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Dewatering Behavior of Fine Oil Sands Tailings: A Summary of Laboratory Results

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ABSTRACT

To evaluate the disposal technology for fine oil sands tailings, the appropriate engineering properties of the tailings should be ascertained. A laboratory study was conducted by Delft University of Technology (the Netherlands) on the geotechnical properties and dewatering behavior of the fine oil sands tailings (MFT, TT), obtained from Shell Canada's Muskeg River Mine. In this program, the tailings were characterized by performing various laboratory tests including index property tests, flocculation tests, column settling tests, oedometer tests, shrinkage and swelling tests, water retention tests, cracking tests and air drying tests. In this paper, a summary of the main tests results is presented. The data obtained for the MFT and flocculated MFT are compared to identify the effects of flocculation on the dewatering behavior.

INTRODUCTION

Fluid fine tailings resulted from the Alberta oil sands mining process are the major challenge facing the oil sands industry as they cannot be disposed economically due to poor engineering properties. The fluid fine tailings, mostly stored in ponds, must be dewatered before these ponds can be reclaimed by engineering methods. The existing tailings dewatering technologies involve making use of natural dewatering processes (e.g. self-weight consolidation, atmospheric drying, freezing and thawing) and physical/mechanical processes (e.g. filtration, centrifuge, prefabricated vertical drains) or using chemical treatment or mixing tailings with different materials and wastes to improve the tailings dewaterability (BGC, 2010). In order to evaluate the existing technologies or develop new techniques, the appropriate engineering properties of the tailings must be ascertained.

An experimental study has been conducted by Delft University of Technology, in the Netherlands. The main objective of the study was to determine the geotechnical properties of fine oil sands tailings and develop their dewatering behavior related to consolidation and drying processes. The research program consisted of a series tests relating to soil classification, flocculation behavior, sedimentation and consolidation behavior, drying and rewetting behavior and some benchmark dewatering tests. The research was aimed to provide experimental data to better understand the fine tailings dewatering process.

This paper presents a summary of the important results obtained from the experimental study. Detailed results and extensive discussions are available in a doctorate dissertation titled "Dewatering behaviour of fine oil sands tailings, an experimental study" which has been published by Delft University of Technology in 2016.
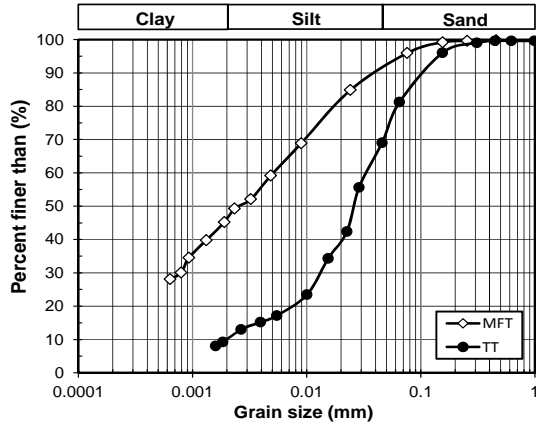
EXPERIMENTS AND RESULTS

Materials

The tailings used in this research were obtained from Shell Muskeg River Mine. Four barrels (180L each) of oil sands thickened tailings (TT) and three barrels of mature fine tailings (MFT) were delivered to Delft University of Technology. Two weeks after arrival, the tailings were mixed in barrels using a top entering mixer to re-homogenize the material. The mixed tailings were poured into a series of 20L buckets which were kept air tight in a room at 10°C. Samples used for the experiments were prepared from these materials. The homogenous TT and MFT suspensions had an initial solid content of about 35%.

Basic properties

Laboratory classification tests were performed to determine the basic geotechnical index properties. Figure 1 shows representative particle size distribution curves for TT and MFT samples. Table 1 summarizes the basic properties of each tailing.

Figure 1. Particle size distributions of MFT and TT samples

Table 1. The basic properties of the MFT and TT used in this work

	MFT	TT
Specific gravity, G_s	2.3	2.3
Bitumen content (%)	2	1.8
Liquid limit (%)	55	48
Plastic limit (%)	28	22
Plasticity index (%)	27	26
Shrinkage limit (%)	16	12
Fines content (<44 μm%)	91	71
Clay content (<2 μm%)	48	14
USCS	CH	CL

