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Evaluation of oil sands thickened tailings consolidation and shear strength parameters using 3 geotechnical testing techniques

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Abstract

The stability of a tailings dam depends upon the strength of the tailings. Approximately 1.3 billion cubic metres of mature fine tailings (MFT) from Canadian Oil Sands mines are stored in tailings dams. The MFT need to be treated to achieve solids contents and strengths sufficient to support dams' reclamation. Thickening is one of the potential technologies for converting MFT into a material with sufficient strength to support trafficability. Characteristics that can be reasonably investigated at the design stage, and may contribute to foundation failure, include shear strength, compressibility and permeability. In this research, these 3 characteristics for thickened tailings (TT) were evaluated using the large strain consolidation with shear strength (LSC-SS), consolidated-drained direct shear (CD-DS), and consolidated-undrained triaxial (CU-TR) testing techniques. The TT tested had a high sand content of 61% and exhibited dense sand behaviour. The characteristic stress–strain curve showed a peak stress at a relatively low strain and, thereafter, the stress decreased. Results showed that the TT was less compressible with a compression index Cc of 0.04. The hydraulic conductivity K decreased by one order of magnitude (i.e. 10^{-8} to 10^{-9} m/s) as the void ratio decreased from 1.3 to 0.92. The LSC-SS technique provided an effective friction angle (ϕ') value of 19.3°. The CU-TR and CD-DS tests provided effective friction angle (ϕ') values of 36 and 46°, respectively. These 2 values of ϕ' confirmed that the TT behaved as a dense sand. The LSC-SS test that uses the vane shear device yielded a lower value of ϕ' due to various factors, including the rotation rate, vane insertion disturbances, and vane shape which destroyed the fabric and decreased its ϕ' value. The reconstituted and consolidated TT sample had a low effective cohesion (c') value of about zero. The results of the strength parameters, compressibility, and K are crucial in any stability analyses of slopes against failure and landslides.

Keywords: *large strain consolidation, direct shear, triaxial testing, angle of internal friction, cohesion*

1 Introduction

Thickening is one of the potential technologies used for converting mature fine tailings (MFT) into a material with sufficient strength to support trafficability. Sand is added to thickened tailings (TT) to increase strength. Shear strength is an important engineering property in the design and closure of tailings dams. Approximately 1.3 billion cubic metres of MFT have been stored in Canadian tailings dams awaiting reclamation, as of 2018 (Alberta Energy Regulator 2018). This vast accumulation of MFT in the dams is due to the slow consolidation of the MFT. The stability of a tailings dam depends upon the strength of the tailings. In this study, the strength parameters of the TT were evaluated using 3 different techniques: large strain consolidation with shear strength (LSC-SS), consolidate-drained direct shear (CD-DS), and consolidation undrained triaxial (CU-TR). Two shear strength parameters are required to define a failure envelope of an unsaturated soil, which is an extended form of the Mohr–Coulomb equation (Equation 1):

$$\tau_f = c + \sigma \tan \phi \quad (1)$$

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where:

τ_f = shear resistance at failure

σ = normal stress at the failure plane

ϕ = angle of internal friction

c = cohesion.

The above equation (Mohr–Coulomb failure criterion) can also be expressed in terms of effective stresses (as in saturated soils) as:

$$\tau_f = c' + \sigma' \tan \phi' \tag{2}$$

where:

c′ = effective cohesion

ϕ' = angle of internal friction

σ′ = effective stress.

These 2 parameters are crucial in any stability analyses of slopes against failure and landslides. The value for ϕ is a measure of the resistance of soil to shear stress, reflecting soil's ability to withstand deformation and maintain stability under load (Craig 1992). This angle is crucial in understanding the strength and behaviour of the soil. The term *c* in the Coulomb shear-strength equation significantly influences the location of the slip surface and the safety factor. Determining ϕ is vital for calculating bearing capacity and slope stability in geotechnical projects. In practice, higher ϕ indicates better stability and resistance to failure under load. When dealing with normally consolidated clays, the cohesion intercept is typically assumed to be zero. By contrast, over-consolidated clays typically exhibit a non-zero cohesion intercept. In such soils, the magnitude of *c* generally increases with an increase in the over-consolidation ratio. The objective of this study was to evaluate the consolidation properties and shear strength parameters of TT using 3 geotechnical testing techniques: LSC-SS, CD-DS, and CU-TR.

A very similar methodology was published in Kabwe et al. (2025) to evaluate the effect of centrifugation on the consolidation properties and shear strength parameters of MFT. The tailings material analysed in Kabwe et al. (2025) was centrifuged MFT (cake) with a sand content of 18%. In contrast the TT analysed in this paper has a sand content of 61%. The findings from these 2 papers are:

- The hydraulic conductivity of the treated TT (in this paper) is higher than that of the centrifuged MFT in Kabwe et al. (2025). Therefore, an increase in hydraulic conductivity will result in the treated TT tailings consolidating much faster.
- The centrifuged MFT is more compressible than the TT and it will require less storage space than the TT.
- The shear strength of centrifuged MFT is higher than that of the TT.
- The value of ϕ for the centrifuged MFT ranged from 20–22.9° and those for the TT ranged from 36–46°, indicating that the centrifuged MFT is classified as very soft clay and the TT as condensed sand.

