Evaluation of Temperature and Multiple Freeze-Thaw effects on the Strength Properties of Centrifuged Tailings

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ABSTRACT
Laboratory freezing and drying tests were conducted to evaluate the effect of natural conditions in order to improve the trafficability of the centrifuged oil sands tailings deposit. The enhanced solids content resulting from the freeze thaw and drying-wetting process causes further dewatering and subsequent increase in undrained shear strength at the tailings surface. The results suggest that the strength of the centrifuged tailings is affected by the temperature gradient and the number of freeze-thaw cycles. Tailings sample subjected to lower temperature gradient resulted in marginal increase in thaw strain and subsequent higher shear strength. The electrical conductivity measured at each cycle and after drying – wetting phase predicted that the solute is migrated upwards and this phenomena is predominantly driven by the unfrozen water migration towards the ice lens due to convection.

RÉSUMÉ
Des essais de congélation et de séchage en laboratoire ont été effectués pour évaluer l'effet des conditions naturelles afin d'améliorer la circulation sur le dépôt de résidus de sables bitumineux centrifugés. La teneur en solides améliorée résultant du processus de décongélation-congélation et de séchage-mouillage provoque une déshydratation supplémentaire et une augmentation subséquente de la résistance au cisaillement non drainé à la surface des résidus. Les résultats suggèrent que la résistance au cisaillement des résidus centrifugés est influencée par le gradient de température et le nombre de cycles de congélation-décongélation. L'échantillon de résidus soumis à un gradient de température inférieur a entraîné une augmentation marginale de la déformation à la décongélation et, par la suite, une teneur plus élevée en solides et une résistance au cisaillement plus élevée. La conductivité électrique mesurée à chaque cycle et après la phase de séchage-mouillage a prédit que le soluté est migré vers le haut et ce phénomène est principalement entraîné par la migration de l'eau non gelée vers la lentille de glace en raison de la convection.

1 INTRODUCTION

Oil sands mining operations in Northern Alberta, Canada generate a growing volume of fluid fine tailings that is typically stored in tailings ponds or in-pit cells. The warm water extraction process generates dispersed fine tailings material that do not dewater under self-weight consolidation (Wells, 2011). As a result, the untreated tailings material remains soft and saturated such that the conventional reclamation and capping of these deposits is difficult. One of the cost- efficient solutions to stabilize, cap and reclaim the fine tailings is to increase the strength of the tailings material itself prior to capping. Of the many methods to improve the trafficability and strength properties of tailings surface, the centrifuge technology with an addition of flocculant/polymer has demonstrated promising results for the oil sands tailings industry (Mikula et al., 2008). However, in an effort to provide a geotechnically stable landscape in a timely manner for colder climate like Western Canada, the physical processes such as freeze-thaw, and drying have potential to further improve the dewatering rate of centrifuged tailings. The objective of the research reported in this paper is to evaluate the effect of natural conditions (repeated freeze-thaw cycles, summer drying and precipitation) on the strength of existing treated centrifuged tailings deposit waiting for reclamation. It is assumed that the natural weathering effects would leave limited or no water on the surface of the deposit. This research aims to see whether the multiple cyclic freeze and thaw process is effective in forming a surface crust capable of gaining sufficient strength. Depending on the extent of stabilization and attained strength, it could be possible for equipment to start placing reclamation covers. This may potentially reduce the required amount of geosynthetics and result in savings of the reclamation cost.

2 LITERATURE REVIEW

The extensive research (Dawson and Sego, 1993; Johnson et al., 1993; Proskin, 1998) conducted at both laboratory and pilot scale showed that the fluid fine tailings samples subjected to multiple freeze thaw cycles experienced significant dewatering. However, the studies were predominantly limited to mature fine tailings (MFT) samples and the results concluded that the samples experienced the highest thaw strain in their first cycle. The previous research results also suggested that the solids content enhancement resulting from freeze-thaw cycle was marginal for the tailings sample with higher initial solids content (50%-60%) compared to MFT. Given the predominance of the number of freeze thaw cycles, temperature gradient and the freezing rate, there is a need to develop a fundamental understanding of the freeze thaw effect on the stability of oil sands tailings surface area.