Comparing these two tailings, TT had a lower fines and clay content than MFT. The difference is largely due to the fact that TT represents the chemically treated flocculated system while the MFT was non-treated. The particle size distribution and the Atterberg limits of the MFT were close to the values presented by Rima (2013) and Gholami (2014). The TT had a larger fines content than that presented by Innocent-Bernard (2013), however, the clay content values were comparable. It is hypothesized that the mixing process applied prior to sampling may affect the size of flocs in the TT but did not affect the amount of clay size particles.
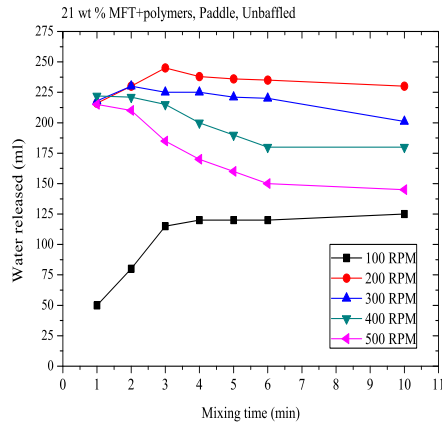
Both the MFT and TT had a significantly larger fines and clay content values compared to those of different tailings (e.g. copper, gold, and coal wash tailings) presented by Qiu and Sego (2001). This implies that dewatering these fluid fine tailings is more challenging than conventional mine tailings due to low permeabilities. It was found that the particle size distributions and the plastic limit of the MFT were close to the very soft clay dredged from Rotterdam harbor (Limsiri, 2008).
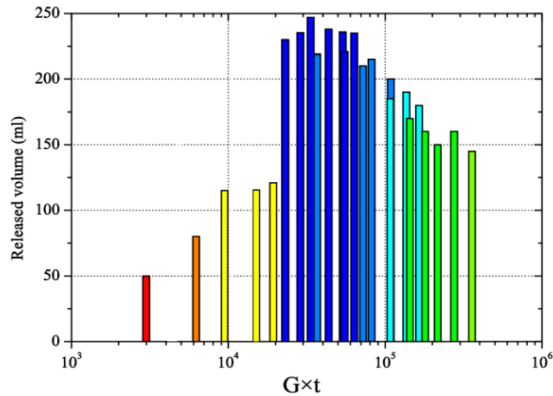
Flocculation tests

In this study, a high molecular weight polymer (FLOPAM DPR 5285) was used to produce chemically amended tailings. To flocculate fine particles in MFT, the tailing suspension and the polymer were mixed in a glass beaker (88 mm in diameter) with a two-blade flat paddle impeller (60 mm in radius). In order to determine the optimum flocculation condition and the maximum dewaterability of the treated tailing, a series of flocculation tests were conducted by using various mixing parameters (e.g., mixing speed and time), polymer dosage and concentration of tailing. An inexpensive device was developed to monitor the impeller torque during mixing. The torque data were used to calculate the impeller power in each system. According to the results presented by Demoz and Mikula (2011), the mixing energy input played a critical role in the flocculation results.

Figure 2 shows the effect of the mixing variables on the flocculation. The flocculation outcome was presented by the volume of water released from 500 ml polymer treated MFT after a settling period of 24 hours. It can be seen that the MFT-polymer mixtures agitated at constant 200 rpm released the largest amount of water compared to other groups. The peak dewatering result was obtained after 3 min mixing and a total amount of 245 ml water was released. It suggests that under ideal condition up to 52% of the tailing water can be discharged from the treated tailings within one day after the deposition. The figures also show poor dewatering results for the group mixed at the speed of 100 rpm. This can be explained by that the turbulence created in the tank was too mild to distribute the added polymer, which caused local overdosing in some polymers rich areas while the whole tailing was still under-dosed and the flocculation was not complete. The results indicate that rapid mixing is desired for effective flocculation. However, based on the data, prolonged vigorous mixing created mediocre dewatering results since the high shear rate and stress destroyed the formed flocs forming smaller and micro flocs. It must be pointed out that the dewatering results for the over-mixed samples were still superior to the samples which were insufficiently mixed. Therefore, over-mixing would still be acceptable in engineering while insufficient mixing should be avoided.

Figure 2. Volumes of water released by 500 ml polymer treated MFT produced under different mixing conditions

Figure 3. Dependence of dewaterability of FMFT (volume of water released in 24h) of FMFT on mixing energy input (G×t values)

In Demoz and Mikula (2012)'s work, the product of velocity gradient (G) and mixing time, G×t, was used as indicative of mixing energy input into each test and it may be used as a controlling parameter for the flocculation result. Figure 3 shows the dependence of the dewatering results on the measured G×t values obtained from above tests. It is apparent that the dewaterability data falling into the G×t range from 2×10^4 to 7×10^4 $s^{-1} \cdot s$ are obviously better than those in the rest of the test range, yielding the maximum volume of water released. This range is therefore considered to be the optimum operating envelop for the tailing in the current research.

Flocculation tests determined that the optimum polymer dosage was 1000g/t (1000 gram dry flocculant per 1 ton tailing solids). Increasing the dosage above the optimum did not improve the dewaterability but increased the fluid's resistance

to settling. Table 2 suggests that using a higher solid content MFT will obtain a higher degree in the increase of the net water release (NWR) value after the flocculation. The NWR is given as follows

