GEOTECHNICAL PROPERTIES DETERMINATION TO EVALUATE STABILITY OF THICKENED FLUID FINE TAILINGS DEPOSITS

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ABSTRACT
Thickened fluid fine tailings (FFT), resulting from dewatering in deep-pits or produced rapidly using scroll decanter centrifuge (SDC) separation, are deposited to create a dry landscape. Consolidation and shear strength studies were conducted in this study to predict the long-term settlement and strength of such deposits. Direct shear strength of the cake gave a linear Mohr-Coulomb failure envelope of 1.2 kPa cohesive strength and 5.9º friction angle for normal stress up to 1 MPa. The calculated hydraulic conductivity of the cake was non-linear for stresses up to 300 kPa and ranged from 1.5 x 10^{-11} to 10 x 0^{-9} m.s^{-1}. Consolidation results confirmed that the cake exhibits properties similar to those of active clay minerals. The cake compression index is governed by the same relationship as for active clays suggested by Terzahgi (1996). The coefficient of consolidation for the cake was nearly constant and had a mean value of 0.099 $m^2 \cdot s^{-1}$, also similar to that of active clays. The void ratio – effective stress – hydraulic conductivity power law empirical relation constants were used to predict settlement with a finite-strain model. Model calculations suggest that the top portion of FFT deep-pit deposits remain as moist as the original deposits. This means that options which increase the permeability and shear strength of FFT, such as co-disposal with coarse tailings, should be incorporated prior to final tailings placement to form stable deposits.

RÉSUMÉ
Les résidus fins fluides épaissis (FFT), résultant de la déshydratation dans des fosses profondes ou produits rapidement à l'aide de la séparation par centrifugeuse à décanteur à spirale (SDC), sont déposés pour créer un paysage sec. Des études de consolidation et de résistance au cisaillement ont été menées dans le cadre de cette étude pour prédire le tassement et la résistance à long terme de ces dépôts. La résistance au cisaillement direct du gâteau a donné une enveloppe de rupture linéaire Mohr-Coulomb de 1,2 kPa de force cohésive et un angle de frottement de 5,9º pour une contrainte normale jusqu'à 1 MPa. La conductivité hydraulique calculée du gâteau était non linéaire pour des contraintes allant jusqu'à 300 kPa et variait de 1,5 x 10-11 à 10 x 0-9 m.s-1. Les résultats de consolidation ont confirmé que le gâteau présente des propriétés similaires à celles des minéraux argileux actifs. L'indice de compression du gâteau est régi par la même relation que pour les argiles actives suggérées par Terzahgi (1996). Le coefficient de consolidation du gâteau était presque constant et avait une valeur moyenne de 0,099 m2 · s-1, également similaire à celle des argiles actives. Le rapport de vide - contrainte effective - loi de puissance de conductivité hydraulique constantes de relation empirique a été utilisé pour prédire le tassement avec un modèle de déformation finie. Les calculs du modèle suggèrent que la partie supérieure des dépôts profonds de FFT reste aussi humide que les dépôts originaux. Cela signifie que les options qui augmentent la perméabilité et la résistance au cisaillement des FFT, comme la co-élimination avec les résidus grossiers, doivent être incorporées avant le placement final des résidus pour former des dépôts stables.

1 INTRODUCTION

Fluid fine tailings (FFT) generated by the extraction of surface-mined oil sands ore are being discharged into containment ponds. These ponds afford long term storage to stagger reclamation activities and to provide time to apply emerging reclamation technologies. Reducing the water content by dewatering (thickening) is a necessary step for the restoration of FFT as a dry landscape.

All of the current technologies that the oil sands industry utilizes result in a thickened (*i.e.* dewatered) FFT whose solids content converges to a maximum of approximately 60%. At a void ratio of about 160%, such a deposit of fine solids requires further dewatering to form a stable landscape. Investigating whether or not such a deposit can become the expected reclamation-ready deposits is important in light of the amount of material to be reclaimed and the associated environmental risks.

