Preliminary evaluation of Speswhite kaolin as a physical analogue material for unsaturated oil sands tailings

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ABSTRACT
Thin-lift deposition of treated oil sands tailings is currently investigated as a potential solution for creating a trafficable cap layer for future reclamation activities. To determine the optimal thickness of the cap layer, physical modeling experiments using the 50g-ton geotechnical beam centrifuge at University of Alberta were proposed. Prior to the deposition of fresh layers, the cap layer is often unsaturated due to freeze-thaw and atmospheric drying. In this paper, Speswhite kaolin is investigated as the candidate for a physical analogue of unsaturated oil sands tailings. Due to its high brightness and repeatability, Speswhite kaolin has been widely used as a modeling clay in geotechnical centrifuge experiments. However, its suitability of simulating unsaturated tailings with high clay content was rarely considered in the past. Two different sample preparation methods using Tempe cells and air-drying to create blocks of unsaturated Speswhite kaolin are evaluated. Undrained shear strength was measured by the miniature vane shear device and unconfined compression test while drained shear strength was determined by the direct shear device. Test results showed that the two materials behaved similarly in drained conditions while Speswhite kaolin exhibited a higher shear sensitivity in undrained conditions. Test results also showed different drying behaviour between the two materials: Speswhite kaolin dries faster, more uniformly and to a higher void ratio than treated oil sands tailings. Potential causes behind these observations are discussed in the paper.

RÉSUMÉ

Le dépôt en couches minces de résidus de sables bitumineux traités est actuellement étudié comme solution potentielle pour créer une couche de recouvrement praticable pour les futures activités de remise en état. Pour déterminer l'épaisseur optimale de la couche de couverture, des expériences de modélisation physique utilisant la centrifugeuse à faisceau géotechnique de 50 g de l'Université de l'Alberta ont été proposées. Avant le dépôt des couches fraîches, la couche de couverture est souvent insaturée en raison du gel-dégel et du séchage atmosphérique. Dans cet article, le kaolin Speswhite est étudié comme candidat pour un analogue physique des résidus de sables bitumineux insaturés. En raison de sa grande luminosité et de sa répétabilité, le kaolin Speswhite a été largement utilisé comme argile à modeler dans les expériences de centrifugation géotechnique. Cependant, son aptitude à simuler des résidus insaturés à forte teneur en argile a rarement été envisagée dans le passé. Deux méthodes différentes de préparation d'échantillons utilisant des cellules Tempe et le séchage à l'air pour créer des blocs de kaolin Speswhite insaturé sont évaluées. La résistance au cisaillement non drainé a été mesurée par le dispositif de cisaillement miniature à palettes et le test de compression non confiné tandis que la résistance au cisaillement drainé a été déterminée par le dispositif de cisaillement direct. Les résultats des tests ont montré que les deux matériaux se comportaient de manière similaire dans des conditions drainées, tandis que le kaolin Speswhite présentait une sensibilité au cisaillement plus élevée dans des conditions non drainées. Les résultats des tests ont également montré un comportement de séchage différent entre les deux matériaux : le kaolin Speswhite sèche plus rapidement, plus uniformément et à un taux de vide plus élevé que les résidus de sables bitumineux traités. Les causes potentielles derrière ces observations sont discutées dans le document.

1 INTRODUCTION

In Alberta's oil sands mining operation, there are currently 220km^2 of tailings that are mandated by Directive 085 to be reclaimed to a "self-sustaining, maintenance-free" landscape (Alberta Energy Regulator 2021). Meeting the requirement of Directive 085 has eluded experts for over a decade. One of the reasons why it has remained elusive is because of the geological variability in the clay minerals of the McMurray formation in Alberta, which affects the composition of tailings. Additionally, operators add various chemicals to strengthen the highly variable oil sands tailings, creating unique properties in each tailings deposit.

