HYSTERESIS OF THE SOIL-WATER CHARACTERISTIC CURVE IN THE HIGH SUCTION RANGE

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ABSTRACT
An experimental research program has been carried out on Clay and Clayey Silt to investigate hysteresis of the SWCC in the high suction range. Total soil suction values were measured using a dew-point “Water PotentiaMeter”, WP4-T, and the results were compared with those obtained through equilibration of a small soil sample placed over saturated salt solutions. Measurements on the drying and wetting soil-water characteristic curves indicated some hysteretic effects for the Clay soil; while the observed hysteresis for the Clayey Silt was almost imperceptible. Higher suction values were measured when using the WP4-T apparatus for soil suctions less than 50,000kPa. Further measurements of equilibrium soil suctions using a Traceable Hygrometer showed that the higher suction values obtained from the WP4-T may be related to a slightly reduced relative humidity inside some of the chambers.

RÉSUMÉ
Un programme de recherche expérimental a été effectué sur l'argile et la vase argileuse pour étudier l'hystérésis du SWCC dans les gammes élevées d'aspiration. Des valeurs totales d'aspiration de sol ont été mesurées en utilisant un potentiomètre à eau avec point de condensation, WP4-T, et les résultats ont été comparés à ceux obtenus par l'équilibration d’un petit échantillon de sol placé au dessus de solutions de sels saturées. Les mesures sur les courbes caractéristiques sol-eau durant les cycles de séchage/mouillage ont indiqué quelques effets d’hystérésis pour le sol d'argile; tandis que l'hystérésis observée pour la vase argileuse était presque imperceptible. Des valeurs plus élevées d'aspiration ont été mesurées à l'aide de l'appareillage WP4-T pour des aspirations de sol moins que 50,000 kPa. D'autres mesures des aspirations de sol d'équilibre à l'aide d'un hygromètre décelable ont montré que les valeurs d'aspiration plus élevées obtenues à partir du WP4-T peuvent être liées à une humidité relative légèrement réduite à l’intérieur de certaines cuves.

1 INTRODUCTION

The Soil-Water Characteristic Curve, SWCC, relationship between soil suction and water content, has played a key role in implementing unsaturated soil mechanics into geotechnical engineering practice (Fredlund 2000). Numerous models have been developed for the estimation of the coefficient of permeability and shear strength through use of the SWCC. Hysteresis results in a difference between suction on the drying and wetting curves. Hysteresis has long been known to be of relevance when modeling water flow in the low range of suction. Studies on hysteresis have been primarily limited to the low suction range on the SWCC.

Different methods have been used to measure soil suction in the high suction range. The primary method has involved using equilibration of small soil samples over salt solutions of known osmotic suction (Fredlund, 1964; and Campbell and Gee 1986), or by thermocouple psychrometry (Fredlund and Rahardjo, 1993; and Rawlins and Campbell, 1986). The former method is time consuming, while the latter method is limited to the maximum suction of 8000 kPa (Fredlund and Rahardjo, 1993).

Another method of measuring high soil suction is to measure the water activity. The principles involved in the method are similar to that of the hygrometric technique of thermocouple psychrometry. The methodology was presented by Gee et al. (1992). The method is rapid and involves the measurement of water activity from 0.1 to 1 (i.e., suction of 0-316,000kPa). The device was first introduced as a water activity meter (Gee et al. 1992) and commercialized by Decagon Company. The dew-point Water PotentiaMeter, WP4, which has been used by several geotechnical researchers (Leong et al. 2003; Thakur et al. 2006; Agus and Schanz, 2005, Campbell et al. 2007) is a modification of the water activity meter. The dew-point Water PotentiaMeter, WP4, has also been called chilled-mirror dew-point psychrometer (Cardoso et al. 2007) or chilled-mirror hygrometer (ASTM D 6836-02, 2005). The decagon company recently added a new feature to the WP4 in order to prevent the effect of the temperature fluctuation of the ambient on the suction measurements. The new device with internal temperature control is termed WP4-T.