$$NWR = \frac{W_R - W_A}{W_0} \times 100\% \qquad [1]$$

where W_0 is the initial mass of water in the tailing, W_R is the mass of water released, and W_A is the mass of water added with the polymer solution into the tailing. Although the 32% solid content MFT had the largest degree (i.e. 12 times) in the increase of the NWR value after flocculation, the flocculated MFT material exhibited high yield strength, which is challenging for transportation of tailings via pipelines,. Therefore, in practice the original MFT should be prepared at a lower solid content before flocculation so that the generated flocculated tailings are easy to handle. By doing this, based on the optimum G×t values, the mixing energy required can also be reduced substantially.
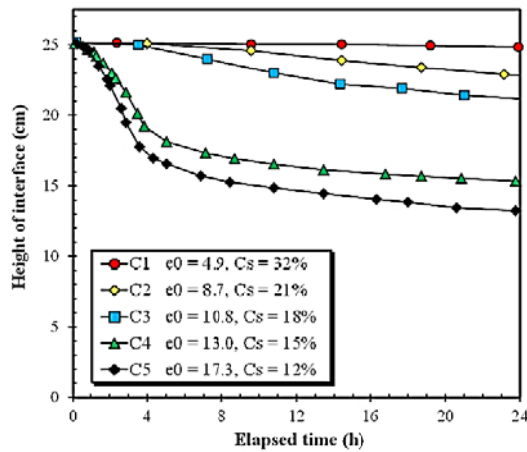
Table 2. Dewaterability (NWR values) of the MFT samples and the optimum mixing energy (G×t values)

Soil content (%)	MFT NWR$_{24h}$ (%)	FMFT G×t ($s^{-1} \cdot s$)	FMFT NWR$_{24h}$ (%)
15	47.8	11,160	65.2
21	9.2	33,488	52.1
32	2.5	165,960	30.4

Column settling tests

The column settling tests were performed on the tailings (MFT, FMFT and TT) suspensions to investigate their settling behavior. The clay suspensions were well-mixed before they were transferred to a series of 500 ml cylinders. During settling the height of the mud in each column was recorded with time.

In order to create the hindered settling condition, the original MFT was diluted with tailing water to various solid content between 32% and 2%. Figure 4 shows the determined settling curves for one part of samples during the first 24h. The rest of the results are not presented for clarity. It can be seen that sample C4 (e_0 =15%) and C5 (e_0 =12%) showed a classic "S" shape which consisted of three primary stages referred to as flocculation, hindered sedimentation (zone settling) and self-weight consolidation. Unlike sample C4 and C5, C1 and C2 settled gradually at the significantly smaller rates.

Figure 4. Settling curves for MFT suspensions at various initial solid content

The initial settling velocity of the fluid tailing was determined from the initial linear part of the settling curve. It was found that the tailings with a higher initial void ratio had larger initial settling velocity. The velocity dropped abruptly with initial void ratios between 10 and 11 (e.g. samples C4 and C5 in Figure 4). This void ratio is regarded as the boundary void ratio between hindered (zone) settling and consolidation and is designated as the soil formation void ratio, e_m. In most practical applications, e_m is about 7 times the void ratio at the liquid limit, e_L (Carrier,1983). For the MFT in this research, e_m was about 8.6 times e_L, this coefficient is close to that reported by Xu et al. (2012) for several dredged sludges (fine clays). Since the initial void ratio of the original MFT was lower than e_m, its settling behavior was controlled by consolidation.

Similar tests were performed on TT and polymer treated MFT samples. The setting transitioned from zone settling to consolidation when the initial void ratio decreased from 11.3 to 8.6. Newly prepared TT samples settled faster than TT that had been mixed intensively, indicating that the shear stress played a role in the floc size and hence influenced the settling rate.
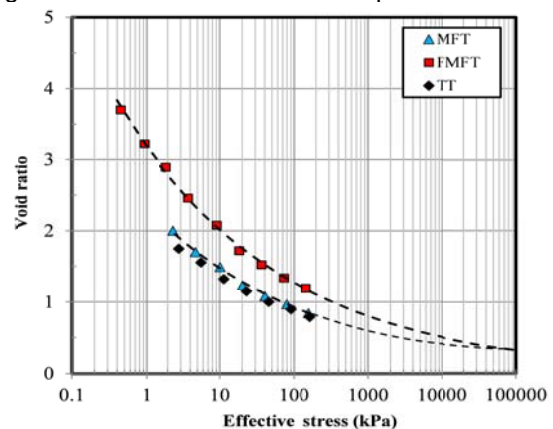
The hydraulic conductivities of the tailing suspensions were calculated from the measured initial settling velocities using the equations proposed by Been (1980) and Pane and Schiffman (1997). For all the fluid fine tailings, the relationship between hydraulic conductivity and void ratio was highly non-linear. The results showed that use of polymer in flocculation of MFT greatly enhanced the hydraulic conductivity and therefore the settling rate. The initial hydraulic conductivity of the 21% solid content MFT was increased by 4 magnitudes

after the treatment. For the optimally treated MFT, the flocs and aggregates settled rapidly during the first 1h, the settling rate then decreased sharply and became zero after 24h. Different from the non-flocculated MFT which settled continuously throughout the test, the FMFT did not settle when an equilibrium between the self-weight and the yield strength of the flocs was reached.

