CGS.ca GeoVirtual 2020 September 14-16
Resilience and Innovation

Aging and large-scale consolidation of centrifuge cake oil sands tailings

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ABSTRACT
Dewatering fluid fine tailings (FFT) in centrifuges has recorded large scale success, making it one of the technologies available to operators for tailings processing and improving deposits for reclamation in the oil sands industry. Further densification of tailings in these deposits occur through the natural process of consolidation which will take years to decades; this time factor increases the possibility of time-dependent behavior such as creep and aging effect having an influence on consolidation. This paper reports on experiments carried out to investigate aging effect and consolidation of centrifuge oil sands tailings on a larger scale. These experiments include column dewatering tests, fall cone tests, oedometer tests and modified consolidation test using a steel box with dimensions 0.49m x 0.35m x 0.72m. Cores were extracted from the steel box; pore water pressure and volumetric water content measurements were taken with sensors inserted at different elevations. Preliminary results will be discussed.

RÉSUMÉ
La déshydratation des résidus fins fluides (FFT) dans les centrifugeuses a enregistré un succès à grande échelle, ce qui en fait l'une des technologies disponibles pour les opérateurs pour le traitement des résidus et l'amélioration des dépôts pour la récupération dans l'industrie des sables bitumineux. Au fil du temps, la consolidation favorise la densification des résidus dans ces dépôts, augmentant la possibilité qu'un comportement dépendant du temps comme l'effet du vieillissement ait une influence sur la consolidation. Cet article rend compte des expériences menées pour étudier l'effet du vieillissement et la consolidation des résidus des sables bitumineux des centrifugeuses à plus grande échelle. Les expériences comprenaient des tests d'assèchement de colonne avec des mesures de l'eau interstitielle, des tests de cône de chute, des tests d'œdomètre et un test de consolidation modifié à l'aide d'une boîte en acier de dimensions 0.49 m x 0.35 m x 0.72 m. Afin de mieux évaluer le comportement de déshydratation des résidus de centrifugation des sables bitumineux, des carottes ont été extraites de la boîte en acier et des capteurs mesurant la pression interstitielle, la teneur en eau volumétrique et la pression terrestre au fil du temps ont été insérés à différentes altitudes. Les résultats préliminaires seront discutés.

1 INTRODUCTION

Surface mining of Alberta Oil sands ore deposits and the subsequent process of bitumen extraction from ore generates a mixture of water and solids called tailings; they consist of water, sand, fine clay particles, residual oil and organic matter from the bitumen. The tailings are conveyed to large man-made impoundments. The sand fraction settles rapidly to form beaches. Considerable mass of fine particles, however, remains suspended in the water and settles very slowly. Within a few years after deposition this suspension densify to a solids content of about 30% - 35% (by weight) or water content of 200% (geotechnical gravimetric) and are known as fluid fine tailings (FFT). Further densification of the FFT is much slower (about 100 time slower) than at the beginning when freshly discharged into the dam. Due to this slow dewatering a large volume of impoundments are needed to accommodate the tailings. As of 2017, over 1 billion m^3 of FFT are accumulated in these ponds, and the projection for 2034 is approximately 2 billion m^3 (BGC Engineering Inc., 2010; McNeill & Lothian, 2017).

To tackle the environmental impacts of the oil sands industry production, the Alberta Energy Regulator has proposed the current regulation for oil sands tailings management ‘Directive 085 Fluid Tailings Management for Oil Sands Mining Projects’. This regulation requires oil sands operators develop reclamation plans to reclaim all tailings impoundments within 10 years of the end-of-mine life (Alberta Energy Regulator, 2017). Some operators interpret the goal as being able to have the tailings held in the impoundments achieve enough strength to be deposited on natural sloped landform; this would require an undrained shear strength of over 20 kPa to avoid slope stability failure (Mckenna et al., 2016). The target critical undrained shear strength translates to a solids content greater than 70% (by weight), or a geotechnical water content (w) of about 40%.

