Desiccaton and consolidation modelling of oil sands fine tailings deposits

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ABSTRACT
Oil sands tailings deposition is regulated by enforcing reduction of the volume of fluid fine tailings over the life of an operation. Operators are meeting these targets by improving dewatering and consolidation characteristics of fine tailings through various techniques, often involving addition of polymer or other flocculation-inducing treatment. Dewatering occurs through several mechanisms, including particle aggregation through application of the polymer, but also consolidation and desiccation through evaporation, drainage, or freeze-thaw. Understanding the relative contribution of each mechanism will assist in selecting optimal thickness, polymer dose, and rate of rise, to minimize and control impoundment footprints. In this paper, we examine the utility of consolidation and desiccation modelling to interpret laboratory experiments and field trials, to separate out the contribution of each mechanism, and to generalize these contributions to hypothetical deposition scenarios.

RÉSUMÉ
La déposition des résidus des sables bitumineux est régie par l'application de la réduction du volume de la partie fluide des résidus fins pendant la vie de l'exploitation. Les exploitants rencontrent ces objectifs en améliorant l'expulsion de l'eau et les caractéristiques de consolidation des résidus fins à l'aide de diverses techniques, impliquant souvent l'addition de polymères ou d'autres traitements favorisant la floculation. L'assèchement survient par l'entremise de plusieurs mécanismes, incluant l'agrégation des particules grâce à l'inclusion d'un polymère, mais aussi de la consolidation et de la dessiccation par évaporation, drainage ou cycles de gel-dégel. La compréhension des contributions relatives de chaque mécanisme aidera à déterminer l'épaisseur optimale, la dose de polymère ainsi que le taux de montée, afin de minimiser et de contrôler l'emprise des bassins. Dans cette publication, nous examinerons la pertinence de la modélisation de la consolidation et de la dessiccation afin d'interpréter les essais de laboratoire et de chantier, de séparer les contributions de chaque mécanisme et de généraliser ces contributions à un scénario théorique de déposition.

1 INTRODUCTION

In oil sands surface mining, separation of bitumen from the original ore body leaves a residual material (or tailings) that consists of water, sand, and fine particles (silt and clay), as well as small portion of residual bitumen. The solid content of whole tailings after extraction is about 45-55%. Conventionally, the tailings are pumped to a dammed tailings disposal site. During or relatively soon after deposition, the coarser particles (sands) segregate out to form beaches, while the fine particles and bitumen accumulate to form a floating layer called fluid fine tailings, which initially has a very low solid content of about 8%. Over several years, fluid fine tailings undergo hindered settlement forming a relatively clear water layer on top of Mature Fine Tailings (MFT), which typically has solid contents between 35% and 38 %, corresponding to gravimetric water contents (GWC) between 200% and 180%. MFT does not appreciably dewater past this point, even in very deep deposits. This is due to at least two reasons: One, the chemistry of the extraction process causes a high degree of dispersion of the clays, which results in very low hydraulic conductivity; Second, during deposition, thixotropic buildup generates a network structure that impedes consolidation – the latter effect has been demonstrated in a 30 year study on a 10 m column of MFT described by Scott et al. (2013). MFT at 35% solids content do not possess any substantial strength, and therefore the tailings are now stored in impoundments with substantial footprints, that cannot be reclaimed without further intervention.

To improve rates of tailings dewatering, several technologies have been developed by the industry that use a polymer to facilitate clay particle flocculation, which improves rates of sedimentation and consolidation. Such technologies include centrifugation, in-line flocculation, thickening, and recombining fine tailings with sand tailings. The amended fine tailings streams generated by these methods generally achieve solid contents in the range of 50-55% a relatively short time after deposition (less than a week). However, to achieve trafficable and reclaimable deposits that can allow and will not excessively deform during and after reclamation, solids contents of at least 70% (44% or lower gravimetric water content – GWC) must be achieved.

