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# Dewatering in a laboratory simulation of a multilayer deposit of inline flocculated mature fine tailings

**E Rozina** *Carleton University, Canada*

**S Mizani** *Carleton University, Canada*

**M Malek** *Carleton University, Canada*

**M Sanchez-Sardon** *Carleton University, Canada*

**P Simms** *Carleton University, Canada*

## Abstract

*This paper examines the dewatering behaviour of in-line flocculated oil sand mature fine tailings. Tailings used in this study had an initial solids concentration of 36% and were dosed at 650 g/t, using laboratory procedures that have previously been shown to represent field mixing conditions. Three layers of initial thicknesses of 0.3 to 0.35 m were successively placed in an instrumented box 0.7 by 1 m in plan, mounted on scales and equipped with a drainage system. Water content sensors and porewater pressure sensors were placed at various heights. Volume change was tracked by non-contact displacement sensors and by time-lapse imaging and hand measurement of crack development.*

*Increases in evaporation were found to be strongly correlated with the appearance of cracks. The actual evaporation rate exceeded the potential evaporation rate as long as crack development continued to occur. This is the first documented case of evaporation exceeding the potential rate in any controlled laboratory study.*

*Despite substantial drainage, supernatant water formed on top of the tailings, and remained there longer than the initial consolidation phase of dewatering. Consolidation alone was able to increase solids concentration of the tailings to about 53%. For these tailings, which show a relatively high shear strength (achieving the directive 74 requirement between 55 and 60% solids, if porewater pressure is near zero or negative), not much drying is required to bring the tailings to regulatory compliance; even less is required if the tailings consolidate further when buried by new layers.*

*Conservatively extrapolating the results of this test, it is estimated that a rate of rise of 2.2 m per year would still allow for the regulatory shear strength of 5 kPa to be achieved. This rate of rise is comparable to that proposed by field studies on similar tailings in thin lifts.*

## 1 Introduction

The waste stream from the bitumen extraction process, in Northern Alberta, Canada, produces low solid content slurry called oil sand tailings. Oil sand tailings comprise a range of solid particle sizes, the coarse particles (sands) settling out following deposition, leaving behind a fines fraction with solids content of 8%. After several years, fine tailings will typically settle out to a solids concentration of about 35% in the ponds. At this point (where it is called mature fine tailings or MFT) the material is still in a soft state with little strength (<1 kPa undrained shear strength), preventing any kind of reclamation work. Slow or negligible dewatering past 35% solids is due to the poor consolidation properties of MFT as well as the build-up of pre-consolidation pressure due to thixotropic re-alignment of particles (Scott et al. 2013).

Regulators enacted Directive 74 in 2009, which mandates that half of the fine tailings that are generated at a given operation must be deposited so as to achieve trafficability in the near future. Deposits are considered 'on the road' to trafficability based on achieving an undrained shear strength of 5 kPa after one year and 10 kPa after five years. As a consequence, the oil sands industry has investigated several techniques at pilot and commercial demonstration scales, to improve the rate of fluid fine tailings dewatering. Technologies that have had some success at larger scales include in-tank thickening, centrifugation, and in-line flocculation, all of which are combined with some sort of deposition control to maximise post-deposition dewatering. Variants on in-line flocculation using anionic polymers and controlled lift deposition, termed Atmospheric Fines Drying (AFD) and Tailings Reductions Operations (TRO), have been employed at Shell and Suncor operations (Matthews et al. 2011; Wells et al. 2011; Dunmola et al. 2013; Caldwell et al. 2014).

Mechanisms contributing to post-deposition dewatering include evaporation, self-weight consolidation, and freeze-thaw consolidation. While thin layer deposition maximises the contribution of evaporation and freeze-thaw to dewatering, it may minimise the contribution of consolidation. Properly assessing the contribution of each mechanism to dewatering is important to optimise this technology, and minimises required footprints of tailings disposal areas. The work presented in this paper focuses on quantifying the rate of evaporation from polymer-amended MFT deposits, particularly tracking the influence of cracking on the evaporation rate. The movement of salts may also affect the evaporation rate. Both phenomena have been shown to affect evaporation from hard rock and finer grained tailings (Fujiyasu et al. 2000; Fisseha et al. 2010). With respect to oil sand tailings, Innocent-Bernard et al. (2013) showed that cracking is intimately linked with evaporation from fluid fine tailings treated in a thickener; evaporation rates were shown to cycle from the potential rate down to a residual value as surface crust dried out, cracks subsequently formed, cracks dried out, and new cracks formed again. By contrast, Daliri et al. (2012) and Simms et al. (2013) showed that cracking in thickened gold tailings did not measurably affect the evaporative behaviour. In all cases, however, evaporation at the surface at some point became limited by mass transport to the surface and salt formation.

This work complements another ongoing work on evaluating the suitability of desiccation-consolidation numerical models to assist deposition design (Soleimani et al. 2014).

Post-deposition dewatering of polymer amended MFT product prepared in the laboratory is studied by multilayer deposition in a ‘drying box’, 0.7 by 1 m in plan. The outcomes of the test are compared to other drying box simulations of different tailings, and to the field behaviour of in-line flocculated tailings.

## 2 Material

MFT and a high molecular weight anionic polymer were used in this study. The raw MFT had an initial solids content of 36% and a sands to fines ratio of 0.27. The geotechnical properties of the MFT can be found in Mizani et al. (2013). A high molecular weight polymer was used as the flocculant agent. Flocculant solutions of 0.4% (w/w) were prepared by adding 4 g of polymer to 996 g of reclaimed water. Mine reclaim water was used to prepare the flocculant solution. A dosage of 650 mg/kg mass of polymer per dry mass of tailings was employed, based on maximising water release due to consolidation only over one week (Soleimani et al. 2014). The procedures followed for preparing flocculant solutions and amended MFT are as outlined in Mizani et al. (2013), where the material was prepared so as to replicate the properties of field generated polymer amended MFT by comparing yield stress values measured by the stress growth technique. Slump and moisture content measurements were taken at specific intervals to ensure consistency in the produced material during testing.