The objective of this research was to determine (i) the geotechnical properties of thickened FFT (cake) to assess if the material can form stable deposits, and (ii) to obtain constants for numerical modelling to predict settlement. The majority of studies on FFT consolidation reported in the public domain were mainly conducted with higher-void-ratio slurries. For this reason, there is a scarcity of data on the geotechnical properties of FFT with void ratios less than or equal to 2 (McKenna *et al*. 2016). Therefore, starting with cake samples extends consolidation research beyond that studied so far.

Consolidation and direct shear measurements were chosen to determine the necessary geotechnical properties of the cake. Consolidation measurements provided the compressibility and hydraulic conductivity of thickened FFT. Direct shear strength studies of the consolidated thickened FFT (cake) were conducted to determine Mohr–Coulomb failure envelopes. These two complementary studies provided information about strength and settlement, informing the prospect of creating a dry landscape out of thickened FFT deposits.

2 Materials and Methodology

FFT sample was obtained from one of the oil sands production companies. The solids content of the FFT as received was 36%. The particle size distribution (PSD) was measured by the SediGraph X-Ray absorption method (Folio Instruments SediGraph III analyzer, Norcross, GA, USA) after Dean–Stark extraction of the FFT slurry. Important size distribution percentages are summarized in Table 1. Methylene blue titration of the as-received FFT slurry revealed a clay content of 58 solids%.

Dewatered test samples (cake) were produced using scroll decanter centrifuge (SDC) separation as detailed in Demoz (2018). The plastic limit of the cake was measured using the soil-thread method in accordance with ASTM Standard D4318-10 (ASTM 2007). The liquid limit, W_L, was measured following the ASTM cone penetration method ASTM D3441-16 (ASTM 2016). Hydraulic conductivity of the cake was measured in a large-strain consolidation (LSC) cell. The particular cell design, and its use for permeability measurements, are referenced in publications of the University of Alberta, Department of Civil and Environmental Engineering (Scott *et al.* 2008).

Table 1. Characteristics of FFT used for this study.

Parameter	FFT
Solids specific gravity (Gs)	2.4
Water content (%)	178
Initial solids (%)	36
Fines content (%)	98
Void ratio	4.27
Clay size (%)[a]	58
Clay size (%)[b]	91
Bitumen content (%)	2.72
Index properties	**Cake**
Liquid limit (%)	61
Plastic limit (%)	16
Plasticity index (%)	45
Activity	0.77
USCS classification	CH
Grain size	
D_{10} (μm)[c]	0.30
D_{30} (μm)	0.58
D_{50} (μm)	1.37
D_{60} (μm)	2.18

[a]From methylene blue titration.

[b]Particles < 2 μm in size.

[c]Limit of sedigraph measurement.

The shear strength of specimens was measured using the direct shear test method ASTM D3080-98 (ASTM 1998). A 100 mm diameter shearbox was filled with the pasty cake specimen (57.5% solids) directly using a spatula. Drainage was facilitated by placing the cake between two porous stones. A high-vacuum grease (Dow Corning Corp. Midland, MI, USA) was lightly applied around the edges of the shearbox to reduce edge-to-edge friction. During the consolidation phase the two halves of the shearbox were tightly held together using plastic screws to eliminate short path water escape.

Multiple load steps were needed to reach the required test normal stress so that the FFT will not exude around the edges of the top porous stone. The consolidated specimen was thereafter sheared for 10 mm at a constant horizontal displacement rate of 0.025 mm/min while the normal stress was maintained using a Humboldt E5706 instrument (Humboldt Mfg. Co., Elgin, IL, USA). Normal load on samples was applied using a house air supply system controlled by the direct shear instrument solenoid valves.

The compressibility behaviour of the cake was also determined using the Humboldt E5706 instrument but operated as a consolidometer (oedometer). The normal stress was increased successively following ASTM D2435-11 (ASTM 2011). Monitoring of the outputs of the Humboldt E5706 LVDTs and control of the instrument were achieved by a computer using the NEXT application software from Humboldt Mfg. Co.

3 Results and Discussion

Direct shear strength measurements of oil sands tailings in the open literature have been completed on samples that have a sizeable fraction of coarse particles, which is not representative of the large inventory of FFT being held in tailing ponds (Kouakou, 2014). In direct shear testing the sample is sheared in a prescribed plane, and although this may be an issue for soils that have well developed fabric, it is less relevant for uniform, freshly produced specimens like FFT cake.