At present, experience suggests that self-weight consolidation aided by surface processes (freeze-thaw or evaporation) will be the dominant dewatering mechanism in these amended fine tailings deposits. This begs the question as to what is the optimal deposition scenario. Very thin lift deposition, though it maximizes the contribution of surface processes, is expensive because of the relatively large footprint of the required tailings disposal area and the substantial operating costs involved in ensuring adequate spreading of the tailings within the disposal area. Deep deposits, while operationally less complex, decrease in dewatering efficiency as they grow deeper, due to increasing drainage path. Therefore perhaps something in between may be optimal.

To properly evaluate potential deposition scenarios, and to interpret and extrapolate from field trials that are underway, a useful tool would be a model that achieves some degree of coupling of desiccation and consolidation. Soleimani et al. (2014) reviewed a number of different modelling approaches to coupling desiccation to consolidation (Simms et al. 2013, Fisseha et al. 2010 Abu-Hejleh and Znidarčić 1995, Seneviratne et al. 1996). Our group is working with a custom version of a coupled unsaturated flow – generalized consolidation model, developed by the software company SoilVision. The attraction of this model over other methods lies in its relatively realistic treatment of unsaturated flow.

As a backup, or check on this model, we also use FSConsol, a well-known commercial large strain consolidation model.

In saturated conditions, finite or large strain consolidation formulations require relations between void ratio (e) and effective stress (σ'), and between hydraulic conductivity (k_{sat}) and void ratio:

$$e = A\sigma'^{B} \quad (1)$$

$$k_{sat} = Ce^{D} \quad (2)$$

In unsaturated conditions, the relationship between water content and void ratio with matric suction is determined by measuring the soil-water characteristic curve (SWCC). These tests are usually performed on samples of about 20 – 90 centimetres in height, which therefore have low total vertical stress. For fine-grained soils, volume change must be measured during the SWCC test in order to accurately determine the degree of saturation and the relationship between void ratio and suction. Hydraulic conductivity as a function of the degree of saturation is usually determined theoretically from the measured SWCC (Leong and Rahardjo, 1997).

In the case of a fine-grained soil, where consolidation may be occurring simultaneously with desaturation, the material properties required (volume change, water content, and hydraulic conductivity) are now functions of both total stress and matric suction. Therefore, all these properties are now three-dimensional surfaces. In the SoilVision formulation, these surfaces are represented using a six-parameter fitting function developed by Vu (2002). We fit this function to data in the 0 suction plane (saturated consolidation data) and the 0 total stress plane (data measured during the SWCC test), in order to define the six fitting parameters.

2 MATERIAL PROPERTIES

Geotechnical properties of the MFT obtained at the Shell site and characterised in our laboratory are presented in Table 1. For modelling, the necessary material properties include the finite consolidation relationships (Equations 1 and 2) and the SWCC. We considered three separate sources of data for the consolidation parameters: i) our own data, measured during column tests on laboratory-prepared material, ii) independent tests carried out for Shell on its material (Dunmola et al., 2013), and iii) data on polymer-amended cyclone overflow tailings, measured by Jeerivapoolvarn (2010). The SWCC of the polymer-amended material was determined in our laboratory using an axis-translation device and by measurement of total suction, using a dewpoint hygrometer for suctions greater than 1,000 kPa.

Table 1 Select properties of MFT and polymer-amended MFT

Property	Raw MFT	With 650 ppm polymer
Specific gravity (dimensionless)	2.2	2.5
Liquid limit (%)	45*	77*
Plastic limit (%)	21	43
Fines content (< 44 µm) (%)	90%**	55%**

* LL using fall cone method
** By hydrometer, without dispersing agent

Figure 1 presents the void ratio effective stress relationships determined from our own column tests and from the literature sources mentioned above. Our column tests used MFT prepared with 650 ppm anionic polymer, using the mixing method described in Mizani et al. (2013). The prepared material was deposited in a column 0.50 m high with free bottom drainage (port under a geotextile) and no evaporation. Volumetric water content sensors were used to monitor density with depth, and tensiometers (Model T5 from UMS, accuracy 0.1 kPa) were used to monitor both positive and negative pore-water pressure. Density data and pore-water pressure data during the initial phase were used to construct the void ratio data.