## 3 Methods

Oil sand tailings were deposited in three layers into a plexiglass box with steel framing with dimensions of 98.7 × 69.7 × 63.0 cm (L × W × H), similar to the set-up used by Innocent-Bernard et al. (2013) and Daliri et al. (2012). Geotextile material was secured along the base and sides to prevent the loss of solids with drainage. A tipping bucket rain gauge collected the water lost by drainage through a valve in the centre of the bottom of the box. The box was mounted on load cells, which were connected to a data logger that recorded the loss of mass due to evaporation and drainage. The change in height of the material was recorded by Senix (height) sensors mounted on wooden beams as shown in Figure 1. Deagon 5TE (volumetric water content) sensors, and UMS T5 tensiometers (porewater pressure and matric suction) were placed at every 16 cm height interval in the box to monitor the variability of consolidation and drying in the soil profile. A relative humidity Easy Log USB sensor was placed on one of the beams to monitor temperature change and relative humidity above the tailings. Two electrical fans were placed at opposite ends of the box in order to simulate wind. As soon as the tailings surface was exposed, grab samples (~50 g) were obtained from the surface and within cracks to measure water content, total suction using a dew point hygrometer (Wenglor model WPT4), and electrical conductivity.

The tailings were deposited in three layers of a thickness of approximately 31, 35, and 33 cm, at average solids concentrations of 35, 34, and 33% respectively, with a flocculant dosage of approximately 650 mg/kg The layers were left to consolidate and dessicate to the shrinkage limit of the material, before the deposition of the subsequent layer.

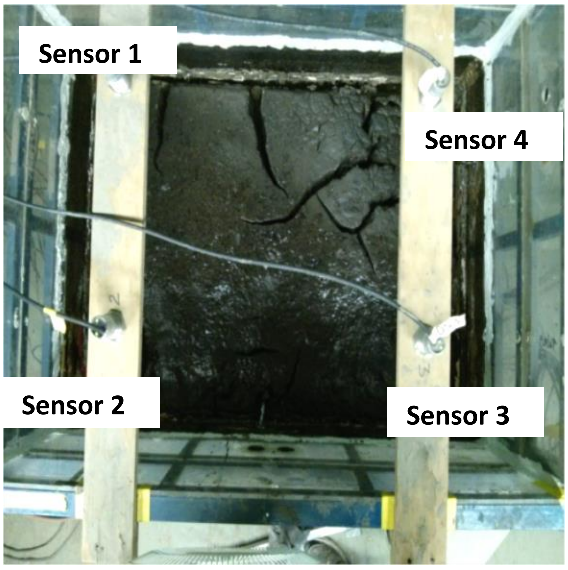

**Figure 1 Senix sensor set-up**

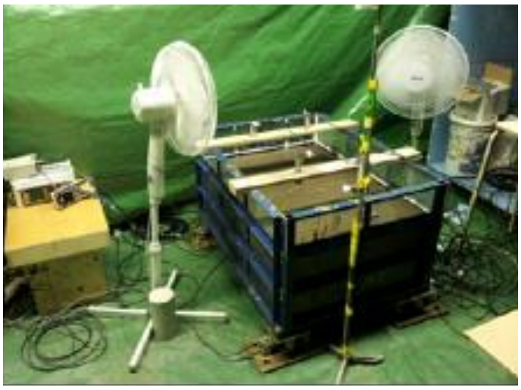

**Figure 2 Drying box in profile**

# 4 Results

## 4.1 Evaporation behaviour

The potential or pan evaporation rate was measured by filling the box up with water. The effective wind speed was then back-calculated using the Penman–Monteith equation and employing the measured RH and temperature values. When tailings were placed, the potential rate was calculated using measured relative humidity and temperature values, and knowing that the contribution of wind (generated by fans) remained the same. The evolution of RH, temperature and the corresponding dewpoint is shown in Figure 3.

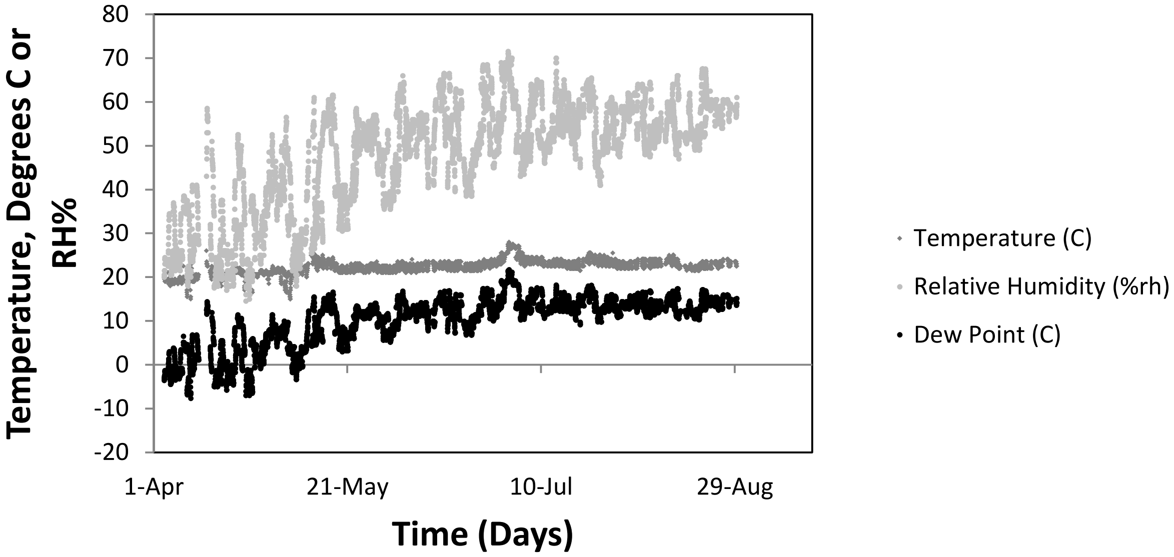

**Figure 3 Relative humidity, temperature and dew point above the tailings**

While the air temperature varies between 19° and 23°C, the relative humidity shows a gradual but substantial increase from April to mid-June, as the seasons change from winter to summer. The change in the relative humidity is reflected in the variation of the predicted potential evaporation rate (Figure 4), which gradually decreases from 4 to 2.5 mm/day.

