PREDICTING UNSATURATED SOIL MOISTURE DIFFUSIVITY COEFFICIENT USING SLOPE OF SWCC AND SATURATED PERMEABILITY COEFFICIENT

By

YI TIAN

Bachelor of Science in Environmental Engineering

Hunan Agriculture University

Changsha, Hunan

2008

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2014

PREDICTING UNSATURATED SOIL MOISTURE DIFFUSIVITY COEFFICIENT USING SLOPE OF SWCC AND SATURATED PERMEABILITY COEFFICIENT

Thesis Approved:

Dr. Rifat Bulut

Thesis Adviser

Dr. Avdhesh Tyagi

Dr. Xiaoming Yang

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my academic advisor, Dr. Bulut, for his guidance and support. Dr. Bulut guided me how to do a research and academic paper writing. Dr. Bulut also inspired my potentials on research. I am also grateful to Dr. Tyagi and Dr. Yang for being my committee.

I would like to thank to project teammates: Sruthi Mantri, Omar M. Amer and Lizhou Chen for patiently and nicely cooperating with each other and achieving the objects for DOT project.

Last, but not least, I thank to my family for their unconditional love, support and understanding all the time.

Name: Yi Tian

Date of Degree: DECEMBER, 2014

Title of Study: PREDICTING UNSATURATED SOIL MOISTURE DIFFUSIVITY COEFFICIENT USING SLOPE OF SWCC AND SATURATED PERMEABILITY COEFFICIENT

Major Field: Civil Engineering

Abstract: The diffusion coefficient is a crucial parameter which is used to evaluate the moisture movement in unsaturated soils. The diffusion coefficient can be measured in laboratory on tube soil specimens subjected to certain boundary conditions using thermocouple psychrometers. However, the testing range of thermocouple psychrometer is restricted from about 3.5 pF to 4.5 pF, while the suction range in engineering practice is much wider. This thesis presents a wider suction range estimation of diffusion coefficient determined by using slope SWCC and saturated permeability. In this research, diffusion coefficients of two clayey soils with different plastic limits were tested by using both methods. Then, the estimated diffusion coefficient at 3.5 to 4.5 pF is compared to the diffusion coefficient tested by thermocouple psychrometers. It turns out that thermocouple psychrometer result is lower than the estimated results from slope of SWCC and saturated permeability. For the low plastic clay soil, the thermocouple psychrometer testing result is 53.8% lower than the results from slope of the SWCC and saturated permeability. For the high plastic soil, the thermocouple psychrometer testing result is 12.5% lower than the result from slope of the SWCC and saturated permeability coefficient. In general, the diffusion coefficient is decreasing with the soil suction increasing. Further study on this area of using improved and advanced testing equipment might be useful to verify the wider ranges of diffusion coefficients.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Diffusion Coefficient

The diffusion coefficient of unsaturated soil is an important parameter to estimate the moisture movement caused by suction gradient in the soil. In unsaturated soil, the moisture subjected to the suction gradient diffuses from low suction area to high suction area (Mitchell 1979). It is crucial to reliably and cost-effectively estimate the moisture diffusivity.

One of the practical laboratory testing method for measuring the unsaturated diffusivity was proposed by Mitchell in 1979. Mitchell (1979) proposed drying and wetting test to determine the moisture diffusion in unsaturated soil. In the drying test, the cylindrical soil specimen with sealed surface and one open end which is exposed to the air of known relative humidity. The suction changes over time of soil are monitored by thermocouple psychrometer at certain locations. The Mitchell (1979) testing approach was further improved by Lytton et al. (2004) and Bulut et al. (2005). In this study, another testing approach to estimate the diffusivity based on the Mitchell (1979) analytical study, in which the diffusion coefficients over a wider suction range can be determined by the slope of Soil Water Characteristic Curve and coefficient of saturated permeability is used. In the study, the diffusion test results by thermocouple psychrometers and by SWCC and saturated permeability are compared.

1.2 Research Objectives

This research is to evaluate the range diffusion coefficients over a wide suction range of unsaturated soil by using the slope of SWCC and coefficient of saturated permeability and to make comparisons with the diffusion coefficients determined by thermocouple psychrometers from 3.5 pF to 4.5 pF suction. Therefore, the research will:

- Evaluate the diffusion coefficient by using the slope of SWCC and coefficient of saturated permeability for compacted soil specimens.
- Compare the predicted diffusion coefficients to the thermocouple psychrometer based test results.
- Evaluate the incremental diffusion coefficients over a wider suction range.

1.3 Organization of the Thesis

Chapter II reviews the soil suction measurement concepts and current techniques for suction measurements.

Chapter III presents the Mitchell's test procedures and the diffusion test by using SWCC and permeability of saturated soil. At first, this chapter explains how to apply thermocouple psychrometers to measure suction change over time and calculate diffusion coefficient. The chapter also includes the SWCC test and saturated permeability test procedures and the diffusion coefficient calculation by using the SWCC and coefficient of saturated permeability test results.

Chapter IV includes test equipment, the sample preparation and testing protocols for Mitchell's method, SWCC test and permeability test.

Chapter V presents results of the diffusion test by thermocouple psychrometers and diffusion test by SWCC and coefficient of saturated permeability tests.

Chapter VI concludes the research study and provides suggestions for the future study.

Appendix includes the step by step test procedures and data interpretation.

CHAPTER II

SUCTION MEASUREMENTS IN UNSATURATED SOILS

2.1 Soil Suction

Soil suction is one of the soil basic physical properties which reflects the unsaturated soil hydro-mechanical behavior (Fredlund et al. 2012). The soil suction levels are related to the soils strength, volume change and permeability. The suction scale for different consistency levels given by Aubeny et al. (2003) is shown in Figure 2.1.

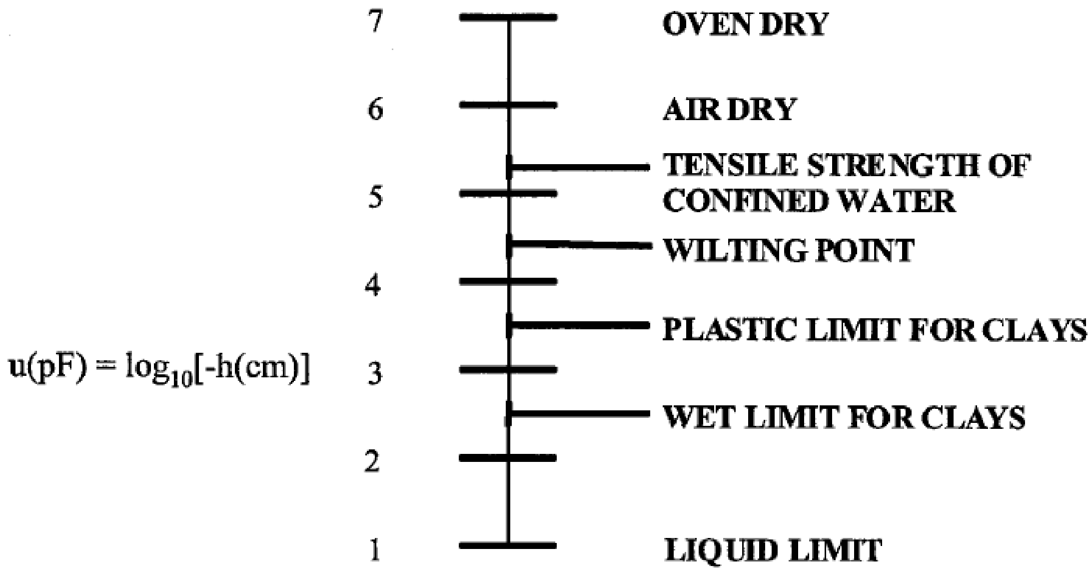


Figure 2.1 Suction Scale in pF (Aubeny et al. 2003)

In general, only the term soil suction may be used when the matric suction, osmotic suction or total suction is referred.

The soil suction is associated with the amount of water in the unsaturated soil, thus the amount of water in the soil can be used to estimate the soil suction.

The matric suction is from capillary phenomenon, and absorptive forces of soil matrix (Fredlund et al. 2012). Matric suction can be measured with equipment in which a high air-entry disk is in use, such as pressure membrane and pressure plate. Matric suction can also be measured by contact filter paper method, tensiometer, and thermal conductivity sensor.

The osmotic suction is associated with the salts dissolved in the pore water (Fredlund et al. 2012). The amount of dissolved ions decreases the relative humidity, which increases the osmotic suction.

The sum of matric suction and osmotic suction equals to the total suction. Soil suction depends on water content of soil. The soil water characteristic curve (SWCC) describes the relationship between suction and water content (Lu and Likos 2004). The suction in the SWCC is described as matric suction or total suction.

2.2 Measurement of Soil Suction

2.2.1 Total Suction Measurement

The relationship between total suction, relative humidity and its temperature is given by Kelvin's equation (Sposito 1981):

$$h_t = \frac{RT\rho_w}{M_w}\ln(\frac{P}{P_0}) \qquad [2.1]$$

where h_t = total suction (kPa)); R = universal gas constant (8.31432 J $mol^{-1}K^{-1}$); T = absolute temperature in Kelvin (T = 273.16 + °C); ρ_w = density of water as a function of temperature (kg/m^3); M_w= molecular mass of water vapor (18.016 kg/kmol); p/p_0 = the relative humidity (decimal).

The relative humidity, which is used to calculate total suction, can be indirectly measured by psychrometer and chilled-mirror device, or filter paper method.

2.2.1.1 Thermocouple Psychrometer

Thermocouple psychrometer (shown in Figure 2.2) can be used to measure the total suction by measuring the relative humidity in the air phase of the unsaturated soil. For relative humidity measurements, the measuring junction is cooled to dew point temperature, which leads to moisture condensation on the junction. Depending on termination of the passing current, the condensed moisture begin to evaporate which causes further temperature reduction, leaving a temperature difference between the junction and the surrounding atmosphere. Then the current, which is a function of the temperature difference, was determined.

The suction is reliably measured from about 3.5 pF to 4.5 pF by thermocouple psychrometer. A datalogger is utilized to record and retrieve data from thermocouple psychrometer. Calibration of psychrometers is performed by suspending the sensors in NaCl solutions of known concentrations and osmotic potentials. Thermocouple psychrometer is very sensitive to the temperature fluctuations, thus, a temperature constant environment is required for either calibration or soil suction tests.

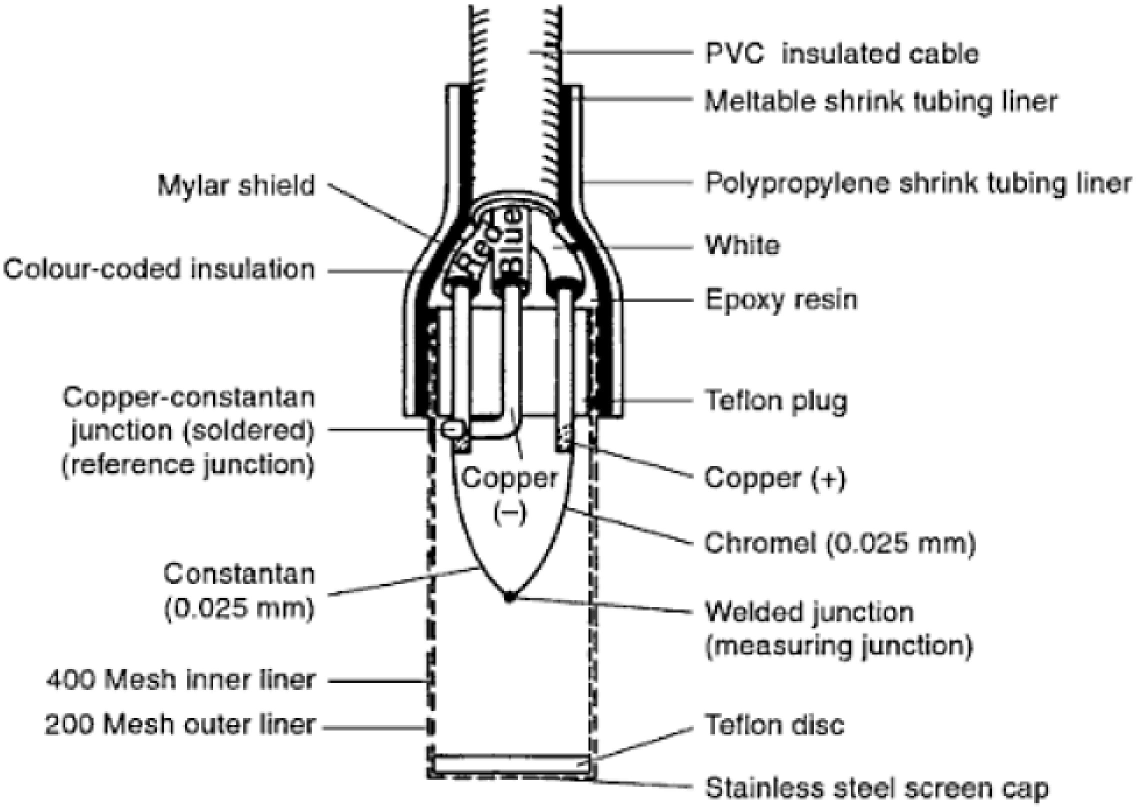


Figure 2.2 Thermocouple Psychrometer (Brown and Collins 1980)

2.2.1.2 Chilled-Mirror Device

The chilled-mirror device (shown in Figure 2.3) uses a dew-point measurement technique to measure the suction of unsaturated soil. In this type of instrument, the sample is equilibrated with the headspace of a sealed chamber that contains a mirror and a means of detecting condensation on the mirror. At moisture and temperature equilibrium, the water potential of the air in the chamber is the same as the water potential of the sample. The mirror temperature is precisely controlled by a thermoelectric cooler. Detection of the exact point at which condensation first appears on the mirror is observed with a photoelectric cell. A beam of light is directed onto the mirror and reflected into a photodetector cell. The photodetector senses the change in reflectance when condensation occurs on the mirror. The thermocouple attached to the mirror then records the temperature at which condensation occurs. The final water potential and temperature of the sample is then displayed.

It has a reliable suction measurement range of 3,000 to 300,000 kPa (Fredlund et al. 2012). The device consists of a sealed chamber with a mirror, a fan, a photo-electric cell and a thermometer. The specimen is tested in a plastic container which has a 40 mm diameter. During the test, the cooling system reduces the temperature of the mirror to dew-point temperature; and the dew-point temperature is measured by the thermocouple.

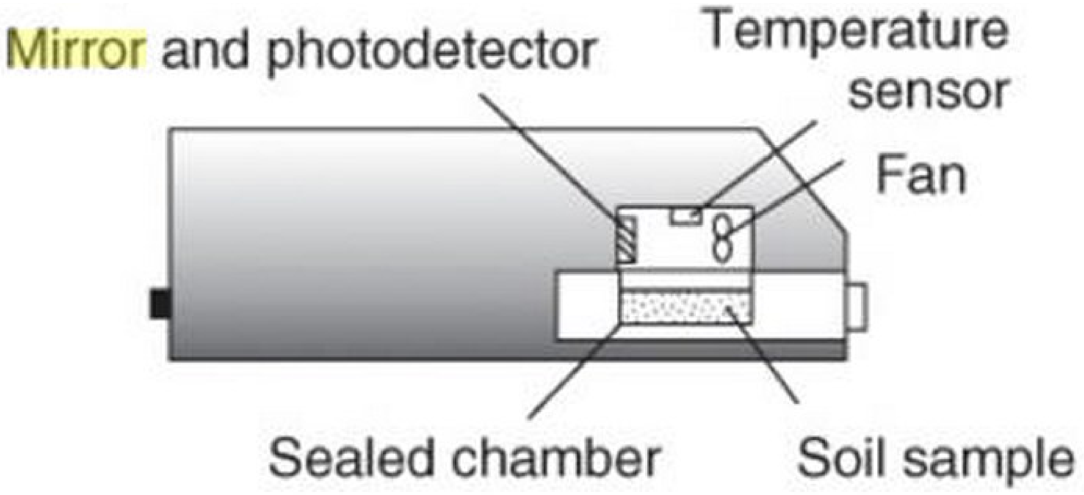


Figure 2.3 Schematic diagram of Chilled-mirror WP4 Device (Leong et al., 2003)

2.2.1.3 Filter Paper

The filter paper method is used to test a wide range of soil suctions (Fawcett and Collis-Geoge, 1967). It is also low cost and simple for soil engineering research. It can be used to measure either matric suction or total suction (as shown in Figure 2.4). In the glass jar shown in Figure 2.4, the filter paper, soil and the air will reach to the suction equilibrium with time in a constant temperature environment (Bulut and Wray 2005). At the equilibrium condition, the contact filter paper (for matric suction measurements) and the noncontact (for total suction measurements) would hold a certain amount of water. The suction of the soil can be calculated by using the water content of the filter paper and a calibration curve (shown in Figure 2.5). The calibration curve between water content of filter paper and suction is established using salt solutions or other suction measuring equipment.

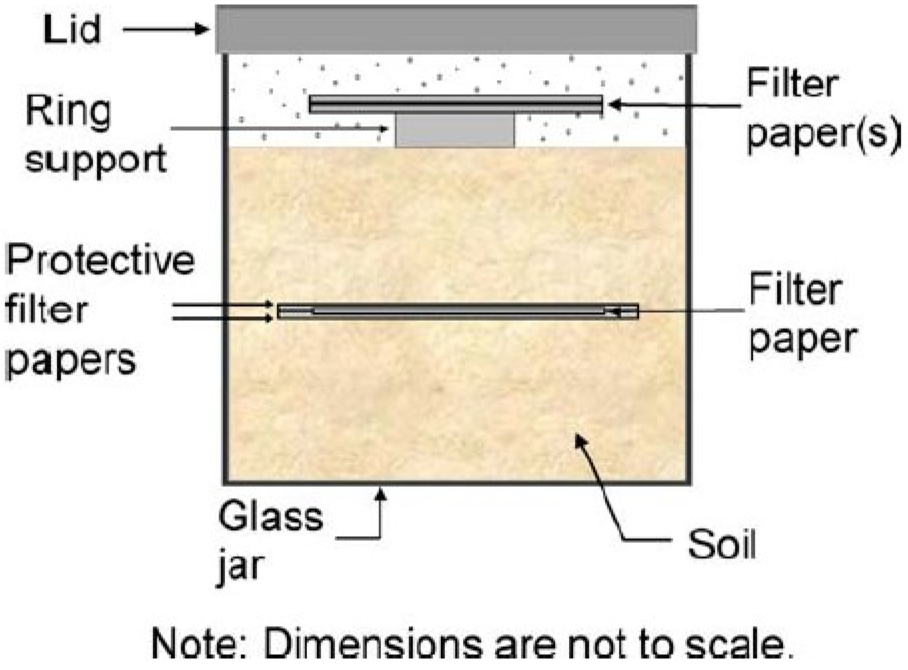


Figure 2.4 FilterPaper Method (Bulut and Wray 2005)

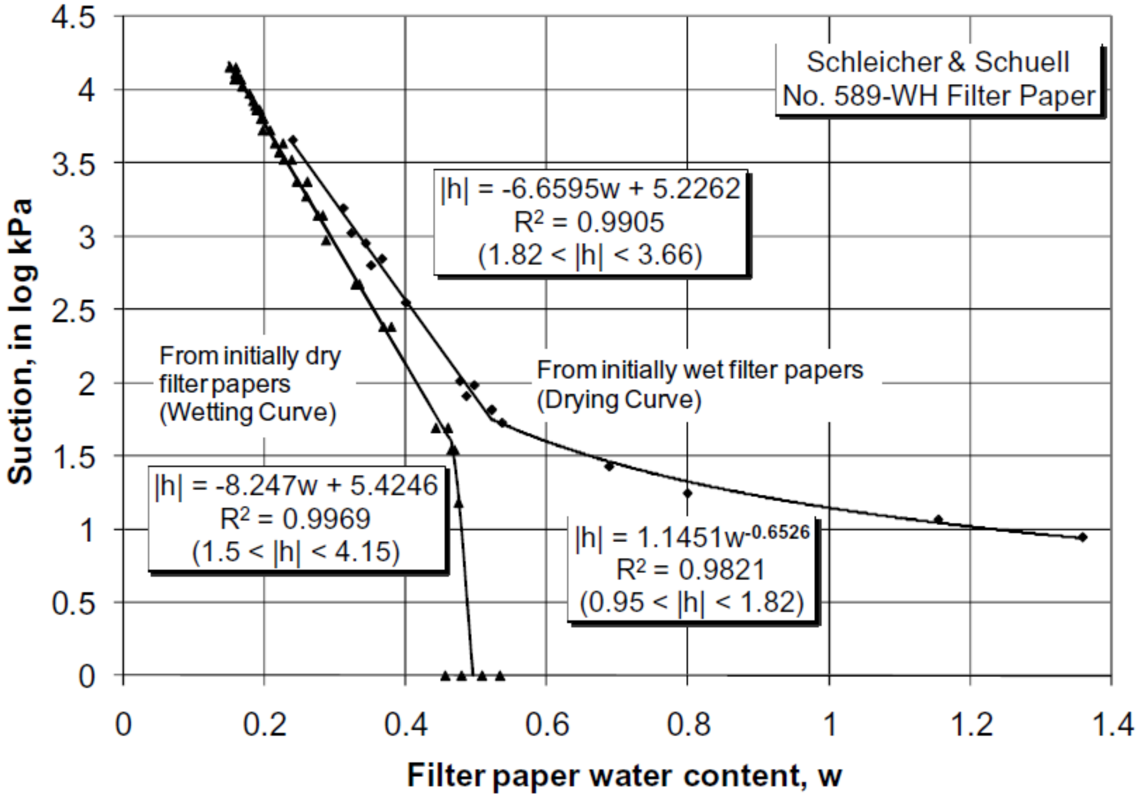


Figure 2.5 Filter Paper Calibration Curve (Bulut et al. 2001)

2.2.2 Matric Suction Measurements

The matric suction can be expressed by Equation 2.2 (Fredlund and Rahardjo 1993) for an apparatus which utilizes a high air-entry disk:

$$h_m = (u_a - u_w) \qquad [2.2]$$

where h_m = matric suction; u_a = applied air pressure; and u_w = pore water pressure. The matric suction decreases when soil moisture content increases and vice-versa. It can be indirectly determined by using noncontact filter paper method as mentioned above. The tensiometer and thermal conductivity sensors can also be used for matric suction measurement.

