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Determination of Water Storage and Permeability Functions for Oil Sands Tailings

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Abstract

The paper describes how soil-water characteristic curve, SWCC, tests can be conducted on high volume change materials and used in conjunction with an independently measured shrinkage curves to provide the required unsaturated soil property functions for numerical simulations of the drying process. The saturated-unsaturated soil property functions are used for modeling the drying of oil sands tailings. A laboratory test procedure was developed for the accurate measurement of the shrinkage behavior of oil sands tailings. A laboratory test procedure for measuring and interpreting the shrinkage curve results is also presented. A regression curve-fitting analysis was used to obtain a closed-form equation for the shrinkage curve. The shrinkage curve results are combined with the measured soil-water characteristic curve and used to identify the "true" air-entry value and residual conditions for the oil sands tailings. The meaning of various forms for the SWCC is described along with a designation of the correct interpretation that needs to be placed on the soil-water characteristic curve when determining both the permeability function and the water storage function. The saturated coefficient of permeability is combined with the SWCC to compute the hydraulic properties for the oil sands tailings. The paper concludes with a description of the manner in which each of the unsaturated soil properties can be used for the numerical simulation of drying oil sands tailings.

Introduction

Many of the estimation procedures used to characterize unsaturated soil property functions are based on the assumption that the soil will not undergo significant volume change as soil suction is increased. While this assumption may be acceptable for sands and coarse-grained materials, it is not acceptable for some fine-grained silts and clays, particularly those that are deposited as slurry and then left to dry and increase in strength. Projects associated with the mining of Oil Sands in Alberta, Canada, have tailings that are initially in a slurry form at high water content. The engineering challenge involves converting the tailings into a material with sufficient strength for trafficability. Thin lift deposition is a potential solution, and involves tailings deposition in thin lifts that are subsequently allowed to dry and gain strength. The fine-grained tailings undergo considerable volume change as soil suction is increased during the drying process.

Geotechnical engineers have been requested to under-take numerical simulations of the drying of the initially wet tailings material. The objective is to determine the optimum material and geometric conditions for depositing the tailings. The tailings can be exposed to random weather conditions; however, there will be a drying of the tailings with time since the climate is semi-arid in the Fort McMurray, AB, region. Questions related to the rate of drying and the thickness at which the tailings can be deposited are addressed through use of soil-atmoshperic modeling software, (e.g., SVFlux from SoilVision Systems 2010). The required saturated-unsaturated soil properties take the form of nonlinear functions which can be estimated from measured water content versus soil suction relationships, (i.e., soil-water characteristic curves, SWCC). It is important that the soil property functions be properly quantified for usage as input to numerical model simulations.

The objective of this paper is to describe the manner in which a conventional soil-water characteristic curve test can be conducted on high volume change materials and used in conjunction with an independently measured shrinkage curve to provide the proper unsaturated soil property functions for numerically modeling the drying process. The laboratory test procedure used to measure, interpret and apply the shrinkage curve is described in this paper.

A regression curve-fitting procedure is used to obtain a closed-form equation for the shrinkage curve. The shrinkage curve results are then combined with the soil-water characteristic curve to identify the correct air-entry value and residual conditions, (i.e., water content and soil suction), for the material. The SWCC information is then used to calculate the unsaturated soil property functions for the Oil Sands tailings.

Role of the soil-water characteristic curve, swcc

The SWCC shows the relationship between the amount of water in a soil and various applied soil suctions, (Fredlund and Rahardjo 1993). There are two primary reference points on the SWCC; namely, the air-entry value and residual conditions. Changes in slope along the SWCC assist in identifying the air-entry value of the soil. However, the change in slope is dependent on how the amount of water in the soil is quantified.

The air-entry value appears to occur at different suction values when a soil undergoes volume change as soil suction is increased. The apparent differences in air-entry values are related to how the amount of water in the soil is defined. Each variable used to designate the amount of water in the soil has significance but it is important that the correct interpretations be applied at various stages of the analysis, (Fredlund 2002).

The variables commonly used to quantify the amount of water in the soil are:

i) gravimetric water content, w;
ii) volumetric water content, θ; with the instantaneous total volume used in calculating volumetric water content,
iii) volumetric water content with the volume of water, V_w, referenced to original total volume of the specimen, V_o, (i.e., $\theta = V_w / V_o$).
iv) degree of saturation, S.

Each of the above designations for the amount of water in the soil can be used to plot a SWCC. Each form of SWCCs would provide similar information to the geotechnical engineer if the soil did not undergo volume change as soil suction is increased. When the soil undergoes volume change, as is the case for Oil Sands tailings, the geotechnical engineer must be able to plot each of the SWCCs and use the appropriate curves in the correct manner for evaluating unsaturated soil property functions to be used for subsequent numerical simulations of physical processes.

Gravimetric water content is the most basic measurement of the amount of water in a soil because it requires only the measurement of mass. Volumetric water content, θ, has been commonly used in agriculture-related disciplines and is defined as the amount of water in the soil referenced to the instantaneous total volume of the soil specimen. The total volume of the soil specimen must be known when computing the volumetric water content in this manner. Therefore, it is necessary to know the total volume of the soil specimen corresponding to equilibrium soil suction conditions. It is the change in volumetric water content that defines the water storage function as suction changes. However, there are two possible ways to compute volumetric water content. If the overall volume of the soil changes by a small amount during the increase in soil suction, then either designation of volumetric water content is satisfactory. If the volume changes are substantial, then the instantaneous total volume should be used for the calculation of the water storage function.

