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Evaporation, Unsaturated Flow and Oxidation in Multilayer Deposits of Gold Paste Tailings

B. Fisseha *Golder Associates Ltd, Canada*

R. Bryan *Department of Civil and Environmental Engineering, Carleton University, Canada*

P. Simms *Department of Civil and Environmental Engineering, Carleton University, Canada*

Abstract

The behaviour of surface deposited paste mine tailings is strongly influenced by the evaporation and saturated-unsaturated flow through the tailings, which not only controls desiccation, but also governs salt accumulation and oxidation. Select data is presented from a series of drying tests on multilayer deposition of a gold paste tailings. During drying, rewetting after precipitation, and interlayer flow after placement of fresh layer, including small scale tests (0.15 m diameter column tests) and large scale tests (1.7 x 1.7 m in plan) were undertaken to study unsaturated flow and evaporation from two-layer deposits of two gold paste tailings. It is shown that the interlayer flow after addition of the second layer can be reasonably modelled using unsaturated flow codes. 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. The accumulation of salts could be tracked by sampling the surface of the tailings and measuring the electrical conductivity of the pore-water. Mass transport could be qualitatively modelled by one-dimensional contaminant transport theory. Profiles of sulphide oxidation with depth and time are also presented. The degree of oxidation is shown to be small but significant, and can be reasonably approximated by oxygen diffusion modelling coupled to the unsaturated flow codes.

1 Introduction

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 occurs post-deposition (Cincilla et al., 1997). Paste deposition has been employed at full-scale at the Bulyanhulu Gold Mine in Tanzania (Simms et al., 2007; Shuttleworth 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.

The Bulyanhulu deposition scheme is in part successful due to the high rate of potential evaporation driving desiccation. In general, evaporation is an important parameter for 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. The exact optimal water content depends on the acid generating potential of the tailings as well as the strength requirements for a particular tailings stack.

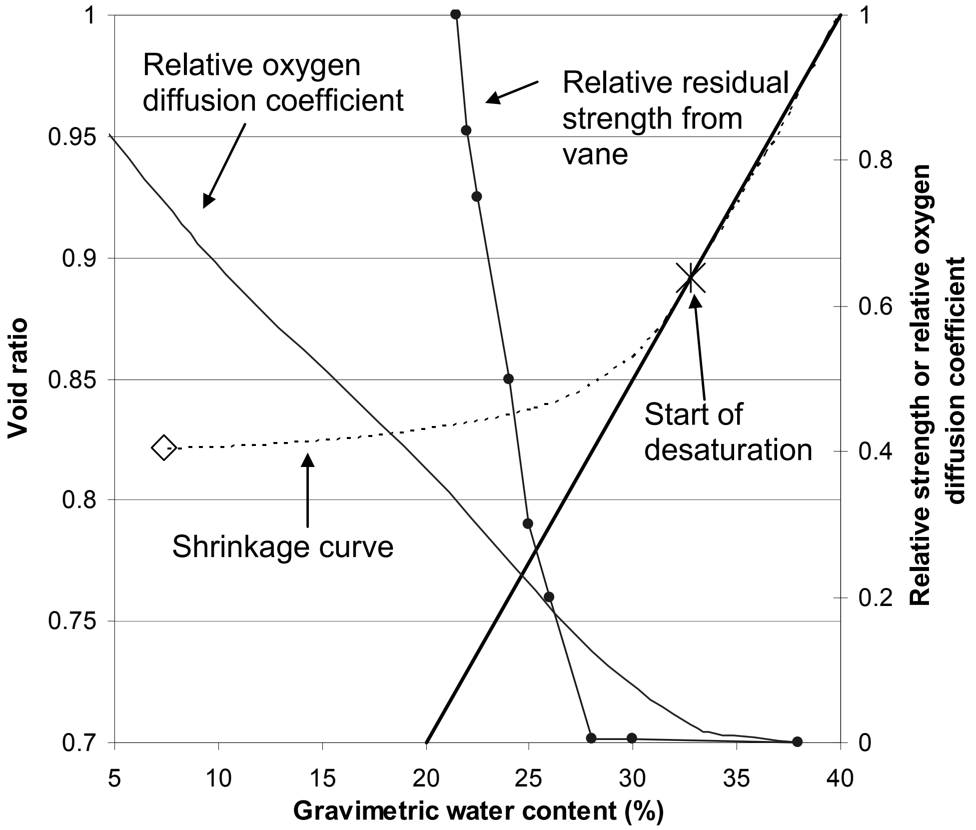

Figure 1 Shrinkage curve of paste tailings and associated geotechnical and geoenvironmental parameters (modified from Simms et al., 2007)

The principal issues addressed in this paper are: 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 three weeks after deposition (Simms et al., 2007).