After mine operators add polymers (known as flocculants) and in some cases coagulants to the "fluid-like" oil sands tailings, the resultant product has a "yogurt-like" consistency (McKenna et al 2016). Desiccation during summer and freezing/thawing during winter and spring are known methods to further strengthen treated tailings (Kolstad et al 2016). Figure 1 shows a field trial where the mine operator placed treated tailings in thin layers over a large area allowing the current layer to sufficiently dry or freeze/thaw before placing the next layer (Song et al 2011, COSIA 2022). Despite the inevitable rewetting, the thin-lift deposit is still stronger than tailings placed continuously in thick layers (Daliri et al 2016).

The overarching objective of this research program is using scaled physical models to investigate the optimal thickness of the stiff layer created by thin-layer placement. In physical modelling experiments, this stiff layer can be idealized as a single block of soil (see Figure 2). Using tailings samples collected in the field, while valuable, can make interpretation difficult due to inherent geological variability, sample disturbance and logistical challenges. Synthetic soils are often used in physical modelling experiments. This paper evaluates Speswhite Kaolin as a candidate for simulating unsaturated tailings. Previous works on unsaturated kaolin are concentrated on statically compacted material (Sivakumar 1993, Tarantoni and Tombolato 2005, Tarantino and De Col 2008). This paper aims to characterize Speswhite Kaolin subjected to desiccation, mimicking the stress path in the field.

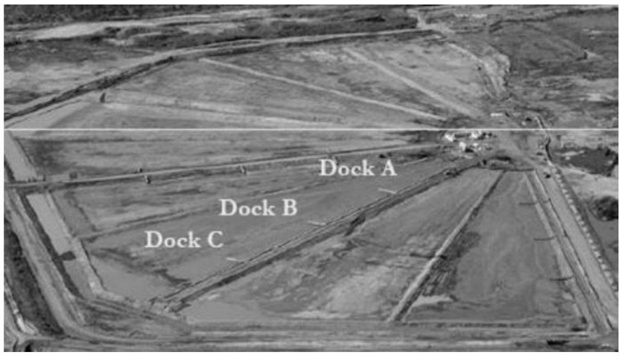

Figure 1. Field trials of thin-lift deposition of flocculated oil sands tailings with instrumentation installed in the docks (Matthews et al 2011).

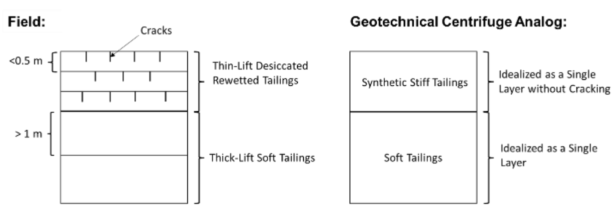

Figure 2. Idealization of field conditions in a geotechnical centrifuge

2 MATERIAL PROPERTIES

Unsaturated centrifuged tailings (known as centrifuge cake) and Speswhite Kaolin are compared in this paper. Centrifuge cake is currently produced commercially at several oil sands mining operations. The centrifugation process involves dilution and flocculation of FFT with a flocculating agent (typically high molecular weight anionic polyacrylamide) and coagulant (typically gypsum or lime), followed by dewatering in a bowl centrifuge press prior to deposition. Flocculant injection often occurs close to the bowl centrifuge feed tube to avoid over-shearing. The end-product typically has a solids content of more than 50%. (Spence et al. 2017). Geotechnical index properties of centrifuge cake in Table 1 are based on previous work from Rima and Beier (2022) and Schafer and Beier (2020). The coefficient of consolidation (Cv) is derived from oedometer tests on desiccated rewetted centrifuge cake.

