Creep and structuration in centrifuge cake oil sands tailings

Igbinedion, D., Salam, M.& Simms. P. H
Department of Civil and Environmental engineering – Carleton University, Ottawa, Ontario, Canada

ABSTRACT

Operators in Alberta's oil sands industry are required to improve the density and strength of existing tailings deposits to facilitate permanent reclamation to pre-existing boreal forest conditions. Several types of tailings deposits are envisaged and are either being attempted at commercial or pilot scales. One of these, deep deposits of fluid fine tailings (FFT) dewatered in centrifuge, may contain substantially deep (> 50 m) deposits that require substantial dewatering through consolidation. However, as the consolidation will take years to decades, time variant phenomenon such as creep and structuration may be important. This paper reports on preliminary experiments designed to investigate creep and structuration in centrifuge cake oil sands tailings. The experiment includes column dewatering tests with pore water pressure measurements, oedometer tests and fall cone tests. Preliminary results show similar behaviours reported for in-line flocculated FFT in previous studies

RÉSUMÉ

Les exploitants du secteur des sables bitumineux de l'Alberta doivent améliorer la densité et la résistance des dépôts de résidus afin de faciliter la remise en état permanente des conditions de la forêt boréale préexistantes. Un certain nombre de types de dépôts de résidus sont envisagés et sont en train d'être essayés à des échelles commerciales ou pilotes. L'un d'entre eux, les dépôts profonds de résidus fins fluides (FFT) déshydratés dans une centrifugeuse, peut contenir des dépôts très profonds (> 50 m) qui nécessitent une déshydratation importante par consolidation. Cependant, comme la consolidation prendra des années, voire des décennies, un phénomène variant dans le temps, tel que le fluage et la structuration, peut être important. Cet article présente des expériences préliminaires conçues pour étudier et structurer les résidus de sables bitumineux de gâteaux. Les tests comprennent des tests de déshydratation de colonne avec des mesures de pression d'eau, des tests oedomètres et des tests de cônes de chute. Les résultats préliminaires sont similaries d'autres études de « in-line flocculated » FFT.

1 INTRODUCTION

Oil sands tailings deposits in Alberta, Canada, are generated by surface mining of the oil sands ore body and the subsequent bitumen extraction process; they consist of water, sand, fine clay particles, residual oil and organic matter from the bitumen. The tailings are transported to dammed impoundments with substantial footprint. Sands in the tailings settle down to form beaches relatively quickly. More problematic is that a considerable mass of fine particles remain suspended. This suspension equilibrates at about 30% - 35% solids (by weight) or about 200% water content (geotechnical gravimetric) within a few years after deposition, at which point it is termed fluid fine tailings (FFT). This state is far above the liquid limit (50-80%) of the tailings. Further settlement or consolidation is slow, leading to increasing tailings footprint in the ponds with time (Beier et al. 2013, Owolagba and Azam 2017). As of 2017, FFT in tailing ponds cover more than 250 square kilometers, with some dam heights exceeding 80 m (Chandler 2017).

The current regulation for oil sands tailings management 'Directive 085 Fluid Tailings Management for Oil Sands Mining Projects' requires that oil sands operators develop reclamation plans to reclaim all tailings impoundments within 10 years of the end-of-mine life (Alberta Energy Regulator 2017). The target state of the tailings is "ready to reclaim". Some operators have interpreted these regulations to imply that tailings deposits must be sufficiently strong to enable their placement in gently sloped landforms, similar in topography to the surrounding boreal forest uplands. From simple slope stability calculations, this implies than an undrained shear strength greater than 20 kPa is needed to avoid deep seated slope stability failures (McKenna et al. 2016). This in turn implies, for fines dominated deposits, a solids concentration greater than 70%, or a geotechnical water content (*w*) at about the plastic limit of the tailings (~40%)

A variety of tailings dewatering technologies have been developed to aid the operators in realizing the current regulation requirements. Some of the dewatering technologies include in-line flocculation, tank thickening and centrifuge technologies, which use polymers to aid dewatering through increased flocculation.