The above tests were only performed on single layer deposits of paste tailings. This paper reports select results from 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. During some of these tests the oxidation rate was monitored through the determination of sulphide content. The selected results are presented to illustrate the coupling between evaporation, unsaturated flow, mass transport leading to salt accumulation at the surface, and oxidation, and therefore the potential application of unsaturated flow modelling for aiding deposition management.

2 Materials and methods

2.1 Materials

Tests were performed on a gold tailings prepared as a paste. The tailings were transported from the site at the pumping water content (~40% geotechnical, mass of water over mass of solids). During transport, the tailings would segregate, the solids 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.

Table 1 Properties of tested tailings solids

Properties	Values
Solids relative density	2.9
D_{10}, D_{50}, D_{60} (microns)	2, 35, 55
Cu (D_{60}/D_{10})	27.5
W_l, W_p, W_{sh} (%)	20, 19, 18
Hydraulic conductivity (m/sec)	2×10^{-7}

The tailings solids and bleed water were analysed 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 were performed in cylinders 15 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 x 1.7 m. 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). Volume change was monitored by point measurements using string, hung from set reference points on a wooden frame over the tests (Fisseha, 2008). 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 codes SoilCover and SVFlux 1D. Both codes solve for the fluxes of water in liquid and vapour form, and both incorporate a coupled soil-atmosphere boundary condition at the surface. However, SoilCover solves for heat transport in soils whereas SVFlux assumes isothermal conditions. SVFlux has the advantage that it reports more regular output, so it was a better tool to examine the interlayer fluxes. Parameters required for these codes 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 unsaturated flow codes 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.

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

3 Results

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

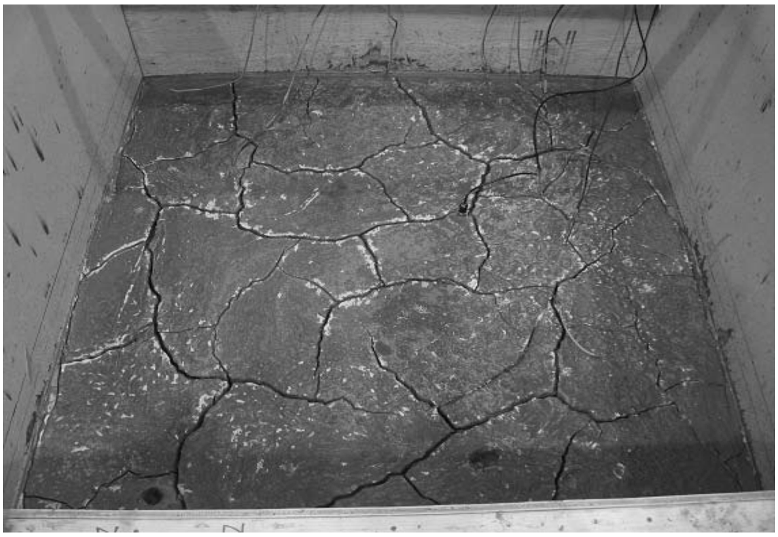

Figure 2 End of first layer (Day 9)