3 MATERIALS AND METHODS

3.1 Characterization of Tailings

The flocculated centrifuged tailings sample was received in a 200L barrel of tailings at the Geotechnical Centre of the University of Alberta. The sample was treated with flocculants created from proprietary material prior to delivery. Test sample was obtained from the middle of the bucket using a scoop sampler after thorough mixing with a hand mixer to ensure homogeneity. Next, the index properties including solids content, grain size properties, specific gravity, and consistency limits tests were conducted using standard ASTM procedures. Solids mineralogy and pore water chemistry tests were conducted using standard test methods.

3.2 Freeze-Thaw Test Setup

A one-dimensional closed system freezing test was conducted in the laboratory for five consecutive freeze thaw cycles at three different temperature profiles (-15°C, -10°C and -5°C vs 0°C) resulting in temperature gradients of 0.083°C/mm, 0.056°C/mm and 0.028°C/mm, respectively. The ranges of these temperatures were selected on the basis of historical weather data of Fort McMurray during winter. A filter paper was first placed on the bottom porous stone. The sample was poured into the freezing cell of 100 mm diameter with an initial height of 180 mm. The sample along with the cell was then transferred to a walk-in freezer where the temperature was maintained between 0°C to 1°C.

Figure 1 shows the schematic diagram of the freeze thaw test setup for the centrifuged samples. Two temperature baths were connected to the freezing cell through its base cooling plate at the bottom and an attached cap at the top for providing a constant temperature. Additionally, three thermistors were placed along the walls of the cell at fixed distances of 40 mm, 80 mm and 120 mm from the bottom plate. A data logger attached to these sensors continuously tracked the temperature within the soil at different depths. Insulation was wrapped around the cell and at the top to minimize the radial thermal conduction. Afterwards, the sample was allowed to freeze from the top down for at least 96 hours until a constant equilibrium temperature was observed. The top down freezing was preferred over bottom up to depict the freezing state in nature and to restrict the upward heaving during freezing.

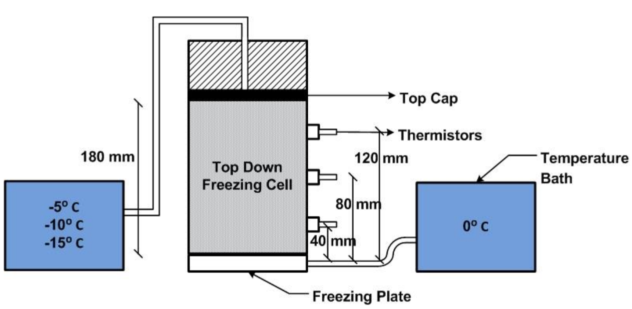

Figure 1. Schematic diagram of freeze thaw test setup

Upon freezing, the cell was disconnected from the temperature baths and allowed to thaw at approximately 1°C for a day. On the next day, the top cap was removed from the cell and subsequently, the sample cell was removed from the cold room. The sample was allowed to thaw at the room temperature (≈20°C). Upon complete thaw, the free water accumulated at the top was removed and the change in height was recorded. Removal of water contributed to the increase in solids content of the tailings sample.

The freeze thaw test was followed by the undrained shear strength and electrical conductivity (EC) measurements tested at a depth of 15 mm from the sample surface using laboratory vane shear apparatus and benchtop pH/EC meter, respectively. Prior to EC analysis, the instrument was calibrated using standard solutions. After the measurements, the freezing cell and the thawed sample were returned to the freezer and the cycles were repeated five times.

3.3 Atmospheric Drying and Wetting Test

After the cyclic freeze-thaw tests were completed, each of the samples were subjected to the atmospheric drying tests and measurement of simultaneous near surface shear strength tests. The drying test was carried out at room temperature (≈20°C) using two identical cells, one of which was filled with water to measure the potential evaporation (PE) and the other contained the thawed soil sample to measure the actual evaporation (AE). The changes in weight loss due to evaporation were recorded on a daily basis along with the subsequent shear strength measurements. The drying test was continued for a month followed by a single wetting event to simulate the rainfall. The volume of water evaporated during atmospheric drying was re-introduced as distilled water for wetting test and the drying test was repeated once again for another twenty days.

3.4 Sectional Analysis

After the cyclic freeze-thaw and drying-wetting tests were terminated, the sample was sectioned into five equal parts of approximately 2 cm in height. Each of the sections was analyzed for the moisture content and EC measurement throughout the depth of the sample.

4 RESULTS

4.1 Index Properties and Pore Water Chemistry Tests

Table 1 summarizes the geotechnical index properties and Table 2 summarizes the physicochemical properties of the investigated centrifuged tailings.

