Soil water retention curves for remolded expansive soils

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ABSTRACT: Volume change in expansive soils occurs due to changes in the soil water system that change the stress equilibrium of the soil. Consequently, when determining the soil water retention relationship of an expansive soil, it is important to consider the volume change that occurs as the suction, and hence water content, changes during the test. Experiments using the Fredlund SWCC device and the filter paper method were conducted to take into account the effect of the volume changes on the soil water retention relationship of expansive soils. Claystone samples of the Denver and Pierre Shale Formations obtained near Denver, Colorado, USA were used in the study. A moist tamping system was used to obtain "identical" soil specimens. The observed experimental data were used to evaluate the previously published mathematical equations of SWRC. It is shown that the Fredlund and Xing equation is in the best agreement with the experimental data among the equations. In addition, a bilinear form was used to express the SWRCs for the expansive soils. It is concluded that the bilinear form of the SWRC gives the best fit to the measured experimental data.

1 INTRODUCTION

The soil water retention curve (SWRC) has played a dominant role in unsaturated soils in disciplines such as soil science, soil physics, agronomy, and agriculture. There is some discussion within the soil water research community regarding the use of the term soil water retention curve (SWRC) as opposed to the term soil water characteristic curve (SWCC). The term soil water retention curve (SWRC) has been adopted in this paper. However, when reference is made to the Fredlund SWCC device and test results therefrom, the term SWCC has been retained in connection with that device.

The SWRC has been identified as the key soil information required for the analyses of seepage, shear strength, and volume change problems involving unsaturated soils. The SWRC is usually measured assuming no volume change of the soil specimen. This is not the case for an expansive soil. When determining the SWRC of an expansive soil, it is important to consider the volume change that occurs as the suction changes during the test.

The SWRC of a soil is hysteretic. Therefore, depending on whether the process being simulated in the field is a wetting or drying process, an appropriate wetting or drying curve needs to be determined for the soil. Heaving of expansive soils/bedrock is related to the wetting process. Consequently, a wetting curve should be utilized in simulations of the migration of water in the subsoils/bedrock for modeling heave phenomena. This paper focuses on an evaluation of the wetting curves of the expansive claystone of the Denver and Pierre Shale Formations.

A moist tamping system was used to obtain identical soil specimens. The Fredlund SWCC device and the filter paper test were utilized in the experiments. The observed experimental data were used to evaluate previously published mathematical equations for the SWRC. This paper presents the results of the experimental data of the claystone and a proposed equation for the SWRC curve.

2. EXPERIMENTAL PROGRAM

2.1 *Soil Description and Index Properties*

Samples of claystone of the Denver and Pierre Shale Formations were obtained using drilling with a continuous core sample at sites near Denver, Colorado, USA. The boring log of the claystone of the Denver Formation indicates that the claystone bedrock was slightly moist and consisted of yellowish brown, hard claystone with some oxidation and occasional silty claystone lenses. The boring log of the claystone taken from the Pierre Shale Formation indicates that the claystone bedrock was slightly moist and consisted of light olive brown and gray claystone with oxidation along the bedding planes.

The results of the laboratory tests are provided in Table 1. The samples of the claystone of both the Denver and Pierre Shale Formations were classified as high plasticity clay (CH). They exhibited moderate to very high swell potential.

Table 1. Summary of Geotechnical Properties of Denver and Pierre Shale.

Formation of Claystone Bedrock	Natural Water Content (%)	Natural Dry Density (Mg/m^3)	LL / PL$^{(1)}$ (%)	Consolidation-Swell Test$^{(2)}$ Percent Swell (%)	Consolidation-Swell Test$^{(2)}$ Swell Pressure (kPa)
Denver	20.1 – 26.5	1.54 – 1.67	56 – 68/ 32 – 43	6.5 – 7.4	1150 – 2,550
Pierre Shale	15.2 – 16.3	1.81 – 1.92	60 – 61/ 41 – 42	3.1 – 5.7	710 – 1300