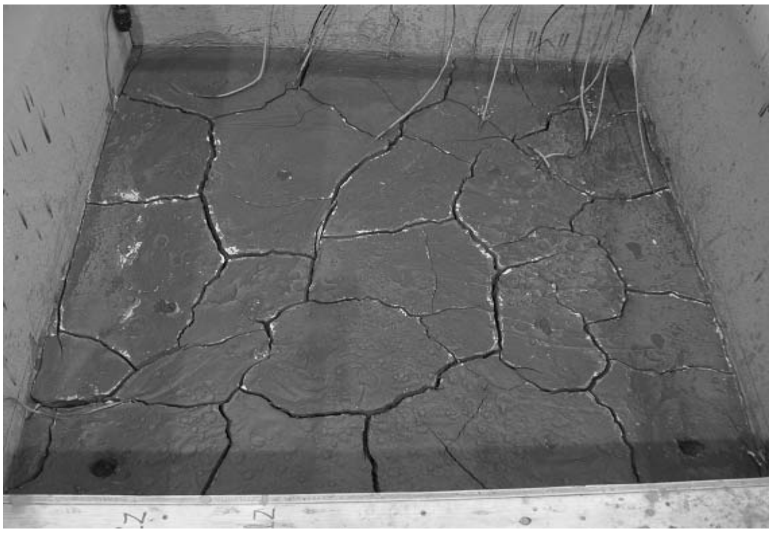

Figure 3 End of second layer (Day 14)

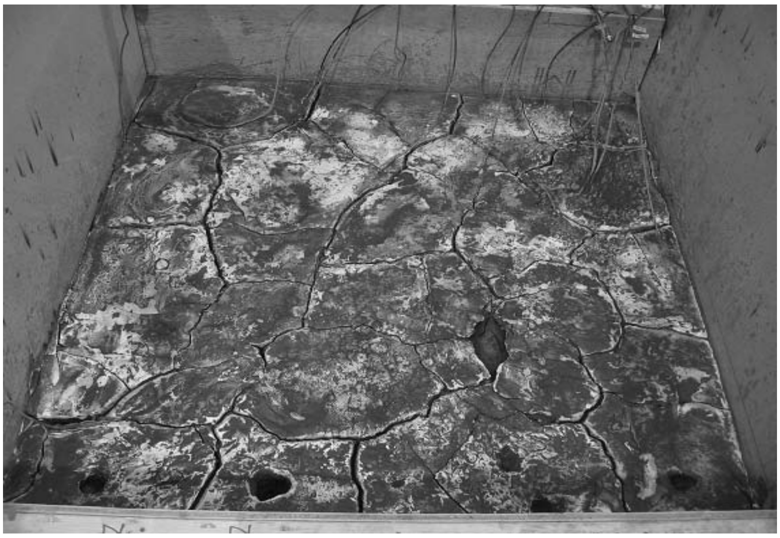

Figure 4 Four days after rewetting (Day 19)

3.1 Volume change

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 three hours after placement of the second layer. Rewetting did not appear to substantially reduce the volume of cracks.

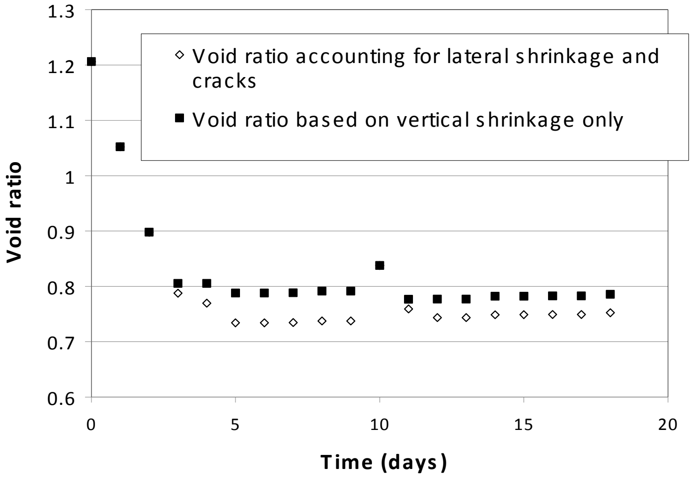

Figure 5 Volume change in large scale test

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.