Centrifuge technology involves the application of a force several times that of gravity resulting in denser tailings effluent with solids content as high as 60% solids (by weight) (Devenny 2010). Syncrude began pilot studies for this technology in 2005 and after successful studies they opted for implementation on a larger scale in 2015 with a 1.9 billion full scale centrifuge plant and about 16 centrifuges (Chandler 2017). Although this centrifuge technology has been shown to reliably produces tailings with solids content greater than 50%, there is need for further dewatering to achieve the targeted solids concentration of 70% (by weight). Understanding long term dewatering processes such as consolidation and how potential effects of creep and structuration affect the settling of these tailings after deposition could be vital in achieving regulatory requirements.

Consolidation in deep deposits of oil sands tailings is usually analyzed using large strain consolidation theory (Gibson et al. 1981), where the material parameters are the compressibility function, which relates void ratio to effective stress, and the permeability function, which relates hydraulic conductivity to void ratio. In oil sands tailings these are usually measured using a slurry consolidometer (Jeeravipoolvarn et al., 2008). However, there are other factors that may influence the rate of consolidation, such as creep and thixotropy. These factors have been found to influence untreated tailings consolidation behaviour and, quite recently, the dewatering behaviour of polymer amended FFT (Salam et al. 2018, 2017; Jeeravipoolvarn, 2005; Jeeravipoolvarn et al., 2009; Miller, 2010).

“Creep” refers to any change that takes places in volume over time and is independent of changes to effective stress. “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 constant porosity (Mitchell, 1960). In other words, thixotropy deals with the time dependent of clay particles due to electrochemical forces and it is manifested in time-dependent strength recovery of clay after remolding at constant density (Mitchell, 1960; Jeeravipoolvarn, 2005). Jeeravipoolvarn et al. (2009) and Miller (2010) suggested that thixotropy affected the compressibility of FFT through increase in pre-consolidation pressure results in less volume change during consolidation - this change in pre-consolidation pressure is reffered to as “structuration” or “ageing” in the literature.

Thixotropic and creep behaviors exhibited by tailings materials have also been observed in many natural clays and soft soils (Zhang et al. 2017). A time dependent behavior called ‘structuration’ effected changes in the microstructure of these clays and leads to an increase in the apparent pre-consolidation pressure. Subsequently, the clay showed changes in strength, stiffness, and compressibility leading to an increased resistance to compression (Locat & Lefebvre, 1986; Delage, 2010; Mohamadi et al. 2017). Processes other than consolidation or compaction, such as cementation, delayed compression (creep), and ageing effects (thixotropy) have been found responsible for such changes and the subsequent development of strength and stiffness in fine-grained soils (Locat & Lefebvre, 1986; Burland, 1990).

This paper reports on the creep and ‘structuration’ effects observed in centrifuge cake tailings. Long-term column dewatering tests with pore water pressure measurements through tensiometers were combined with modified oedometer and fall cone tests to characterize both consolidation and non-consolidation volume change behavior under the saturated conditions. Comparisons are made with previous work by Salam et al. (2018) on in-line flocculated FFT. Based on the findings, the implications of non-consolidation behavior for the dewatering and consolidation performance of tailings deposits in the longer term are discussed.

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 when remixed with their bleed water, the initial solids content ranged from 50% to 53% (by weight) or a gravimetric water content from 89% to 100%. The specific gravity is 2.34, and the PL and LL are 40% and 65% (by fall cone on slowly air dried samples).

To prepare tailings for the testing program, samples of re-mixed tailings were used to fill 2 barrels. The tailings in these barrels were mixed with a mechanical mixer at 200 rpm for 24 hours, prior to the start of the experimental program. Water content was measured at the bottom, middle and top of the barrel, to confirm a relatively homogeneous sample of 96% to 100% water content.

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 daily during the first week and thereafter weekly 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, performing 3 fall cone measurements, and subsequently either destructively sampling the tailings for water content with depth, or preparing oedometer samples. A fall cone device, which has an angle of 30° and a weight of 19 g, was used to measure strength, employing a K factor of 1.00 and the shear strength equation of Hansbo (1957). An electric oven was used to dry the sample for 24 hours at 105 C to measure moisture content of the tailings.

Standard oedometer test 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 with the tailings (~ 5 mm intrusion). This is subsequently called the modified oedometer (Figure 1). The pore-water presssure data is used to identify end of primary consolidation.