2.2.2.1 Tensiometer

A tensiometer is used to measure the negative pore-water pressure directly in unsaturated soil. There are different types of tensiometers in engineering practice. A typical jet-fil tensiometer is shown in Figure 2.6. It consists of a high-air-entry value ceramic cup connected with a pressure measuring device by a small-bore tube. The tube and the cup are filled with deionized water. The water in the tensiometer has the same pressure as the pore-water pressure in the tested soil when the soil and the tensiometer system reach the suction equilibrium (Fredlund et al. 2012). The highest suction can be measured in tensiometer is approximately negative 90 kPa.

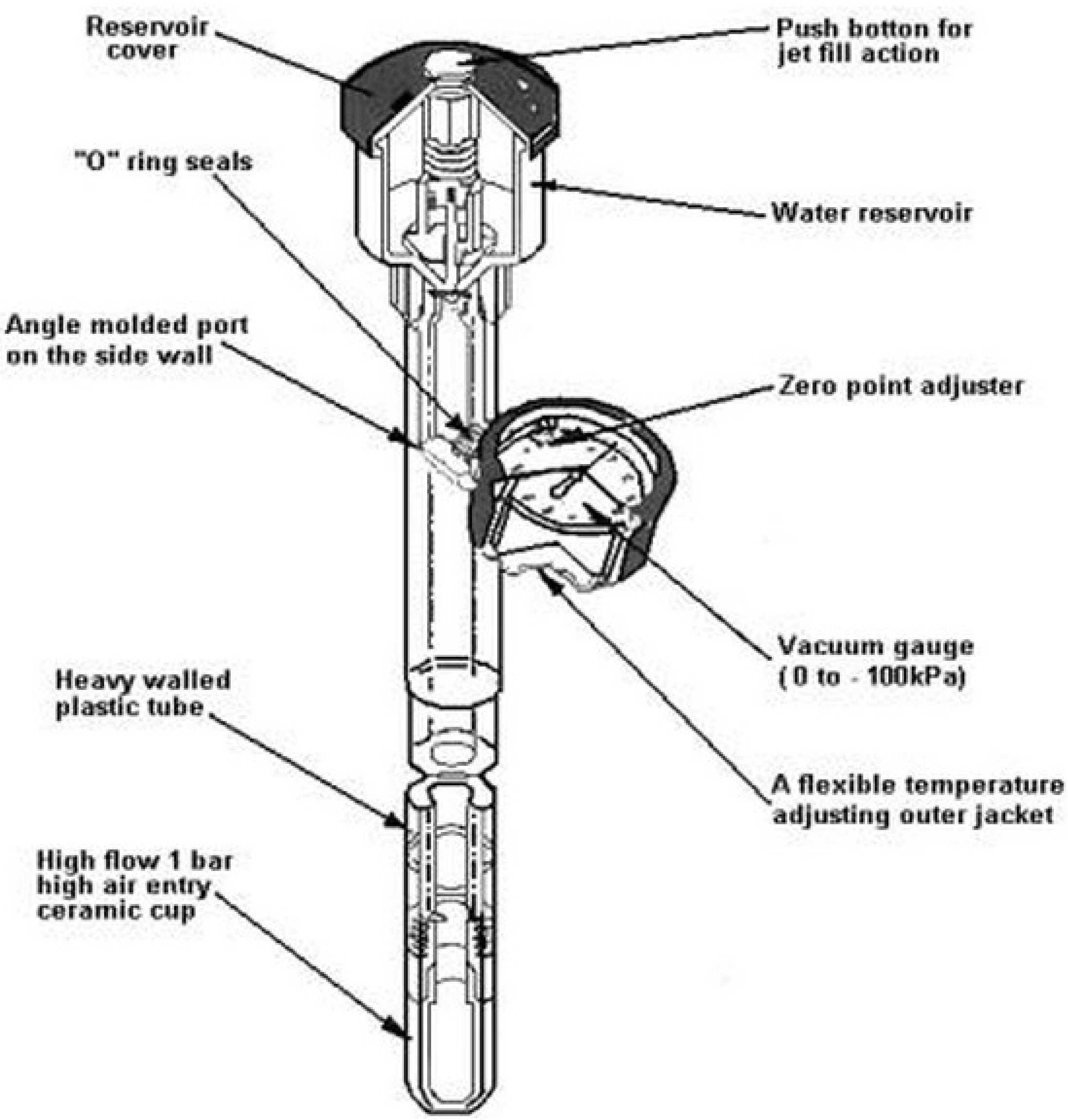


Figure 2.6 Jet-fill tensiometer (Soil Moiture Equipment Corp., USA, www.soil moisture.com)

2.2.2.2 Thermal Conductivity Sensor

The thermal conductivity sensor (shown in Figure 2.7) is based on the phenomenon that the thermal conductivity of the soil will change when the water content of the soil changes (Fredlund et al. 2012). As shown in Figure 2.7, the thermal conductivity sensor consists of a temperature sensing element covered by a ceramic stone and a heater. Thermal conductivity measurement is performed by testing the heat dissipation in the ceramic media. The heat that is not dissipated results in a temperature rise at the center of the block. The temperature rise is measured by the temperature sensing element after a specified time interval, and its magnitude is inversely proportional to the water content of the porous block (Fredlund et al. 2012). The measured temperature rise can be expressed in terms of a change of voltage output.

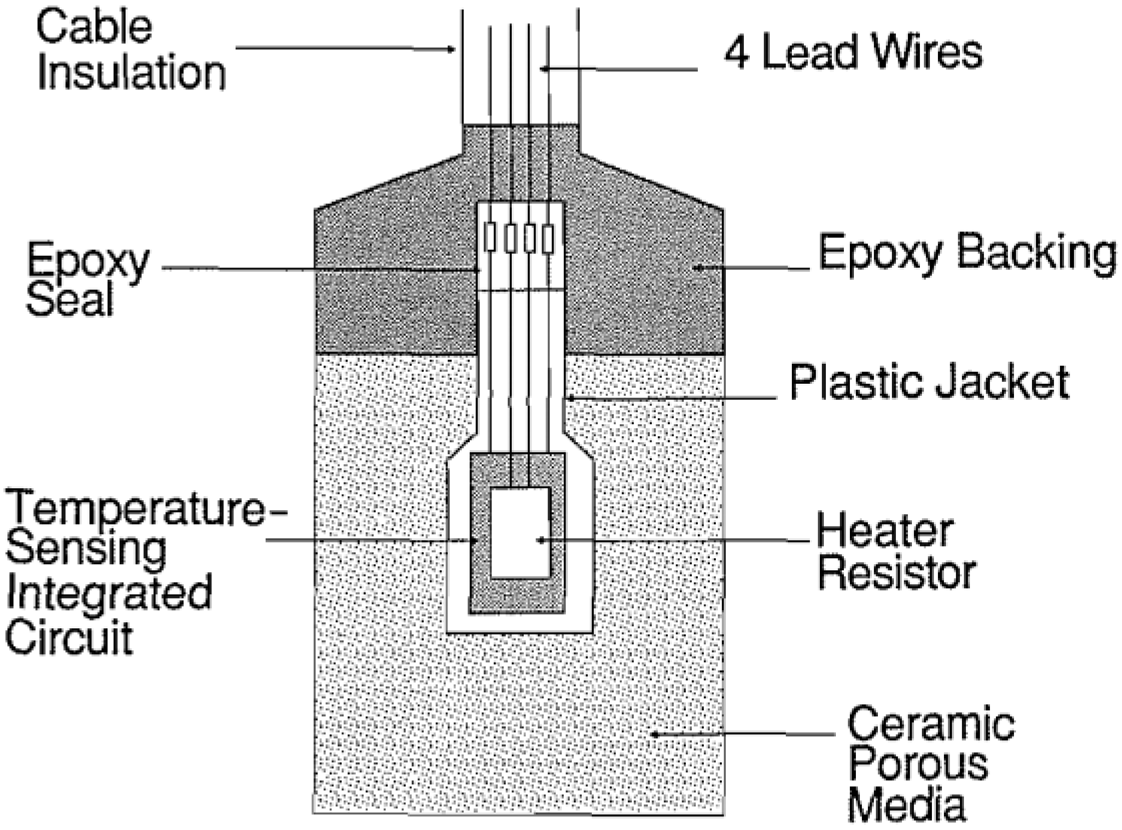


Figure 2.7 Diagram of the Thermal Conductivity Sensor Cross-section (Pamela and Fredlund 1989)

2.2.3 Osmotic Suction

The osmotic suction comes from the dissolved ions in pore water. The presence of dissolved ions increases the osmotic suction. The osmotic suction can be calculated using the relationship between osmotic coefficients (ϕ) and osmotic suction for different salt solutions (Bulut et al.

2001). The osmotic suctions for different salt solutions can be calculated by using Equation 2.3 (Lang 1967; Bulut et al. 2001):

$$\phi = \frac{\rho_w}{vmM_w}\ln(\frac{P}{P_0}) \qquad [2.3]$$

where ϕ = osmotic coefficient; v = number of ions from one molecule of salt; and m = molality (moles solute per 1000 grams of solvent). Table 2.1 shows the osmotic suction in different salt solutions at 25 ^{o}C.

Table 2.1 Osmotic Suctions for Salt Solutions in kPa (Bulut et al. 2001)

Osmotic Suctions at 25 ^{o}C							
Molality (m)	**NaCl**	**KCl**	**NH_4Cl**	**Na_2SO_4**	**$CaCl_2$**	**$Na_2S_2O_3$**	**$MgCl_2$**
0.0010	5	5	5	7	7	7	7
0.0020	10	10	10	14	14	14	14
0.0050	24	24	24	34	34	34	35
0.0100	48	48	48	67	67	67	68
0.0200	95	95	95	129	132	130	133
0.0500	234	233	233	306	320	310	324
0.1000	463	460	460	585	633	597	643
0.2000	916	905	905	1115	1274	1148	1303
0.3000	1370	1348	1348	1620	1946	1682	2000
0.4000	1824	1789	1789	2108	2652	2206	2739
0.5000	2283	2231	2231	2582	3396	2722	3523
0.6000	2746	2674	2671	3045	4181	3234	4357
0.7000	3214	3116	3113	3498	5008	3744	5244
0.8000	3685	3562	3558	3944	5882	4254	6186
0.9000	4159	4007	4002	4384	6799	4767	7187
1.0000	4641	4452	4447	4820	7767	5285	8249
1.2000	5616	5354	5343	…	…	…	…
1.4000	6815	6261	6247	…	…	…	…
1.5000	…	…	…	6998	13397	7994	14554
1.6000	7631	7179	7155	…	…	…	…
1.8000	8683	8104	8076	…	…	…	…
2.0000	9757	9043	9003	9306	20457	1021	22682
2.5000	12556	11440	11366	11901	29115	14489	32776

CHAPTER III

REVIEW OF DIFFUSIVITY MEASUREMENTS

The unsaturated soil diffusivity is used for the moisture movement estimation in practice. One of the popular methods for diffusivity measurements is based on Mitchell's (1979) method which tests the soil suction value with time using thermocouple psychrometers.

The Mitchell's diffusivity tests give a constant diffusion coefficient (Mitchell 1979). However, the suction gradient changes may lead to the diffusion coefficient change (Brooks and Corey 1964). In order to determine incremental changes in diffusion coefficient depending on variations in suction, an approach using SWCC and coefficient of saturated permeability is undertaken in this study.

3.1 Mitchell's Diffusivity Equation

Mitchell (1979) used a one dimensional flow (shown in Figure 3.1) to depict the moisture movement through the unsaturated soil, and defined a moisture source though the soil at a rate per unit volume as *f (x, t)*. The moisture into the soil is proposed by Mitchell (1979):

$$\Delta Q = v_x \Delta y \Delta z \Delta t|_x - v_x \Delta y \Delta z \Delta t|_{x+\Delta \mathrm{x}} + f(x,t)\Delta x \Delta y \Delta z \Delta t \qquad [3.1]$$

Where Δx, Δy, Δz = dimensions of the specimen; v_x, v_y, v_z = the velocity of flow in three directions; and ΔQ = quantity of water based on the flow travel time Δt.

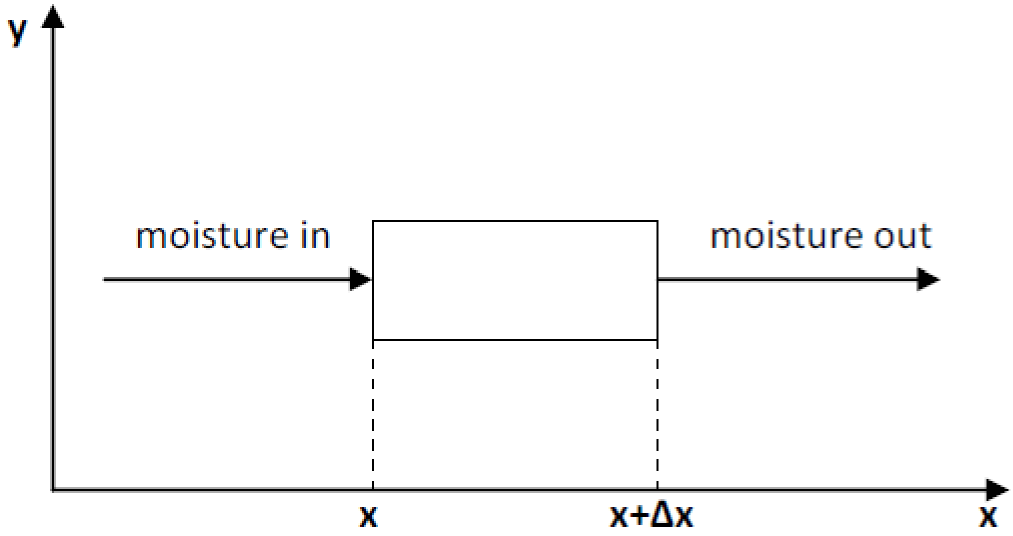


Figure 3.1 Moisture Flow (Mitchell 1979)

Based on the one dimensional flow in unsaturated soil, drying test was performed by Mitchell (1979). A cylindrical soil specimen with sealed surface and one open end from which the moisture evaporates to the atmosphere is shown in Figure 3.2. The moisture evaporates from the top surface where the atmospheric suction and the initial suction of the soil are known. The relationship between atmospheric suction u_a and the initial soil suction u_i at the soil surface ($x=L$) is given by Mitchell (1979):

$$(\frac{du}{dx})_{x=L} = h_e(u_a - u_i) \qquad [3.2]$$

Where h_e = evaporation constant. The boundary conditions of the drying test as shown in Figure 3.2 are as follows (Mitchell 1979):

Initial suction: $u(x,0) = u_0$

Sealed boundary: $\frac{\partial u(0,t)}{\partial x} = 0$

Open boundary $\frac{\partial u(L,t)}{\partial x} = h_e[u_a - u(L,t)]$

The one-dimensional solution for Equation 3.2 with those boundary conditions is given by Mitchell (1979):

$$u(x,t) = u_a + \sum_0^\infty \frac{2(u_0 - u_a) sinz_n}{z_n + sinz_n cosz_n} exp\left(\frac{{z_n}^2 \alpha t}{L^2}\right) cos(\frac{z_n x}{L}) \qquad [3.3]$$

Where $u\ (x,\ t)$ = suction as a function of location and time; z_n= solution of cot $z_n = (z_n/h_e L)$; h_e = evaporation coefficient; α = drying diffusion coefficient. The diffusion coefficient can be determined by measuring soil suction with time in a cylindrical soil specimen according to Equation 3.3.

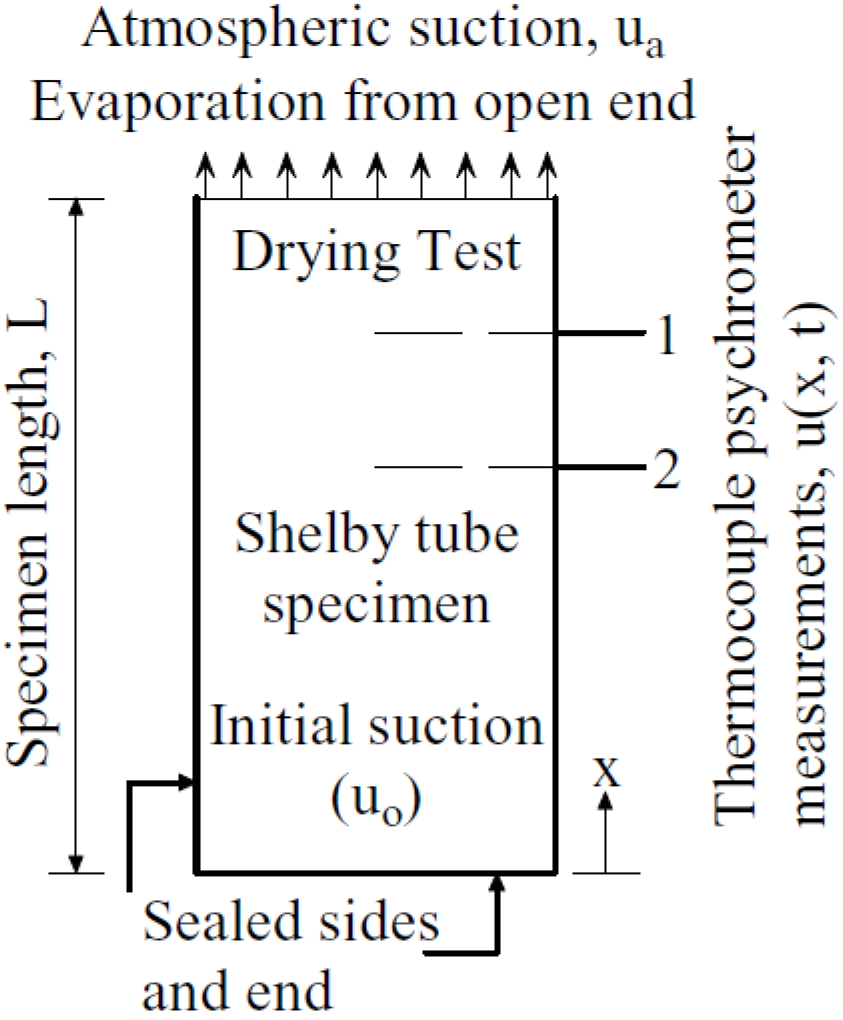


Figure 3.2 Boundary Conditions for Drying Test (Mabirizi and Bulut 2010)

3.2 Diffusivity Determined by SWCC and Permeability Coefficient

The diffusivity of unsaturated soils can also be expressed by the slope of the soil water characteristic curve (SWCC) and saturated permeability of soil (Mitchell 1979):

$$\alpha = \frac{k_0 h_0}{c} \frac{\gamma_w}{\gamma_d} \qquad [3.4]$$

where, k_o = saturated permeability of soil, h_o = a constant suction equal to 100 cm, γ_w = unit weight of water, γ_d = dry unit weight of soil, and c = slope of suction in logarithmic scale versus gravimetric water content.

In this equation, the diffusion coefficient can be derived from soil-water characteristic curve and coefficient of saturated permeability. The determination of SWCC and permeability coefficient will be presented, and the incremental measurements of diffusion coefficients will be discussed in the following sections.

3.2.1 Soil Water Characteristic Curve (SWCC)

The SWCC describes a nonlinear relation between the water content and the water potential in soil mass. The original models and analysis of the SWCC are from soil science and agriculture research (Fredlund and Xing 1994). There are many conceptual models for SWCC equations, and the most frequently used model in geotechnical engineering practice was proposed by Fredlund and Xing (1994).

3.2.1.1 Terminology

The SWCC is mainly about the relation between the water content and the suction. In geotechnical engineering, the gravimetric water content, volumetric water content, and degree of saturation are used to plot SWCC. The volumetric water content is more preferable for geotechnical engineers, because the volumetric water content or degree of saturation is more representative for the analysis of the soil behavior associated with volume change (Fredlund et al. 2012).

There are two crucial transition points for SWCC: the air-entry value and the residual value (shown in Figure 3.3) (Fredlund et al. 2010). The air-entry value and residual value divide the SWCC into three zones: transition zone, boundary effect zone and residual zone. The air-entry value is the data point "where the air starts to enter the largest pores in the soil" (Fredlund and

Xing 1994). The residual value is the point when a large suction is needed to remove the water in soil (Fredlund and Xing 1994).