Speswhite Kaolin is a naturally occurring clay deposit quarried near Cornwall in Southwest England. Due to the extensive use in physical modelling experiments, its geotechnical properties are well documented in the literature. Index properties from the supplier (Imerys 2008), Jia (2021) and unsaturated Cv measured by Sivakumar (1993) are listed in Table 1

Table 1. Material properties of centrifuge cake and Speswhite Kaolin

Material Properties	Centrifuge Cake	Speswhite Kaolin
Liquid Limit (%)	57	65
Plastic Limit (%)	26	35
Shrinkage Limit (%)	21	32
Specific Gravity (Gs)	2.48	2.61
Clay Fraction (%)	52	76 to 83
MBI (meq/100g)	4.80	1.79*
Specific Surface Area (m2/g)	20	14
Cv (m^2/yr)	0.20	2.27

*Back-calculated from specific surface area using equations from Hang and Brindley 1970

3 EXPERIMENTAL METHODS

3.1 Sample Preparation

Centrifuge cake is collected shortly after deposition while Speswhite Kaolin is shipped in bagged powder form. The initial water content for the centrifuge cake samples ranges from 52% to 70% while the Speswhite Kaolin samples are pre-mixed with de-ionized water at twice the liquid limit. Prior to desaturation, both materials are homogenized by a hand-held electrical mixer for a minimum of two minutes.

Unsaturated samples are prepared by ambient air-drying and dewatering inside Tempe cells. Ambient air-drying is performed under controlled laboratory environment (i.e. room temperature at 20 Celcius). Air-dried samples, denoted by “AD”, are slowly desiccated inside a Shelby ring with a diameter of 63.5mm and height of 32mm for the shrinkage tests and inside a standard 20L pail for the vane shear test.

Tempe-dried samples, denoted by “TD”, are desaturated by applying a positive air pressure to the sample sitting on top of a high air-entry ceramic porous stone (1-bar and 5-bar) which allows the pore water to drain through the water outlet while keeping the air in the cell (see Figure 3). Tempe cells use the axis-translation technique to achieve target matric suction in the soil sample (Fredlund et al. 2012). The tempe cell is weighed daily to calculate how much pore water is expelled. Equilibrium is reached when the weight difference after 24 hours is less than 0.5g, and then the specimen can be extracted for further testing. Air pressures of 25, 50,100, 200 and 400kPa are applied to achieve matric suctions in a single load step, using the technique developed by Kabwe et al. 2023. Multiple Tempe cells are used to speed up the sample preparation process. Moisture distribution of TD samples at the end of the test is highly uniform without any discernible cracking (see Figure 4). The walls of the Shelby rings and Tempe cells are well-greased in petroleum jelly to minimize side friction.

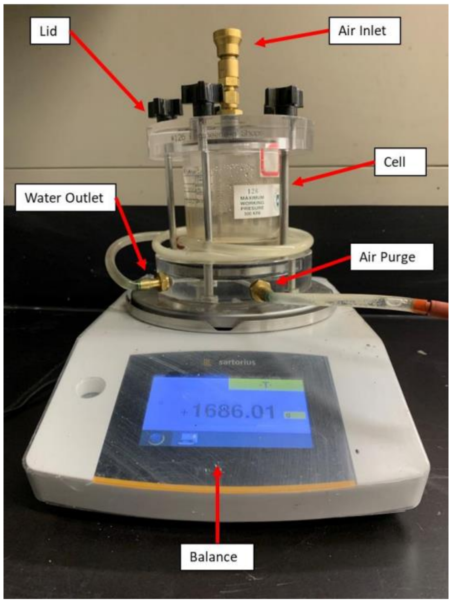

Figure 3. Tempe cell setup for preparing Tempe-dried samples (Kabwe et al 2023)

Figure 4. Centrifuge cake (left) and Speswhite Kaolin (right) at the end of the Tempe cell test under an applied matric suction of 400kPa

3.2 Drained Test (Direct Shear)

All samples in the direct shear box have been Tempe-dried under an applied matric suction of 400kPa. At equilibrium, the sample is removed from the Tempe cell and trimmed by a Shelby ring. The trimmed sample is then transferred into the direct shear box.

Once the direct shear box is attached to the direct shear machine, de-ionized water starts rewetting the sample and a vertical load of 15kPa is immediately applied. Subsequent load steps are applied at twice the magnitude of the previous load step until the target normal stress is reached. The sample is sheared at a rate of 0.008 mm/min.

