al.* 2007, Suttleworth *et al.* 2005, Theriault *et al.* 2003). It has been shown at Bulyanhulu, that if the deposition is cycled between a number of points in the impoundment and the geometry of the flow is properly controlled (Shuttleworth *et al.* 2005), the tailings will densify and gain significant strength through desiccation, allowing the development of stable stacks with up to a 6 degree slope.

Evaporation is an important parameter to the deposition of thickened or paste tailings. On one hand, evaporation is desirable as it promotes desiccation and strength gain, but on the other hand excess evaporation can lead to desaturation of the tailings and the consequent ingress of oxygen. If the tailings are sufficiently sulphidic, this can lead to acid generation. Therefore, it is desirable to manage the deposition so as to target an optimal rate of drying. This optimal point can be illustrated by comparisons between void ratio, water content, degree of saturation, and associated increases in strength and oxygen diffusivity, as shown in Figure 1..

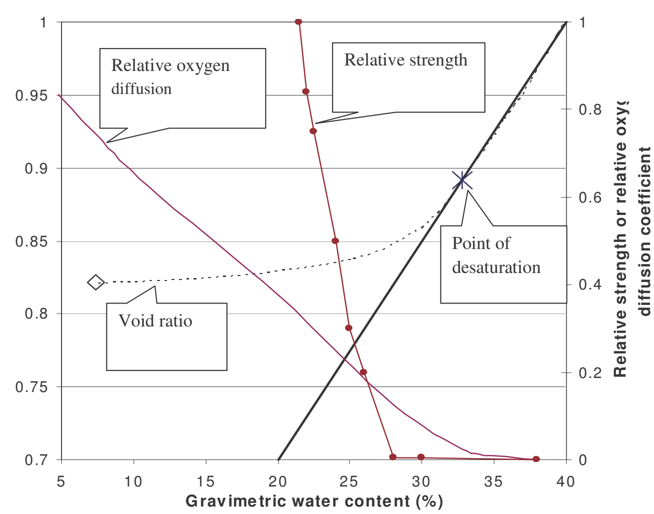

Figure 1. Shrinkage curve of paste tailings and associated geotechnical and geoenvironmental parameters (modified from Simms et al. 2007)

It is desirable to obtain a water content in the tailings that gives a sufficiently high degree of densification and strength gain, but still high enough to minimize the risk of acid generation.

Given that the climatic variables are known, is it possible to predict the rate of evaporation and the evolution in water content and void ratio in paste tailings?

Simms et al (2007) examined the capacity of a 1-D unsaturated flow model for predicting the rate of evaporation in thin single layer deposits of gold paste tailings. It was found that the evaporation rate could be reasonably predicted, but that the presence of cracks and the accumulation of salts at the surface during drying were phenomena that complicated the prediction of evaporation. It was found that the accumulation of salts in a single layer field trial eventually shut down evaporation 3 weeks after deposition (Simms et al. 2007).

The above tests were only performed on single layer deposits of paste tailings. This paper reports experimental studies on multilayer deposition of paste tailings. The writers study interlayer flow subsequent to deposition of a fresh layer of tailings, and investigate the effect of salts and cracking on the evaporation rate.

2 MATERIALS AND METHODS

2.1 Materials

Tests were performed on two types of tailings prepared as a paste. The tailings were transported from each site at the pumping water content (~40% gravimetric). During transport, the tailings would segregate, the tailings consolidating down to a water content of ~25%. For the experiments, the tailings were mixed with the bleed water generated during transport, to bring the tailings back up to the pumping water content. Basic geotechnical properties of the tailings are shown in Table 1.

Properties	Bulyanhulu	Toromocho
Specific gravity	2.9	3.0
D_{10}, D_{50}, D_{60} (microns)	2, 35, 55	1, 100, 120
Cu (D_{60}/D_{10})	27.5	120
W_l, W_p, W_{sh} (%)	20, 19, 20	20,18,18
k sat (m/sec)	2 x 10^{-7}	2 x 10^{-7}

Table 1: Properties of tested tailings

Each of the tailings solids and bleed water was analyzed for composition. The bleed water concentrations were dominated by sulphate, calcium, magnesium and iron. Detailed information on the pore-water can be found in Fisseha (2008).

