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Estimating the SWCC from the SFCC for mine waste tailings using TDR

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Abstract: The unsaturated properties of a soil are required to predict the rate of dewatering and magnitude of strength gain of a mine waste tailings deposit during desiccation dewatering. This prediction requires the soil water characteristic curve (SWCC), which is time-consuming and challenging to attain and may take anywhere from weeks to months to complete a single test. As a result, alternative methods are needed to estimate the SWCC. Past research has indicated that the soil freezing characteristic curve (SFCC) can be used to estimate the SWCC in some soils. An experimental method and apparatus was developed to measure the SFCC to estimate the SWCC for different mine waste tailings, including copper tailings, gold tailings, and oil sands centrifuge cake. The experimental method involved using a resistance temperature detector (RTD) to measure the temperature and time domain reflectometry (TDR) to determine the unfrozen water content of the soil. The results showed that the SFCC could be used to estimate the SWCC for tailings from metal mines (gold tailings and copper tailings) with a high portion of sand sized particles and a small amount of clay sized particles, but was not able to estimate the SWCC for oil sands tailings.

Key Words: SFCC, SWCC, TDR, tailings, unsaturated, dewatering
INTRODUCTION

Mineral processing results in the generation of large volumes of tailings that consist of different combinations of sand, fines, and water (Bussiere 2007). These tailings are often subject to various dewatering processes to promote the development of strength for the creation of a trafficable surface for reclamation purposes. One such process is desiccation dewatering, which requires the unsaturated soil properties to be known in order to predict behavior of the soil as it transitions from a saturated to an unsaturated state (Daliri et al. 2014; Wells and Riley 2007). The unsaturated soil properties can be estimated using the soil water characteristic curve (SWCC), which allows designers to determine the unsaturated hydraulic conductivity function, water storage function, shear strength function, and the volume change properties (Fredlund et al. 2012; Qiu and Sego 2006; Simms and Grabinsky 2004; Vardon et al. 2014). Traditional methods for determining the SWCC in the laboratory are challenging and time-consuming, taking anywhere from weeks to months to get a single test result. As a result, it is desirable to develop alternative methods to rapidly estimate and measure the SWCC. One such method is to estimate the SWCC from the soil freezing characteristic curve (SFCC), which defines the relationship between unfrozen water content and subzero temperatures in frozen soil (Azmatch et al. 2012a; Azmatch et al. 2012b; Banin and Anderson 1974; Liu et al. 2012; Spaans and Baker 1996; Zhou et al. 2014). This estimation technique is possible because the forces that prevent water from draining also prevent it from freezing (Spaans and Baker 1996). This method has not been applied to mine waste tailings with low solids contents.

The objective of this research was to assess the feasibility of using the SFCC to estimate the SWCC in mine waste tailings. To accomplish this, two phases of laboratory testing were completed. The first phase involved developing an experimental method and apparatus to determine the SFCC.
The second phase involved extending the methodology to apply to various tailings slurries. The measured SFCC was used to estimate the SWCC for each tailings material, which was then compared to the SWCC determined using traditional methods. This paper discusses the development of the SFCC laboratory method and the applicability of using the SFCC to estimate the SWCC in mine waste tailings.

**BACKGROUND**

**Soil Water Characteristic Curve**

SWCCs define the relationship between water content or degree of saturation and water suction for a soil (Fredlund et al. 2012). The SWCC may be subject to hysteresis and the overall shape depends on a number of factors, such as the initial density and stress history (Fredlund and Xing 1994; Fredlund et al. 2012; Williams 1964). It should be noted that the SWCC may be expressed in terms of the total volumetric water content ($\theta$), the gravimetric water content ($w$), the instantaneous volumetric water content ($\theta_i$), and the degree of saturation ($S$) (Fredlund et al. 2011). This yields four different SWCCs, namely the $\theta$-SWCC, $w$-SWCC, $\theta_i$-SWCC, and S-SWCC.