Notes: (1) LL = Liquid Limit, PL = Plastic Limit
(2) Inundation Pressure, σ'_i = 48 kPa

2.2 *Specimen Preparation*

A variety of methods have been developed for reconstituting soil specimens in the laboratory. The moist tamping method is one of the successful methods proposed for preparing nearly identical soil specimens (Mulilis, et al., 1975). The early implementation of the moist tamping method involved the soil specimen being prepared using a number of layers of equal dry weight and volume wherein each layer was being compacted to the same target density. Mulilis, et al. (1975) found that this could result in the lower portion of the specimen becoming denser than the desired specimen density because the compaction of each overlying layer also resulted in the densification of underlying layers.

Noorany (2005) proposed to prepare a soil sample with a number of layers of equal soil weight and volume when compacting each layer into a compaction mold, as shown in Figure 1. Noorany (2005) found that this modified moist tamping method was successful in preparing uniform soil specimens for the oedometer test.

The modified moist tamping method was utilized to prepare and compact soil specimens for the laboratory testing. The soil specimens were prepared for testing by compacting them to 100% of the maximum Standard Proctor dry density at a water content 3% less than the optimum water content. The sample rings used for the experiment have dimensions of 6.2 cm inside diameter and 3.1 cm thick. The thick steel plate shown in Figure 1 is 0.5 cm in height. The soil sample at the completion of compaction within each ring was 2.5 cm in height. In addition, four (4) layers with each layer being 0.6 cm in height were selected for the compaction process.

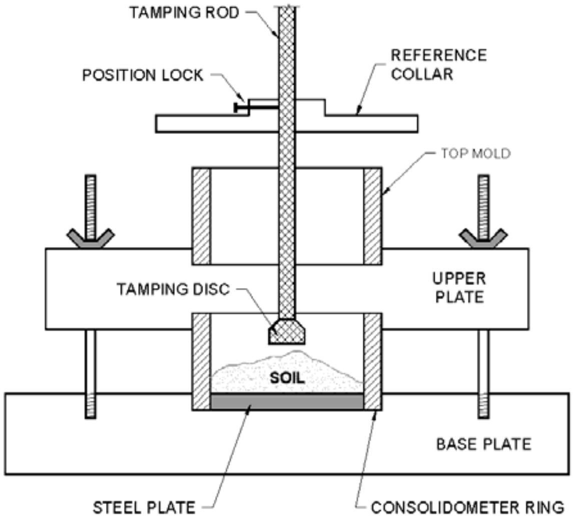

Figure 1. Schematic of Moist Tamping System (modified from Noorany, 2005).

2.3 *Experimental Procedure*

2.3.1 *Filter Paper Test*

The filter paper method was used to obtain the soil water retention relationship of both soil types for a soil suction ranging from approximately 1 to 175,000 kPa. This range corresponds to a pF of 1.01 to 6.25. Whatman No. 42 filter paper was used in this study. The weight of the filter paper was measured to the nearest 0.0001 g during the test.

The filter paper method was adopted to measure total and matric suctions of soil specimens in accordance with both non-contact and contact techniques described in ASTM D5298-94. ASTM D5294-94 recommends a minimum equilibration time of 7 days for running the filter paper contact and non-contact tests. However, in examining the required time for filter paper to reach equilibrium, it was found that the equilibration time is dependent on suction source, measured suction type (contact or non-contact method), material type, water content of soil specimen (suction level), number of pieces of filter paper used, relative humidity of the air, and soil mass and space in the container. The time required for equilibration of the filter paper when measuring the suction of the claystone from the Pierre Shale Formation was evaluated in Chao (2007).

For determining the boundary wetting curve, the soil specimen was initially air-dried in the laboratory. The weight and volume of the air-dried sample were measured. Calipers were used to measure the height and diameter of the sample in order to determine the volume. A filter paper test was performed on the air-dried sample to obtain a soil suction corresponding to the lowest water content of the sample. At the completion of the first filter paper test, water was sprayed onto the soil specimen to obtain a desired water content of the sample for the next filter paper test. The values of water content of the sample were increased at intervals of approximately 5%. The wetting curve test continued until the last desired value of water content of the soil specimen was reached. Measurements of the weight and volume of the sample at equilibrium were taken throughout the experiment.