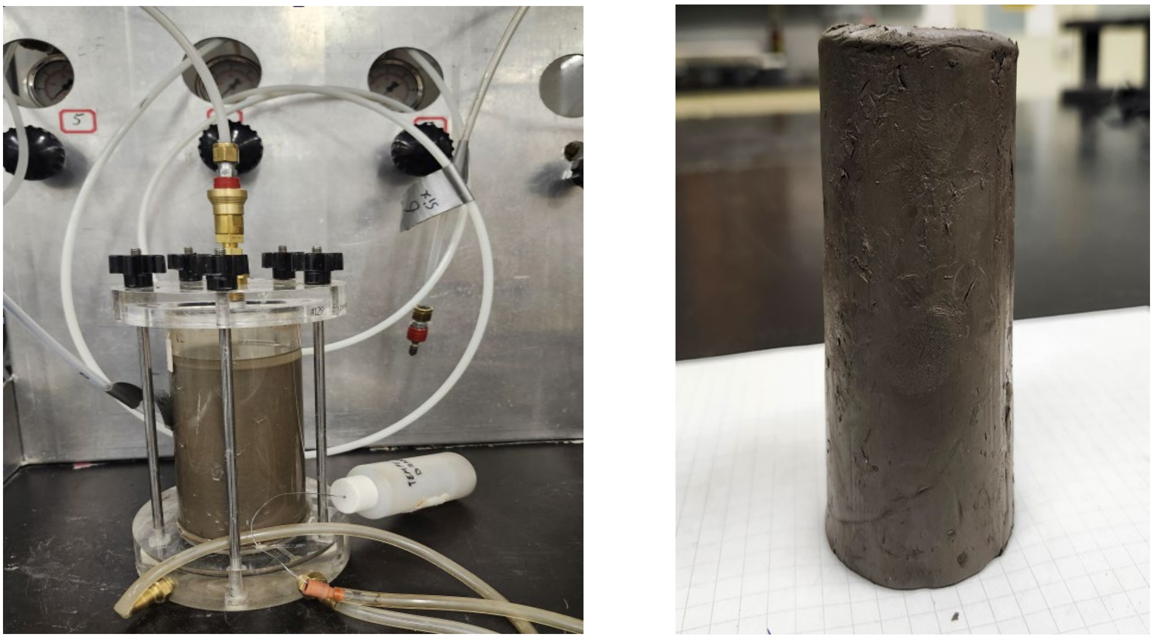
However, in both papers, the value of the LSC tests are lower than those of DD-SS and CU-TR (v). The effective stress graphs of the centrifuged MFT move to the left and those of the TT move to the right, indicating that the centrifuged MFT is contractive and the TT is dilative soils. The soils with dilative behaviour are less susceptible to liquefaction than soils with contractive behaviour.

2 Methodology

The following section presents 3 methods used in the determination of the consolidation properties and shear strength parameters. For more details about the apparatus and methodology, please refer to Kabwe et al. (2025).

2.1 Specimen preparation

The specimens were reconstituted using the Tempe cell with a high entry value porous stone of 500 kPa at the bottom (Figure 1a). The slurry sample was poured into the Tempe cell and then consolidated to a vertical pressure of 40 kPa to produce the specimen for the CU-TR and CD-DS tests (Figure 1b). As water was removed from the sample, the changes in the mass of the Tempe cell were monitored until it reached a steady-state condition (constant weight). The specimen was then extruded from the Tempe cell and trimmed to the desired height and diameter to fit in the DS and TR apparatus.



(a) (b)

Figure 1 (a) Sample preparation in a Tempe cell; (b) Specimen extruded from the Tempe cell

2.2 Large strain consolidation with shear strength test

Large strain consolidation with shear strength (LSC-SS) was performed using the University of Alberta's system (Kabwe et al. 2022). The slurry sample is confined in a consolidation cell (15 cm in diameter × 15.5 cm in height). The bottom of the cell is sealed, so drainage during consolidation is only upward. A piston load of less than 1 kPa is applied as the first load step. After this, loads are applied by using dead loads and then by an air pressure Bellofram super cylinder model ss-36-f-bp-6 8-6.0. The load increments are doubled for each load step until the maximum vertical stress is reached (about 500 kPa). During consolidation, the sample's height change is continuously monitored with a linear variable differential transducer. When no further change in height is observed at each load step, it is assumed that consolidation is complete for that load step. At this stage, the excess pore pressure is also monitored at the base of the sample to ensure that the excess pore pressure is fully dissipated. The hydraulic conductivity is measured at the end of consolidation for each load step (Wilson et al. 2018; Jeeravipoolvarn 2010). Following the hydraulic conductivity measurement, the sample surface is exposed, and the shear strength is measured using a Brookfield DV3T Rheometer for low strength (up to 6 kPa) and motorised geotechnical vane shear apparatus for testing stiffer consistencies per ASTM International (2024) for shear strengths higher than 6 kPa. The Brookfield Rheometer tests were performed using 2 types of spindles number 73 and 74 and using the rotation speed of 1 RPM. The motorised vane shear tests were performed using 2 types of vane sizes of diameter and length of (12 × 12 mm and 25 × 25 mm) using the same set rotation speed of 75°/min. A subsequent load is then applied after the shear strength measurement. Consolidation of oil sand fine tailings takes considerable time due to the material's low permeability. For example, with 10 load steps used in the LSC, it can take anywhere from 4–9 months to complete the consolidation test (Amoako et al. 2020; Abdulnabi et al. 2021).

The LSC-SS is a specialised method used in geotechnical engineering to analyse the settlement and consolidation behaviour of soft, saturated, high-water-content materials, such as mine tailings, soft clay, or dredged sediments. Unlike conventional small-strain (Terzaghi) theory, which assumes constant material properties and negligible changes in geometry, LSC accounts for large, nonlinear changes in void ratio, permeability, and sample thickness.

2.3 Consolidated-drained direct shear test

The consolidated-drained direct shear (D-DS) test was performed to determine peak strength parameters of the TT sample under fully drained conditions using the DS apparatus (model: 2001D Load Frame HM-5620). Before shearing, the sample was consolidated under Ko conditions under various vertical pressures ranging from 10–200 kPa. The sample was then sheared slow enough to allow complete dissipation of the pore pressure generated during shear, using the criteria presented in ASTM International (2011b).