The degree of saturation, *S*, references the volume of water in the soil to the instantaneous volume of voids and therefore needs a measure of the total volume of the specimen. When a soil undergoes volume change as soil suction increases, the air-entry value and residual conditions need to be determined from a plot of degree of saturation versus soil suction. In addition, it is the degree of saturation versus soil suction plot that must be used during the integration process to calculate the permeability function. The permeability function may also need to be computed differently to accommodate changes in void ratio prior to reaching the air-entry value of the soil.

It is important to note that unsaturated soil property functions need to be computed in distinctly different ways when the soil undergoes substantial volume change as soil suction increases. It is the instantaneous volumetric water content designation that must be used to compute water storage and the degree of saturation designation that must be used to define the air-entry value of the soil. The degree of saturation designation is extremely important in developing the proper unsaturated permeability function for the soil.

The soils of primary concern in this paper are the high water content tailings that are a by-product from Oil Sands extraction. These materials may start with a natural water content well above the liquid limit of the material and undergo large volume changes upon drying.

The difficulties associated with the testing of soils that undergo large volume changes with increasing soil suctions are not a recent discovery. Fredlund (1964) showed that shrinkage curve measurements were needed in addition to conventional measurement of the SWCC in order to properly interpret the unsaturated soil behaviour of high volume change soils. Fredlund (*loc. cit.*) performed a series of tests on highly plastic Regina clay that had a liquid limit of 75%, a plastic limit of 25%, and had 50% clay size particles.

Shrinkage limit and the shrinkage curve

The shrinkage limit of a soil has been one of the classification properties since the inception of soil mechanics, (ASTM D427). Mercury immersion was originally used for the measurement of the volume of the soil specimen. This technique is no longer considered acceptable in most countries for health safety concerns.

The shrinkage limit is defined as the water content corresponding to the minimum volume that a soil can attain upon drying to zero water content. It is a fictitious water content that generally falls slightly below the plastic limit of the soil.

The entire shrinkage curve from an initial high water content condition to completely dry conditions is called the “shrinkage curve”. The shrinkage curve has an important role to play in the interpretation of SWCC data. Figure 1 shows the drying curve for an initially high water content soil. As a clay soil dries, a point is reached where the soil starts to desaturate. This point is generally quite close to the plastic limit of the soil. Consequently, there is an approximate correlation between the plastic limit of a soil and its air-entry value. Upon further drying, another point is reached where the soil dries without any further change in overall volume. This can be referred to as the true “shrinkage limit” of the soil and the gravimetric water content appears to approximately correlate with residual soil conditions.

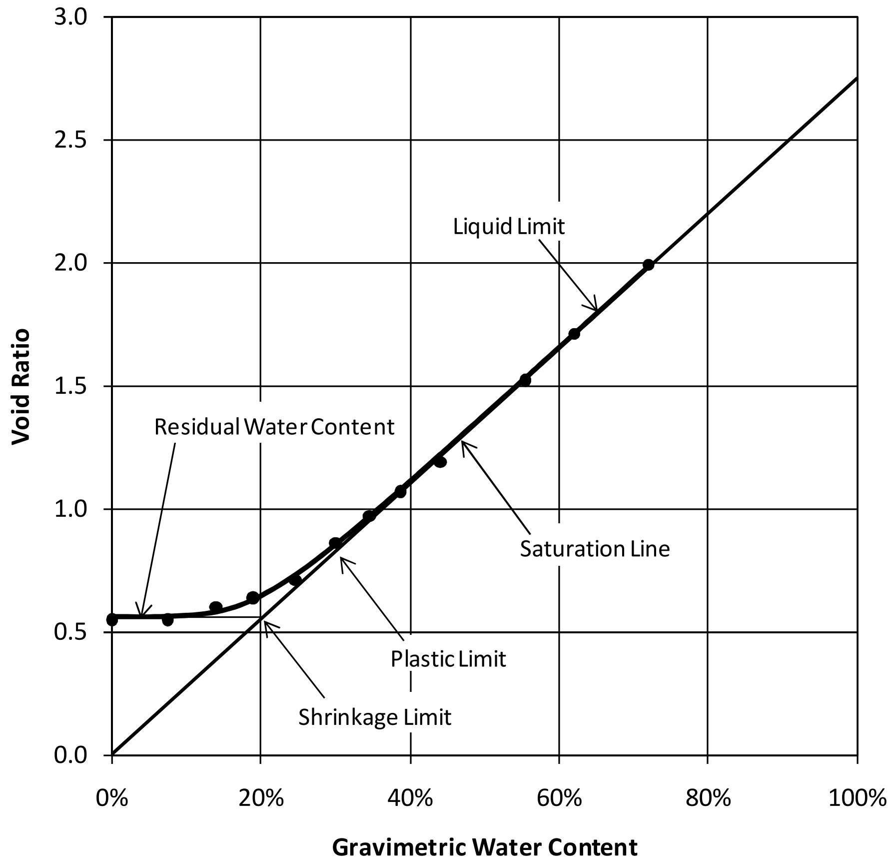

Figure 1: Shrinkage curve with its relationship to the Atterberg Limit classification properties.