Directive 085 entails no mandatory pathway in meeting the target outlined in the guidelines hence varying tailings dewatering processes ranging from in-line flocculation, tank thickening and centrifuge technologies are used by the oil sands operators in tailings management.

Centrifuge technology involves accelerated dewatering of tailings by applying ‘g force’ (up to a thousand times of gravity) resulting in producing centrifuge cake oil sands tailings (Solid by-product) with solids content up to 60% (by weight) (Devenny, 2010; Rima, 2013). Syncrude’s industrial implementation of centrifuge technology has shown its reliability in producing tailings (effluent cake) with

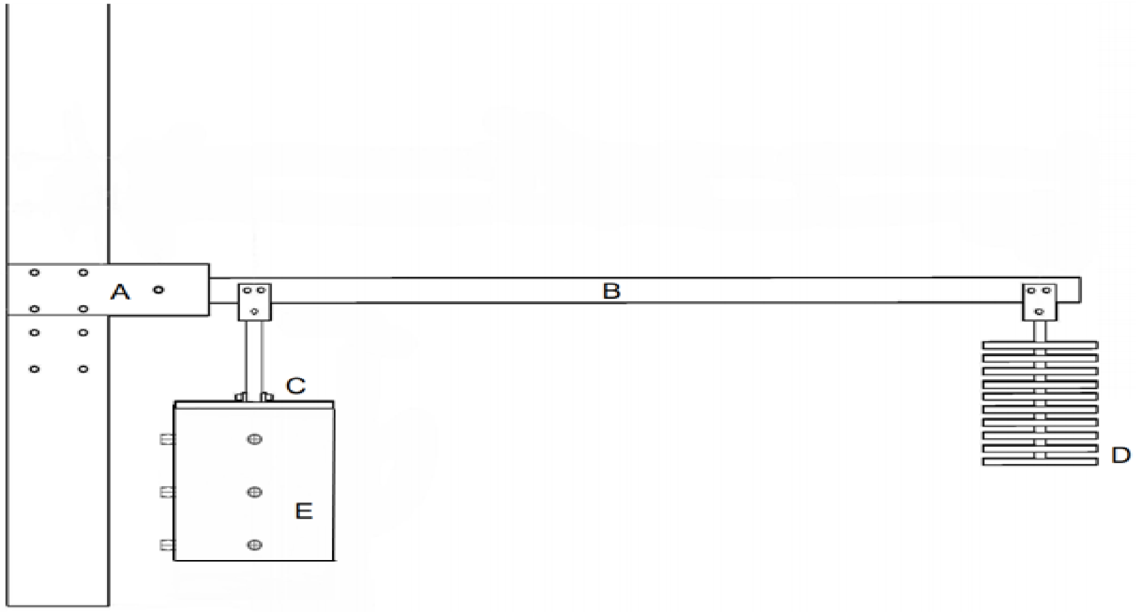

Figure 1. Schematic diagram of the large-scale consolidation test apparatus: A: Steel beam; B: Loading arm; C: Load transfer; D: Weights; E: Steel box.

solid content greater than 50%(by weight); they currently have $1.9 billion full scale centrifuge plant and 16 centrifuges (Devenny, 2010; Chandler, 2017). Despite the success of this technology, post-deposition dewatering is still required to achieve necessary densities and strength to support reclamation.

This paper reports on aging and large-scale consolidation of centrifuge cake. In 1923, Karl Terzaghi proposed the conventional one-dimension small-strain consolidation theory for the estimation of settlement in saturated soils; this theory has its limitation when considering very soft soils such as tailings that experience very large settlement and non-linear compressibility and permeability. In 1967, Gibson et al. proposed the large strain consolidation theory that resolved the small strain deformation and linearity limitations of Terzaghi's theory while allowing for much complex problems to be evaluated and enabling modelling of large deformation in soft soils (Jeeravipoolvarn, 2010). The rate of consolidation in large strain consolidation is primarily controlled by the void ratio-effective stress relationship and hydraulic conductivity-void ratio relationship, making both relationships \ properties important for consolidation in oil sands tailings (Jeeravipoolvarn et al., 2008a; Lekha et al., 2013; Babaoglu et al. 2018). Other non-consolidation responsible for such factors like secondary compression (creep) and 'aging - preconsolidation' are known to be important to the magnitude of consolidation in clayey soils, and may be important to centrifuge tailings as well (Locat & Lefebvre, 1986; Burland, 1990; Athanasopoulos, 1993).

