Effect of various treatments on consolidation of oil sands fluid fine tailings

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Louis K. Kabwe, G. Ward Wilson, J. Don Scott, Amarebh Sorta & Nicholas A. Beier
Department of Civil and Environmental Engineering – University of Alberta, Edmonton, Alberta, Canada

ABSTRACT
Regulatory policy and regulations in Alberta require oil sands companies to reduce their production and storage of fluid fine tailings by creating deposits that can be reclaimed in a more timely manner. To meet the regulatory requirements, some companies are adding flocculants to the fluid fine tailings, using thickeners or centrifuges to increase the solids content and then using freeze/thaw processes to further thicken the tailings. The effects of flocculating, thickening and freeze/thaw treatments on fluid fine tailings were investigated by performing large strain consolidation tests and shear strength tests. The consolidation and shear strength results were then compared to those of untreated fluid fine tailings. All of the treatments increased the hydraulic conductivity of the fine tailings to some degree, but had no effect on the compressibility and shear strength. The effects and evaluations of the treatments are discussed.

RÉSUMÉ
La politique réglementaire et les législations de l'Alberta exigent que les entreprises des sables bitumineux réduisent leur production et leur stockage de résidus fins fluides en créant des dépôts qui peuvent être mis en valeur d'une manière plus opportune. Pour répondre à ces exigences réglementaires, certaines entreprises ajoutent des floculants aux résidus fins fluides, utilisent des épaississeurs ou des centrifugeuses afin d'augmenter la teneur en matières solides, puis elles utilisent des processus de gel/dégel pour épaissir davantage les résidus. Les effets de la floculation, de l'épaississement et du gel/dégel ont été étudiés sur les résidus fins fluides ayant subit ces traitements en réalisant des essais de consolidation à grande déformation et des essais de résistance au cisaillement. Les résultats de la consolidation et de la résistance au cisaillement ont ensuite été comparés à ceux obtenus pour les résidus fins fluides n'ayant pas été traités. Tous les traitements ont augmenté la conductivité hydraulique des résidus fins à un certain degré, mais n' ont eu aucun effet sur la compressibilité et la résistance au cisaillement. Les effets et l'évaluation des traitements sont discutés.

1 INTRODUCTION

Oil sands tailings have been produced for 47 years and now cover an area of 220 km² (AESRD 2014). The volume of fluid fine tailings (FFT) stored in tailings ponds is approaching a billion cubic metres (AESRD 2014). As the tailings from the oil sands contain toxic products, the tailings water and the FFT cannot be released and have to be stored in tailings ponds. Concern about the significant volume of FFT that has been accumulated resulted in the Energy Resources and Conservation Board (ERCB, now Alberta Energy Regulator, AER) to set out performance regulations for fines capture and deposit strength requirements of FFT deposits through Directive 074 (ERCB 2009). The objective was to reduce the amount of fluid tailings being produced through capturing 50% of the fines in the tailings feed in dedicated disposal areas (DDAs). The criteria for acceptable disposal is that the FFT deposit have a minimum undrained shear strength of 5 kPa after one year. The performance criteria proved difficult for the industry to achieve as the four operating mines were only able to meet from 0% to 73% of their required fines capture from July 1, 2011, to June 30, 2012 (Flanagan & Grant 2013). More recently, the Alberta Government (2015) replaced Directive 074 with a new policy document known as the Tailings Management Framework (TMF). The TMF sets out limits on the amount of fluid tailings that can be accumulated at each mine; requires tailings to be progressively treated and reclaimed throughout the project life-cycle; and requires all tailings to be ready-to-reclaim within 10 years of the end-of-mine-life of that project.

Much research has been performed over the years to reduce the amount of FFT being produced. Sobkowicz (2012) reports on the development of an oil sands tailings technology roadmap and action plan. In this project, over 550 tailings technologies were identified that could have potential use in the oil sands industry. Several of these tailings technologies are in commercial use, many of which are mature and others in an advanced development stage. A promising technology is to add flocculants to the FFT and to use thickeners or centrifuges to increase the solids content. A further technology would be to then use freeze/thaw processes to further thicken the tailings.

The objective of the research reported in this paper was to investigate the effects of flocculating, thickening and freeze/thaw treatments by performing large strain consolidation tests and shear strength tests on these treated fine tailings. The consolidation and shear strength of the treated FFT was then compared to those of untreated FFT to assess the effects of the treatments.

2 CHARACTERIZATION OF THE TAILINGS

Six tailings samples have been tested in this research: a typical untreated fluid fine tailings (FFT) and five thickened tailings (TT 1 to TT 5) which were all flocculated and thickened. Sample TT 4 was used to evaluate the effect of flocculent dosage, and samples TT 2 and TT 5 were subjected to freeze/thaw to evaluate the effect of this treatment.

