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Application of Tempe Cell to Measure Soil Water Characteristic Curve along with Geotechnical Properties of Oil Sands Tailings

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Abstract: The traditional Tempe cell can be used to adequately determine the soil water characteristic curve (SWCC) for soils that do not undergo significant volume change as matric suction is increased, such as coarse-grained material such as sand with a low air entry value (AEV) (<500 kPa). When soils undergo substantial volume change as soil suction increases, such as fine-grained silts, clays, and oil sands tailings material, the soils need to be tested with distinctly different methods involving two apparatuses when using the Tempe cell. A single-step Tempe cell technique was developed and tested to measure the geotechnical and unsaturated properties of oil sands tailings samples. A series of nine Tempe cells were simultaneously used to measure the geotechnical and unsaturated soil properties of untreated fluid fine tailings (FFT) and treated flocculated centrifuged tailings (FCT). The results of the single-step Tempe cell technique provide several useful engineering functions relating matric suction to water content (SWCC), void ratio (volume change), solids content, and undrained shear strength. Both the traditional and single-step Tempe cell techniques yield comparable SWCC results, but the single-step Tempe cell yields result about three times faster than the traditional Tempe cell. The geotechnical results indicate that both the solids content and undrained shear strength of the FCT are greater than those of the untreated FFT and this indicates that flocculation and centrifugation increase solids content and undrained shear strength of the treated samples. Furthermore, the results indicate that the FFT starts at higher fine void ratio than the FCT and loses more water (volume change) at matric suctions lower than 7 kPa. Beyond 7 kPa, the compressions of both samples become the same. The single-step Tempe cell technique is, however, labor-intensive. The number of Tempe cell can be reduced to six depending on the starting load of the test. The use of the single-step Tempe cell technique in providing fast estimates of SWCC and geotechnical properties for oil sands tailings will be attractive to practitioners who intend to incorporate matric suction in oil sands geotechnical engineering problems.

Keywords: Tempe cell; soil water characteristic curve; matric suction

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1. Introduction

Geotechnical and unsaturated soil properties, including the soil water characteristic curve (SWCC), are required to understand the consolidation behavior of oil sand tailings that undergo large volume changes upon drying [1]. The fluid fine tailings (FFT) consolidate extremely slowly, and this has resulted in the accumulation of about 1.3 billion cubic meters of FFT in the ponds [2]. Extensive research is underway by a number of organizations to develop methods to understand the reasons for this slow consolidation and to design treatment methods for mine closure [3–5]. FFT behavior is directly related to the mineralogy and water chemistry of the tailings [4]. The samples consisted mainly of Kaolinite with lesser amounts of illite. Due to the complex nature of oil sands tailings, measuring the tailings' geotechnical and unsaturated soil properties is time-consuming, and it takes anywhere from weeks to months to complete the tests using the traditional Tempe cell and large strain consolidation. This fact has led to a slow implementation of unsaturated soil mechanics into oil sands tailings geotechnics. [6] noted, "Although a complete theory for the analysis of geotechnical problems involving unsaturated soils has been developed in the last three decades and despite the well-recognized importance of suction, unsaturated soil mechanics has not yet been widely implemented by practicing engineers [7–9]".

The Tempe cell is normally used to adequately determine the SWCC for soil with a low air entry value (AEV) (<500 kPa) that does not undergo significant volume change as suction is increased, such as sands and coarse-grained material [10–12]. For fine-grained silts, clays, and oil sands material, the soils need to be tested with different methods involving two apparatuses when using the Tempe cell [1,9,13,14]. Pressure plate and salt solution, are commonly used in combination with Tempe cell for measurements of SWCC [10,15–17]. The axis translation technique is one of the most common methods and the procedure is simple. However, it requires a long equilibrium period. Tempe cell with 1 bar and 5 bars ceramic discs is used for SWCC tests at a suction range up to 100 and 500 kPa, respectively. A pressure plate with 15 bars ceramic disc is used for SWCC tests at suction range between 100 and 1500 kPa, whereas the salt solution method is used for suction range above 1500 kPa. For clayed soils, it takes 8 to 10 weeks to complete a test for 10 data points [10,18], compared SWCCs from Conventional testing and a combination of small-scale centrifuge and dew point methods. The results that the SWCC data obtained from tests using a small-scale centrifuge and dew-point methods were in good agreement with those obtained from Tempe cell, pressure plate, and salt solution methods. The time duration by the alternative methods was one-fifth of the time associated with conventional techniques [10], also explain the different types of apparatus for SWCC measurements including the usage of tensiometers within soil specimen and can only measure suction up to 100 kPa. Some of the newer equipment for determination of SWCC include Hyprop, small-scale centrifuge, and dew-point chilled mirror. Each technique has its own limitation in terms of suction [12], used Hyprop to determine SWCC of sand and sandy silt soils. This method showed quick and reliable measurements of SWCC for sand and silt soils. The test duration was within 10 days for the tested soils [19], also used Hyprop2 for the measurement of SWCC of both clay loam and sandy loam soils to show the differences in the SWCC [20] compared Hyprop outputs with the outputs from sandbox (or pressure plate), which validated the use of Hyprop as a potential method for creating SWCC. None of the methods discussed above measure the SWCC along with geotechnical properties such as shear strength, solids content, and void ratio.