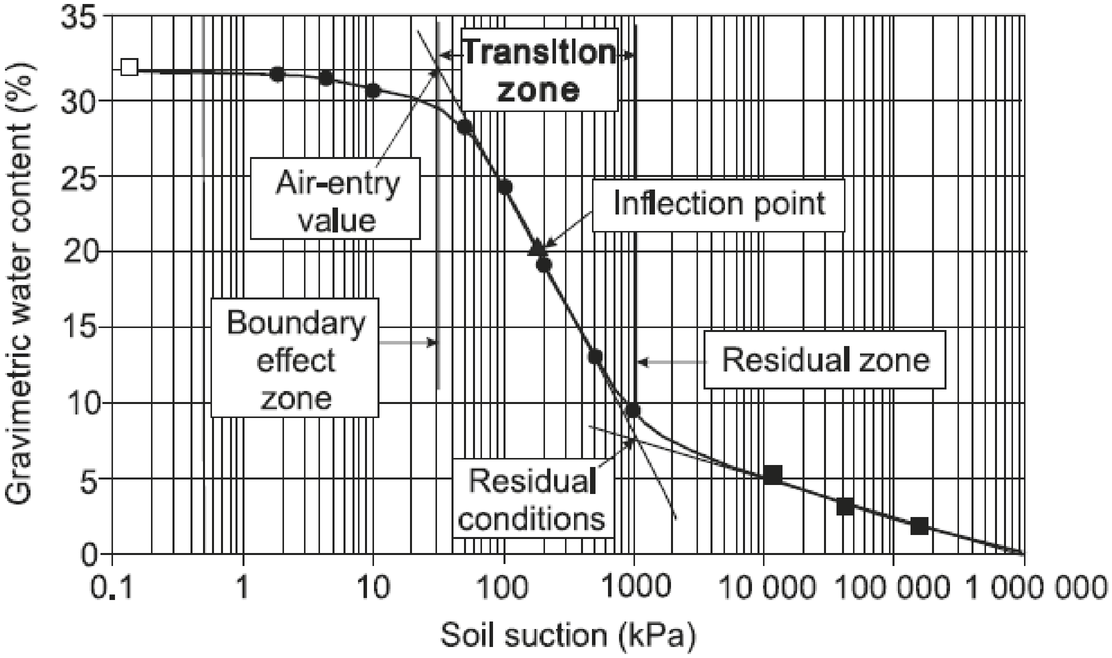


Figure 3.3 Desorption SWCC distinct zones (Fredlund et al. 2010)

3.2.1.2 Empirical Equations for SWCCs

There are a large number of empirical equations for SWCC based on fitting laboratory data (Fredlund et al. 2012). In the early years, the gravimetric water content is used to describe SWCC. With the understanding of SWCC, the volumetric or degree of saturation has been applied to the empirical equations.

One of the earliest empirical equations to describe soil-water characteristics is given by Gardner (1958):

$$\Theta_d = \frac{1}{1+a_g\psi^{n_g}} \qquad [3.5]$$

where Θ_d = dimensionless water content ($\Theta = \frac{w}{w_s}$), w = gravimetric water content of soil, w_s = saturated water content, a_g = fitting parameter (a function of air-entry value), n_g = fitting parameter.

Brooks and Corey (1964) proposed their best fit equation:

$$\Theta_n = (\frac{\psi_b}{\psi})^{\lambda} \tag{3.6}$$

where Θ_n = normalized water content ($\Theta = \frac{w-w_r}{w_s-w_r}$), w = gravimetric water content of soil, w_s = saturated water content, w_r = residual water content, ψ_b = air-entry value, λ= pore size distribution, and ψ = suction variable.

In Brutsaert's 1967 best fit curve, both fitting parameters and normalized water content have been used:

$$\Theta_n = \frac{1}{1+({\psi}/{a_b})^{n_b}} \tag{3.7}$$

where a_b = fitting parameter (a function of air-entry value), n_b= fitting parameter.

Laliberte (1969) first proposed a triple-parameter empirical equation in which the fitting parameters are related to pore-size distribution.

$$\Theta_n = \frac{1}{2} erfc[a_1 - \frac{b_1}{c_1+\left({\psi}/{\psi_b}\right)}] \tag{3.8}$$

where a_1, b_1, c_1 = fitting parameters, ψ = suction variable, ψ_b= air-entry value, and erfc is Gauss error function.

Van Genuchten (1980) gave a closed-form expression for hydraulic conductivity, in which m is related to n through the equation m = (1-1/n).

$$\Theta_n = [\frac{1}{1+(p\psi)^n}]^m \qquad [3.9]$$

where p, n, and m = three different soil parameters.

Boltzmann distribution has been applied to analyze SWCC by Mckee and Bumb (1984). Mckee and Bumb (1987) proposed another SWCC exponential function which is based on Fermi distribution:

$$\Theta_d = \frac{1}{1+\exp[\frac{(\psi-a_{m2})}{n_{m2}}]} \qquad [3.10]$$

where a_{m2}, n_{m2} = fitting parameters, and ψ = suction variable.

The most frequently used empirical equation in geotechnical engineering practice is proposed by Fredlund and Xing (1994). This best fit curve covers the low suction range and high suction range with a correction factor:

$$\theta(\psi, a_f, n_f, m_f) = C(\psi)\frac{\theta_s}{(\ln(e+\left({}^{\psi}/_{a_f}\right)^{n_f})^{m_f}} \qquad [3.11]$$

where a_f, n_f, and m_f = curve fitting parameters, θ_s = saturated volumetric water content, θ = volumetric water content corresponding to a selected soil suction, e = a constant equal to 2.71828, and $C(\psi)$ is correction factor:

$$C(\psi) = 1 - \frac{\ln(1+{}^{\psi}/_{\psi_r})}{\ln[1+({}^{10^6}/_{\psi_r})]} \qquad [3.12]$$

where ψ_r = the suction at residual value.

There are difficulties for those equations (Gardner 1958, Brooks and Corey 1964, Brutsaert's 1967, Mckee and Bumb 1984 and Mckee and Bumb 1987) to describe the SWCC (from 0 kPa to

1,000,000 kPa) with a continuous function (Fredlund et al. 2012). Pham and Fredlund (2005) proposed a piecewise linear equation to fit the SWCC data:

$$\begin{cases} w_1(\psi) = w_u - S_1 log(\psi) & 1 \leq \psi \leq \psi_a \\ w_2(\psi) = w_a - S_2 log\left(\frac{\psi}{\psi_a}\right) & \psi_a \leq \psi \leq \psi_r \\ w_3(\psi) = S_3 log\left(\frac{10^6}{\psi}\right) & \psi_r \leq \psi \leq 10^6 \end{cases} \qquad [3.13]$$

where S_1, S_2, S_3 = slope of SWCC at three zones, w_u = water content at 1 kPa, w_a = water content at air-entry value, w_1, w_2, w_3 = water content for the three zones.

Figure 3.4 lists some of the SWCC empirical equations. Those equations are divided into three categories and the application of those equations depends on the suction range of the soil (Fredlund et al. 2010).

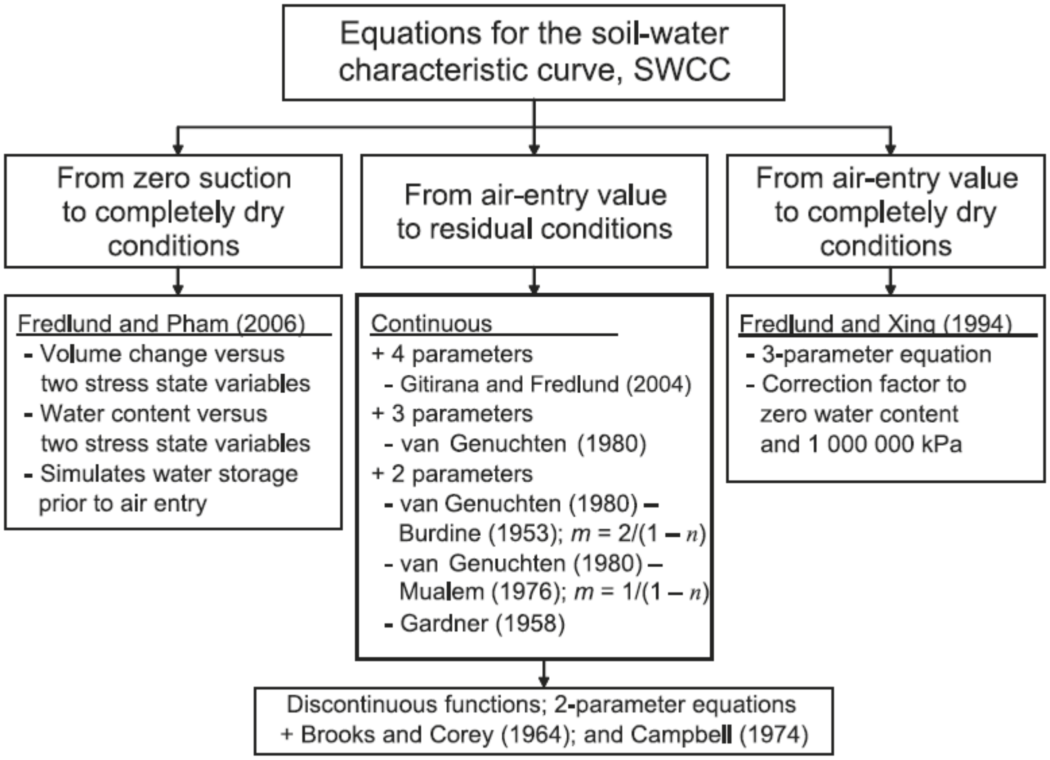


Figure 3.4 Categorization of SWCC (Fredlund et al. 2010)

3.2.2 Permeability of Soil

The flow rate of water through a porous medium is regulated by the hydraulic conductivity (also called coefficient of permeability). For unsaturated soil, the water storage should be considered when coefficient of permeability is evaluated (Fredlund et al. 2012).

Unlike the coefficient of permeability in a saturated porous medium, the coefficient of permeability is a non-constant parameter related to the degree of saturation of the unsaturated soil (Brooks and Corey 1964). Gardner (1958) and Arbhabhirama (1968) proposed equations to evaluate the coefficient of permeability by using matric suction.

In this research study, the saturated permeability of the soil is used to analyze the diffusion coefficient. The tests of saturated permeability are based on Darcy's equation. The permeability test equipment amplifies the hydraulic gradient and quantity of water discharge from the soil to calculate the coefficient of permeability.

In practice, as shown in Figure 3.5 the saturated permeability can also be evaluated by empirical correlations (Aubeny and Lytton 2004).

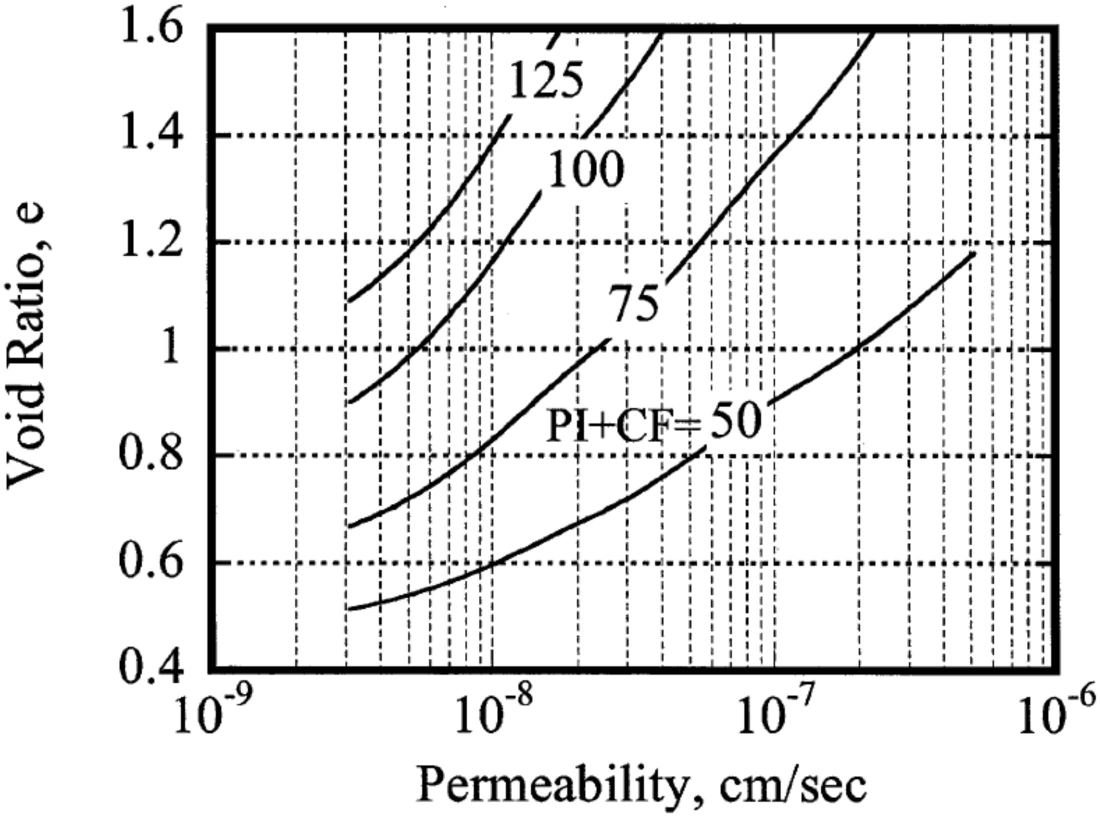


Figure 3.5 Empirical Correlations of Clay Permeability (Tavenas et al. 1983)

CHAPTER IV

LABORATORY TESTS

In this chapter, the sample preparation for the diffusion, psychrometer, SWCC and permeability tests are discussed. The testing procedure includes thermocouple psychrometer calibration, suction measurements by psychrometer and filter paper, Fredlund SWCC device test and coefficient of saturated permeability test.

4.1 Sample Preparation

The soil specimens from two sites are tested. The two sites are located in Oklahoma City near Lake Hefner and along Interstate Highway I-35 in Ardmore. In order to make comparisons of the diffusion coefficient of the soils with different properties, the compacted soil specimens are used in the tests. For each soil, six compacted soil specimens are prepared. The soil specimens are compacted at optimum water contents and left for moisture equilibration for at least three weeks. Then, the compacted and moisture equilibrated soil specimens are prepared further to fulfil the requirements of the test protocols as described in the following sections.

4.1.1 Compaction Test

Standard Proctor compaction tests were conducted. The soil sample was taken and oven dried at 110 ^{o}C for 24 hours and grounded in the soil crusher. About 2000 grams of the sample was used for the compaction test. The soil sample was mixed with water and allowed to cure per ASTM D698 guidelines. The mold and collar were assembled and secured to the base plate. The soil was compacted in three layers, each layer receiving 25 of drops from 12 inches.

After the compaction, the collar and base plate were removed from the mold. A knife was used to trim the soil at the top. The mass of the compacted specimen and mold was determined and recorded to the nearest gram. The compacted specimen was then removed from the mold using a hydraulic jack. The compaction curves (given in Appendix A) were determined by applying best fit curve proposed by Li and Sego (2000).

4.1.2 Compacted Specimen Preparation and Curing

The optimum water content is determined from the compaction curve. The water is added to the crushed oven dry soil to reach to the optimum water content, and fully mixed with the soil. According to the standard Proctor compaction protocol (ASTM D698), the soil specimen is compacted, extracted and trimmed.

The soil specimens are weak and not moisture equilibrated inside. Moisture equilibration and strength gain will take at least two weeks before further trimming and testing. In the curing period, plastic wrap and aluminum foil are used to wrap the soil specimen to prevent any moisture gain or loss (shown in Figure 4.1). The well wrapped soil specimens are kept in an ice chest for two weeks.

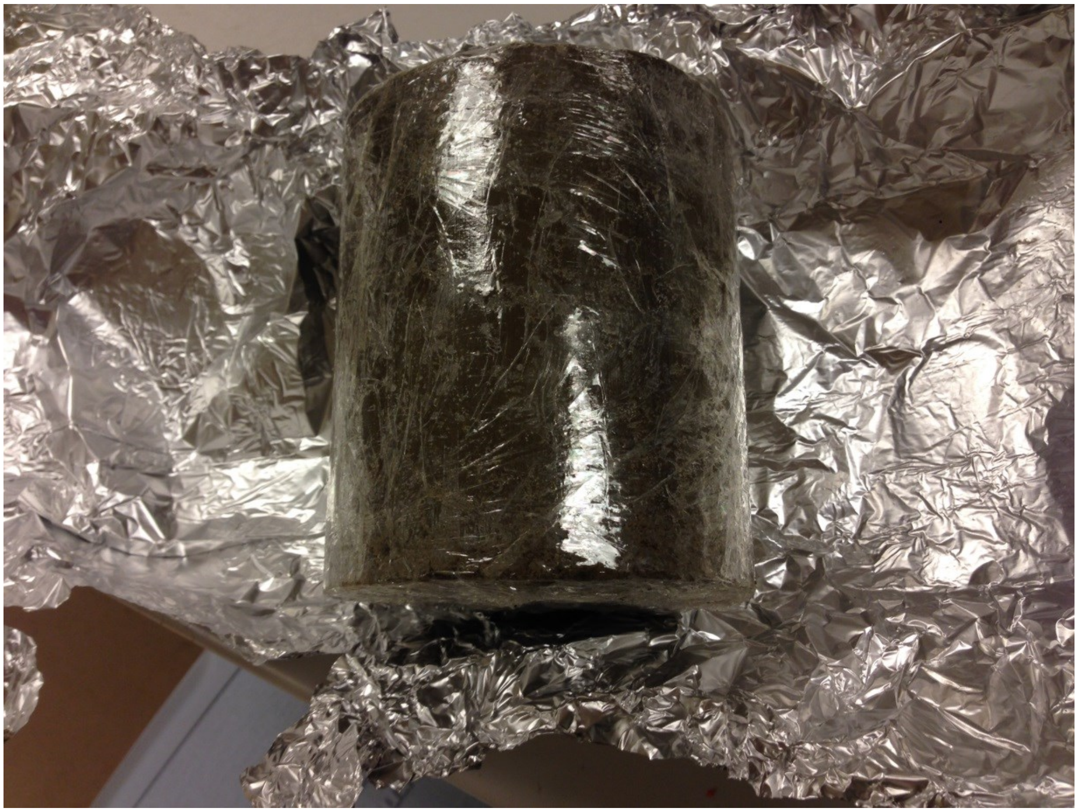


Figure 4.1 Compacted Soil Specimen Curing in Plastic Wrap and Aluminum Foil

4.2 Diffusivity Test by Thermocouple Psychrometer

Mitchell (1979) proposed testing methods for the drying diffusivity and wetting diffusivity measurements. Lytton et al. (2004) and Mabirizi (2010) made improvements to the drying test and wetting test. In this research study, only the drying testing is performed.

4.2.1 Thermocouple Psychromter Calibration

Before diffusivity tests were performed, the thermocouple psychrometers were calibrated (Figure 4.2) using salt solutions with known concentrations by immersing the sensor in solutions (Figure 4.3). The calibration curve for each psychrometer reflects the relationship between the output microvolt and osmotic suction at equilibrium condition.

Figure 4.2 Thermocouple Psychrometer

Figure 4.3 Thermocouple Psychrometer Calibration (Mabirizi 2010)

Thermocouple psychrometers from Wescor, Inc. were used to test total suction changes over time. Different concentrations of sodium chloride (NaCl) solutions with known molalities and osmotic suction (Table 4.1) were used to calibrate the psychrometers. Glass jars were used to calibrate six psychrometers at once at 25±0.1 ^{o}C as shown in Figure 4.3. Temperature fluctuation is crucial in psychrometer total suction measurements (Lytton et al. 2004). The water bath designed for diffusivity tests (Figure 4.4) is used to maintain a constant temperature environment for calibration.

Table 4.1 NaCl Osmotic Suctions (Bulut et al. 2001)

Molality of NaCl (m)	Osmotic Suction (bar)	Osmotic Suction (kPa)	Osmotic Suction (log kPa)	Osmotic Suction (pF)	Osmotic Suction (g/liter)
0.01	0.4799	47.9937	1.6812	2.6897	0.5844
0.02	0.9502	95.0235	1.9778	2.9863	1.1688
0.05	2.3390	233.9024	2.3690	3.3775	2.9221
0.10	4.6232	462.3164	2.6649	3.6735	5.8442
0.20	9.1608	916.0757	2.9619	3.9704	11.6885
0.30	13.7019	1370.1870	3.1368	4.1453	17.5327
0.40	18.182658	1826.5788	3.2616	4.2702	23.3770
0.50	22.8615	2286.1486	3.3591	4.3676	29.2212
0.60	27.4942	2749.4170	3.4392	4.4478	35.0655
0.70	32.1682	3216.8152	3.5074	4.5159	40.9097
0.80	36.8870	3688.6952	3.5669	4.5754	46.7540
0.90	41.6531	4165.3100	3.6196	4.6282	52.5982
1.00	46.4691	4646.9124	3.6672	4.6757	58.4425
1.20	56.2615	5626.1507	3.7502	4.7587	70.1310
1.40	66.2798	66.27.9768	3.8214	4.8299	81.8195
1.50	71.3777	7137.7693	3.8536	4.8621	87.6637
1.60	76.5384	7653.8384	3.8839	4.8924	93.5079
1.80	87.0498	8704.9848	3.8839	4.9483	105.1964
2.00	97.8247	9782.4672	3.9904	4.9990	116.8849
2.20	108.8735	10887.3465	4.0369	5.0454	128.5734
2.40	120.2025	12020.2474	4.0799	5.0884	140.2619
2.50	125.9757	12597.5653	4.1003	5.1088	146.1062

1 mole of NaCl = 58.442468 grams

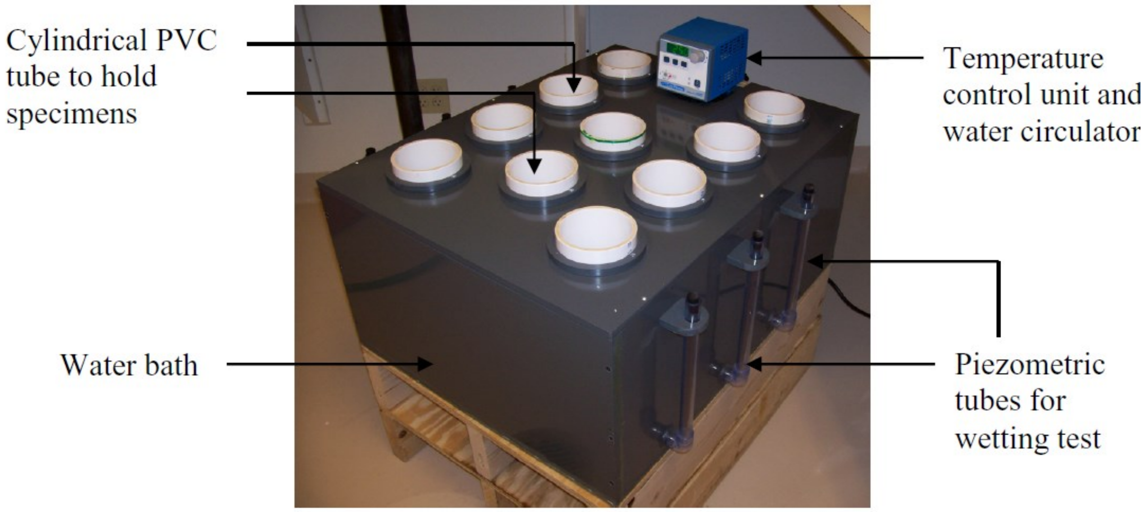


Figure 4.4 Water Bath for Calibration (Mabirizi 2010)

A CR7 datalogger (Figure 4.5) was employed to record and retrieve microvolt data. The microvolt outputs were plotted against the osmotic suction values to obtain a psychromter’s calibration curve. A typical calibration curve is given in Figure 4.6. A step by step calibration procedure was proposed by Mabirizi (2010).