Table 1 shows the initial properties of the tailings. The properties of the TT samples are after flocculating and thickening. The initial solids content of the FFT sample was 46% while solids contents of TT 1 and 2 were 49%, TT 3 was 40%, and TT 4 and TT 5 were 55%, so the initial solids contents were somewhat similar. The main difference between the FFT sample and the TT samples was in their sand content. The FFT sample had only 4% sand while TT 1 and 2 had 46% sand, TT 3 had 33% sand, and TT 4 and TT 5 had 49% sand. The table also shows other parameters, including fines solid content (mass of fines/total mass) and fines void ratio (volume of voids/volume of fines). These parameters will be used later to evaluate the effect of sand content on consolidation and shear strength properties.

Geotechnical properties of Atterberg limits, specific gravity and bitumen content are given in Table 2. The FFT sample had a liquid limit of 50%, typical of most untreated FFT, while those of TT 1 and 2 were 28%, and those of TT 4 and 5 were 25%. Atterberg limits were not performed on sample TT 3. The lower liquid limits for the TT samples are caused by the sand contents. Generally for oil sands fine tailings the addition of flocculants raises the liquid limit, but in this case the presence of the large amount of sand dominates the liquid limit. Bitumen content is usually defined as the mass of bitumen divided by the total mass of the tailings. As a change in water content will change the calculated bitumen content with this definition, in geotechnical engineering it is preferable to define bitumen content as the mass of bitumen divided by the mass of fines and bitumen. With this definition the bitumen contents of the FFT and TT samples are approximately similar. Both calculations of bitumen content are given in Table 2. As the bitumen is generally integrated into the fines, in all analyses of tests on FFT and TT the bitumen is considered as part of the fines.

Table 1. Initial properties of the tailings

Sample designation	Treatment methods	Solids content [%]	Fines content [%]	Fines solids content [%]	Void Ratio	Fines void ratio	Clay* Size [%]	Clay** Size
FFT	none	46.1	96	45.9	2.853	2.971	15	(-)
TT 1	FF + TH	49.0	54	26.5	2.737	2.175	18	38
TT 2	FF + TH + FRT	49.0	54	26.5	2.737	2.175	17	38
TT 3	FF + TH	40.0	67	26.8	3.870	9.675	14	NM
TT 4	FF + FF + TH	55.0	51	28.1	2.037	3.704	14	NM
TT 5	FF + FF + TH +FRT	55.0	51	28.1	2.037	3.704	14	NM

FF= flocculated, TH = thickened, FRT= freeze/thaw, FF+FF = double flocculated, NM= Not measured,
* by nondispersed hydrometer test, **by Methylene Blue Index

Table 2. Geotechnical properties of the tailings

Sample designation	Liquid limit [%]	Plastic limit [%]	Plasticity [%]	Activity	Specific gravity	Bitumen content by total mass [%]	Bitumen content by fines mass [%]
FFT	50	21	29	0.58	2.44	1.6	3.6
TT 1	28	18	10	0.29	2.63	0.4	1.5
TT 2	28	18	10	0.29	2.63	0.4	1.5
TT 3	NM	NM	NM	NM	2.58	0.4	1.5
TT 4	25	17	8	0.24	2.49	0.6	2.1
TT 5	25	17	8	0.24	2.49	0.6	2.1

NM= Not measured

The particle size distributions (PSD) of the FFT and TT samples are given in Figures 1 and 2. The fine material (< 45 µm) in the tailings originates from inter-bedded clay bands in the oil sands formations. The extent to which these clay bands are broken up depends on the mining methods, the bitumen extraction processes and the composition of the oil sands ore. Non-dispersed and dispersed hydrometer tests were performed to determine PSDs and the degree of fines dispersion for both the FFT sample and the TT samples. The tailings underwent hydrometer tests following the procedure outlined in ASTM D 4221-99R05 (ASTM 2005) for determining the dispersive characteristics of clay soil by double hydrometer in conjunction with the ASTM D 0422-63R07 procedure for the standard particle size analysis of soils (ASTM 2007). The double hydrometer method compares the clay-sized fraction of a standard hydrometer test with a second hydrometer test that involves no mechanical agitation or addition of dispersing agent. From previous testing, the non-dispersive test better defines the particle sizes in flocculated oil sands tailings. These particles are composed of flocs and non-dispersed clay aggregates while the dispersed test disperses these particles into their individual grain sizes. The non-dispersed PSD is used to define the fines content (< 45 µm) and the clay size content (< 2 µm). The Methylene Blue Index (MBI) measurements of the clay size content in Table 1 are larger than the non-dispersed hydrometer measurements because the MBI test disperses the clay aggregates and flocs (ASTM 1999).