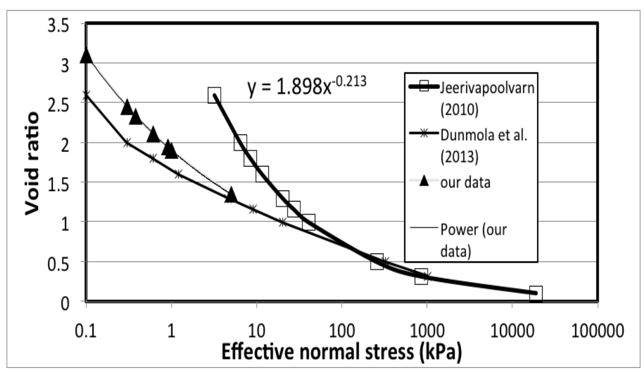

Figure 1 Compressibility relationships (the power law is for our data)

Hydraulic conductivity data were estimated from a column test where drainage was allowed out the bottom, and therefore the flow rate could be calculated with time.

The gradient, as determined using tensiometers, could then be used to estimate the hydraulic conductivity using Darcy's law. This was then related to the average void ratio as determined by the mass and volume of the whole column. The results are compared with the two literature sources in Figure 1 ad 2 (Dunmola et al. 2013; Jeerivapoolvarn, 2010), and show a reasonable comparison.

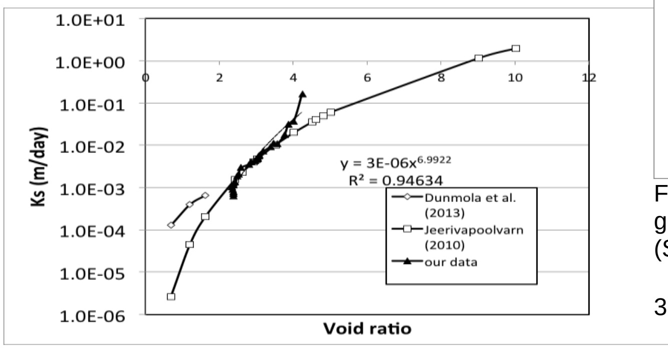

Figure 2 Hydraulic conductivity-void ratio relationships (power function is for our data)

The soil-water characteristic curve was determined using axis-translation with vertical volume change measurement. As shown in Figure 3, the material shows a pronounced decrease in water content and void ratio in the first step of 20 kPa. Thereafter, the water content and void ratio decrease with a gentle slope. The degree of saturation does not drop below 60% up to 800 kPa suction.

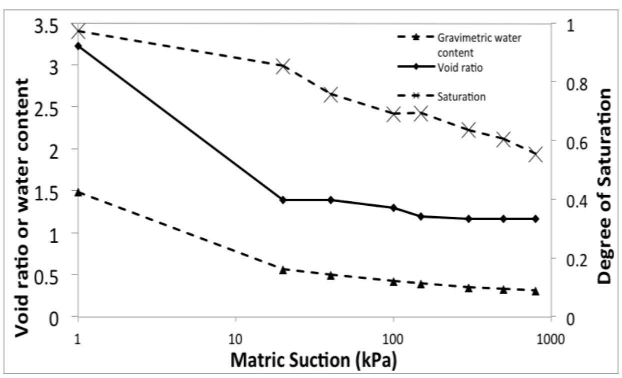

Figure 3 Gravimetric water content and void ratio versus matric suction (Soleimani et al. 2014)

These unsaturated properties are then interpolated with the compressibility data to generate three-dimensional (3-D) relationships of void ratio, hydraulic conductivity, and degree of saturation. The void ratio 3-D surface is shown in Figure 4 below. These are then fitted with the 3-D curves described in Vu (2002).