Measurement of the Shrinkage Curve

An experimental procedure was developed for the measurement of the entire shrinkage curve for a soil. The soil specimen is prepared at initial high water content conditions and allowed to slowly dry by exposure to air. A digital micrometer can be used to measure the volume of the specimen at various stages of drying as shown in Figure 2. Brass rings were machined to contain the soil specimens (i.e., the rings have no bottom). The rings with the soil were placed onto wax paper and drying was commenced. The dimensions of the soil specimens were selected such that cracking of the soil was unlikely to occur during the drying process. The ring dimensions selected for the shrinkage curve specimens were a diameter of 3.7 cm and a thickness of 1.2 cm.

The mass and volume of each soil specimen were measured on a daily basis. Four to six measurements of the diameter and thickness of the specimen were made at differing locations on the specimens. Figure 3 shows typical measurements of water content and void ratio as the soil dried. It was observed that as the specimen diameter began to decrease, with the specimen pulling away from the brass ring, the rate of evaporation increased significantly (i.e., about twice as fast).

The increase in the evaporation rate was related to the increased surface area from which evaporation was occurring. Consequently, it is recommended that the measurements of mass and volume should be increased to once every two to three hours once the soil shows signs of pulling away from the sides of the ring.

Figure 2: Digital micrometer for the measurement of the diameter and thickness of shrinkage specimens.

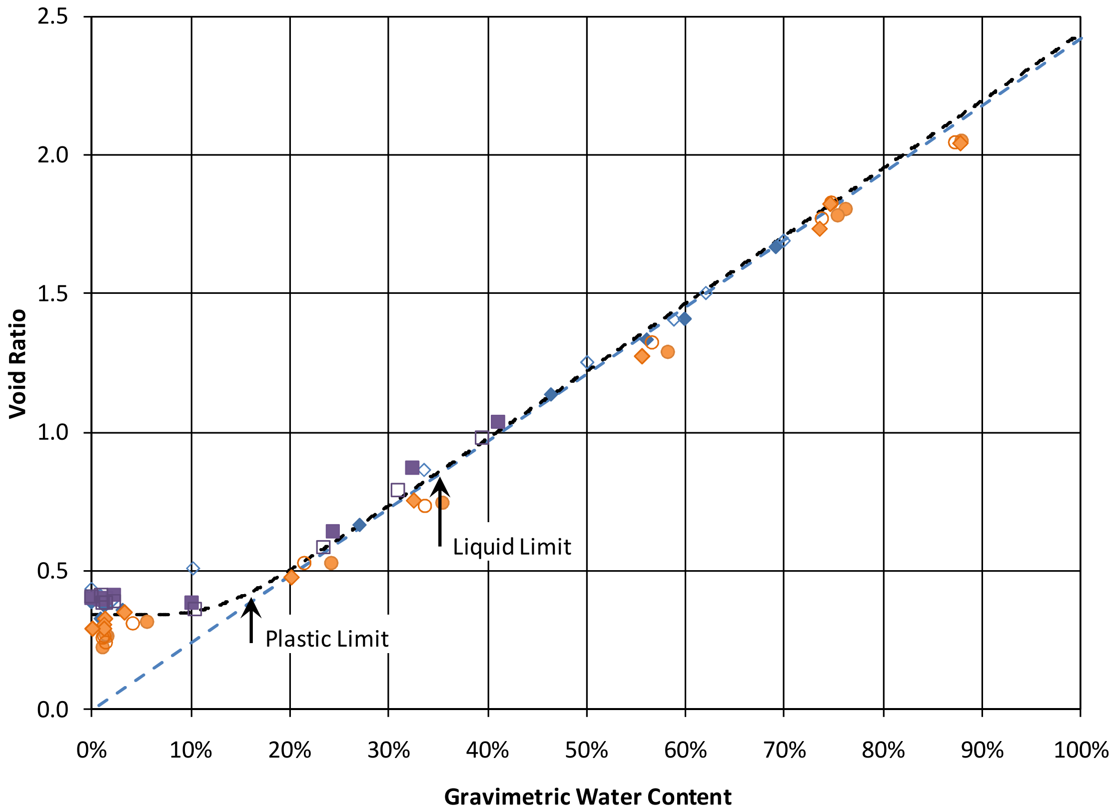

Figure 3: Typical shrinkage curve for a clay soil.

Equation for the Shrinkage Curve

The shrinkage curve has the form of a hyperbolic curve. Fredlund et al. (1997, 2002) proposed an equation to best-fit data for the shrinkage curve. The equation has parameters with physical meaning and is of the following form:

$$e(w) = a_{sh}\left[\frac{w^{c_{sh}}}{b_{sh}^{\ c_{sh}}} + 1\right]^{\left(\frac{1}{c_{sh}}\right)} \quad \textbf{(1)}$$

where: a_{sh} = the minimum void ratio, (e_{min}), b_{sh} = slope of the line of tangency, (e.g., drying from saturated conditions), c_{sh} = curvature of the shrink-age curve, and w = gravimetric water content. The ratio, is a constant for a specific soil; G_s is the specific gravity and S is the degree of saturation.

$$\frac{a_{sh}}{b_{sh}} = \frac{G_s}{S} \quad \textbf{(2)}$$

It is possible to estimate the remaining parameters required for the designation of the shrinkage curve once the minimum void ratio of the soil is known. The minimum void ratio the soil can attain is defined by the variable, a_{sh}. The c_{sh} parameter provides the remaining shape of the shrinkage curve. The curvature of the shrinkage curve is controlled by varying the c_{sh} parameter.