In addition, five remolded samples of the Pierre Shale claystone were oven-dried to obtain the soil suction of the claystone at oven-dry water content conditions using the filter paper method. The sample was cut in two pieces and filter papers were placed between the pieces. A rubber band was placed around the sample to ensure contact between the filter papers and the soil.

2.3.2 *Fredlund SWCC Test*

The Fredlund SWCC device was utilized to determine the SWRC over a range of soil suction from 2 to 900 kPa for the claystone of the Denver Formation. This soil suction range overlapped the range used in the filter paper tests to verify the measured laboratory data from each other. A schematic of the Fredlund SWCC device used in this study is shown in Figure 2. The sample rings used for the test are 6.4 cm in diameter and 2.5 cm in height. The Fredlund SWCC device was calibrated to account for compressibility of the device, filter paper, and porous stone (Chao, 2007).

Similar to the filter paper test, the soil specimen was compacted to 100% of the maximum Standard Proctor dry density at a water content 3% less than the optimum water content, and then air-dried until a minimum water content was reached in the laboratory. The weight and volume of the air-dried sample were measured.

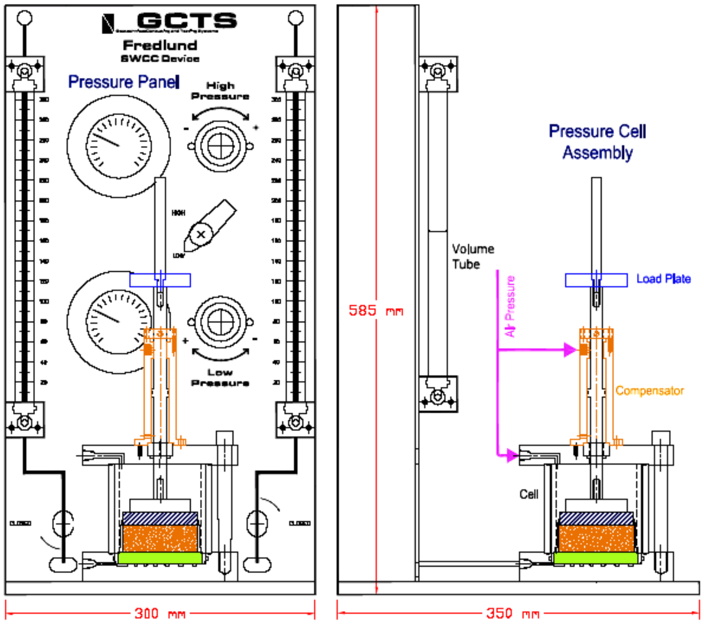

Figure 2. Schematic of Fredlund SWCC Device (from GCTS 2004)

The air-dried soil specimen was transferred to a ceramic stone placed in the pressure cell of the Fredlund SWCC device. The water below the ceramic stone was maintained at atmospheric pressure. A specified air pressure was applied into the pressure cell. In response to the applied suction, the water was drawn into the soil specimen through volume indicator tubes and through the ceramic stone until equilibrium was established.

It was possible for air to diffuse through the ceramic stone and collect on the bottom of the cell. Therefore, the diffused air was flushed out before reading the levels in the volume indicator tubes. The water content of the specimen was calculated using the volume indicator tube readings. The change in the height of the soil specimen was measured from an attached dial gauge. This procedure was repeated for successive pressure decrements to obtain a series of data points on the wetting curve. The pressure values that were used were 900, 400, 100, 10, and 2 kPa. At the end of the wetting curve test, the soil specimen was removed from the cell and its water content and dry density were determined.

2.4 *Experimental Results*

Figures 3 and 4 present the SWRCs in terms of volumetric water content from the average values of the experimental data for the Denver and Pierre Shale Formation samples, respectively. The osmotic suction curves shown in Figures 3 and 4 were computed by subtracting the matric suction values from the total suction values.