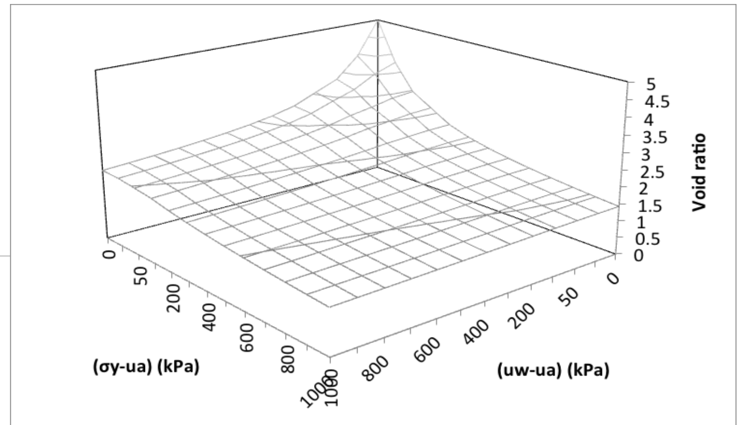

Figure 4 Void ratio-suction-net normal stress 3-D surface generated from compressibility and SWCC data (Soleimani et al. 2014)

3 ANALYSIS OF LABORATROY EXPERIMENTS AND FIELD TRIALS

Calibration of the SoilVision model to laboratory column tests is described in Soleimani et al. (2014). That calibration involved increasing the measured saturated hydraulic conductivity – void ratio function by 5. This gives a function 1.5 x 10^{-5} e^{7} m/day. This was the function used in all modelling of laboratory and field data presented in this paper.

The experimental work presented in this paper is from a laboratory simulation of multilayer deposition of polymer amended MFT, in which three layers of about 0.35 m at 36% solids were sequentially deposited in a 1 m by 0. 9 m plan area steel and plexiglass drying box. This type of drying box is described in Daliri et al. (2015), while the details of this particular experiment are described in Rozina et al. (2015). Deformation is tracked using non-contact vertical displacement sensors manufactured by Senix, pore-water pressure by T5 tenisometers, volumetric water content by EC-Series water content sensors manufactured by Decagon. Drainage is monitored by a port at the bottom using a tipping bucket – a geotextile is placed at the bottom of the box before the first layer is placed. Overall mass is determined using load cells upon which the box rests. Actual evaporation is determined as the difference between overall mass change and drainage. Potential evaporation (PE) is determined using the Penman-Monteith equation using measured relative humidity and temperature data and a wind speed value determined by measuring evaporation when the box is filled with water at different heights.

Evaporation data and pictures of crack development are shown in Figures 5 and 6. As described in Rozina et al. (2015), one of the significant aspects of the dewatering behaviour is the increase in apparent AE above subsequent to the appearance of cracks. Cracks started to appear within hours after the supernatant water disappeared. Despite drainage, supernatant water remained on the surface of the tailings for 20 days in the first layer.

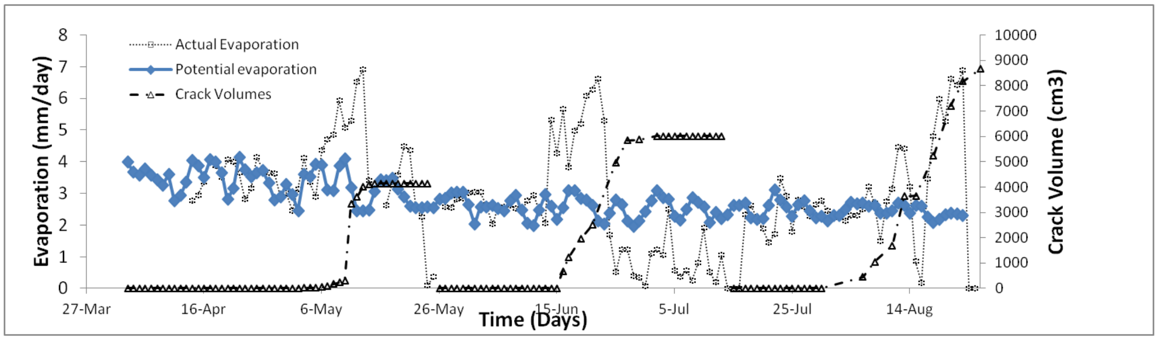

Figure 5 Potential Evaporation, actual evaporation, and crack volume in a 1m^2 plan area drying box simulation of polymer amended MFT. Each lift is deposited at 0.35 m and 38% solids content.