2.2 Experimental Methods

Drying tests were performed on sequentially deposited layers of initial thicknesses of 10 cm each. Tests on both materials were performed in cylinders 27 cm in diameter mounted on scales, while one “large” scale test was performed inside of a steel box mounted on load cells, with a plan area of 1.7 by 1.7 m, using the Bulyanhulu tailings. In each, case, evaporation was controlled using fans placed around the experiment. Relative humidity and air temperature were monitored 0.5 m above the surface of the tailings. Tests were performed when the receptacles were only filled with water, to measure the potential evaporation (PE) as a function of relative humidity and air temperature, assuming a constant wind speed. The only radiation impacting the surface of the tailings was ambient lighting. It was found that when the fans were turned off, the amount of evaporation was very low, less than 0.1 mm/day in each case, compared to a PE of 7-8 mm/day when the fans were turned on.

While drying, the tailings were monitored for volume change, crack propagation, matric suction, and surface gravimetric water content. In the large test, surface samples were also obtained to measure the electric conductivity of the pore-water, as a means to track ion transport within the tailings. Pore-water conductivity can be converted to osmotic suction using the USDA equation (Fredlund and Rahardjo, 1993).

Matric suctions were measured using miniature tensiometers (Model T5 from UMS) and heat-dissipation sensors (Model 229-L from Campbell Scientific). Volume change was monitored by point measurements using string, hung from set reference points on a wooden frame over the tests (See Fisseha 2008 for more details). Cracking was tracked by a combination of overhead photos and thickness measurements.

Some of the tests were also rewetted at certain times to simulate rainfall. The rewetting was accomplished by slowing adding water over the course of several hours. The amount of water added is apparent in the results from the change in mass of the test.

2.3 Numerical Simulations

The drying experiments were simulated using the unsaturated flow code SoilCover. Parameters required for the model that were measured include the drying water-retention curves, saturated hydraulic conductivity measured from falling head tests, volume change versus suction data obtained from volume change measurements made between stages of the water retention curve test. The unsaturated hydraulic conductivity function was determined from degree of saturation versus suction measurements, as per Simms et al. (2007). The mesh size was changed from day to day to account for actual shrinkage. The change in size of individual mesh elements was based on the calculated suctions for that mesh, and the corresponding void ratio obtained from the void ratio – suction relationship measured during water retention curve tests, as described in Bryan and Simms (2008).

Significant detail on modelling drying in paste tailings using SoilCover is described in Simms et al. (2007), therefore we report only the differences in our approach for the present study. When the second layer is placed, a new mesh must to be created. The final suction profile from the simulation up to that point is used as the initial profile for the older layer, while a hydrostatic pore pressure distribution, 0 kPa at the top of the tailings, is assumed for the fresh layer. The underlying tailings undergo “wetting” not drying, but we have ignored any differences between the wetting curve and the drying curve in our simulations. This potential source of error is addressed in the discussion.

3.0 RESULTS

For lack of space only a sampling of results from the various tests are presented. Readers are referred to Fisseha (2008) for more detail.

Most of the data presented is from the large scale test on the Bulyanhulu tailings, which comprised drying an initial 10 cm layer for 10 days before adding a second layer. After another 5 days of drying, the test was rewetted to bring the average water content back up to 25% gravimetric, and subsequently allowed to dry for 5 more days. The progression of the experiment is shown in Figures 2 through 4.

Figure 2 End of First layer (Day 9)

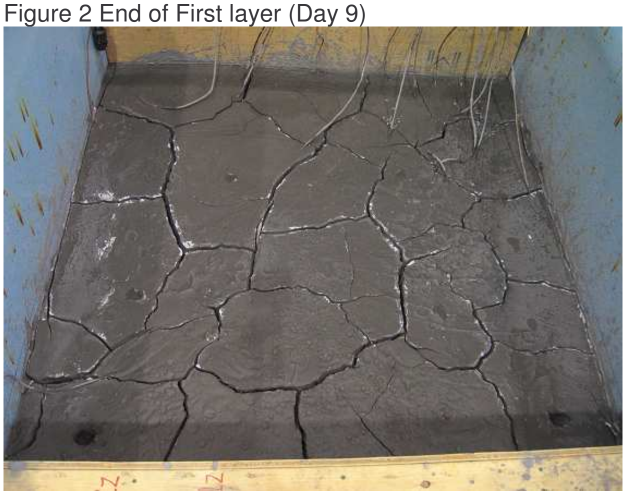

Figure 3 End of second layer (Day 14)

Figure 4 Four days after rewetting (Day 19)

3.1 Volume change and water content

Figure 5 tracks the evolution of void ratio, with and without accounting for the additional decrease in void ratio due to lateral shrinkage. Most vertical shrinkage occurred before the formation of cracks. Cracking and lateral shrinkage away from the walls started late on Day 3 and finished by Day 5. Cracks again started forming within 3 hours after placement of the second layer. Rewetting did not appear to substantially reduce the volume of cracks.