The investigated centrifuged tailings were found to contain about 48% non-clay minerals comprising predominantly quartz (40%) and about 52% clay minerals comprising mainly of kaolinite (36%) and illite (15%). The dewatering properties of the tailings materials are predominantly governed by the complex physicochemical interactions at the solid-liquid phase boundaries (Scott et al., 1985). Na^+ and HCO_3^- were found to be the dominant ions in the investigated tailings water that measured 780 mg/L and 1207 mg/L, respectively. The presence of Na^+ is attributed to the addition of NaOH during the extraction process and that of HCO_3^- is associated with the CO_2 adsorption during aeration for bitumen extraction (Jeeravipoolvarn, 2005). Likewise, the higher concentrations of Cl^- (446 mg/L) is attributed to the higher natural salt content in the ore (Proskin et al., 2012).

Table 1. Summary of Index Properties of Tailings

Characteristics	Value
Water content (%)	89
Solids content (%)	53
Bitumen Content (%)	5.7
Specific Gravity	2.24
Fine Fraction (<0.044 mm) (%)	87
Clay Fraction (<0.002 mm) (%)	52
Liquid Limit	57
Plastic limit	26
USCS Classification	CH

Table 2. Summary of Physicochemical Properties of Tailings

Characteristics	Value
pH	8.7
Electrical Conductivity (µs/cm)	3560
Total Dissolved Solids, TDS (mg/L)	2573
Ionic Strength (mol/L)[1]	0.039
SAR[2]	27

[1]Ionic strength, $I = \frac{1}{2}\Sigma n_0 v^2$; where, n_o = ion concentration and v = valence

[2]$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}]}{2}}}$

4.2 Cyclic Freeze-Thaw Tests

Figure 2 summarizes the thaw strain measured upon thaw after each freeze thaw cycle for each of the samples subjected to three different temperature gradients. Thaw strain was calculated as the change in height after thaw (ΔH) divided by the total frozen height just before thaw (H) for each cycle. The computed thaw strain was converted to the void ratio by the following equation:

$$\frac{\Delta H}{H} = \frac{\Delta e}{1+e_0} \qquad [1]$$

where, Δe is the change in void ratio and e_o is the initial void ratio. Based on the change in void ratio, the corresponding water content and average solids content of the entire sample were computed.

The total thaw strain after five freeze thaw cycles were calculated to be 28.2%, 24.9% and 28.3% for the samples subjected to three temperature gradients of 0.083°C/mm, 0.056°C/mm and 0.028°C/mm, respectively. As expected, the highest thaw strain was observed during the first cycle.

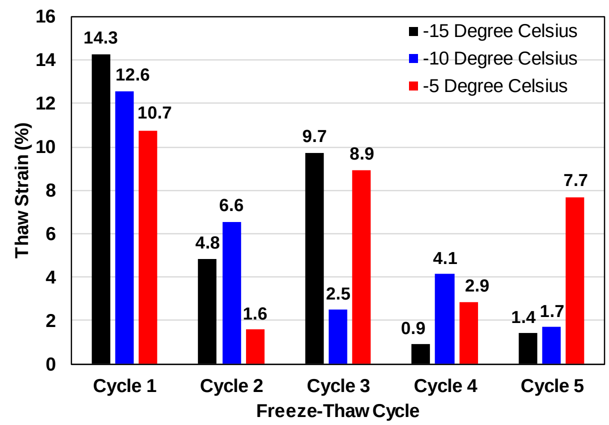

Figure 2. Thaw strain data for each cycle

Figure 3 shows the corresponding cumulative increase in average solids content after each freeze thaw cycle. The final solids content increased from 53% to 66.1%, 64.3% and 66.3% for the cyclic freeze thaw samples subjected to three temperature gradients of 0.083°C/mm, 0.056°C/mm and 0.028°C/mm, respectively. As evident in the figures, the lower temperature gradient (0.028°C/mm resulting from -5°C at top and 0°C at bottom) exhibits a gradual increase in thaw strain and solids content beyond 3rd freeze thaw cycle. On the contrary, the other two boundary conditions show asymptotic trend where the significant effect was observed in the first three cycles. However, the overall total thaw strain and solids enhancement were marginal among these aforementioned three temperature gradients.