Figure 1. Modified oedometer with T5x tensiometers 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 an elevation of 4.1 cm and 5.3 cm respectively) to monitor pore water pressure, as shown in Figure 2.

Figure 2. Two T5x tensiometers installed into two replicate columns.

3 RESULTS

3.1 Water content and pore-water pressure in replicate columns

The settlement in the replicate columns was small (< 1 cm) over the whole test period. For both replicate columns with tensiometers, there was an initial sharp decrease in pore water pressure followed by a gradual decrease over time (Figure 3 & 4), with values equilibrating between 20 and 30 days. This seemed to correlate with water content versus depth profiles shown in Figure 5, where a pronounced decrease in water content near the bottom of the column was observed up to 21 days. Thereafter only a small but uniform decrease in water content with depth occurred.

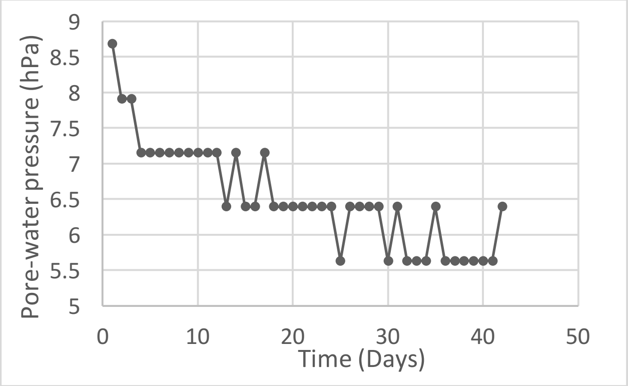

Figure 3. Pore-water pressure (hPa) at 4.1 cm (T5) from the base of the column.

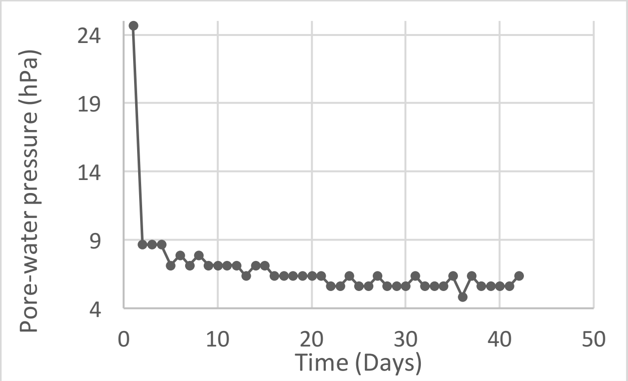

Figure 4. Pore-water pressure (hPa) at 5.3 cm (T7) from the base of the column.

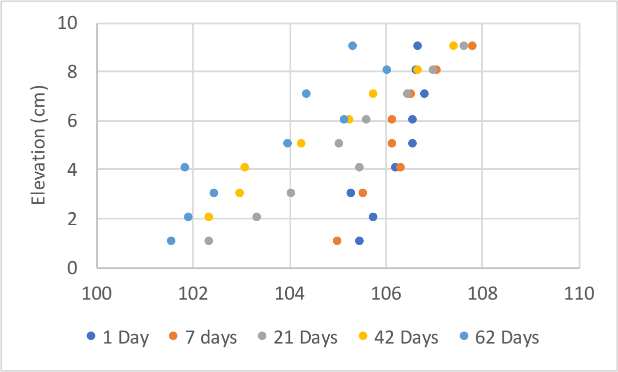

Figure 5. Depth profiles of water content in replicate columns

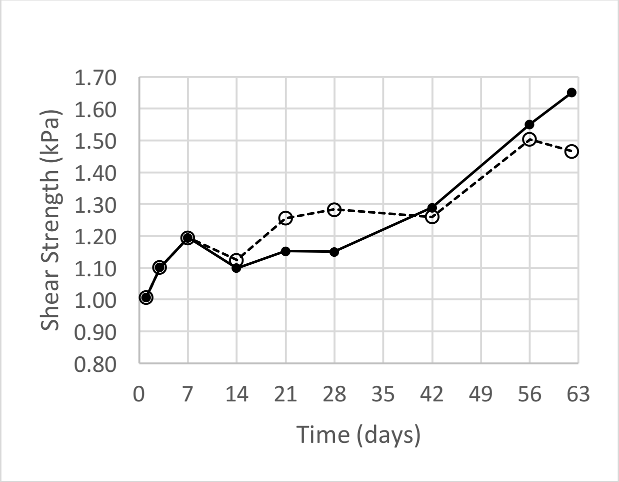

Figure 6. Fall cone shear strength from replicate columns (2 repeats)