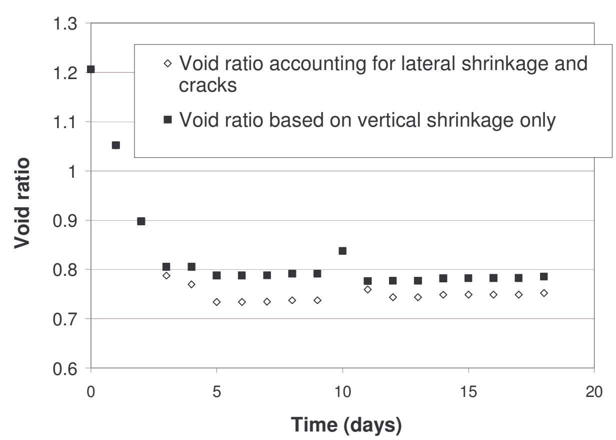

Figure 5 Volume change in large scale test

Average and surface gravimetric water contents are presented in Figure 6. The water contents corresponding to the end of vertical shrinkage and the end of horizontal shrinkage are 23% and 18% respectively. Non-uniform drying starts when the average water content drops below 23%.

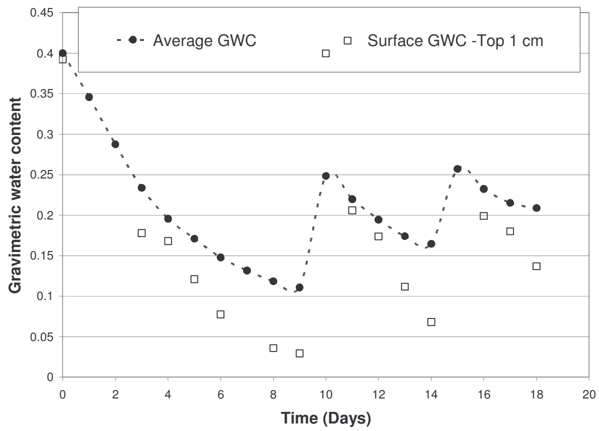

Figure 6 Average and surface gravimetric water contents in large scale test

3.2 Measured and predicted evaporation

Daily averages of measured evaporation and predicted potential and actual evaporation are shown in Figure 7 Until after rewetting (Day 15), the predicted and measured actual evaporation show reasonably good agreement, with some under-prediction of the measured evaporation occurring during Stage II drying. After rewetting, the measured evaporation rate is strongly over predicted.

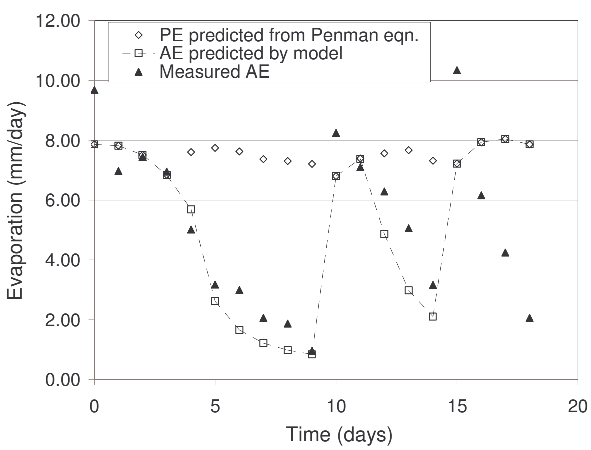

Figure 7 Evaporation during large scale test

3.3 Matric suctions

Measured matric suctions can be reasonably simulated by the SoilCover model subsequent to addition of a second layer (Figure 8 – from small scale test on Toromocho tailings). Figure 8 illustrates the effect of the older layer on the new one as it can be seen that the suctions in the two layers converge to a quite close value of suction, and the suction in the fresh layer rises at a much quicker rate than the suction during initial drying of the first layer. This same behaviour is illustrated for the large scale test in Figure 9, though not quite as dramatically as in Figure 8, due to cavitation of the sensors in the first layer prior to deposition of the second layer. Matric suctions achieve 100 kPa in less than a day, compared to 3 days for the initial drying period. This agrees with the evaporation data (Figure 7), which shows that Stage II drying begins much sooner after the second layer is placed than for the initial layer.