Figure 4 depicts the undrained shear strength measured near the surface after each freeze thaw cycle. The strength continued to increase from non-measurable (345 Pa) to 4-8 kPa after five cycles of freeze-thaw. The increase in undrained shear strength was found more significant for the sample subjected to lower temperature gradient (0.028°C/mm). The strength at this gradient continued to increase beyond 3rd freeze thaw cycle while the trends in the other two boundary conditions became asymptotic at 5th freeze-thaw cycle. The highest strength was measured, on the lower temperature gradient (0.028°C/mm) sample, to be approximately 8 kPa after five freeze-thaw cycles.

Potential salt migration during freeze thaw was assessed through EC measurement and was compared with its initial EC. Figure 5 illustrates the EC measurement after each freeze thaw cycles. A gradual increase in EC values after each freeze thaw cycles suggested an increase in ion concentration and a gradual salt migration to the surface. This will be discussed further in the discussion section.

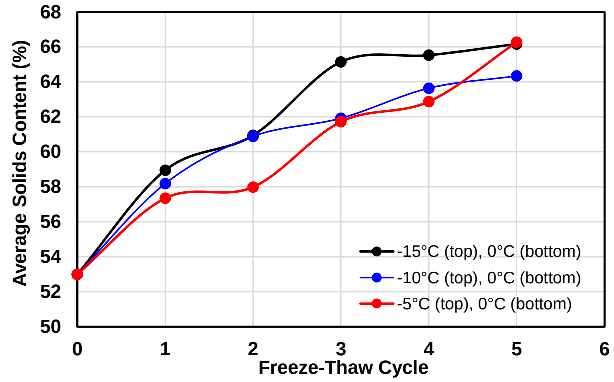

Figure 3. Computed final solids content versus number of freeze thaw cycles

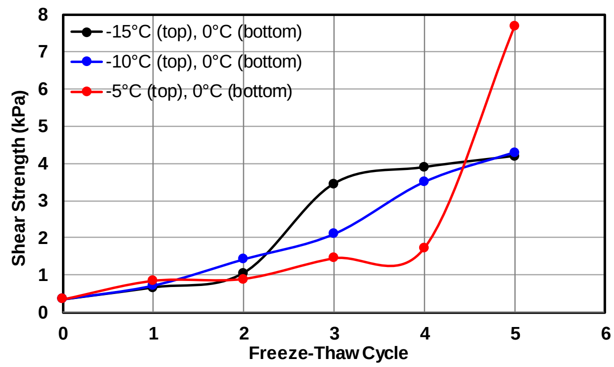

Figure 4. Measured shear strength versus number of freeze thaw cycles (measured at a depth of 15 mm)

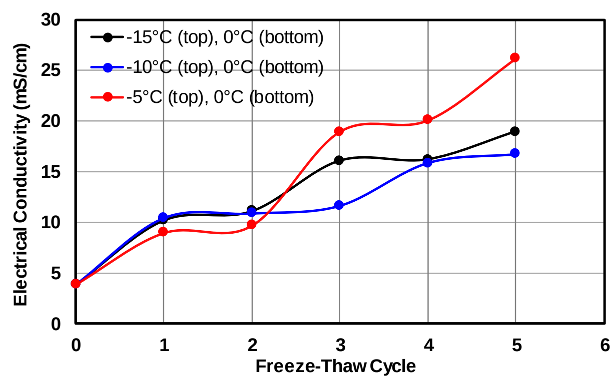

Figure 5. Measured electrical conductivity versus number of freeze thaw cycles (measured at a depth of 15 mm)

Figure 6 depicts the change in pH measured near the surface after each freeze thaw cycle. A gradual decrease in pH after each freeze thaw cycle was observed suggesting a change in physicochemical properties with each freezing cycle. A significant decrease from 8.7 to 7.43 was observed for the sample subjected to a temperature gradient 0.028°C/mm. However, the decreasing trend from the initial pH suggests an increase in positive counter-ions that may lead to double layer compression and overall flocculation.