The need to reduce the measurement time of SWCC and geotechnical properties including shear strength, and volume change (compression), and to incorporate matric suction in oil sands geotechnics resulted in the development of a single-step Tempe cell technique. In this research study, a series of Tempe cells (up to nine) was used simultaneously to measure useful geotechnical functions relating matric suction to undrained shear strength and solids content along with the SWCC for fluid fine tailings (FFT) and flocculated centrifuged tailings (FCT) tailings samples. The main objective of this research study was to ascertain the ability of the single-step Tempe cell technique to provide fast estimates of geotechnical and unsaturated soil properties for the untreated FFT and treated FCT tailings. The technique is discussed and evaluated.

2. Materials and Methods

2.1. Characteristic Properties

Two oil sands tailings samples were tested in this research study (Figure 1): one untreated and aged FFT and one aged FCT treated using a proprietary process. The samples were not further treated or modified upon receipt from an oil sands operator in Alberta. Table 1 and Figure 1 present the initial characteristic properties of the FFT and FCT samples. The initial solids content of the FFT was 46%, while the initial solids content of the FCT was 54%. The solids content was determined by oven-drying the samples over a period of 24 h at 105 °C following ASTM D2216 [21]. The initial total void ratios (volume of voids/volume of solids) of the FFT and FCT were 3.10 and 2.08, respectively. Table 1 also shows the fine void ratios (total void ratio/mass of fines) of the FFT (3.23) and FCT

(2.44). Depending on the fine contents of oil sand tailings, the fines void ratio may have to be used instead of the total void ratio. Ref. [22] concluded that above a fines content of 50%, the fines void ratio controls the compressibility. At fines contents below 25%, the compressibility at high effective stresses appears to be a function of the sand void ratio. The fines void ratio was used in this research study for comparison purposes. The FFT and FCT samples had bitumen contents of 3.0% and 0.37% on a total mass basis, respectively. In geotechnical engineering, it is preferable to define bitumen content as the mass of bitumen divided by the mass of fines and bitumen [23]. As the bitumen is generally integrated into the fines, the bitumen is considered part of the fines.

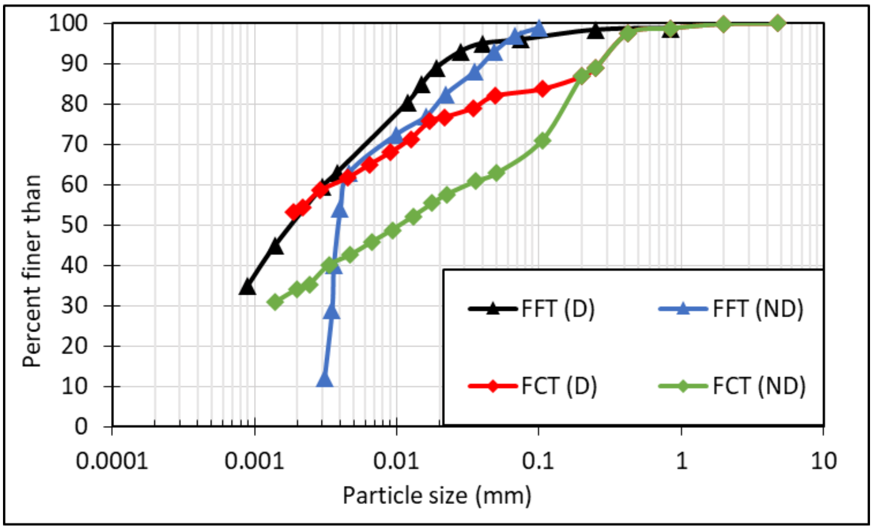

Figure 1. Particle size distribution and dispersed (D) and nondispersed (ND) hydrometer for the FFT and FCT samples.

Table 1. Initial characteristics of the tested FFT and FCT samples.

Characteristics	FFT	FCT
Initial solids content (%)	46	54
Void ratio	3.10	2.08
Fines void ratio	3.23	2.44
Fines content (%)	94	82
Clay size content (D) (%)	54	54
Clay size content (ND) (%)	35	30
Clay size by MBI (%)	44	35
Bitumen content by fine mass (%)	3.0	0.37

Figure 1 shows the particle size distribution (PSD) for the FFT and FCT tailings. The PSD was measured using the ASTM hydrometer-sieve test procedure [24,25]. Dispersed (D) and nondispersed (ND) hydrometer tests were performed to determine PSDs and the degree of fines for both tailings samples. The D-hydrometer involves mechanical agitation and the addition of a dispersing agent. The ND PSD is used to define the fines content (<44 μm) and the clay size content (<2 μm). The D-Hydrometer and ND-hydrometer PSDs (Figure 1) indicate that the FFT had 94% fine content (or 6% sand), while the FCT had 82% fine content (or 18% sand). Both the FFT and FCT had clay size contents of 54% (D-Hydrometer). The ND-hydrometer indicates that the FFT had 35% fine content, while FCT had 30%. The oil sands industry commonly measures clay size amounts using the methylene blue index (MBI) test [26–28]. The MBI test detects all the clay surfaces that are exposed and therefore is an effective method to determine the total amount of clay material present in the tailings. The MBIs of the clay size content for the FFT and FCT were 44% and 35%, respectively. The MBI measurements of the clay content are larger than the ND-hydrometer measurements because the MBI test disperses the clay aggregates and flocs.