There are two primary objectives of this research paper; namely, i) to investigate the hysteresis of the SWCC relationship in the high soil suction range and ii) to compare the soil suction results from dew-point Water PotentiaMeter, WP4-T, with those from the equilibration of small soil samples placed over saturated salt solutions of known osmotic suction.

2 BACKGROUND

2.1 Relative Humidity and Total Suction

The relationship between the soil suction and the partial pressure of the pore-water pressure can be written as follows (Fredlund and Rahardjo, 1993):

$$\psi = -\frac{RT}{V_{wo}\omega_v}\ln\left(\frac{\bar{u}_v}{\bar{u}_{vo}}\right) \qquad [1]$$

where ψ is soil suction or total suction (kPa), R is the universal gas constant [i.e., 8.31432 (Jmol^{-1} K^{-1})], T is absolute temperature [i.e., T = (273.16 + t^o) (K)], t^o is temperature (^{o}C), V_{wo} is specific volume of water (kg/m^3), ω_v is molecular mass of water vapour (i.e., 18.016 kg/kmol), $\bar{u}_v$ is the partial pressure of pore-water vapour and $\bar{u}_{vo}$ is the saturation pressure of water pressure over a flat surface of pure water at the same temperature (kPa).

In Eq. 1 the term $\frac{\bar{u}_v}{\bar{u}_{vo}}$ is called relative humidity, RH, or water activity.

2.2 Hysteresis

Hysteresis results in a difference between suctions on the drying and wetting curves. Figure 1 shows schematic of the initial drying, main drying and main wetting soil-water characteristic curves from saturation (i.e., zero suction) to the completely dry condition (i.e., suction of 1,000,000 kPa). In the high range of suction, beyond the residual condition, it is usually assumed that there is a high suction value at which main drying and wetting curves meet. The existence of aforementioned meeting point will be tested for two types of soils in this research paper.

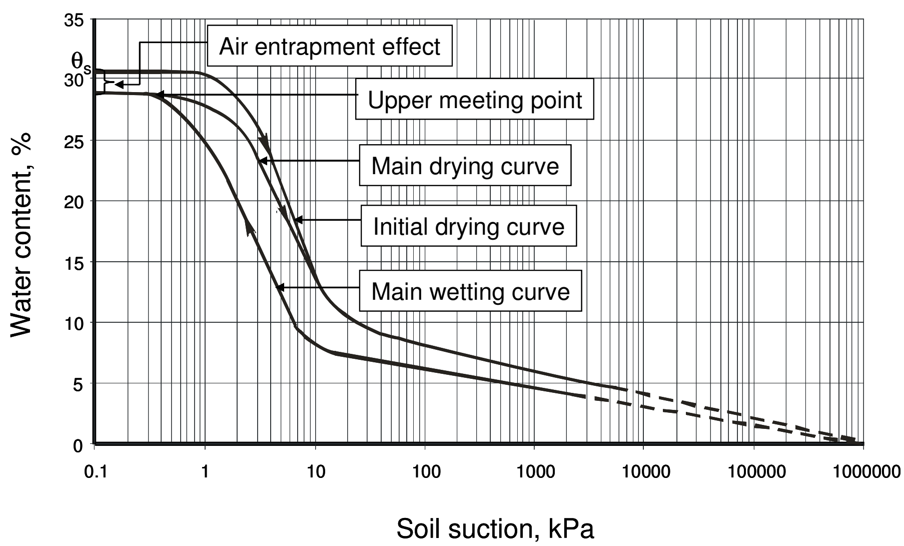


Figure 1. Schematic diagram of initial and main drying and main wetting SWCCs

3 TEST DEVICES

Two types of devices, the dew-point Water PotentiaMeter, WP4-T, and an air-tight chamber, ATC, are used to determine the suction of the soil samples at different moisture contents. The details of these devices are explained in the following sections.

3.1 Air-Tight Chamber (ATC)

One of the methods to measure the SWCC in the high suction range is through equilibrating the soil samples over salt solutions of known osmotic suction inside an airtight chamber. The salt solution creates a constant relative humidity inside the chamber for a given temperature. Various types of salts can be used; however, in some cases the accuracy may decline with time due to chemical instability. A plastic container can be used as an air-tight chamber provided the salt solution is placed in a dish made of a proper material, such as glass (ASTM E 104-02, 2003).