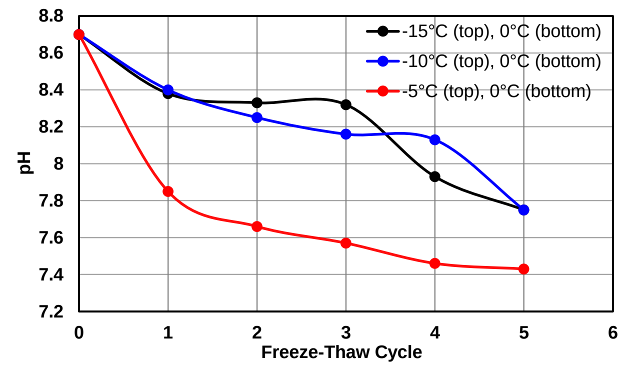

Figure 6. Measured pH versus number of freeze thaw cycles (measured at a depth of 15 mm)

4.3 Atmospheric Drying and Wetting Test

After going through the cyclic freeze-thaw, each sample underwent further volume reduction and subsequent increase in shear strength when exposed to atmospheric drying for a month. On the contrary, upon the re-introduction of the evaporated water to the cell after drying phase, the tailings surface was re-wetted, thereby allowing an increase in moisture content and the closure of desiccation cracks formed during the drying phase (Innocent-Bernard, 2013). However, the weaker zones tend to be increased since some new microcracks were observed at the tailings surface. Figure 7a through c show the atmospheric drying test results in two phases: a. initial drying phase and b. drying phase after wetting event.

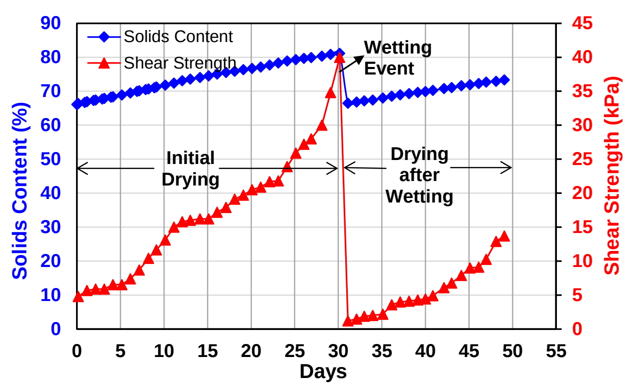

Figure 7a. Solids content and shear strength versus time at a temperature gradient of 0.083°C/mm

The initial atmospheric drying led to improved strength properties by approximately a magnitude higher compared to the strength measured after cyclic freeze thaw run.

Similar to the freeze thaw cycles, the sample subjected to lower temperature gradient (Figure 7c) resulted in significantly higher shear strength (>100 kPa) with a calculated solids content of 89%. On the contrary, the other two boundary gradients (0.083°C/mm and 0.056°C/mm; Figures 7a and 7b, respectively) resulted in undrained shear strengths of 40 kPa and 38 kPa with the associated solids contents of 81% and 79%, respectively.

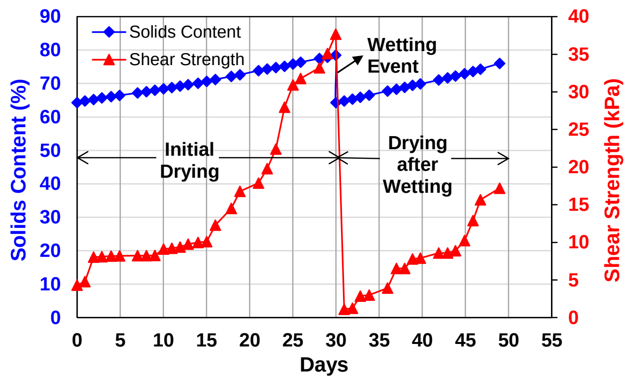

Figure 7b. Solids content and shear strength versus time at a temperature gradient of 0.056°C/mm

Conversely, the second phase drying results after wetting event showed a reduction in shear strength compared to the initial drying phase, for two of the three temperature gradients. The samples at the temperature gradients of 0.083°C/mm and 0.056°C/mm, reduced to the shear strengths of 14 kPa and 17 kPa, respectively. Due to the crust formed at the surface, the shear strength of the sample at lower temperature gradient was generally unaffected by the re-wetting test and as a result, the strength remained unchanged (> 100 kPa) after an initial drop on the day of wetting.

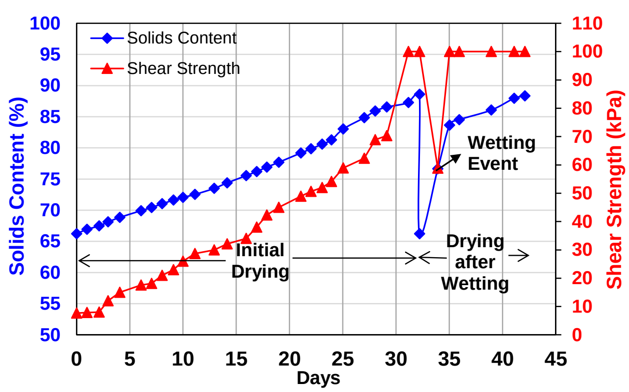

Figure 7c. Solids content and shear strength versus time at a temperature gradient of 0.028°C/mm

4.4 Sectional Analysis

Figure 8 shows the measured final solids content profile and was compared with the initial solids content prior to testing. Likewise, Figure 9 depicts the EC profiles throughout the depth of the sample.