2.2. Index Properties

2.2.1. Atterberg Limits

The FFT had a liquid limit and plastic limit of 50% and 21%, respectively, and were determined as per the ASTM standard [29] (Table 2). The value of the liquid limit is fairly typical for FFT although tailings generated from ores with different geological origins have higher liquid limits. The liquid limit and plastic limit for the FFT and FCT samples were 50% and 57%, respectively. Generally, for oil sands fine tailings, the addition of flocculants raises the liquid limit. The specific gravity of the FTT was 2.44 while the specific gravity of the FCT was 2.48.

Table 2. Geotechnical characteristics of the tested samples.

Characteristics	FFT	FCT
Liquid limit (%)	50	57
Plastic limit (%)	21	26
Plasticity index	29	32
Specific gravity	2.44	2.48

2.2.2. Mineralogy

Table 3 presents the mineralogy of the FFT and FCT samples as determined by X-ray diffraction (XRD) (AGAT Laboratories, Calgary, Canada). The combined bulk and clay results indicated that the samples consisted mainly of kaolinite (aluminum silicate hydroxide, Al4Si4O10(OH)8) with lesser amounts of Illite (potassium aluminum silicate hydroxide, KAl2(AlSi3O10)(OH)2).

Table 3. Summary of the X-ray diffraction XRD analysis of the FFT and FCT samples.

	Clay Minerals		
	Kaolinite	**Illite**	**Total**
FFT			
Bulk fraction	36	22	58
Clay fraction	68	23	91
Bulk + clay	42	22	64
FCT			
Bulk fraction	45	28	73
Clay fraction	81	16	97
Bulk + clay	56	24	80

2.3. Tempe Cell

Figure 2 shows the Tempe cell device. The Tempe cell comprises three main parts: the base, Plexiglas cell (7 cm in diameter and 7 cm high), and lid. The base is fitted with a high air entry ceramic porous stone with a maximum high AEV of 500 kPa and an outlet for water release. The lid is fitted with an inlet for air pressure supply.

In the traditional axis translation technique [30], one Tempe cell is used to measure the SWCC. The sample is confined in the cell to about three-quarters of the cell volume (about 6 cm high). Air pressure is applied over the sample, and then the water content is allowed to reach a new equilibrium when the changes in the mass of the cell become stable for 2 or more consecutive measurements at each suction step. The water released from the soil is collected at the base of the cell. Higher air pressure steps are applied until the maximum suction is reached. After the final equilibrium is reached, the lid is removed from the cell and the final water content is measured by oven-drying. This water content together with the previous changes in mass is used to back-calculate the water contents corresponding to the other suction values. The matric suctions are then plotted against their corresponding water contents to yield the SWCC. Figure 3 shows a typical graphical plot for the traditional Tempe cell technique for an FCT sample, showing the water released at each applied suction ranging from 10 kPa to 400 kPa and the time it takes to complete the test (i.e., 52 days).

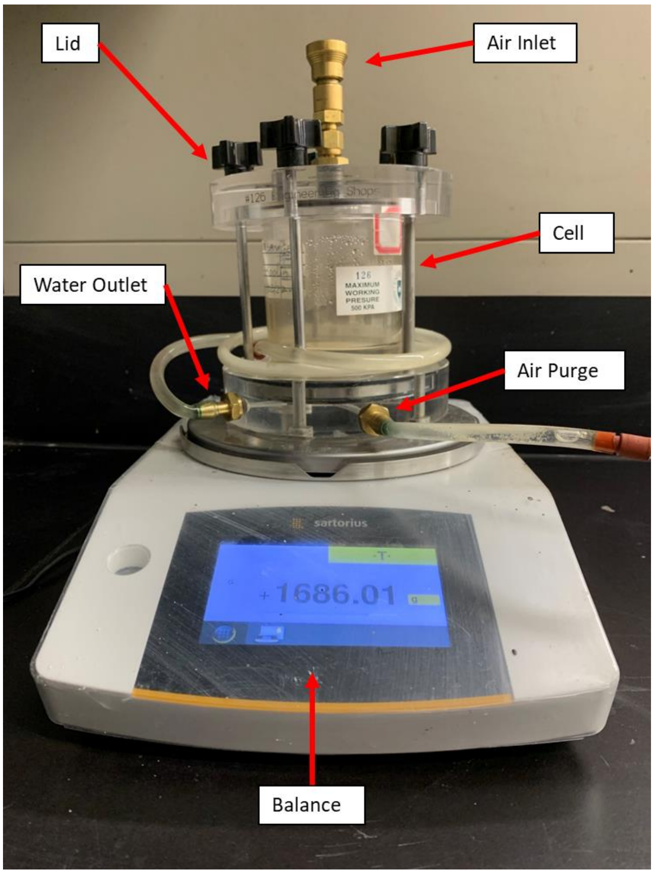

Figure 2. Tempe cell device used for SWCC measurement.