Figure 4.5 CR7 Data-logger (Mabirizi 2010)

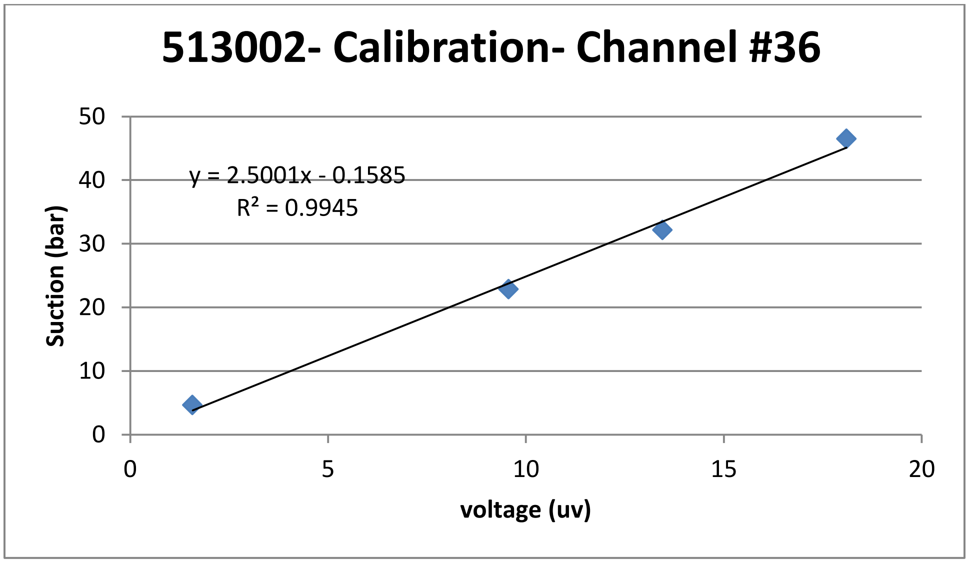


Figure 4.6 A Typical Calibration Curve

4.2.2 Measurement of Initial Suction

The initial suction is the suction for the cured and equilibrated suction of the soil. The initial suction should be determined prior to thermocouple psychromter test (Mabirizi 2010). The filter paper total suction test (Bulut et al. 2001) is used to determine the initial suction. In this test, the

Schleicher & Schuell No. 598 filter papers were used to measure soil suction. The testing procedure given by Bulut et al. (2001) was applied for suction measurements of the soil. A trimmed portion of a compacted soil specimen was placed in a glass jar (Figure 4.7). Two filter papers are placed on a support ring which provides a filter paper-soil non-contacted system (Mabirizi and Bulut 2010). The sealed glass jar was left in an ice chest which has a constant temperature environment. After seven days of equilibration, the water contents of the filter papers were measured. The initial suction of soil was calculated by using calibration curve of filter paper (Figure 4.8). The procedure of suction measurements by using filter paper discs is given by Bulut et al. (2001).

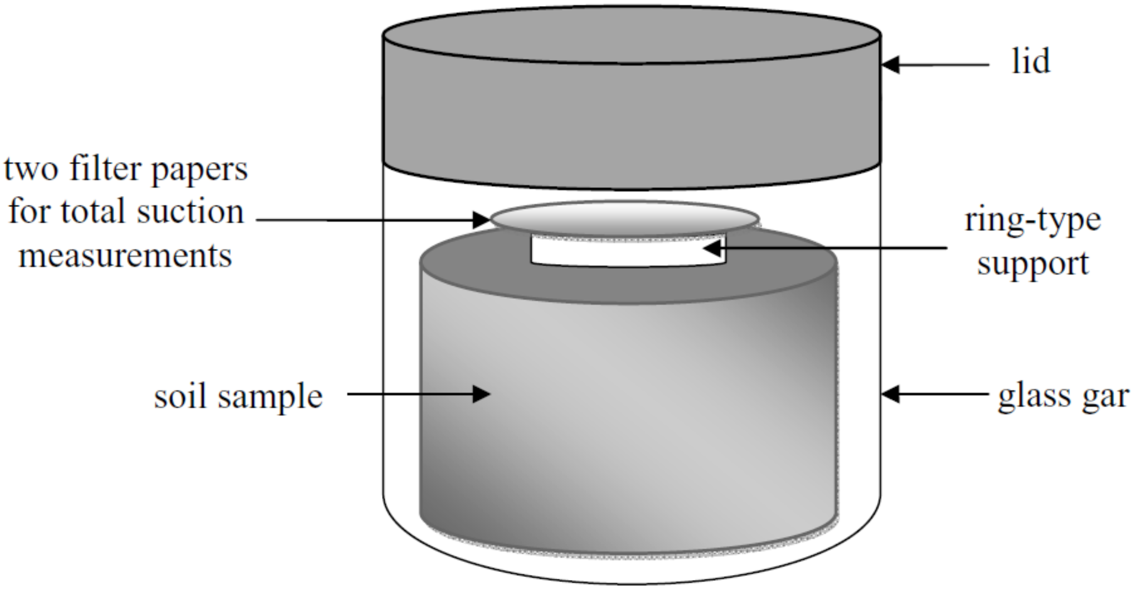


Figure 4.7 Filter Paper Total Suction Measurements (Mabirizi 2010)

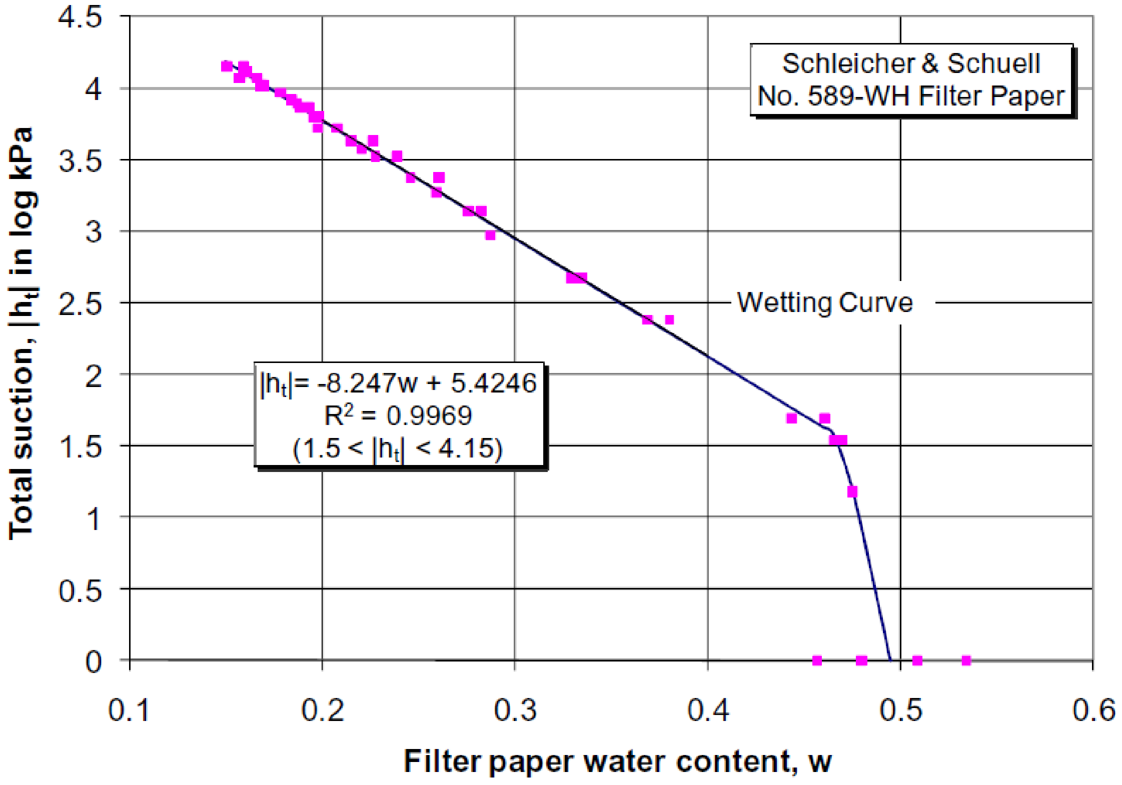


Figure 4.8 Filter Paper Wetting Calibration Curve (Bulut et al. 2001)

4.2.3 Soil Suction Measurements by Thermocouple Psychrometer

In this research study, the diffusivity test was performed on a 101.6 mm diameter and 157.4 mm height compacted soil specimen. In order to accurately determine the distance from thermocouple psychrometer sensor to the surface, the smooth end of the soil specimen was selected to expose to the open air with known relative humidity. For the test, thermocouple psychrometers are installed nearby the open end of the soil specimen, the closer to the end the better for shorter testing periods.

A hole created by a driller was used to install the psychrometer sensor into the soil specimen. It is crucial to make sure there are no cracks formed during the drilling, which will disturb the suction measurement (Mabirizi 2010). After the soil specimen was wrapped with plastic wrap and aluminum foil to prevent any moisture exchange with atmosphere, the holes were made and the psychrometer installed (shown in Figure 4.9).


(a)
(b)
(c)
(d)

Figure 4.9 Thermocouple Psychromter Installations

The well wrapped specimen with the psychrometer is placed in an ice chest with plastic fillings to provide a constant temperature environment. It needs one or two weeks for the drying diffusion test. A step-by-step test procedure is given by Mabirizi (2010).

4.2.4 Diffusivity Test Data Interpretation

The data collected by data logger is microvolt output versus time. The data was transferred into the suction versus time by using the calibration curve of the psychrometer. A theoretical line (Figure 4.10) was used to fit those suction versus time data points (Mabirizi and Bulut 2010). The data plots required parameters include: u_o = initial suction, u_a = atmospheric suction, x = psychrometer distance from the close end, L = sample length, h_e = evaporation constant and α = drying diffusion coefficient.

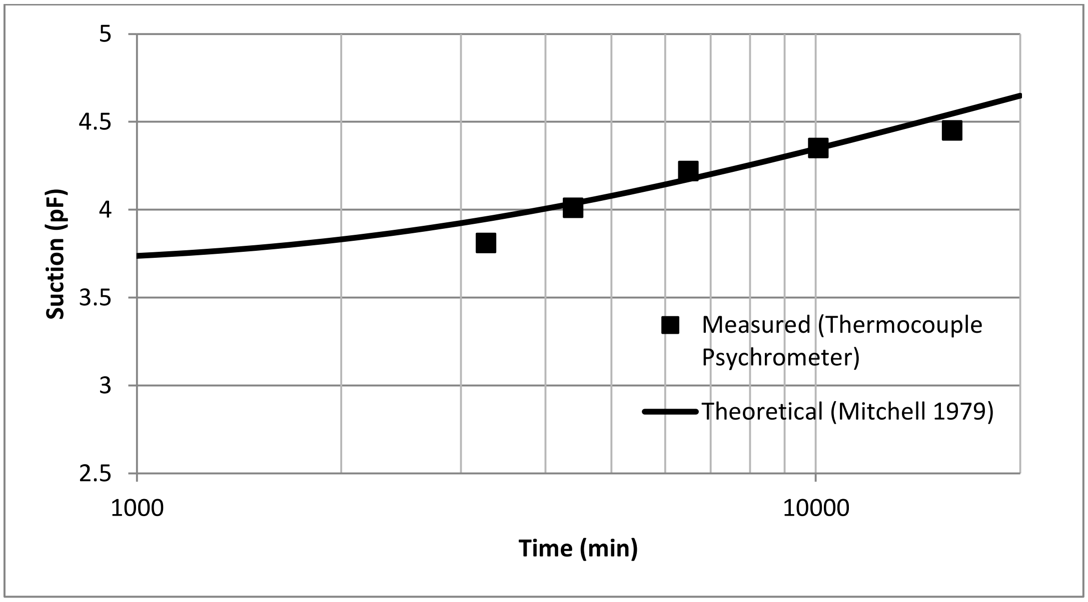


Figure 4.10 Theoretical versus Measured Suction with Time

Interpretation of data given by Lytton et al. (2004) was used to determine the drying diffusion coefficient. The least square error method is employed to calculate diffusion coefficient. By minimizing the square errors, the optimum diffusion coefficient is obtained. This procedure can be simply programed in a computer. Matlab was used to assist in calculating the diffusion coefficient in this study.

4.3 Diffusivity Determined by SWCC and Permeability

Diffusion coefficient can be calculated by using the slope of SWCC and saturated permeability (Mitchell 1979). In this study, the SWCC and saturated permeability tests were conducted on the soil specimens which are prepared at optimum water contents and cured for more than two weeks.

4.3.1 SWCC Test

Soil water characteristic curve (SWCC) can be determined in the laboratory by measuring the water content using pressure plate device. The disturbed soil or undisturbed soil samples can be used to perform SWCC tests.

In this research, Fredlund and Xing's (1994) best fit curve with three fitting parameters, which are widely used in geotechnical engineering practice, was applied to plot and analyze the testing results. Fredlund Pressure Plate Cell (shown in Figure 4.11) was employed to obtain SWCCs. The testing data were fitted using the equation proposed by Fredlund and Xing (1994).

In the following sections, the calibration of SWCC equipment, saturation of soil specimen, SWCC testing procedure and data interpretation are discussed.

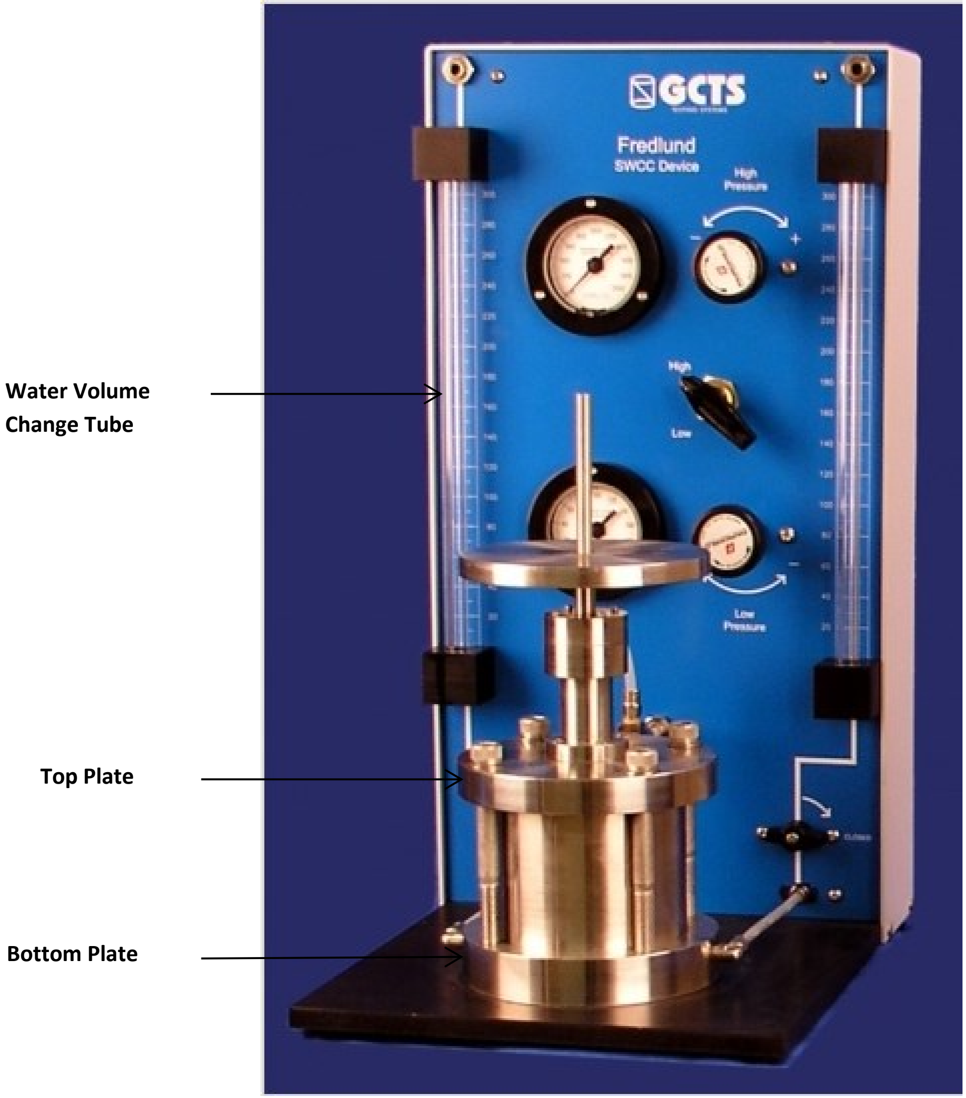


Figure 4.11 Fredlund Pressure Plate Cell (SWC-150)

4.3.1.1 Calibration of Water Volume Change Tubes

Fredlund Soil Water Characteristic Device was employed to modify applied suction and monitor the water content in the soil. Before SWCC test was performed, the water volume change tube should be calibrated. The measurements from the water volume change tubes represent a linear measurement in millimeter. These linear measurements should be converted to a gravimetric calibration factor α. A step-by-step procedure of how to calibrate the water volume change tubes is given in Appendix B.

4.3.1.2 Saturation of Soil Specimen

Before the drying SWCC test, soil specimen should be trimmed and fully saturated. The soil specimen was placed on a porous stone covered with filter paper in a container. The container was filled with demineralized water till 2 mm to the top of specimen as shown in Figure 4.12. This allows the soil to be saturated from bottom up, which prevents air entrapped in the soil.

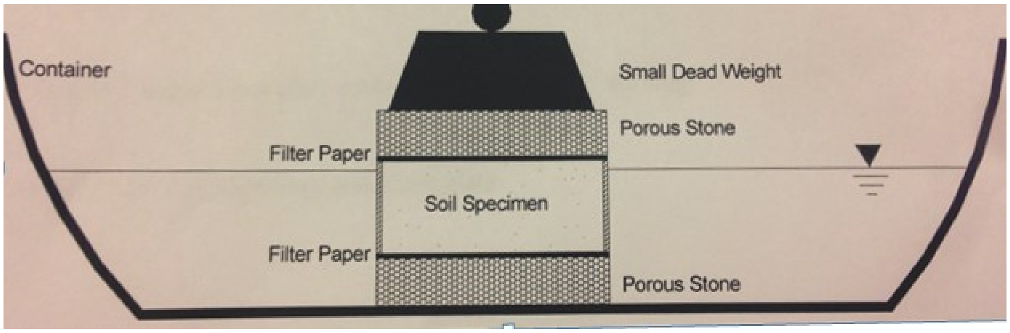


Figure 4.12 Saturation of Soil Specimen (SWC-150 Testing Manual)

The time for saturation will be several hours for granular soil, while several days for highly plastic clay soil (Fredlund et al. 2012).

4.3.1.3 SWCC Tests

The soil properties such as water content, grain-size distribution, plasticity index and specific gravity were determined prior to SWCC tests.

The saturated soil specimen with a 15 bar ceramic stone is placed on the base of the test chamber as shown in Figure 4.13. After the testing device is assembled as shown in Figure 4.11, the air pressure is applied to the soil; the water volume change tube reading is recorded every 3 hours. When the reading in tubes becomes constant which represents the soil-water inside the testing chamber is in equilibrium condition, the applied air pressure is increased to test another data point for the SWCC.