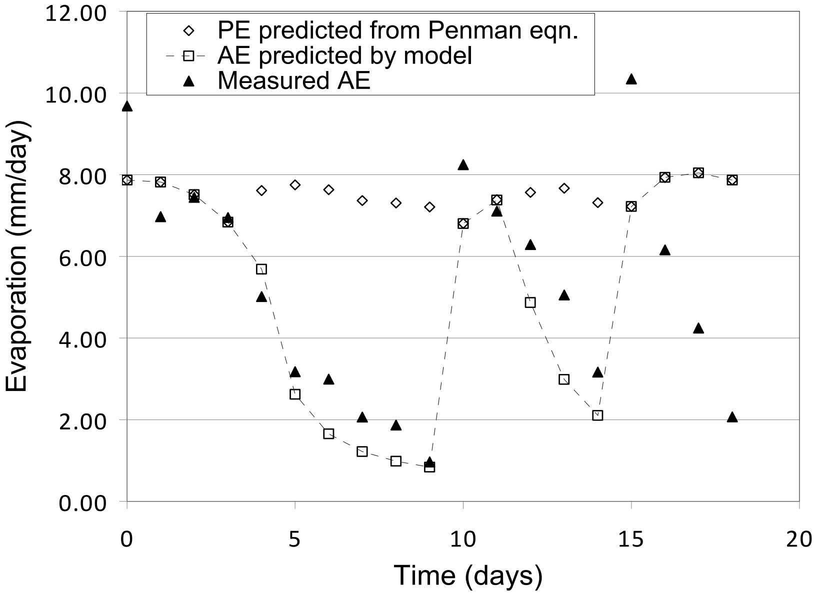

Figure 6 Evaporation during large scale test

3.3 Matric suctions

Measured matric suctions can be reasonably simulated by the unsaturated flow codes subsequent to addition of a second layer Figure 7 shows only the variation in matric suction in the fresh layer, as the tensiometers in the old layers had cavitated and did not recover. Figure 8 shows measured and modelled matric suctions in a small scale test, where the evaporation rate was lower and the next layer was added sooner. One can see that the older layer quite dramatically sucks moisture out of the fresh layer and that this behaviour can be very well approximated using the 1-D unsaturated flow codes.

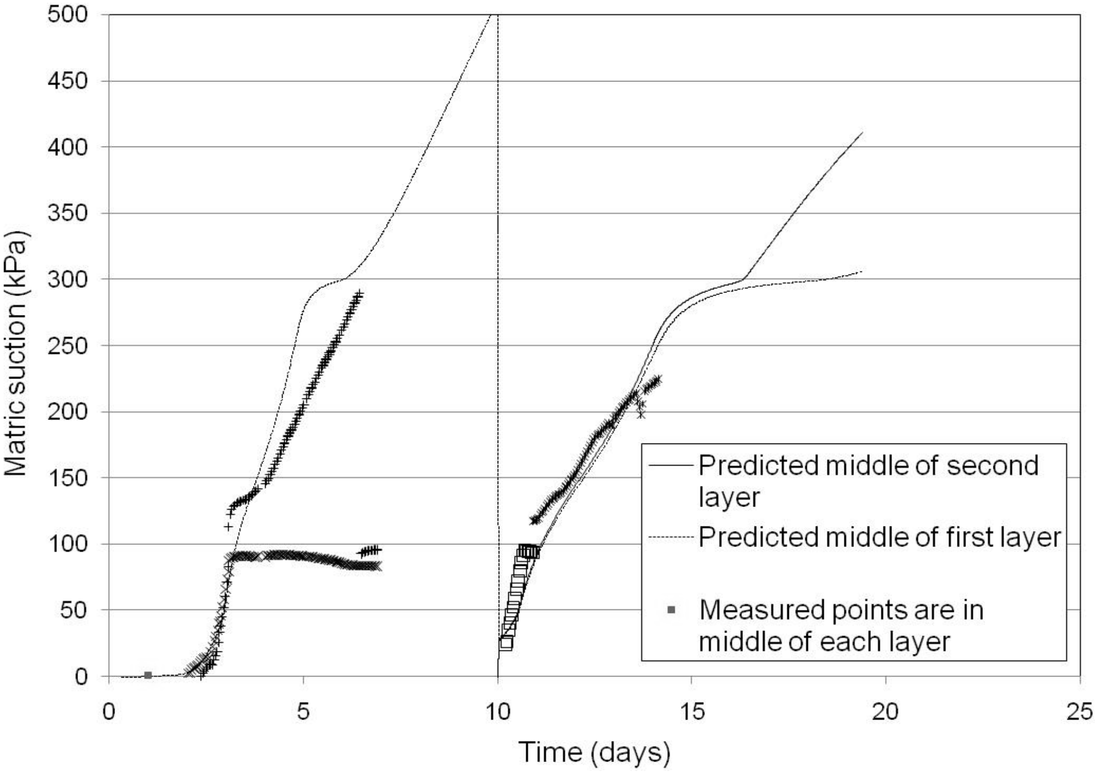

Figure 7 Matric suctions (negative pore pressure) measured by tensiometers and modelled during sequential deposition in the large scale test