Small soil samples are placed and kept inside an air-tight chamber, with an environment of a known relative humidity created by a saturated salt solution, until the equilibrium condition is reached. At equilibrium the relative humidity and the temperature inside the chamber and within the soil pores are equal. The relative humidity inside the chamber is constant and is related to the saturated salt solution inside the chamber. Having the required data, relative humidity and temperature within the soil pores, the soil suction can be calculated using Eq. 1.

After the equilibrium condition is reached the gravimetrical water content of the soil samples is determined. Having the water contents and corresponding soil suctions, the soil-water characteristic curve can be determined. The resulted soil-water characteristic curve is drying if the soil samples are initially in saturated condition. It can be also wetting if the soil samples were initially in dry condition. The number of the required points on the SWCC determines the required number of various salt solutions, and therefore, the number of air-tight chambers.

The air-tight chambers and salt solutions used in this research will be explained in detail in section 4.2.

3.2 Dew-Point Water PotentiaMeter (WP4-T)

Figure 2 shows a schematic diagram of a dew-point Water PotentiaMeter, WP4 (Leong et al. 2003). The device consists of a sealed chamber with a fan, a mirror and a photoelectric cell, and an infrared thermometer. The soil sample is placed in a stainless steel or plastic container of approximately 40 mm diameter and slid into the chamber using a tray. The sample thickness may vary between 1 to 5mm. The chamber is closed and the sample becomes thermodynamically equilibrated with the environment inside the chamber before measurements can be made. The fan helps to accelerate the equilibration process. A peltier cooling system is used to reduce the temperature on the surface of mirror to dew-point temperature. The photoelectric cell detects the condensation on the mirror which first appears at dew point. The dew-point temperature is then measured by a thermocouple. The infrared thermometer is used to measure the temperature of the chamber which is assumed to be the same as the temperature of the soil specimen at equilibrium.

Vapour pressure above the soil sample in the chamber and the saturated vapour pressure at the same temperature are computed using the dew-point and specimen temperatures, respectively. Kelvin's equation (Eq.1) is then used to calculate the total suction of the specimen. The calculations are done by software within the device and the value of the total suction in MPa unit along with the specimen temperature is displayed on an LCD panel.

3.2.1 Evaluation of the WP4-T

The manufacturer instructions request that the WP4-T be calibrated prior to usage with a standard solution of

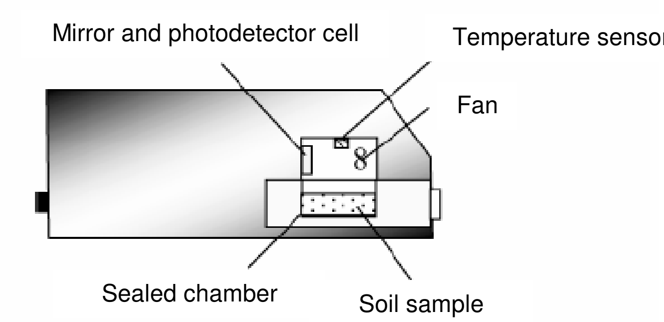


Figure 2. Schematic diagram of a chilled-mirror dew-point, WP4 device (from Leong et al. 2003)

0.5 M KCl, which should yield a suction of 2.19 ± 0.1 MPa, at 25 ^{o}C. Cardso et al. (2007) found that the calibration procedure suggested by the manufacturer for the WP4 device was not satisfactory. In the current research study in order to ensure the reliability of the calibration, the device was evaluated after calibrating through manufacturer instructions.

Different saturated salt solutions with known osmotic suction were prepared and the suction value was measured using the WP4-T. This was done in order to ensure that the apparatus was working properly. Figure 3 shows the theoretical suction values versus the measured values using the WP4-T device. Good agreement was obtained between the theoretical and measured values.