The CD-DS test is widely used in geotechnical engineering due to its simplicity, speed, and cost-effectiveness compared to more advanced methods like the LSC and TR tests. It is primarily used to determine the cohesion and angle of internal friction of soil by forcing a sample to fail along a predetermined horizontal plane. The test is generally quick to perform, especially for drained tests on coarse-grained soils (sand/gravel), making it ideal for routine, urgent, or preliminary assessments. Due to the small thickness of the specimen, consolidation occurs rapidly. This rapid dissipation of excess porewater pressure allows for faster completion of consolidated-drained (CD) and consolidated-undrained (CU) tests compared to triaxial tests. Sample preparation is relatively straightforward. It is easy to perform, requiring minimal training.

2.4 Consolidated and undrained triaxial (CU-TR) test

The TR tests were performed using the apparatus system HM-5020, HUMBOLDT. The tests were conducted under consolidated and undrained conditions (CU-TR) on the TT to determine the shear strength parameters according to ASTM International (2011a). The CU-TR testing procedure involved back-pressure saturation and consolidation to an all-around pressure before shearing. The sample was slowly sheared at a speed of 2 mm/s to allow equilibration of the pore pressures (Head 1986). At the end of shearing, the sample was removed from the triaxial cell and the final solids content was measured by oven-drying. A test series was conducted at different cell pressures of 440, 490, and 590 kPa. The TR test is a widely used, versatile geotechnical method that offers precise control over stress conditions (axial and confining), allows measurement of porewater pressure, and permits consolidation stages, providing comprehensive strength parameters. Its primary disadvantages include high cost, complex and time-consuming procedures, potential for non-uniform stress distribution, and requiring specialised expertise for operation.

3 Data

3.1 Index properties

The material used, as received, in this study was TT sourced from an oil sands mining site in Northern Canada.

3.1.1 Particle size distributions

Figure 2 shows the TT particle size distribution measured by sieve analysis and dispersed hydrometer by Paul (2024). Figure 2 shows that the sample had a solids (SC) and sand contents of 44.9 and 60.7%, respectively. The fine content determined by dispersed hydrometer was 39.3% with a sand fine ratio (SFR) of 1.5. In oil sands mining, the fine content is defined as the material passing 40 µm. The clay size (i.e. that below 2 µm) determined by dispersed hydrometer was 5%.

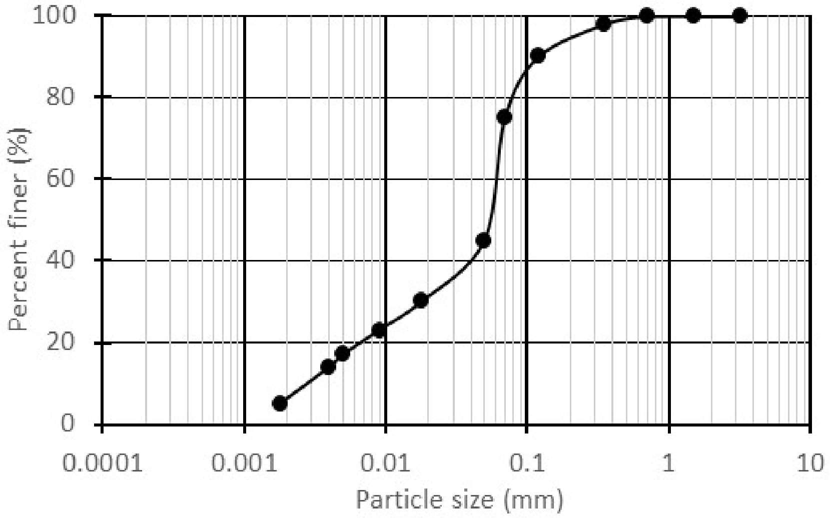


Figure 2 Particle size distribution of the thickened tailings sample

3.1.2 Soil–water characteristic curve

Figure 3 shows the soil–water characteristic curve of the TT measured using a Tempe cell. The solid marks represent the measured data, and the solid curve represents the best-fit line (generated using the Fredlund & Xing [1994] method). The air entry value (AEV) and residual water content of the TT sample were determined graphically and were found to be about 7.5 kPa and 10%, respectively. The AEV value was characteristic of fine sand. The amount of sand added to the TT tailings had the effect of reducing the AEV.

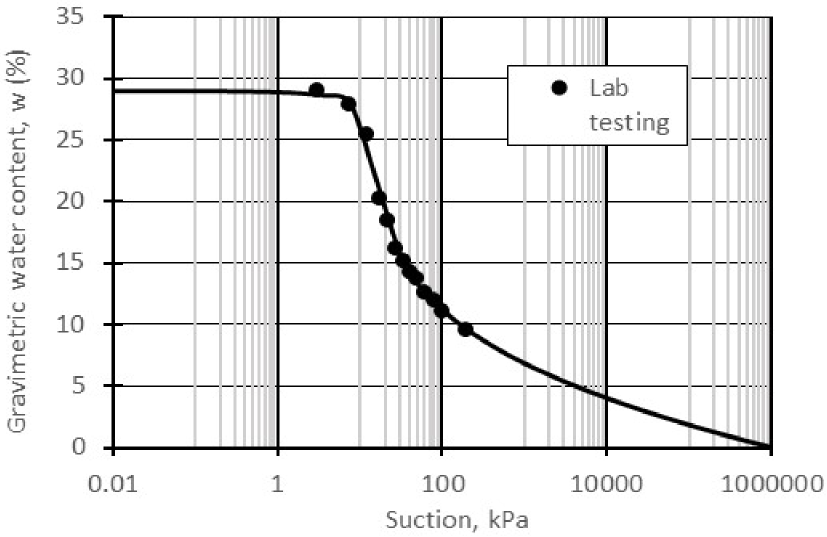


Figure 3 Soil–water characteristic curve of the thickened tailings sample

3.2 Geotechnical properties

The geotechnical properties of Atterberg limits are presented in Figure 4. The TT sample had a liquid limit (LL) and plastic limit of 42.7 and 14.9%, respectively, with a plasticity index of 27.8. The TT sample tested would be classified as medium-plasticity clay. The bitumen content was 1.29%.