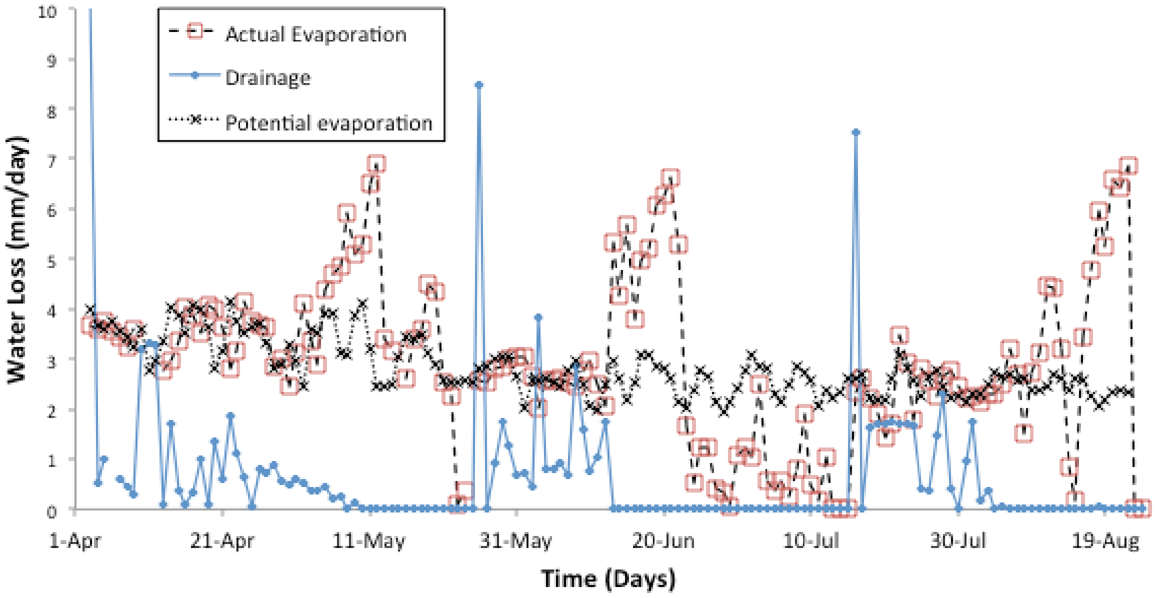

**Figure 4 Total water loss, daily evaporation, and daily drainage**

Figure 4 also shows drainage and actual evaporation. Deposition of each lift occurred on 3 April, 26 May, and 17 July. Actual evaporation (AE) is calculated by subtracting drainage from the total water loss measured by the load cells. Actual evaporation matches closely with the predicted potential evaporation (PE) values from after deposition until 5 May, 13 June, and 17 August for each layer, after which there is a period where AE substantially exceeds PE. The start of this period correlates with the commencement of cracking and ends when crack development stops. Figure 5 shows the evolution of crack geometry in

Layer 1, and evaporation is compared to crack volumes in Figure 6. Crack volumes are calculated by measuring crack surface area by surface photo analyses, measuring crack depth by hand and assuming a triangular cross-section.

April 30 | May 5 | May 10

May 15 | May 20 | May 25

**Figure 5 Progression of cracking – Layer 1**

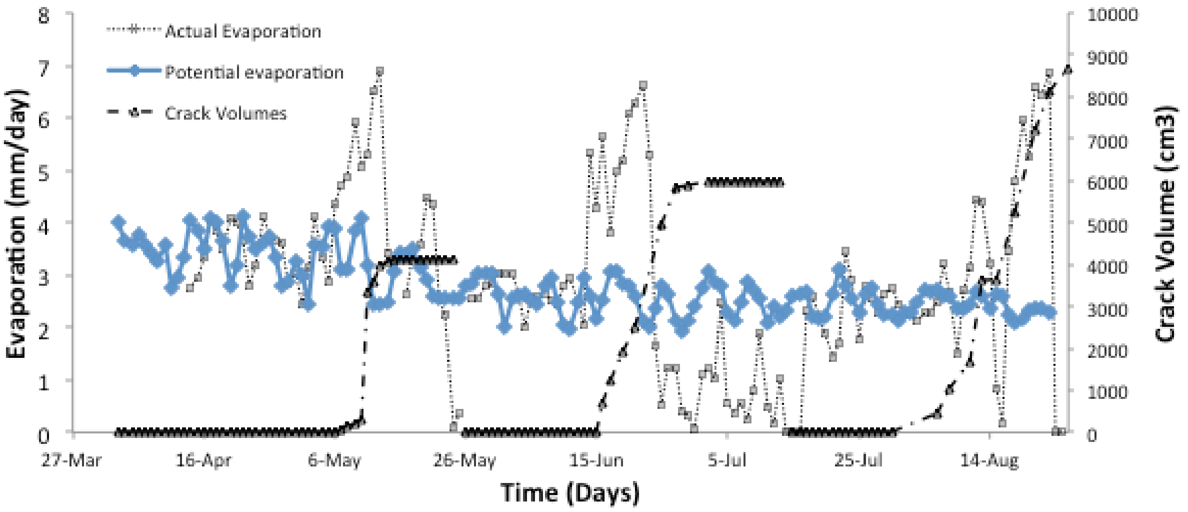

**Figure 6 Total daily water loss and daily water loss through evaporation**

In general, evaporative behaviour can be divided into three stages: the first, in which evaporation is close to the potential rate; the second, in which actual evaporation exceeds potential evaporation and is co-incident with crack growth; and the third, when evaporation decreases below the potential value, coincident with termination of crack growth. The third stage is also characterised by the development of high total suctions (>1 MPa) at the surface of the tailings (Figure 7). This behaviour is expected and is similar other oil sand tailings streams and hard rock tailings (Innocent-Bernard et al. 2013; Daliri et al. 2013).