3.3 Undrained Test (Unconfined Compression, Vane Shear)

Unconfined compression strength (UCS) tests are conducted according to the ASTM (2016) standard at a constant displacement rate of 1%/min. Specimen for the UCS test are trimmed from TD samples by a Shelby tube with a diameter of 28mm. Due to volume shrinkage and insufficient height of the dried sample inside the Tempe cell, a length-to-diameter ratio of 1 is adopted instead. While this is a deviation from the length-to-diameter ratio of 2 as per the ASTM standard, it is considered acceptable here since the objective is to compare the load-displacement responses under identical boundary conditions.

For vane shear tests, a vane blade with 12.7mm height and 12.7mm width is attached to a motorized vane shear device which rotates at a speed of 60 degrees per minute. The vane shear test is conducted according to ASTM D4648. For remolded strength, the vane blade is rapidly rotated 5 times before strength is re-evaluated. This remolding procedure is repeated until there are no further decreases in the remolded strength.

3.4 Drying Test (Air-Drying and Tempe Cell)

Slurried samples are placed in a series of Shelby rings on top of a petri dish (see Figure 5). The bottom of the glass dish is covered by well-greased wax paper to avoid leakages from the side. Dimensions of the AD samples are measured by a caliper at different stages of air-drying to calculate the void ratio and the shrinkage curve. Gravimetric water contents from the top and bottom layer are taken at different stages of drying.

Soil water retention properties are measured using the procedure from Fredlund and Houston (2009). The Tempe cell procedure is similar to Section 3.1 except that air pressures are step loaded instead. Samples are subjected to increasing air pressure in the Tempe cells until reaching a maximum matric suction of 400kPa.

Figure 5. Air-dried sample preparation setup

4 RESULTS AND DISCUSSION

4.1 Drained Behaviour (Direct Shear)

Based on best-fit lines of the data points in Figure 6, the frictional angle in direct shear is similar between Tempe-dried centrifuge cake (18 degrees) and Tempe-dried Speswhite Kaolin (19.9 degrees). The similarity in frictional angle can be explained, in part, by the identical stress path the two materials experienced which produced similar fabric prior to shearing.

The over-consolidation ratio by desiccation (OCR-d) can quantify stress history during the desaturation process in Tempe cells. OCR-d is defined by the ratio of the maximum suction stress during desiccation and the maximum effective consolidation stress achieved during the consolidation stage of the direct shear tests. The maximum suction stress is calculated as the applied matric suction multiplied by the degree of saturation based on Lu and Likos (2006) and Akin and Likos (2020). The degree of saturation is derived from the shrinkage curves and the Tempe cell tests.

In Figure 7, the horizontal strain at which peak shear occurs converges at lower OCR-d. At higher OCD-d, Speswhite Kaolin exhibited a stiffer response. Figure 8 is an alternative way to look at the stress-strain behaviour. The peak shear stresses of both materials were mobilized at a greater horizontal strain with increasing normal stresses. The absence of flocculant/coagulant treatment and centrifugation process in Speswhite Kaolin does not seem to create a stress-strain behavior different from the centrifuge cake provided that both materials undergo the same desiccation stress path.

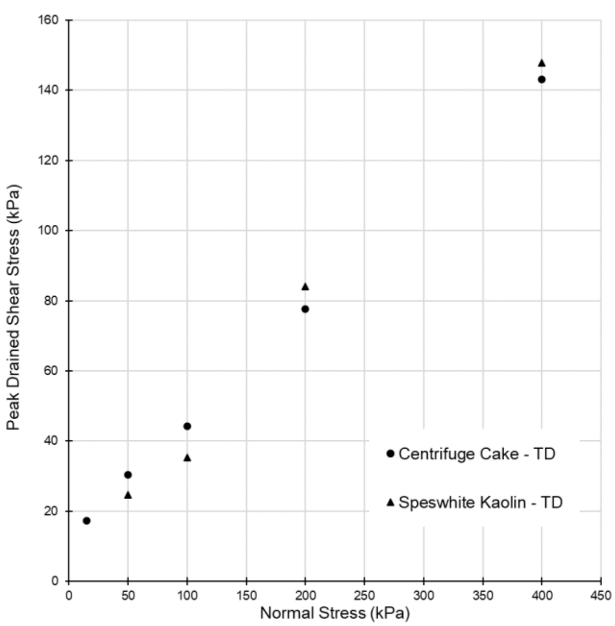

Figure 6. Comparison of peak shear stresses from direct shear testing of Tempe-dried (TD) samples