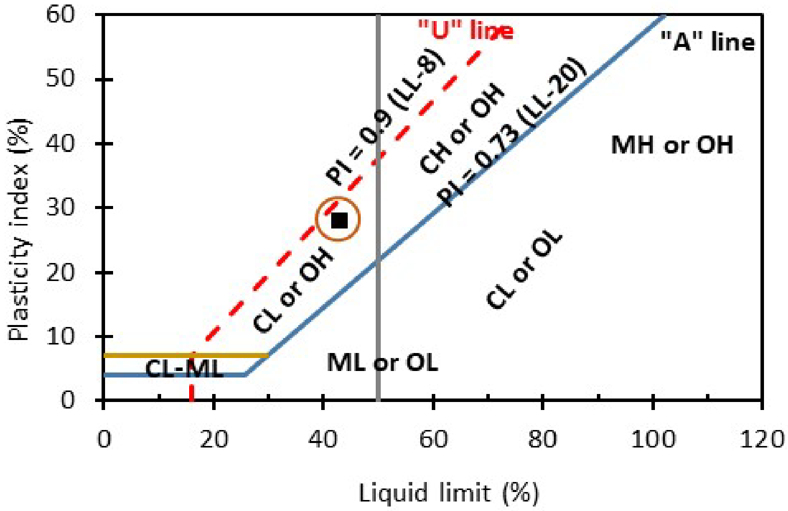


Figure 4 Plasticity chart of the thickened tailings sample

4 Results and discussion

4.1 Large strain consolidation with shear strength

4.1.1 Consolidation properties

The 2 consolidation properties measured on the TT sample, included compressibility and hydraulic conductivity as shown in Figures 5 and 6, respectively. Figure 5 showed that the TT material was more compressible at low effective stresses below 40 kPa. The compressibility became negligible at higher effective stresses. As the effective stress was increased from 0.2 to 40 kPa, the void ratio decreased from 1.3 to 0.9. The compression index C_C was 0.04. This low compressibility is characteristic of sand. The compressibility of sand is low because it is a coarse-grained, cohesionless material with high stiffness and strength, allowing it to resist volume changes under pressure.

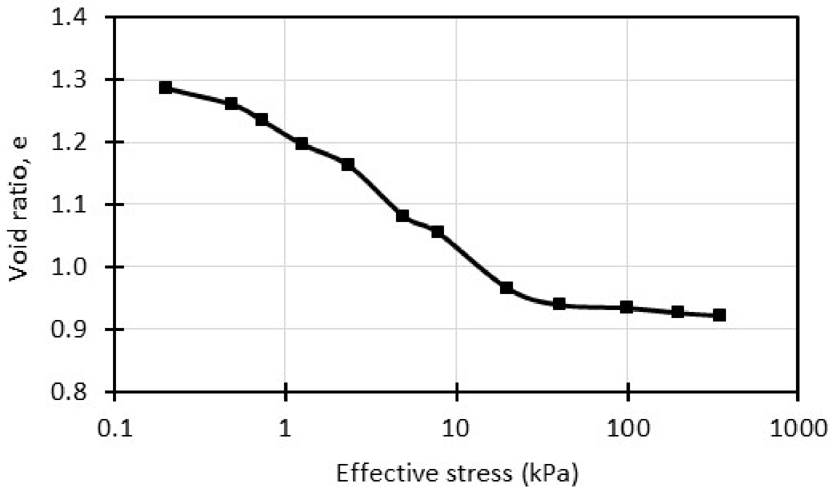


Figure 5 Compressibility curve of the thickened tailings sample

Figure 6 shows the hydraulic conductivity K of the TT measured at the end of each step-load of the LSC-SS test, with a power function fitted to the data. The values of K slowly decreased with decreasing void ratio, and dropped by about one order of magnitude (i.e. from 10^{-8} to 10^{-9} m/s) when the void ratio decreased from 1.3 to 0.9. The range of K measured for the TT was characteristic of silty sand.

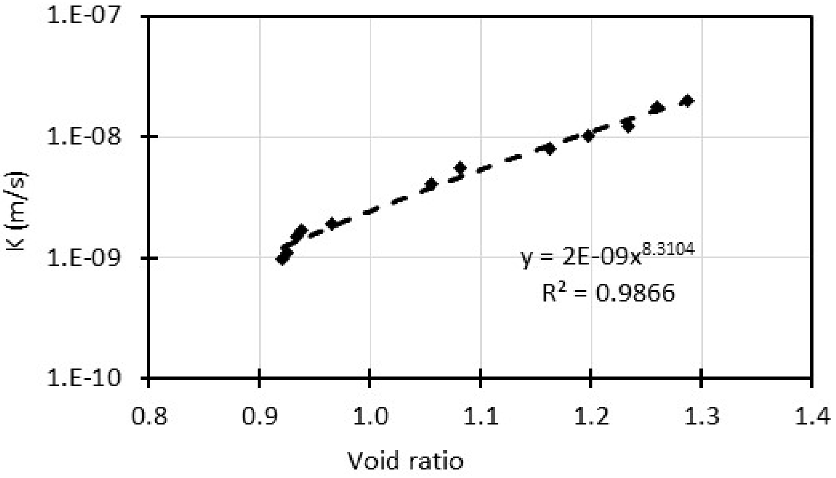


Figure 6 Hydraulic conductivity curve of thickened tailings sample

4.1.2 Shear strength

Figure 7 presents the relationship between the shear strength τ and the normal effective stress σ' obtained using the LSC-SS test. The shear strength was measured using the rheometer for low shear strengths up to 5 kPa and the vane shear device (ASTM International 2019) for higher shear strengths. The shear strength plot exhibited the characteristics of dense sand with a peak τ_f of about 35 kPa and ultimate shear strength τ_{ult} of about 23 kPa.