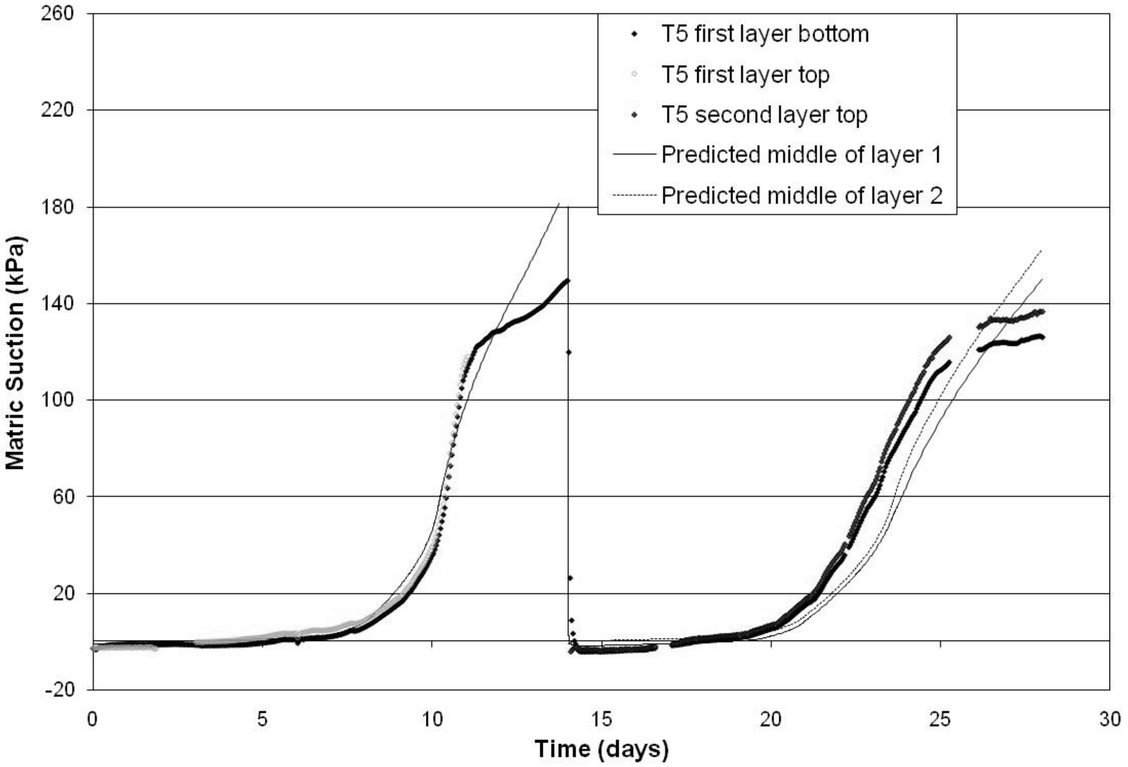

Figure 8 Measured and modelled matric suctions in small scale test

3.4 Salt accumulation in the large scale test

The accumulation of salts at the surface is tracked using measurements of electrical conductivity are shown in Figure 9. Unfortunately, the tailings became too dry to extract sufficient water for the conductivity test by Day 5, Day 13 (three days after second layer deposition), and Day 17 (three days) respectively. The general trend suggests increasing salt accumulation with time, and indicates potentially heavy salt accumulation subsequent to rewetting.

The authors decided to investigate the transport of salts, using the code Chemflux 1D. This code solves the unsteady advection-dispersion equation, and can be coupled to SVFlux 1D. Assuming standard values of diffusion coefficient and dispersitivity, as well as assuming an initial uniform distribution of ions with depth, the concentration of ions at the surface, expressed in terms of equivalent osmotic suction, is presented in Figure 10. This analysis is semi-quantitative at best, as it ignores many processes that may affect mass transport. The reductions of concentration towards the end of each phase is due to the drop in evaporation rate (Figure 6), which allows for mass to be reflected back into the tailings due to diffusion.