Creep refers to any change that takes places in volume over time and is independent of changes to effective stress. This process involves a time dependent rearrangement of particles and the rate of deformation is controlled by viscous friction (Feda,1989; Kuhn & Mitchell, 1993; Le et al., 2012). 10--meter standpipe experiments conducted at the University of Alberta over a period of 20 years showed creep deformation contribute significantly to settlement in tailings deposits at a constant effective stress (Jeeravipoolvarn, 2005; Jeeravipoolvarn et al., 2009).

Changes in strength, stiffness, and compressibility in clay leading to an increased resistance to compression has been linked to a time dependent behavior called 'structuration'. (Locat & Lefebvre, 1986; Delage, 2010; Sakami et al. 2017). This process effects changes in the microstructure of these clays with time and leads to an increase in the apparent pre-consolidation pressure (aging). Aging effects in tailings ponds are linked with slow dissipation of excess pore water pressure leading to low effective stress development; aging leads to the development of an over-consolidated structure that affects dewatering of tailings (Somogyi et al., 1977; Jeeravipoolvarn, 2010; Miller, 2010).

Thixotropy can be defined as a process of softening caused by remolding, followed by a time dependent return to the original harder state at a constant water content and porosity (Mitchell, 1960; Kuhn & Mitchell, 1993). Jeeravipoolvarn et al. (2009) and Miller (2010) suggested that thixotropy affected the compressibility of FFT through increase in pre-consolidation pressure resulting in less volume change during consolidation. Understanding natural dewatering process such as consolidation and potential effect of creep, thixotropy and structuration on long term deposited tailings is imperative.

This paper reports on the large-scale consolidation and 'time dependent' effects such as aging effects (aging-pre-consolidation) and creep observed in centrifuge cake tailings. Long-term column dewatering tests with pore-water pressure measurements were combined with fall cone tests and large-scale consolidation test consisting of a 0.49m x 0.35m x 0.72m steel box with linear variable differential transformer (LDVT), pore-water pressure and volumetric water content measurements to characterize consolidation and aging effects behavior under saturated conditions.

2 MATERIALS AND METHODS

Centrifuged oil sands tailings (~1 m^3) were transported from a bitumen mining operation in Northern Alberta, Canada, and shipped to Carleton University in Ottawa. The tailings consolidated somewhat during transport but were remixed with their bleed water prior to use in experiments. A suite of laboratory tests and analyses were performed to determine the physical, mineralogical, and chemical characteristics of the cake.

The initial solids content ranged from 50% to 54% (by weight) or a gravimetric water content from 83% to 107%. The specific gravity is 2.34, and the PL and LL are 40% and 65% (by fall cone on slowly air-dried samples). The clay content obtained from the Methylene Blue Index (MBI) analysis was approximately 53%. According to the X-ray diffraction (XRD) results, the composition of the clay fraction was 80%% Kaolinite and 16% Illite. Total Dissolved Solids (TDS) in the pore water collected from the raw fluid fine tailings was 744 mg/L, electrical conductivity was 967 micro-S/cm, while the dominant cations were sodium at 93 mg/L.

Tailings used in this test were prepared by mixing in a 1000L blue tote with a 200-rpm mixer for 24 hours, prior to the start of the experimental program.

2.1 Large-scale Consolidation Experiment Set-up

The large-scale consolidation apparatus used for the test is shown in Figure 1 and 2. The loading arm was made from steel, 369 cm wide and 1 cm thick. The weight and load application sections were attached to the loading arm at 60 cm and 300 cm from the fulcrum point, respectively. This was done to achieve a mechanical advantage of five times the load applied at the weight section being transferred to the steel box.