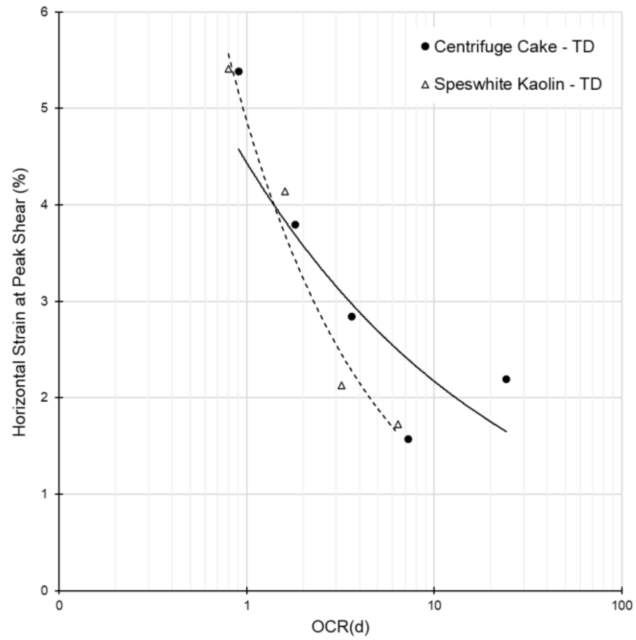

Figure 7. Variation of mobilized horizontal strain during direct shear tests at peak shear stresses under different desiccation over-consolidation ratio (OCR-d)

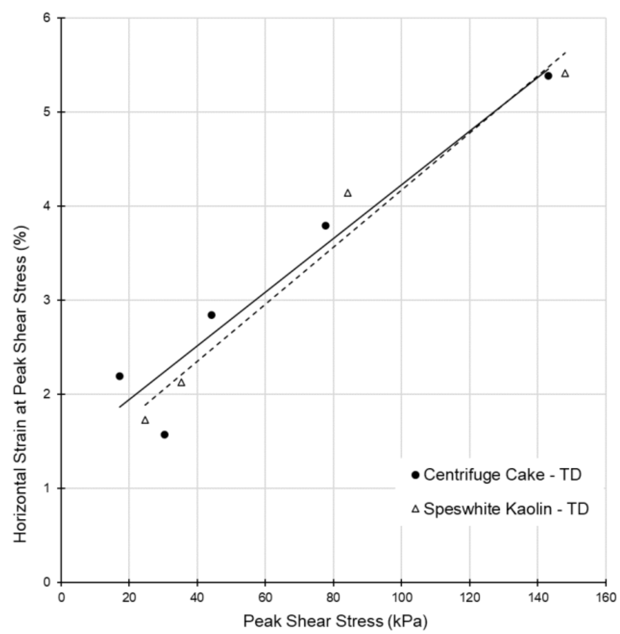

Figure 8. Comparison of mobilized horizontal strain at peak shear stresses in Tempe-dried samples under direct shear

4.2 Undrained Behaviour

As shown in Figure 9, both materials showed similar trends in undrained shear strength regardless of the sample preparation method. Figure 10 shows that Speswhite Kaolin is three to five times more sensitive than centrifuge cake as liquidity index decreases toward the plastic limit. Unlike the Speswhite Kaolin, shear sensitivity in centrifuge cake increases only slightly near the plastic limit, possibly due to aggregation and bonding from the flocculation, coagulation and centrifugation treatment during the slurry forming stage.

The load-displacement response curves under unconfined compression in Figure 11 showed similar stress-strain behaviours in Tempe-dried samples at 400kPa applied matric suction near the plastic limit. At 100kPa applied matric suction, centrifuge cake showed a higher shear strength at a larger strain. The final water content of the failed specimen decreases less than 1% compared to the initial water content of the TD samples, indicating minimum moisture loss during UCS.