Integration of the Shrinkage Curve and the laboratory measured SWCC

A laboratory measured SWCC describes the relationship between gravimetric water content and soil suction. The Fredlund and Xing (1994) equation (Equation 3) can be used to best-fit the SWCC curve.

$$w(\psi) = w_s\left[1 - \frac{\ln\left(1+\frac{\psi}{h_r}\right)}{\ln\left(1+\frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\left[\ln\left[\exp(1)+\left(\frac{\psi}{a_f}\right)^{n_f}\right]\right]^{m_f}}\right] \quad \textbf{(3)}$$

where: $w(\psi)$ = gravimetric water content at any specified suction, ψ; w_s = saturated gravimetric water content; h_r = residual soil suction; a_f, n_f, and m_f = the fitting parameters for the Fredlund and Xing (1994) SWCC equation.

Equation 3 is written using the gravimetric water content designation; however, it should be noted that it can be best-fit to any of the designations of water content versus soil suction because of the flexibility of the equation with three fitting soil parameters.

It is possible to compute the degree of saturation versus soil suction as well as any other designation for the amount of water in the soil by combining Equations 1 and 3. The degree of saturation equation will provide the proper designation for the air-entry value for the soil.

Measurement and interpretation of oil sands tailings results

Soil-water characteristic curves were measured on samples of Oil Sands tailings that were mixed with 10% sand and 45% sand, (i.e., 0.1 and 0.8 sand to fines ratios, SFR, respectively). The tailings are from development studies on Oil Sands tailings from northern Alberta, Canada. The shrinkage curve results were presented in Figure 3. The 0.1 SFR tailings have plastic and liquid limits of 30 and 55, respectively. The 0.8 SFR tailings have plastic and liquid limits of 15 and 38, respectively. Approximately 60% of the material classifies as clay size particles. The slurry material has a gravimetric water content of about 100%. The intent is to deposit the thickened tailings material in lifts of varying thicknesses that are then allowed to dry.

As water is removed from the tailings, the volume of the material decreases and there is a slow increase in shear strength. As the material begins to desaturate near the plastic limit there is a substantial increase in shear strength.

Figure 4 shows the gravimetric water content, *w*, plotted versus soil suction for two samples tested with each of the sand to fines ratios (SFR). Box #11 had a SFR of 0.8 and a starting gravimetric water content of about 70%. Box #6 was the same material; however, it was dried to about 25% before the SWCC test was performed. Box #2 had a SFR of 0.1 and the initial gravimetric water content was near 70%. Box #5 was the same material; however, it was dried to about 47% before the SWCC was performed.

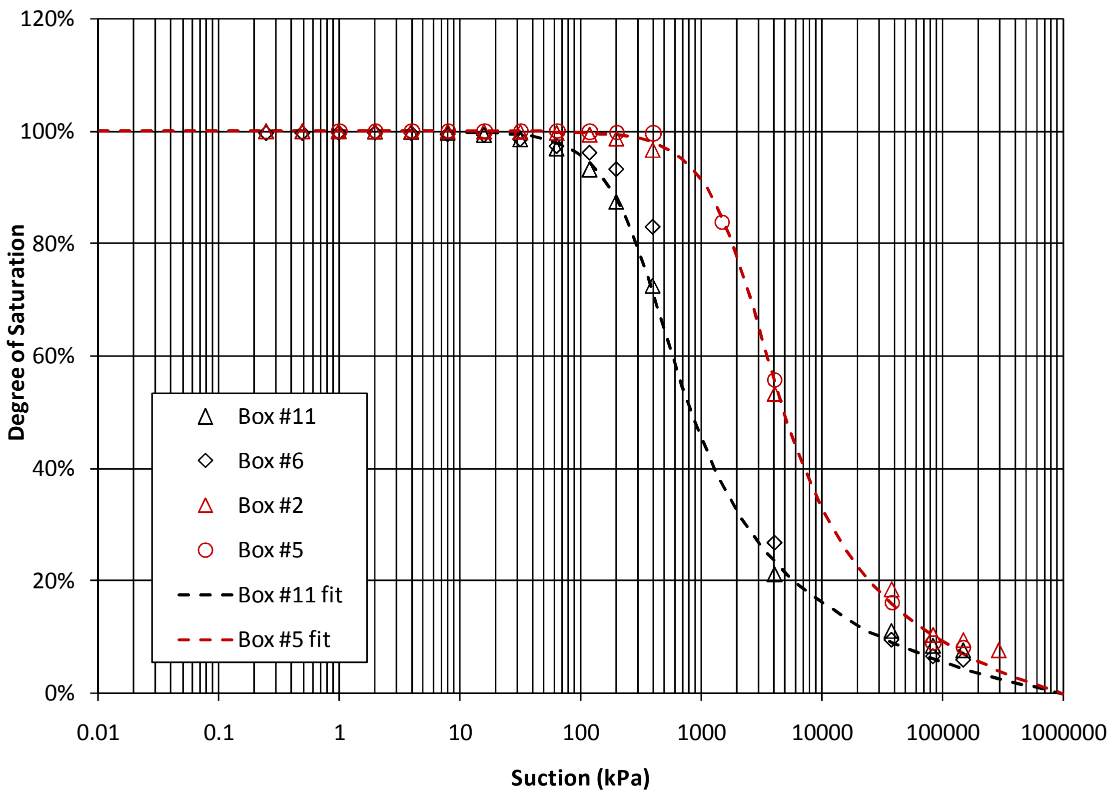

Figure 4: Gravimetric water content SWCC's measured on the Oil Sands tailings.