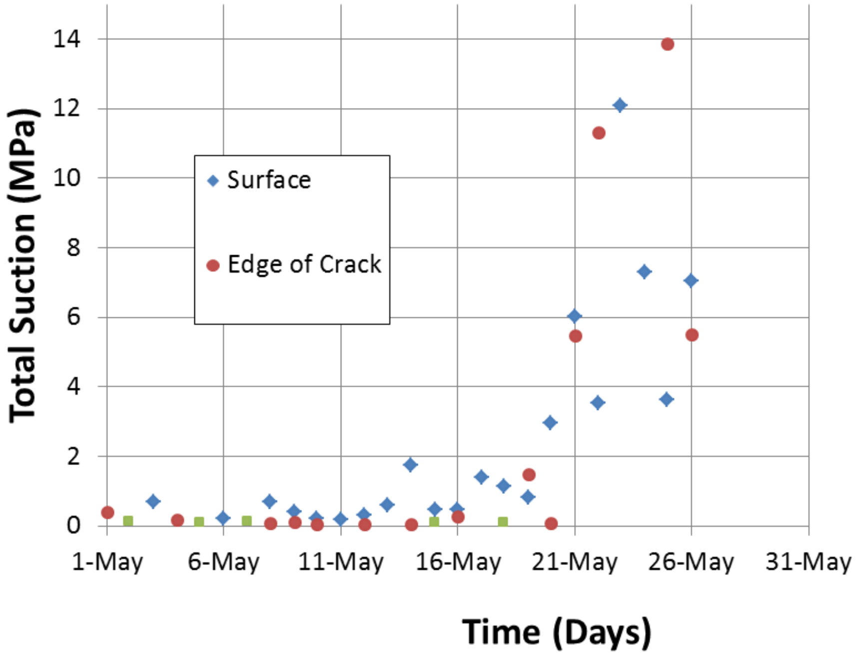

**Figure 7** **Total suction at surfaces for Layer 1**

## 4.2 Dewatering behaviour

Figure 8 shows the expected height of the tailings for each layer, if the tailings were added instantaneously. Of course, as they are not added instantaneously, the height at the end of day one is somewhat smaller than this height, and there is much more of a difference in the second and third layers. For the latter layers, this is due to capacity of the older layers to absorb moisture.

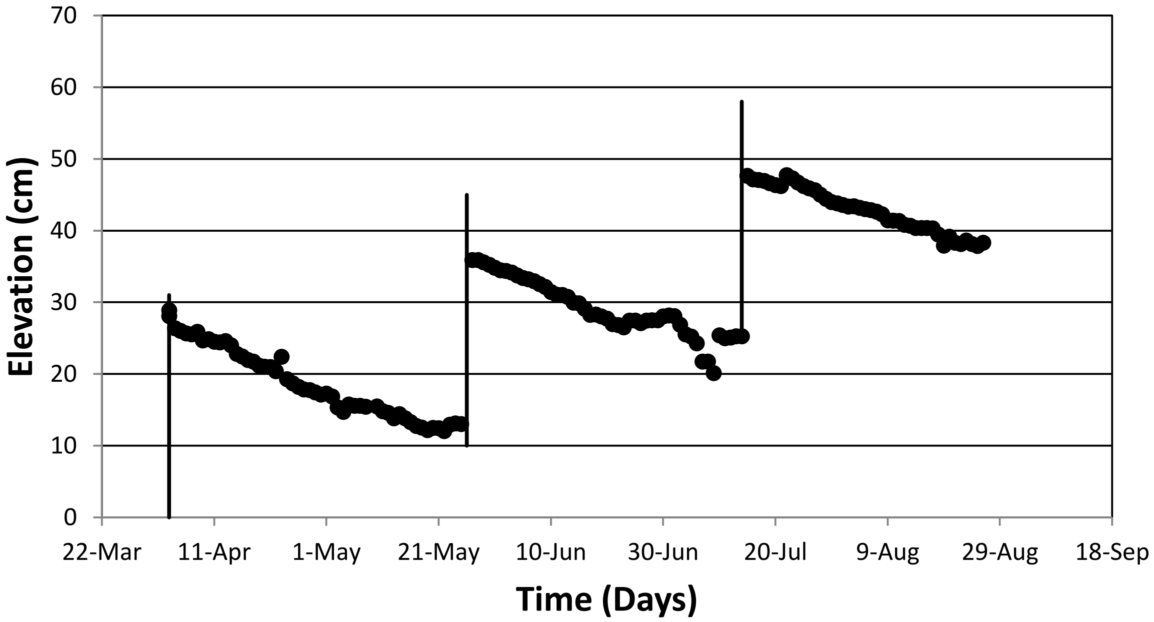

**Figure 8** **Height tracked by displacement sensors. Black lines show initial thickness if a layer would be instantaneously deposited at 36% solids**

For all layers, the tailings produced supernatant water that stayed for several days on the surface, despite substantial drainage. The supernatant water evaporated or drained on the same day that the surface gravimetric water contents measurements started (Figure 9) on 30 April, 14 June, and 5 August . The average water content of the tailings in Figure 9 thus includes the supernatant water before those dates. Therefore, substantial dewatering that occurs up to these dates, to average geotechnical gravimetric water content (GWC) of 90% and an average solids concentration (Cs) of 53% in Layer 1, is entirely due to consolidation. Hand measurements of the height indicate that volume change due to consolidation ceased by 15 April, 11 days after deposition.

We differentiate between volume change in individual layers using the volumetric water content (VWC) sensors. The VWC in Layer 1 is shown in Figure 10. At the beginning of dewatering, the sensors show a variation of water content with depth, lower water content and therefore higher density at the bottom, which would be expected from self-weight consolidation. Note that the top sensors were ratcheted out of the tailings and had to be re-positioned. Once drying sets in, the water contents sensors show lower water contents at higher elevation sensors. After placement of the new layers, the VWC of Layer 1 settles down to about 0.35. One sensor rises in VWC value, but this sensor was in contact with fresh tailings. The VWC in the two other layers is shown in Figure 11. The sensor at the top of Layer 2 is exposed to fresh tailings during placement of Layer 3.

The VWC values in Figures 10 and 11 are not calibrated. After calibration, the VWC in Layer 1 tailings after rewetting was equivalent to a gravimetric water content of about 47%. Constructing a shrinkage curve from measured void ratio and GWC data from Layer 1, it is clear that 47% GWC is the shrinkage limit of the material, corresponding to a void ratio of 1, as shown in Figure 12. Thus the tailings resaturate, but do not swell appreciably upon rewetting. Figure 12 also shows the results for shrinkage curve obtained from a small sample in a ring. The resulting shrinkage curves for both cases are very similar.