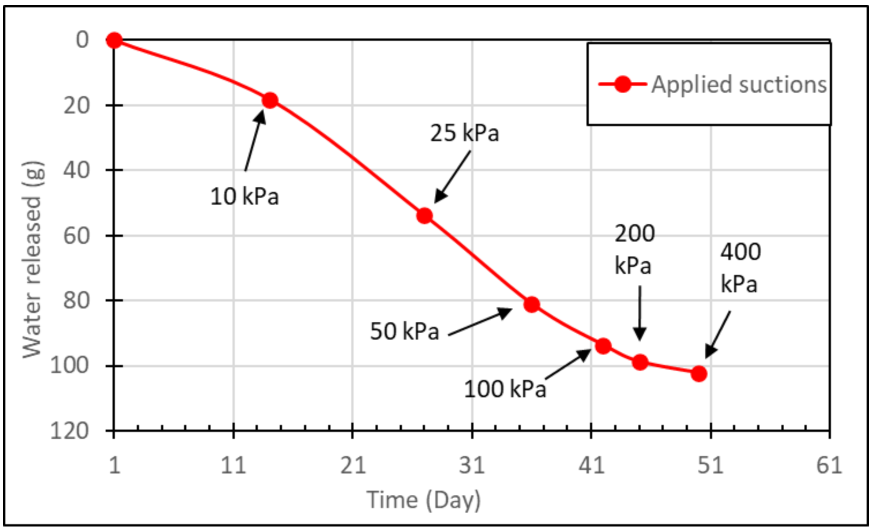

Figure 3. A typical graphical plot for water released at each applied suction versus time from a traditional Tempe cell test of an FCT sample.

In the single-step Tempe cell technique used in this study, a series of up to nine Tempe cells were used simultaneously to measure the early data points of the SWCC along with other geotechnical parameters for the FFT and FCT samples. The number of Tempe cells used was determined based on the initial load and maximum load for the test. The load increments are doubled from the initial load up to the maximum load. The initial load selected in this research study was 7 kPa matric suction. The air pressure was elevated in each sample in one step, allowing the water contents to reach new equilibriums. Figures 4 and 5 show the water release curves measured using a series of Tempe cells. After the water content steady state was reached for each matric suction, the lids were removed, and the final heights of the samples were measured. The final heights of the samples ranged from 2.5 cm to about 5 cm from the initial height of about 6 cm. The final undrained shear strength was measured in each sample using a motorized vane shear apparatus using a vane size (22 mm in height and 12 mm in diameter). The water and solid contents were also determined by oven-drying the samples following the ASTM standard [21]. The dewatering time at various matric suctions ranged from 10 days to 20 days (see Figures 4 and 5).

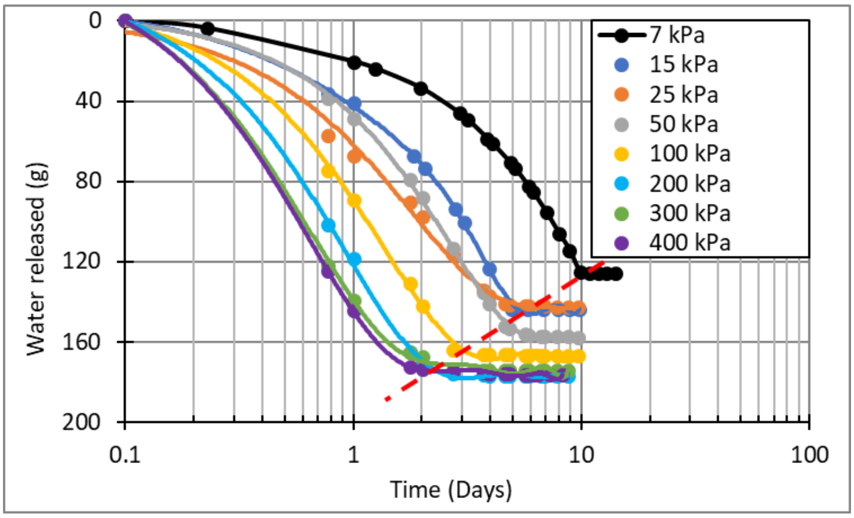

Figure 4. Water released from the FFT sample with time at each applied suction using the single-step Tempe cell technique. The interception of the broken line with the curves represents the points when water in the samples reaches equilibrium.

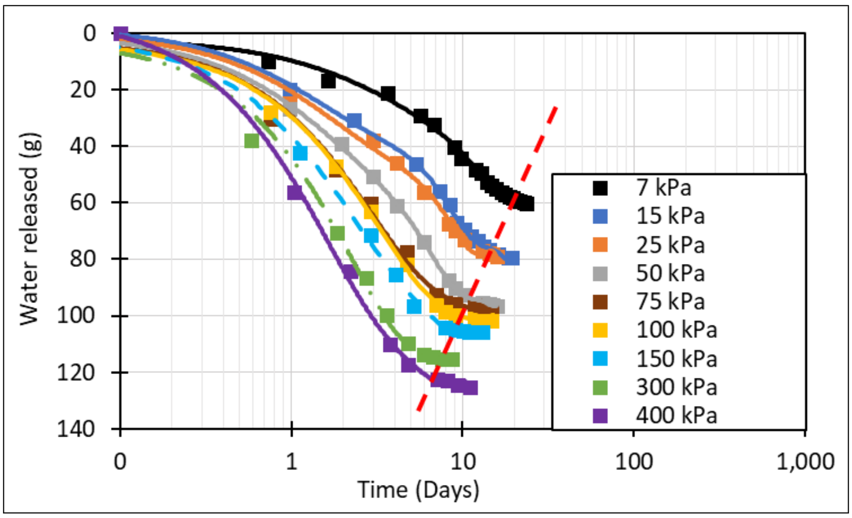

Figure 5. Water released from the FCT sample with time at each applied suction using the single-step Tempe cell technique. The interception of the broken line with the curves represents the points when water in the samples reaches equilibrium.

