Desiccaton and consolidation modelling of oil sands fine tailings deposits

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ABSTRACT
Oil sands tailings deposition is regulated by enforcing reduction of the volume of fluid fine tailings over the life of an operation. Operators are meeting these targets by improving dewatering characteristics of fine tailings through various techniques, often involving addition of polymer or other flocculation-inducing treatment. However, the assessment of the strength performance of these technologies is typically quantified using a field vane. Element testing, while challenging for mature fine tailings, does give a richer description of strength behaviour. We compare shear behaviour of samples consolidated and sheared in simple shear and in triaxial element tests, and compare these findings to available field data on in-line flocculated mature fine tailings. Both un-amended and amended tailings behave as a structured soil, showing very high shear strength to effective stress ratios. Shear strength values as a function of density show values comparable in trend but lower than shear strength measured by field vane at some field trials.

RÉSUMÉ
Le dépôt des résidus de sables bitumineux est régi par l'application de la réduction du volume des résidus fins fluides sur la durée d'une opération. Les opérateurs répondent à ces objectifs en améliorant les caractéristiques de déshydratation de résidus fins grâce à diverses techniques, impliquant plus de polymère ou un autre traitement de floculation. Toutefois, l'évaluation de la performance de la résistance de ces technologies est généralement faite en utilisant un scissomètre de chantier. Le test, bien que plus difficile avec les résidus fins mûrs, donne une description plus riche du comportement de la force. Nous comparons le comportement en cisaillement d'échantillons consolidés et cisaillés, en cisaillement simple et dans les tests d'éléments triaxiaux, et comparons ces résultats aux données de terrain disponibles sur les résidus floculés, fins et mûrs. Les résidus amendés et non-amendés se comportent comme un sol structuré, montrant une force de cisaillement très élevée à des rapports de contrainte effective. Les valeurs de résistance au cisaillement en fonction de la densité montrent des valeurs comparables à la tendance mais inférieures à la résistance au cisaillement mesurée par le scissomètre de chantier à quelques essais de terrain.

1 INTRODUCTION

In oil sands surface mining, the tailings that come directly from the extraction plant consist of water, a combination of coarse (sand) and fine particles (silt and clay) as well as small portion of residual bitumen. The solid content (mass of solids / total mass) of these whole tailings after extraction varies in the range of 45-55%. In the conventional deposition technique the whole tailings are pumped to a dammed tailings disposal site. During or relatively soon after deposition, the coarser particles (sands) segregate out to form beaches, while the fine particles and bitumen accumulate to form a floating layer called fluid fine tailings, which has a very low solid content of about 8%. Over several years, fluid fine tailings undergoes hindered settlement and the excess water drains in order to create Mature Fine Tailings (MFT), which typically has solid contents between 35% and 38 %, corresponding to gravimetric water contents between 200% and 180%. MFT does not appreciably dewater past this point, even in very deep deposits. This is due to low hydraulic conductivity generated by the high dispersion of clay particles generated during bitumen extraction process, and also due to the thixotropci buildup of network structure that impedes consolidation – the latter effect has been demonstrated in a 30 year study on a 10 m column of MFT described by Scott et al. (2013). MFT at 35% solids content do not possess any substantial strength, and therefore the tailings are now stored in impoundments with substantial footprint, that cannot be reclaimed. Regulations are therefore recently implemented (Directive 074, as well as recent regulatory modifications as of March 2015) that require oil sand operators to improve shear strength of deposited tailings to be at least 5kPa to be no long considered fluid fine tailings, and to be considered as on the road to trafficability and therefore closure.

To improve rates of tailings dewatering, several technologies have been developed by the industry that use a polymer to facilitate clay particle flocculation, which improves rates of sedimentation and consolidation. Such technologies include centrifugation, in-line flocculation, thickening, and recombining fine tailings with sand tailings. However, most of the tracking of strength behaviour of polymer amended fine tailings has been using total stress techniques, and indeed mostly measuring undrained strength using as field vane.