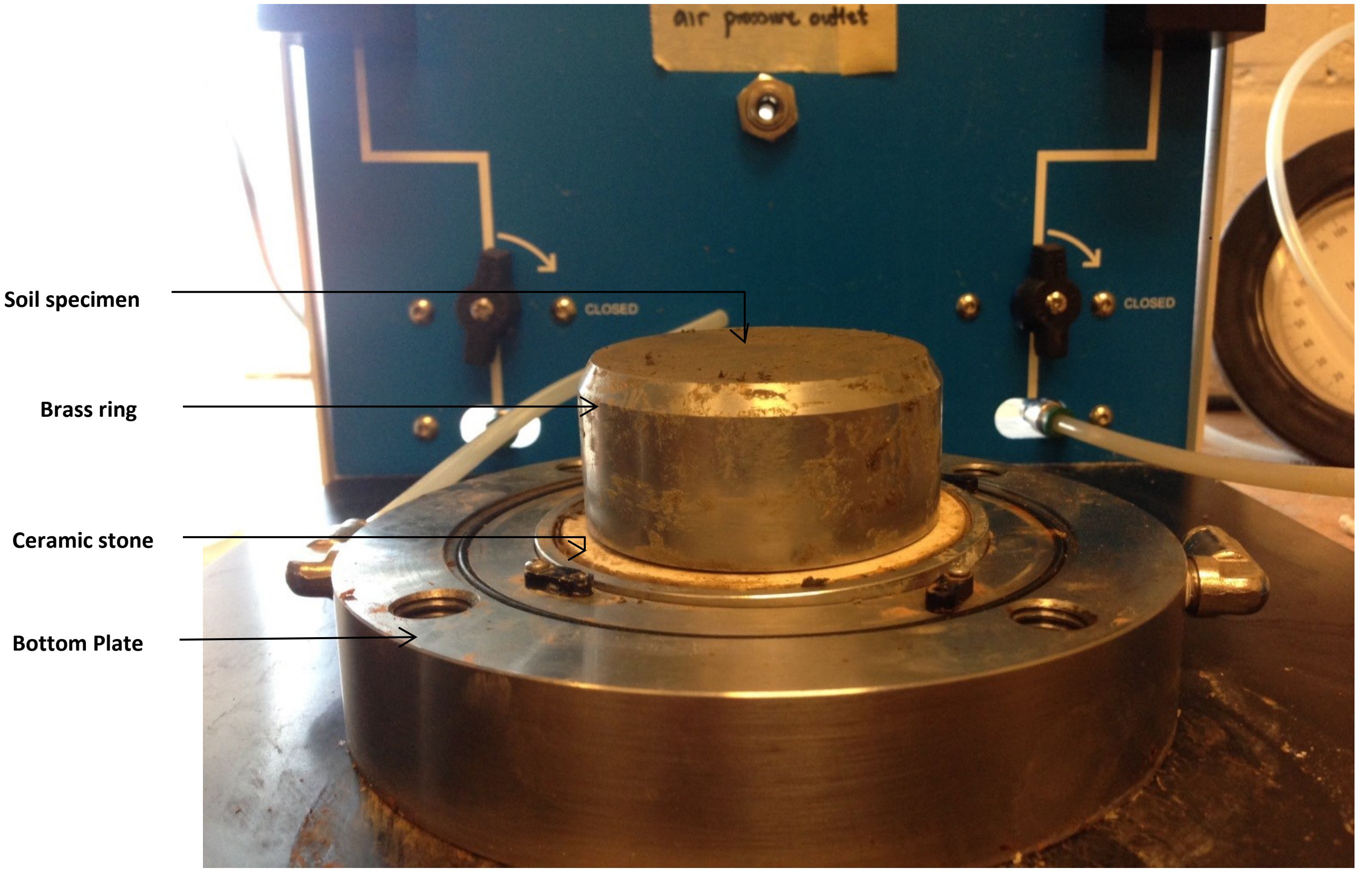


Figure 4.13 Saturated soil with ceramic stone on the base of testing chamber

4.3.1.4 SWCC Data Interpretation

Using the applied air pressure and corresponding degree of saturation or water content from the drying processes, the drying SWCC can be determined as shown in Figure 4.14. The degree of saturation or gravimetric (volumetric) water content versus suction data is then fit with a theoretical curve given by Fredlund and Xing (1994).

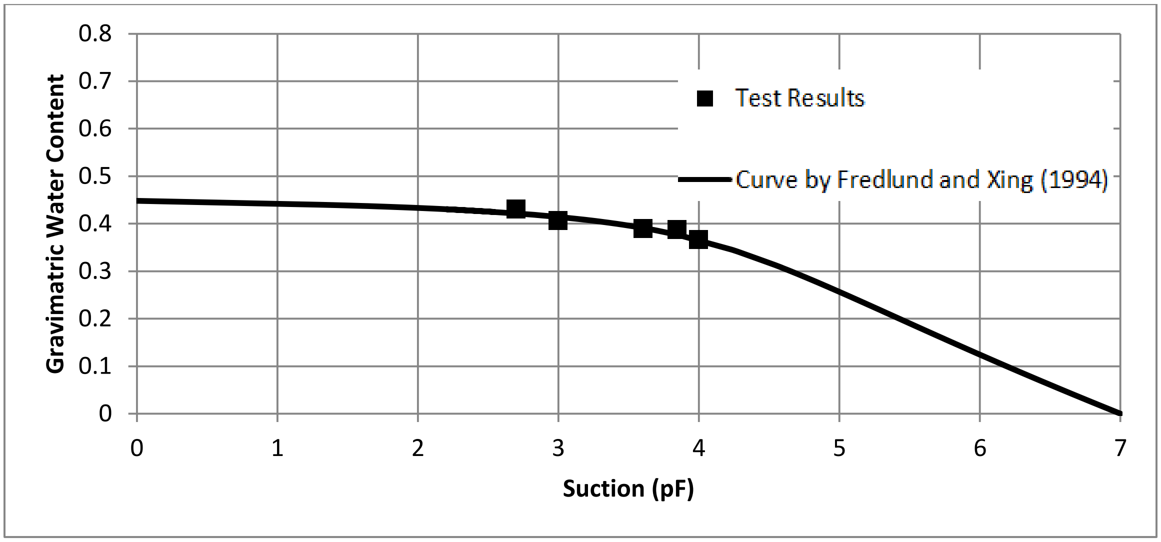


Figure 4.14 Theoretical versus tested water content with suction in pF

The least square error method was employed to determine the SWCC. The procedure is as follows:

1. Initially give a random value within the reasonable range to the fitting parameters (i.e. for clay soil, $a_f = 10$, $n_f = 0.8$, $m_f = 0.5$) for Equation 3.11.
2. Compute the error between the theoretical degree of saturation and measured degree of saturation for each test data points with the assumed fitting parameters.
3. Change the fitting parameter a_f to calculate and find optimum parameter a_f with the least square errors.
4. Use optimized a_f and assumed m_f find the optimized n_f; and then use a_f and m_f to determine the fitting parameter m_f.
5. Plot the SWCC by using the three optimized fitting parameters.

An example of data interpretation is given in Appendix C.

4.3.2 Saturated Permeability Test

The permeability of saturated clay soil can be determined by measuring the discharged water under certain water head using a triaxial chamber and permeability control panel. For the compacted clay soil which has a very low permeability, in order to measure the discharged volume of water, the soil specimen was installed into the triaxial chamber with a membrane and an air pressure (larger than 5 psi) was applied to create larger gradient.

In this part, the soil specimen preparation, specimen saturation and test will be discussed.

4.3.2.1 Soil Specimen Installation and Saturation

A triaxial chamber was used to test the saturated permeability of the soil specimens. Prior to the test, the soil specimen in the membrane was placed in the triaxial chamber with porous plates and filter papers on both sides as shown in Figure 4.15.

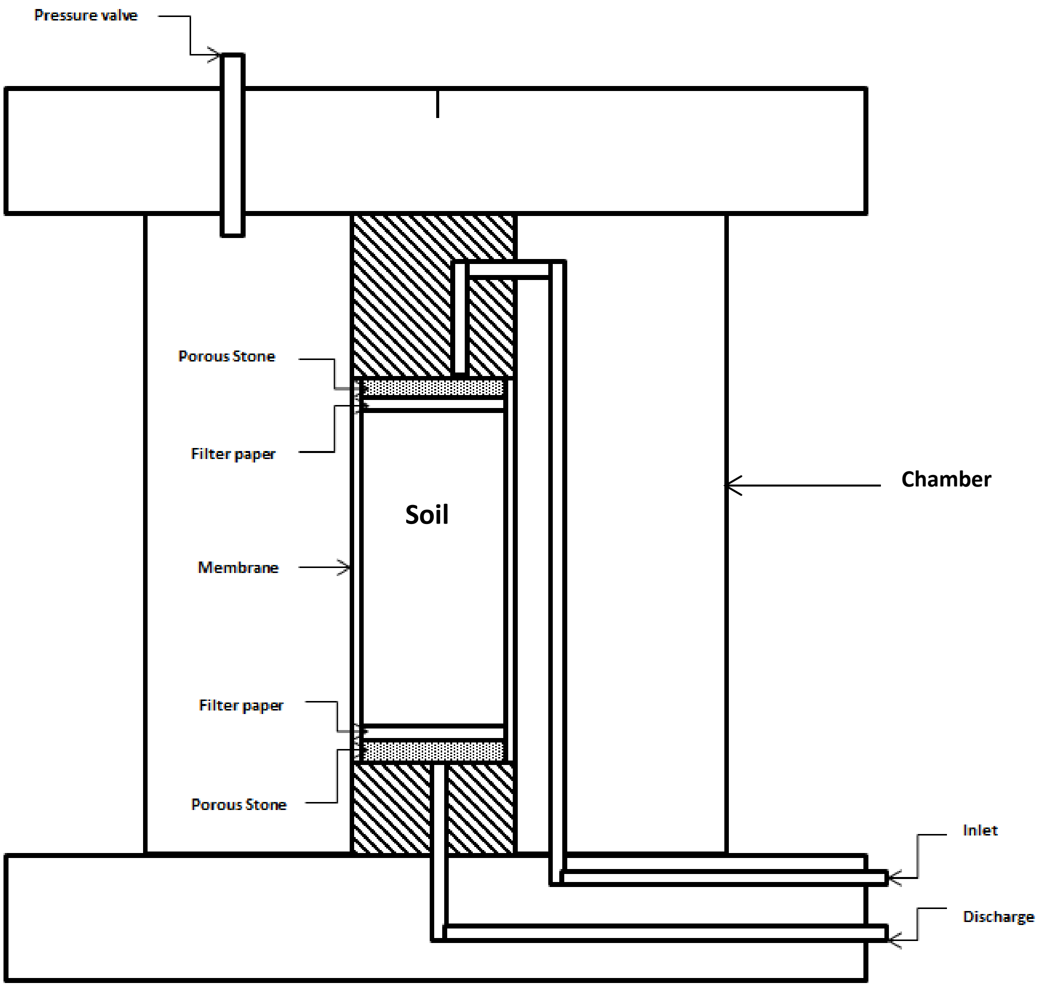


Figure 4.15 Sample Installation

Because of the low permeability of the clay soil, one week was needed to saturate the specimen in the triaxial chamber. After the quantity of inlet water equals to the discharged water during saturation, the soil is fully saturated and ready for the permeability test.

4.3.2.2 Permeability Test

After the soil is fully saturated, the inlet water pressure and discharged water pressure are modified accordingly (set inlet pressure 5 psi and cell pressure 10 psi). The one dimensional continuous flow through the soil specimen fulfills the Darcy’s equation in which the permeability of the soil equals to the quantity of water divided by cross-section area multiplied by the water head gradient.

As shown in Figure 4.16, the quantity of water can be read from the burettes and the gradient can be modified on the control panel. The data was recorded every 6 hours until the quantity of water can be observed in the burettes. A step by step testing and calculation procedure is given in Appendix C.

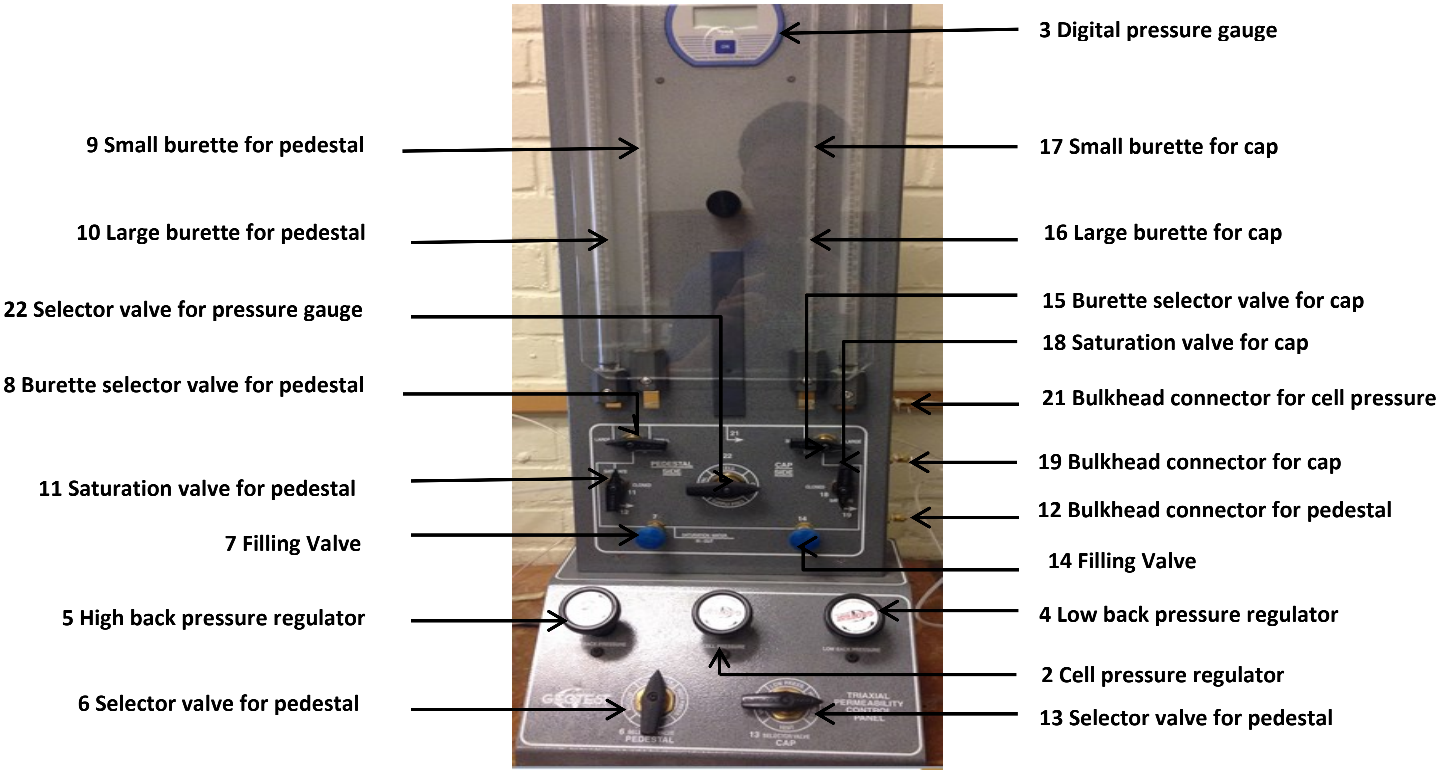


Figure 4.16 Saturated Permeability Test Control Panel

4.3.3 Diffusivity Calculated by SWCC and Permeability

The diffusion coefficient of unsaturated soils can be expressed by the slope of SWCC and saturated permeability of the soil according to the following equation (Mitchell 1979):

$$\alpha = \frac{k_0 h_0}{c} \frac{\gamma_w}{\gamma_d} \qquad [4.1]$$

where k_o is saturated permeability of soil, h_o is a constant suction equal to 100 cm, γ_w is unit weight of water, γ_d is dry unit weight of soil, and c is slope of suction in logarithmic scale versus gravimetric water content. The dry unit weight of soil was determined before SWCC and permeability tests. In this research, the non-constant parameter c is used to calculate diffusion coefficient, which changes with the suction change. Thus, an incremental diffusion coefficient α value can be determined by equation 4.1.

CHAPTER V

TEST RESULTS AND DISSCUSSIONS

The soil specimens from Lake Hefner and Ardmore sites were obtained from Oklahoma Department of Transportation. The soils from Lake Hefner are in red color with low PI while the soils from Ardmore site are in brown color with high PI.

In this research study, both diffusion coefficient test by thermocouple psychrometer and diffusion coefficient evaluation by SWCC and saturated permeability tests were performed on the compacted soil specimens from the two sites. In practice, the thermocouple psychrometer gives a quick and cost effective approach to determine the diffusion coefficient. However, as mentioned in the previous sections, the thermocouple psychrometer testing range, which is usually from 3.5 pF to 4.5 pF suction, is limited and the measured diffusion coefficient may not be representative of the whole suction range. The diffusion coefficient tested by the SWCC and permeability tests is an alternative way to evaluate the incremental diffusivity for whole suction range, which divides the SWCC curve according to the suction scale given in Aubeny and Lytton (2003).

5.1 Soil Properties

Compaction tests, Atterberg limits and sieve analysis were performed on the soils from the two sites, and then the soils were compacted at optimum water content and equilibrated before the diffusion tests started. The soil properties are listed in Table 5.1.

Table 5.1 the Properties of Soils from Two Sites

Site	Water content (%)	Initial Suction (pF)	Liquid Limit (%)	Plastic Limit (%)	% Passing Sieve No. 200	% Passing 2 Micron Size	Optimum Moisture Content (%)	Maximum Dry Unit Weight (pcf)
Lake Hefner	19.04	3.36	37.6	23.4	63.3	20	22.5	102.5
Ardmore	23.04	3.70	52.6	27	52	21	24.5	98.8

5.2 Diffusion Coefficient Tested by Thermocouple Psychrometers

Two diffusion tests by thermocouple psychrometer, which presented in 4.2, were performed for each soil. The theoretical curve given by Mitchell (1979) and test data of diffusion coefficient tests for Lake Hefner and Ardmore soils are summarized in Tables 5.2 and 5.3 and in Figures 5.1 and 5.2.

Table 5.2 Drying Diffusion Coefficient Test Results for Lake Hefner Compacted Soil

Parameter	**Value**	**Units**
Evaporation Coefficient (h_e)	0.54	cm^{-1}
Atmospheric Suction (u_a)	6.05	pF
Initial Suction (u_o)	3.36	pF
Psychrometer Location (x)	10.64	cm
Sample Length (L)	11.64	cm
Laboratory Suction Measurements Using Thermocouple Psychrometers	**Time (min)**	**Suction (pF)**
	13890	3.868
	14870	4.042
	15840	4.138
	16820	4.255
	17790	4.255
Drying Diffusion Coefficient (α_{dry})	0.0024	(cm^2/min)

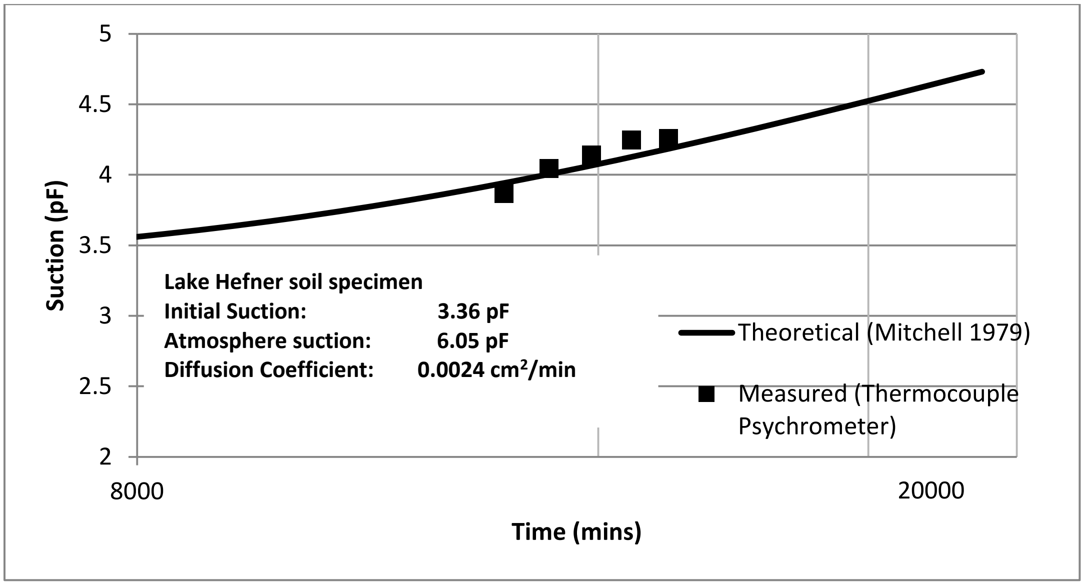


Figure 5.1 Theoretical versus tested data for Lake Hefner Site

Table 5.3 Drying Diffusion Coefficient Test Results for Ardmore Site Compacted Soil

Parameter	Value	Units
Evaporation Coefficient (h_e)	0.54	cm^{-1}
Atmospheric Suction (u_a)	6.08	pF
Initial Suction (u_o)	3.70	pF
Psychrometer Location (x)	10.64	cm
Sample Length (L)	11.64	cm
Laboratory Suction Measurements Using Thermocouple Psychrometers	**Time (min)**	**Suction (pF)**
	3270	3.79
	4390	3.95
	6490	4.12
	10090	4.28
	15890	4.45
Drying Diffusion Coefficient (α_{dry})	0.000208	(cm^2/min)

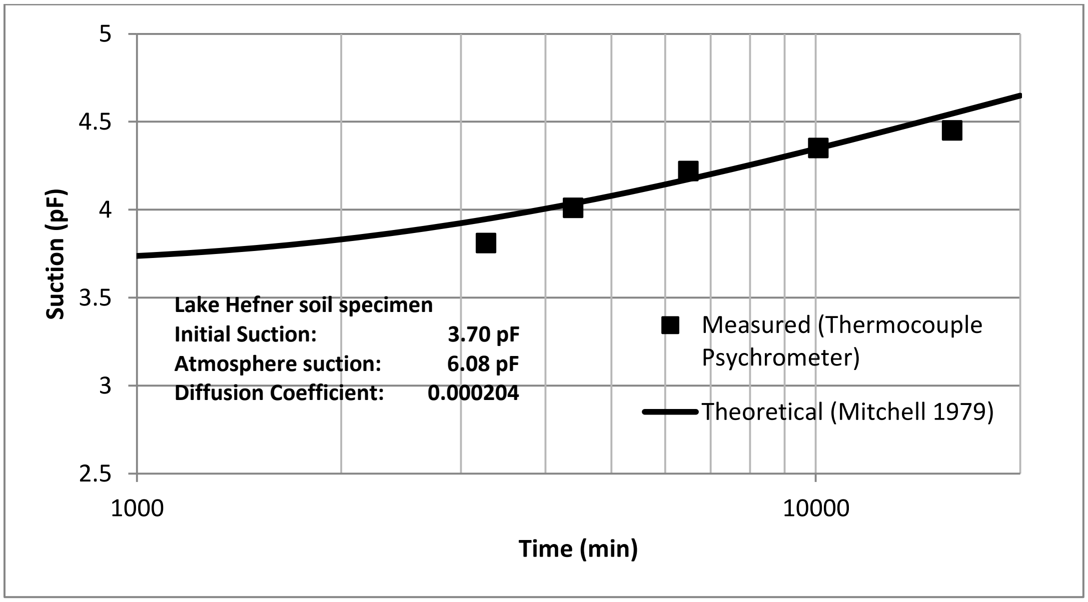


Figure 5.2 Theoretical versus tested data for Ardmore Site

5.3 Diffusion Coefficient Tested by SWCC and Permeability

In this research study, two SWCC tests and two saturated permeability tests were performed for each soil. Soil specimen numbers are L#1 and L#2 from Lake Hefner Site, and A#1 and A#2 from Ardmore Site.