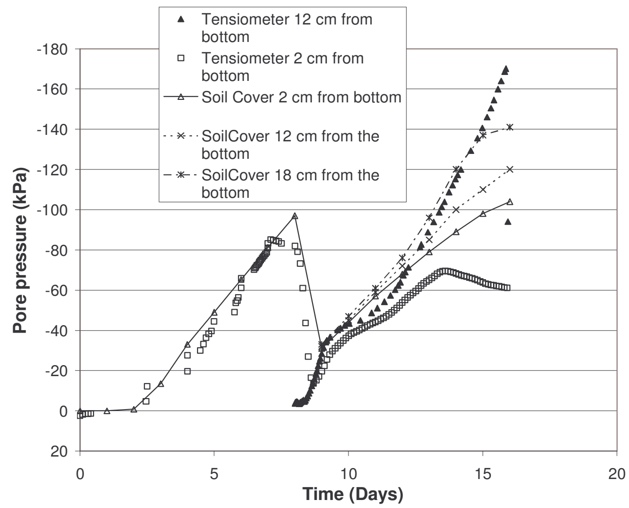

Figure 8 Matric suctions (negative pore pressure) measured and modelled during sequential deposition in the small-scale test on the Toromocho tailings

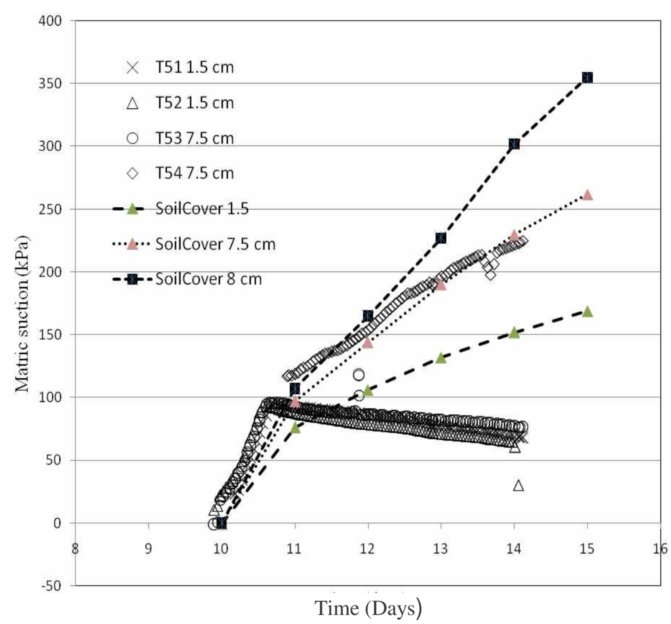

Figure 9 Matric suctions measured and modelled in second layer after deposition in large scale test.

4.0 DISCUSSION

4.1 Interlayer transmission of moisture

It is not surprising that the older layer has the capacity to suck water out the fresh layer. It is perhaps somewhat surprising that this behaviour can be reasonably simulated using the SoilCover model without using a "wetting" water retention curve for the bottom layer. However, SoilCover only generates daily output. Further analysis with a code without this restriction may give more insight; Nevertheless, the predictions made by the SoilCover model compare reasonably well with the measured data.

4.2 Influence of cracks on evaporation rate.

Previous research on slurried tailings shows that cracking may significantly increase evaporation during Stage II drying (Fujiyasu et al. 2000), sometimes maintaining evaporation near the potential rate even after evaporation from the ground surface has virtually stopped. However, this was clearly not the case in our experiments, as shown in Figure 7. The under prediction of values during Stage II drying may possibly be attributed to cracks, but the contribution is hard to quantify as the under prediction may have other sources, such as the difficulty of the model to accurately predict the evaporation rate due to poor knowledge of the water retention curve at high suctions. However, even if the discrepancy in evaporation rate was fully attributable to cracks, the effect is relatively small, and may not be important to consider in field predictions of evaporation.

4.3 Influence of salts on evaporation rate

The precipitation of salts is known to affect the evaporation rate of tailings through a number of mechanisms (Simms et al. 2007, Fujiyasu and Fahey 2000), including change in albedo, suppression of vapour pressure, and acting as a physical barrier. The largest discrepancy between predicted and modelled evaporation rates occurs after rewetting of the tailings, where the measured rate decreases below the predicted rate. The authors believe this to be the effect of salts – it can be seen visually that the degree of salt precipitation is greatest after rewetting (Figures 2 to 4). In an attempt to quantify the effect of salts on the vapour pressure, the osmotic suction was tracked at the surface using electrical conductivity measurements (Figure 10). Unfortunately, it was only possible to obtain sufficient water from pore-squeezing for the first few days following deposition of a layer or rewetting. Nevertheless, one can see an exponential trend in the increase of osmotic suction at the surface during drying – osmotic suction is a component of total suction, which is fundamentally related to the vapour pressures at the surface. In turn, the vapour pressure gradient between the soil surface and the ambient condition in the overlying air drives evaporation.