None of the SWRCs shown in Figures 3 and 4 exhibit a distinct point of bifurcation to define the displacement pressure head. This trend of not having a distinct displacement pressure head for expansive soil has also been reported by others (Chao, 1995; Al-Mukhtar, 1995; Alonso, et al., 1995; Wan, et al., 1995; and Miller, 1996).

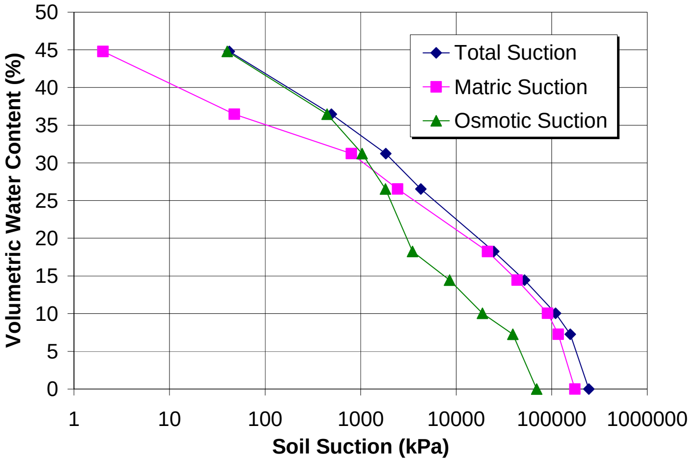

Figure 3. Wetting SWRC – Total, Matric, and Osmotic Suctions from Filter Paper Test – Remolded Claystone of Denver Formation.

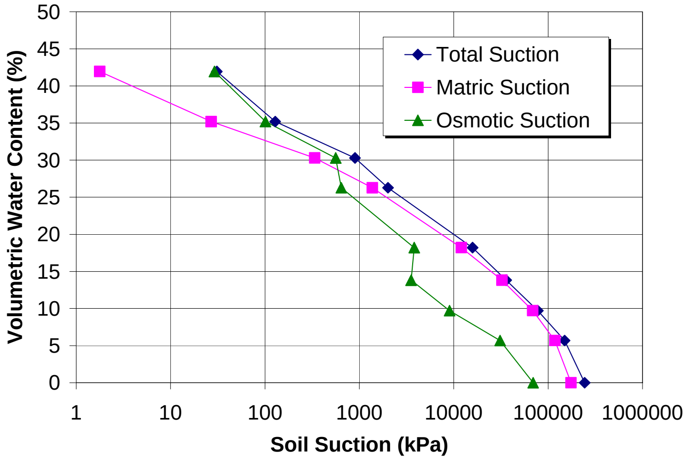

Figure 4. Wetting SWRC – Total, Matric, and Osmotic Suctions from Filter Paper Test – Remolded Claystone of Pierre Shale Formation.

The Fredlund SWCC test was conducted on the remolded claystone of the Denver Formation and the results were compared with those obtained using the filter paper method. Figure 5 shows that the filter paper test reproduced the results obtained from the Fredlund SWCC test.

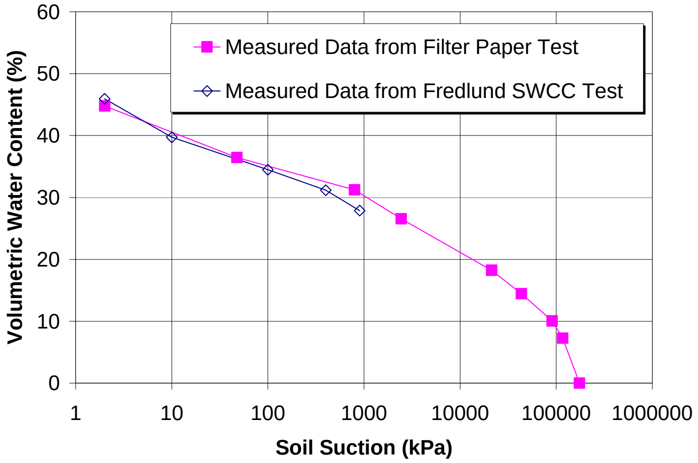

Figure 5. Comparison of Wetting SWRCs from Filter Paper Test and Fredlund SWCC Test – Remolded Claystone of Denver Formation.