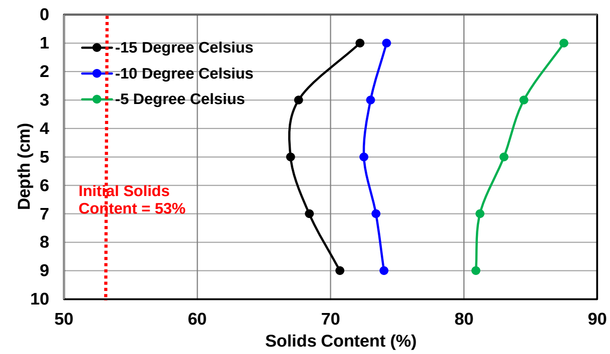

Figure 8. Solids content profile within one dimensional freezing cell

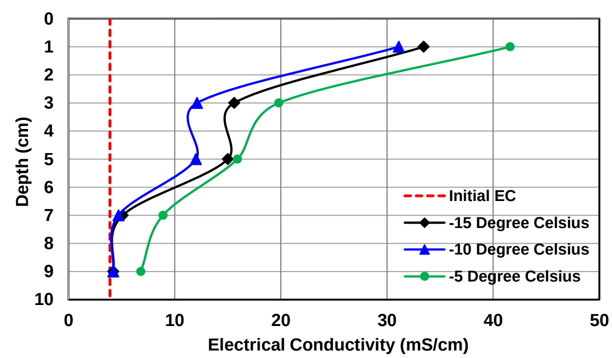

Figure 9. EC profile within one dimensional freezing cell

It is expected that the increase in the electrical conductivity from its initial value was due to the reduction in moisture content through cyclic freeze-thaw and drying-wetting phase (Bernard, 2007). Likewise, the higher solids content at the surface resulted in a higher EC value followed by a gradual decrease with the depth of the sample cell.

5 DISCUSSION

5.1 Index Properties and Pore Water Chemistry Tests

Table 1 summarizes the geotechnical index properties and Table 2 summarizes the physicochemical properties of centrifuged tailings. The water content measured 89% corresponding to a solids content of 53%. The presence of bitumen resulted in low specific gravity compared to the natural soils. The liquid limit and plastic limit values indicate a moderate adsorption on to the clays and are highly influenced by water chemistry and clay mineralogy (Scott et al., 1985).

Apart from consistency limit, the dewatering properties of the oil sands tailings are highly influenced by the combined effect of clay mineralogy and water chemistry

(Scott et al., 1985). The predominance of kaolinite clay in a basic pH (pH=8.7) medium facilitates negative charges at the edges of the clay particles with OH^- being the potential determining ion (Prasanphan and Nuntiya, 2006). Overall, the low ionic strength (strength = 0.04 mol/L, an order of magnitude lower than seawater), high SAR value (>20 indicates likely to be dispersed microstructure as reported by Miller et al., 2010), and the predominance of Na^+ and HCO_3^- ions in the pore water (these two ions are responsible for the dispersed cardhouse structure of kaolinite water system as reported by Jeeravipoolvarn, 2005) as a whole contributed to the dispersed microstructure of the centrifuged tailings, albeit improved properties were achieved over MFT through centrifugation.

5.2 Cyclic Freeze-Thaw Tests

As expected, measured thaw strains, final solids content and shear strength properties (Figure 2 to 4) of the investigated samples were all improved through cyclic freeze thaw dewatering. During the freezing process, the freezing front advanced through the tailings that induced large suctions below the front and developed bands of soil and segregated ice. The suction attracts water to migrate upwards from the unfrozen zone and develops ice lenses (Andersland and Ladanyi, 2004). In the closed system freezing, water from within the tailings is transported to the three-dimensional reticulate network of ice lenses surrounding the soil peds (Beier and Sego, 2009). The formation of soil peds at microscale and fissures at large scale result in the changes in soil structure and its mechanical behavior (Proskin et al., 2012). Upon thawing, these ice lenses become conduit channels for upward water movement, thereby facilitating the settlement of heavier soil peds at the bottom and overall volume reduction.