A shown in Figure 6, fall cone tests were used to track the ageing effect (structuration) in the replicate samples. For the first 30 or 40 days, the increase in shear strength is small and could attributed to the slight increase in water content. After 40 days, however, the strength begins to increase. Similar behaviour is shown for in-line flocculated material, where the rate of consolidation must decrease below some critical value before ageing starts (Salam et al. 2018).

3.2 Oedometer tests with pore-water pressure measurement

Figure 7 shows the change in compressibility curve apparent from oedometer testing for 28 and 42 days,. These curves do not show any structuration effect. Indeed the 28 days sample appears to show a pre-consolidation pressure of about 20 kPa, though the 42 day sample does not. The lack of development of larger apparent preconsolidation pressures correlates with the fall cone data, as no substantial development of strength is observed before 40 days. Testing of 64 day oedometer samples is currently underway.

Pore-water pressure dissipation was tracked using a tensiometer inserted through the base, as described in the methods section. Two examples at the load increment at 220 kPa are shown from both oedometer tests in Figures 8 and 9. In these plots, the return of pore-water pressure to the expected initial value before loading was observed. However, settlement continued to occur, apparently as expected from classical secondary compression. Future work will verify this observation by simulating the oedometer test using the large-strain consolidation model to check if the apparent secondary compression is due to continued consolidation in the centre of the sample, as suggested by Carrier (2018).

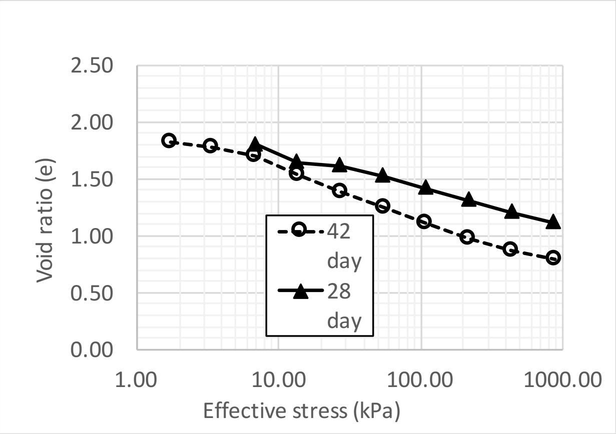

Figure 7. Compressibility curves from modified oedometer tests started at 28 days and 42 days

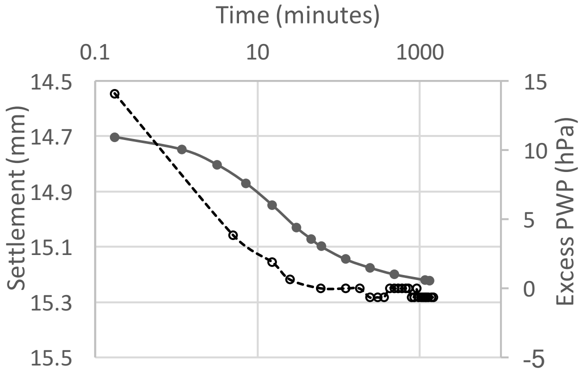

Figure 8. Settlement (Black points) and pore-water pressure dissipation for the 220 kPa load step for the 28 days oedometer sample

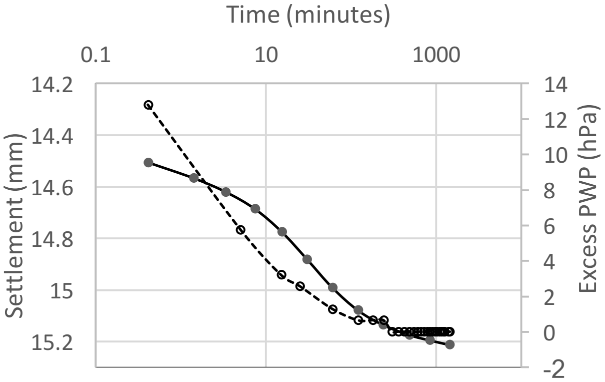

Figure 9. Settlement (black points) and pore-water pressure dissipation for the 220 kPa load step for the 42 days oedometer sample

