

The effect of flyash addition on the consolidation properties and shear strength of oil sands fluid fine tailings

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ABSTRACT

Concern about the growing volume of fluid fine tailings resulted in the Alberta Energy Regulator setting out requirements for the disposal and closing of the tailings ponds through Directive 085, a policy document known as the Tailings Management Framework. The Tailings Management Framework policy requires oil sands companies to reduce their production and storage of fluid fine tailings (FFT) by creating deposits that can be reclaimed in a timely manner. A great number of commercial tailings technologies has been developed, many of which are mature and others are in an advanced development stage. The objective of the research reported in this paper was to investigate the effects of flocculation with flyash addition and thickening treatments by performing large strain consolidation tests and shear strength tests on 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. The effect of adding flyash to the flocculent varied, but was not sufficient to achieve the required void ratios. The flyash-treated thickened tailings (TT) were less compressible than untreated TT. It appears that the flyash cements the fine tailings, increasing its resistance to consolidation. The flyash-treated TT had a much larger shear strength than untreated TT, which is an effect of the cementation of the particles.

RÉSUMÉ

En raison d'inquiétudes concernant le volume croissant de résidus fins fluides, le Régulateur de l'Énergie de l'Alberta a établi des exigences relatives au stockage et à la fermeture des bassins de résidus par la directive 085, un document des règles connu sous le nom de structure de gestion des résidus. La politique de structure de gestion des résidus miniers exige des sociétés de sables bitumineux qu'elles réduisent leur production et leur stockage de résidus fins fluides (FFT) en créant des gisements pouvant être mis en valeur rapidement. Un grand nombre de technologies au stade commerciales de traitement des résidus ont été mises au point, dont beaucoup sont matures et d'autres en sont à un stade de développement avancé. L'objectif de la recherche présentée dans cet article était d'étudier les effets des traitements de l'ajout de cendre au flocculant et d'épaississement en effectuant de tests de consolidation à grande déformation et des tests de résistance au cisaillement sur les résidus fins traités. La consolidation à grande déformation et la résistance au cisaillement de FFT traité ont ensuite été comparés à ceux de FFT non traitée afin d'évaluer les effets des traitements. L'effet de l'ajout de cendres au flocculant variait, mais n'était pas suffisant pour atteindre les taux de vide requis. Les résidus épaissis (TT) traités avec des cendres étaient moins compressibles que les résidus épaissis TTs non traités avec des cendres. Il semble que les cendres cimentent les résidus fins, augmentant ainsi leur résistance à la consolidation. Les TTs épaissis traités avec des cendres avaient une résistance au cisaillement beaucoup plus grande que le TTs non traités avec des cendres, ce qui est un effet de la cémentation des particules.

1 INTRODUCTION

The first oil sands mining project in the Athabasca oil sands deposit in Alberta, Canada, started production in 1967. As the tailings from the oil sands contain toxic products, the tailings water and the fluid fine tailings (FFT) cannot be released and have to be stored in tailings ponds. As of 2017, there were 176 operating and approved oil sands projects in Alberta. Of these, six were producing mining projects (two more are presently experimental) and are producing about 900,000 barrels of bitumen per day; the remaining projects use various in situ recovery methods (Alberta Government, 2017). On average, about 1 m³ of sand and 0.25 m³ of FFT at a solids content of about 30% to 35% are created for every barrel of bitumen produced. This has led to the accumulation of approximately one billion m³ of FFT which require long-term storage in tailings ponds as the water is toxic and cannot be released. The

total area covered by tailings ponds in 2010 was 176 km², and as 200 million liters per day continues to be accumulated, the area is forecast to increase to 250 km² by 2020.

Concerned about the growing volume of FFT, the Alberta Energy Regulator (AER) issued in October 2017 a revised *Directive 085: Fluid Tailings Management for Oil Sands Mining Projects*. This directive, under the *Oil Sands Conservation Act (OSCA)*, sets out requirements for managing fluid tailings volumes for oil sands mining projects, including application information requirements, the application review process, fluid tailing management reporting, and the performance evaluation and compliance and enforcement processes. This directive replaces *Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes* and enables the implementation of the *Tailings Management Framework for the Mineable Athabasca Oil Sands (TMF)*.