The induced suction in the ice fringe is predominantly controlled by the temperature gradient. Lower temperature gradient allows the freezing front to advance slowly and draws more water to the frost front by suction causing higher thaw strain and high solids content (Knutsson et al., 2016). This explanation supports the findings of this paper that lower temperature gradient results in higher thaw strain and subsequent higher shear strength, although the calculated average solids content among the three temperature gradients were found comparable. These findings were also similar to the freeze thaw experiments conducted by Dawson (1994) and Proskin (1998). However, the ever-increasing thaw strain and solids content for the lower gradient sample beyond 3rd freeze-thaw cycle were found in disagreement with the previous research studies (Othman and Benson, 1992; Dawson, 1994; Proskin, 1998) on freeze thaw that suggested the insignificant volume reduction beyond 3rd cycle.

Figure 4 shows the increase in near surface undrained strength with the number of freeze-thaw cycles. The improved unfrozen strength corroborated well with the increased thaw strain and is attributed to the removal of free melt water accumulated at the surface upon thawing. Furthermore, the soil peds developed during freezing promotes internal attraction, thereby causing internal strength that, in turn, contributes to the unfrozen shear strength increment (Beier and Sego, 2009). The higher amount of free melt water accumulated at the surface of the sample subjected to the lower temperature gradient contributed to the higher shear strength, although the computed average solids content for both the higher and lower temperature gradients were similar.

The dewatering properties due to freeze thaw cycle can be correlated to the physicochemical properties through electrical conductivity (EC) measurement. Figure 5 illustrates the increase in EC values at the near surface with the increase in freeze-thaw cycle. An increase in EC value indicates an increase in ion concentration or ionic strength. For the fine-grained materials like tailings, solutes are re-distributed with water during freezing. The exclusion of solutes from the developing ice crystals/lenses with each cycle leads to the gradual increase in ion concentration within the remaining water and this can be attributed to the overall water volume reduction due to the phase change from water to ice (Proskin et al., 2012). According to the double layer theory, the increase in ion concentration promotes neutralization of the negative charges, thereby, facilitating double layer compression and particle flocculation (Mitchell and Soga, 2005) which is evident in Figure 3 (the increase in solids content versus number of freeze-thaw cycles).

The aforementioned explanation can be further supported by the salt migration mechanism during freeze-thaw. For the fine-grained tailings material, the salt is migrated upward with unfrozen water towards the frozen zone due to the convection followed by the exclusion of salt molecules from the growing ice lenses that leads to the increase in salt concentration at the surface. Upon thawing, the migrated salts start to get transferred downwards in the opposite direction due to the solute gradient or diffusion. However, the amount of salt diffused due to the solute gradient is marginal compared to the salt migrated due to convection during freezing. The migrated water along with salt during freezing can never be fully infiltrated back to the original location upon thawing due to the influence of gravity and water potential. The latent heat of freezing is significantly higher than the sensible heat flux developed in the transition layer between the unfrozen and frozen zone due to temperature gradient. As a result, a segregated ice layer and the potential gradient of unfrozen water co-exist interminably, causing upward water and salt migration. However, the migration of salt is predominantly controlled by the temperature gradient and the soil structure. The higher temperature gradient promotes the rapid movement of freezing front that might occupy the transfer channel and limits the amount of salt concentration that can migrate (Bing et al., 2015). This finding corroborated well with the results from Figure 5 where the highest EC value was recorded for the sample at lower temperature gradient.

The physicochemical interactions of the tailings are highly sensitive to the changes in pH (Proskin et al., 2012) as evident in Figure 6. As mentioned earlier, higher pH allows electrostatic repulsion to dominate over attractive forces due to the deprotonation of OH^- groups (Mitchell and Soga, 2005). Apart from the clay particles and the residual bitumen coating being sensitive to pH, the efficiency of polymer is also strongly affected by pH and ionic strength. The adsorption of flocculent/polymer which is added during centrifugation, is promoted under acidic pH or at high ionic strength (Theng, 1982). During the multiple freeze thaw process, the polymer is subjected to high shear stresses, which tend to disrupt the stability of the polymer (King et al., 1969). This may cause the rearrangement of adsorbed chains on the clay particle surface and increase the collision between the coated particles (Agarwal, 2002). The increase in ion concentration (as illustrated in Figure 5) and a decrease in pH (as illustrated in Figure 6) due to multiple freeze-thaw cycles, thus suggest the change in conformation of polymer that might increase the collision probability and result in the formation of flocs (Demoz et al., 2010). As expected, lower temperature gradient resulted in the lowest pH that contributes to the near surface solids content and shear strength increment and overall supports the findings of this paper regarding the effect of freezing temperature gradients on the tailings sample.