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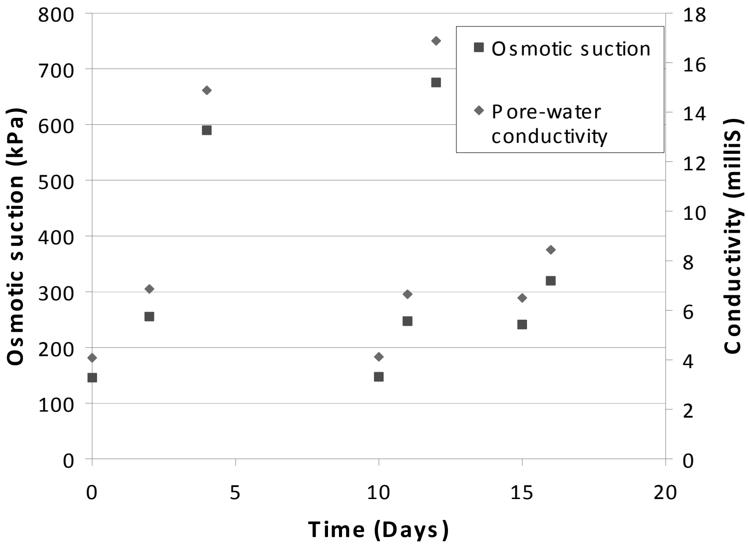


Figure 9 Evolution of pore-water conductivity and osmotic suction in the top one cm of the tailings in large scale test

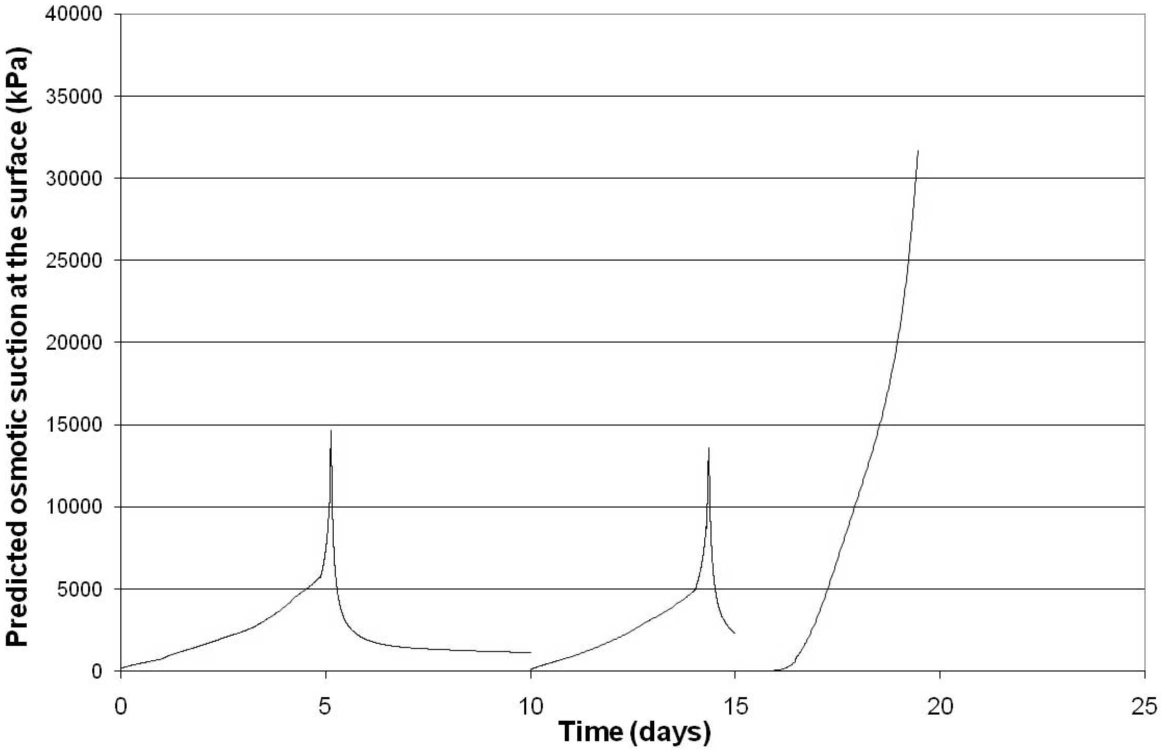
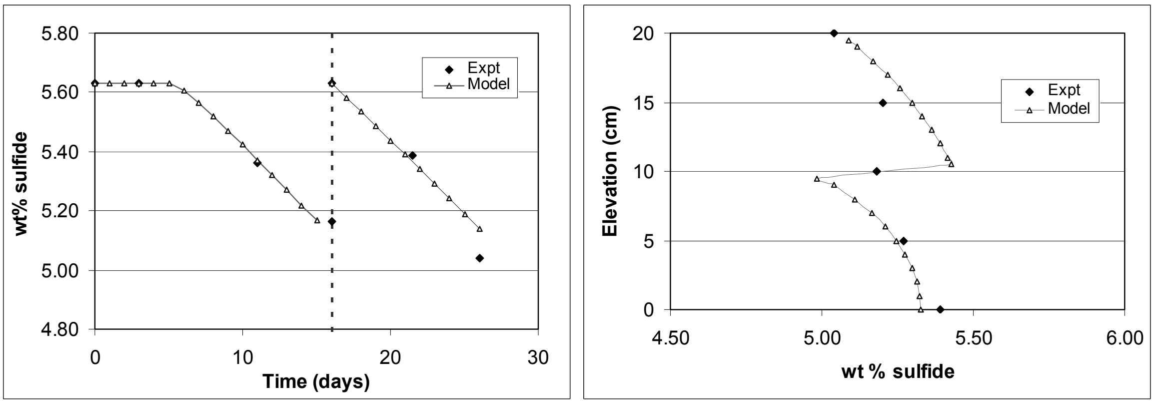