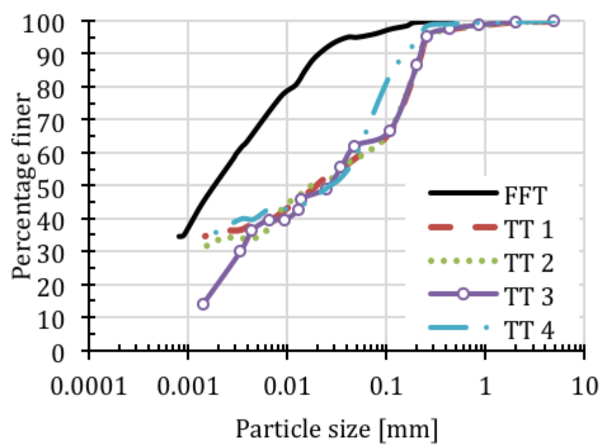

Figure 1. Dispersed particle size distribution

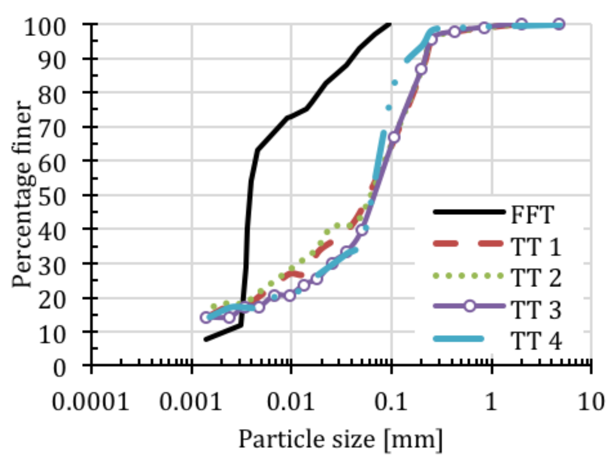

Figure 2. Non-dispersed particle size distribution

3 LARGE STRAIN CONSOLIDATION TESTS

Since infinitesimal consolidation theory is not valid for soft soils that undergo large amounts of volume change, a finite strain consolidation theory has been developed and widely used for oil sands fine tailings (Jeeravipoolvarn et al. 2008; Suthaker & Scott 1994). The finite strain consolidation theory requires compressibility (void ratio-effective stress relationship) and hydraulic conductivity (hydraulic conductivity-void ratio relationship) to be obtained from a large strain consolidation test. A large strain consolidation testing apparatus (slurry consolidometer) was used to determine the consolidation characteristics of all the tailings samples and provide these compressibility and hydraulic conductivity relationships. Both of these relationships are required to define the material relationships to be used in large strain consolidation numerical modeling of tailings ponds. As well, a second large strain consolidation test with vane shear tests at each effective stress (> 1kPa) was performed to provide undrained shear strength (void ratio-shear strength relationship).

The large strain consolidation apparatus used in this research confined the slurried material in a consolidation cell 10 cm in diameter x 15.5 cm in height (Scott et al. 2008). A piston load of about 1 kPa was applied as the first load. After this, loads were applied first by dead loads up to about 12 kPa and then by an air pressure bellofram. The vertical stresses were doubled for each load step until the maximum vertical stress was reached (100 kPa and 500 kPa in these tests). During consolidation, the change in height of the sample was monitored and plotted against time. When the height change stopped at each load stepit was assumed that consolidation was complete for that load step At this stage the excess pore pressure was also monitored at the base of the sample to ensure that the excess pore pressure had fully dissipated. The hydraulic conductivity was measured at the end of consolidation for each load step. An upward flow constant head test was performed with the head loss being kept small enough so that seepage forces would not exceed the applied stress. The undrained shear strength was also measured following the hydraulic conductivity test. The sample surface was exposed, and the shear strength was measured using a Rheometer for strengths up to 1 kPa. A vane shear apparatus was used for shear strengths greater than 1 kPa. After the shear strength measurement, a subsequent load was then applied to the sample to continue the large strain test (Scott et al. 2008)..

Analytical modeling of the rate and magnitude of settlement and consolidation of FFT and TT is beyond the scope of this paper. However, the compressibility, hydraulic conductivity and shear strength relationships determined by the large strain consolidation tests may be applied to any future modeling of the tailings to predict whether the materials can meet the required shear strengths in the specified amount of time.

4 LARGE STRAIN CONSOLIDATION OF FLUID FINE TAILINGS

The consolidation and shear strength of FFT is used as the base case to evaluate the advantages of the various treatments on oil sands fine tailings. The FFT sample used for the consolidation test was obtained from a CNRL tailings pond, was allowed to settle to its initial solids content and then was gently stirred to become homogeneous. Tailings water was used for the hydraulic conductivity tests and any mixing of the FFT so the chemistry of the pore water was not changed. Initial properties were first determined (Tables 1 and 2), and then the consolidation test was performed. Figures 3 and

4 are the consolidation results and Figures 5 and 6 are the shear strengths of the FFT.