The exponential trend is due to both accumulation of mass at the surface by evaporation, and by the increase in concentration due to the decrease in water at the surface. By Day 17 (2^{nd} day after rewetting), it was impossible to obtain a sufficient pore-water sample without significantly disturbing the test.

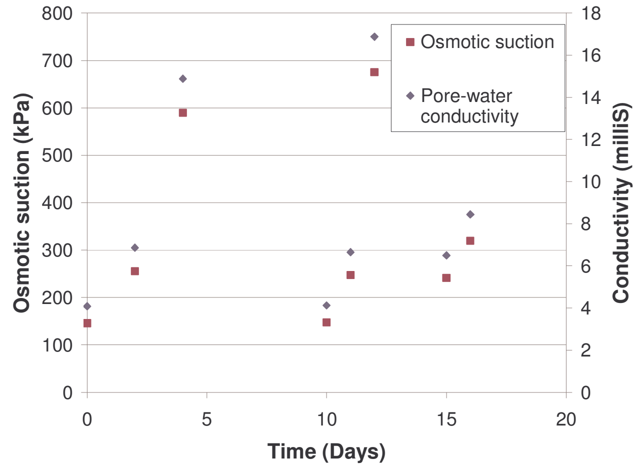

Figure 10 Evolution of pore-water conductivity and osmotic suction in the top 1 cm of the tailings in large scale test

Given the strong influence of salts, future work should investigate modelling ion transport to the surface, subsequent precipitation as salts, and coupling with evaporation.

5.0 SUMMARY AND CONCLUSION

The effects of interlayer flow, cracking, and salt deposition on evaporation from paste gold tailings was investigated. It was found that the interlayer flow could be reasonably simulated using a one dimensional unsaturated flow model, without accounting for hysteresis of the water retention curve. Cracks appear to make a relatively small contribution to Stage II drying during these experiments, when compared to older studies on evaporation from slurried tailings. Salts appeared to strongly suppress the evaporation rate below predictions towards the end of the large scale test. Future research should attempt to model the transport of ions and precipitation of salts at the surface to better investigate their influence on the evaporation rate.

ACKNOWLEDGEMENTS

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REFERENCES

Bryan, R. and Simms, P. 2008. Drying and Oxidation during Surface Disposal of Paste Tailings. *Proceedings of the 23rd International Conference on Solid Waste*

Technology and Management, Pittsburgh, Pennsylvannia, USA, March 30 - April 2, 2008

Cincilla, W.A., Landriault, D.A., Verburg, R. 1997. Application of paste technology to surface disposal of mineral wastes. *Proceedings of the Fourth International Conference on Tailings and Mine Waste '97*. pp. 343–356.

Fisseha, B. 2008. Evaporation and unsaturated flow in multilayer deposits of gold paste tailings. Master of Applied Science Thesis, Department of Civil and Environmental Engineering, Carleton University, May 2008.

Fredlund, D.G, and Rahardjo, L. 1993. *Soil Mechanics for unsaturated soils*, Wiley, New York, 1993.

Fujiyasu, Y. and Fahey, M. 2000. Experimental study of evaporation from saline tailings. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, **126**: 18-27.

Fujiaysu, Y., Fahey, M. and Newson, T. 2000. Field investigation of evaporation from freshwater tailings. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, **126**: 556-567.

Shuttleworth, J.A,. Thomson, B.J., and Wates, J.A. 2005. Surface disposal at Bulyanhulu- practical lessons learned. *6th International Conference on Paste and Thickened tailings*, Santiago, Chile, April 20th-22nd.

Simms P., Grabinsky M.W., and Zhan, G. 2007. Modelling evaporation of paste tailings from the Bulyanhulu mine. *Canadian Geotechnical Journal*, 44: 1417-1432.

Theriault, J., Frostiak, J., and Welch, D. 2003. Surface disposal of paste tailings at the Bulyanhulu gold mine, Tanzania. *In Proceedings of Sudbury 2003, Mining and the Environment*, Sudbury, Ontario, Canada, May 26th-28th 2003. Editors G. Spiers, P. Beckett, H. Conroy, pp. 265-269.