This paper analyzes shear strength behaviour of both polymer amended MFT (henceforth called amended MFT) and unamended (Raw) MFT using element tests (simple shear and triaxial), the first such attempt in the public domain to the authors' knowledge.

2 SAMPLE PREPARATION AND TESTING

METHODOLOGY

In order to document the consolidation behaviour as well as shearing characteristics of amended MFT and raw MFT, a laboratory investigation was developed. Raw MFT with solid content of 35.5% was amended by adding high molecular weight anionic polymer, using a mixing protocol developed by Mizani et al. (2013), which simulated mixing energies and duration typical of some field application of in-line flocculation. Flocculated MFT were prepared at different dosages of 600 gr/T, 700 gr/T, 800 gr/T, 900 gr/T, and 1000 g/T. According to tracking of water release in 0.5 m high column tests (Mizani et al. 2013), 700 gr/T was found to be the optimum over a two week period.

The key challenge to perform the element tests was to facilitate sufficient strength development to enable transfer of specimens to the element tests without collapse. To do this, two methods were applied to generate amended MFT samples. Samples were initially prepared in 25 cm deep 7 cm diameter cylindrical molds. After addition of the polymer, these samples typically increase to about 50-55 % solids (100-90% GWC) after about 10 days, which is still about their LL (generally between 80-90% GWC for sample dose at the optimal polymer concentration – see Bajwa and Simms 2013). At this point, the tailings cannot be transferred to either element test.

Preparation Method A

One option was to weight another three months, during which time samples would dewater to ~60 % solids (64-67% GWC) and gain strength to the point that they could stand on top of the bottom platen in a triaxial test. These samples were in sealed plastic containers, with the exception of a small hole at the bottom (5 mm diameter). Pore-water pressure in some tests was measured using a miniature transducer inserted in the side. Interestingly, pore-water pressures were stable after two-three weeks, despite subsequent volume change and dewatering, implying substantial volume change due to secondary compression or other thixotropic mechanism.

Preparation Method B

Though samples prepared by the previous method were sufficiently strong, there was a substantial gradient in GWC with depth, up to 10%. To attempt to improve sample homogeneity some samples were placed in a fine metal mesh, so as to facilitate dewatering by 3-D desiccation under ambient laboratory conditions. This did allow faster preparation of samples (less than a month) to achieve 60% solids. The evaporation rate was effectively so small as to dissipate power-pore pressures in the sample without generating substantial suction at the surface. Such samples were more homogeneous (less than 5% different in water content top to bottom) than samples prepared by Method A, and did not seem to very horizontally (no trend detected) in water content. drainage and 3D desiccation during preparation phase.

Preparation method C

This was only used to generate samples of un-amended (or raw) MFT. MFT cannot achieve a stable water content through consolidation, hence we decided to air-dry MFT to less than its shrinkage limit (~18% GWC), and remould with process water back up it's a variety of water contents. It was found that 70% solids (43% GWC) was the highest water content at which a stable sample could be reconstituted.

2.1 Simple shear test

All samples were subjected to one-dimensional consolidation in a modified oedometer apparatus, in which cylindrical specimens with 70 mm diameter and 40 mm height were facilitated. The samples were consolidated through one-step loading while the load varied between 25 kPa and 100 kPa. Once consolidation completed, the samples removed from oedometer and then carefully placed in an NGI simple shear device. This simple shear device is extensively described in journal papers on other studies by our group (Al-Tarhouni et al. 2011, Daliri et al. 2014).

2.2 Triaxial test

A Shelby tube with 70 mm diameter and 30 mm height was used to get undisturbed samples for triaxial tests. A cylindrical specimen with an approximate 2:1 height to diameter ratio was then gently placed within a rubber membrane in a conventional triaxial cell which was pressurized later within the range of 25 kPa and 100 kPa. Each test contained three phases of saturation, consolidation and shearing. According to ASTM standard (1995), "Specimens shall be considered to be saturated if the value of B is equal to or greater than 0.95, or if B remains unchanged with addition of backpressure increments".