3. Results and Discussions

Unsaturated soil mechanics involve the evaluation of the soil suction and the net normal stress [10,31]. These stress-state variables must be related to void ratio, shear strength, and water and solids contents for the tested soils. The net normal stress is not the topic of this research and is not discussed. The use of the terms solids content, water content, undrained shear strength, and associated fines void ratio for the single-step Tempe cell technique indicate average values of two or three measurements. The solids content data were obtained by oven-drying as per the ASTM standard [21]. The standard deviations were very low and ranged from 0.05% to 0.2%. The use of the term shear strength in this research is always indicating peak undrained shear strength. The fines void ratio is used in the comparison of the soil properties of the FFT and FCT samples [22].

3.1. Water Content and SWCC

Figure 6 shows the results of the water contents of the FCT and FFT samples measured using the traditional (Trad.) and single-step (S-step) Tempe cell techniques. These data represent the early data points of the SWCC curves of the FCT and FFT samples extending from 7 kPa to 400 kPa matric suctions. The AEVs of the tested FCT and FFT samples are well beyond 400 kPa and cannot be displayed on the early curves. A comparison of the test results for the early curves shows that the two techniques yield very comparable results within experimental errors. The single-step Tempe cell technique, however, yields results about three times faster than the traditional Tempe cell technique (see Figures 3–5). The single-step Tempe cell technique, however, is labor-intensive.

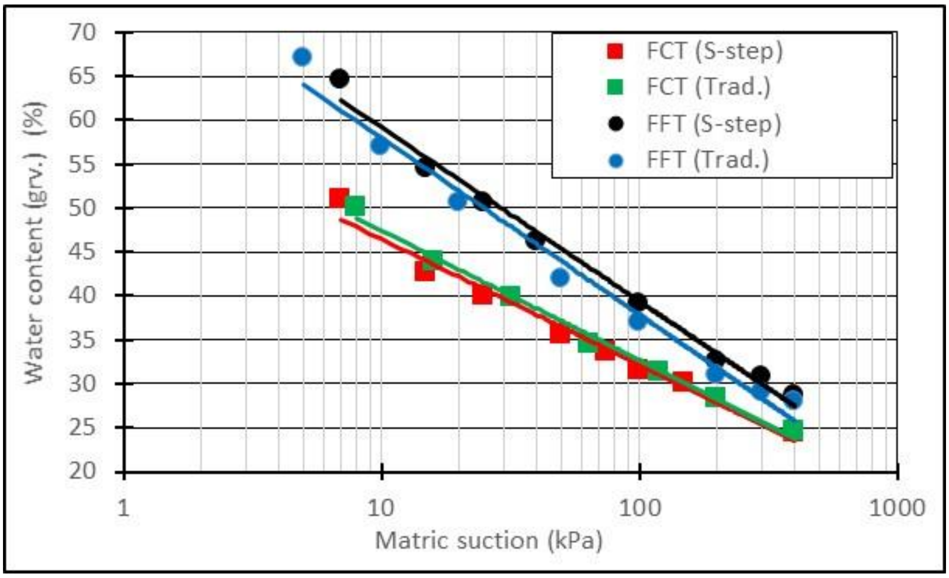

Figure 6. Comparison of the results of the Traditional (Trad.) and single-step (S-step) Tempe cell techniques for FCT and FFT samples.

Figures 7 and 8 show the shrinkage curves and the complete SWCCs for the FFT and FCT in terms of degree of saturation. The single-step Tempe cell data combined with those obtained using the glass desiccator were used in the Fredlund and Xing equation [32] to fit an initial SWCC. The original and fitted data were then used to fit a shrinkage curve based on the methodology of Fredlund [33]. Values obtained from the shrinkage curve were then used to calculate the saturation curves.

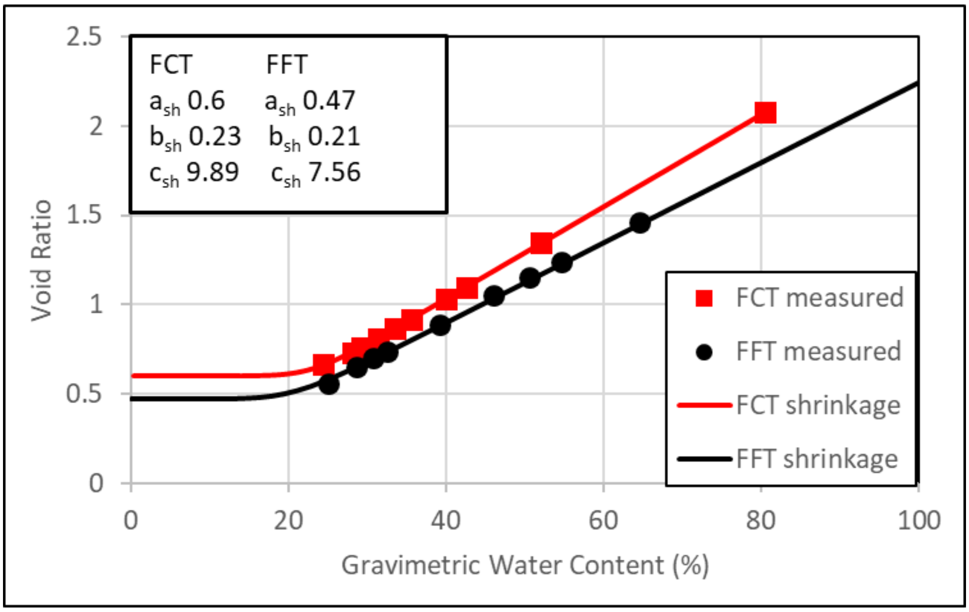

Figure 7. Fitted shrinkage curves [33] for FFT and FCT samples were generated using the single-step Tempe cell technique.