Figure 2. Experimental set-up of large-scale consolidation test.

A 1-inch thick steel box with a base of 0.49 m x 0.35 m and height of 0.72 m was balanced on four Artech 70210 load cells (Figure 3); these loads cells are used in monitoring mass changes during the experiment period. The steel box was filled with centrifuge oil sands cake tailings to a height of 0.62 m (+/- 10 mm) and left to self-consolidate for the first 23 days. Surface sampling was done on a two-day interval starting from day 1 and an electric oven was used to dry samples for water content measurement at 105 deg C, 200 deg C and 550 deg C. At the beginning of the test (Day 1), and end of self-weight consolidation (Day 23) core sampling by depth was carried out and water content analysis carried out. Thereafter the sample was loaded incrementally at 2, 3, 8, 16, 32 and 56 kPa.

Figure 3. Steel box showing pore-water pressure and volumetric water content sensors.

The steel box was modified with 3 holes at 2 sides for sensors to be inserted into the box for measurement during the experiment. 6 decagon 5TE volumetric water content sensors (at depths of 10 cm, 22 cm, 30 cm, 35 cm and 50cm respectively) and 5 UMS Model T5x pore-water pressure sensors (at depths of 11.5 cm, 30.5 cm and 54 cm respectively) were inserted into the box for measurement during the test. The steel box was covered with a plastic sheet and sensor holes sealed with silicone during the duration of the test to minimize any evaporation. LDVT was attached to the top wall of the box and placed on the load transfer section to monitor tailings displacement over time. Pore-water pressure and volumetric water content data were used to identify the end of primary consolidation.

2.2 Column Dewatering Tests

Twenty-one 10 cm diameter columns made from polypropylene (PP) were then filled with the prepared tailings to heights of 10 cm (+/- 2mm). PP has been shown to be superior to other plastics such as acrylic or PVC, as the latter are hydrophilic and show pronounced sidewall effects, while the PP material shows no detectable sticking of the material to the sides, and no variability in settlement over time occurs when larger diameter experiments are employed. The samples were covered with air-tight lids.

All replicate columns were regularly weighed. The lids were removed periodically to measure the height of accumulated bleed water. Replicates were “processed” at 1, 3, 7, 14, 21, 28, 42, 56, 70, 84 and 98 days. This processing involved removing and weighing the surface bleed water and subsequently either destructively sampling the tailings for water content with depth or preparing oedometer samples. An electric oven was used to dry the sample for 24 hours at 105 C to measure moisture content of the tailings.

A standard oedometer apparatus was modified by making a hole through the bottom cast and bottom porous stone for a UMS Model T5x pore-water pressure sensor to be inserted into the bottom of the sample, so as to enclose the ceramic tip within the tailings (~ 5 mm intrusion). The modified oedometer is shown in Figure 4.

Figure 4. Modified oedometer with T5x pore-water pressure sensors installed in the base and connected to DL 2e data logger.

Some additional replicate columns were used to monitor pore-water pressure. The same PWP sensors were installed into each respective column (at depths of 6.4 cm and 5.9 cm respectively), as shown in Figure 5.

Figure 5. Two T5x tensiometers installed into two replicate columns.

3 RESULTS

3.1 10 cm Replicate Columns and Oedometer Results

The settlement in the replicate columns was small (< 1 cm) over the whole test period. For both replicate columns with

PWP sensors, there was an initial sharp decrease in pore water pressure followed by a gradual decrease over time (Figure 7), with values equilibrating after 42 days. This seemed to correlate with the water content versus depth profiles shown in Figure 6, where most of the changes in water content near the bottom of the column was observed up to 42 days. Thereafter only a small but uniform decrease in water content with depth occurred.