Based on the TMF policy, the AER will set limits for total volume of FFT permitted on each site and the timelines for creating ready-to-reclaim tailings deposits. The TMF currently defines fine tailings or FFT as any fluid waste with a solids content by mass greater than 5% and an undrained shear strength of 5 kPa or less. In the absence of a definition for the TMF's ready-to-reclaim tailings deposit, Directive 074's trafficable surface definition of a minimum undrained shear strength of 10 kPa will be used instead. The effectiveness of the various TT tailings treatments will be evaluated for their ability to meet the TMF's requirements.

Therefore, the procedure for the evaluation is to determine the above shear strengths as a function of fines void ratio and effective stress and then determine what effective stress is necessary to achieve the required shear strength, which will indicate the required thickness of the deposit. Following this, the determination of what the hydraulic conductivities are will indicate how faster or slower it will take to consolidate to the required fines void ratio. For the FFT, from Figure 5, a shear strength of 5 kPa is reached at a fines void ratio of about 1.60 and a shear strength of 10 kPa at a fines void ratio of about 1.40. From Figure 3, the required effective stress at a fines void ratio of 1.60 is about 22 kPa and at a void ratio of 1.40 is about 44 kPa. For the TT samples, the shear strength will also be plotted as a function of effective stress to determine what effective stress is necessary to achieve the required shear strength and fines void ratio. From Figure 4, the FFT hydraulic conductivity at a fines void ratio of 1.60 is about 1.8 x 10-10 m/s and at a fines void ratio of 1.40 is about 1.0 x 10-10 m/s. These values of fines void ratio, effective stress and hydraulic conductivity will be compared to those of the treated TT samples at shear strengths of 5 kPa and 10 kPa to evaluate the effectiveness of all the tailings samples to meet the TMF policy.

5 LARGE STRAIN CONSOLIDATION OF TREATED FFT

5.1 Fabricating the TT Sample

All under-flow flocculated TT samples used in this research were treated with a flocculent dosage of 150 g/t except for samples TT 4 and 5. The TT samples were received in 25-L plastic pails from the Saskatchewan Research Council in Saskatoon. The method of production of the thickener under-flow TT samples is beyond the scope of this paper and is not discussed. The initial solids and water contents, void ratios, specific gravities and index properties of the TT samples (Tables 1 and 2) were determined upon delivery to the University of Alberta Geotechnical Center.

One-dimensional freeze/thaw tests were conducted on samples TT 2 and 5 to investigate the effect of freezing and thawing on the consolidation properties (compressibility and hydraulic conductivity) and undrained shear strength. The freezing test was conducted in a closed conduction freezing apparatus comprised of a 150-mm high x 100-mm diameter PVC cell fitted with a bottom removable PVC cap. A temperature-controlled plate was applied to the top of the sample to freeze the sample vertically downward in one dimension. The cell was filled with a slurried specimen up to about its full height (~140 mm), and the specimen was frozen by conduction with a top cold plate temperature of -10°C for seven days. After freezing, the frozen specimen was transferred into a consolidation cell of similar diameter which was placed directly beneath the freezing cell with the bottom cap removed. The transfer of the specimen into the consolidation cell was facilitated by gently warming the cell outside surface using a heated blower. The specimen was left thawed in the consolidation cell at room temperature between 20°C and 23°C for seven days prior to the consolidation test to allow the excess thaw water to drain off and self-weight thaw strain to take place. The thaw strain was measured after self-settling to calculate the void ratio after freeze/thaw. In some cases a duplicate sample was used to determine the void ratio by oven-drying the specimen after self-settling. Both procedures yielded similar values of the void ratio after thaw.

5.2 Effect of flocculating, thickening and freeze/thaw

The effects of the flocculating, thickening and freeze/thaw treatments on the consolidation and shear strength properties of oil sands fine tailings are evaluated in this section. The properties of the TT 1 sample, which was flocculated and thickened, are compared to those of the untreated FFT to evaluate the effect of flocculating and thickening. The properties of the TT 2 sample, which initially was flocculated and thickened and then was treated with the freeze/thaw process, are compared to those of the FFT and TT 1 to evaluate the effect of freeze/thaw.