The TMF provides policy direction to the AER to manage fluid tailings volumes during and after mine operation in order to manage and decrease liability and environmental risk resulting from the accumulation of fluid tailings on the landscape. The objective of the TMF is to minimize fluid tailings accumulation by ensuring that fluid tailings are treated and reclaimed progressively during the life of a project and that all fluid tailings associated with a project are ready to reclaim (RTR) ten years after the end of mine life of that project. The TMF is intended to be reviewed every five years.

The reason for this massive accumulation is that FFT consolidate extremely slowly. Further research on FFT disposal options is required, and many have dedicated their time to study how to solve the oil sands tailings problem. Sobkowicz (2012) reports on the development of an oil sands tailings technology roadmap and action plan. In this project, 549 tailings technologies were identified that could have potential use in the oil sands industry. These were reduced to 101 unique technologies which have been discussed by McKenna et al. (2012). There are already 22 tailings technologies 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. An additional promising technology is to use freeze/thaw processes to further thicken the tailings. The latter technology is beyond the scope of this paper, but is presented in Wilson et al. (2018). The objective of the research reported in this paper was to investigate the effects of flocculating with flyash addition and thickening treatments by performing large strain consolidation tests and shear strength tests on 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. The effectiveness of the treated tailings (TT) was then evaluated by reviewing how well they met the shear strength requirement to support reclamation and surface trafficability.

2 MATERIAL AND METHODS

2.1 Characterization of the tailings

Four tailings samples have been tested in this research: a typical untreated fluid fine tailings (FFT) and three thickened tailings (TT1, TT6 and TT7) which were all flocculated and thickened. Table 1 shows the initial properties of the tailings. The properties of the TT samples are after treating by flocculation and thickening. The treatment of TT6 and TT7 was similar to that of TT1 except that flyash was added to the flocculent. TT6, however, was an older or aged flocculated and thickened material that had been in storage for some time. The initial solids content of the FFT was 46% while solids contents of TT1 and TT6 were 49% and TT7 was 46%, so the initial solids contents were similar. The main difference between the FFT and the TT samples was in their sand content. The FFT had only 4% sand while TT1, TT6 and TT7 had 46%, 45% and 52% sand, respectively. The effect of the sand on the oil sand fine tailings properties has been found to be minimal. Recent research by Sorta and Segó (2010) examined the

geotechnical properties of sand and fines mixtures of oil sands tailings and found that the sand only functions as filler material that displaces the fines matrix. The sand increases the solids content and decreases the void ratio, but has little effect on the engineering properties of compressibility, hydraulic conductivity and shear strength.

Table 1. Initial properties of the tailings

ID	Treatment methods	S.C (%)	Fine (%)	Void ratio	Clay (%)	MBI (%)
FFT	none	46.1	96	2.85	15	
TT1	FF+TH	49	54	2.74	18	38
TT6	FFT+TH + 2% flyash	46.3	48	3.10	3	38
TT7	FF+TH + 3% flyash	49	55	2,71	8	40

Geotechnical properties of Atterberg limits, specific gravity and bitumen content are given in Table 2. The FFT had a liquid limit of 50%, typical of most untreated FFT, while that of TT1, TT6 and TT7 were 28%, 41% and 36%, respectively. The lower liquid limits (LL) for the TT samples are caused by the sand contents. Generally for oil sands fine tailings the addition of flocculants raises the LL, but in this case the presence of the large amount of sand dominates the LL. 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 TT samples are the same. 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. The bitumen causes the specific gravity of the tailings to be lower as its specific gravity is only about 1.03. The effect of the sand can be seen in a plasticity chart (Figure 1). All the samples, except for the aged TT6, plot in a line approximately parallel to the A-line, indicating a similar origin and similar clay mineralogy. The location of sample TT6 indicates a material of low plasticity because of its small clay size amount (Table 1) and possibly different clay mineralogy. Because of these properties, sample TT6 would be less affected by a flocculent and flyash.