The initially wet samples show a break in the curvature in the region around 1 kPa. The dried samples show a break in the curvature around 10 kPa. However, the curvature is not distinct and it should not be taken to represent an air-entry value for the material.

It is necessary to use the shrinkage curve results when interpreting the meaning of the SWCC results. A best-fit shrinkage curve equation can be combined with the equation for the Fredlund and Xing (1994) equation for the SWCC. It is then possible to plot the degree of saturation, *S*, versus soil suction as shown in Figure 5.

The results show that there is a distinct air-entry value for the 0.8 SFR tailings at about 100 kPa. The air-entry value for the 0.1 SFR tailings is about 1000 kPa. These are the correct air-entry values for these two materials. It is also the degree of saturation SWCCs that must be used for the estimation of the unsaturated hydraulic conductivity function. The residual condition can also be clearly identified as having a residual suction of about 3000 kPa and a residual degree of saturation of 20% for the 0.8 SFR tailings. The 0.1 SFR tailings have a residual suction of about 15,000 kPa and a residual degree of saturation of about 20%.

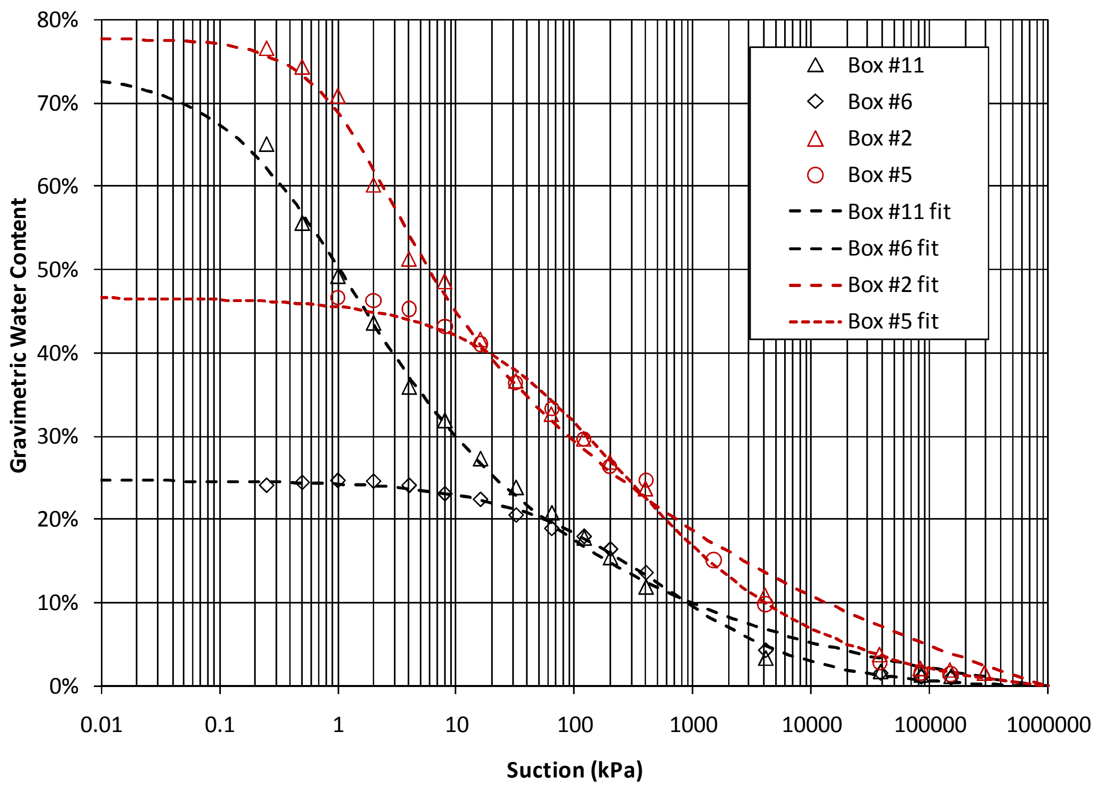

Figure 5: SWCC's plotted as the degree as saturation versus soil suction for the Oil Sands tailings.

Figure 6 shows the volumetric water content versus soil suction plots for the 0.8 SFR and 0.1 SFR tailings. The volumetric water contents were computed using the shrinkage curve information. Therefore, the volumetric water content is referred to as instantaneous volumetric water contents. The graphical presentation of volumetric water content versus soil suction is similar in shape to the gravimetric water content plots. It is the volumetric water content curves that are required when quantifying the unsaturated water storage function. The water storage function, m_2^w, is obtained by performing an arithmetic differentiation of the best-fit SWCC equation through the volumetric water content, θ, versus soil suction plot, ψ, (i.e., $m_2^w = d\theta/d\psi$).