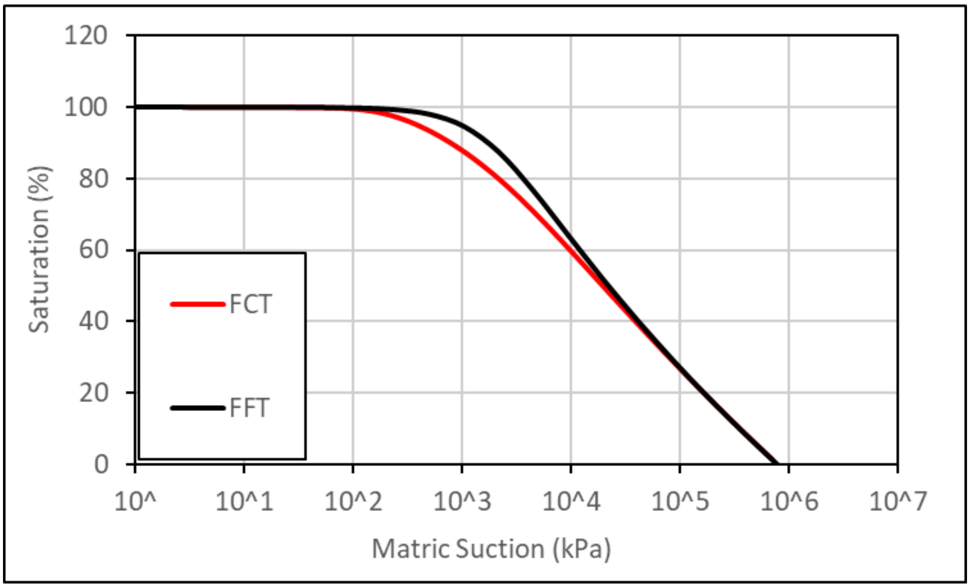

Figure 8. Fitted SWCCs [33] as degree of saturation vs. matric suction for FFT and FCT samples generated using the single-step Tempe cell technique.

The AEVs are graphically determined from the degree of saturation curves [1] and are found to be about 1000 kPa and 700 kPa for the FFT and FCT samples, respectively. The AEV of the FCT is lower than that of the FFT; this reflects the higher amount of sand in the FCT (18%) as compared to the FFT (6%). These AEV values are similar to those reported in the literature [1,14,34]. This ascertain the ability of the single-step Tempe cell technique to provide fast estimates of SWCC and geotechnical properties.

3.2. Solids Content

Figure 9 presents the plots of solids content as a function of matric suction (in log scale) for the FFT and FCT measured with the single-step Tempe cell technique. The samples exhibit linear solids content function trends. The FCT sample plots above the FFT sample at all matric suction values, indicating that the solids content of the FCT is greater than that of the FFT.

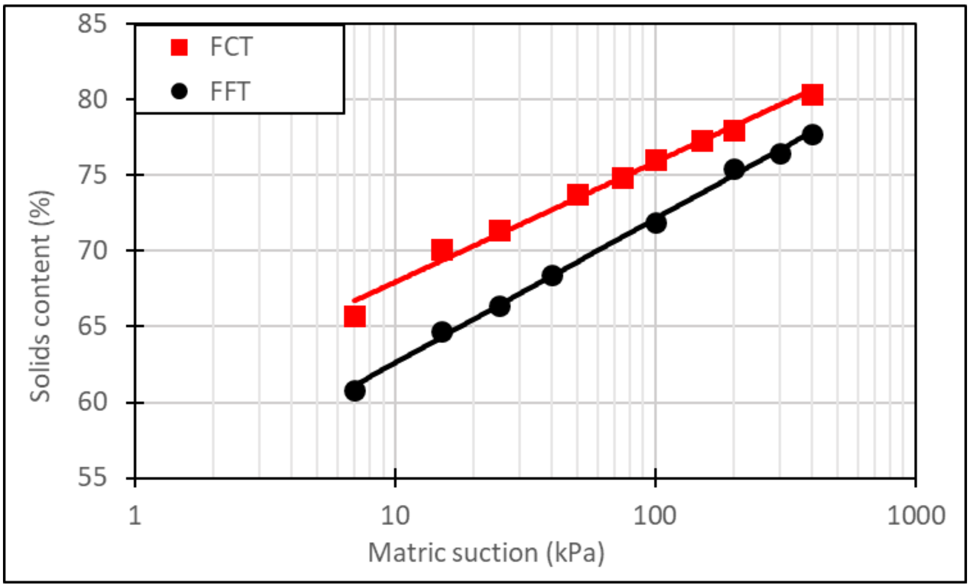

Figure 9. Solids content versus matric suction plots for the FFT and FCT samples measured using the single-step Tempe cell technique.

Figure 10 shows the plots of the solids content as a function of fines void ratio for the FFT and FCT samples obtained with the single-step Tempe cell tests. The samples exhibit solids content linear functions for the FFT and FCT samples. The results show that the solids content of the FCT is greater than that of the FFT at all fine void ratios. This indicates that flocculation and centrifugation increase the solids content of oil sands tailings, and it has been reported by other researchers [11,35,36].