3 ANALYSIS OF EXPERIMENTAL DATA

3.1 *Curve Fitting with Previously Published SWRC Equations*

The observed experimental data were fitted to the previously published mathematical equations for the SWRC. Selected mathematical equations include those proposed by Burdine (1953), Gardner (1958), Brookes and Corey (1964), Mualem (1976), van Genuchten (1980), and Fredlund & Xing (1994). Figures 6 and 7 show the results of the curve fitting for the claystone of the Denver Formation. Figures 8 and 9 show the results of the curve fitting for the claystone of the Pierre Shale Formation. The values of r^2 for regression analyses of the equations are also shown in the figures.

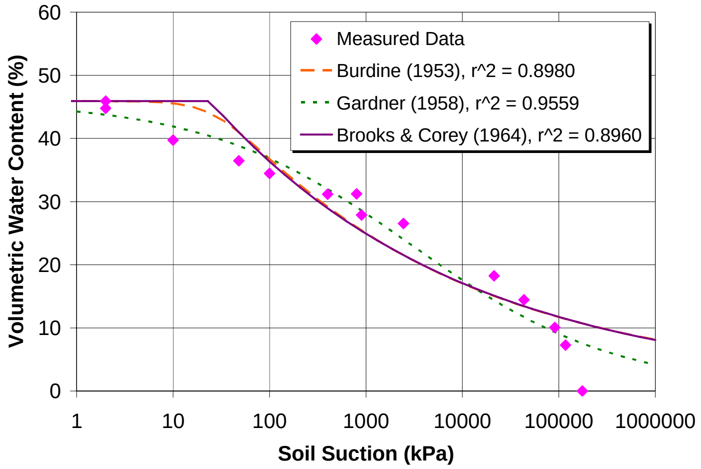

Figure 6. Burdine, Gardner, and Brooks & Corey Equations Fitted to Experimental Data – Claystone of Denver Formation.

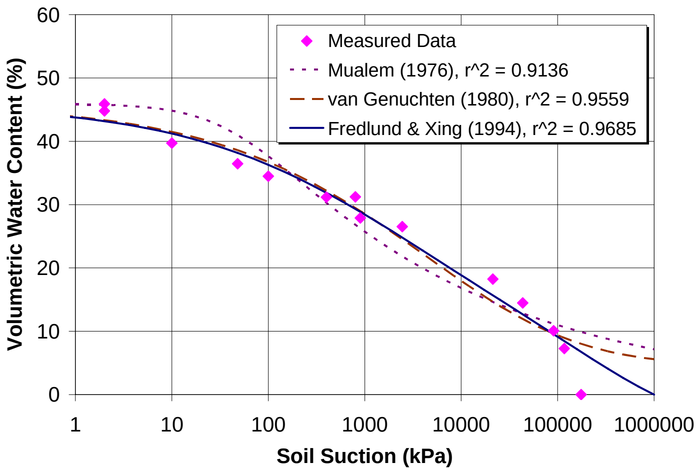

Figure 7. Mualem, van Genuchten, and Fredlund & Xing Equations Fitted to Experimental Data – Claystone of Denver Formation.