A traditional laboratory SWCC yields gravimetric water content and suction, which is then fit with an empirical equation. For this research, the following empirical equations are used to describe the SWCC data. Equation (1) was presented by Fredlund and Xing (1994).

$$w(\psi) = \frac{w_s \left(1 - \ln \left(1 + \psi/\psi_r\right) / \ln \left(1 + 10^6/\psi_r\right)\right)}{\left(\ln \left(\exp \left(1\right) + \left(\psi/\alpha_f\right)^{nf}\right)^{mf}\right)}$$

Where $w(\psi)$ is the water content at any soil suction $\psi$, $w_s$ is the initial saturated gravimetric water content, and $\alpha_f$, $n_f$, $m_f$, $\psi_r$ are curve fitting parameters.
Some materials in this research have a bimodal SWCC, therefore the simplified bimodal equation proposed by Zhang and Chen (2005) is also employed (Equation (2)). This equation will be used where applicable.

\[
w(\psi) = w_s \left[ 1 - \frac{\ln \left( 1 + \frac{\psi}{\psi_{rb}} \right)}{\ln \left( 1 + 10^6 \frac{\psi}{\psi_{rb}} \right)} \left( \frac{p}{\ln \left( \exp (1) + \left( \frac{\psi}{a_{f1}} \right)^{n_{f1}} \right)} \right)^{m_{f1}} + \left( \frac{1-p}{\ln \left( \exp (1) + \left( \frac{\psi}{a_{f2}} \right)^{n_{f2}} \right)} \right)^{m_{f2}} \right]
\]

(2)

Where \(w(\psi)\) is the water content at any soil suction \(\psi\), \(w_s\) is the initial saturated gravimetric water content, \(p\) is a weighting factor between 0 to 1.0 used to divide the bimodal behavior, and \(a_{f1}, n_{f1}, m_{f1}, a_{f2}, n_{f2}, m_{f2}, \psi_{rb}\) are curve fitting parameters.

All of the soils tested in this research were high volume change materials. To attain the different SWCCs for these materials, the shrinkage was described using Equation (3) proposed by Fredlund (2000).

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

(3)

Where \(e(w(\psi))\) is the void ratio as a function of the suction of the soil, \(a_{sh}\) is the minimum void ratio, \(b_{sh}\) is the slope of the line of tangency, and \(c_{sh}\) is the curvature of the shrinkage curve.

The best-fitting equation for the S-SWCC can then be attained using Equation (4).

\[
S(\psi) = \frac{G_s w(\psi)}{e(w(\psi))}
\]
Estimating the SWCC from the SFCC

A soil dependent constant (SDC) can be used to relate the SWCC and the SFCC. Koopmans and Miller (1966) determined that the constant was about 2.2 for a colloid-free soil and about 1.0 for a colloidal soil. For soils that are a mixture of these two types the constant is somewhere between 1.0 and 2.2.

In order to compare the SFCC to the SWCC, temperature measurements are converted to matric potential or suction using the Clapeyron equation. Spaans and Baker (1996) provided an integrated form of the Clapeyron equation as shown in Equation (5), which has been used for this research.

\[
\phi = \psi + \pi = -712.38 \ln \left( \frac{T}{T_0} \right) + 5.545(T - T_0) - 3.14 \times 10^{-3}(T^2 - T_0^2)
\]

Where \( \phi \) is the total potential in kJ/kg, \( \psi \) is the soil matric potential in kJ/kg, \( \pi \) is the soil osmotic potential in kJ/kg, and \( T_0 \) is a reference temperature (273.15 K). In this research, SWCCs estimated from the SFCC will be denoted as SWCC-F.

Time Domain Reflectometry

Time domain reflectometry (TDR) is an electromagnetic technique that measures the dielectric constant of soil by measuring the travel time of an electromagnetic wave in the soil (Benson and Bosscher 1999; Sorta et al. 2013; Topp et al. 1980). The water content (frozen or unfrozen) of the soil can then be determined using empirical correlation equations or dielectric mixing models that relate the water content to the apparent dielectric constant \( (K_a) \). In this research, the following empirical correlations were used: Equation (6) (Topp et al. 1980), Equation (7) (Sorta et al. 2013), and Equation (8) (Smith and Tice 1988). Topp et al.’s (1980) calibration was developed under unfrozen conditions on soils that varied from sandy loam to heavy clay. Sorta et al.’s (2013) calibration was developed under unfrozen conditions on oil sands tailings. Smith and Tice’s
(1988) calibration was developed under frozen conditions using nuclear magnetic resonance (NMR) and TDR for a variety of saturated soils to relate the unfrozen volumetric water content ($\theta_u$) to $K_a$.

$$\theta = 4.3 \times 10^{-6} K_a^3 - 0.00055 K_a^2 + 0.0292 K_a - 0.053$$

$$\theta = -3.08 \times 10^{-7} K_a^3 - 7.4 \times 10^{-5} K_a^2 + 0.0205 K_a - 3.04$$

$$\theta_u = -0.1458 + 0.03868 K_a - 0.0008502 K_a^2 + 9.920 \times 10^{-6} K_a^3$$

In addition to these empirical equations, soil specific empirical correlations were performed under unfrozen conditions and applied to frozen conditions for the different soils. The calibrations were not conducted under frozen conditions as a secondary instrument (i.e. NMR) is required for this type of calibration.