4 COMPARISON WITH SIMILAR TESTS ON IN-LNE FLOCCULATED FFT

Salam et al. (2018) performed simulated tests on in-line flocculated material prepared in the laboratory using industry protocols on preparing laboratory samples simulating field conditions. Figures 10 and 11 present data from tests recently performed by Salam, showing trends in dewatering and structuration in in-line flocculated FFT. These results are similar to those reported in Salam et al. (2018), but with different polymer dose and mixing regime. Figure 10 shows a substantial stiffening of the sample over time. This is reflected by the fall cone strength data in Figure 11. Interestingly, the fall cone strength begins to increase only when the end of the primary consolidation or initial dewatering phase approaches – this is supported by pwp dissipation measurements in the replicate columns in other tests. This is similar to the behaviour shown in centrifuge cake shown in Figure 6.

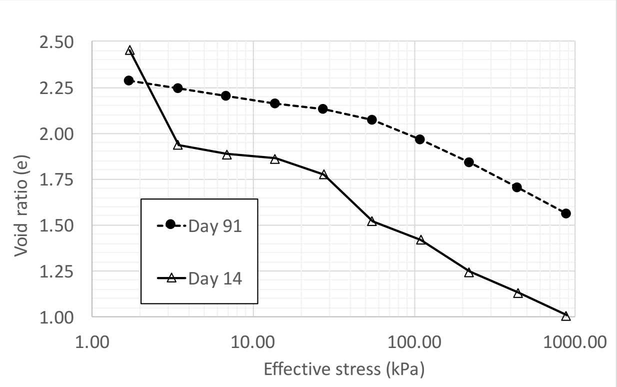

Figure 10. Change in compressibility curve in-line flocculated FFT from replicate 10 cm tall columns

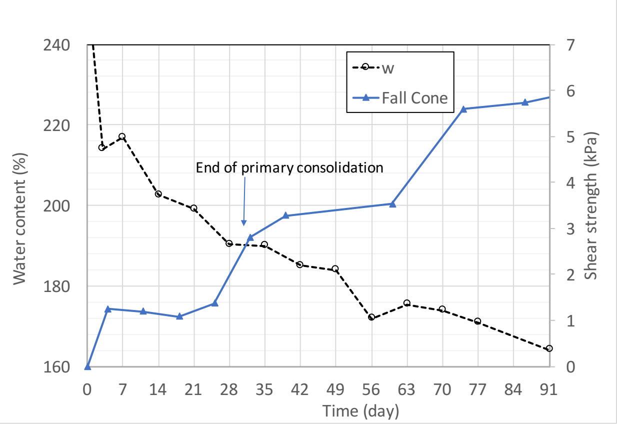

Figure 11. Dewatering and fall-cone strength in replicate 10 cm tall columns of in-line flocculated FFT

5 SUMMARY AND CONCLUSIONS

Replicate columns 10 cm tall were prepared from re-mixed centrifuge cake transported from Northern Alberta. Water content profiles, pore-water pressures, and fall cone shear strength, were measured over 70 days. Additionally, some samples were obtained from the replicate column for testing in oedometers, modified to accommodate pore-water pressure measurement. These tests showed:

- The centrifuge cake showed small settlement and only 10% change in water content (from ~ 110% initial water content) over the test period.
- The largest change in water content occurred up to 20 or 30 days
- Pore-water pressure dissipation in the columns occurred also up to about 30 days
- Fall cone strength began to increase substantially only after about 30 days
- No significant change in the compressibility curve between samples measured at 28 and 42 days was detected; oedometer tests on older aged samples are ongoing
- The fall cone behaviour is qualitatively similar to what is reported for in-line flocculated FFT previously reported (Salam et al. 2018).

The finding that structuration is delayed until the consolidation rate become low may have important implications for tailings deposit design. Generally, one would expect that deeper deposits with longer drainage paths and lower PWP gradients to be more susceptible to negative effects of structuration. Ongoing work is attempting to assess the implications of this behaviour to help operators either rule out or mitigate these effects. This work involves interpretation of pilot studies using coupled large strain consolidation- ageing models.