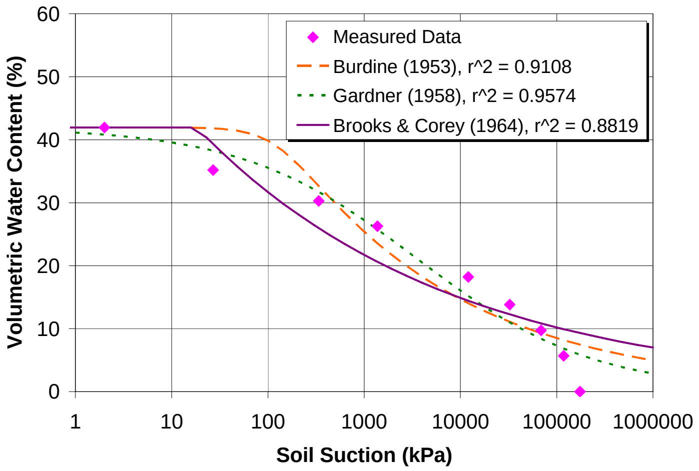

Figure 8. Burdine, Gardner, and Brooks & Corey Equations Fitted to Experimental Data – Claystone of Pierre Shale Formation.

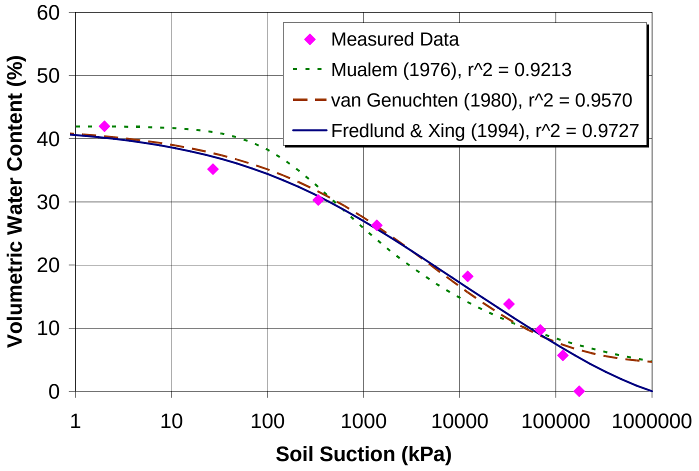

Figure 9. Mualem, van Genuchten, and Fredlund & Xing Equations Fitted to Experimental Data – Claystone of Pierre Shale Formation.

Comparison of Figures 6 through 9 indicates that among all of the equations that were considered, the Brooks and Corey equation provides the least agreement with the experimental data. The reason for the poor fit of the Brooks and Corey equation is that the Brooks and Corey model exhibits a sharp break in the curve at the air entry value which is typically more representative of sandy soil having a relatively narrow grain size distribution. It should be noted that this equation was developed for a rigid porous medium (i.e., no volume change).

It is seen in Figures 6 through 9 that the Fredlund and Xing equation exhibits the best agreement with the experimental data. An interesting observation is that the four-parameter equations (such as the van Genuchten and Fredlund & Xing equations) performed a better curve fitting than the three-parameter equations (such as the Burdine, Brooks and Corey, and Mualem equations). This observation was also made by Leong and Rahardjo (1997) for other soil types.

3.2 *Curve Fitting with Bilinear Equation*

Chao, et al. (1998) indicated that a bilinear form gives a good agreement to the observed experimental data for expansive soils. The bilinear relationship of the SWRC for expansive soils has also been reported by others (McKeen and Neilsen, 1978; Marinho, 1994; and Miller, 1996). The results of the experimental data plotted in bilinear form are shown in Figures 10 and 11 for the claystone of the Denver and Pierre Shale Formations, respectively. It is shown in Figures 10 and 11 that the bilinear form of the SWRC gives the best fit to the measured experimental data compared to the previously published mathematical equations discussed previously. The question mark by the point at zero water content indicates that this point was not used in the curve fitting procedure.

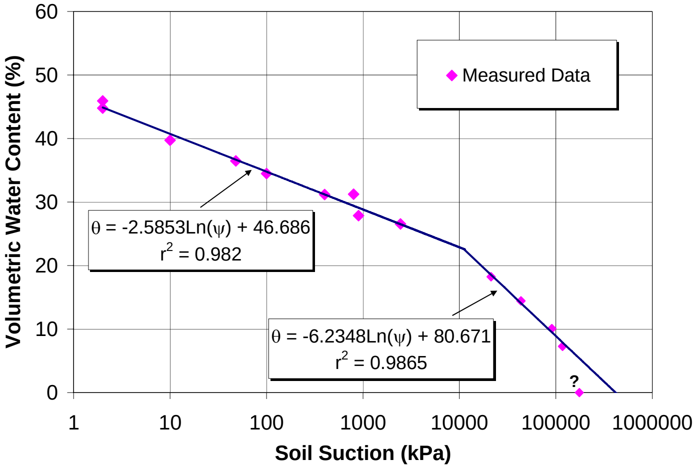

Figure 10. Bilinear Equation Fitted to Laboratory Data – Claystone of Denver Formation.