5.3.1 SWCC Test

In this study, the SWCC is presented in terms of the gravimetric water contents. The SWCC curve with degree of saturation was also plotted and then converted to the SWCC curve with the gravimetric water content. The Lake Hefner soil SWCC testing results are shown in Table 5.4 and the SWCC curves with degree of saturation are shown in Figure 5.3 and Figure 5.4.

Table 5.4 SWCC Testing Data for Lake Hefner Soil

L#1			L#2		
Suction (pF)	**Degree of Saturation**	**Gravimetric Water Content (%)**	**Suction (pF)**	**Degree of Saturation**	**Gravimetric Water Content (%)**
2.69	0.961	43.08	2.00	0.993	28.74
3.00	0.901	40.57	2.30	0.949	27.04
3.60	0.866	38.94	3.00	0.829	23.86
3.84	0.863	38.75	3.69	0.744	21.58
4.00	0.815	36.63	--	--	--

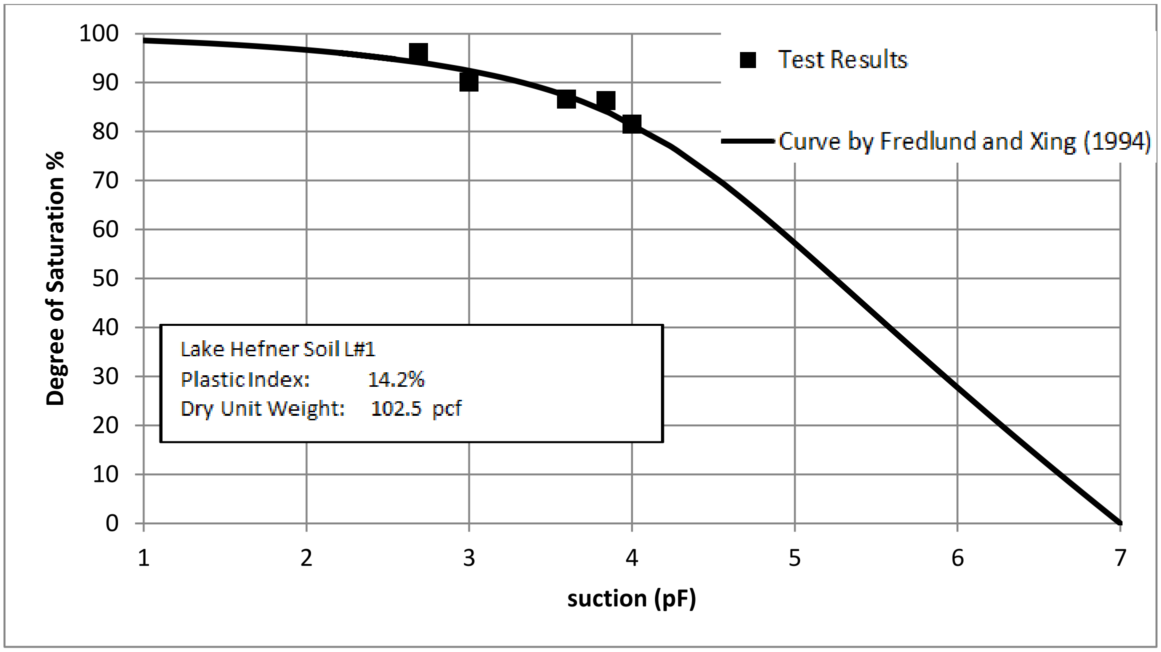


Figure 5.3 SWCC Curve with Degree of Saturation y-Axis for Lake Hefner Soil L#1

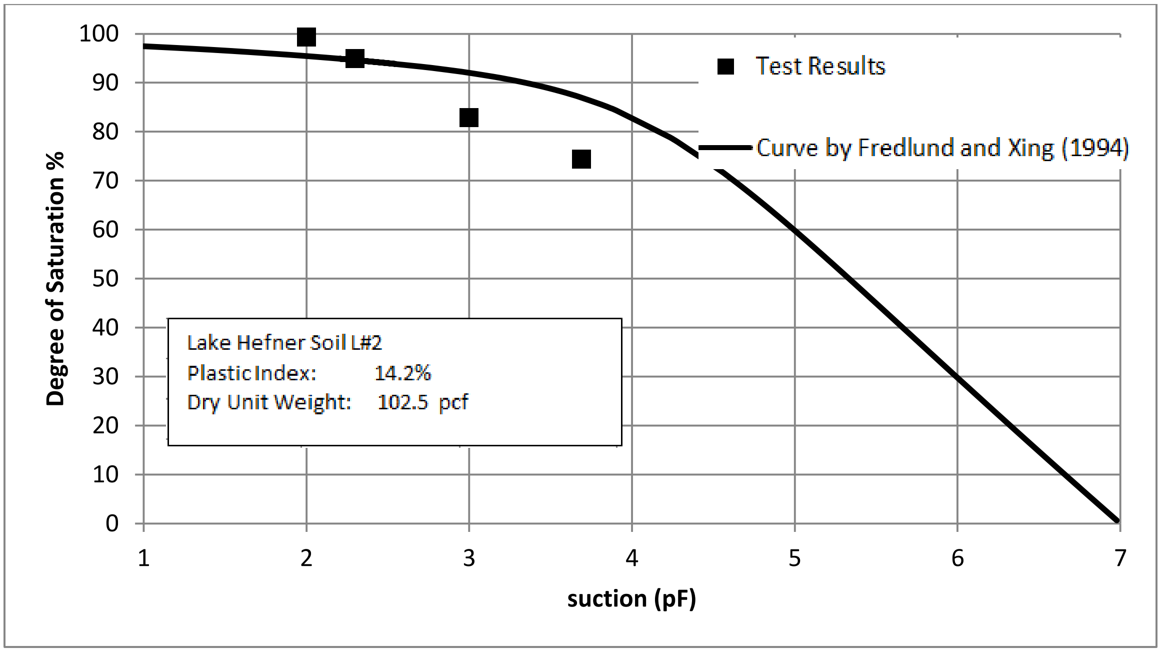


Figure 5.4 SWCC Curve with Degree of Saturation y-Axis for Lake Hefner Soil L#2

The SWCC testing results from the Ardmore site soil are shown in Table 5.5 and the SWCC curves in terms of degree of saturation are shown in Figures 5.5 and 5.6.

Table 5.5 SWCC Testing Data for Ardmore Soil

A#1			A#2		
Suction (pF)	Degree of Saturation (%)	Water Content (%)	Suction (pF)	Degree of Saturation (%)	Water Content (%)
2.0	83.3	32.4	2.6	88.9	34.5
2.6	77	30.7	3.0	84.7	33.1
3.0	66.1	28.3	3.6	79.2	30.9
3.2	62.5	24.9	3.8	72.2	28.3
3.6	53.8	22.4	4.0	61.3	24.0

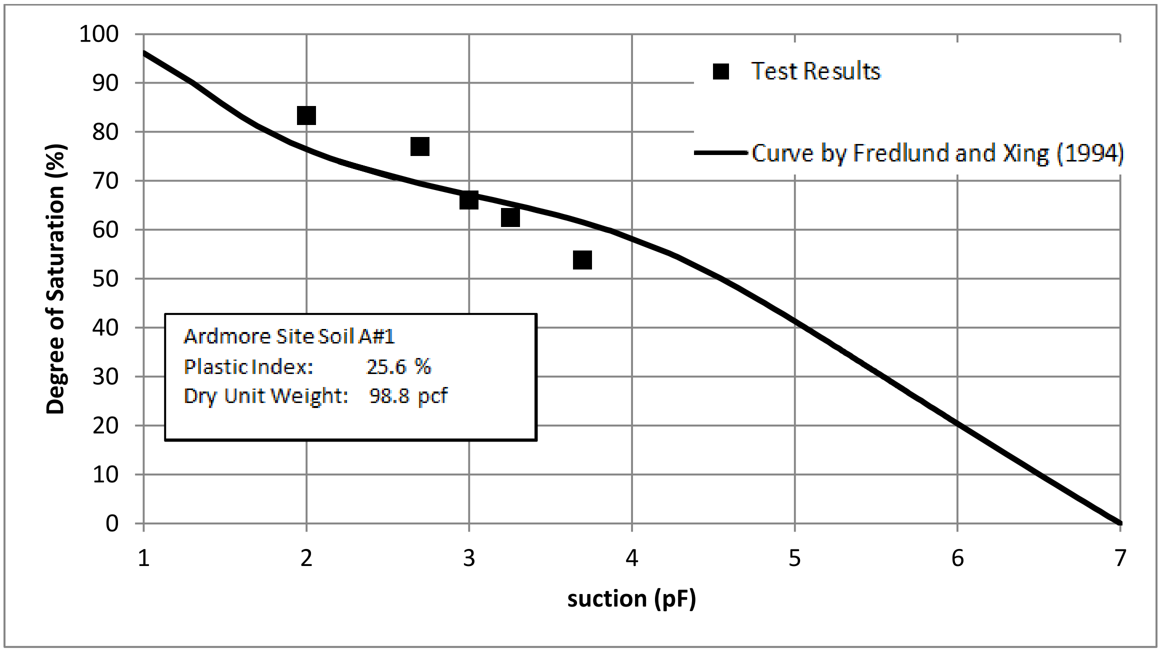


Figure 5.5 SWCC Curves with Degree of Saturation y-Axis for Ardmore Soil A#1

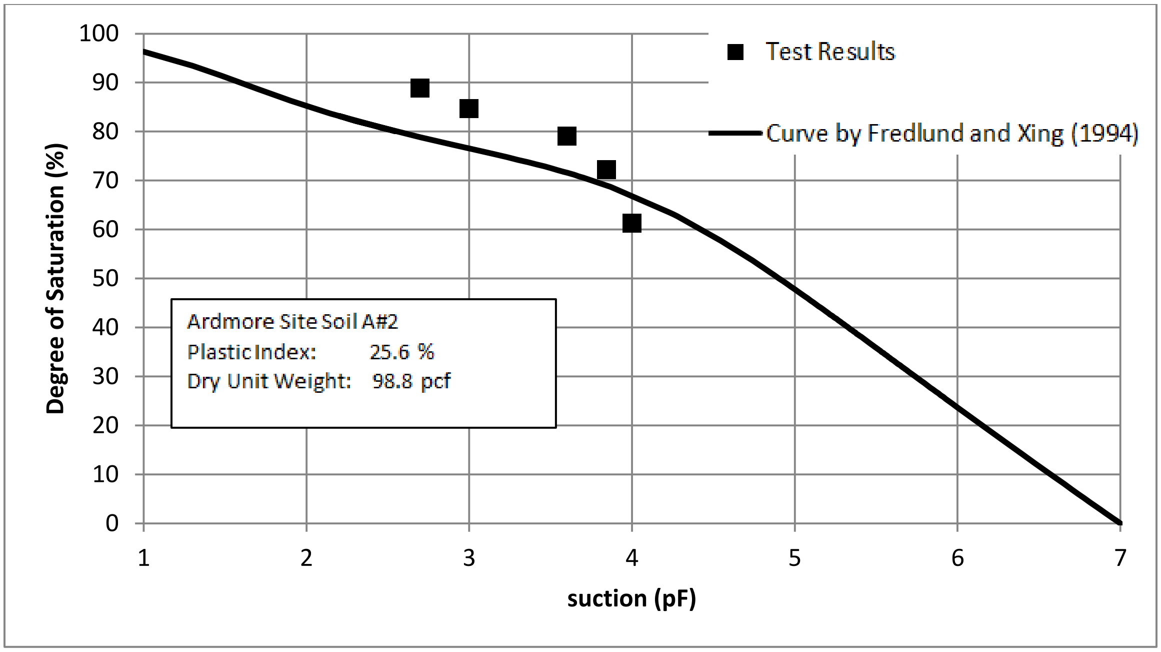


Figure 5.6 SWCC Curves with Degree of Saturation y-Axis for Ardmore Soil A#2

5.3.2 Permeability Test and Diffusion Coefficient Results

Two saturated permeability tests were performed for each soil in the laboratory. The permeability data and slope of SWCC data were used to calculate diffusion coefficients. The permeability data, slopes of SWCC and diffusion coefficients for Lake Hefner soil are shown in Table 5.6. The slope of SWCC is determined by the linear line, which is plotted according to SWCC theoretical curve given by Fredlund and Xing (1994).

Table 5.6 Permeability coefficient and Diffusion Coefficients for Lake Hefner Soil

	Suction Range (pF)	Slope of SWCC (1/pF)	Permeability Coefficient (cm/min)	Diffusion coefficient (cm^2/min)
L#1	1-2.5	0.011	4×10^{-6}	0.022
	2.5-3.5	0.026	4×10^{-6}	0.0093
	3.5-4.5	0.072	4×10^{-6}	0.0033
	4.5-5.3	0.12	4×10^{-6}	0.0020
	5.3-7	0.13	4×10^{-6}	0.0018
L#2	1-2.5	0.0069	2×10^{-6}	0.017
	2.5-3.5	0.016	2×10^{-6}	0.076
	3.5-4.5	0.042	2×10^{-6}	0.029
	4.5-5.3	0.080	2×10^{-6}	0.015
	5.3-7	0.081	2×10^{-6}	0.015

The permeability coefficient data, slopes of SWCC and diffusion coefficients for Ardmore soil are given in Table 5.7.

Table 5.7 Permeability coefficient and Diffusion Coefficients for Ardmore Soil

	Suction Range (pF)	Slope of SWCC (1/pF)	Permeability Coefficient (cm/min)	Diffusion coefficient (cm^2/min)
A#1	1-2.5	0.065	0.8×10^{-6}	0.00077
	2.5-3.5	0.032	0.8×10^{-6}	0.0015
	3.5-4.5	0.046	0.8×10^{-6}	0.0011
	4.5-5.3	0.079	0.8×10^{-6}	0.00064
	5.3-7	0.082	0.8×10^{-6}	0.00061
A#2	1-2.5	0.042	2.2×10^{-6}	0.0033
	2.5-3.5	0.031	2.2×10^{-6}	0.0045
	3.5-4.5	0.050	2.2×10^{-6}	0.0027
	4.5-5.3	0.089	2.2×10^{-6}	0.0015
	5.3-7	0.093	2.2×10^{-6}	0.0014

For soil specimens from both Sites, the SWCC curves, which are obtained from all testing points and average coefficient of saturated permeability, were used to calculate diffusion coefficient (Table 5.8). The trend of diffusion coefficients with suction increments is given in Figure 5.13.

Table 5.8 The Diffusion Coefficient Calculated by Converted SWCC and Average Permeability Coefficient

	Suction Range (pF)	Slope of SWCC (1/pF)	Permeability Coefficient (cm/min)	Diffusion coefficient (cm^2/min)
Lake Hefner	1-2.5	0.0084	3×10^{-6}	0.021
	2.5-3.5	0.018	3×10^{-6}	0.010
	3.5-4.5	0.057	3×10^{-6}	0.0032
	4.5-5.3	0.10	3×10^{-6}	0.0018
	5.3-7	0.11	3×10^{-6}	0.0016
Ardmore	1-2.5	0.054	2×10^{-6}	0.0023
	2.5-3.5	0.031	2×10^{-6}	0.0041
	3.5-4.5	0.047	2×10^{-6}	0.0027
	4.5-5.3	0.083	2×10^{-6}	0.0015
	5.3-7	0.086	2×10^{-6}	0.0014

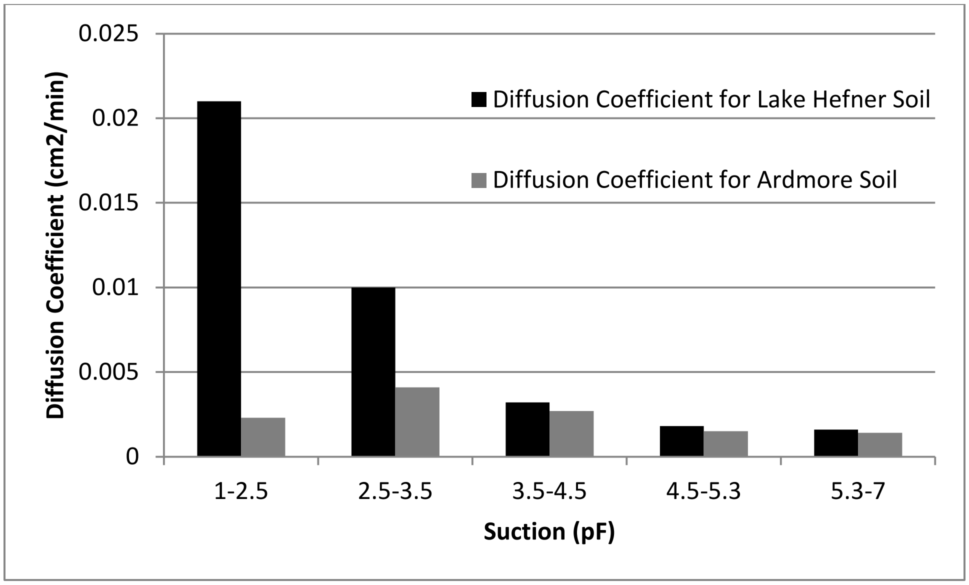


Figure 5.7 Diffusion Coefficients Obtained from Average Permeability Coefficient and SWCC for Lake Hefner Soil and Ardmore Soil

5.4 Comparisons of Diffusion Coefficient Results Using the Thermocouple Psychrometer and Using SWCC and Coefficient of Saturated Permeability

The diffusion coefficients determined by using the thermocouple psychrometers and the combination of the SWCC and saturated permeability test have been summarized in Table 5.9. The variations of the diffusion coefficients with different suction levels are summarized in Table 5.10. As noted previously, the testing range of thermocouple psychrometer is roughly from 3.5 pF to 4.5 pF. Thus the comparisons between the results from the two test methods are within the 3.5 pF and 4.5 pF suction range. Comparisons of diffusion coefficients between 3.5 pF and 4.5 pF suction are shown in Table 5.9 and for all the suction range are given in Table 5.10. The results indicate the following:

- The drying diffusion coefficients measured by thermocouple psychrometers are lower than the results by using the SWCC and average permeability coefficient from 3.5 pF to 4.5 pF. For the Lake Hefner soil, thermocouple psychrometer result is 53.8% lower than the SWCC and saturated permeability. While for the Ardmore soil, the results based on thermocouple psychrometers are lower by 12.5%.

- The diffusion coefficients at different suction levels (Table 5.10) give a better spectrum of variation of the diffusion coefficient with suction. In general, the diffusion coefficient decreases as the suction increases, except at the low suction range which is from 1-3.5 pF. In accordance with unsaturated permeability of soils, the decreasing trend of the diffusion coefficient with the increase in suction fulfills the description given by Laliberte and Brooks (1967). For the low suction range part, the disturbance of the SWCC test is hard to avoid.
- The Lake Hefner soil, which has a PI equals to 14.2%, has a higher diffusion coefficient compared to the soil from the Ardmore site (PI equals to 25.6%).

The diffusion coefficients obtained in this research are generally close to each other for the two soils. According to the results, the diffusion coefficient determined by the SWCC and saturated permeability are in reasonable agreement with the test results using the thermocouple psychrometer, in these two types of soils. This implies that the diffusion coefficient determined by the SWCC and saturated permeability provide an approach to estimate the whole suction range diffusion coefficient.

Table 5.9 Diffusion Test Results of Thermocouple Psychrometer tests and SWCC and Coefficient of Saturated Permeability tests

	Testing Range (pF)	Thermocouple Psychrometer	SWCC and Coefficient of Saturated Permeability
Lake Hefner	3.5-4.5	0.00208 cm^2/min	0.0032 cm^2/min
Ardmore	3.5-4.5	0.0024 cm^2/min	0.0027 cm^2/min

Table 5.10 Diffusion Coefficient for a Wide Range Suction

		Diffusion coefficient (cm^2/min)		
	Suction Range (pF)	L#1	L#2	SWCC and Average Permeability
Lake Hefner	1-2.5	0.022	0.017	0.021
	2.5-3.5	0.0093	0.076	0.010
	3.5-4.5	0.0033	0.029	0.0032
	4.5-5.3	0.0020	0.015	0.0018
	5.3-7	0.0018	0.015	0.0016
		A#1	A#2	
Ardmore	1-2.5	0.00077	0.0033	0.0023
	2.5-3.5	0.0015	0.0045	0.0041
	3.5-4.5	0.0011	0.0027	0.0027
	4.5-5.3	0.00064	0.0015	0.0015
	5.3-7	0.00061	0.0014	0.0014

CHAPTER VI

CONCLUSIONS AND RECOMMANDATIONS

6.1 Conclusions

The diffusion coefficient test determined by thermocouple psychrometers provides a simple method to describe the moisture movement in unsaturated soil. However, the diffusion coefficients determined by thermocouple psychrometers only refer to a suction range between about 3.5 pF to 4.5 pF. On the other hand, the drying diffusion coefficients determined by the SWCC and coefficient of saturated permeability provides an approach to determine the diffusion coefficients in a wider suction range.

The following can be concluded from the research study:

- Based on both thermocouple psychrometer tests and combination of SWCC and permeability test, the soil with higher plastic index has a lower diffusion coefficient for the tested soil specimens, which were fully crushed, dried, compacted and moistured, from Lake Hefner site and Ardmore site with different plasticity indices.
- The diffusion coefficients are decreasing with the suction increasing.
- The diffusion coefficients determined by SWCC and coefficient of saturated permeability are higher than the diffusion coefficients from the thermocouple psychrometer testing.

- The diffusion coefficients decrease quickly in suction range from 1 pF to 4.5 pF, and decrease slowly in high suction range.
- For all specimens, soil with higher coefficients of saturated permeability have higher diffusion coefficient.