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).

REFERENCES

Alberta Energy Regulator. 2017. Directive 085. Retrieved April 2018 from the website: http://www.aer.ca/rules-andregulations/directives/directive-085.

Beier, N., Wilson, W., Dunmola, A. and Sego, D. 2013. Impact of flocculation-based dewatering on the shear strength of oil sands fine tailings. *Canadian Geotechnical Journal*, 50(9): 1001-1007.

Burland, J. B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique*, 40(3): 329-378.

Carrier, D. 2017. "Secondary? What Secondary?", Lecture at University of Alberta, November 2017.

Chandler, G. 2017. "Settling the tailings pond question". *CIM*, (7): 50-53.

Delage, P. 2010. A microstructure approach to the sensitivity and compressibility of some Eastern Canada sensitive clays. *Géotechnique*, 60(5), 353-368.

Devenny, D. 2010. A Screening study of Oil Sand Tailings Technologies and Practices. Alberta Energy Research Institute, 44.

Gibson, R. E., Schiffman, R. L. & Cargill, K.W. 1981. The theory of one-dimensional consolidation of saturated clays. II. Finite nonlinear consolidation of thick homogeneous layers. *Canadian Geotechnical Journal*, 18: 280–293.

Hansbo, S. 1957. A new approach to determination of shear strength of clay using the fall cone test. *Proceedings of the Roya Swedish Geotechnical Institute*, No. 14..

Jeeravipoolvarn, S. 2005. Compression behaviour of thixotropic oil sands tailings. M.Sc. Thesis, University of Alberta, Edmonton, Alberta, Canada.

Jeeravipoolvarn, S., Chalaturnyk, R. J., and Scott, J. D. 2008. Consolidation modeling of oil sands fine tailings: History matching. *Proceedings of GeoEdmonton'08*, Edmonton, Alberta, Canada, 190–197.

Jeeravipoolvarn, S., Scott, J. D., and Chalaturnyk, R. J. 2009. 10 m standpipe tests on oil sands tailings: Long-term experimental results and prediction. *Canadian Geotechnical Journal*, 46(8): 875–888.

Locat, J. and Lefebvre, G. 1986. The origin of structuration of the Grande-Baleine marine sediments, Québec, Canada. *Quarterly Journal of Engineering Geology and Hydrogeology*, 19(4): 365-374.

McKenna, G., Mooder, B., Burton, B. and Jamieson, A. 2016. Shear strength and density of oil sands fine tailings for reclamation to a boreal forest landscape. *Proceedings of the Fifth International Oil Sands Tailings Conference (IOSTC*), December 4-7, 2016, Lake Louise, Alberta.

Miller, W. G. 2010. Comparison of Geoenvironmental properties of caustic and non-caustic oil sand fine tailings, Ph.D thesiss, University of Alberta.

Mitchell, J. M. 1960. Fundamental aspects of thixotropy in soils. *Journal of the Soil mechanics and Foundations Division of ASCE*, 86(3): 19-52.

Mohamadi, M., Wan, R., and Shen, Z. 2017. An elastoplastic description of frictional destructuration in natural clays and shales. *Acta Geotechnica*, 13(4): 911-924.

Motta Cabrera, S. 2009. Characterization of oil sands tailings using low field Nuclear Magnetic Resonance (NMR) technique. Library and Archives Canada = Bibliothèque et Archives Canada, Ottawa, 42.

Owolagba, J., and Azam, S. 2013. Unsaturated soil properties of centrifuged oil sand fine tailings. Proceedings of the 66th C*anadian Geotechnical Conference,* September 29 -3 October 2013, Montreal, pp. 1-6.

Salam, M., Simms, P. and Örmeci, B. 2018. Structuration in Polymer Amended Oil Sands Tailings*. Proceedings of the 71st Canadian Geotechnical Conference*, September 23 -26 2017, Edmonton, pp. 1-9.

Zhang, X., Kong, L., Yang, A., and Sayem, H. 2017. Thixotropic mechanism of clay: A microstructural investigation. *Soils and Foundations*, 57(1): 23-35.