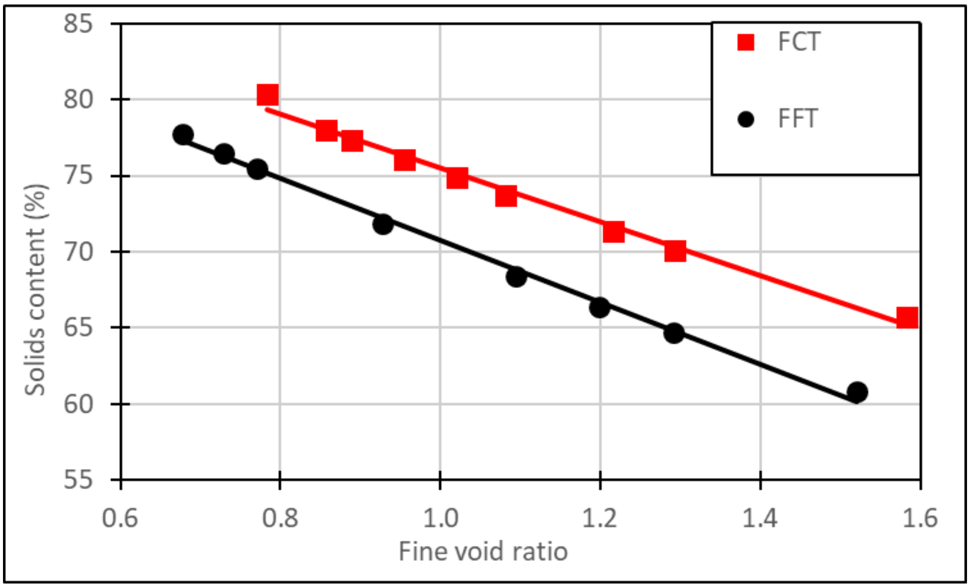

Figure 10. Solids content versus fines void ratio for the FFT and FCT measured using the single-step Tempe cell technique.

3.3. Shear Strength

As stated above, the term undrained shear strength in this research indicates peak undrained shear strength. Figures 11 and 12 show the plots of the undrained shear strength as a function of fines void ratio and matric suction for the FFT and FCT samples obtained with the single-step Tempe cell technique. The results indicate that the undrained shear strength increases exponentially with fines void ratio and matric suction. In Figure 11 the undrained shear strength of the FCT is greater than that of the FFT at void ratios greater than 1.3. This indicates that flocculation and centrifugation increase undrained shear strength. Previous research [3,11,23,35,36] have indicated that flocculation increases the undrained shear strength. Of interest, in Figure 12 the undrained shear strength of the FCT is slightly greater than that of the FFT at matric suctions lower than 50 kPa. At matric suctions greater than 50 kPa the undrained shear strength of the FFT increases more rapidly than that of the FCT. This behavior may be attributed to the suction treatment and greater volume change of the FTT sample.

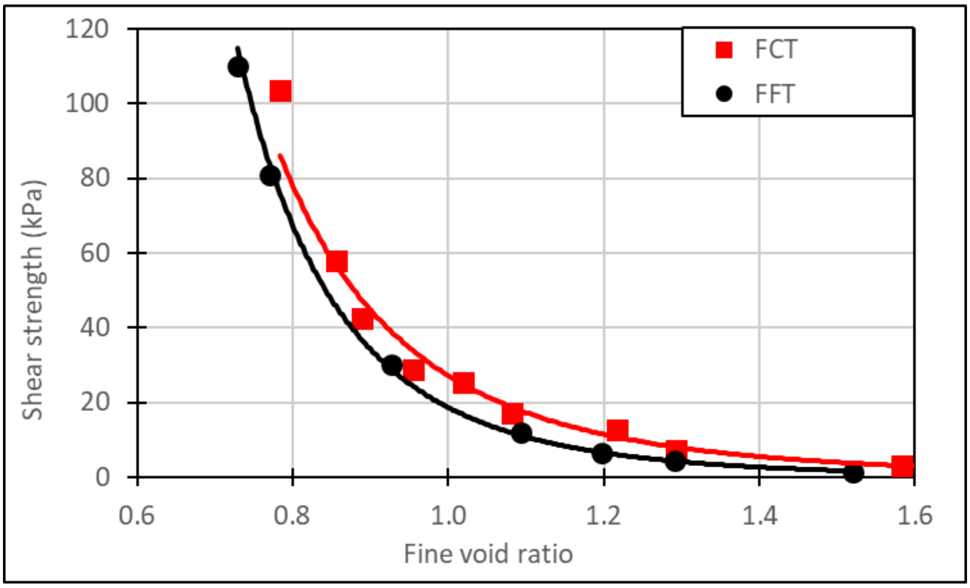

Figure 11. Undrained shear strength versus fines void ratio for the FFT and FCT obtained using the single-step Tempe cell technique.