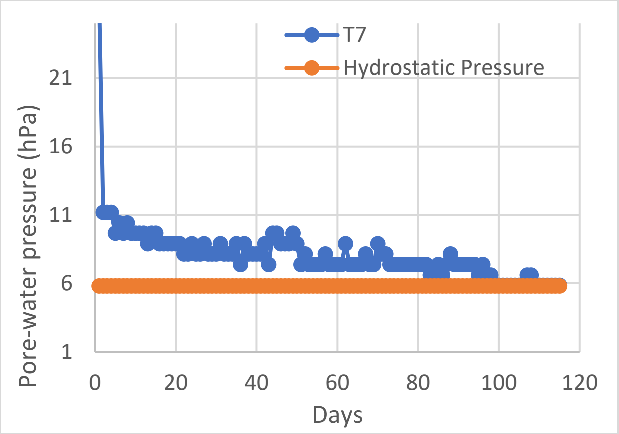

Figure 6. Hydrostatic and pore-water pressure (blue lines) (hPa) at 5.3 cm (T7) from the base of the column.

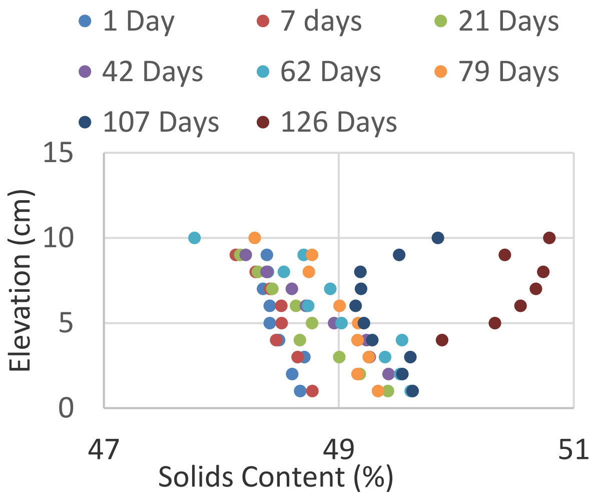

Figure 7. Depth profiles of water content in replicate columns.

Figure 8 shows the compressibility curves of a centrifuge cake sample processed at day 79, the plot seems to correlate with finding in the in-line flocculated FFT with pre-consolidation pressure of about 10 kPa developing in the undisturbed column.

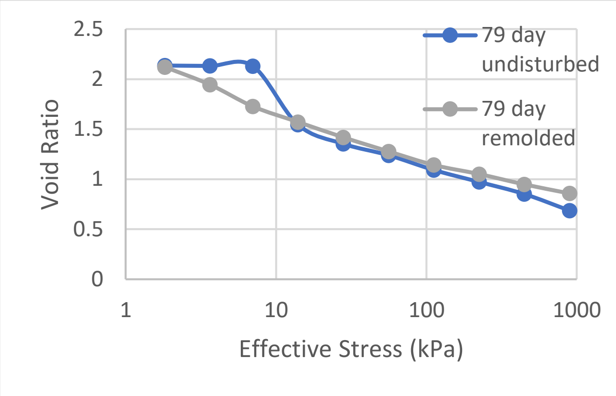

Figure 8. Change in compressibility curve in centrifuge cake tailings from replicate 10 cm tall columns at day 79.

3.2 Steel Box Large Scale Consolidation Test

Self-weight stage

The self-weight settlement in the steel box was small (~2 cm) from LDVT data plotted in Figure 9. Core sampling at the beginning and end of self-weight consolidation in the steel box shows also only a small change in tailings during this stage, as shown in Figure 10.

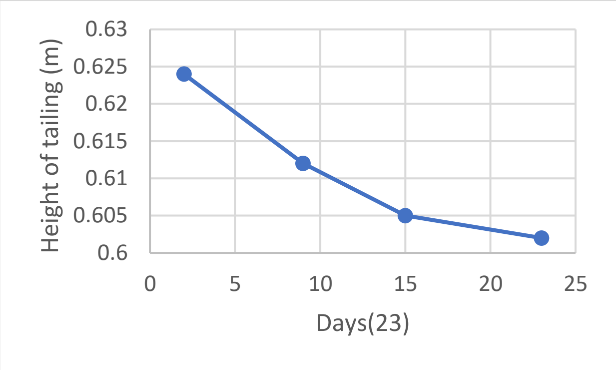

Figure 9. LDVT displacement measurement from steel box test.