3 LABORATORY TEST RESULTS

Stress-strain relationship, pore water pressure build up during undrained shear tests, stress path and also shear strength vs. void ratio were considered to analyze shear strength characteristic of testing materials in both simple shear and triaxial devices.

3.1 Simple shear

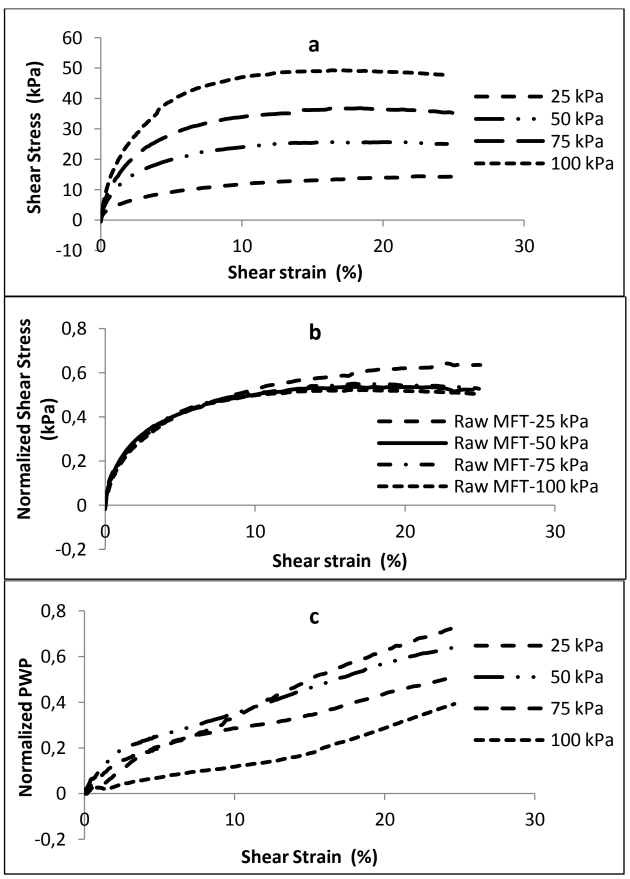
A wide range of strain was considered due to softness of oil sand tailings. Therefore, each shearing test was ceased at 25% strain. Also, a constant rate of strain equal to 20% per hour was chosen in data acquisition system.

The results of shear stress vs. shear strain for raw MFT, amended MFT (Preparation Method A) and desiccated amended MFT (Preparation Method B) are presented in Figure 1 to Figure 3 respectively. Shear behaviour was more or less identical when shear stress was normalized with initial vertical effective stress. Also, all tests reached steady values of shear stress, though all samples all exhibited contractive behaviour throughout these tests. The only sample that was different was the amended

MFT sample at 100 kPa. This behaviour is very different from shear behaviour on hard rock tailings, which are characterized by strain hardening of even lightly desiccated samples (Al-Tarhouni et al. 2011, Daliri et al. 2014). However, the behaviour of the oil sand tailings are similar to the behaviour of soft clays under simple shear, which report similar stress paths (Bro et al 2013). The stress paths also resembles that of structured soils, though apparently more closer to structured residual soils than clays (Lerouil and Vaughan 1985).

The magnitude of the peak shear stress ratios (0.5 to 0.6) is quite large, and this may be due to the development of structure due to secondary compression. Recent work on overconsolidated Leda clay shows similarly high stress ratios (0.54, Theenathayrl 2015).

In terms of effective stress, the difference between the amended and raw MFT samples is relatively minor. The amended MFT samples are slightly stiffer and stronger at a given consolidation pressure but not significant in terms of engineering behaviour. The raw MFT appears to soften slightly a strain larger than 15%. The difference in undrained strength in terms of void ratio, is, however, significant. As shown in Figure 4, the amended tailings for both preparation methods show similar strength at a given void ratio, but substantially higher shear strength than the raw MFT.