6.2 Recommendations

- In this research, Frendlund and Xing's continuous function was employed to determine the SWCC and the slopes in each suction range, which divided the SWCC into several pieces. Further study is required to use piece wised SWCC equations to calculate the slopes of SWCC.
- The comparison of the diffusion coefficient test results between the two methods are from 3.5 to 4.5 pF. Thus, the diffusion coefficient test at the suction range of 1 to 3.5 pF and 5 to7 pF is required to be determined by other testing equipment such as thermal conductivity sensor, tensiometer for low suction range and WP4 for high suction range.

REFERENCES

Arbhabhirama, A., and Kridakorn, C. (1968). "Steady downward flow to a water table." *Water Resources Research*, Vol. 4, No. 6: 1249-1257.

Aubeny, C., Lytton, R.L., and Tang, D. (2003). "Simplified analysis of Moisture Flow through Unsaturated Soil." *Transportation Research Record; Journal of the Transportation Research Board, No. 1821*: 75-82.

Aubeny, C. and Lytton, R. (2004). "Shallow slides in compacted high plasticity clay slopes." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130: 717-727.

Brooks, R.H. and Corey, A.T. (1964). "Hydraulic Properties of Porous Media." *Hydrology Paper* No. 3.

Brown, R.W. and Collins, J. M. (1980). "A screen-caged thermocouple psychrometer and calibration chamber for measurements of plant and soil water potential." *Agronomy Journal* Vol. 72: 851-854.

Brutsaert, W. (1967). "Some methods of calculating unsaturated permeability." *Transactions of ASABE*, Vol. 10: 400-404.

Bulut, R. and Wray, W.K. (2005). "Free Energy of Water-Suction-in Filter Papers." *ASTM Geotechnical Testing Journal,* Vol. 28: 355-264.

Bulut, R., Aubeny, C., and Lytton, R.L. (2005). "Unsaturated Soil Diffusivity Measurements." *Proceedings of an International Symposium on Advance Experimental Unsaturated Soil Mechanics,* Trento, Italy, June 27-29, pp. 281-286.

Bulut, R., Wray, W.K., and Lytton, R.L. (2001). "Soil suction measurements by filter paper." *Geotechnical Special Publication* No. 115: 243-261.

Fawcett, R.G. and Collis-Geoge, N. (1967). "A filter-paper method for determining the moisture characteristics of soil." *Australian Journal of Experimental Agriculture and Animal Husbandry*, Vol. 7: 699-706.

Fredlund, D.G and Rahardjo. (1993). "Soil Mechanics for Unsaturated Soils." John Wiley and Sons, Inc.

Fredlund, D.G. and Xing, A. (1994). "Equations for the soil-water characteristic curve." *Canadian Geotechnical Journal,* Vol. 31(3): 521-532.

Fredlund, D.G. and Xing, A. and Huang, S. (1994). "Predicting the permeability function for unsaturated soils using the soil-water characteristic curve." *Canadian Geotechnical Journal*, Vol. 31: 533-546.

Fredlund, D.G, Sheng, D. and Zhao, J. M.D. (2010). "Estimation of soil suction from the soil-water characteristic curve." *The NRC Research Press Web site at cgj.nrc.ca* January 19, 2011.

Fredlund, D.G, Rahardjo, H, Fredlund, M.D. (2012). "Unsaturated soil mechanics in engineering practice." John Wiley and Sons, Inc.

Gardner, W.R. (1958). "Mathematics of isothermal water conduction in unsaturated soils." Highway Research Board Special Report 40, presented at the International Symposium on Physico-Chemical Phenomenon in Soils, Washington, DC, pp. 78-87.

Laliberte, G.E. (1969). "A mathematical function for describing caplllary pressure-desaturation data." *Bulletin of the International Association Hydrological Scoences*, Vol. 14, No.2 : 131-149.

Leong, E.C., Tripathy, S. and Rahardjo, H (2003). "Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique." *Geotechnique,* Vol.53, No.2:173-182.

Li, H. and Sego, D. (2000). "Equation for complete compaction curve of fine-grained soils and its applications" *ASTM STP 1384*.

Lu, N. and Likos W.J. (2004). "Unsaturated soil mechanics." John Wiley, New York, NY, USA, 2004.

Lytton, R.L, Aubeny, C.P and Bulut, R. (2004). "Design procedure for pavements on expensive soils." *TxDOT Report No. 0-4518-1*, Texas Transportation Institute, College Station, Texas.

Mabirizi, D. and Bulut, R. (2010). "Unified testing method for measuring diffusion coefficients for unsaturated soil drying and wetting in laboratory." *Transportation Research Record: Journal of the Transportation Research Board,* No. 2170: 109-118.

Mabirizi, D. (2010). "Wetting and Drying Unsaturated Soil Diffusivity Measurements in Laboratory." Dissertation, Oklahoma State University. Retrieved from ProQuest Dissertations and Theses. (Accession Order No. 1489066)

Mckee, C.R and Bumb A.C. (1987). "Flow-testing coalbed methane production wells in the presence of water and gas." *Society of Petroleum Engineer Formation Evaluation*, Vol.2, No. 4: 500-608.

Mckee, C.R and Bumb A.C. (1984). "The importance of unsaturated flow parameters in designing a hazardous waste site." *In Hazardous Waste and Environmental Emergencies: Hazardous Materials Control Research Institute National Conference,* Houston, TX, Silver Spring, MD, pp. 50-58.

Mitchell, P.W. (1979). "The structural analysis of footings on expansive soil." *Research Report No.1*, Kenneth W.G Smith and Associates Pty. Ltd,. Newton, South Australia.

Pamela, S. and Fredlund, D.G. (1989). "Use of thermal conductivity sensors to measure matric suction in the laboratory." *Canada Geotechnical Journal*, Vol 26: 491-498.

Pham, H.Q. and Fredlun, D.G. (2005). "A volume-mass constitutive model for unsaturated soils." *Proceedings of the Fifty-Eighth Canadian Geotechnical Conference,* Saskatoon, SK, Vol. 2, :173-181.

Richards, L.A. (1931). "Capillary conduction of liquids through porous medium." *Journal of Physics*, Vol. 1:318-333.

Sposito, G. (1981). "The thermodynamics of soil solutions." *Oxford University Press*, London.

Tavemas, F., Jean, P., Leblond, P. and Leroueil, S. (1983). "The permeability of natural soft clays. Part II: Permeability characteristics." *Canadian Geotechnical Journal*, Vol. 20: 645-660.

Van Genuchten, M.Th. (1980). "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils" *Soil Science Society of America Journal*, Vol. 44: 892-898.

APPENDICES

APPENDIX A — COMPACTION CURVES

The standard soil compaction tests were conducted according to ASTM D-698. The soil was crushed and oven dried (110 °C) for 24 hours. About 2000 grams of the sample was used for the compaction test. The soil sample was mixed with water and allowed to cure per ASTM D698 guidelines. The soil was compacted in three layers, each layer receiving 25 blows from 12 inches. After compaction, a knife was used to trim the soil at the top and the mass of the compacted specimen and mold was measured and recorded to the nearest gram. The compacted specimen was then removed from the mold using a hydraulic jack. The compaction curve (Figure A1 and A2) was determined per ASTM STP 1384 (Li and Sego 2000).

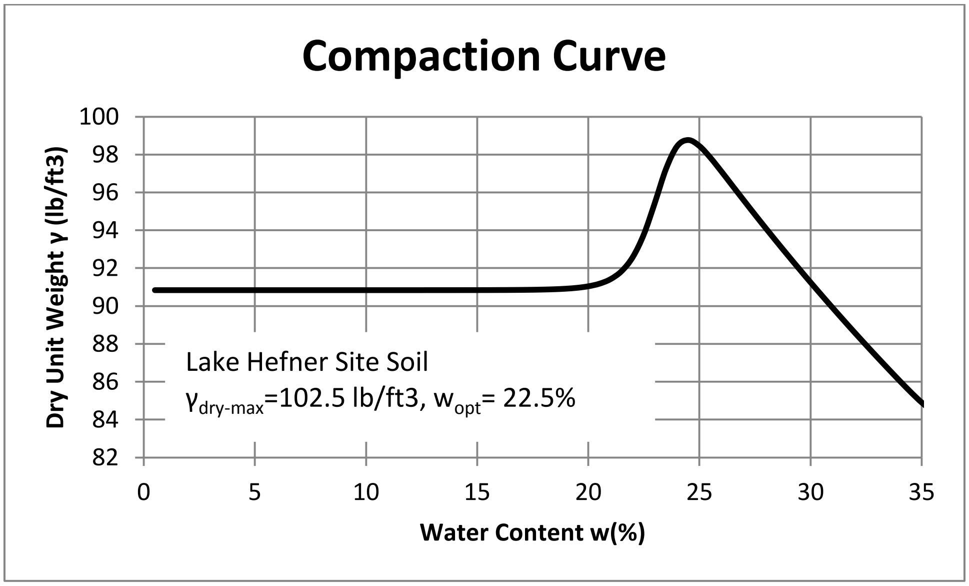


Figure A1 Relation between the Dry Unit Weight and the Water Content for the Soil from Lake Hefner Site

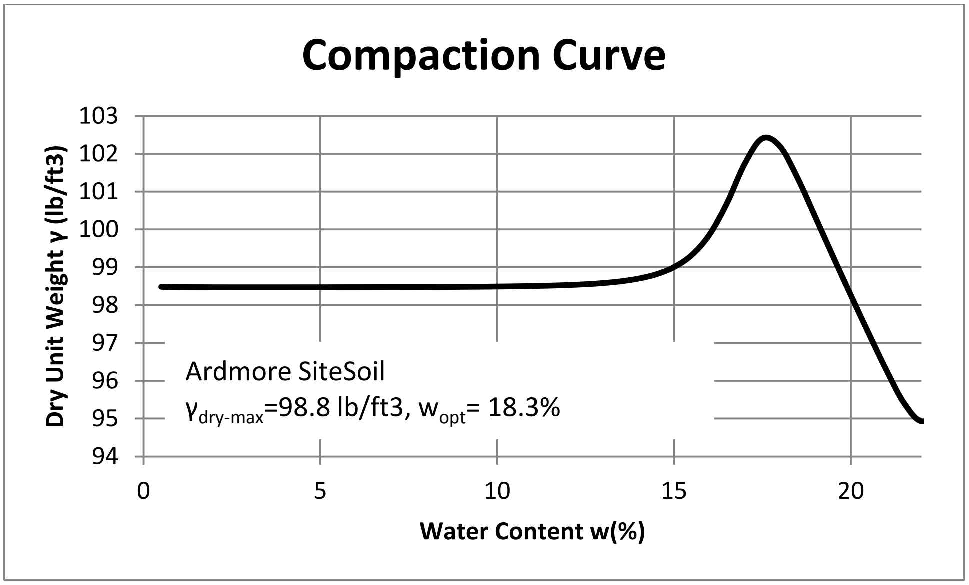


Figure A2 Relation between the Dry Unit Weight and the Water Content for the Soil from Ardmore Sit

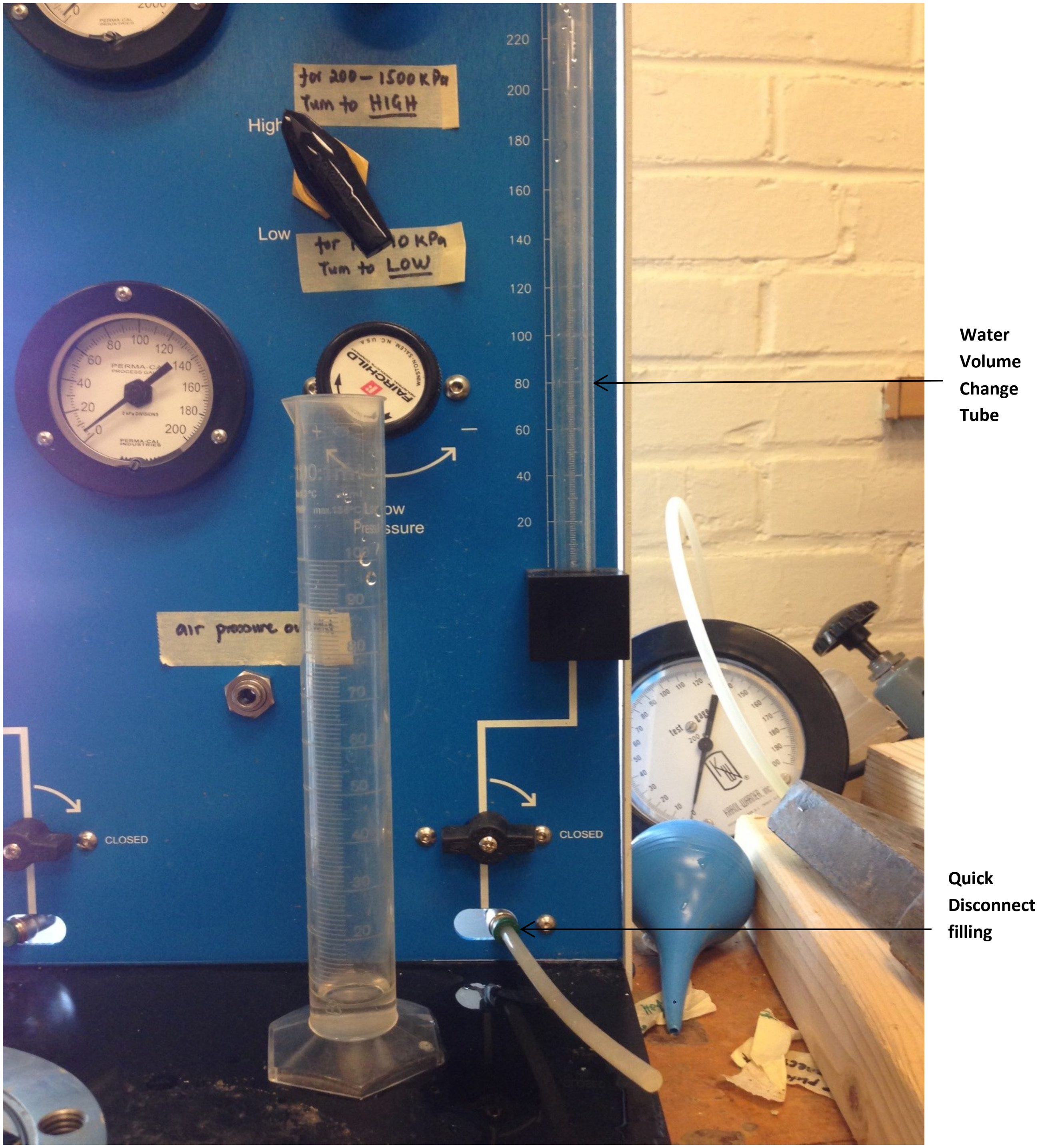
APPENDIX B — CALIBRATION OF WATER VOLUME CHANGE TUBES

The measurements obtained from the water volume change tubes represent a linear measurement in millimeters. These linear measurements should be converted to a gravimetric calibration factor, α, that can be determined as follows:

1. Fill one of the water volume change tubes with water with closed bottom valve. Record the water volume tube reading X_1 (shown in Figure B1).
2. Drain about 100 mm of water from the volume tube into a container by opening the bottom valve. Again, record the water volume tube reading, X_2 (shown in Figure B2).
3. Weigh the collected water in grams, W.
4. Calculate the calibration factor, α, as follows: $\alpha=W/(X_1-X_2)$.
5. Use α to calculate the amount of water released or absorbed during the SWCC tests. For example, if the difference between the initial and final volume tube readings in a particular test is ΔX, the corresponding weight of water in grams is $(\Delta X)*(\alpha)$.

Water
Volume
Change
Tube

B1 Reading in Right Volume Tube Water X_1



B2 the Drained Water and the Reading in Right Volume Tube Water X_2

APPENDIX C — AN EXAMPLE OF SWCC DATA INTERPRETATION

The least square error method is applied to fit SWCC given by Fredlund and Xing (1994). The SWCC data of the Lake Hefner soil L#1 is given in Table C1.

C1 SWCC Testing Data for L#1

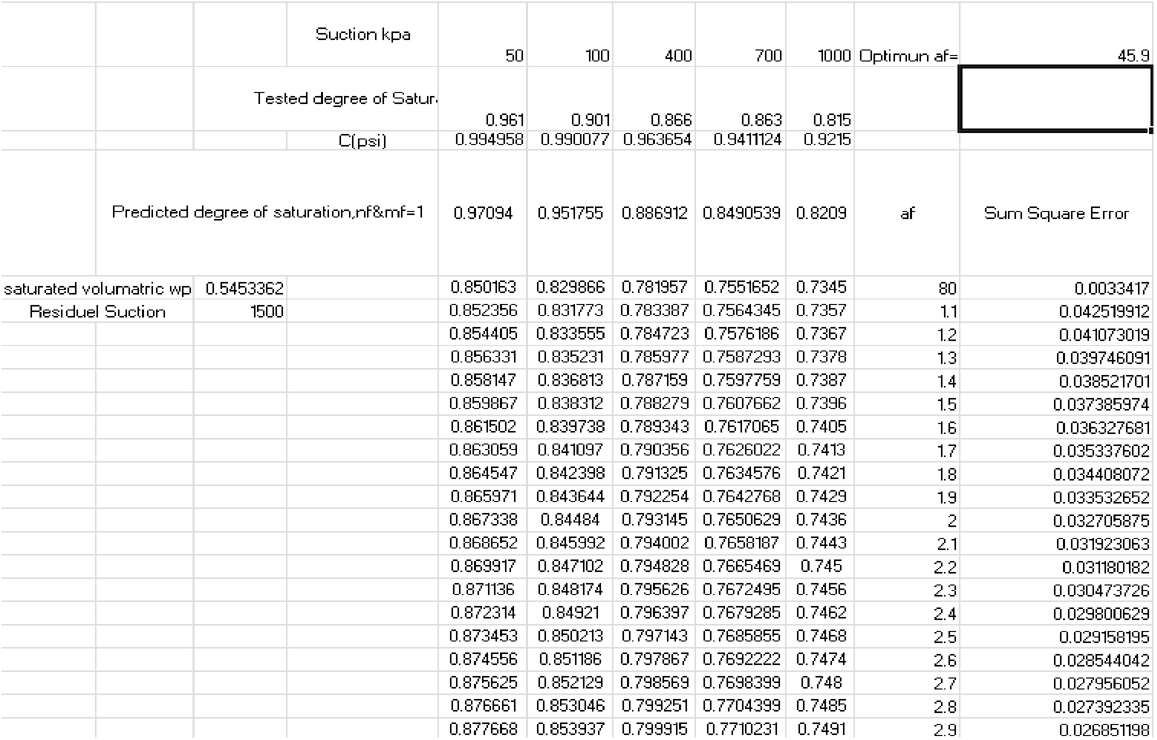
Suction (pF)	2.69	3.00	3.60	3.84	4.00
Water Content (%)	43.08	40.57	38.94	38.75	36.63

The fitting procedure by using Excel spread sheet is outlined as follows:

- Determine the fitting parameters

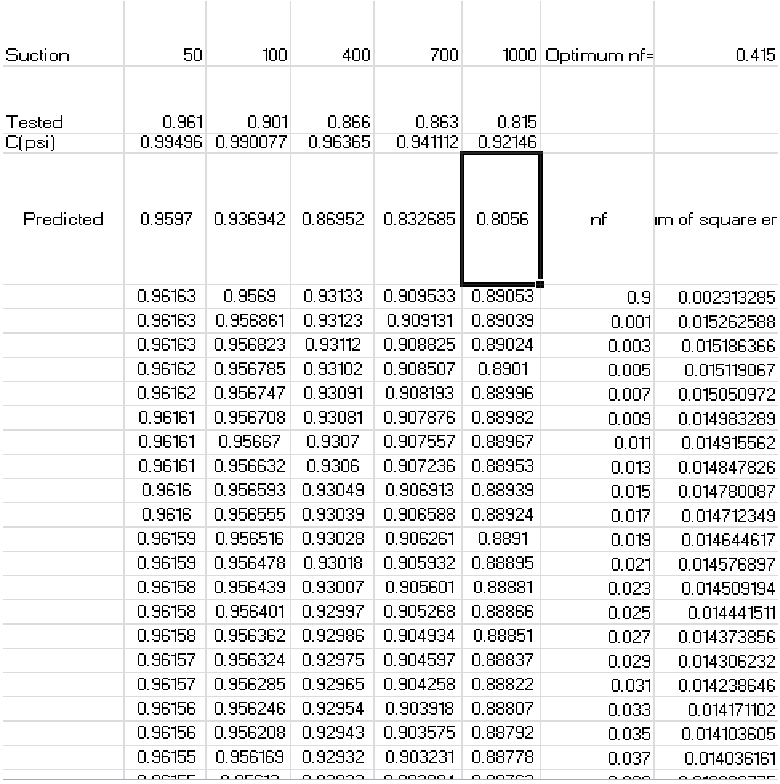
6. Initially give a random value within the suggested range to the fitting parameters for Equation 3.17: n_f=1, m_f=1and a_f= 1 to 100 with increment 0.1. Compute the theoretical water contents by given fitting parameters and tested suction.
7. Sum up the square errors between the theoretical water contents and measured water contents for five tested data points with the assumed fitting parameters.
8. Find optimum parameter a_f with the least square errors. For L#1 soil the optimum a_f= 45.9.
9. Use optimized a_f = 45.9 and given m_f = 1 find the optimized n_f= 0.415; And then use a_f and m_f to determine the fitting parameter m_f=0.2.