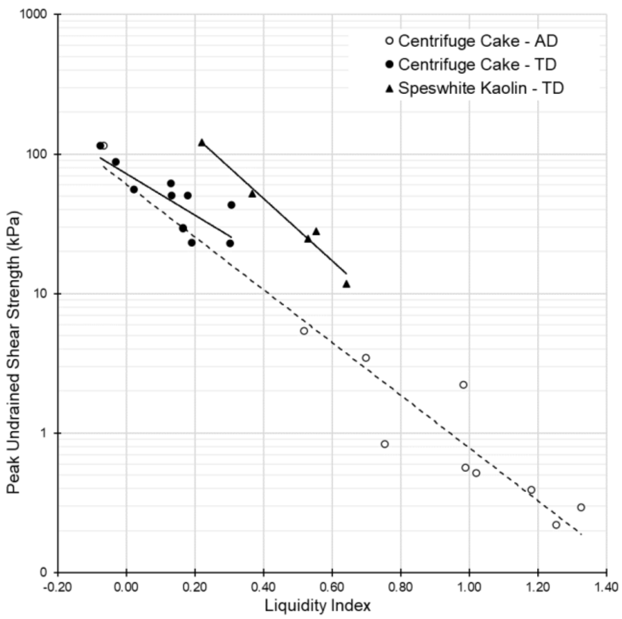

Figure 9. Comparison of peak undrained shear strength measured by vane shear.

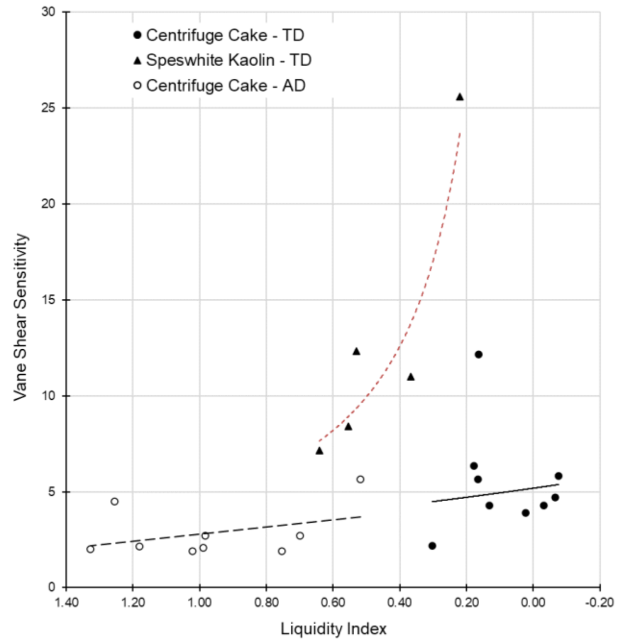

Figure 10. Comparison of shear sensitivity measured by vane shear.

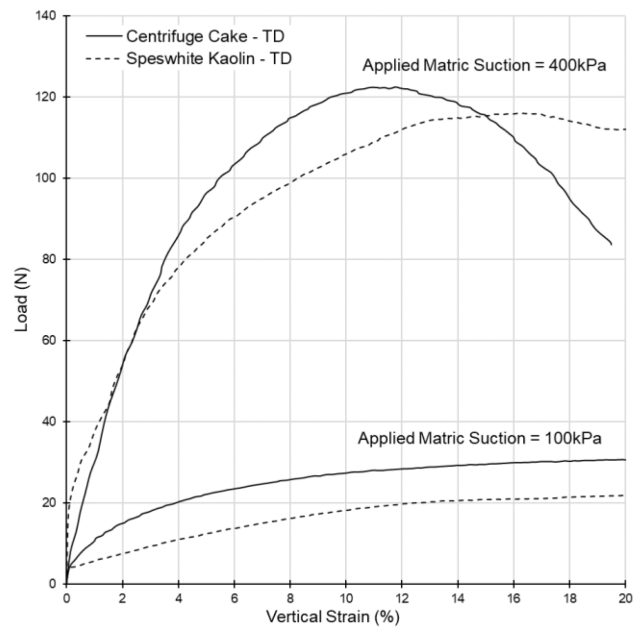

Figure 11. Comparison of load vs displacement curve under unconfined compression loading of Tempe-dried samples.