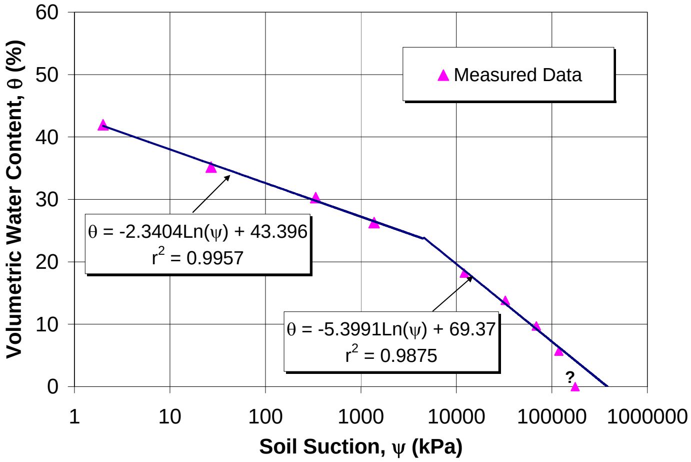

Figure 11. Bilinear Equation Fitted to Laboratory Data – Claystone of Pierre Shale Formation.

4 DISCUSSION AND CONCLUSIONS

Fredlund (2002) stated that matric suction has been shown to dominate the lower suction portion of a SWRC, while osmotic suction dominates the high suction portion of the SWRC. Capillary effects dominate when there is a significant amount of liquid water in the soil, whereas the osmotic suction related to the adsorbed salts begins to dominate the behavior of the soil at a high suction range. It was shown by van der Raadt, et al. (1987) that filter paper results used both in contact and non-contact modes were similar for values of suction above 1,000 kPa, but were different for values of suction less than 1,000 kPa. Leong, et al. (2002) suggested that for “up to 1,000 kPa suction, the contact filter paper method can be used to measure matric suction reliably, while the noncontact method can be used to measure total suction. Beyond 1,000 kPa suction, the filter paper method measures only total suction, regardless if the contact or the noncontact procedure is used.” Review of Figures 3 and 4 indicates that this limit is much higher (closer to 10,000 kPa).

The soil suction at zero water content is used as a boundary point in heave prediction using the soil suction method proposed by McKeen (1992). The soil suction at zero water content was stated by McKeen (1992) to be near 174,385 kPa (6.25 pF). Fredlund and Xing (1994) introduced a correction function, C(ψ), in their SWRC fitting equation to force the SWRC to pass through a soil suction of 10^6 kPa (7.0 pF) at zero water content. The measured average total suction of the five oven-dried claystone samples shown in Figure 5 is approximately 245,000 kPa (6.40 pF) at oven-dry water content. This value of measured soil suction at oven-dry water content is closer to that expressed by McKeen (1992).

The bilinear form used in this study is representative of the observed experimental data for expansive soils. At stress above 100 MPa, the curve tends to increase in slope to a limiting suction value of about 245,000 kPa (6.40 pF). Cumbers (2007) measured points that fell on a straight line between suction values of about 100,000 kPa and 245,000 kPa. Thus, the curves are in fact tri-linear, but for suction values below 100,000 kPa they will be referred to as being bi-linear.

The change in slope of the SWRC for expansive soil has been attributed to the transition from macropore spaces, where water retention is governed by capillary mechanisms, to micropore spaces, where water retention is governed by thermodynamic forces (Miller, 1996).

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