Figure 10 Qualitative prediction of accumulation of ions at the tailings surface in the large scale test, expressed in terms of equivalent osmotic suction

3.5 Oxidation

Sulphide concentrations are presented for a small scale test. The predicted values were obtained by modelling the diffusion of oxygen and assuming a first order reaction of oxygen with pyrite (the dominant sulphide mineral in these tailings). Details are described in Bryan and Simms (2008). Oxygen diffusion coefficients are determined from degree of saturation values calculated by SVFlux, using the relationships presented by Aachib et al. (2004).



a) b)

Figure 11 Sulphide depletion in the small scale test - a) at the surface of the tailings over time; and b) final profile

4 Discussion

The most interesting results are the relatively small effect of cracks on the rate of evaporation, and the apparent effect of salt accumulation in suppressing evaporation after rewetting at the end of the large scale test. The small effect of cracks probably applies only to thin layer deposition of relatively dry tailings. Fujiyasu et al. (2000) certainly noticed a strong contribution of evaporation from cracks when they studied evaporation from deep deposits of slurried tailings.

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 the crust acting as a physical barrier. The effect of albedo, studied for paste tailings in Simms et al. (2007), is eliminated due to the low level of radiation. The mass transport modelling shows that it is certainly possible for large osmotic suctions to occur at the surface, and hence vapour pressure suppression can be an important mechanism to suppress evaporation in paste tailings. Further work is required to quantify the transport of ions in paste and thickened tailings.

5 Conclusions

Unsaturated flow in these tailings could be simulated using standard one-dimensional codes, including interlayer flow.

Although significant cracks formed, the influence of cracks on evaporation was minimal.

Evaporation in the large scale test could be simulated by the unsaturated flow codes, until after rewetting. The suppression of evaporation subsequent to rewetting appears to be due to the accumulation of salts at the surface. Mass transport modelling may potentially be used to couple salt accumulation to suppression of evaporation.

Small but significant oxidation occurred during these relatively short tests. Oxidation cannot be ignored in deposition of potentially acid-generating paste or thickened tailings on surface. The oxidation profiles could be modelled using a contaminant transport code coupled to the unsaturated flow code.

Acknowledgements

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