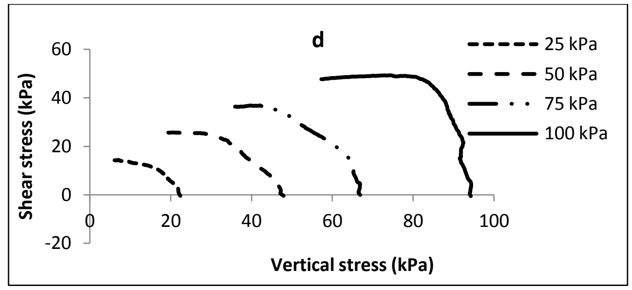


Figure 1.Comparison of Raw MFT behaviour during shearing- a) shear stress vs. shear strain, b) Normalized shear stress vs. shear strain, c) Normalized pore water pressure, d) stress path

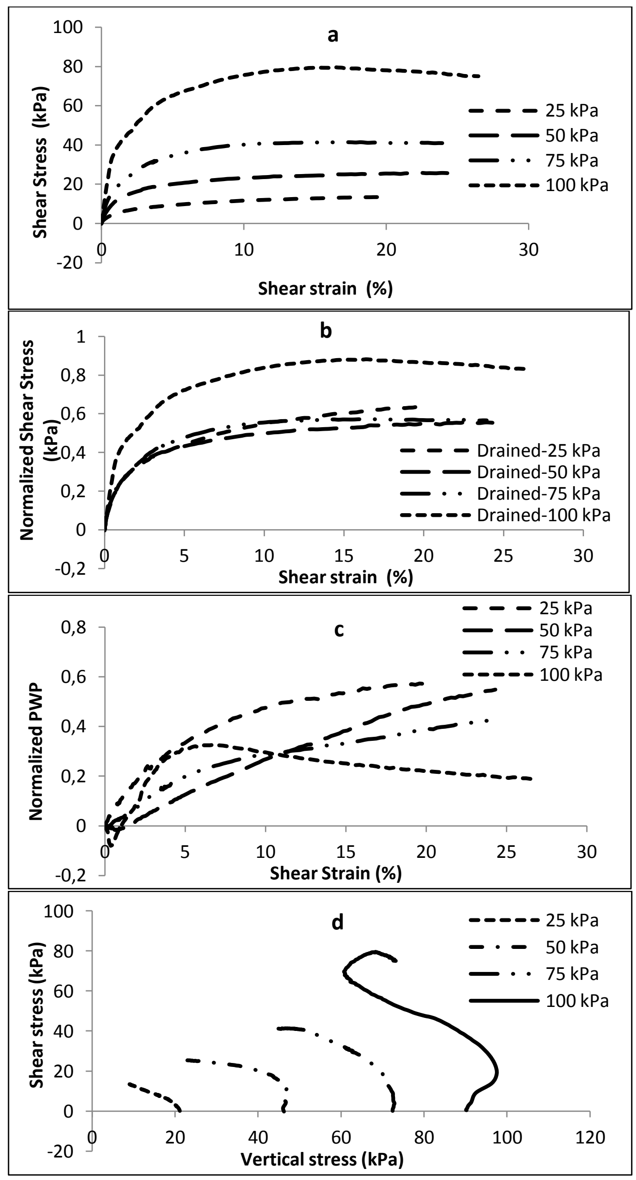


Figure 2.Comparison of consolidated amended MFT behaviour during shearing- a) shear stress vs. shear strain, b) Normalized shear stress vs. shear strain, c) Normalized pore water pressure, d) stress path