Table 2. Geotechnical properties of the tailings

ID	LL (%)	PL (%)	Plasticity (%)	Activity	Gs	Butimen (%)
FFT	50	21	29	0.58	2.44	1.6
TT1	28	18	10	0.29	2.63	0.4
TT6	42	25	17	0.29	2.63	0.5
TT7	36	17	19	0.29	2.61	0.1

LL= Liquid Limits, PL = Plastic Limits and Gs = specific gravity

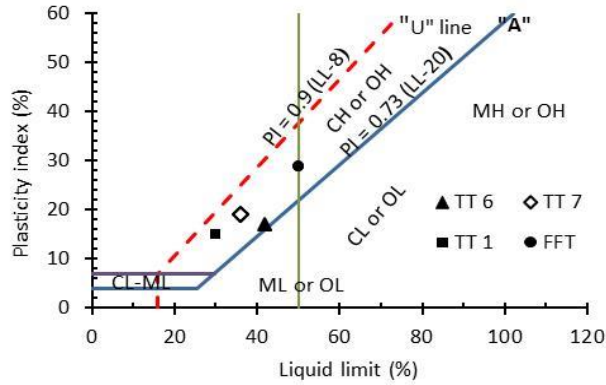


Figure 1. Plasticity chart of FFT, TT1, TT6 and TT7

The particle size distributions (PSD) of the FFT and TT are given in Figures 2 and 3. The fine material (< 45 μm) in the tailings originates from inter-bedded dense clay-shale beds in the oil sands formations. The extent to which these clay-shale beds are broken up depends on the mining methods, the bitumen extraction processes and the composition of the oil sands ore. Nondispersed and dispersed hydrometer tests were performed to determine the PSD and the degree of fines dispersion for the samples. The tailings underwent hydrometer tests following the procedure outlined in ASTM D 4221-99R05 (ASTM, 2005) to determine 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 nondispersive test better defines the particle sizes in flocculated oil sands tailings. These particles are composed of flocs and nondispersed clay aggregates while the dispersed test disperses these particles into their individual grain sizes. The nondispersed 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 nondispersed hydrometer measurements because the MBI test disperses the clay aggregates and flocs (ASTM, 1999).