Shear strength depends on factors such as the mineralogical composition of the grains, grain size, grain shape, surface texture, grading, and moisture content. The PSD of the FFT and the Atterberg limits of the cake are shown in Table 1. The PSD shows that the FFT solid particles can be considered 100% fines. The D_{10} value for the cake was below the detection limit of the measurement method used, which is 0.3 μm. All particles were smaller than 75 μm.

The long times needed for the consolidation of clayey materials were maintained before the shear strengths were measured. In the absence of pore pressure measurement options, the cessation of vertical displacement of specimens was used as the condition of full consolidation. All specimens were consolidated beyond the primary consolidation stage before direct shear strength measurements were taken.

Direct shear tests were conducted on fully saturated and drained specimens so as to correspond as much as possible to field conditions. Figure 1 presents shear stress versus horizontal displacement. The shear stress – displacement plot does not display peaks with every normal load, but in all cases the shear stress slowly increases with shear displacement without approaching a constant value.

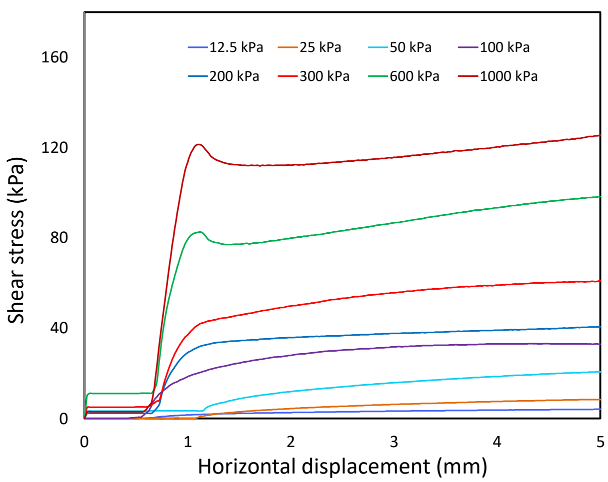

Figure 1. Measured shear stress of consolidated, drained cake as a function of horizontal displacement.

Figure 1 shows that a shear displacement of 1.2 mm was sufficient to mobilize the peak shear stress; beyond that point the shear stress keeps the same plateauing trend. The shear strength curves do not provide the unique peaks typically displayed by structured clays. There was also a lag at the start between shear displacement and shear stress. The lag was not specific to the specimen but was equally observed in tests without any sample conducted to determine the shearbox edge-to-edge friction indicating presence of lateral slack. In this study the shear stress at 3 mm displacement is reported as the failure shear stress. The uncertainty in shear strength due to this interpretation is minimal because the increase of the measured shear stress with displacement is very small.

The line plotted for shear stress dependence upon effective stress forms the Mohr–Coulomb failure envelope, as shown in Figure 2. The low effective stress plot intercept is very close to the shear strength of fresh cake that is commonly observed using vane shear tools (Sobkowicz 2013).

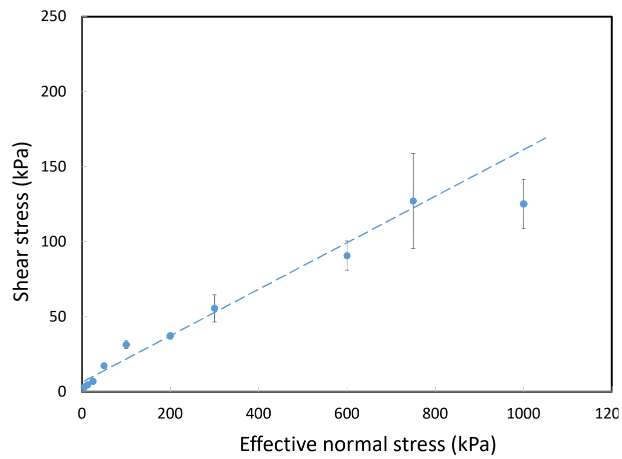

Figure 2. Shear stress obtained at 3 mm horizontal displacement. The error bars are standard deviations for three different measurements.