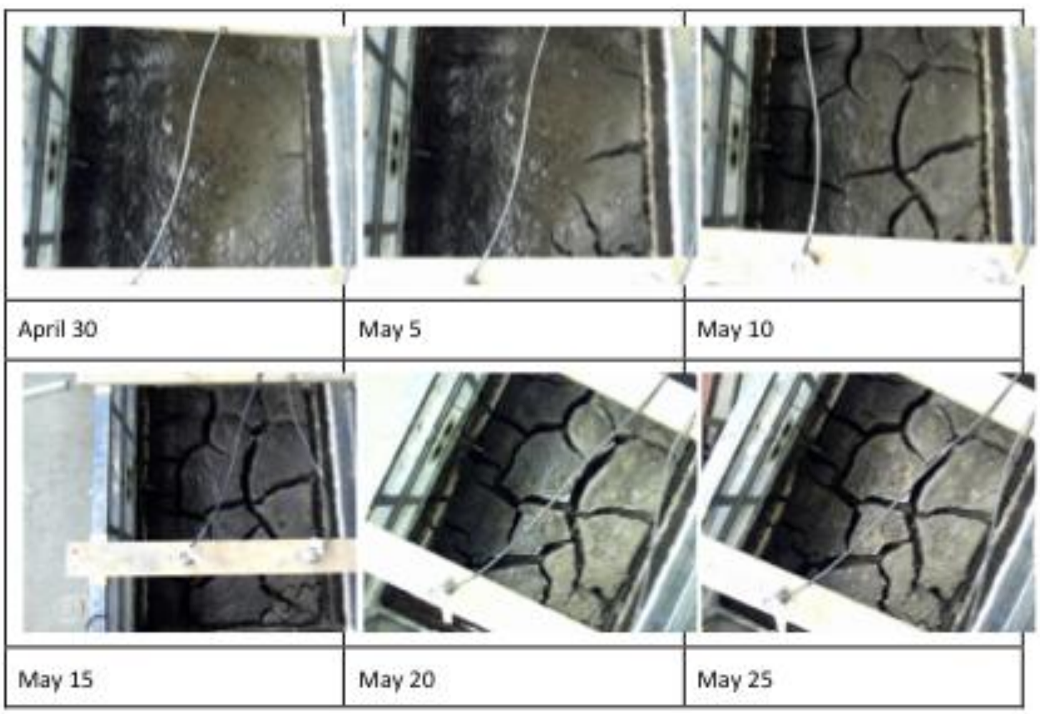

Figure 6 Time series of crack development pictures after placement of Layer 1

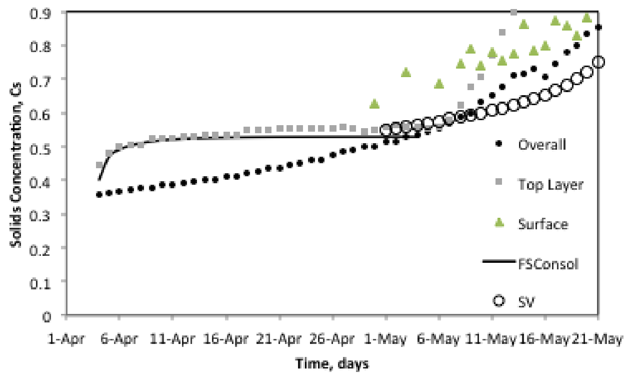

Figure 7 Modelling of solids concentrations in first layer of drying box by both FSConsol and SoilVision product