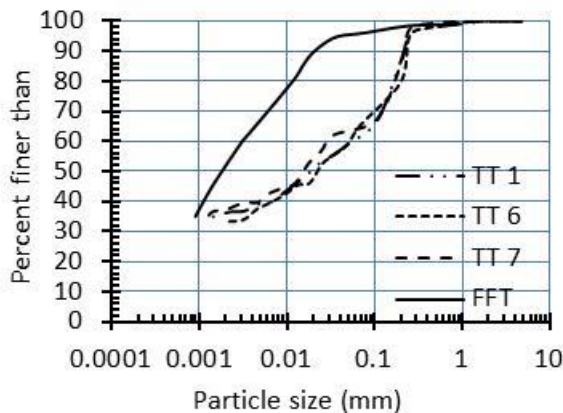


Figure 2. Dispersed particle size distribution

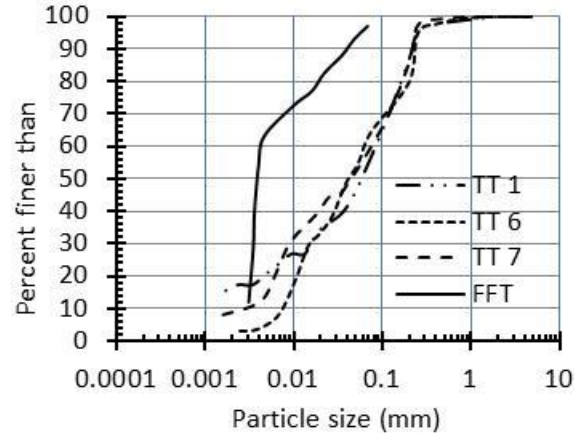


Figure 3. Nondispersed particle size distribution

2.2 Large strain consolidation tests

Large strain consolidation tests were used to determine three relationships: effective stress – void ratio; void ratio – hydraulic conductivity; and void ratio – undrained shear strength. The infinitesimal consolidation theory (Terzaghi consolidation theory) is not valid for soft soils that undergo large amounts of volume change; therefore, a finite strain consolidation theory is used for oil sands fine tailings (Jeeravipoolvarn et al., 2008; Suthaker & Scott, 1994). The finite strain consolidation theory requires the first two relationships mentioned above for analyses. To evaluate whether the tailings meet the shear strength sufficient to support reclamation and stability necessary to establish a trafficable surface, the third relationship is included in the analyses.

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 bellows. 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, it was assumed that consolidation was complete. 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 then 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. A subsequent load was then applied after the shear strength measurement.

3 RESULTS AND DISCUSSION

3.1 Large strain consolidation of FFT and TTs

3.1.1 Effect of flocculating and thickening

The consolidation and shear strength of the FFT was used as the base case to evaluate the advantages of the various treatments on oil sands fine tailings (Wilson et al., 2018). The FFT sample used for the consolidation test 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 (thus, 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. With all underflow flocculated, TT samples used in this research were treated with a flocculent dosage of 150 g/t, and TT6 and TT7 had 2% and 3% flyash by mass added to the flocculent, respectively. The TT samples were received in 25 L plastic pails from the Saskatchewan Research Council in Saskatoon. The method of production of the thickener underflow TT 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 Centre.

Figures 4 and 5 compare the consolidation results of FFT and TT1 which was flocculated and thickened. Figures 6 and 7 compare the shear strengths. Figure 4 indicates that the treated TT1 was more compressible than the untreated FFT. At any consolidation effective stress, the TT was at a lower void ratio. This observation is somewhat deceiving because the sand in the TT decreases the void ratio and the magnitude of the TT void ratio has to be considered in this light. Figure 5 shows the hydraulic conductivity of the TT is considerably greater, about two orders of magnitude, than that of the FFT. This larger hydraulic conductivity is the most important benefit of the flocculating and thickening. Figure 6 shows the shear strength as a function of void ratio. It appears that the TT has much lower shear strengths than the FFT at all void ratios, but this again is deceiving as the void ratio of the TT is affected by the sand content.