Figure 7 shows the volumetric water content versus soil suction plots for the 0.8 SFR and 0.1 SFR tailings. The volumetric water contents were computed based on the original total volume of the soil specimen. Close examination shows that there are differences between the volumetric water content results calculated in two different ways, (See Figs. 6 and 7). In order to more clearly illustrate the relationship between all of the SWCCs, the data in Figs. 6 and 7, for Boxes #5 and #11 has been re-plotted in Figures 8 and 9. The open and closed triangular symbols show that the volumetric water contents calculated based on the instantaneous volume measurements are considerably different than those calculated based on the original volume of the soil specimen. It is the differentiation of the volumetric water contents based on the instantaneous volumes of the soil specimen that are consistent with commonly used formulation for saturated-unsaturated seepage analyses, (e.g., SVFlux, SoilVision Systems, 2010). The significant difference between the two procedures for the calculation for volumetric water content occur because of the large volume changes that occur as soil suction is increased.

The basic volume-mass relationship, (i.e., $S\,e = w\,G_s$), also makes it possible to plot void ratio, *e*, versus soil suction as shown in Figure 10. All curves show that there is essentially no volume change at soil suctions higher than the residual suctions.

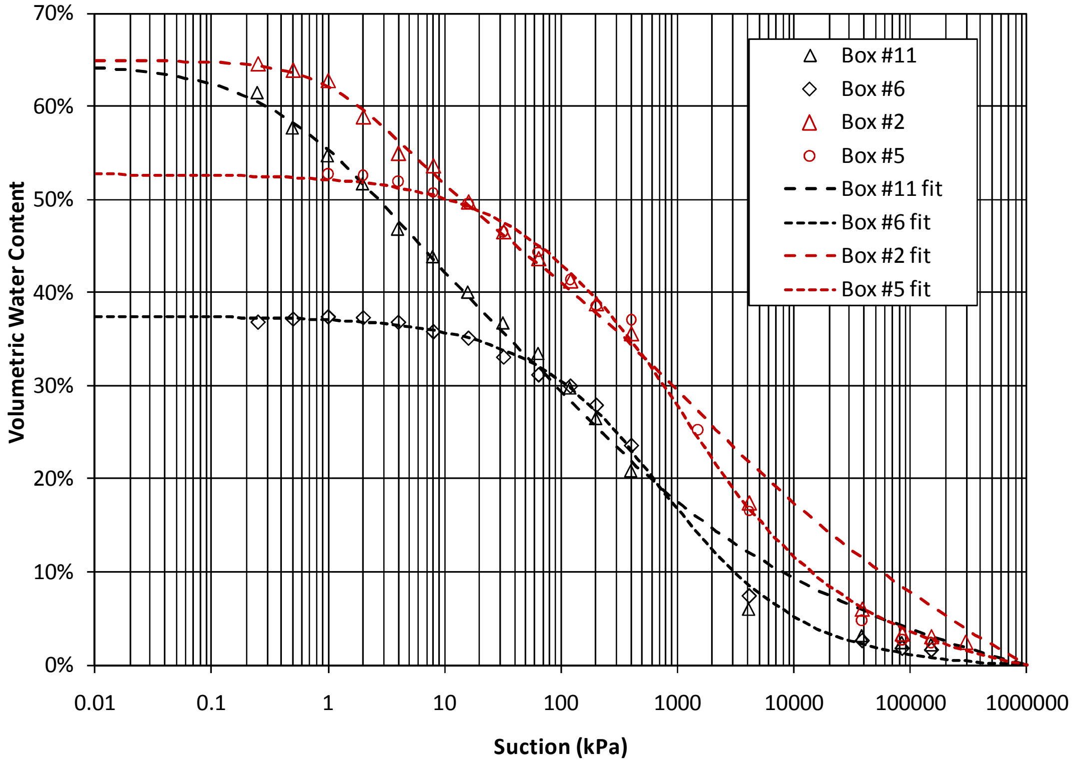

Figure 6: Volumetric water content (based on instantaneous volume) versus soil suction for the Oil Sands tailings.