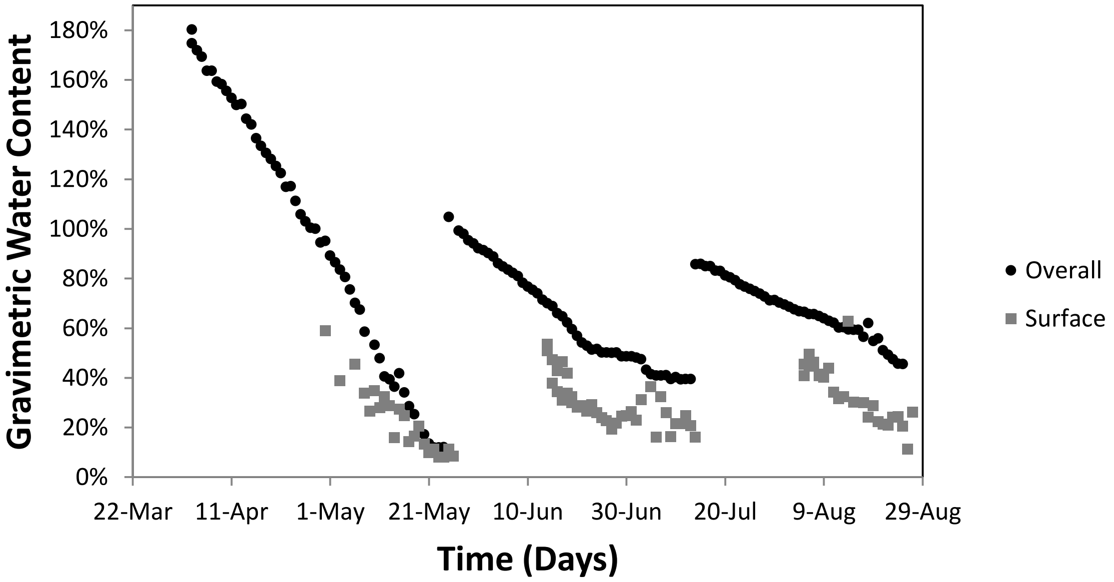

**Figure 9** Overall and surface gravimetric water contents

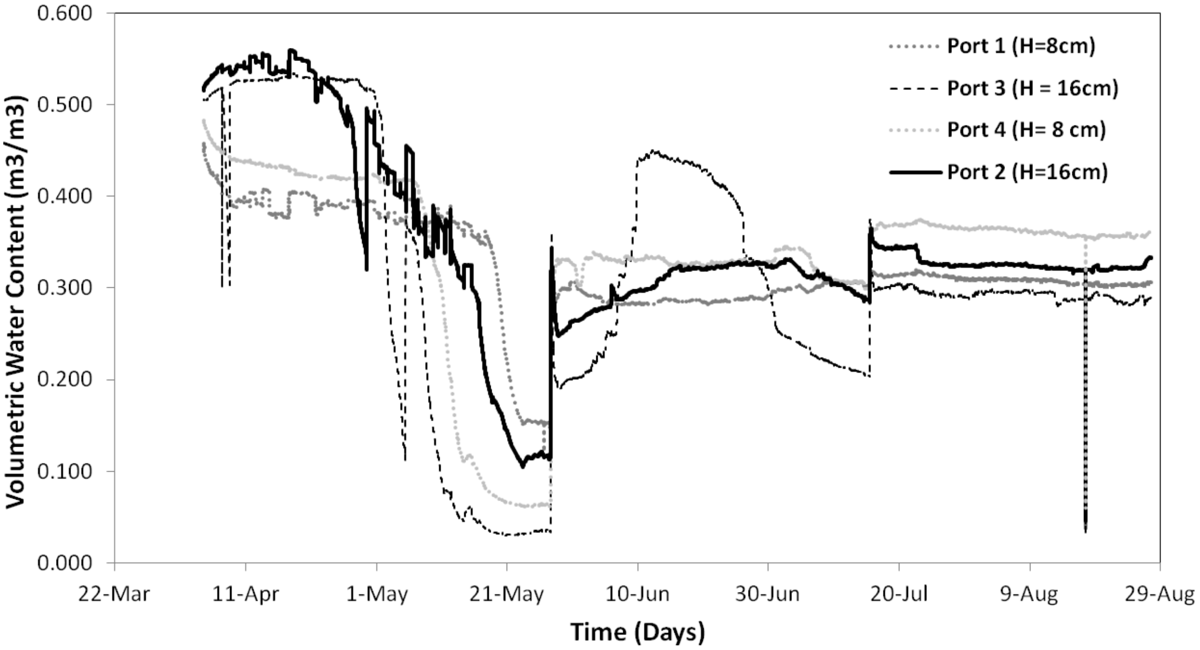

**Figure 10 Volumetric water content in Layer 1**

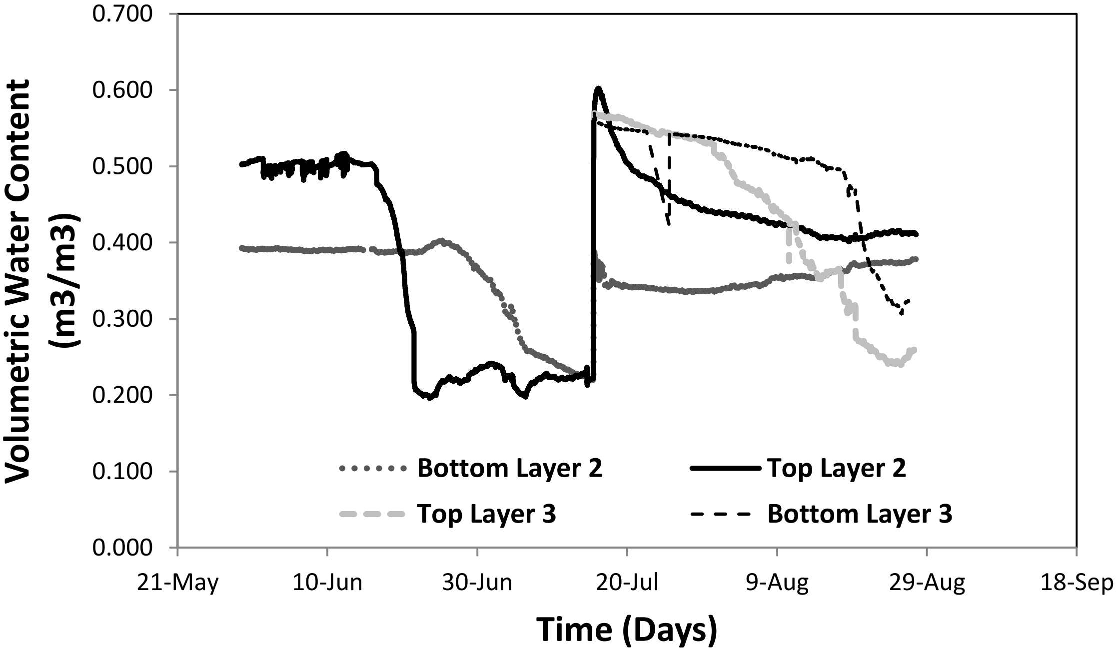

**Figure 11 Volumetric water content in Layers 2 and 3**

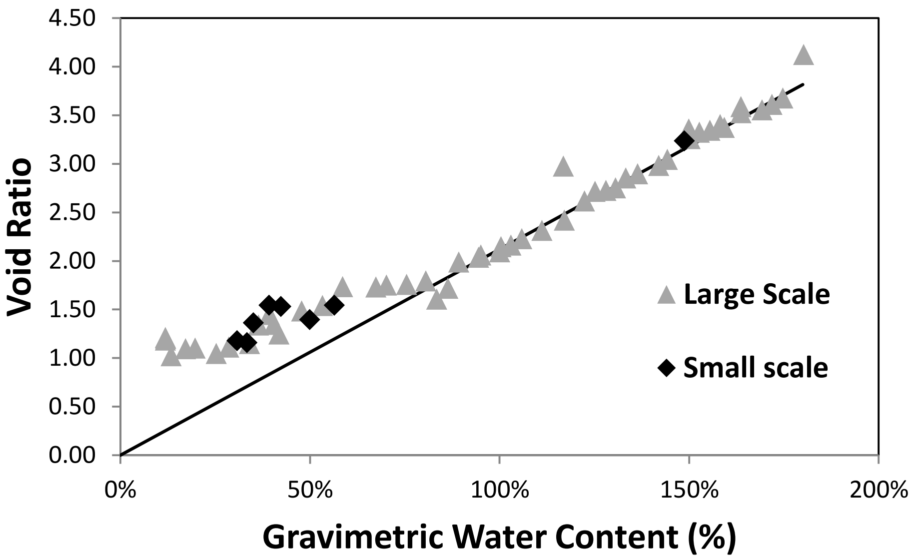

**Figure 12 Shrinkage curve derived from Layer 1 data**

The VWC is used to estimate the change in solids concentration in each of the top layers during dewatering, shown in Figure 13. We see that for Layer 1, the VWC sensors show a faster increase in density. This is because the overall solids concentration includes the supernatant water, but the VWC sensors measure actual water content in the layer.

From Figure 13, we can compare the rate of dewatering to achieve solids concentrations of 53% (post-consolidation) and 68% (shrinkage limit) – these are respectively for each Layer 11, 5, and 11 days to achieve 53% solids, and 35, 30, and 35 days to achieve the shrinkage limit. The difference with Layer 2 is that Layer 1 was substantially desaturated, so that a substantial amount of water could be absorbed when Layer 2 was added. The same cannot be said for Layer 3, since Layer 2 was dried only to about the shrinkage limit.

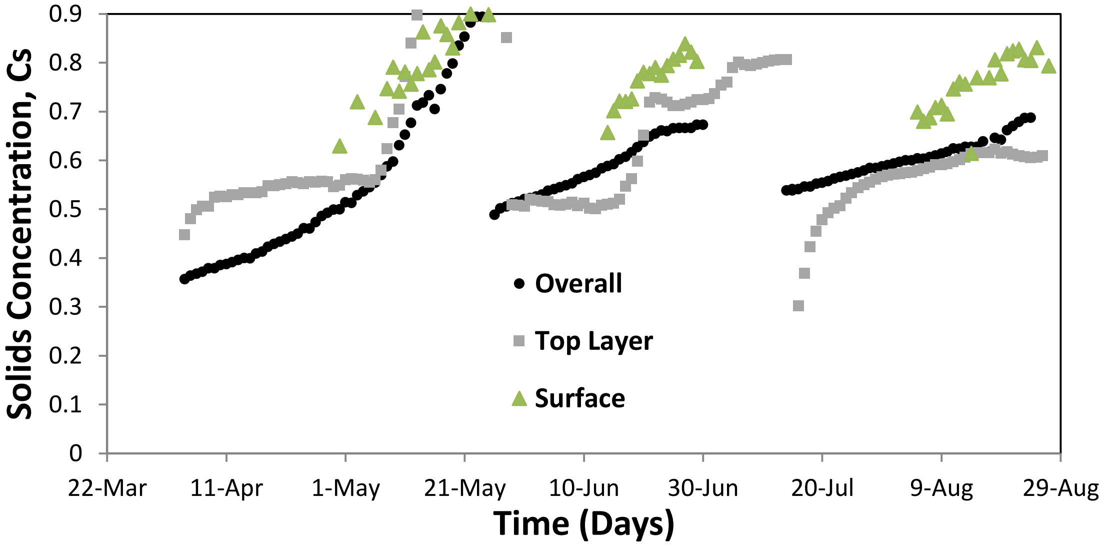

**Figure 13 Solids concentrations overall and for top layers, estimated by VWC sensors**

## 4.3 Degree of saturation, porewater pressure/matric suction, and crack initiation

Overall void ratio and degree of saturation are shown in Figures 14 and 15. There is no significant effect on the overall void ratio due to crack formation (an increase of approximately 0.2 at the most). Degree of saturation begins to fall appreciably below 1 on 4 May, 17 June, and 21 August at about 80% GWC and 55% solids for the average water content of the top layer. In all layers, cracking initiated before the onset of desaturation (Figure 4).

The tensiometer readings (Figure 16) were problematic because tensiometers were exposed to air when cracking started to develop, or were even ratcheted out of the tailings during consolidation. However, the tensiometers provide good data passing from the positive to the negative pore-pressure range. In Layer 1 (Figure 17), we see that the bottom and topmost tensiometer showed greater rates of pore-pressure dissipation than the middle sensor (probably due to drainage), but the middle tensiometer reads higher than the bottom tensiometer once drying commences. For all layers, crack initiation was correlated with one or more tensiometers registering suction (negative porewater pressure), which occurred almost immediately when supernatant water disappeared.