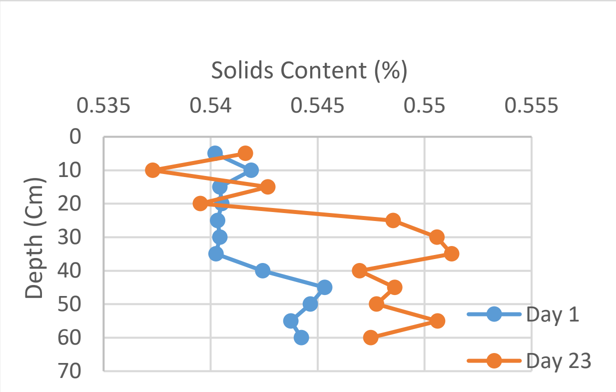

Figure 10. Water content by depth at Day 1 and Day 23 during self-weight consolidation.

The tensiometers positioned at the top, middle and bottom layers did, however, show an initial increase after pouring, followed by gradual decrease over time (Figure 11, 12 and 13,) and by day 15 most of the excess pore-water pressure had dissipated. This seems to indicate the end of primary consolidation occurred in the steel box with the first 23 days of self-weight consolidation.

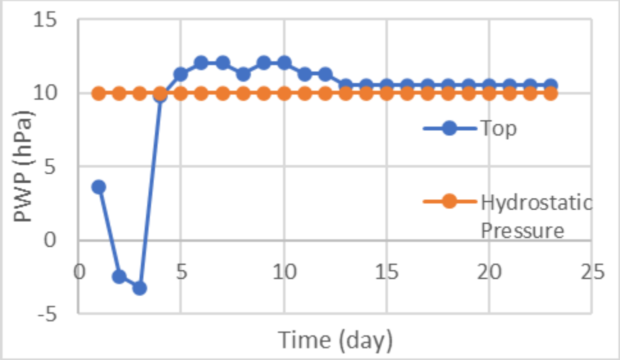

Figure 11. Pore-water pressure (hPa) at 11.5 cm (Top) from the surface of tailings in steel box.

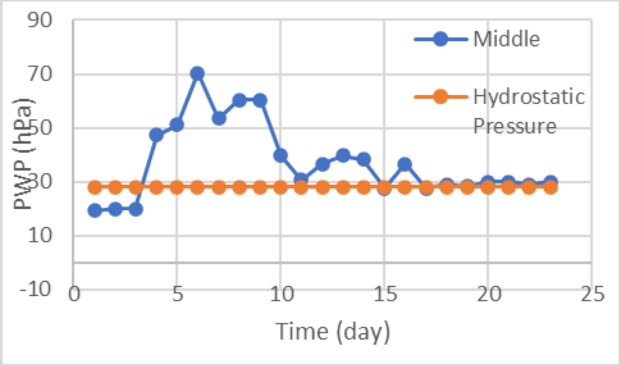

Figure 12. Pore-water pressure (hPa) at 30 cm (Middle) from the surface of tailings in steel box.

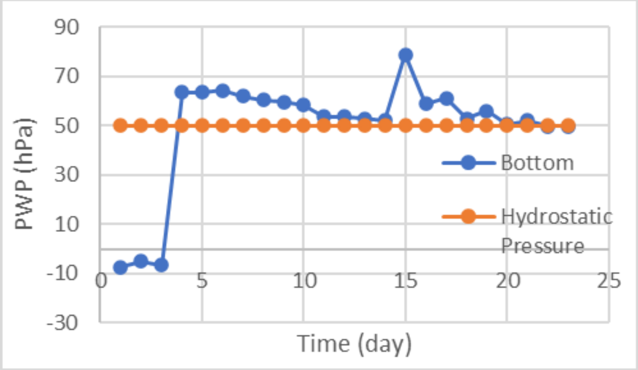

Figure 13. Pore-water pressure (hPa) at 54 cm (Bottom) from the surface of tailings in steel box.