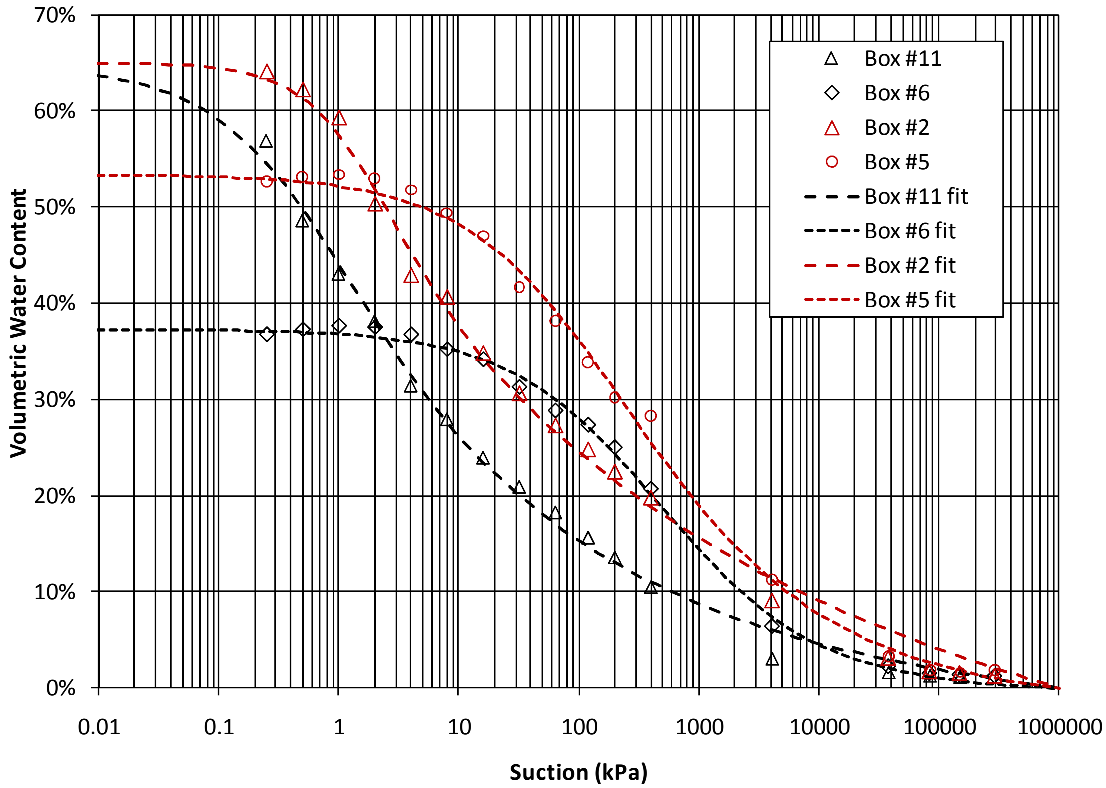

Figure 7: Volumetric water content (based on initial total volume, Vo) versus soil suction for the Oil Sands tailings.

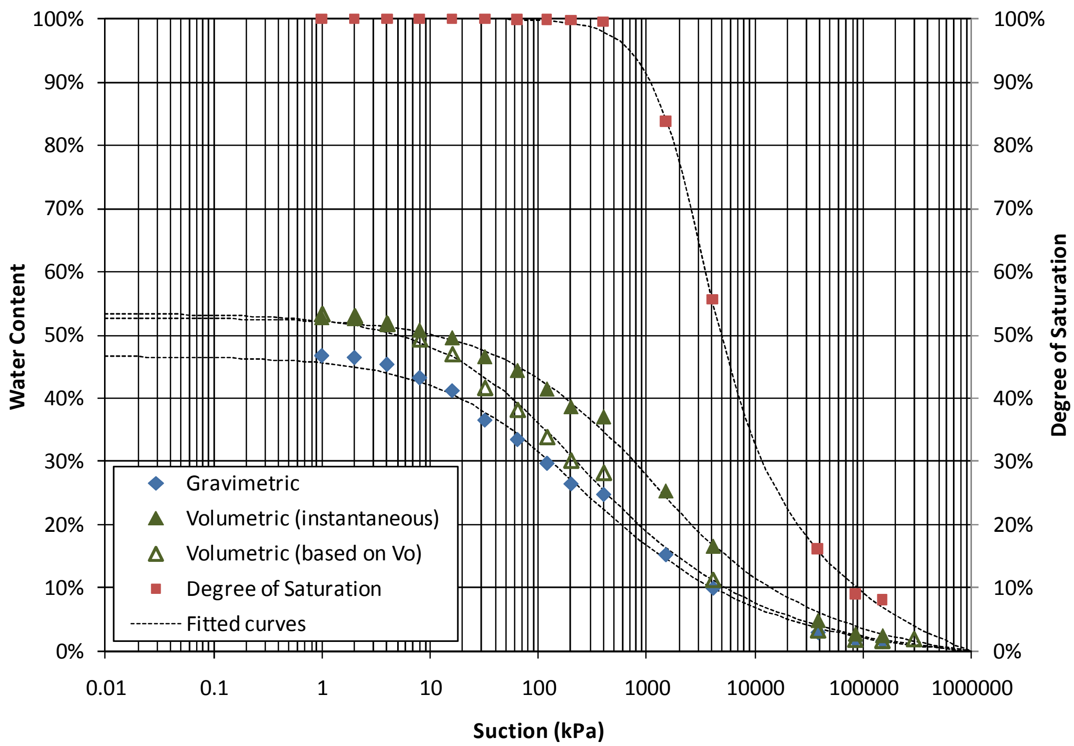

Figure 8: **Gravimetric water content, volumetric water content (based on both instantaneous and initial volumes) and degree of saturation versus soil suction for Box #5 tailings.**