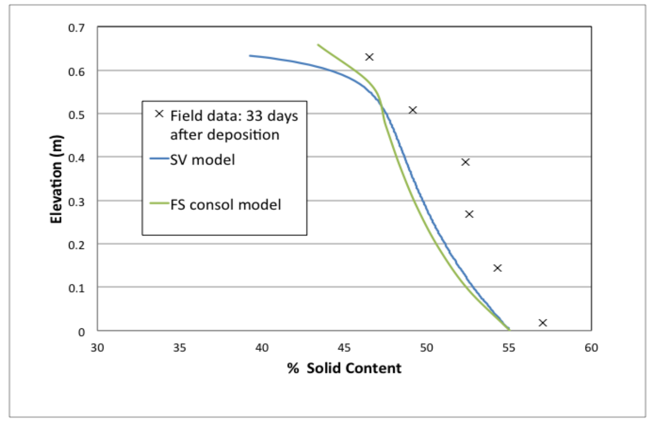

Figure 8 Modelling solids concentration in first thin lift of Shell AFD test site, deposited September 2012 (Modified from Soleimani et al. 2014, plus new data from FSConsols modelling)

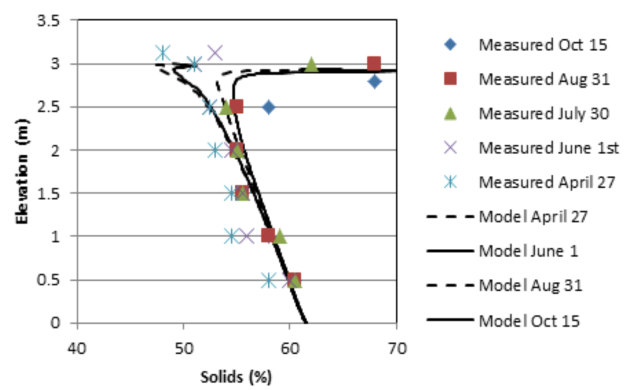

Figure 9 Measured and modelled solids concentrations in Shell AFD Deep stack in summer 2013 using SoilVision product

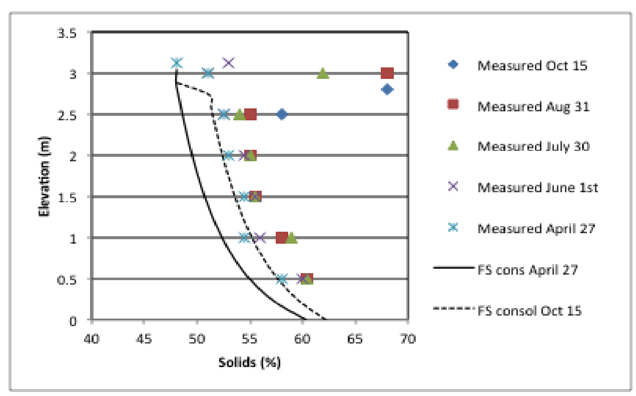

Figure 10 Modelling of deep stack using FSConsol

Figure7 shows measured and modeled dewatering in the first layer. The "overall" plot is the solids content directly measured from the load cells, which therefore incudes the weight of the supernatant water. The solid content of the first layer itself was determined from three VWC sensors placed in this layer. Therefore, even in this relatively thin layer, significant dewatering occurred (to about 53% solids) due to consolidation alone. Consolidation was well-simulated using both models.

The SoilVision model was then used to simulate dewatering behaviour subsequent to the appearance of cracks. Essentially, the model somewhat under-predicted the rate of dewatering, probably to the contribution of cracks to evaporation.

Figure 8, Figure 9, and Figure 10 show data from two of Shell Atmospheric Fines Drying field trials. These trials are described in Dunmola et al. (2013a & 2013b). Two trials are modelled in this paper: an initially 0.85 m deposit, the first layer in a thin multi-lift trial (Figure 8) ,and an initially 3.8 m deposit, the "Deep stack" (Figures 9 and 10). The layer in Figure 9 is modeled for the first month or so after deposition – during this time, (September 2012 in Fort McMurray), the weather was wet, and puddles of water persisted on top of the deposit for most of this time. Therefore, this layer was simulated setting the top evaporation boundary condition to zero. Additionally, through some drainage was expected to occur through the bottom, a no-flow boundary condition was selected for reasons of simplicity. Despite these assumptions, and still using the laboratory calibrated parameters, both models gave a reasonable though slightly conservative estimate of dewatering in this layer. Except for near the surface, both models gave very similar results.