Figures 3, 4, 5 and 6 show the FFT, TT 1 and 2 compressibilities, hydraulic conductivities and shear strengths as a function of fines void ratio, and shear strengths as a function of effective stress, respectively. The most interesting figures are 3 and 5. Figure 3 shows that all samples have, within experimental error, the same compressibility above an effective stress of about 1 kPa. The following sections show that TT 3, 4 and 5 also have the same compressibilities. Therefore, it is concluded that none of the treatment processes increase compressibility when effective stresses are above 1 kPa. Figure 5 shows that all samples have approximately the same shear strength relationship with fines void ratio. At 5 kPa shear strength the fines void ratio is about 1.60, and at a shear strength of 10 kPa the fines void ratio is about 1.40. The following section also shows that TT 5 has this same shear strength relationship. The conclusion from this finding is that none of the treatment processes increase the shear strength of the fine tailings at any fines void ratio. Previous research (Jeeravipoolvarn 2010) has indicated that flocculation increases the shear strength of oil sands fine tailings. This observation depends on how the shear strength is considered. Figure 6, which shows shear strength as a function of effective stress, does show an increase in shear strength for TT 1 and 2 compared to that of the FFT, so Jeeravipoolvarn's observation is verified when comparing shear strengths with effective stress. To compare the shear strengths of different materials, however, it is more appropriate to discuss shear strengths as a function of void ratio or in the case of oil sands fine tailings the fines void ratio, and this is the comparison used in this research. The important observation from Figure 4 is that the hydraulic conductivities of the treated TT samples are much higher than that of the FFT.

With regard to the TMF criteria, Table 3 shows fines void ratios, effective stresses and hydraulic conductivities at undrained shear strengths of 5 kPa and 10 kPa. The fines void ratios at these shear strengths are all approximately the same as discussed above. The effective stresses required to consolidate the tailings to these fine void ratios are also shown. Of most importance are the hydraulic conductivities: with increasing treatment the hydraulic conductivity is much greater with that of TT 2 being two orders of magnitude greater than that of the FFT. Table 3 is a valuable summary which shows that all the untreated and treated tailings have the same fines void ratio and similar compressibilities. The only effect of the treatment processes is to change the hydraulic conductivity. An increase in hydraulic conductivity will result in the treated tailings consolidating much faster. Table 3 shows that TT 2 (the flocculated, thickened and freeze/thawed treated tailings) will closest meet the shear strength requirements of the TMF policy for the treatment options discussed in this section.

Table 3. Summary of consolidation results at specific shear strengths for FFT, TT 1 and 2.

Sample designation	5 kPa shear strength			10 kPa shear strength		
	Fines void ratio	Effective stress (kPa)	Hydraulic conductivity (m/s)	Fines void ratio	Effective stress (kPa)	Hydraulic conductivity (m/s)
FFT	1.60	22.0	1.8×10^{-10}	1.40	44.0	1.0×10^{-10}
TT1	1.70	8.0	6.0×10^{-9}	1.40	20.0	2.5×10^{-9}
TT2	1.52	6.5	1.2×10^{-8}	1.35	25.0	7.0×10^{-9}

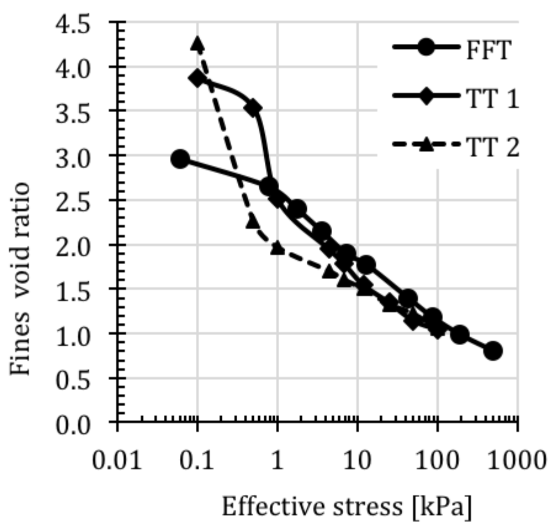

Figure 3. Compressibility of FFT, TT 1 and 2

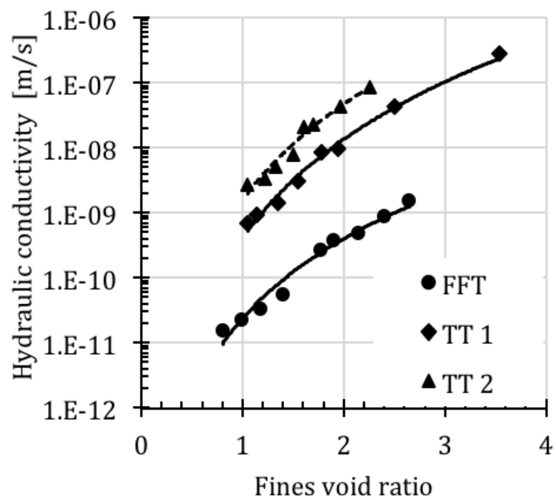

Figure 4. Hydraulic conductivity of FFT, TT 1 and 2

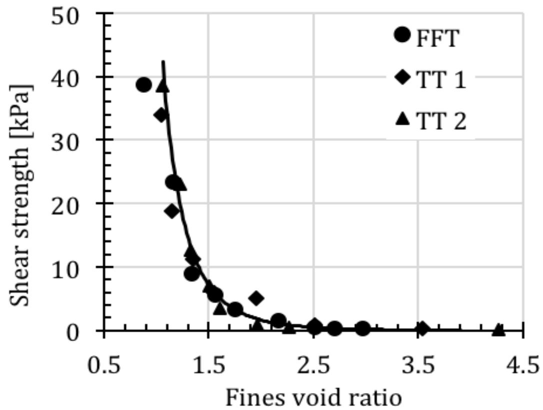

Figure 5. Undrained shear strength of FFT, TT 1 and 2 as a fucntion of fines void ratio.