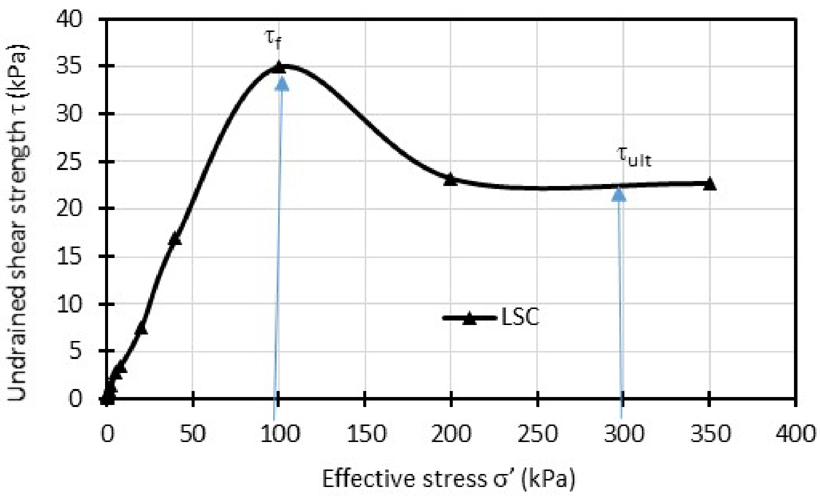


Figure 7 Large strain consolidation (LSC) with shear strength's shear strength as a function of effective stress of thickened tailings

The early linear portion of the curve up to the peak shear strength τ_f was plotted in Figure 8. The equation of the failure envelope is presented in Equation 3.

$$\tau = 0.3617 \times \sigma', \text{ with } R^2 = 0.9917 \tag{3}$$

where:

τ = shear strength

σ' = effective stress.

In fitting the line of best fit to the data, the value of the intercept (c) was fixed to zero. Since the sample tested was normally consolidated, the shear strength interpretation assumed that the effective stress cohesion intercept was zero. The slope of Equation 3 was used to determine ϕ' as 19.8°.

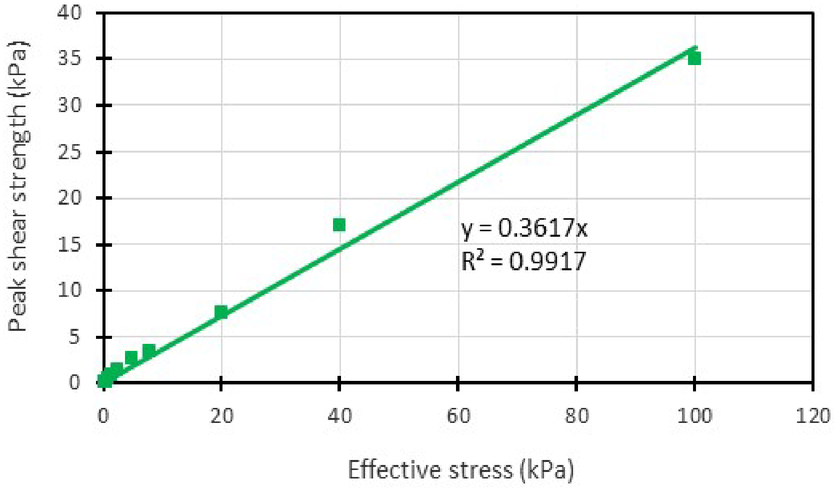


Figure 8 Large strain consolidation's failure envelope of thickened tailings

4.2 Consolidation-drained direct shear

The results from the CD-DS tests performed on normally consolidated TT sample are presented in Figures 9, 10, and 11. Figure 9 shows the variation of shear stress with displacement for different normal stress conditions extending from 10–200 kPa.

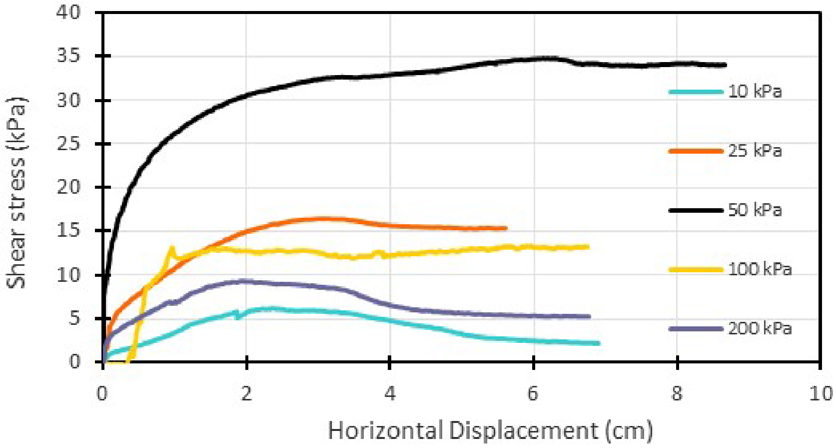


Figure 9 Shear stress with displacement for different normal stress conditions obtained with consolidated-drained direct shear of the thickened tailings sample

In this figure, the resisting shear stress increased with shear displacement until a failure shear stress τ_f is reached. After failure stress is attained, the resisting shear stress gradually decreases as shear displacement increased until it finally reached an ultimate shear strength τ_{ult}. The tests for similar specimen were repeated at various values of normal applied forces (10–200 kPa), so the normal stresses (σ_n) and corresponding values of failure shear resistance (τ_f) were plotted in Figure 10. This plot exhibited the characteristics of dense sand with a peak shear strength τ_f of 35 kPa and ultimate shear strengthen τ_{ult} of about 10 kPa.