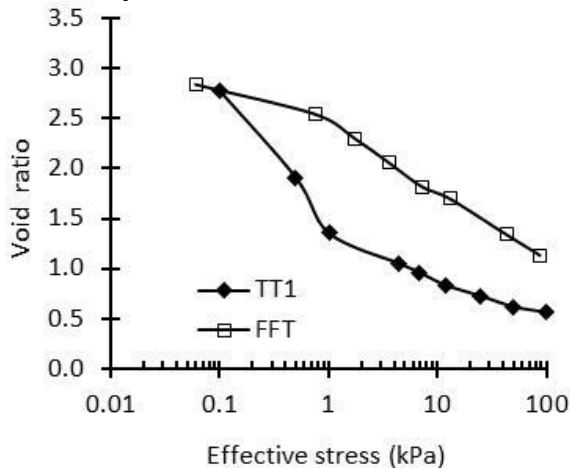


Figure 4. Compressibility of FFT and TT1

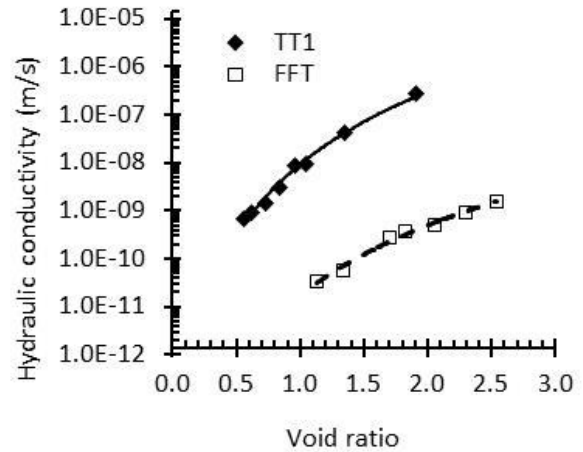


Figure 5. Hydraulic conductivity of FFT and TT1

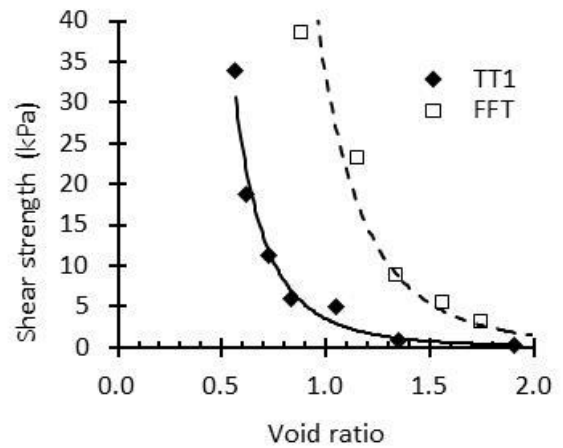


Figure 6. Undrained shear strength of FFT and TT 1 as a function of void ratio

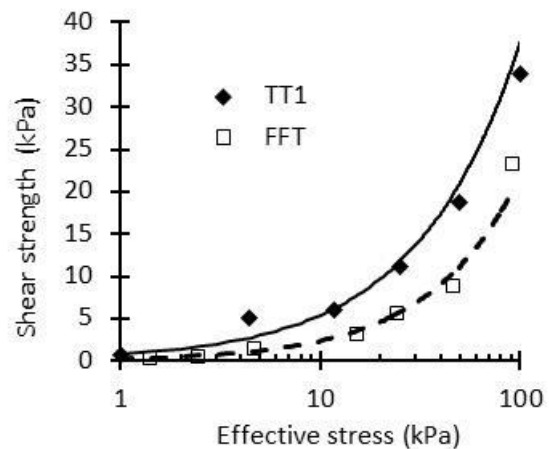


Figure 7. Undrained shear strength of FFT and TT1 as a function of effective stress

A better comparison is in Figure 7, where the shear strength is a function of effective stress and the shear

strength of the TT is greater than that of the FFT. Previous research (Jeeravipoolvarn, 2010) has indicated that flocculation increases the shear strength of oil sands fine tailings, and this is verified by Figure 7.

With regard to whether the tailings can meet the shear strength sufficient to support reclamation and surface trafficability (i.e., Figure 8), Table 3 shows void ratios, effective stresses and hydraulic conductivities at undrained shear strengths of 25 kPa. The void ratios are those where the tailings have these required shear strengths.

Table 3. Summary of consolidation results at specific shear strengths for MFT, FTT1, FTT2 and FTT3

25 kPa shear strength			
	Void ratio	σ' (kPa)	K (m/s)
FFT	1.10	80	3×10^{-11}
TT1	0.60	25	8×10^{-10}
TT6	1.80	1	1×10^{-9}
TT7	1.00	50	2×10^{-7}

σ' = effective stress, K = hydraulic conductivity

Of interest, the FFT reaches the required shear strengths at higher void ratios, but this observation has to be tempered by the effect of the sand content on the void ratios of the TT. The effective stresses required to consolidate the tailings to these void ratios are also shown. These are the effective stresses that must be applied to deposits of the tailings so they meet the shear strength requirements of surface trafficability. The FFT and TT1 must have 80 kPa and 25 kPa surcharge loading of these magnitudes to be consolidated to the required void ratios or be subjected to atmospheric drying to be decreased to these void ratios. TT1 is closer to the required void ratio than the untreated FFT; thus, the flocculating and thickening is beneficial to meeting the shear strength requirements of surface trafficability.