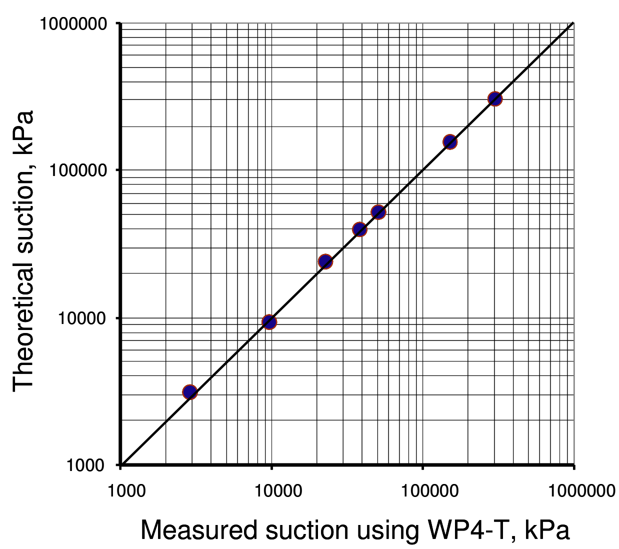


Figure 3. Theoretical and measured suction values using WP4-T for different saturated salt solutions

4 EXPERIMENTAL PROGRAM

To investigate the hysteresis of the SWCC in the high soil suction range and to compare the soil suction results from the dew-point Water PotentiaMeter, WP4-T, and the air-tight chamber, ATC, an experimental program was conducted on two types of soil. The properties of the soils, the saturated salt solutions used in the test, and test procedures are outlined in this section.

4.1 Properties of the Soils

Two types of soil were used in the experimental program; namely, Clayey Silt and Clay. Some of the properties of the soils were measured and listed in Table 1.

Table 1. Properties of the Clayey Silt and Clay used in this research

Soil Properties	Clayey Silt	Clay
Liquid Limit, %	20.3	81
Plastic Limit, %	15.1	23.1
Plasticity Index, %	5.2	57.9
Specific Gravity	2.71	2.7
Sand, %	35	5
Silt, %	45	21
Clay, %	20	74

4.2 Saturated Salt Solutions

The experimental tests were conducted in a temperature-controlled room with a constant temperature of 25 °C. Seven various saturated salt solutions with known osmotic suction (ASTM E 104-85, 1998 and E104-02, 2003) were made and placed at the bottom of the air-tight chambers. The constant relative humidities and corresponding suctions created by each solution are given in Table 2. According to the ASTM standards these salts can be used over a year (ASTM E 104-02, 2003).

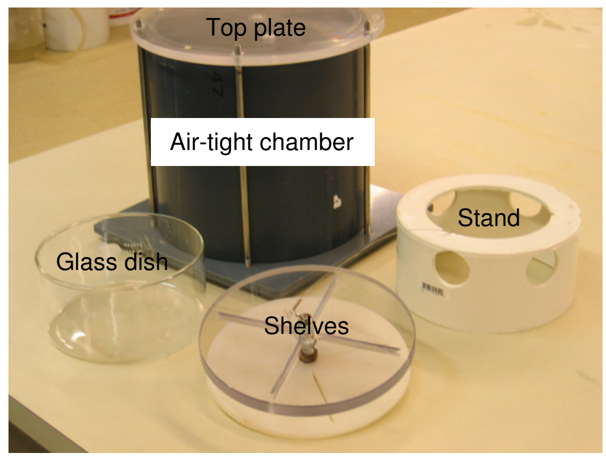
Table2. The saturated salt solutions and corresponding relative humidities (ASTM E 104-85, 1998 and E 104-02, 2003) and suction values calculated using Eq. 1 for t =25 °C

Salt Solution	Relative Humidity, %	Suction, kPa
Lithium Chloride	11.3 ± 0.3	300008
Magnesium Chloride	32.8 ± 0.2	153383
Potassium Iodide	68.9 ± 0.3	51256
Sodium Chloride	75.3 ± 0.2	39034
Potassium Chloride	84.3 ± 0.3	23500
Potassium Nitrate	93.6 ± 0.6	9100
Potassium Sulfate	97.3 ± 0.5	3766

4.3 Experimental Test Procedure

Twenty eight soil samples were prepared for each type of soil. Fourteen soil samples were saturated and the other fourteen were oven-dried. The saturated samples were used to determine the drying SWCC and oven-dried soil samples were used to determine the wetting SWCC. In each chamber eight soil samples, four Clayey Silt and four Clay samples were placed. Two of the four samples were oven-dried and two were saturated. The weight of the samples inside each chamber was monitored until there was no difference in weights between two consecutive weighings.