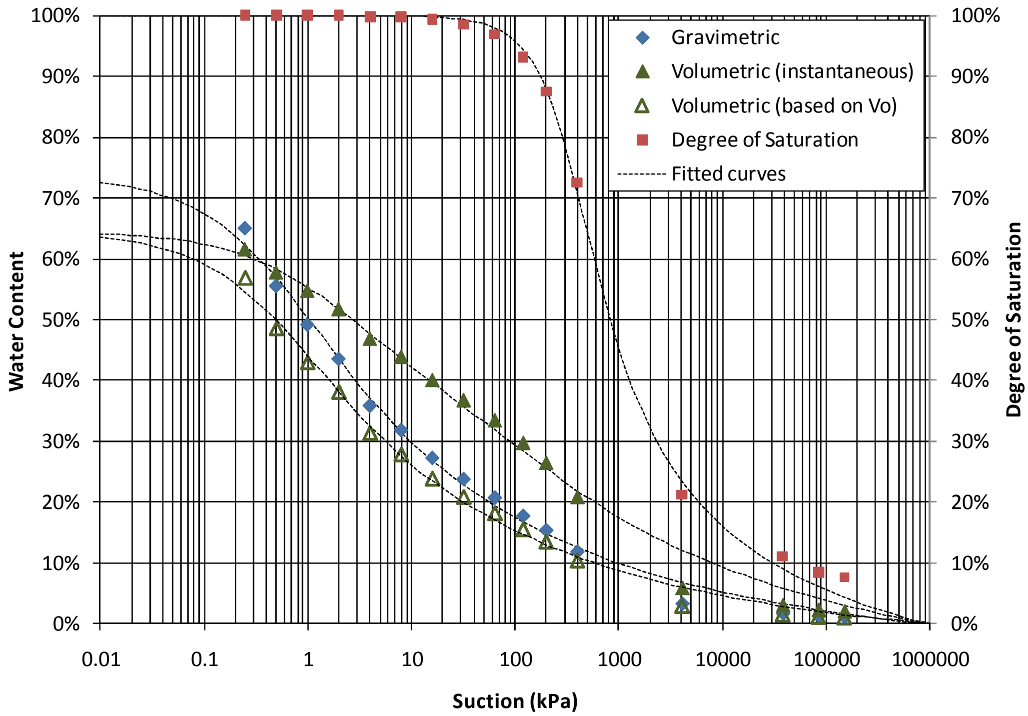

Figure 9: Gravimetric water content, volumetric water content (based on both instantaneous and initial volumes) and degree of saturation versus soil suction for Box #11 tailings.

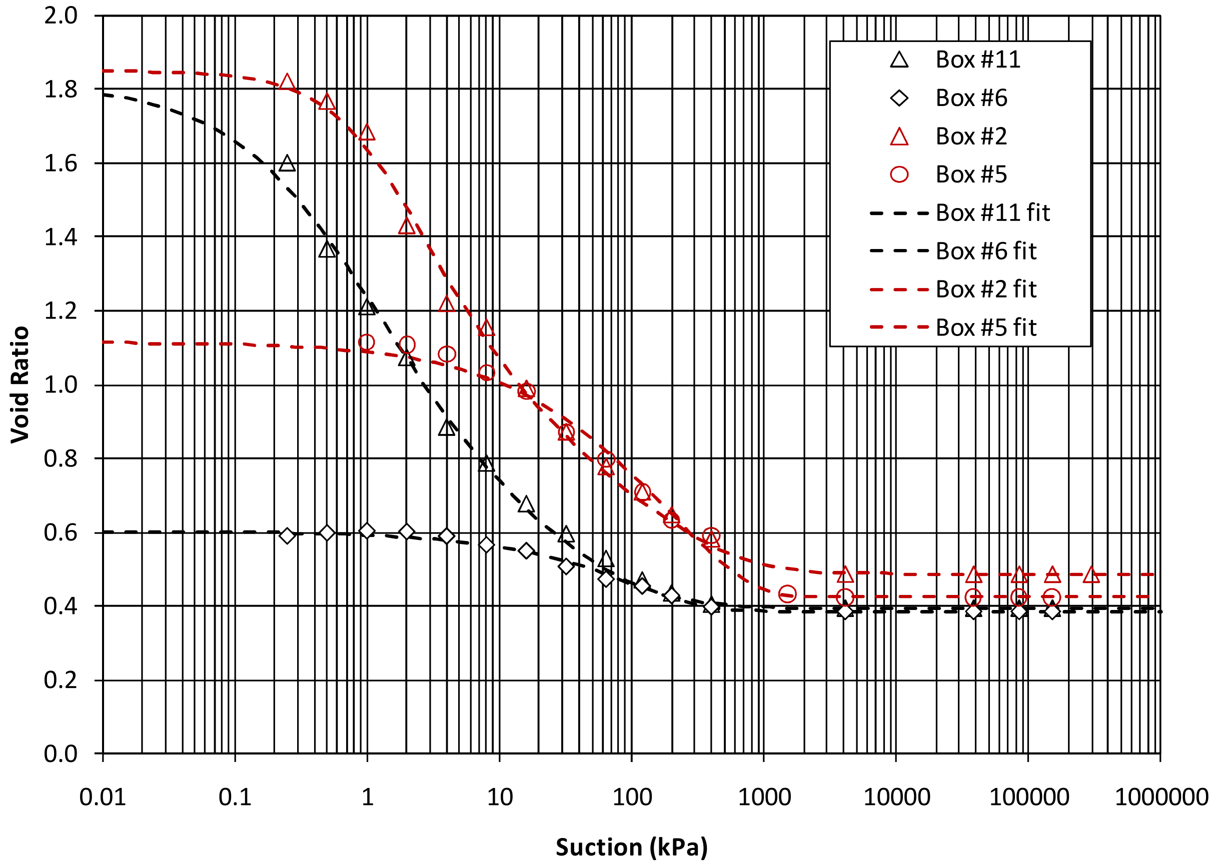

Figure 10: Void ratio versus soil suction plot for the Oil Sands tailings.

Conclusions

The results clearly show that it is important to measure the shrinkage curve when testing high volume change soils such as Oil Sands tailings. It is also necessary to combine the shrinkage curve and the gravimetric water content SWCCs in order to calculate all of the volume-mass properties versus soil suction. The (instantaneous) volumetric water content SWCC is necessary for computing the water storage characteristics of the Oil Sands tailings. The degree of saturation SWCC is necessary for obtaining the correct physical features of the SWCC (i.e., air-entry value and residual conditions), and the subsequent unsaturated permeability function for Oil Sands tailings.

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