**MATERIALS AND METHODS**

**Experimental Program**

The first phase of testing involved developing and validating an experimental method and apparatus to determine the SFCC. The validation was accomplished by performing SFCC testing on Devon silt that was consolidated to a pressure of 100 kPa. The results were compared to those presented by Azmatch et al. (2012a; 2012b) who performed SFCC testing on Devon silt and used the results to estimate the SWCC. The second phase of testing involved extending the SFCC methodology to different tailings slurries, including copper tailings, gold tailings, and oil sands centrifuge cake. In addition to the SFCC testing, index tests, traditional SWCCs, and shrinkage tests were conducted on all of the materials.
**Experimental Method**

The experimental apparatus consists of a temperature control bath that circulates glycol into an insulated box. The glycol is then circulated around the sample using brass coils. The sample sits on an elevated platform to promote isotropic freezing. One RTD probe and one TDR probe are inserted into the sample at marked locations to measure the temperature and the $K_a$ of the soil, respectively. The probes are stabilized using a clamping system. Two additional RTD probes are placed in the insulated box to monitor the ambient air temperature. The TDR probe used for this experiment has three rods with a diameter of 1.6 mm, a spacing of 8 mm, and a free length of 75 mm (Campbell Scientific-CS640). A fan is placed in the corner of the box to circulate air. The entire apparatus is placed in a temperature controlled room to limit the impacts of room temperature fluctuations on the testing. An example of a test set-up inside the freezing cell is shown in Figure 1.

The experimental method is as follows:

1. Prepare the sample and allow it to sit for 24 hours. This may include mixing the sample with process water or distilled water from a dry state to a non-segregating slurry. The Devon silt, copper tailings, and gold tailings were prepared using distilled water. All testing on the oil sands centrifuge cake proceeded with process water.

2. The diameter, length, and mass of the container are recorded, and gravimetric water content measurements are made.

3. The sample is transferred into a container with a diameter of approximately 99 mm and a height of approximately 111 mm. Care is taken to limit the introduction of air voids. The combined mass of the sample and the container are determined. The height and diameter of the Devon silt samples varied from this as it was not tested as a slurry. The Devon silt
samples were approximately 110 mm to 120 mm in height with a diameter of approximately 100 mm.

4. The top of the sample is marked to determine the locations that the RTD and TDR should be inserted to ensure that they are equidistant from the edges. The TDR and RTD are inserted at a distance of 30 mm from the outer edge of the container to prevent interference between the probes and promote simultaneous freezing of the soil adjacent to the two probes for accurate test results. The RTD is considered accurate to the nearest 0.01°C. The error associated with TDR measurements is dependent on a variety of factors, including the material, salinity, and water content. In general, TDR errors resulted in a maximum of a 2.5 percent volumetric water content spread at a given temperature. The highest errors were observed with the Devon silt which is attributed to the consolidation of the material and the potential for air voids adjacent to probes.

5. The sample is placed in the freezing cell on the platform and the RTD and TDR are inserted to the same depth, which is equivalent to the length of the TDR probe (75 mm). The inside dimensions of the insulated box are approximately 520 mm x 405 mm x 285 mm. The outside dimensions of the insulated box are approximately 725 mm x 535 mm x 470 mm.

6. The temperature of the cell is set at approximately 0°C.

7. The freezing test is initiated when the temperature in the sample reaches 0.5°C.

8. The temperature in the freezing cell is decreased to about -2°C to initiate freezing.

9. The sample is monitored until the temperature and the output from the TDR (K_a) in the sample stabilizes. At this point, the temperature in the freezing cell is decreased again by decreasing the temperature bath. The temperature bath is decreased in 4°C increments. It should be noted that this decrease does not result in 4°C drops in the freezing cell. As the
temperatures get lower, the efficiency of the temperature bath decreases and the
temperature drops in the freezing cell and sample will decrease.

10. This process is continued until minor changes in the $K_a$ value are observed.

11. The temperature in the cell is then increased to 0°C to initiate thawing.

12. Once thawing is complete, photographs are taken of the sample and gravimetric water
content measurements are made.

The results from the SFCC test yields temperature measurements from the RTD and $K_a$
measurements from the TDR. In order to estimate the SWCC from the SFCC, the temperature is
converted into suction using Equation (5) and the $\theta_u$ is determined from the $K_a$ using an existing
TDR calibration or a soil specific TDR calibration. The soil specific calibrations consisted of
preparing samples to different known $\theta$s and measuring the $K_a$ of the mixture by fully inserting the
TDR probe into the center of the sample which yielded a relationship between the $K_a$ and the $\theta$.
The calibration was then used to determine the $\theta_u$ under frozen conditions. Then, the following is
performed to estimate the SWCC from the SFCC:

1. The material is assumed to be colloidal or non-colloidal and an appropriate SDC is selected
(Koopmans and Miller 1966).