Oedometer tests

The purpose of the oedometer tests was to determine the consolidation behavior of the tailings over the effective stress range of 1–100 kPa which is operative in the majority of tailings management facilities (Qiu and Sego, 2001). To prepare the specimen, the fluid fine tailing was subjected to consolidation under self-weight and small pre-loading pressure to remove excess water. The specimen was consolidated by step loading method.

Figure 5 presents the experimentally determined compression curves (void ratio versus logarithm of effective stress plots) for the saturated samples of TT, MFT and FMFT. It can be seen that the compression data of the FMFT lay above that of the MFT while the TT is similar to the MFT. Table 3 shows the consolidation parameters calculated from the tests results for the MFT and the FMFT. According to the data, it is concluded that the FMFT was more compressible, more permeable and consolidated faster than the non-flocculated MFT. The differences are attributed to the floc structures formed in the tailing. The figure shows that with the increase of effective stress the compression curves of two tailings approach each other. It is hypothesized that the FMFT will exhibit similar behavior to the non-flocculated tailings at a high stress when all the flocs collapse.

Figure 5. Relationship between initial settling velocity and void ratio
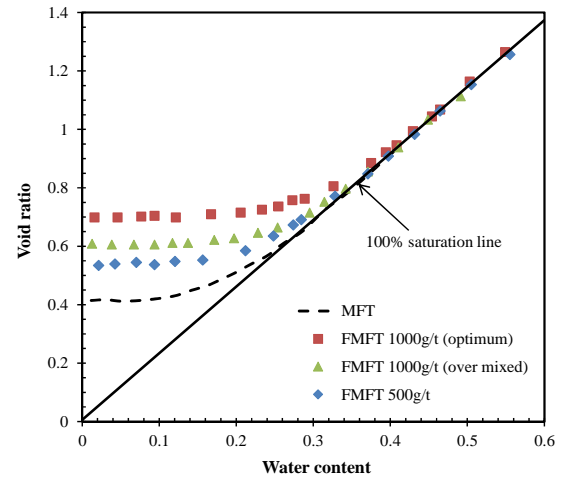
Table 3. Consolidation parameters of MFT and FMFT

	MFT	FMFT
Stress (kPa)	2.3 - 160	0.48 - 160
Void ratio	1.63 - 2.37	1.06 - 3.33
C_c	0.36 - 0.42	0.63 - 1.65
C_v (m^2/year)	0.05 - 0.28	0.13 - 0.52
M_v (m^2/MN)	0.8 - 30	1.5 - 249
K_s (m/s)	4.5×10^{-10} -7.2×10^{-11}	7.2×10^{-8} -1.4×10^{-10}

The compressibility and hydraulic conductivity data of MFT have been provided by many researchers in the open literature. In terms of TT and the polymer treated MFT, the available data were quite limited. The void ratio versus logarithm of effective stress plot of the MFT in current work was in good agreement with those presented by Pollock (1998) and Proskin (1998) for MFT over the effective stress range from 10 to 100 kPa. Some deviations occurring at small effective stresses may be due to different initial water content of the samples.
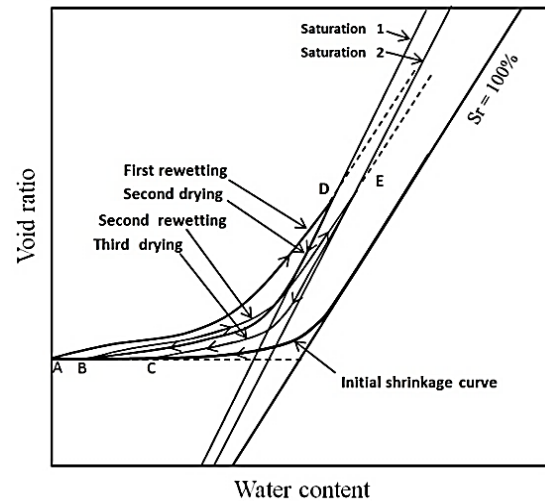
Shrinkage and swelling tests

The shrinkage and swelling tests were performed to determine the shrinkage curves of the fine tailings and their rewetting swelling behavior. The information is required to obtain a quantitative indication of how much volume changes in subaerial tailings disposal. The details about the tests were introduced in IOSTC 2014 (Yao et al., 2014). Figure 6 shows the shrinkage curves, presented as void ratio versus water content plots, for the MFT and three FMFT samples treated at different conditions. The shrinkage curves show a "J" shape consisting of three stages which are normal stage, residue stage and zero stage. The intersection between the saturation line and the horizontal asymptote of the curve when water content tended towards zero was considered as the real shrinkage limit (Fredlund et al., 2002). It can be seen that when the dosage of polymer increased from 0 (non-flocculated MFT) to 500g/t and then 1000g/t (the optimum), the shrinkage limit increased from 18% to 25% and 31%. Meanwhile, the minimum void ratio increased from 0.41 to 0.57 and 0.7. After drying, the over-mixed FMFT had smaller void ratio than the optimally mixed FMFT. Since there was no external pressure applied to the samples, varieties in the shrinkage curves were related to the different soil structures that were formed by flocculation. Based on the data, it is estimated that the volume of the desiccated FMFT is 25% larger than the non-flocculated MFT. This behavior should be considered in the design of the tailing disposal facility.