The air-tight chambers used in this research were built of PVC tubes at University of Saskatchewan (Dadgar, 2005). Seven identical air-tight chambers were used in this research. Figure 4 shows one of the air-tight chambers and its compartments. The chamber comprised a PVC tube of diameter 190mm and a height of 200mm with two plates at top and bottom. To ensure the prevention of the vapour diffusion O-rings were used between the plates and the tube.



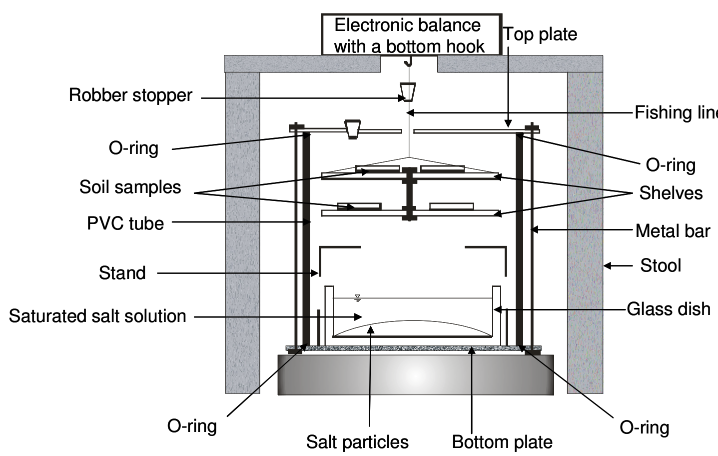


Figure 4. Air-tight chamber and its compartments

About 400-500cc of a saturated salt solution of known osmotic suction was prepared and poured in a glass dish. The glass dish was placed at the bottom of the air-tight chamber. Using a pair of shelves, eight individual soil samples were placed inside the chamber on a stand. Two length of fishing lines were attached to the top plexi-glass shelf to allow the samples to be easily lifted from the stand for weighing. The fishing lines passed through a hole made on the top plate of the chamber. The weight of the shelves along with the soil samples was monitored, without removing the soil samples from the chamber, using an electronic balance with a bottom hook (Figure 4). This weight changes with time due to adsorption or desorption. An equilibrium condition is reached when the weight stayed constant. It took about five month for the samples inside the chamber with higher humidity, RH= 97.3 ± 0.5, to reach the equilibrium condition. The higher the relative humidity inside the chamber, the higher the time required for equilibration. At equilibrium conditions, the relative humidity within the soil pores becomes the same as the relative humidity of the environment inside the chamber created by the saturated salt solution. Using Eq. 1 the relative humidity values were converted to the total suction values.

After the equilibrium condition was reached, four soil samples (two samples of each soil type, one oven-dried and one saturated) were taken from each chamber. The gravimetrical water contents were measured. The precision of the electronic balance for the measurement of water contents was 0.0001g. The other four samples from each chamber were used to measure total soil suction values with the WP4-T device.

5 TEST RESULTS AND DISCUSSION

5.1 Drying and Wetting SWCCs Using the Air-Tight Chamber

Figure 5 shows the drying and wetting curves for Clayey Silt and Clay measured using air-tight chambers, equilibration of soil samples over salt solutions of known osmotic suction. The difference between drying and wetting SWCCs (i.e., hysteresis) increases from high to low suction values in both soils. The difference between drying and wetting curves is greater for the Clay soil than the Clayey Silt. The meeting point of the drying and wetting curves for Clay is located at a soil suction value approaching 1,000,000 kPa.

5.2 Drying and Wetting SWCCs Using Dew-Point Water PotentiaMeter, WP4-T

Figure 6 shows the drying and wetting curves for Clayey Silt and Clay measured using the dew-point Water PotentiaMeter, WP4-T. As it can be seen, the results are similar to the results obtained from the air-tight chamber (see Figure 5). The hysteresis is more visible in the Clay than the Clayey Silt. The meeting point of the drying and wetting curves for Clay is located at a soil suction value approaching 1,000,000 kPa. The suction values measured using two devices, the WP4-T and air-tight chamber, are not quite similar (Figures 5 and 6).