4.3 Drying Behaviour

As shown in Figure 14, moisture distribution in air-dried centrifuge cake is non-uniform with the greatest difference observed near the liquid limit. As air-drying progresses toward the plastic limit, differences between the top and bottom water content are reduced. This non-uniformity is confirmed by visual observations after the Shelby ring is removed during the air-drying process. The top stiffer section of the centrifuge cake remains intact while the bottom softer section slumps laterally (see Figure 12).

On the other hand, moisture distribution in Speswhite Kaolin is highly uniform: most data points lie on the 1:1 line in Figure 14 confirmed by visual observations throughout the air-drying process (see Figure 13).

Single-step and step-loaded Tempe cell tests produced similar liquidity indices at a given matric suction (see Figure 15). Liquidity indices of Tempe-dried Speswhite Kaolin is consistent with Tripathy et al (2014) using a similar method. At a given matric suction, centrifuge cake dewaters to a lower liquidity index and a lower void ratio. (Figure 16).

The larger coefficient of consolidation (Cv) in Speswhite Kaolin contributes to the faster and more uniform drying phenomenon compared to centrifuge cake. Tempe-dried centrifuge cake takes approximately two weeks to reach equilibrium while Tempe-dried Speswhite Kaolin takes only one day. It is hypothesized that microstructures and clay-water interaction mechanisms due to flocculation and coagulation, clay mineralogy, and pore water chemistry may have contributed to the different drying behaviours. For Speswhite Kaolin, moisture re-distribution in the bottom layers occurs quickly as water in the top layer evaporates. In contrast, pore water in the centrifuge cake contains elevated salt concentrations at a basic pH (>8) because of the geological environment and the caustic extraction process. The precipitation of salts at the surface suppress evaporation due to increased osmotic suction and reduced hydraulic conductivity (Simms et al 2019). The presence of illite inter-mixed with smectite in centrifuge cake which has a higher specific surface area than pure Kaolinite mineral may also contribute to the slower drying.

Understanding the differences in drying behaviour can help optimize thin-lift placement. Further studies in the microstructure and physio-chemical forces behind the drying behaviour are needed. However, this is outside the scope of this paper.

Figure 12. Profile view of centrifuge cake during ambient air-drying with un-even distribution of water content over depth.

Figure 13. Profile view of air-dried Speswhite kaolin with uniform distribution of water content over depth.

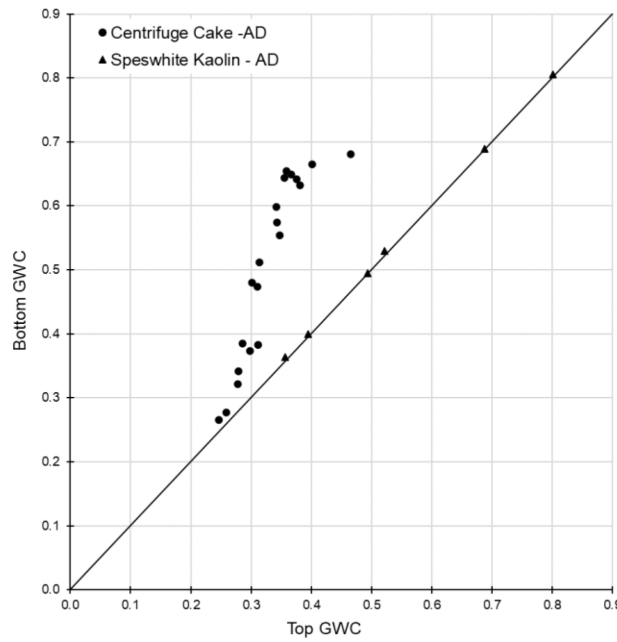

Figure 14. Comparison of top and bottom gravimetric water content during various stages of air-drying