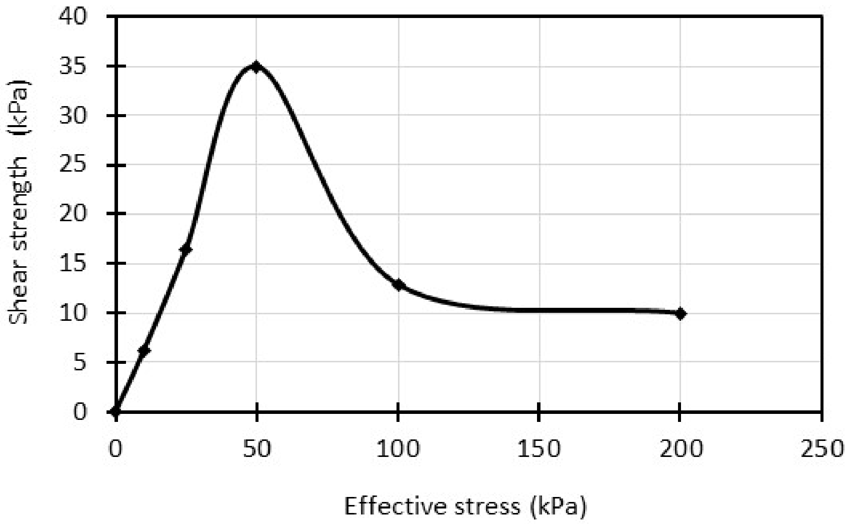


Figure 10 Consolidation-drained direct shear's shear strength function of thickened tailings

The early linear portion of the plot up to the τ_f in Figure 10 was plotted in Figure 11 and yielded the following equation:

$$\tau = 0.6898 \times \sigma', \text{ with } R^2 = 0.9981 \quad (4)$$

The effective friction angle ϕ' was determined using the slope of this equation 4 and was found to be 34.6°.

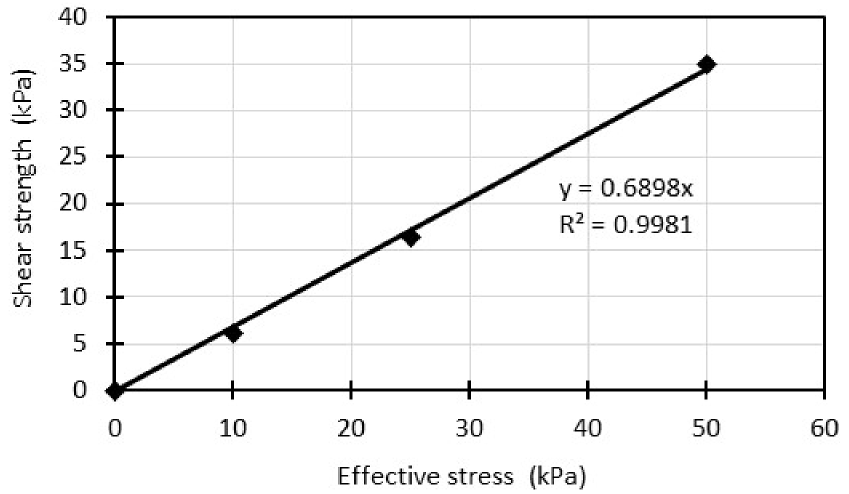


Figure 11 Consolidated-drained direct shear's failure envelope of thickened tailings

4.3 Consolidated-undrained triaxial

The results from the CU-TR test performed on the reconstituted consolidated TT sample are presented in Figures 12 and 13 – the former showing Mohr circles and the latter the failure envelope of the TT. It should be noted that the Mohr circles for dense sand will generally be 'larger' as shown in Figure 12. The resulting Mohr–Coulomb failure envelope will have a steeper slope (higher φ), indicating a stronger material.

The shear strength failure envelope in Figure 12 for TT is given in equation 5.

$$\tau = 0.7164 \times \sigma', \text{ with } R^2 = 0.9516 \quad (5)$$

The value of ϕ' was determined using the slope of Equation 5 to be 35.4°.

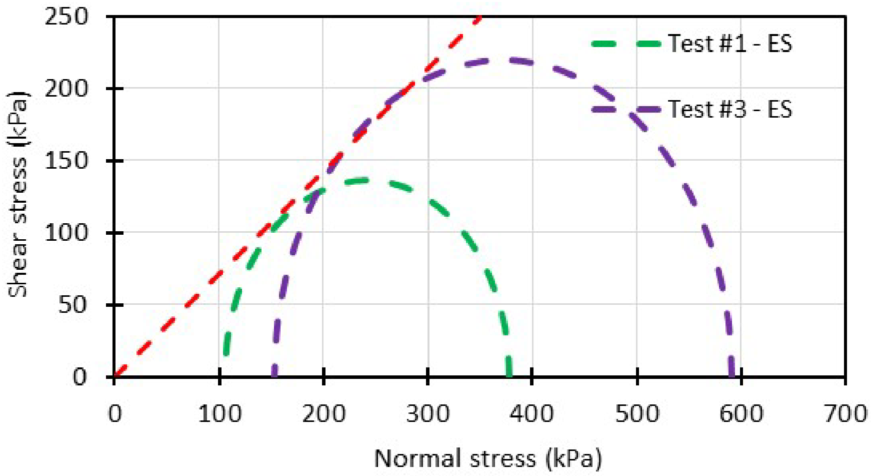


Figure 12 Mohr circles with effective stress failure envelope from consolidated-undrained triaxial test on thickened tailings