2. The unfrozen gravimetric water content and $\theta_u$ are assumed to be equal to the gravimetric
water content and $\theta$ during drying, respectively. This yields an estimated w-SWCC-F and
$\theta$-SWCC-F.

3. High volume change property functions are applied (if appropriate) to attain the estimated
$\theta_i$-SWCC-F and S-SWCC-F.
With high volume change materials, it is important to develop the S-SWCC using the shrinkage curve to attain the true AEV. The AEV was estimated using the graphical method presented by Vanapalli et al. (1998) from the S-SWCC. It is important to note that this method assumes that volume change does not occur during the freezing process.

**Material Properties**

Index testing was performed on the tested soils where relevant to help classify the material behavior, including water content determination (ASTM D2216-10), Atterberg limits testing (ASTM D4318-10), specific gravity testing (ASTM D854-14 using vacuum deairing), and grain size distribution (GSD) (ASTM D422-63). The specific gravity and Atterberg limits of the materials are presented in Table 1. The GSDs of all tested materials are presented in Figure 2. The materials tested had different GSDs to determine the range of materials that this method would be applicable to.

Traditional SWCC tests were conducted on the soils for comparison to the SWCC-Fs. The SWCCs were conducted in accordance with ASTM D6836 using Method A, Method C, and Method D.

Shrinkage testing was also conducted using the methods described by Zhang (2016) and Fredlund et al. (2011). The shrinkage curves for the tested materials are provided in Figure 3. It should be noted that the shrinkage test data was fit with Equation (3) and only the fitted curves have been provided in Figure 3. The best-fitting parameters to Equation (3) are provided in Table 2.

**EXPERIMENTAL RESULTS**

SFCC testing was performed on Devon silt, copper tailings, gold tailings, and oil sands centrifuge cake using the developed experimental method. Table 3 provides a summary of the conditions of
the test, number of tests conducted for each material, the TDR calibration used, the SDC used, and
the equation used to fit the laboratory data.

**Devon Silt**

The SFCC laboratory data was fit with Fredlund and Xing’s (1994) equation (Equation (1)) to
attain the \( \theta \)-SWCC-F, which was compared to the results presented by Azmatch et al. (2012a) as
shown in Figure 4. Of the six tests performed, five showed good agreement with the Fredlund and
Xing (1994) fit from Azmatch et al. (2012a). Sample DS8 did not show good agreement, which
is thought to be a result of segregation prior to the beginning of consolidation resulting in a
different GSD throughout the sample height.

Devon silt was also tested by Zhang (2016) who noted that the material was a high volume change
material and conducted shrinkage testing and traditional SWCC testing. To further evaluate the
Devon silt results, high volume change properties were applied to the SFCC test data using the
shrinkage curve measured by Zhang (2016). The resulting S-SWCC-Fs were fit with Zhang and
Chen’s (2005) simplified bimodal equation (Equation (2)) and compared to the results presented
by Zhang (2016) as shown in Figure 5. A comparison between the degree of saturation predicted
from the S-SWCC-F and the degree of saturation measured by Zhang (2016) is provided in Figure
6. The AEV for the Devon silt samples was determined from the S-SWCC-F and the results are
provided in Table 4. The AEV varied from 410 kPa to 3180 kPa. If Sample DS8 is eliminated, the
AEV ranged from 410 kPa to 820 kPa. The AEV determined by Zhang (2016) was 590 kPa.

Variation was also observed between the experimental data and the data presented by
Zhang (2016) at higher suctions as shown in Figure 5 and Figure 6. In the higher suction range,
Zhang’s (2016) best fitting curve yields a lower degree of saturation for a given suction. This
difference is attributed to the use of Topp et al.’s (1980) TDR calibration to attain the \( \theta_u \) from the \( K_a \).

**Copper Tailings**

The copper tailings S-SWCC-Fs were fit with Zhang and Chen’s (2005) simplified bimodal equation (Equation (2)) and compared to results from a S-SWCC as shown in Figure 7. A comparison between the degree of saturation predicted from the S-SWCC-F and the degree of saturation measured using traditional SWCC methods is provided in Figure 8. Overall, a good fit was attained between the S-SWCC-F and the S-SWCC in the high suction range.