Generally, the shear strength of freshly produced cake is approximately 1.2 kPa at the upper limit. The shear strength of clays at the liquid limit, W_L, is about 1.7 kPa and the shear strength of fresh cake with moisture content slightly higher than its W_L corresponds to that of clays (Head and Epps 2011). A constraint of a 1.2 kPa intercept was therefore introduced in deriving the Mohr–Coulomb envelope. The generalized Mohr–Coulomb failure model, after correcting for the edge-to-edge friction effect over the test stress range, yielded a friction angle of 5.9°. The Mohr–Coulomb failure envelope for a consolidated, drained cake (thickened FFT) tested in this study follows the empirical relationship given below:

$$\tau' = 1.2 + \sigma' \tan 5.9 \quad [1]$$

where τ' is the effective shear stress and σ' is the effective normal stress at failure. Both the effective cohesion strength and the effective friction angle of cake are small. Its lack of intercalating and cementing minerals explains the lower cohesive shear strength of cakes.

The deposit needs to be firm to stiff in consistency (*i.e.*, at least 50 kPa in shear strength) for it to support small landscaping equipment (McKenna *et al.* 2016). The empirical Mohr–Coulomb failure expression in equation 1 indicates that the upper part of a thickened FFT deposit does not have enough strength to support landscaping equipment.

The shear strength analyses above are discussed independently of the time required to attain full consolidation. The vertical deformation of the cake sample with time was measured to capture that; Figure 3.

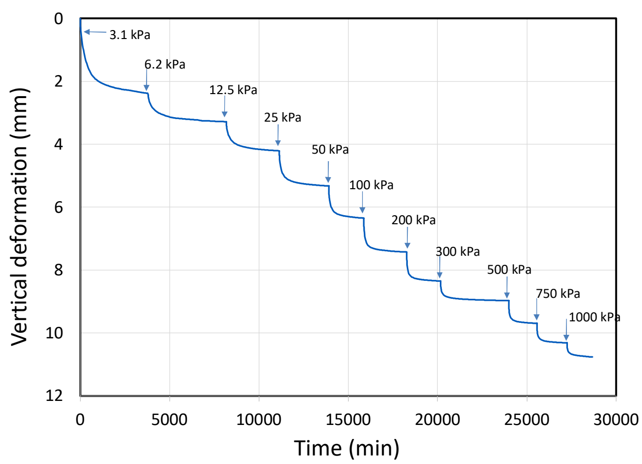

Figure 3. Vertical deformation versus time data from consolidometer.

The *e*–log σ′ relationship for the cake was linear, similar to that for soils that naturally have a far smaller compressibility by comparison. The compression index, C_c, of the cake, with a void ratio from 1.6 to 0.57, was constant and equal to 0.45. This is practically the same as that from the previously reported C_c relationship to W_L, $C_c = 0.009*(W_L - 10)$, for normally consolidated clays, which for the cake yields $C_c = 0.46$ (Terzaghi *et al.* 1996). The relationship between void ratio and stress for highly compressible material and soils is often expressed by a power function (Khan and Azam 2016, Pollock 1988). The following *e*–σ′ power fit relation with a least squares fit correlation factor of 0.98 was derived from the compression tests.

$$e = 9.09\sigma'^{-0.197} \qquad [2]$$

where *e* is the void ratio and σ′ is in Pascals. The coefficient of volume compressibility, m_v, and the value of coefficient of consolidation, C_v, were calculated using Terzaghi's infinitesimal-strain consolidation theory and Taylor's square root of time fitting method (Terzaghi *et al.* 1996). The mean of the cake C_v is 0.099 (± 0.035) $m^2.y^{-1}$, which is in the range reported for active clays (Mitchell and Soga 2005).