Figure 6. Shrinkage data of the MFT and the polymer treated MFT

Figure 7 is a schematic drawing of drying and rewetting curves of a fine tailing sample based on the test results. Point A is the minimum water content attained by the first drying. When the soil is rewetted from this point, the difference between the rewetting and drying path (hysteresis) is the largest. The linear part of the initial rewetting path AD is almost parallel to the 100% saturation line.

Figure 7. Schematic drawing of shrinkage and swelling paths during cyclic drying and rewetting

Once the second cycle starts at point D, the drying path will follow the saturation line 1 and may reach point B, which has the same void ratio as point A. The subsequent wetting path BE and the drying path EC are similar to the curve AD and DB, respectively. It was found that the difference between drying and wetting curve vanished after four successive drying-wetting cycles. This
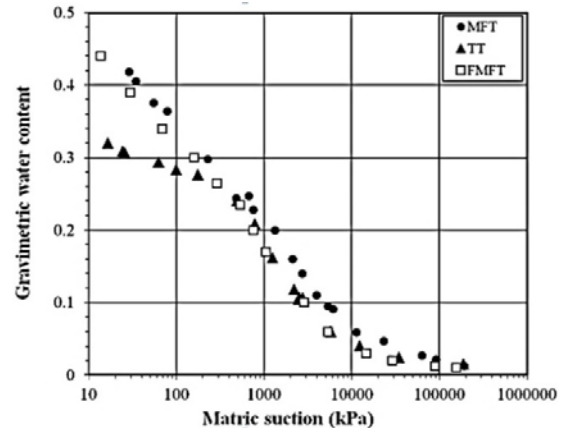
phenomenon reveals that for the tailing lifts in the atmosphere that undergo frequent drying and wetting processes, changes of bulk volume as function of changing water content are reversible. The obtained swelling results suggested that the fine oil sands tailings were not expansive soils.

Water retention characteristic tests

The water retention characteristic tests were used to assess the soil water retention curves (SWRC) of the fine tailings. Determination of SWRC of a soil requires measurement of suction at different water content. In principle, the traditional filter paper method can cover the whole suction range of fine tailing. This method was utilized in this work and the tests were conducted following the procedure described by ASTM D5298. Filter papers were placed in both contact manner (for matric suction) and non-contact manner (for total suction) with the tailing sample. At high suctions, filter papers come to equilibrium with soil only through vapor no matter being placed in contact or non-contact manner, and only total suction is measured. The SWRC at high suctions was determined using the WP4C dew point potentiometer (which is known for its distinct advantage in precisely and instantly determining the high total suction) and the result was combined with the filter paper result to establish the complete SWRC.
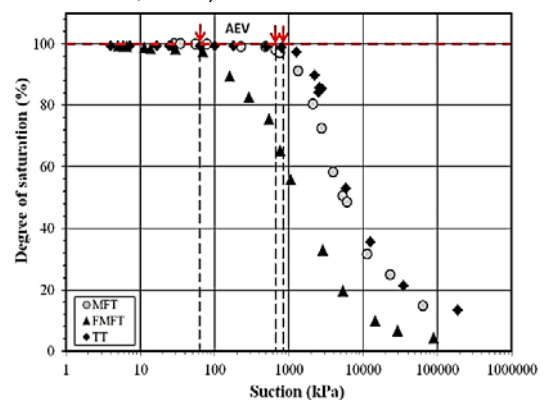
The difference between total suction and matric suction is regarded as osmotic suction. Osmotic suction is generated by the osmotic repulsion mechanism, arising from dissolved salts in the pore water. The results suggest that osmotic suction was major contributor to total suction for the fine tailings. This implies that the pore water in the fine oil sands tailings had relatively high salinity.

Figure 8 presents the SWRC assessed for different tailings. The figures show different water retention characteristics between the MFT and the FMFT. At the same water content, the FMFT had lower suction compared to the non-flocculated MFT. The cause of different behavior is related to changes in particle size and soil structures due to flocculation. It is noted that the TT shows over-consolidated characteristic, this is probably due to higher compaction degree of the sample. The SWRC of the MFT was compared to those reported by Fredlund et al. (2013) and Owolagba & Azam (2013) for different MFT samples. Despite some deviations in the lower suction range, these curves converge at above 1000 kPa.

Figure 8. The soil water retention curves determined for different tailings

From the determined SWRC, it is difficult to determine the air entry value (AEV) since there is no distinct curvature in the region of low suctions. Fredlund and Houston (2013) proposed that the independent shrinkage curves should be used to properly interpret the SWRC. With the use of the shrinkage curve, the previously presented SWRCs are expressed as water content versus degree of saturation plots, as shown in Figure 9. From these plots, distinct air entry value (AEV) of each tailing can be identified by the break in the curvature of the curve at the 100% degree of saturation. For the FMFT, the AEV of SWRC was about 60kPa, which is significantly smaller than those of MFT (about 700kPa) and TT (about 800kPa). With the shrinkage data, the volumetric water content can be calculated based on the instantaneous volume measurements. The SWRC can thus be converted to the volumetric water content versus soil suction plot. This plot was used for the numerical work undertaken to simulate fine tailings drying, see the complementary paper presented in this conference (Vardon et al., 2016).