The deep stack provided a good opportunity to test the coupled unsaturated-consolidation formulaton of the

SoilVision product. The Deep Stack was depositied in October 2012. The potential effects of freeze-thaw over the winter are ignored. Figure 9 shows measured and modelled solids concentrations from April to October 2013. In the unsaturated zone, no more than the top 1 m of the deposit, the model results are reasonable, though they predict a less uniform degree of drying with depth than indicated by the measured data. In the bottom of the deposit, thought the final profile of the measured and modelled results agree quite closely, the rate of consolidation is overestimated by the model. This may have to do with the how the saturated finite strain parameters are interpolated in this model.

By contrast the FSConsol model, while it shows a better agreement in terms of the rate of consolidation at depth, it underpredicts the degree of dewatering at depth. This is in part due to the additional volume of water removed by evaporation over this time, about 0.21 m of water (3.5 mm/day average PE from May to October). This is enough ot increase the average solids content from 55 % of the FSConsol results in October to the average 58% solids of the measured profile in October. Therefore, the FSConsol model works as intended ,and the discrepency with the measured results can be explained by the difference in dewatering due to evaporation.

The measurements show that the influence of evaporation extends deeper than predicted by either model. This is likely due in part to the presence of cracks. Substantial cracking occurred in all of the Shell AFD deposits. One means to illustrate the influence of cracks in the field is to measure water content and total suction from grab samples from the surface and from within cracks. The total suction results are obtained from waxed samples transported back to Carleton and analyzed using a WP4 Dewpoint hygrometer. The paired oven dried water contents and total sucton readings from the field show similar results to matric suction and total suction measurements made on laboratoy prepared specimens (Figure 11). One profile of total suction measurments across a crack opening from the field in shown in Figure 12. The total suctions measured at the surface are very high, and we expect suppression of AE at these values. By contrast, the low total suction measurements in the cracks indicate that crack surfaces may serve to extend the influence of evaporation to deep in the tailings.

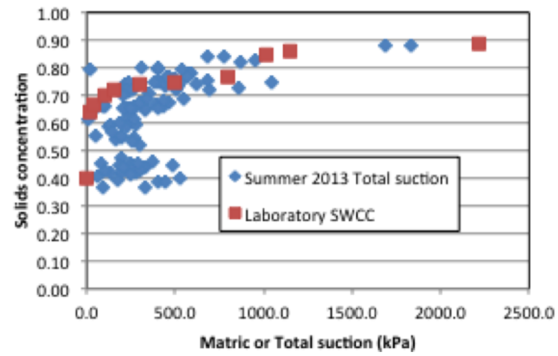

Figure 11 Laboratory and field derived SWCC

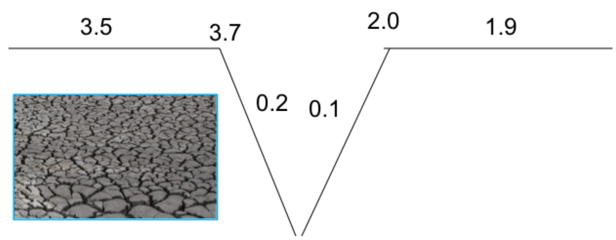

Figure 12 Transect of total suctions (MPa) across crack in thick multi-lift cell early August

CONCLUSIONS

The relatively good predictions of both models is encouraging, and it appears these types of models may have utility to aid tailings deposition design. Cracking seems to extend the influence of evaporation deeper into the the tailings then would be anticipated by one dimensional flow, therefore the predictions of current unsaturated flow–consolidation models will be conservative. The models are not perfect of course, and practioners should be enouraged to use models of different forumulations when exploring hypothetical tailings deposition scenarios.

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