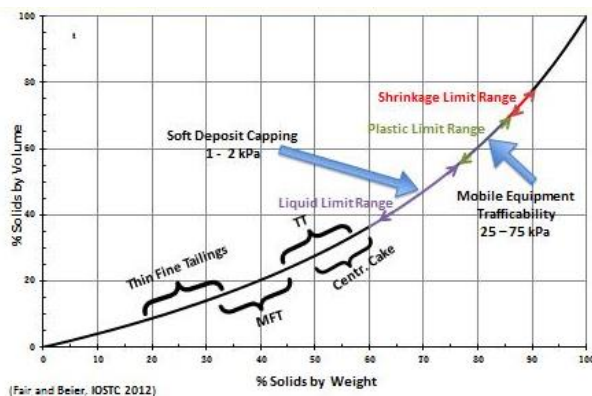


Figure 8. FFT dewatering processes for oil sands tailings

Of most importance are the hydraulic conductivities: with the flocculating and thickening treatment, the hydraulic conductivity of TT1 is much greater than that of the FFT. Table 6 is a valuable summary which compares the required void ratio and effective stress to meet the shear

strength requirements of surface trafficability. The major effect of the treatment process is to increase the hydraulic conductivity by one and a half orders of magnitude, which will result in the treated tailings consolidating much faster.

3.1.2 Effect of adding flyash to the flocculent

The effect of adding different amounts of flyash to the flocculent is evaluated in this section. Figures 9 and 10 compare the consolidation of the FFT and TT samples. Figures 11, 12 and 13 compare the shear strengths. The compressibilities in Figure 9 show that the flyash-treated TT6 and TT7 were less compressible than TT1 which was only treated with the flocculent. At effective stresses over 1 kPa, the flyash-treated TTs were an order of magnitude more resistant to compression. It appears that the flyash cements the fine tailings, increasing its resistance to consolidate. The lower compression of the FFT is somewhat deceiving because of the sand in the TTs, as discussed in the previous section. Figure 9 shows that the 3% flyash TT7 had a higher hydraulic conductivity than the other tailings. However, TT1 with no flyash was more permeable than the 2% flyash TT6. Figure 11 shows the shear strengths as a function of void ratio: the two flyash-treated TTs have a much larger shear strength than TT1, which is an effect of the cementation of the particles. As mentioned previously, the high shear strength of the FFT is deceiving as the void ratio of the TTs is affected by the sand content.

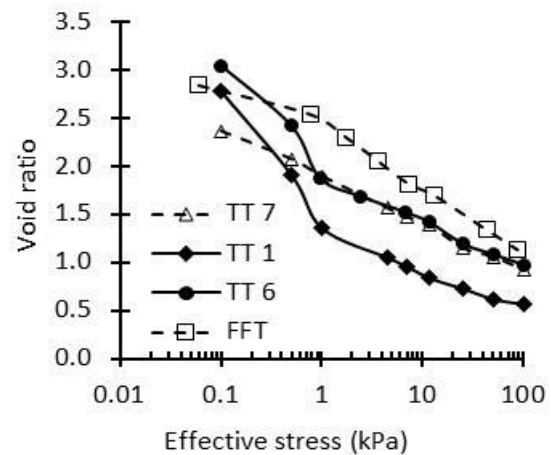


Figure 9. Undrained shear strength of FFT, TT1, TT6 and TT7 as a function of fines void ratio