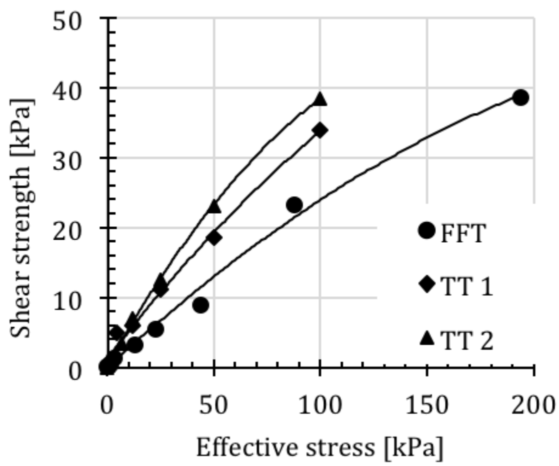

Figure 6. Undrained shear strength of FFT, TT 1 and 2 as a function of effective stress.

5.3 Effect of flocculation dosage, thickening and freeze/thaw

TT 4 and 5 had flocculation dosages of 300 g/t (150 g/t applied twice) compared to TT 3 which had a flocculation dosage of 150 g/t. The effect of these dosages is evaluated by comparing the consolidation properties of the FFT, TT 3 and 4. Shear strength tests were not conducted on TT 3 and 4, so shear strength properties cannot be evaluated. Figures 7 and 8 show the compressibilities and hydraulic conductivities, respectively. From Figure 8, both the FFT and the flocculated samples had similar compressibilities over 10 kPa. The observation from Figure 8 is that although both flocculated samples had higher hydraulic conductivities than the FFT, the lower dosage TT 3 had a considerable higher hydraulic conductivity than the higher dosage TT 4. The conclusion is that the lower dosage was better than the higher dosage. Table 4, which shows the hydraulic conductivity properties at shear strengths of 5 kPa and 10 kPa, gives the same conclusion. For this table, the shear strength relationship with fines void ratio for TT 3 and 4 was assumed to be the same as the other four samples.

The effect of the freeze/thaw process on the higher dosage TT samples is evaluated by comparing the consolidation and shear strength properties of the FFT, TT 4 and 5. Figures 9, 10, 11 and 12 show these samples' compressibilities, hydraulic conductivities, shear strengths as a function of fines void ratio, and shear strengths as a function of effective stress, respectively. In Figure 9 the TT samples had approximately the same compressibilities to that of the FFT, similar to the findings in Figures 3 and 7. Figure 11 shows the relationship of shear strength with fines void ratio for TT 5 is similar to that in Figure 5 for the other samples. Figure 12, which also shows shear strength, agrees with Jeeravipoolvarn (2010) that flocculation and freeze/thaw treatments increase the shear strength as a function of effective stress. The test results for hydraulic conductivity are shown in Figure 10. Both treated TT samples have higher hydraulic conductivities than the FFT and that of TT 5 is higher than that of TT 4 at larger fines void ratios, but becomes lower at low fines void ratios.

Table 4. Summary of consolidation results at specific shear strengths for FFT, TT 3, 4 and 5

Sample designation	5 kPa shear strength			10 kPa shear strength		
	Fines void ratio	Effective stress (kPa)	Hydraulic conductivity (m/s)	Fines void ratio	Effective stress (kPa)	Hydraulic conductivity (m/s)
FFT	1.60	22.0	1.8×10^{-10}	1.40	44.0	1.0×10^{-10}
TT3	1.60	1.8	4.0×10^{-8}	1.40	4.0	1.8×10^{-8}
TT4	1.60	18.0	1.5×10^{-9}	1.40	80.0	6.0×10^{-10}
TT5	1.75	12.0	2.2×10^{-9}	1.52	200.0	2.2×10^{-10}