Figure 9. SWRCs presented as degree of saturation against suction

Cracking tests

Cracking tests were performed to investigate the cracking behavior of thin layers (~1 cm) of soft tailings. Homogenous fluid tailings or high water content clay paste was placed in a glass cup (98 mm diameter, 11 mm deep). The cup was placed on an electrical scale which was used to monitor the evaporative weight loss. The clay sample was dried by horizontal air flow created at constant rate above the tailing surface. A camera was fixed on top of the specimen to capture the images of the surface (Figure 10). The tests were performed in the climate controlled chamber where the temperature was maintained at 24°C.
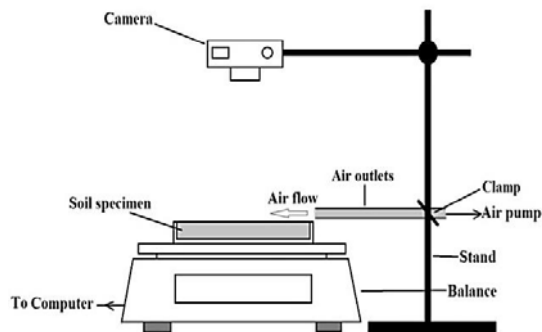

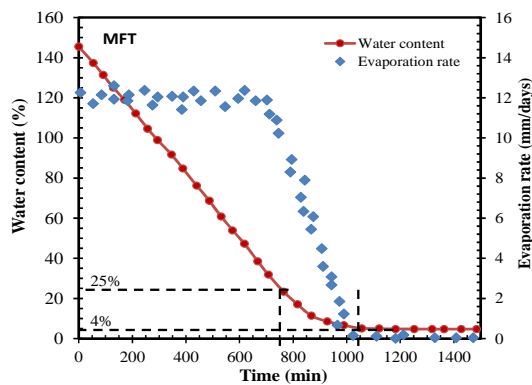**Figure 10. The set-up used for cracking tests**

Figure 11. Water content and evaporation rate versus time curves for a MFT sample during drying

Figure 11 shows the monitored evaporation rates and the average water content of a 11 mm thick MFT sample during drying. It can be seen that variations of evaporation rate with decreasing water content can generally be divided into three stages: (1) the constant-rate stage at an average value of 12 mm/day (0 -700min); (2) the falling-rate stage (700-1000min) and (3) the low-rate stage (>1000min). The evaporation rate dropped rapidly

at water content 25%, which was close to the plastic limit. At the end of test, the residual water content was about 4%.

Figure 12 illustrates how desiccation cracks occur and propagate on a 11 mm thick FMFT layer during drying. It can be seen that the first crack was initiated by connecting two tiny pits (surface defects) at a water content (52%). Another crack then occurred and small branches were born. The secondary cracks formed at the exiting primary cracks and terminated when they joined other cracks or extended to the rim of specimen. When the average water content decreased below the shrinkage limit, there was no change in the crack networks. According to the water contents reported in Figure 12 and the evaporation rate shown in Figure 11, the majority of cracks were formed in the constant evaporation rate stage.
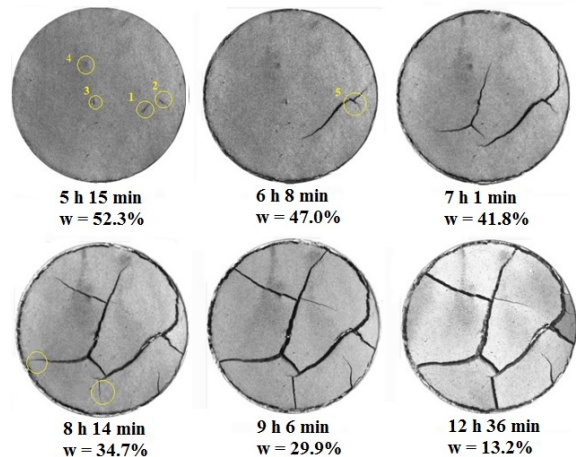

Figure 12. Formation and propagation of desiccation cracks on a thin FMFT
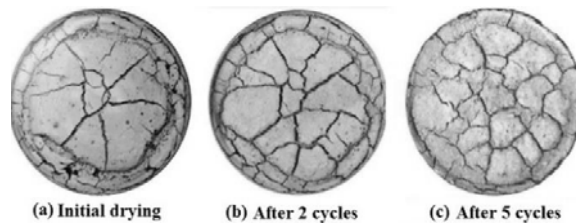

Figure 13. Changes of crack networks of MFT during multiple wetting-drying cycles

Unlike the FMFT, a large amount of clay in the MFT adhered to the glass wall during drying. This affected the formed crack pattern as some circumferential cracks were formed at the margin area of the surface (Figure 13a). The cracked sample was rewetted by soaking with water to allow most cracks close, then it was dried again.