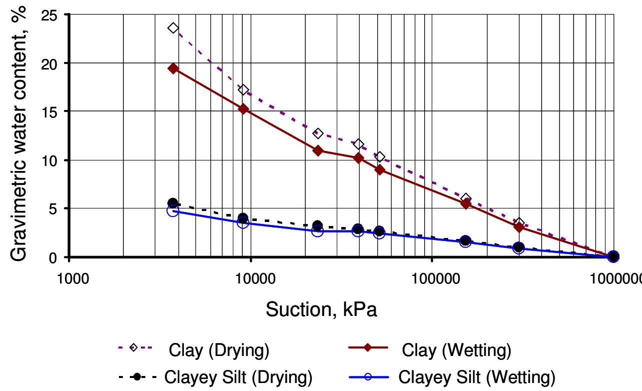


Figure 5. Drying and wetting SWCCs for Clay and Clayey Silt using Air-Tight Chamber

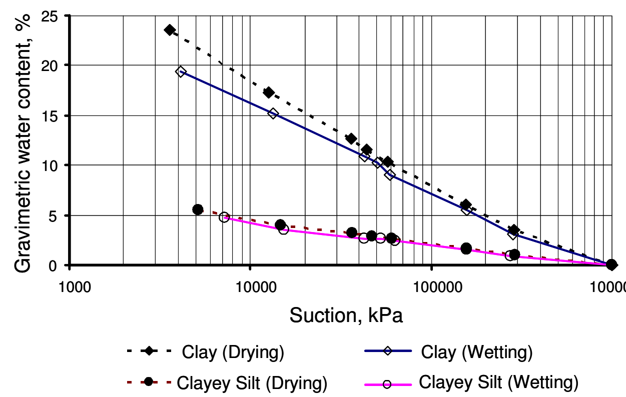


Figure 6. Drying and wetting SWCCs for Clay and Clayey Silt using WP4-T device

5.3 Comparison of the Results from Two Devices

Figure 7a compares the suction values for drying and wetting curves obtained from the ATC and the WP4-T devices for Clay soil. Figure 7b indicates the results for Clayey Silt. There is a good agreement between suction values at very high suction range (i.e., suction values greater than 50,000 kPa). In the range of suctions less than 50,000 kPa, with the exception of the lowest measured suction for Clay, there was not good agreement between suction values obtained using the WP4-T and ATC. The WP4-T gives higher suction values compared to the ATC. Further investigation was done to figure out the reason for this discrepancy (section 5.4).

5.4 Further investigation using a Traceable Hygrometer

In the previous section it was shown that there was a difference between the suction values obtained from the ATC and WP4-T for the suction range less than

50,000 kPa. Further investigation was done to find out the reason for this discrepancy. The relative humidity created inside the air-tight chambers using various saturated solutions were measured through the access hole on the top plate (see Figure 4) using a Traceable Hygrometer. The relative humidities measured using the Traceable Hygrometer were converted to total suction values using the Kelvin equation (i.e., Eq. 1). The suction values resulted from these calculations were plotted against those obtained from the WP4-T device for Clay and Clayey Silt soils (Figure 8a and 8b). The results indicate fairly good agreement between the two methods of suction measurements for both soils. These results indicate that the difference between the suction values from the WP4-T and ATC may be attributed to a slightly reduced relative humidity inside some of the chambers.