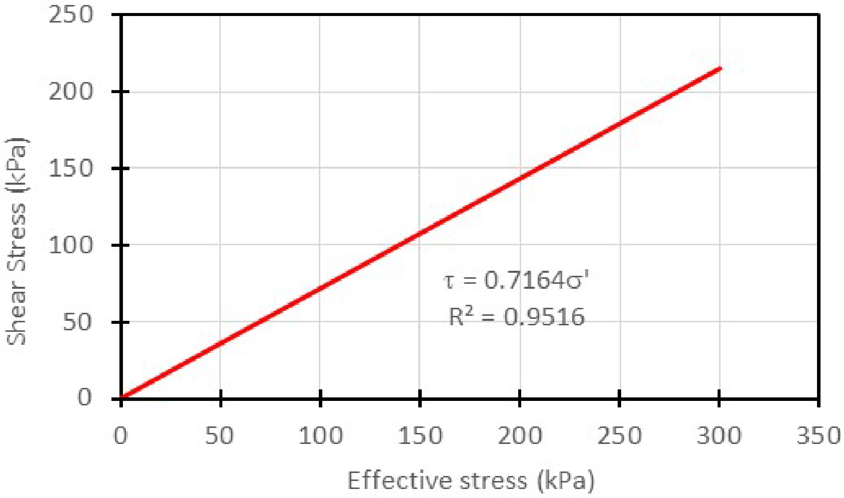


Figure 13 Undrained TR's effective stress failure envelope of thickened tailings

Figure 14 shows the TT's effective and total stress paths plotted as deviator stress q (kPa) versus mean stress p (kPa) to describe the TT's behaviour. In this graph, the effective stress moved to the right, as expected for dilative soils. The tendency of a compacted dense granular material is to dilate (expand in volume) as it is sheared. This occurred because the grains in a compacted state are interlocking and therefore do not have the freedom to move around one another. The TT tested with dilative behaviour is less susceptible to liquefaction than soils with contractive behaviour.

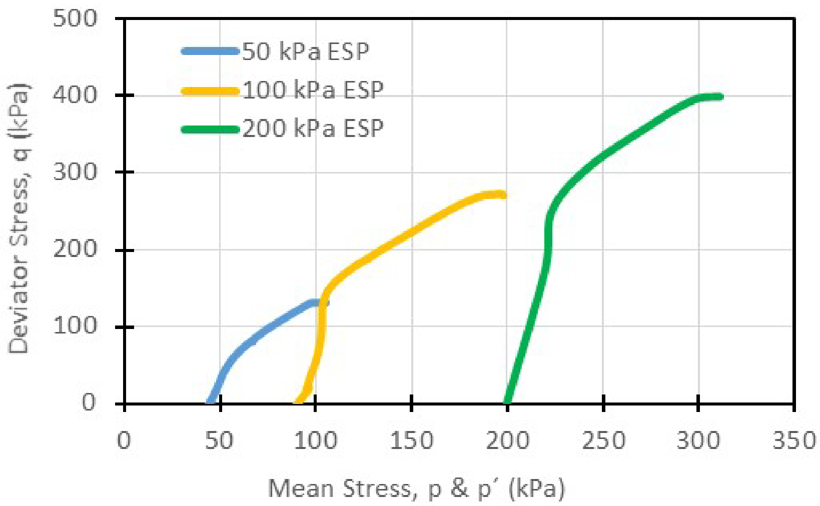


Figure 14 Undrained TR's effective stress paths obtained at 50, 100, and 200 effective pressures of thickened tailings

4.4 Comparison of shear strength parameters from different tests

Table 1 and Figures 15 and 16 compare the values of shear strength parameters obtained using the 3 techniques discussed above: LSC-SS, CD-DS, and CU-TR. The TT specimens tested were normally consolidated; hence, the effective stress cohesion intercept is zero (as noted in column 2 of Table 1). The 3 techniques provided values of ϕ' of 19.8, 34.6 and 35.4° for LSC-SS, CD-DS, and CU-TR, respectively. Based on these values ϕ', the tested TT sample was classified as dense sand. The CD-DS and LSC-SS techniques exhibited similar peak strength τ_f of 35 kPa with their corresponding ultimate shear strengthens τ_{ult} of 22.7 and 10 kPa for the LSC and CD-DS, respectively. The results show no significant differences in ϕ' obtained between the CD-DS and CU-TR techniques. Remoulding soil destroys any previous layering or structure that might have been present, and the resulting samples are more or less homogenous (Castellanos & Brandon 2013; Maccarini 1993).

Table 1 Summary of shear strength parameters

Test ID	Effective cohesion (c') (kPa)	Effective friction angle (ϕ') (degrees)
LSC-SS	0	19.8
CD-DS	0	34.6
CU-TR	0	35.4

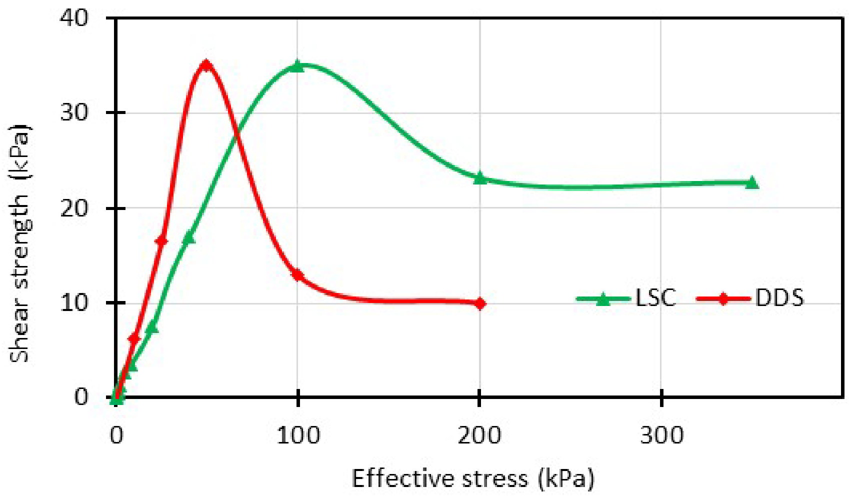


Figure 15 Shear strength functions obtained with large strain consolidation with shear strength and consolidated-drained direct shear of thickened tailings