Figure 13 shows changes of the crack networks of a MFT sample after up to 5 drying-wetting cycles. It can be seen that with the increase number of cycles the number of cracks increased and the mean cell area reduced. This behavior has been previously observed for normal clayey soils (e.g. Yesiller et al., 2000, Tang et al., 2011). The cracked FMFT was also subjected to several wetting-drying cycles, but there was almost no change in the crack pattern. This different behavior suggests that FMFT has stronger particle bonds and tensile strength than non-flocculated MFT.

Air Drying Tests

A laboratory study on air drying of fluid TT was presented in IOSTC 2010 (Yao et al., 2010a). These preliminary results demonstrated that the TT can be effectively and efficiently dewatered by atmospheric drying. In order to obtain a deeper understanding of the tailings drying behavior and the specific measurements for numerical modelling and validation, a new experimental program was conducted. In this program, the fluid fine tailings (MFT and the FMFT at initially 35% solid content) were allowed to consolidate and desiccate in two layers in a series of PVC cylinders. The apparatus is shown in Figure 14. Air circulation was created above the tailing at constant rate (400 L/h) to accelerate the drying. The weight of the column was monitored throughout the test to determine the actual evaporation (AE) rate of the tailing. One cylinder was filled with water and placed in the same condition as the tailings to monitor the potential evaporation (PE) in laboratory conditions. All the tests were performed in the climate controlled environment. At regular intervals, the columns were scanned with the CT technique to identify the internal changes of the tailings during drying.
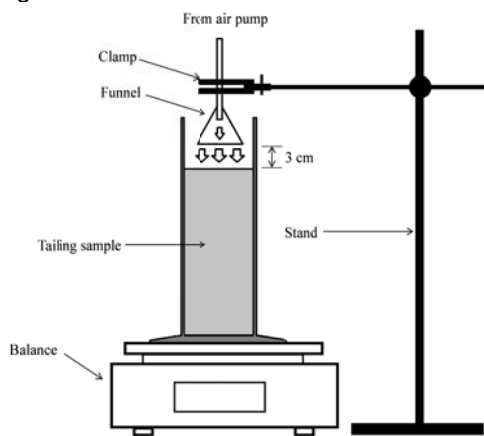

Figure 14.   Set-up for column air drying tests

Due to the side wall adhesion, the height of the MFT was not always correctly measured. This effect also influenced the evaporation rate. Compared to the non-cracked tailing surface, the amount of evaporation from the cracked tailing and the suspended soils was significantly larger.

In the FMFT tests, settling of the tailing did not leave much material on the side wall while the whole soil column showed lateral shrinkage after the stagnant water was evaporated. Figure 15 shows the temporal change of the total height of the FMFT during drying. The diamonds on the graph stand for the total height of the material (mud + water) and the red squares represent the height of the mud surface. It can be seen the stagnant water completely evaporated by Day 11, this is the start of the desiccation of the sediment. The second layer was filled to an equivalent thickness of 19.1 cm, but it resulted in a height increase of 18.1 cm, indicating that about 1 cm slurry (about 61 cm^3) was filled to the shrinkage gap between the first layer and the side wall. At Day 40 the final height of the tailing was 16.3 cm.
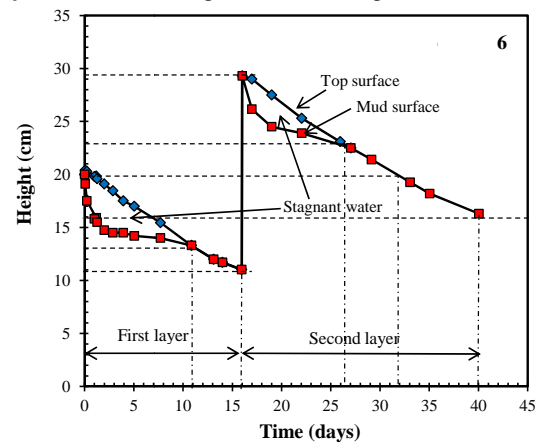

Figure 15. Changes of the height of the FMFT during drying

The measured evaporation rates suggest an average AE/PE ratio of 0.7 for the FMFT shortly after the supernatant water vanished. This value was slightly lower than the average monthly AE/PE ratio (0.75) reported by Kolstad et al. (2012) for a newly deposited FMFT in field tests. It is assumed that the lower AE/PE ratio was caused by a bitumen film remaining on the surface (as there was no run-off mechanism for supernatant water) and the salinity of pore water which suppresses evaporation by developing high osmotic suctions. Above assumptions are made based on the observed bitumen and salt crystals on the desiccating tailing surface, as shown in Figure 16.