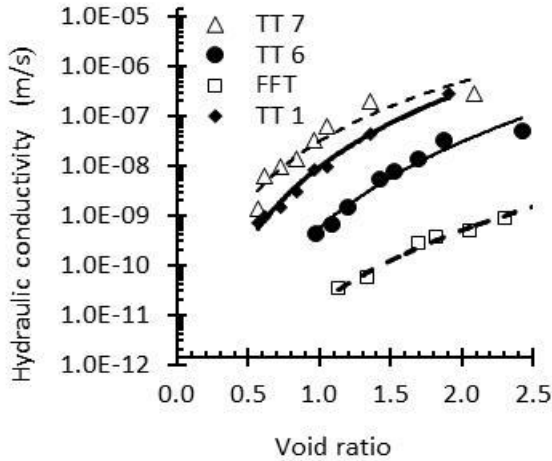


Figure 10. Hydraulic conductivity of FFT, TT1, TT6 and TT7

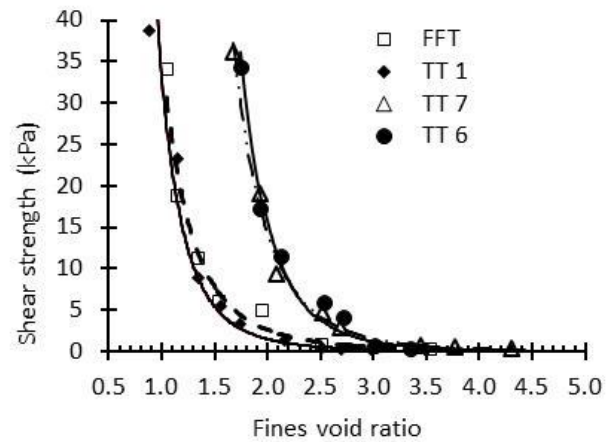


Figure 12. Undrained shear strength of FFT, TT1, TT6 and TT7 as a function of fines void ratio

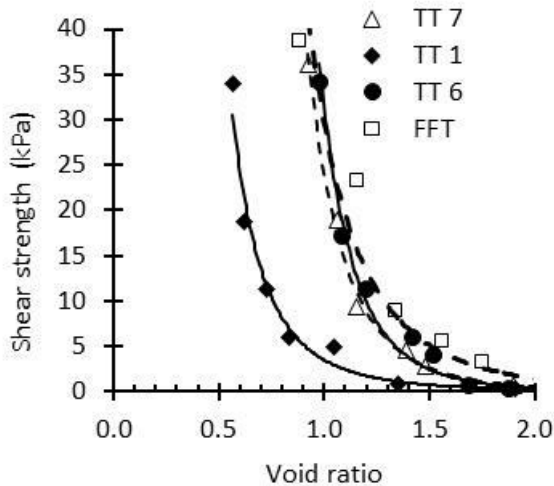


Figure 11. Undrained shear strength of FFT, TT1, TT6 and TT7 as a function of effective stress

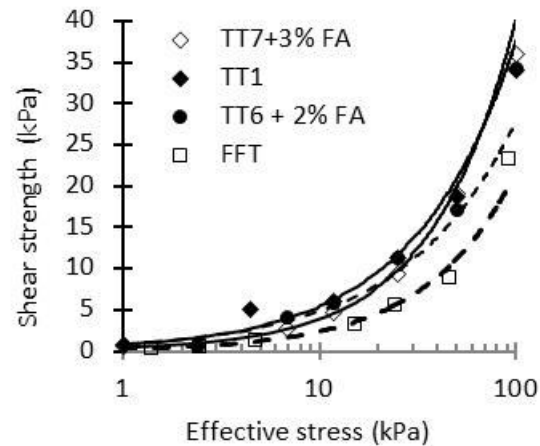


Figure 13. Undrained shear strength of FFT, T1, TT6 and TT7 as a function of effective stress

To explore the effect of sand content on the void ratio – shear strength relationship, these same shear strengths are plotted as a function of fines void ratio in Figure 12. This plot shows that flocculating, thickening and flyash addition has a major effect on increasing the shear strength. With this plot, the effect of the sand is removed and the FFT has the same shear strength as TT1. Figure 13, where shear strength is plotted as a function of effective stress, shows that all TTs have approximately the same shear strengths. The higher shear strengths of TT6 and TT7 are masked with this comparison because they have higher void ratios than TT1; thus, they achieve their shear strengths with less compression.