An increase in thaw strain beyond 3rd cycle can be explained through the above hypothesis since the volume reduction during freeze thaw is traditionally more pronounced during the first three cycles (Othman and Benson, 1992; Dawson, 1994). The combined effect of polymer application and the multiple freeze-thaw cycles might be responsible for the improved dewatering properties beyond 3rd cycle for the investigated centrifuged sample unlike the previous research studies (Othman and Benson, 1992; Dawson, 1994; Proskin, 1998) where polymer application was precluded.

5.3 Atmospheric Drying and Wetting Test

Figure 7 illustrates the atmospheric drying and wetting results that correlate the average computed solids content with the undrained shear strength. The drying phase promotes volume shrinkage and cracking that contributes to the increase in surface area for the preferential flow path for evaporation (Innocent-Bernard, 2013). Upon drying, the integrity of the sample appeared to diminish and the evaporation rate continued to increase that resulted in the change in moisture content of the sample. As expected, the drying phase improved the strength properties by a magnitude higher than the freeze-thaw cycles. Sample subjected to lower temperature gradient (0.028°C/mm) experienced the higher shear strength (>100 kPa) and this is attributed to the formerly achieved higher solids content due to cyclic freeze thaw and the lower relative humidity throughout the drying phase compared to the other two samples.

Upon drying, the wetting event introduced a large number of new micro-cracks that was developed due to the differential swelling pressures and the inner stresses. The wetting induced cracks lead to the significant re-arrangement of the particles (Tang et al., 2011). As a result, the sample heterogeneity was intensified. As expected, the drying after wetting event resulted in a decrease of solids content and subsequent lower shear strength compared to the initial drying phase. However, the sample subjected to lower temperature gradient was unaffected by this phase due to the formerly developed crust during initial drying phase.

5.4 Sectional Analysis

The measured solids content profile in Figure 8 shows a significant increase from the initial value. All the three samples experienced the higher solids content at the near surface. The samples subjected to the freezing temperature gradients of 0.083°C/mm and 0.056°C/mm showed an inconsistent pattern of the solids content profile while, the solids content for the sample subjected to the lower temperature gradient gradually decreased at the bottom. The inconsistent pattern observed in the former two samples might be attributed to the complex irregular cracking pattern during wetting phase and the observational difficulties associated with the lower statistical population.

The EC profile (as shown in Figure 9) suggested that the solute transport takes place from the bottom to the top due to convection and resulted in salt accumulation at the top. The drying-wetting phase further facilitates the solute accumulation by evaporating water from the surface and thereby, leaving behind the salt precipitates at the top. As expected, the lower temperature gradient sample experienced higher EC values (an order of magnitude higher than the initial) throughout the depth.

6 CONCLUSION

Fundamental understanding of tailings properties (dewatering and physicochemical properties) is pivotal for the sustainable reclamation strategies. The experimental results have shown that the solids content and the undrained shear strength of the fine-grained tailings can be increased by simply exposing the tailings surface to the cold natural environment. The tailings are expected to dewater and gain sufficient strength for reclamation activities to proceed within a reasonable time through freezing in winter, thawing in spring and desiccation during summer. The undrained shear strength of the tailings sample with an initial solids content of 53% increased from non-measurable to a maximum 8 kPa after five cycles of freeze thaw. Depending on the thawing temperature and relative humidity, the experimental data seem to suggest further increase in strength by an order of magnitude higher during drying phase.

The electrical conductivity measured after each drying –wetting phase suggested the solute transport phenomena and corroborated quite well with the measured solids content variation. A hypothesis was introduced to correlate the physicochemical interaction with the dewatering properties. Overall, the test results suggest that cyclic freeze thaw and drying/wetting process in the nature for subsequent years could be evaluated to enhance the stability of the tailings surface area.

Future research should attempt to measure osmotic suction after each freeze thaw cycle to better investigate the solute transport phenomena and their influence on the overall natural weathering.

7 ACKNOWLEDGEMENTS

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