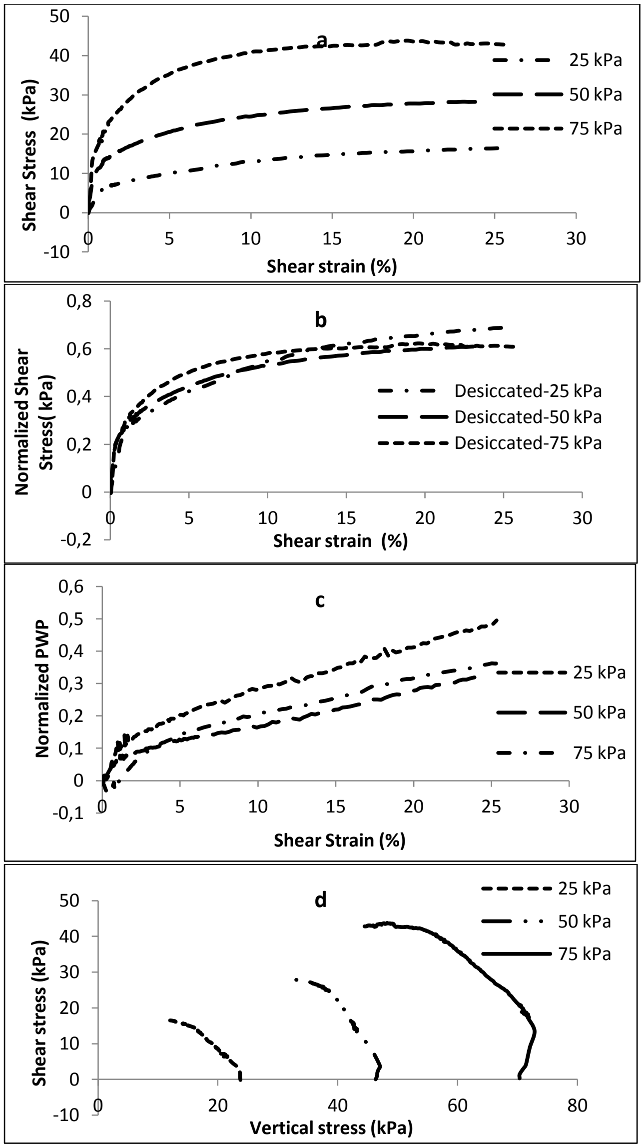


Figure 3.Comparison of desiccated amended MFT behaviour during shearing- a) shear stress vs. shear strain, b) Normalized shear stress vs. shear strain, c) Normalized pore water pressure, d) stress path

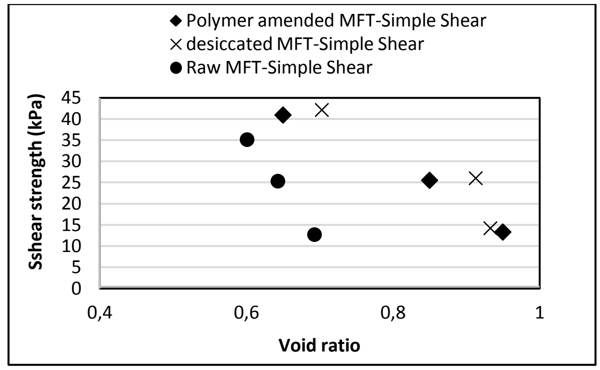


Figure 4. Shear strength-void ratio relationship in simple shear

3.2 Triaxial

Consolidated Undrained (CU) triaxial compression test was conducted on polymer amended MFT to investigate the shearing behaviour. All samples had 135 mm height and 70 mm diameter before starting the test. After saturation and consolidation phases, shear deviator stress was applied to the specimen. The shearing speed was set at 1 mm/min by controlling the axial deformation rate. The shear test was terminated once the axial strain reached 15%.

The triaxial results, shown in Figures 5 and 6, were similar to the simple shear tests in that the pore-pressure response was contractive, and that the shear stress seemed to be approaching a constant value towards the end of the tests. However, the peak shear stress normalized with initial consolidation pressure was much lower (0.15 to 0.2 compared to 0.55 to 0.6) in triaxial than in simple shear. Similarly, shear strength at a given void ratio (Figure 7) was about half the value reported in simple shear tests (Figure 4).

This is an unusual result. In many other soils, simple shear reports a lower shear strength than for the same sample in triaxial compression (e.g. Vaid and Sivathayalan 1996). The triaxial tests, however, did exhibit variation in density with depth, even after consolidation, up to 5% change in GWC for samples with an average GWC of 50%. By contrast, the simple shear samples were obtained from the bottom of the preparation molds, and were much more uniform in water content (< 1% difference in GWC).