Figure 16. The surface of the FMFT column showing bitumen and salt crystals

The CT scanning results for the FMFT are presented in Annex 1. These images were calibrated and processed in Matlab and the real bulk density values of the tailing were obtained. The bulk density profiles were derived from the x-ray images by plotting the average density values of the tailing with the height, as presented in Annex 2. The data show that a thin desiccated crust was formed on the top of the tailing and the thickness of the crust increased as drying progressed. One day after the filling of the second layer, the peak density of the first layer decreased from 1680 to 1550 kg/m^3. It indicates that the wet upper layer exerted a rewetting effect on the dried lower layer. Based on the images, no significant rewetting swelling was identified from the first layer. This highlights the potential advantage of depositing the tailing in layers.

Through the x-ray images, some gas bubbles were identified in the lower part of the tailing at the later stage of drying. The production of gas bubbles may be the result of decomposition of organic matter. In the previous test, it was found that a larger quantity of gas was released by fresh TT during the settling (Yao et al., 2010a). The gas bubbles formed in the FMFT were relatively small according to what they appear on the image (i.e. at average radius of 2mm).

CONCLUSIONS

A series of laboratory tests were performed to study the dewatering behavior of fine oil sands tailings. The main conclusions are summarized as follows:

- The developed properties (e.g. basic properties, compressibility, shrinkage property, water retention characteristic) of the MFT in current study were in general close agreement with the data reported in the open literature for the MFT. The TT showed different behavior to the reported, in particular the particle size and the settling behavior. One possible reason is that the flocs were destroyed by laboratory mixing and sampling process prior to the tests.

- Flocculation tests showed that an initial rapid mixing was desired for efficient flocculation. Prolonged vigorous mixing destroyed the flocs and led to mediocre dewatering results. There was an optimum range of mixing energy for the MFT-polymer system. The original MFT should be to some extent diluted before the flocculation to ensure the pumpability of the flocculated tailings.

- Upon deposition, the MFT experienced different settling processes depending on the initial void ratio. Transition from sedimentation to consolidation occurred at a void ratio which was about 8.5 times the void ratio at the liquid limit. Flocculation of MFT greatly accelerated the settling of the tailing slurry. The initial hydraulic conductivity of a 21% solid content MFT was increased by 4 magnitudes after flocculation.

- Flocculation of MFT affected the compressibility of the tailing. Oedometer tests suggest that the FMFT were more compressible and permeable than the MFT. At the same effective stress, the FMFT had larger void ratio than the MFT due to larger voids in floc structures. The floc structure tended to collapse at high surcharge pressure.

- The shrinkage data of the saturated fine tailing showed a J-shaped curve in a progressive drying pattern consisting of three stages. Hysteresis existed in the swelling curve when the soil was rewetted., This effect vanished after the soil experienced four consecutive wetting-drying cycles. Flocculation affected the shrinkage curve. When there was no external pressure applied on the sample, drying FMFT sample resulted in a larger void ratio in the residual shrinkage stage compared to drying the original MFT.

- Changes of the rate of evaporation from a thin tailing sample can be divided into three stages: constant-rate, falling-rate and low-rate. Most of volumetric change and desiccation cracks occurred in the constant-rate stage. Desiccation cracks initiated when the clay matrix was still fully saturated.

- The flocculated MFT contained in a column experienced a 3-D deformation upon drying.

- The actual evaporation rates measured from the tailing were smaller than the evaporation rates measured from pure water even at the beginning of drying. Some bitumen and salts found at the surface may suppress the evaporation. Deposition of a fresh tailing rewetted the underneath layer but did not cause large vertical swelling.
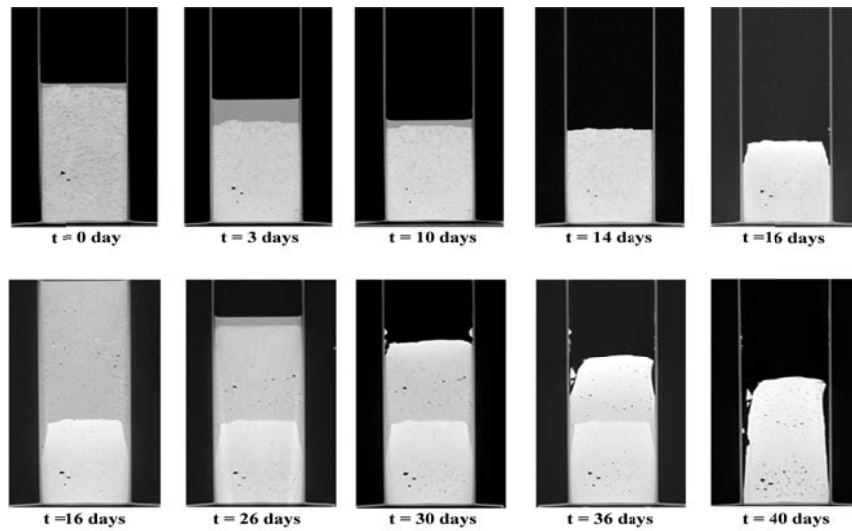
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Annex 1. X-RAY IMAGES OBTAINED FROM CT SCANNING FOR FMFT

ANNEX 2. SOIL DENSITY PROFILES DERIVED FROM CT SCANNING