The next phase of the experiment involved incrementally loading the centrifuge cake sample in the steel box beginning with a load of 2 kPa. Figure 14 shows the pore-water pressure data for the self-weight consolidation phase (day 3 – day 27), 2 kPa loading (day 27 – day 46) and 3 kPa loading (day 27 – day 58).

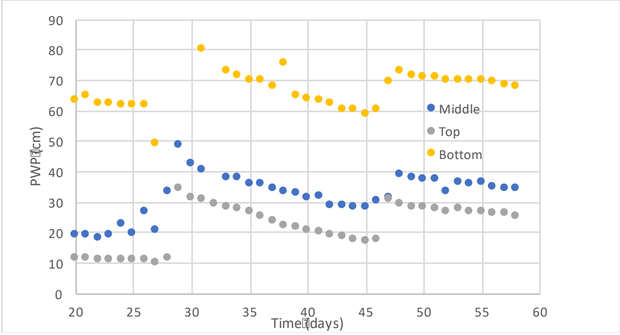

Figure 14. Pore-water pressure(cm) showing response to 2 kPa and 3 kPa loading steps and subsequent dissipation.

Figure 15 compares the compressibility curve from the steel box of compressibility curves from the previously discussed oedometer tests (see Figure 8). More data is required to estimate the degree of aging, if any. The effective stresses are calculated using the measured PWP distribution at the end of the loading increment.

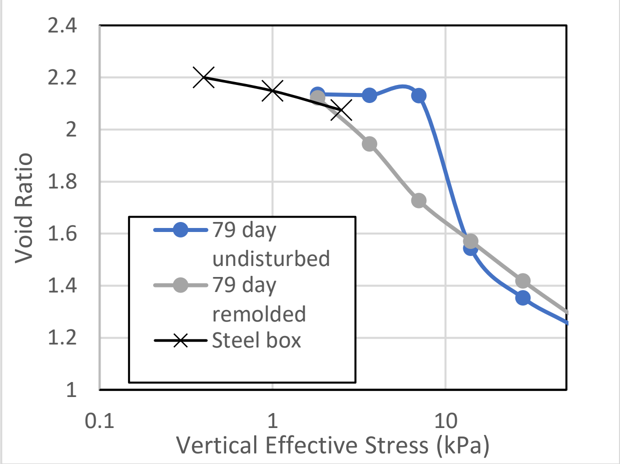

Figure 15. Estimated compressibility curve for steel box (plotted with compressibility curves from oedometer tests started at 79 days remolded and undisturbed samples.

4 SUMMARY & DISCUSSION

Findings from the small column and aged oedometer samples showed significant changes in water content and substantial dissipation of PWP in the small columns for the first 42 days and development of pre-consolidation pressure by day 79. These results indicate that there is an aging effect, and substantial non-consolidation dewatering. Preliminary results from the large consolidation test show:

- The centrifuge cake settlement due to self-weight consolidation was small (< 2cm)
- Excess pore-water pressure dissipation due to self-weight consolidation occurred for about 23 days
- A comparable compressibility curve to the oedometer tests, but further data is required to evaluate the degree of aging in this test.

The finding of aging (pre-consolidation pressure development) with time has serious implication for tailings deposit remediation and modelling. Currently, industry operators and researchers have attempted to model pilot studies using large-strain consolidation theory based models to predict dewatering behavior of tailings but these models do not incorporate non-consolidation behavior such as aging effects which are apparent from experimental results. On-going research is attempting to integrate aging effect such as (aging pre-consolidation) into large-scale consolidation models to help operators develop better final settlement prediction of tailings deposits. This on-going work involves conducting lab scale experiments on aging effects and interpretation of the experimental studies using a large-strain consolidation model that accounts for these effects.

ACKNOWLEDGMENTS

This study is funded by a collaborative research and development grant co-sponsored by the Natural Science and Engineering Research Council of Canada (NSERC 429272-11) and Canada’s Oil Sands Innovation Alliance (COSIA).

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