Cake hydraulic conductivity, k_c, was measured under mechanical load in a large strain consolidation cell (LSC) using the constant head method (Scott *et al.* 2008). An empirical correlation between k_c and σ′ was obtained so that the hydraulic conductivity can be calculated at varying σ′. Similarly, the k_c–e dependence best empirical power function fit is given as follows:

$$k_c = 1.23 * 10^{-10} e^{3.4} \qquad [3]$$

where the coefficient is a constant with units of velocity ($m.s^{-1}$) and the power is a dimensionless constant. These are of similar magnitude to those of phosphatic clays (Khan and Azam 2016). Having already determined the constitutive equations for *e* and k_c of the cake finite-strain consolidation theory was applied to model the settlement of its deposit over long times. The question that this addresses is evaluate whether thickened FFT could form timely geotechnically stable deposits. FSConsol, a finite-strain consolidation modelling software (GWP Geo Software Inc., Edmonton, AB) that is widely used in industry, was used for the analyses in this study (Tito 2015). In addition to the constitutive equations 2 and 3, the inputs of the program include the initial solids content, pit capacity, and rate of filling. To complete the inputs to the model, a 30 m deep pit is set to fill with cake in 8 years and specified to consolidate in two ways; upward only and double drainage flow.

The settlements calculated using the finite-strain consolidation model at 25, 50, and 100 years after the end of filling are 0.42, 0.84, and 1.67 m, for upward water drainage only and 1.56, 2.30, 3.54 m for double drainage conditions, respectively. The deposit still will have high water content under both drainage conditions and is therefore weak. The extent of consolidation is made clear by the solids content profile in the pit as shown in Figure 4.

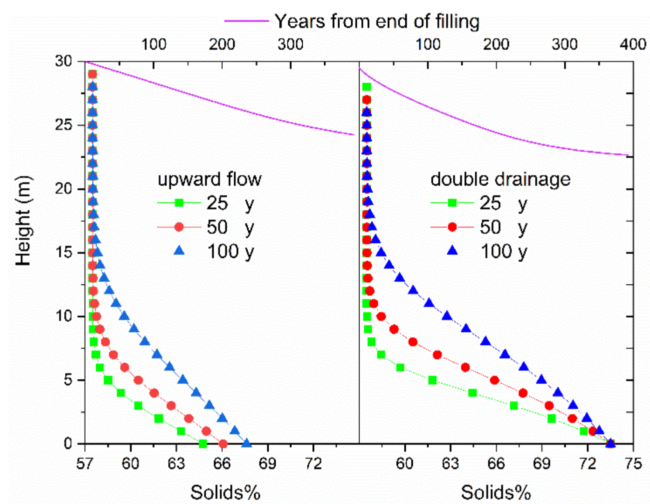

Figure 4. Finite-strain model solids profile and settlement in time of a 30 m deep-pit thickened tailings deposit. Upward flow only and double drainage flow condition model results are presented side-by-side.

The increase in solids content begins from the bottom under both drainage conditions. The model results show that even after a hundred years of consolidation the top third of the deposit is as moist as the original deposit, neglecting the impacts of environmental effects such as freeze–thaw and/or evaporation. Realistically, the self-weight consolidated cake or thickened (dewatered) FFT deposit will remain saturated and of such a high moisture content that it cannot be relied on as a route toward reclamation in the form of a dry landscape.

4 Summary and Conclusion

In this study the direct shear strength and long term consolidation of thickened FFT samples (and specifically SDC-produced cake) were examined to evaluate in-pit deposit stability. The shear strengths for normal stress up to 1 MPa gave a linear Mohr–Coulomb failure envelope for the cake. The results showed that the FFT cake had very small cohesive strength and small friction angle. These results suggest that the upper portion of thickened FFT deposits, lacking overburden load, remain metastable and liquefiable. Specifically, the FFT deposits are too weak to form a trafficable landscape. The e–σ'–k_c power law curve constitutive constants were used as model inputs to predict tailings settlement using a finite-strain 1D model software. The model output indicated that consolidation by self-weight of cake, or FFT-thickened deposit, would take an extremely long time to create reclamation-ready deposits. These results suggest that any tailings treatment options that increase the shear strength and hydraulic conductivity must be integrated into the process prior to the discharge of tailings at final disposal sites. It is suggested that co-disposal of FFT with coarse tailings could simultaneously increase the shear strength and hydraulic conductivity of thickened FFT. The advantages of co-disposal, have not yet been demonstrated, perhaps because the coarse material was added into slurry (viscous) FFT, rather than thickened (plastic consistency) FFT, reducing its impact (Devenny 2010; Beier *et al*. 2013; Wilson *et al*. 2018).

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