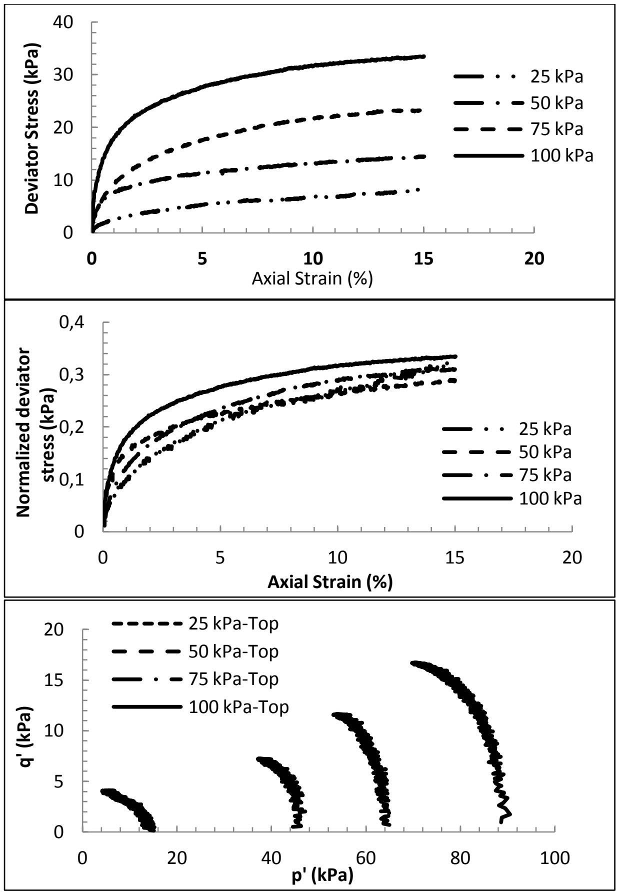
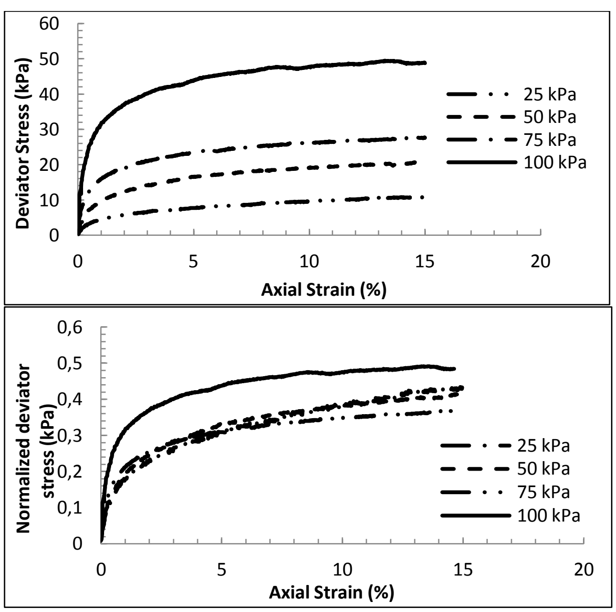
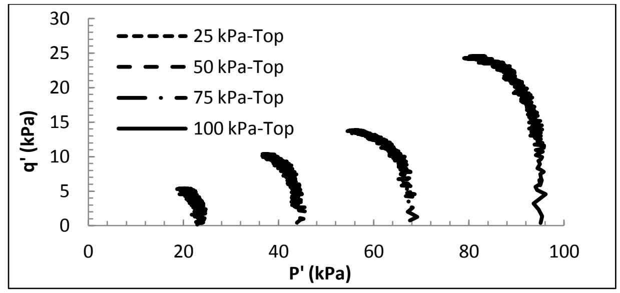


Figure 5.Comparison of consolidated amended MFT behaviour during shearing a) Deviator stress vs. strain, b) Normalized stress, c) Stress path