The AEV for the copper tailings was determined from the saturation curves, and the results are provided in Table 4. The AEV for the S-SWCC-Fs ranged from 160 kPa to 220 kPa. The AEV determined from the S-SWCC was 120 kPa, which is approximately 40 kPa to 100 kPa less than the AEVs determined for Sample CT1, CT2, and CT3. Despite the good fit in the high suction range, the slopes of the S-SWCC-Fs and the S-SWCC varied. The difference in the AEVs and the slopes is thought to be due to the selected SDC and/or the TDR calibration.

**Gold Tailings**

The S-SWCC-Fs were fit with Fredlund and Xing’s (1994) (Equation (1)) and compared to results from a S-SWCC measured by Zhang (2016) as shown in Figure 9. A comparison between the degree of saturation predicted from the S-SWCC-F and the degree of saturation measured by Zhang (2016) is provided in Figure 10.

The AEV for the gold tailings was determined from the saturation curves, and the results are provided in Table 4. The AEV for the S-SWCC-Fs ranged from 100 kPa to 110 kPa. The AEV determined by Zhang (2016) was 90 kPa, which is approximately 10 kPa to 20 kPa less than the
AEVs determined for Samples BG1, BG2, and BG3. Overall, a good fit was attained between the S-SWCC-F and the results presented by Zhang (2016). The best-fitting curves all had similar slopes. Variation was observed between the experimental data and the data presented by Zhang (2016) at higher suctions. In the higher suction range, Zhang’s (2016) best fitting curve yields a higher water content/degree of saturation for a given suction.

There is also a difference between the S-SWCC and the S-SWCC-F below the AEV suction as shown in Figure 9. This could be attributed to how the SFCC and SWCC are measured. A suction of approximately 1.2 kPa equates to a temperature of approximately .001°C. The RTDs used for this experiment are only accurate to the nearest 0.01°C. As a result, it is difficult to get an accurate temperature reading in this suction range.

**Oil Sands Centrifuge Cake**

The S-SWCC-Fs were fit with Zhang and Chen’s (2005) simplified bimodal equation (Equation (2)) and compared to results from a S-SWCC as shown in Figure 11. A comparison between the degree of saturation predicted from the S-SWCC-F and the degree of saturation measured using traditional SWCC methods is provided in Figure 12.

The centrifuge cake testing results further showed that this method was repeatable and reliable for a slurry as the SWCC-Fs yielded similar curves; however, more variation was observed between the four samples compared to the copper and gold tailings samples. This variation is likely a result of the high gravimetric water content (approximately 92 percent) of the centrifuge cake. The high gravimetric water content has two direct impacts:

- Increased probability of movement of probes after insertion; and
- Increased water migration and potential for ice pockets to develop adjacent to probes.
The AEV for the centrifuge cake was determined from the saturation curves, and the results are provided in Table 4. The AEV for the S-SWCC-Fs ranged from 160 kPa to 290 kPa. The AEV determined from the S-SWCC was 1450 kPa. This AEV is significantly higher than the AEVs determined for Samples CC1 to CC4. This mismatch clearly shows the poor fit between the SWCC-Fs and SWCC. The poor fit is thought to be a result of the TDR calibration.

**DISCUSSION**

**TDR Calibration**

The fit of the SWCC-F with the SWCC is highly dependent on the TDR calibration. As the purpose of this research is to provide a simple alternative to conducting a time-consuming, challenging SWCC test, soil specific TDR calibrations were performed under unfrozen conditions and applied to frozen conditions. This methodology is supported by a number of authors who have shown that calibrations developed for unfrozen saturated soils can be used on frozen soils with success (Azmatch et al. 2012a; Azmatch et al. 2012b; Patterson and Smith 1981).

Regardless, this method of calibration may result in a number of complications. Some authors suggest that that $\theta_u - K_a$ calibrations developed for unfrozen soils should not be applied to frozen or partially frozen soils as the $\theta_u$ will generally be overestimated with increasing total water content or increasing specific surface area (SSA) (Flerchinger et al. 2006; Seyfried and Murdock 1996; Spaans and Baker 1995; Watanabe and Wake 2009; Zhou et al. 2014). However, the majority of this body of research was conducted on unsaturated natural soils, many of which were tested in situ where the total water content was unknown. The mine waste tailings that were tested for this research were fully saturated. The $\theta_u$ will generally be overestimated with increasing total water content or increasing SSA due to the following:
• The dielectric constant of ice (3.2) is higher than air (1.0) (Flerchinger et al. 2006; Spaans and Baker 1995; Watanabe and Wake 2009). When a TDR calibration is conducted under unfrozen conditions, the air phase may be present. When the calibration is then applied to frozen conditions, the air phase (whether or not present) is replaced by the ice phase with a different dielectric constant. These issues will be amplified when the sample is unsaturated prior to the freezing process and there is ice and air present during the freezing process. As the tailings tested were fully saturated, this is expected to be a minor contributor to the overestimation of the $\theta_u$.