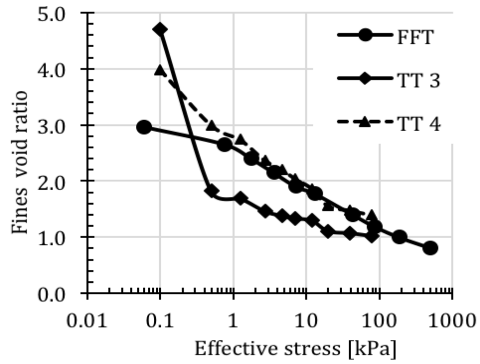

Figure 7. Compressibility of FFT, TT 3 and 4

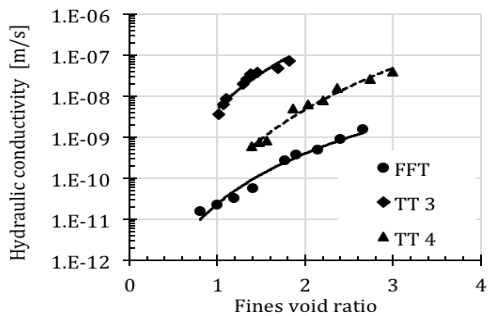

Figure 8. Hydraulic conductivity of FFT, TT 3 and 4

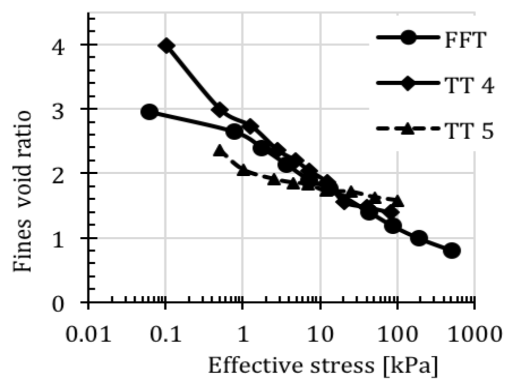

Figure 9. Compressibility of FFT, TT 4 and 5

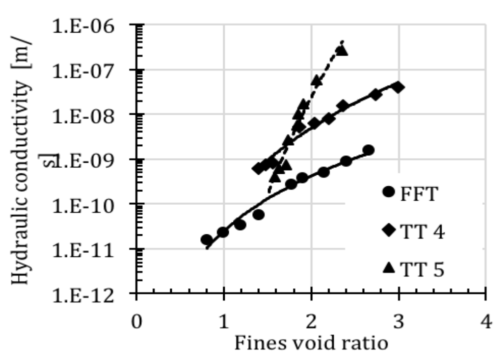

Figure 10. Hydraulic conductivity of FFT, TT 4 and 5

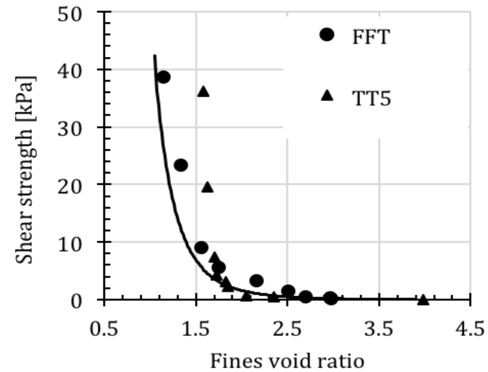

Figure 11. Undrained shear strength of FFT and TT 5 as a function of fines void ratio

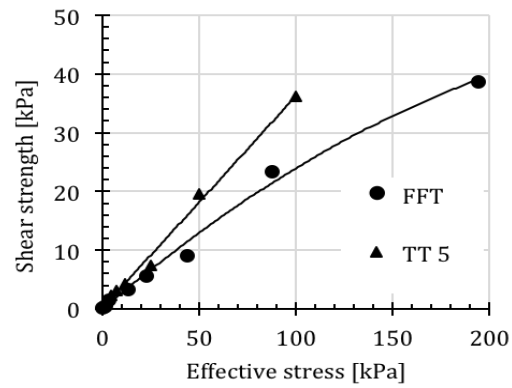

Figure 12. Undrained shear strength of FFT and TT 5 as a function of effective stress.

Similar to Table 3, Table 4 shows that all the untreated and treated tailings have, within experimental error, the same fines void ratio and the same compressibilities. The only effect of the treatment processes is to change the hydraulic conductivity. A larger hydraulic conductivity will result in the treated tailings consolidating much faster. Table 4 shows that TT 3 (the flocculated and thickened tailings) will closest meet the shear strength requirements of the TMF for the treatment options discussed in this section.

6 DISCUSSION AND CONCLUSIONS

Large strain consolidation tests and shear strength tests were performed on untreated oil sands fluid fine tailings (FFT) and on five thickened tailings (TT) samples which had various treatments. All the TT samples were flocculated and thickened; some were also treated with a freeze/thaw process and some with a higher flocculent dosage. These test results were analyzed to evaluate the effectiveness of the following treatments:

1. Effect of flocculating and thickening;
2. Effect of the freeze/thaw process;
3. Effect of a higher flocculent dose; and
4. Effect of a higher flocculent dose and the freeze/thaw process.

These evaluations were considered with respect to the shear strength requirements of 5 kPa and 10 kPa from the Government of Alberta's Tailings Management Framework (TMF).

Treatments 1 to 4: It was found that all six samples had similar compressibilities and the same shear strength relationship with fines void ratio. The conclusions from these findings are that none of the treatment processes significantly increases the compressibility at any effective stress nor increases the shear strength of the fine tailings at any fines void ratio.