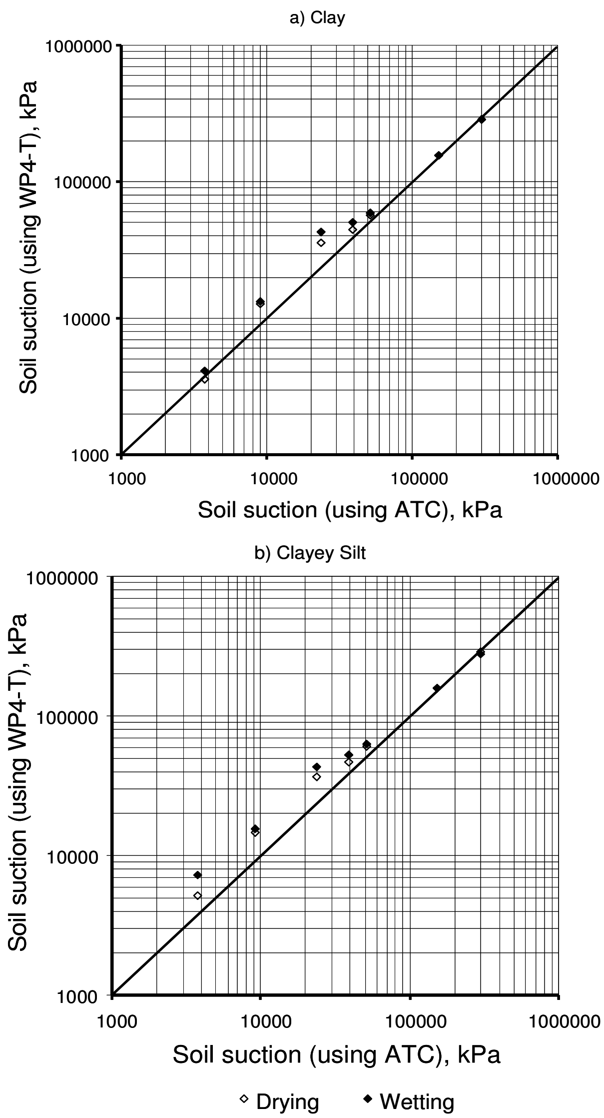


Figure 7. Comparison of soil suctions from ATC and WP4-T devices: a) Clay and b) Clayey Silt

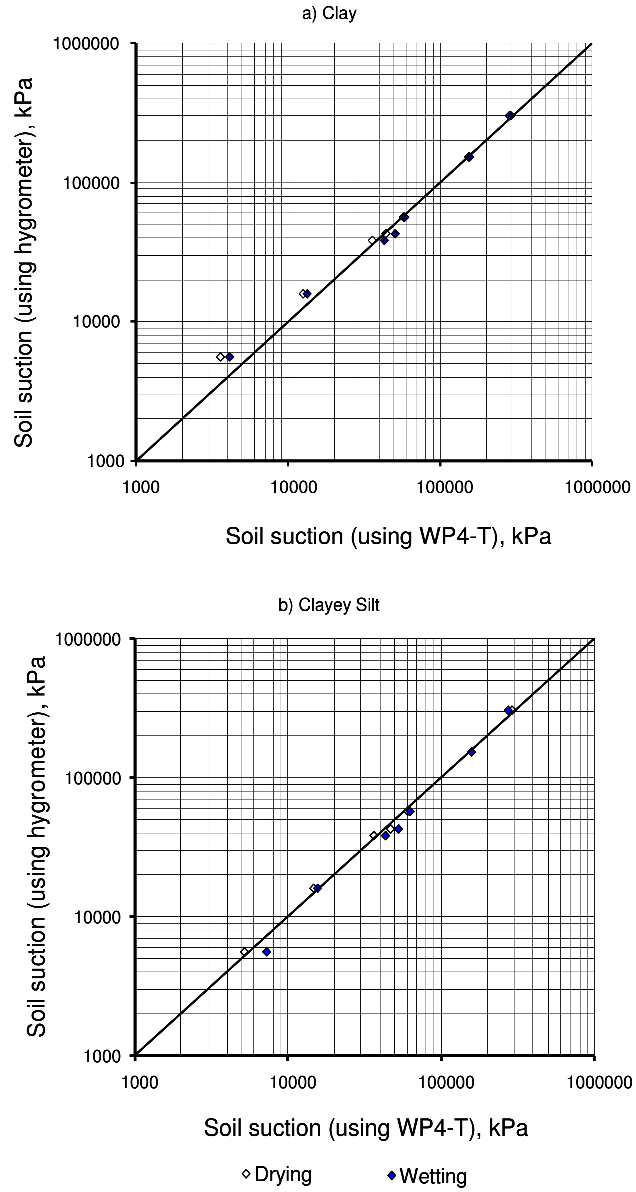


Figure 8. Comparison of the results from Traceable Hygrometer and WP4-T devices: a) Drying SWCCs and b) Wetting SWCCs