• The $K_a$ of the soil is influenced by the unfrozen water content, ice content, air, and soil; however, the $\theta_u$ is only affected by the temperature (Flerchinger et al. 2006; Seyfried and Murdock 1996; Spaans and Baker 1995; Watanabe and Wake 2009; Zhou et al. 2014). When the sample is fully saturated, as in the case of the tailings, the $K_a$ will be influenced by the unfrozen water content, ice content, and soil during freezing.

• As the SSA of a soil increases, the amount of adsorbed water will increase. The adsorbed water has a lower dielectric constant than the bulk water (Smith and Tice 1988; Watanabe and Wake 2009).

The overestimation of the $\theta_u$ was clearly observed in the case of the Devon silt where the experimental data showed a higher degree of saturation than the measured SWCC data for a given suction using Topp et al.’s (1980) calibration as shown by Figure 5 and Figure 6. In the higher suction range, Zhang’s (2016) best fitting curve yields a lower degree of saturation for a given suction.

The impact of the TDR calibration on the overall fit was investigated for each material by using a variety of calibrations to estimate the S-SWCC-F for comparison to the S-SWCC. It should be
noted that not all calibration equations were applied to all of the materials. Of the calibrations
conducted by other authors, the Smith and Tice (1988) is the only calibration that was conducted
under frozen conditions using NMR and TDR. The comparisons for Devon silt, copper tailings,
gold tailings, and the oil sands centrifuge cake are provided in Figure 13, Figure 14, Figure 15,
and Figure 16, respectively. For the Devon silt and the gold tailings, the best fit to the S-SWCC
was attained using the Smith and Tice (1988) calibration as shown in Figure 13 and Figure 15.

For the copper tailings, the Topp et al. (1980) calibration, the Smith and Tice (1988) calibration,
and the soil specific calibration yielded very different S-SWCC-Fs as shown in Figure 14. Overall,
the Smith and Tice (1988) calibration and the soil specific calibration provided the best fit to the
S-SWCC. However, the Topp et al. (1980) calibration had the closest slope to the S-SWCC. This
suggests that the calibration for frozen conditions for the copper tailings is somewhere between
these three calibrations.

For the oil sands centrifuge cake, the soil specific TDR calibration and the Smith and Tice (1988)
calibration provide very similar curves, while the Sorta et al. (2013) and Topp et al. (1980)
calibrations provide similar results as shown in Figure 16. The soil specific TDR calibration and
the Smith and Tice (1988) calibration provide the worst fit to the SWCC. The poor fit with the
Smith and Tice (1988) calibration is likely due to the high fines content of the centrifuge cake.
Smith and Tice (1988) suggested that the $K_a$ for a given $\theta_u$ decreases with increasing fines content.
As the fines content increases (and the SSA), the amount of adsorbed water will also increase and
result in an overall decrease in the $K_a$ at a given $\theta_u$. Smith and Tice’s (1988) calibration worked
well on a variety of soils with the exception of high SSA soils where the water contents predicted
by the calibration were noticeably lower than the corresponding NMR values. As a result, it is
likely that the actual calibration is somewhere between the Topp et al. (1980) and Smith and Tice
(1988) calibration. Regardless of the TDR calibration, the SWCC-F will not provide a good fit to the SWCC for the oil sands centrifuge cake.

Another issue with developing soil specific TDR calibrations on unfrozen soil is due to the problems associated with testing materials at low water contents as it is very difficult to create a homogeneous mix below a gravimetric water content of 15 percent. Ultimately, this requires assumptions to be made regarding the $K_a$ of the soil below a water content of 15 percent. These assumptions are problematic as many soils will not begin to de-saturate until gravimetric water contents around 20 percent. In these cases, much of the S-SWCC-F will be based on assumptions rather than TDR calibration measurements. As discussed, there was variation observed between the gold tailings experimental data and the data presented by Zhang (2016) in the high suction range, as shown by Figure 9. This variation is attributed to the development of the soil specific calibration where it was assumed that the gold tailings would completely freeze with an unfrozen water content of zero based on the low clay content. Based on the poor fit of the soil specific calibration with the data presented by Zhang (2016) in the high suction range and the better fit with Smith and Tice (1988) (Figure 15), it is likely that this assumption was incorrect. These issues may be avoided if the TDR calibration were conducted under frozen conditions using a secondary method such as NMR.