Treatment 1: The flocculated and thickened TT hydraulic conductivity is higher than that of the FFT. This treatment therefore will result in the tailings consolidating faster than the untreated FFT.

Treatment 2: The hydraulic conductivities of the treated TT samples are much higher than that of the FFT. With increasing treatment, the hydraulic conductivity is much greater with that of the freeze/thaw TT being two orders of magnitude greater than that of the FFT. Therefore, the treated tailings will consolidate much faster.

Treatment 3: The observation is that although both flocculated samples had higher hydraulic conductivities than the FFT, the lower dosage TT had a considerable higher hydraulic conductivity than the higher dosage TT. The conclusion is that the lower flocculent dosage was better than the higher flocculent dosage. The consolidation properties in Table 4 at shear strengths of 5 kPa and 10 kPa give the same conclusion.

Treatment 4: Both higher flocculent treated TT samples have hydraulic conductivities not too different from that of the FFT at 10 kPa shear strength. The hydraulic conductivity of freeze/thaw TT 5 is higher than that of TT 4 at larger fines void ratios, but becomes lower at low fines void ratios. At shear strengths of 5 kPa and 10 kPa, the conclusion is that the freeze/thaw process is a better treatment only at lower effective stresses and higher fines void ratios for the higher flocculent dosage TT samples.

The summary tables, which show all the untreated and treated tailings' consolidation and shear strength properties, are valuable to compare these properties. They show that all the tailings, within experimental error, have the same compressibilities and the same shear strength relationships with fines void ratio. The only effect of the treatment processes is to change the hydraulic conductivity. A larger hydraulic conductivity will result in the treated tailings consolidating faster. Based on the hydraulic conductivities, the tables show which treated tailings will closest meet the 5 kPa and the 10 kPa shear strength requirements of the TMF in the specified time. The tables show that TT 3 (the flocculated and thickened sample with a fines content of 67%) had the best consolidation properties. TT 2 (the flocculated, thickened and freeze/thawed sample with a fines content of 54%) had almost as good consolidation properties. Although these evaluations are numerically specific, they only show which treatments are the closest to meet the requirements of the TMF and not whether they will meet these requirements.

ACKNOWLEDGEMENTS

The authors would like to thank Total E&P for funding this research project and the Saskatchewan Research Council for providing the flocculated and thickened samples.

REFERENCES

Alberta Environment and Sustainable Resource Development (AESRD). 2014. Reclamation Information System, 2013. Annual Conservation and Reclamation Report Submissions.

Alberta Government. 2015. *Lower Athabasca Region – Tailings Management Framework for the Mineable Athabasca Oil Sands*.

ASTM Standard C837-99. 1999. Standard test method for Methylene Blue Index of clay. West Con-shohocken, PA: *ASTM International*, DOI: 10.1520/C0837-99.

ASTM Standard D4221-99, 1999. 2005. Standard test method for dispersive characteristics of clay soil by double hydrometer. West Conshohocken, PA: *ASTM International*, DOI: 10.1520/D4221-99R05.

ASTM Standard D422-63, 1963. 2007. Standard test method for particle-size analysis of soils. West Con-shohocken, PA: *ASTM International*, DOI: 10.1520/D0422-63R07.

ERCB. 2009. Directive 074: Tailings performance criteria and requirements for oil sand mining schemes. Calgary, AB: Energy Resources Conservation Board of Alberta.

Flanagan, E. and Grant, J. 2013. *Losing ground: Why the problem of oilsands tailings waste keeps growing*. Edmonton, AB: Pembina Institute.

Jeeravipoolvarn, S., Scott, J.D. and Chalaturnyk, R.J. 2008. Multi-dimensional finite strain consolidation theory: Modeling study. *61st Canadian Geotechnical Conference*, Edmonton, AB, 22-24 September 2008.

Jeeravipoolvarn, S. 2010. *Geotechnical behavior of in-line thickened tailings*. PhD Thesis, University of Alberta, Edmonton, Alberta, Canada. 410p.

Scott, J.D., Jeeravipoolvarn, S. and Chalaturnyk, R.J. 2008. Tests for wide range of compressibility and hydraulic conductivity of flocculated tailings. *61st Canadian Geotechnical Conference*, Edmonton, AB, 22-24 September 2008.

Sobkowicz, J. 2012. The oil sands tailings technology roadmap and action plan: Introduction and key recommendations. *Third International Oil Sands Tailings Conference*, Edmonton, AB, 2-5 December 2012. Edmonton, AB: University of Alberta Geotechnical Centre.

Suthaker, N.N. and Scott, J.D. 1994. Large scale consolidation testing of oil sand fine tails. *1st International Congress on Environmental Geotechnics*, Edmonton, AB, 10-15 July 1994.