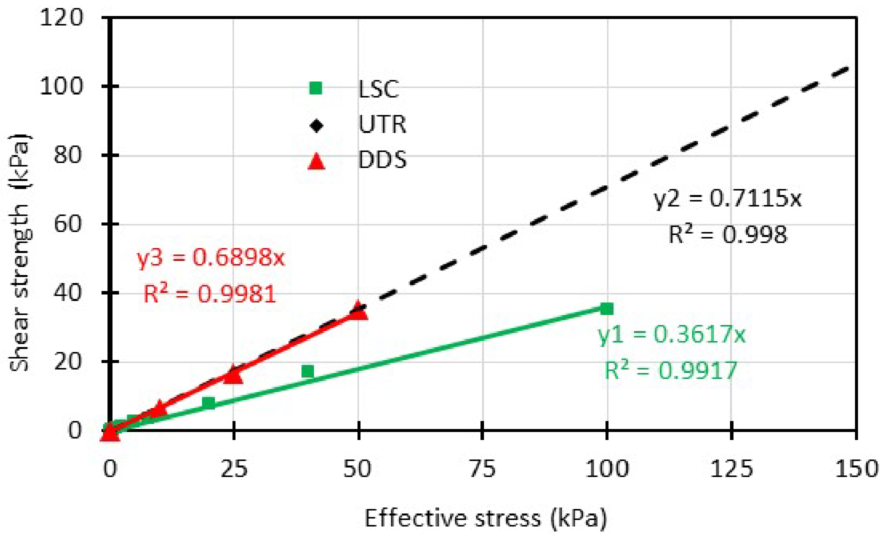


Figure 16 Effective failure envelopes obtained with large strain consolidation with shear strength, consolidated-drained direct shear and consolidated-undrained triaxial tests on thickened tailings

The LSC-SS technique produced a lower value of ϕ' (19.8°) than the 2 other techniques (CD-DS and CU-TR) techniques. The difference is due to the specimen preparations and the use of the vane shear device in the LSC-SS test, which destroyed the fabric and decreased its ϕ' value (Castellanos & Brandon 2013; Casagrande 1964). However, various factors, including the rotation rate (Sharifounnasab & Ullrich 1985; Peuchen & Mayne 2007), vane insertion disturbances, and vane shape (Chandler 1988) can affect the test results. The vane test is designed for soft and saturated clay and generally produces lower shear strength and consequently lower friction angles (or apparent friction angles) compared to CD-DS and CU-TR primarily because they measure the undrained strength of soft, cohesive soils, whereas CD-DS tests – particularly when performed on sand or as consolidated-drained tests – are influenced by effective stress and frictional resistance. The peak and residual effective internal friction angles are sensitive to the shear rate. At lower shear rates (below 0.25 s^{-1}), the peak friction angle remains relatively stable, but as the shear rate increases, the peak effective internal friction angle decreases – particularly in materials like sand-foam mixtures (Meng & Laue 2024; Sharifounnasab & Ullrich 1985).

In summary, the angle of internal friction ϕ', cohesion c', and shear strength τ are foundational parameters in geotechnical engineering used to determine if soil or rock can withstand structural loads without failing.

They are primarily used in the Mohr–Coulomb failure criterion ($\tau = c' + \sigma' \tan \phi'$) to calculate the safety factor (ratio of resisting forces to driving forces) for dams, foundations, and excavations. The stability of dams depends heavily on the shear strength of materials to prevent sliding, slope failure, or piping (Skempton 1964). ϕ' and c' are used in limit equilibrium methods (e.g. Bishop or Spencer) to analyse upstream/downstream slope stability. In rockfill dams, ϕ' is the most critical parameter; higher ϕ' values significantly increase the safety factor. The shear strength helps evaluate if the soil can resist internal erosion and piping. The ability of soil to support structures (buildings, dams, machinery) without excessive settlement or collapse is determined by its shear strength. c' and ϕ' are used in Terzaghi's or Meyerhof's bearing capacity equations to determine the maximum pressure a soil can support. For granular soils (sand), high ϕ' indicates higher stability. For cohesive soils (clay), c' (or undrained strength cu) is critical.

5 Conclusion

Three different techniques (LSC-SS, CD-DS, and CU-TR) were used to evaluate the consolidation properties and the shear strength parameters on reconstituted and slurry TT samples. The TT sample tested had a high sand content of 61% and SFR of about 1.5 and behaved as a dense sand. The CD-DS and LSC techniques exhibited similar peak strength τ_f of 35 kPa. The compressibility curve yielded a low compression index C_C of 0.04, characteristic of sand. The hydraulic conductivity of the TT exhibited the clayed sand characteristics and remained high in the range of 10^{-8} m/s at low void ratio of 0.9. The 3 techniques provide values of ϕ' of 19.8, 34.6 and 35.4° for LSC, CD-DS, and CU-TR, respectively. Based on these values ϕ', the tested TT was classified as dense sand. The results show that no significant differences in ϕ' obtained between the CD-DS and CU-TR techniques. The LSC technique produced a lower value of ϕ' (19.8°) than the 2 other techniques (CD-DS and CU-TR). The difference was due to the specimen preparations and the use of the vane shear device in the LSC-SS test, which destroyed the fabric and decreased its ϕ' value. The reconstituted and consolidated TT sample had low effective cohesion (c') value of about zero. The stress path of the TT indicated that the effective stress moved to the right, as expected for dilative material. The TT tailings tested with dilative behaviour is less susceptible to liquefaction than soils with contractive behaviour.

Although these 3 different techniques can provide similar shear strength parameter results, they have marked differences in complexity and cost. The CD-DS is the simplest and cheapest technique, whereas the LSC-SS and CU-TR techniques are expensive, difficult to run, and time-consuming. While the direct shear test offers significant advantages in speed and simplicity, it does not allow for measuring porewater pressure and forces a specific, often unrealistic, horizontal failure plane, which may lead to slightly higher shear strength results compared to triaxial tests. The results of the shear strength parameters for the oil sands TT sample tested are crucial in the design and management of oil sands tailings dams.

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