As shown by Figure 13, Figure 14, Figure 15, and Figure 16, not one calibration equation worked better than the others, although the Smith and Tice (1988) calibration performed well overall with the exception of the oil sands centrifuge cake. The TDR calibration poses a problem with using this method as a reliable way of estimating the SWCC. However, the method is useful as a screening tool for metal tailings to rapidly test a large number of tailings to determine which should have detailed traditional SWCCs.
TDR Errors

Aside from the TDR calibration, a number of other TDR errors could be responsible for variation in lab data. Errors in TDR measurements may occur when there are air gaps between the probe and the soil from installation, which can result in significant underestimation of the $K_a$ (Sorta et al. 2013; Topp and Davis 1985). Air gaps may also develop after installation due to shrinkage and swelling (Topp and Davis 1985). As discussed, the Devon silt was consolidated to a pressure of 100 kPa prior to testing resulting in a solid free-standing sample with gravimetric water contents that ranged from approximately 20 percent to 25 percent, which is close to the Devon silt’s plastic limit of 20 percent. As a result, it is suspected that air gaps are responsible for the variation in the AEV. It should also be noted that the research conducted by Azmatch et al. (2012b) showed that the ice entry value (IEV) increased with a decrease in the initial void ratio. The IEV is considered to be an analogue for the AEV and is the temperature that ice first begins to enter the largest pores in the soil (Azmatch et al. 2012b). As a result, it is suspected that variations in the initial void ratio may have also contributed to the variation in the AEV.

Signal attenuation due to high electrical conductivity may also cause problems with TDR measurements. This may limit the application of this technology in the oil sands industry as oil sands tailings often have high electrical conductivity. Additionally, in order for a material to be tested using TDR, it must be non-segregating. Segregation will negatively impact the test results as the material tested by the probes may not be representative of the overall soil behavior. These issues were not encountered in this research.

SDC Parameter

Estimating the SWCC-F relies on the selection of a soil dependent constant (SDC) (Koopmans and Miller 1966). Selection of the SDC may be problematic in cases where the soil cannot be
classified as purely colloidal or non-colloidal. For example, the copper tailings were assumed to be colloidal based on the clay content and plasticity of the material. As a result, a SDC of 1.0 was used for this material. Due to the mixture of coarse and fine sized particles present in this material, it is possible that it cannot be simply classified as a colloidal or colloid-free soil. To investigate this, the S-SWCC was estimated from the SFCC using SDCs of 1.0, 1.5, and 2.2 for Sample CT2 as shown in Figure 17. The SDC of 1.5 appears to provide the best fit to the SWCC in terms of the AEV. Based on this, it is likely that the SDC for the copper tailings is between 1.0 and 2.2. This clearly shows the reliance of the S-SWCC-F on the selection of the SDC.

**Supercooling**

Supercooling was experienced throughout the experimental program (Kozlowski 2009). For samples where supercooling was encountered, the data points associated with this action were not considered representative of the SFCC and were eliminated from the test data to allow for the SWCC to be estimated. Ideally, the SFCC would be estimated from the thawing curve as supercooling does not occur during thawing (Kozlowski 2009). Due to the high initial water contents of the materials tested, the freezing SFCC was considered more reliable than the thawing SFCC as the TDR and RTD probes move substantially and a lot of water may be released during the thawing process. As a result, the freezing SFCC was used to estimate the drying SWCC for this experiment despite the effects of supercooling.

**Other Impacts**

Another challenge of estimating the SWCC-F is the influence of solutes. The SWCC is not impacted by the presence of solutes in the soil (Azmatch et al. 2012a). In contrast, solutes will result in a decrease in the freezing point of the pore water which leads to a decrease in the unfrozen water content at a given temperature (Hivon 1991). Ultimately, this freezing point depression...
leads to a mismatch in the SWCC and SFCC. All materials were tested using distilled water with the exception of the oil sands centrifuge cake. However, the poor fit attained between the SWCC-F and the SWCC for the centrifuge cake is not thought to be a result of the salinity of the centrifuge cake. In general, solutes tend to shift the SFCC towards lower temperatures (i.e. higher suctions) (Anderson and Morgenstern 1973; Azmatch et al. 2012a). Based on this, it is expected that the SWCC-F would be shifted to the right of the SWCC if the salinity of the centrifuge cake was responsible for the mismatch, which is the opposite of the actual results as shown in Figure 11.