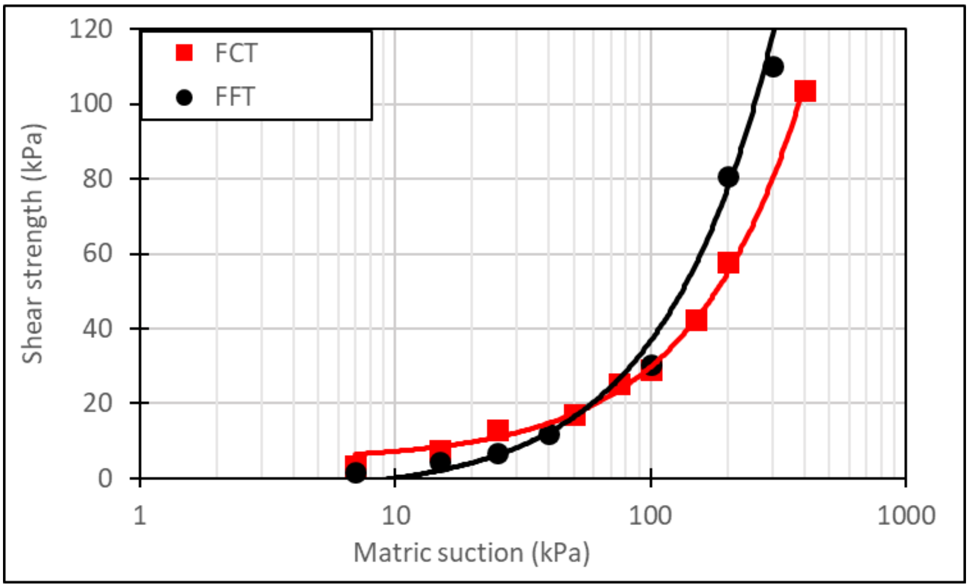

Figure 12. Undrained shear strength versus matric suction plots for the FFT and FCT measured with the single-step Tempe cell technique.

3.4. Volume Change

Figure 13 presents the single-step Tempe cell plots of fine void ratio as a function of matric suction (volume change) for the FFT and FCT samples. There were no measurements conducted at matric suctions between 0.1 kPa and 7 kPa (broken lines). The fine void ratios of the FFT and FCT start at 3.23 and 2.44, respectively. At 7 kPa matric suction, the fine void ratios of both samples decrease to about 1.5 kPa. This indicates that the volume change of the FFT is greater than that of the FCT at matric suctions lower than 7 kPa. Between 7 kPa and 400 kPa, the FCT and FFT have similar volume changes within experimental errors. Other researchers [3,11,23,35,36] have indicated that flocculation decreases the compressibility of treated oil sands tailings as a function of effective stress.

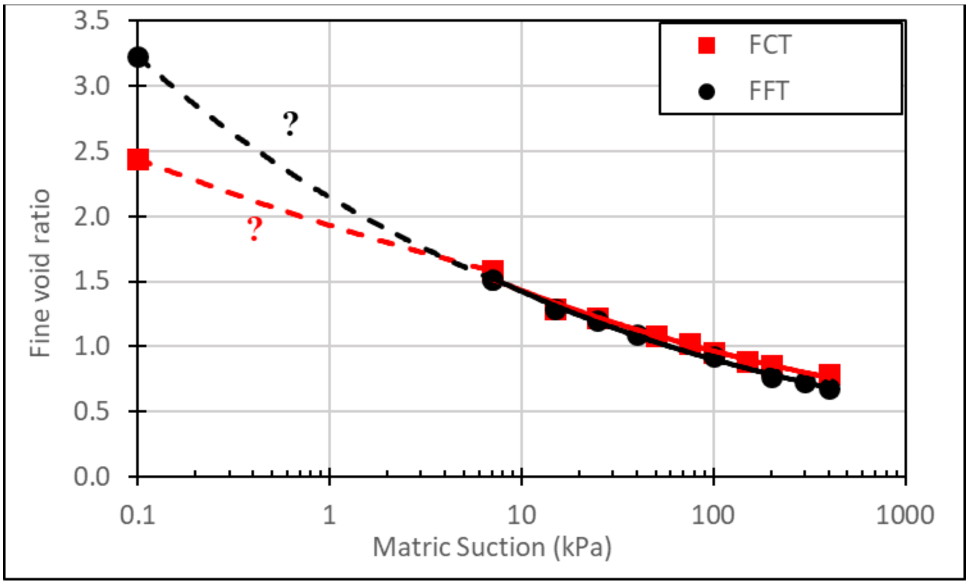

Figure 13. Fines void ratio versus matric suction plots for the FFT and FCT samples obtained with the single-step Tempe cell technique.

4. Summary and Conclusions

This research study was conducted with the single-step Tempe cell technique to assess its ability to rapidly measure both geotechnical and unsaturated soil properties from oil sands tailings samples (i.e., FFT and FCT). The single-step Tempe cell technique measures SWCC along with geotechnical functions relating matric suction to void ratio (volume change), solids content, and undrained shear strength from the same test samples. The traditional Tempe cell method can only measure SWCC after the completion of a full range of suctions is tested. The two techniques yield comparable SWCC results; the single-step Tempe cell technique, however, yields SWCC about three times faster than the traditional Tempe cell technique. Results of the geotechnical properties indicate that the solids content and undrained shear strength of the FCT are greater than those of the untreated FFT and this indicates that flocculation and centrifugation treatments increase solids content and undrained shear strength of the treated tailings. Shear strength and solids content are key parameters in the evaluation of the strength of the oil sands deposit for reclamation. Furthermore, the results indicate that the volume change of the FFT is greater than that of the FCT at matric suctions lower than 7 kPa, and beyond 7 kPa the compressions of the two samples become the same. The main setback of the single-step Tempe cell is that the technique is labor-intensive, requiring multiple Tempe cells to run the test. The number of Tempe cells, however, can be reduced to six when the initially applied matric suction is 25 kPa. The load increments are doubled for each load step until the maximum load is reached (i.e., 400 kPa) for the Tempe cell used in this research. The results of this research study can be helpful in the implementation of unsaturated soil mechanics in oil sands tailings geotechnics.

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Conflicts of Interest: The authors declare no conflict of interest.

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