*F*igure *6*.Comparison of desiccated amended MFT behaviour during shearing a) Deviator stress vs. strain, b) Normalized stress, c) Stress path

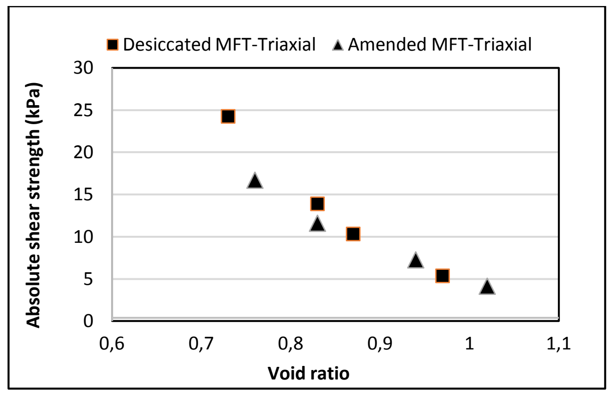


Figure 7. Shear strength-void ratio in triaxial

4 COMPARISON OF LABORATORY AND FIELD RESULTS

Beier et al. (2013) analyzed shear strength behaviour of oil sand fine tailings using undrained shear strength field data from vane shear tests. These authors showed that polymer amended MFT might exhibit characteristics of sensitive, metastable deposits, even if regulatory strength requirements are met. In fact, considerable differences are reported between in peak and residual shear strength values for polymer amended tailings. Nonetheless, results of the current study show that polymer amended MFT /approaching a steady value of shear strength in simple shear and triaxial, and show no evidence of strain softening behaviour. Indeed, only the raw MFT shows some slight softening at very high strains (> 15%).

The results of present study is compared with field measurements of vane tests on MFT samples and peak undrained strength measured in polymer amended tailings shown in Beier et al. (2013). The comparison is shown in Figure 8. Interestingly, all the laboratory results plot relatively close to the MFT line rather than the peak polymer amended line. The amended MFT in simple shear lies somewhat above this line, while the raw MFT lies below the line. These differences may have to do with the rate of shearing in the element tests versus the field vane measurements – this issue deserves further investigation.

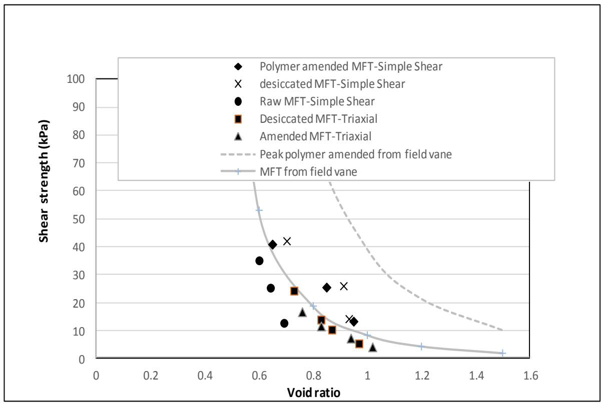


Figure 8 Comparison of element test shear strength to field vane data – lines best fits to data presented in Beier et al. (2013).

5 CONCLUSION

In simple shear, raw MFT, consolidated amended MFT, and desiccated amended MFT samples all reached a constant value of shear stress, despite continuously increasing pore-water pressure. Very high ratios of shear strength to initial vertical effective stress are reported, which are usually associated with structured and / or over-consolidated soils,

Similar to simple shear, the shear strength of amended MFT increased with increasing consolidation pressure in triaxial apparatus. However, amended MFT samples approached a constant value of shear strength rather than reaching a constant shear stress value.

Simple shear showed much stronger response compared to triaxial at a given void ratio. It is suspected that this may be due to less homogeneous samples in the triaxial tests.

Peak shear stress values from the simple shear tests were somewhat lower than reported for similar materials in the field obtained from peak shear strengths measured from field vane tests. This may be due to rate of shearing effects.

ACKNOWLEDGEMENTS

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