5.5 Comparison of the Results for Regina Clay

Fredlund (1964) conducted an experimental test on Regina Clay using the equilibration of a small soil sample placed over saturated salt solutions. The procedure was similar to the air-tight chamber method in this research, except desiccators were used as air-tight containers. The results obtained from Fredlund (1964) are compared with the ones obtained from air-tight chamber in Figure 9. Both tests are showed hysteresis in Regina Clay. The difference between the curves was expected as the soil properties of two soils were not quite the same. For example the percentage of the clay particles for the Regina Clay tested by Fredlund (1964) was less than that of tested in this research (51% versus 74%).

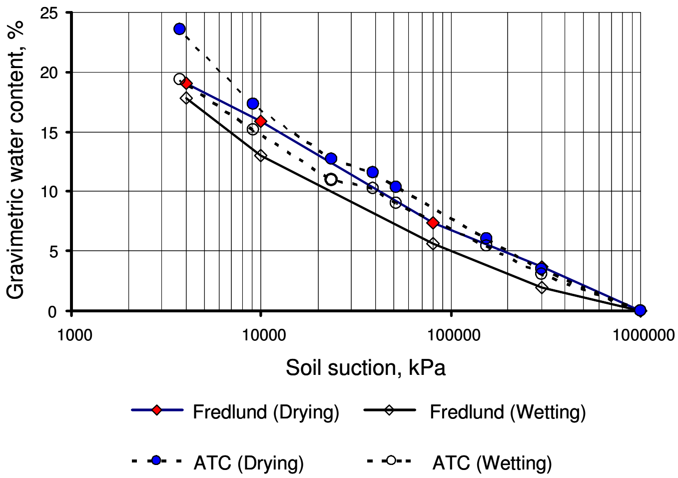


Figure 9. SWCC hysteresis for Regina Clay (results from this research and from Fredlund, 1964)

6 SUMMARY AND CONCLUSION

In this research study the hysteresis of the soil-water characteristic curve in the high soil suction range is investigated for two types of fine-grained soils, Clay and Clayey Silt. Soil suction values resulted from the dew-point Water PotentiaMeter, WP4-T, a relatively new apparatus recently used in the geotechnical research area, has been compared with those obtained through equilibration of a small soil sample placed over saturated salt solutions with the known osmotic suction.

Soil suctions in the high suction range was measured for a Clay and Clayey Silt soil. The measurements were made using two devices; the air-tight chamber, ATC, which uses the method of equilibration of small soil samples over the saturated solutions of known osmotic suction and the dew-point Water PotentiaMeter, WP4-T, which uses the chilled-mirror technique to determine the total suction of soils. The measurements of the gravimetrical water content of the soil samples provided required data to determine the drying and wetting soil-water characteristic curves in the high suction range.

Soil suction values obtained from the ATC and WP4-T devices showed a good agreement at suction values greater than 50,000 kPa; while, the agreement between the soil suctions at values less than 50,000 kPa were not as good. To further investigate the source of the disagreement at the suction range less than 50,000 kPa relative humidities inside the air-tight chambers were individually measured using a Traceable Hygrometer through an access hole on the top plates of the chambers. Corresponding suctions of the measured relative humidity values inside the chambers were calculated using the Kelvin Equation, Eq. 1. Comparison of these calculated suction values with the values obtained using the WP4-T showed a good agreement throughout the measured suction range. The findings indicated that the difference between suction values from the WP4-T and ATC may be attributed to a slightly reduced relative humidity inside some of the chambers.

The measurement of drying and wetting SWCCs proved the existence of the hysteresis in the high suction range for the Clay soil. The findings agreed with data obtained from Fredlund (1964) for Regina Clay. The measured drying and wetting SWCCs for Clayey Silt showed a small and insignificant hysteresis in the high suction range.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Boulfiza for kind assistance with the French translation of the abstract.

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