A conclusion from these test results is that the addition of flyash hinders consolidation, which is an advantage because it will finish consolidating faster. It is also disadvantageous in that a deposit will not compress as much and therefore will require more room in a dedicated disposal area (DDA). An advantage of the 3% flyash is that it has a slightly larger hydraulic conductivity than the no flyash TT1 sample, which means that, coupled with the smaller compressibility; it will complete consolidation much faster. The 2% aged flyash, however, has a significantly lower hydraulic conductivity than the no flyash TT1 and, even with the smaller compressibility, will consolidate slower. With regard to surface trafficability, Table 3 shows the significant advantage for the inclusion of flyash in the flocculent. TT6 and TT7 reach the required shear strengths at higher void ratios, which reflect their resistance to consolidation.

All three TT materials are significantly better than the FFT in hydraulic conductivity. The reasons why the aged TT6 sample had lower hydraulic conductivities closer to that of the FFT are because of its lower clay size content

and possible less plastic clay mineralogy. These differences made the TT6 material less susceptible to changes by flocculants and flyash.

4 SUMMARY AND CONCLUSIONS

Four tailings samples were tested: a typical untreated FFT and three TTs which were flocculated and thickened. Two of the TTs had flyash added to the flocculent. Large strain consolidation tests were used to determine three relationships: effective stress – void ratio; void ratio – hydraulic conductivity; and void ratio – undrained shear strength for all of the samples. The consolidation and shear strength of FFT was used as the base case to evaluate the various treatments on oil sands fine tailings. The effect of flocculation and thickening was evaluated by comparing the tests results of TT1 with those of the untreated FFT. The effect of adding flyash to the flocculent was evaluated by comparing the test results of all four samples.

With regard to surface trafficability-required shear strengths, a summary table was developed showing void ratios, effective stresses and hydraulic conductivities at undrained shear strengths of 10 kPa and 25 kPa. The void ratios shown are those where the tailings have these required shear strengths. The effective stresses required to consolidate the tailings to these void ratios are also shown. These are the effective stresses that must be applied to deposits of the tailings so they meet the shear strength requirements of surface trafficability. The conclusions from these tests are:

1. The effect of flocculation and thickening was not sufficient to achieve the required void ratios. Both the FFT and TT1 must have surcharge loading to be consolidated to the required void ratios or be subjected to atmospheric drying to decrease to these void ratios. TT1 was closer to the required void ratio than the untreated FFT; thus, flocculation and thickening is beneficial to meeting surface trafficability.

2. With the flocculation and thickening treatment, the hydraulic conductivity of TT1 was much greater than that of the FFT. An increase in hydraulic conductivity will result in the treated tailings consolidating much faster.

3. The effect of adding flyash to the flocculent varied, but was not sufficient to achieve the required void ratios. The flyash-treated TTs were less compressible than TT1. At effective stresses over 1 kPa, the flyash-treated TTs were an order of magnitude more resistant to compression. It appears that the flyash cements the fine tailings, increasing its resistance to consolidation. Though it will finish consolidating faster, the deposit will not compress as much and will require more room in a DDA.

4. The flyash-treated TTs had much larger shear strength than TT1, which is an effect of the cementation of the particles. Further, an advantage of the 3% flyash TT is that it has a slightly larger hydraulic conductivity than the no flyash TT which means, coupled with the smaller compressibility, it will complete consolidation much faster. The 2% aged flyash TT, however, has a significantly lower

hydraulic conductivity than the no flyash TT1 and even with the smaller compressibility will consolidate slower.

5. The reasons why the aged TT6 sample had lower hydraulic conductivities closer to that of the FFT are because of its lower clay size content and possible less plastic clay mineralogy. These differences made the TT6 material less susceptible to changes by flocculants and flyash. The clay size amount and the clay mineralogy, therefore, are important variables when planning flocculent treatments.

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