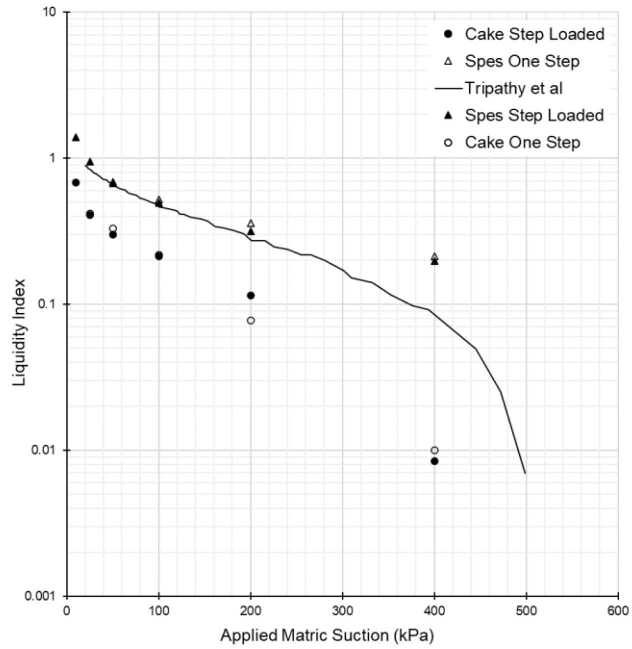

Figure 15. Comparison of liquidity indices achieved by the step-loaded and one-step Tempe cell method.

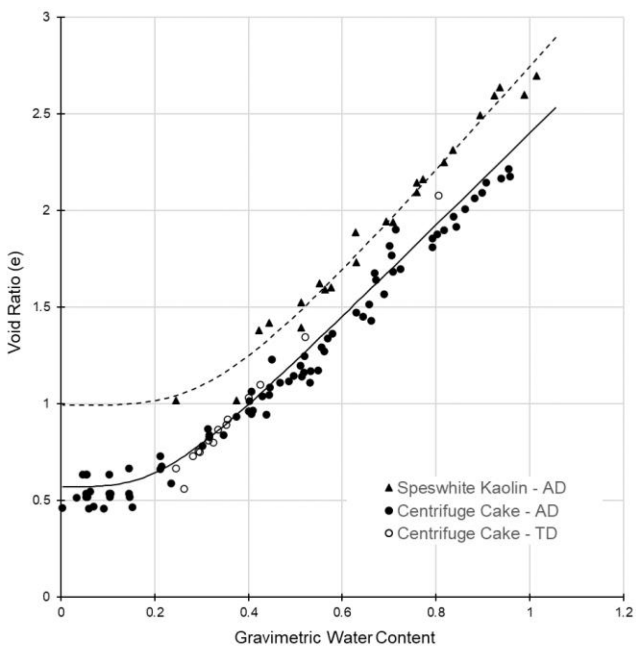

Figure 16. Comparison of shrinkage curves between centrifuge cake and Speswhite Kaolin

5. CONCLUSION

A suite of geotechnical tests is conducted on unsaturated Speswhite Kaolin and centrifuge cake. The two materials behave similarly in drained conditions and at lower water content in undrained conditions except that Speswhite Kaolin is more sensitive in the vane shearing mode. The two materials behave differently during air-drying: Speswhite Kaolin dries more quickly and uniformly with a higher void ratio at the shrinkage limit. The suitability of Speswhite Kaolin as a physical analogue of unsaturated centrifuge cake depends on the purpose of the experiment. Speswhite Kaolin is a suitable candidate if the objective of the physical modelling experiment is to assess bearing capacities and long-term stability of the closure landform. If the objective is to investigate the impact of thin-lift deposition and climate, an alternative recipe needs to be developed for a better match of the drying and rewetting behaviour.

6. ACKNOWLEDGEMENT

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