The electrical conductivity of the centrifuge cake was measured to be 3890 µs/cm, corresponding to a sodium chloride concentration of approximately 2425 mg/L based on Beier (2006). This concentration is less than the salinity of samples used to study the impacts of salinity on the SFCC by many authors (Azmatch et al. 2012a; Ma et al. 2015). As a result, it is thought that the high water content, clay content, and adsorbed water are responsible for the mismatch between the SWCC-Fs and the SWCC.

CONCLUSIONS

SFCC testing was performed on a variety of materials with different GSDs, including Devon silt, copper tailings, gold tailings, and oil sands tailings. The SFCCs were used to estimate the SWCC for comparison to traditional SWCCs. Based on the results of the testing, the following conclusions can be made:

- The method appears to be applicable to metal tailings that have large quantities of sand sized particles with less than 25 percent of material smaller than 75 µm. In general, it is recommended that a shrinkage test be conducted in conjunction with the SFCC testing so that a S-SWCC-F can be attained for determination of the AEV.
• It may be difficult to specify tailings as purely colloidal or non-colloidal and therefore the selection of a soil dependent constant may not be obvious.

• Regardless, this method is useful as a screening tool as it can be used to rapidly test a large number of tailings to decide which materials should have traditional SWCCs conducted.

• At the current time, it does not appear that this method can be used to estimate the SWCC from the SFCC for oil sands tailings. This is attributed to the high clay content (and associated adsorbed water) and water content of the tailings. Based on the results of the testing, it does not appear that the salinity of the centrifuge cake is responsible for the mismatch between the SWCC-F and the SWCC.

• If the SFCC method is to be used for more than just screening tests, then it is recommended that the TDR calibration be conducted using two methods (i.e. NMR and TDR) under frozen conditions. Conducting a soil specific calibration under unfrozen conditions and applying it to frozen conditions resulted in a large degree of uncertainty with respect to the low water content range. This uncertainty is concerning as this may correspond with desaturation of the material, which is a critical portion of the estimated SWCC. Requiring two methods for TDR calibration may limit the adoption of estimating the SWCC from the SFCC as NMR and other methods are expensive and complex to use compared to TDR alone. In these cases, it may be easier to conduct a traditional SWCC.

ACKNOWLEDGEMENTS

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and to Dr. Louis Kabwe and Christine Hereygers for their assistance with the laboratory component.
REFERENCES


### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( w )</td>
<td>Gravimetric water content</td>
</tr>
<tr>
<td>( w_s )</td>
<td>Saturated gravimetric water content</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Volumetric water content</td>
</tr>
<tr>
<td>( \theta_u )</td>
<td>Unfrozen volumetric water content</td>
</tr>
<tr>
<td>( \theta_i )</td>
<td>Instantaneous volumetric water content</td>
</tr>
<tr>
<td>( S )</td>
<td>Degree of saturation</td>
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<td>( \text{SWCC-F} )</td>
<td>Soil water characteristic curve estimated from the soil freezing characteristic curve</td>
</tr>
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<td>( w\text{-SWCC} )</td>
<td>Gravimetric water content soil water characteristic curve</td>
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<tr>
<td>( \theta\text{-SWCC} )</td>
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<tr>
<td>( \theta_i\text{-SWCC} )</td>
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<td>( w(\psi) )</td>
<td>Gravimetric water content at any soil suction</td>
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<td>( p )</td>
<td>Weighting factor between 0 to 1.0 used to divide bimodal behavior</td>
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<td>( e(w) )</td>
<td>Void ratio at any gravimetric water content</td>
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<tr>
<td>( b_{sh} )</td>
<td>Slope of the line of tangency on a shrinkage curve</td>
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<tr>
<td>( c_{sh} )</td>
<td>Curvature of the shrinkage curve</td>
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<td>( \varphi )</td>
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<td>( \pi )</td>
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<td>Temperature</td>
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<tr>
<td>( K_a )</td>
<td>Apparent dielectric constant</td>
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Table 1: Specific gravity and Atterberg limits for tested materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Liquid Limit (%)</th>
<th>Plastic Limit (%)</th>
<th>Plasticity Index (%)</th>
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Table 2: Shrinkage curve best-fitting parameter (Equation 3)

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<th>(c_{sh})</th>
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<td></td>
<td>BG3</td>
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<td>Zhang (2016)</td>
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<td>CC1</td>
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152x117mm (300 x 300 DPI)
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152x117mm (300 x 300 DPI)
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