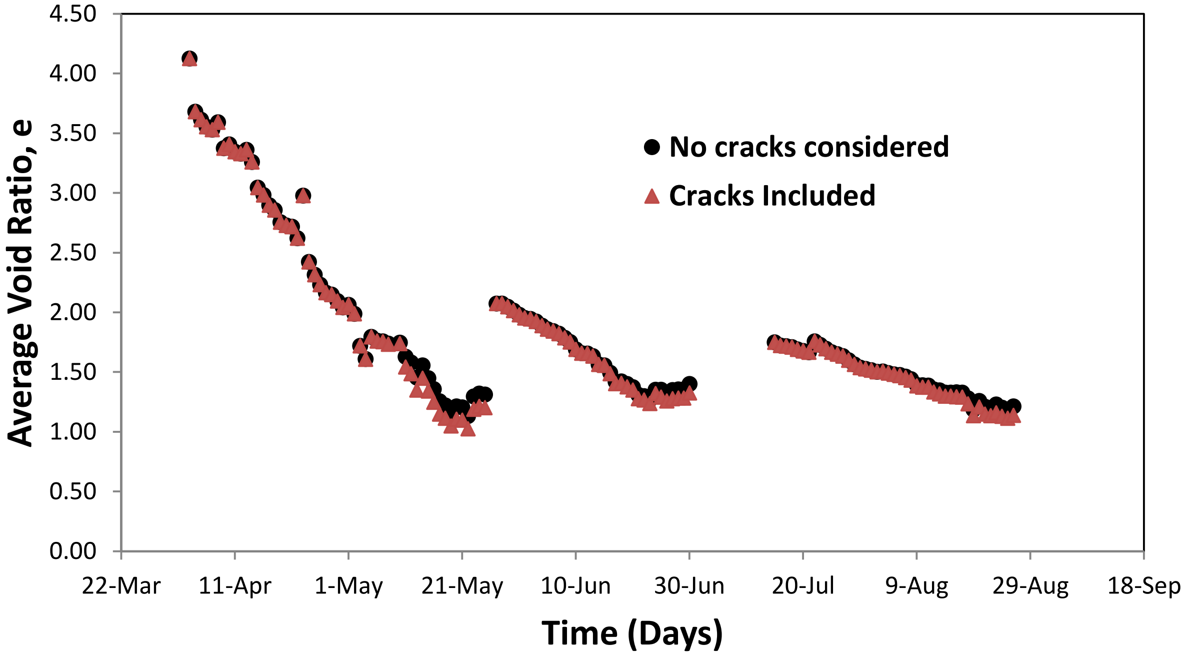

**Figure 14 Overall void ratio**

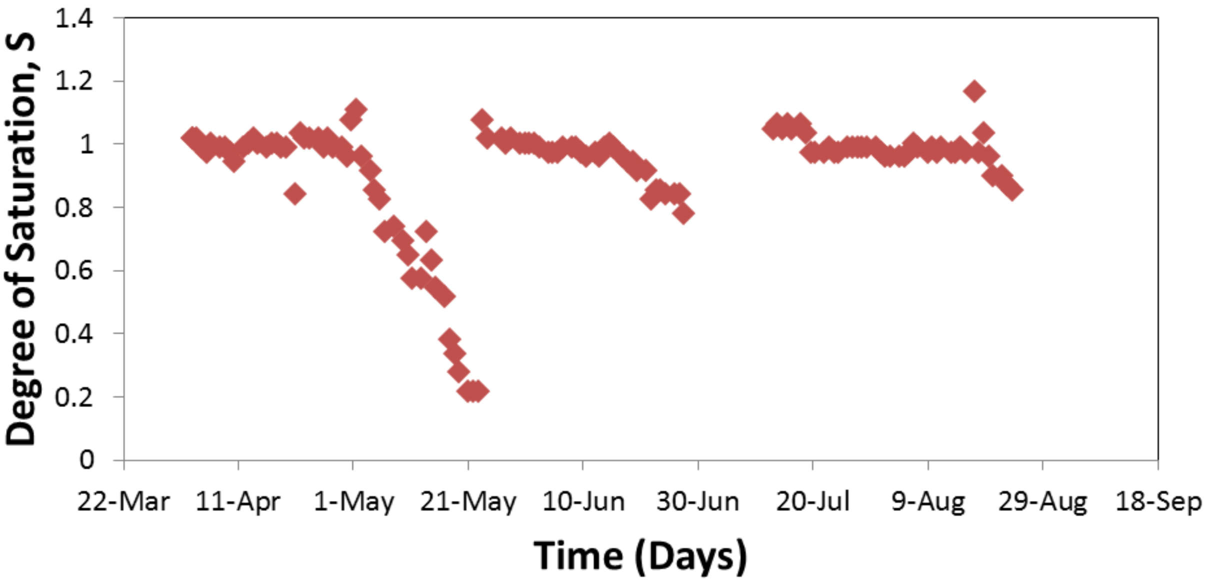

Figure 15 Overall degree of saturation

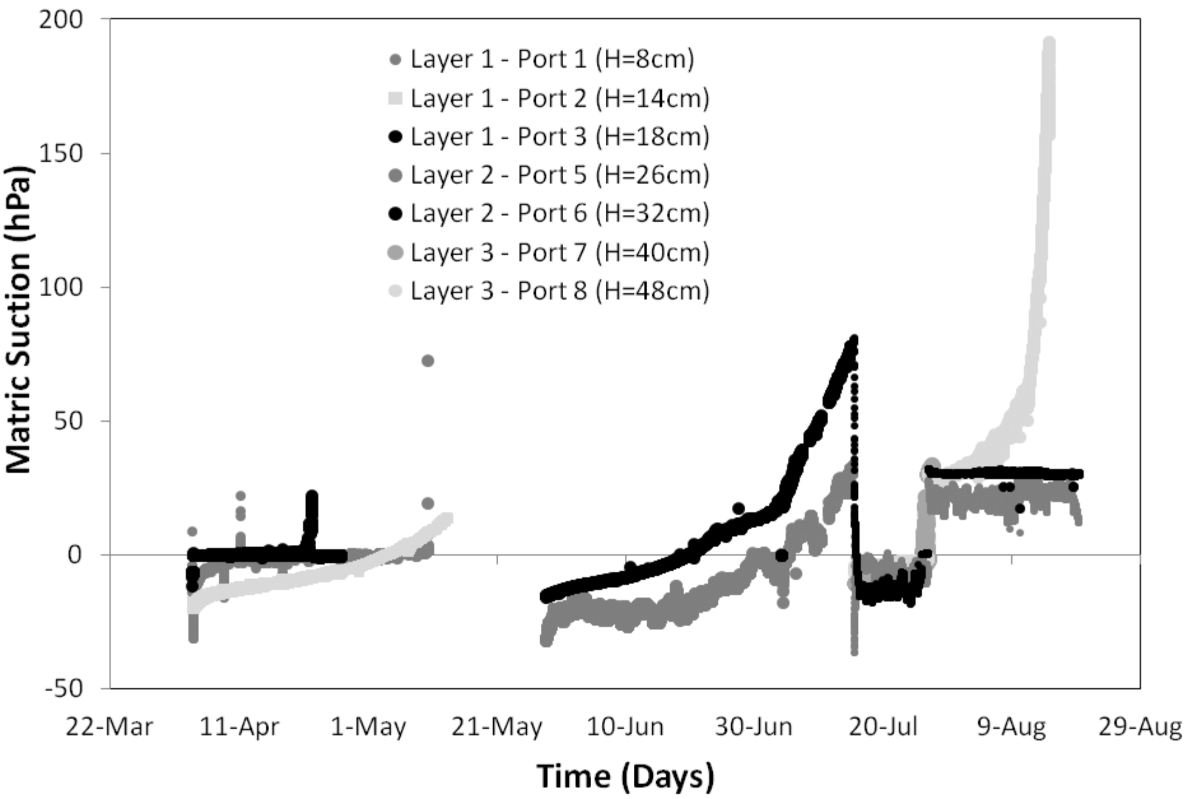

Figure 16 Matric suction/porewater pressure values in hPa

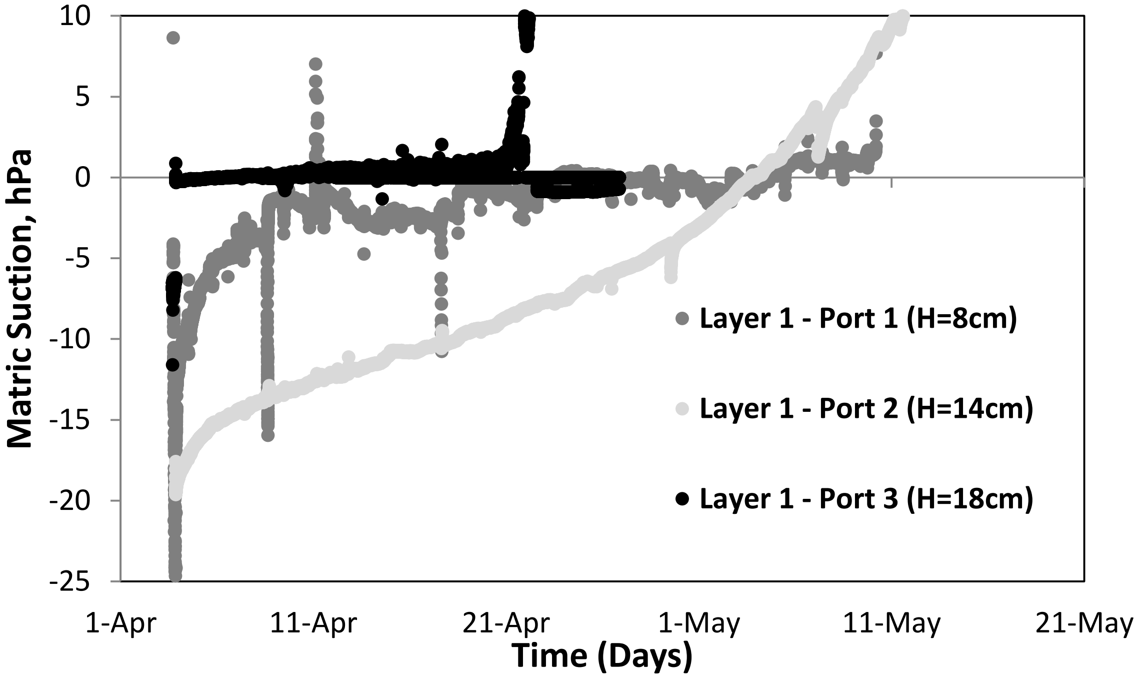

**Figure 17 Matric suction/porewater pressure in Layer 1**

## 5 Implications

For these tailings, the 5 kPa requirement as per ERCB Directive 74, is achieved for solids concentration between 55% and 60%, at least when pore-pressures are reduced to near zero or negative values. Given that this needs to be accomplished within one year after deposition, it is likely that no more than 55% solids concentration needs to be achieved before placement of the second layer. Therefore, for this scenario of quite thin lift deposition (30-35 cm), this would be achieved by one month or sooner, if supernatant water would drain off due to placement of tailings on a slope. Considering a four-month summer season (mid-May to mid-September), a summer rate of rise of 1.2 m is possible. Coupled with a 1 m lift placement prior to the winter for freeze-thaw, a rate of rise of 2.2 m a year is possible. This would require a footprint of 4 by 4 km for an operation generating 100,000 m$^3$ of mature fine tailings per day. The rate of rise is comparable to that suggested by the experience with thin lift drying at Suncor (Caldwell et al. 2014).

## 6 Conclusions

All three layers exhibited a consolidation phase, followed by a lag in dewatering due to the presence of supernatant water, followed by drying and crack development. Consolidation brought the top layer to about 53% solids. Consolidation was accelerated in the case of the second layer, due to the first layer having a low degree of saturation upon placement of the second layer.

After crack initiation, actual evaporation increased substantially over the potential evaporation rate. This is, to the authors' knowledge, the first demonstration of sustained AE/PE>1 for tailings in a controlled laboratory setting.

A solids concentration of 55% is reached in these thin lifts very shortly after the initiation of cracking. This may be a criterion for placement of the next lift.

Of course, controlling lift thickness is not trivial, and this problem remains the most important obstacle to implementing thin lift deposition.

## Acknowledgement

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