The screen shots of fitting parameters determination is shown in Figure C1



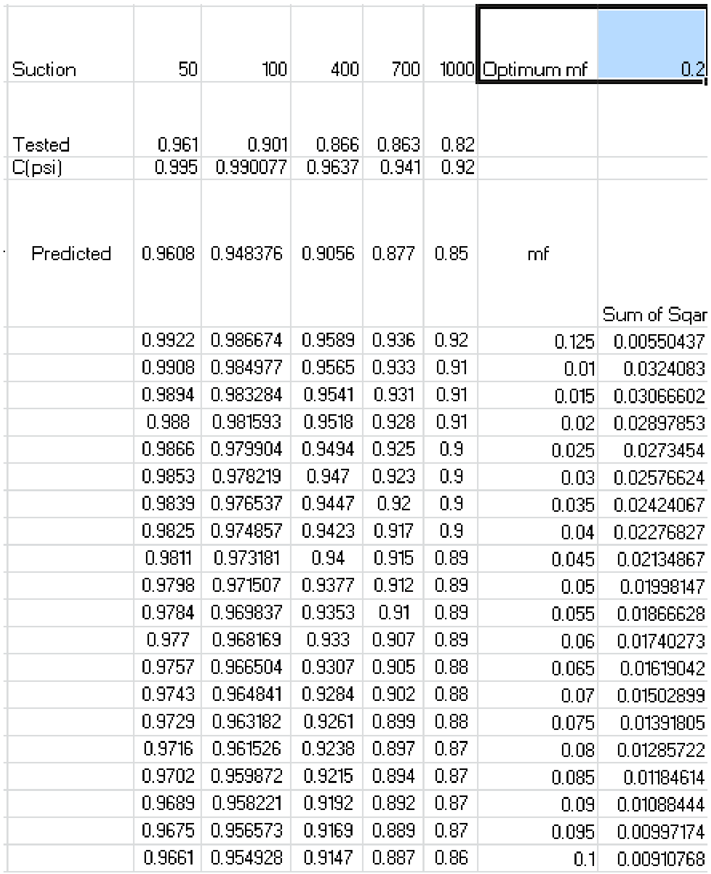
		Suction kpa	50	100	400	700	1000	Optimun af=	45.9
		Tested degree of Satur	0.961	0.901	0.866	0.863	0.815		
		C(psi)	0.994958	0.990077	0.963654	0.9411124	0.9215		
		Predicted degree of saturation,nf&mf=1	0.97094	0.951755	0.886912	0.8490539	0.8209	af	Sum Square Error
saturated volumatric wp	0.5453362		0.850163	0.829866	0.781957	0.7551652	0.7345	80	0.0033417
Residuel Suction	1500		0.852356	0.831773	0.783387	0.7564345	0.7357	1.1	0.042519912
			0.854405	0.833555	0.784723	0.7576186	0.7367	1.2	0.041073019
			0.856331	0.835231	0.785977	0.7587293	0.7378	1.3	0.039746091
			0.858147	0.836813	0.787159	0.7597759	0.7387	1.4	0.038521701
			0.859867	0.838312	0.788279	0.7607662	0.7396	1.5	0.037385974
			0.861502	0.839738	0.789343	0.7617065	0.7405	1.6	0.036327681
			0.863059	0.841097	0.790356	0.7626022	0.7413	1.7	0.035337602
			0.864547	0.842398	0.791325	0.7634576	0.7421	1.8	0.034408072
			0.865971	0.843644	0.792254	0.7642768	0.7429	1.9	0.033532652
			0.867338	0.84484	0.793145	0.7650629	0.7436	2	0.032705875
			0.868652	0.845992	0.794002	0.7658187	0.7443	2.1	0.031923063
			0.869917	0.847102	0.794828	0.7665469	0.745	2.2	0.031180182
			0.871136	0.848174	0.795626	0.7672495	0.7456	2.3	0.030473726
			0.872314	0.84921	0.796397	0.7679285	0.7462	2.4	0.029800629
			0.873453	0.850213	0.797143	0.7685855	0.7468	2.5	0.029158195
			0.874556	0.851186	0.797867	0.7692222	0.7474	2.6	0.028544042
			0.875625	0.852129	0.798569	0.7698399	0.748	2.7	0.027956052
			0.876661	0.853046	0.799251	0.7704399	0.7485	2.8	0.027392335
			0.877668	0.853937	0.799915	0.7710231	0.7491	2.9	0.026851198

a. Determine Fitting Parameter a_f



Suction	50	100	400	700	1000	Optimum nf=	0.415
Tested	0.961	0.901	0.866	0.863	0.815		
C(psi)	0.99496	0.990077	0.96365	0.941112	0.92146		
Predicted	0.9597	0.936942	0.86952	0.832685	0.8056	nf	m of square er
	0.96163	0.9569	0.93133	0.909533	0.89053	0.9	0.002313285
	0.96163	0.956861	0.93123	0.909131	0.89039	0.001	0.015262588
	0.96163	0.956823	0.93112	0.908825	0.89024	0.003	0.015186366
	0.96162	0.956785	0.93102	0.908507	0.8901	0.005	0.015119067
	0.96162	0.956747	0.93091	0.908193	0.88996	0.007	0.015050972
	0.96161	0.956708	0.93081	0.907876	0.88982	0.009	0.014983289
	0.96161	0.95667	0.9307	0.907557	0.88967	0.011	0.014915562
	0.96161	0.956632	0.9306	0.907236	0.88953	0.013	0.014847826
	0.9616	0.956593	0.93049	0.906913	0.88939	0.015	0.014780087
	0.9616	0.956555	0.93039	0.906588	0.88924	0.017	0.014712349
	0.96159	0.956516	0.93028	0.906261	0.8891	0.019	0.014644617
	0.96159	0.956478	0.93018	0.905932	0.88895	0.021	0.014576897
	0.96158	0.956439	0.93007	0.905601	0.88881	0.023	0.014509194
	0.96158	0.956401	0.92997	0.905268	0.88866	0.025	0.014441511
	0.96158	0.956362	0.92986	0.904934	0.88851	0.027	0.014373856
	0.96157	0.956324	0.92975	0.904597	0.88837	0.029	0.014306232
	0.96157	0.956285	0.92965	0.904258	0.88822	0.031	0.014238646
	0.96156	0.956246	0.92954	0.903918	0.88807	0.033	0.01417102
	0.96156	0.956208	0.92943	0.903575	0.88792	0.035	0.014103605
	0.96155	0.956169	0.92932	0.903231	0.88778	0.037	0.014036161

b Determine Fitting Parameter n_f



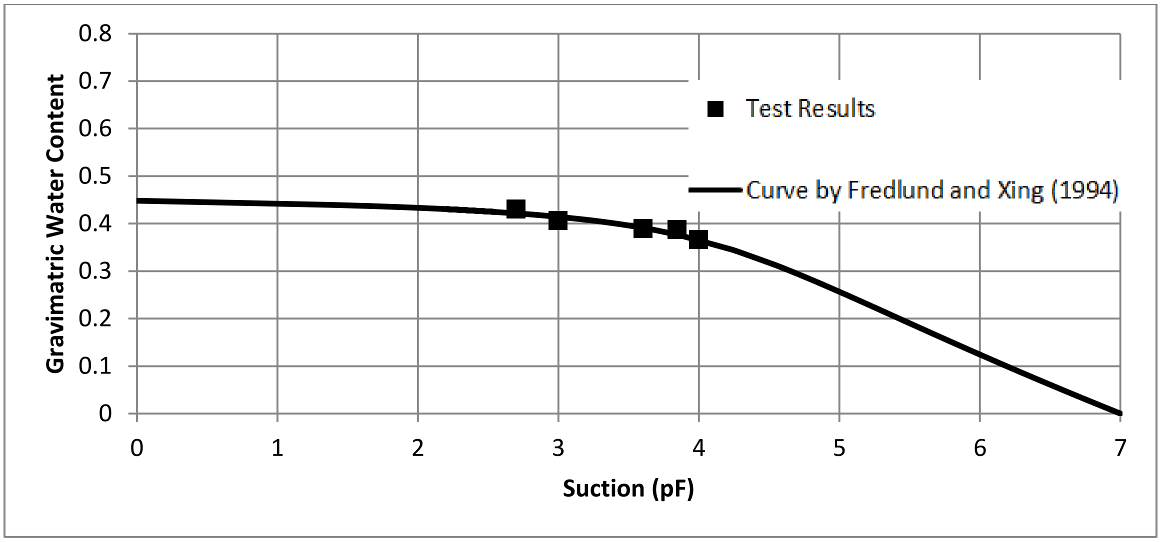
Suction	50	100	400	700	1000	Optimum mf	0.2
Tested	0.961	0.901	0.866	0.863	0.82		
C(psi)	0.995	0.990077	0.9637	0.941	0.92		
Predicted	0.9608	0.948376	0.9056	0.877	0.85	mf	Sum of Sqar
	0.9922	0.986674	0.9589	0.936	0.92	0.125	0.00550437
	0.9908	0.984977	0.9565	0.933	0.91	0.01	0.0324083
	0.9894	0.983284	0.9541	0.931	0.91	0.015	0.03066602
	0.988	0.981593	0.9518	0.928	0.91	0.02	0.02897853
	0.9866	0.979904	0.9494	0.925	0.9	0.025	0.0273454
	0.9853	0.978219	0.947	0.923	0.9	0.03	0.02576624
	0.9839	0.976537	0.9447	0.92	0.9	0.035	0.02424067
	0.9825	0.974857	0.9423	0.917	0.9	0.04	0.02276827
	0.9811	0.973181	0.94	0.915	0.89	0.045	0.02134867
	0.9798	0.971507	0.9377	0.912	0.89	0.05	0.01998147
	0.9784	0.969837	0.9353	0.91	0.89	0.055	0.01866628
	0.977	0.968169	0.933	0.907	0.89	0.06	0.01740273
	0.9757	0.966504	0.9307	0.905	0.88	0.065	0.01619042
	0.9743	0.964841	0.9284	0.902	0.88	0.07	0.01502899
	0.9729	0.963182	0.9261	0.899	0.88	0.075	0.01391805
	0.9716	0.961526	0.9238	0.897	0.87	0.08	0.01285722
	0.9702	0.959872	0.9215	0.894	0.87	0.085	0.01184614
	0.9689	0.958221	0.9192	0.892	0.87	0.09	0.01088444
	0.9675	0.956573	0.9169	0.889	0.87	0.095	0.00997174
	0.9661	0.954928	0.9147	0.887	0.86	0.1	0.00910768

c Determine Fitting Parameter m_f

C1 Fitting Parameters Determination

- Fit the theoretical curve to tested data

In Equation 3.17, the three unknown parameters a_f, n_f and m_f are fixed by using least square errors method. Plot the SWCC by using the three optimized fitting parameters to check the theoretical curve fitting (Figure C1).



C2 Fitting Curve for L#1 Soil Specimen

APPENDIX D— SATURATED PERMEABILITY TEST

Triaxial Chamber and permeability control column (Figure C1) were used to measure saturated permeability of soil. The laboratory procedure is as follows:

Figure D1 a Triaxial Chamber

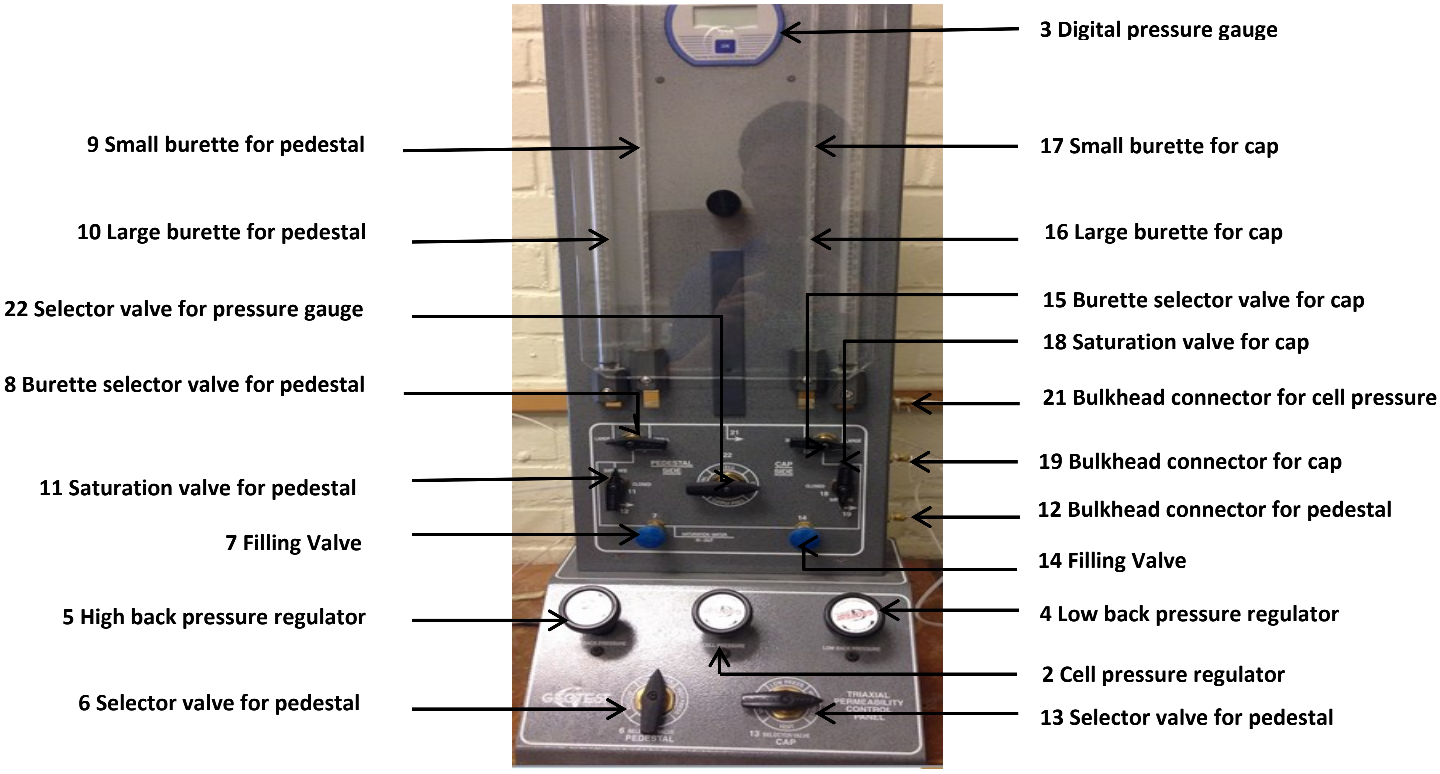


Figure D1 b Permeability Control Column (front)

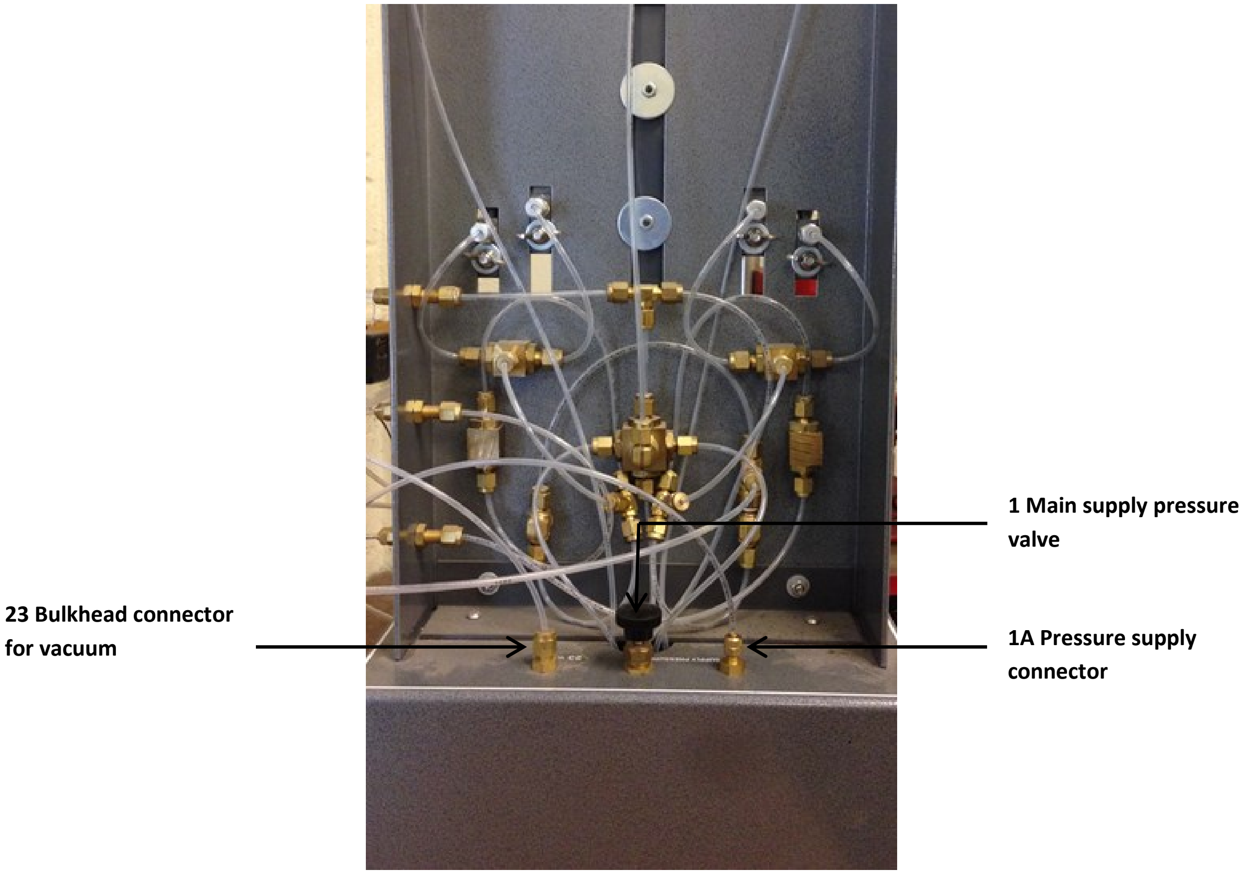


Figure D1 c Permeability Control Column (back)

Figure D1 Triaxial Chamber and Permeability Control Column

D.1 Sample Installation, Application of Cell Pressure

1. Disconnect cell pressure line from top of cell and remove cell top together with cell wall. Leave guide post, which also serves as dial indicator rest, in place. If the cell wall is stuck to the ‘O’ ring on the base, push down on the cell top a couple times to break free the ‘O’ ring.
2. Place porous plate, filter paper and sample on pedestal.
3. Install membrane. To obtain a good seal, applying some vaseline on the ‘O’ ring of the cap and pedestal is suggested before placing the membrane. Install porous plate, filter paper and cap on the top of the sample, and roll membrane up on the cap and pedestal.
4. Connect the two pore lines on the cap. Tighten nuts by wrench with moderate force.
5. Place cell wall together with cell top on base. Guide hole should be lined up with guide post. For triaxial cell the piston rod must be pulled all the way and locked in place.Pass the three tie rods through the holes in the cell top and screw them into the base.
6. Fill cell with water. Leave 1/4’ air under top plate. Loosen locking collar of the piston rod for triaxial cell; bring the rod in contact with the cap and lock the collar again.
7. Connect bulkhead fitting No.21 (on side of control panel) to the top of cell.
8. Connect bulkhead fitting No.12 to bulkhead on cell base labeled “pedestal saturate”, and bulkhead No.19 to bulkhead labeled “cap saturate” on cell base.
9. Apply cell pressure.

D.2 Filling the Burettes and Vacuum Saturation

To fill the cap burettes

1. Close “saturation” valve No.18.
2. Turn selector valve No.13 into “vacuum” position.
3. Connect Vacuum source to bulkhead fitting No.23.
4. Submerge end of saturation tubing into a pool of suitable water.
5. Turn selector No.15 into large burette position.
6. Partially open valve No.14 to let water slowly fill large burette. Then close valve No.14.
7. To fill small burette (step 1 -4 is done) turn selector No.15 into small burette position.
8. Crack valve No.14 slightly to let water slowly fill small burette, than close valve No. 14.
9. Put selector valve No.13 into required position (high or low back pressure)
10. Open saturation valve No. 18 and shut off vacuum.

To fill the pedestal burettes

1. Close “saturation” valve No.11.
2. Turn selector valve No.6 into “vacuum” position.
3. Connect Vacuum source to bulkhead fitting No.23.
4. Submerge end of saturation tubing into a pool of suitable water.
5. Turn selector No.8 into large burette position.
6. Partially open valve No.14 to let water slowly fill large burette. Then close valve No.14.
7. To fill small burette (step 1 -4 is done) turn selector No.8 into small burette position.
8. Crack valve No.14 slightly to let water slowly fill small burette, than close valve No. 14.

9. Put selector valve No.6 into required position (high or low back pressure)
10. Open saturation valve No. 11 and shut off vacuum.

To vacuum saturate proceed:

1. Close saturation valve No.11 and 18.
2. Connect vacuum source to the bulkhead fitting on cell base marked cap purge and pedestal purge.
3. Open cap and pedestal purge valves.
4. Leave vacuum on for 5-10 minutes and then open pedestal saturation valve No.11 and as soon as water appears in tubing at pedestal purge, close pedestal purge valve.
5. Repeat the procedure several times.

D.3 Permeability Measurement

1. Close both saturation valves No. 11 and No.18.
2. Turn pedestal selector valve No.6 into high back pressure pssition.
3. Read low back pressure on digital gauge.
4. Turn selector valve No.22 into high back pressure positon and set high back pressure regulator output to required value.
5. Open both saturation valves No. 11 and 18. Take readings of burettes at suitable time intervals.
6. After permeability has been determined, close both saturation valve No.11 and 18,turn pedestal selector valve to low beck pressure and open both saturation valves NO.11 and 18.

7. Terminate the test. Reduce low back pressure, high back pressure and cell pressure and dissemble the testing equipment.

D.4 Calculation

Using the quantity of water and the pressure applied which were observed from the control panel (Figure C1) to calculate the saturated permeability. According to Darcy's equation, for permeability test, the flow rate of water q, gradient I and cross-section area A are needed. The flow rate of water q equals to quantity of water Q divided by the observation time interval t; Gradient equals to water head loss Δh, which can be modified on the control panel, divided by the length of soil specimen l, which can be easily measured; The cross-section area A was measured before the soil specimen installation.

VITA

Yi Tian

Candidate for the Degree of

Master of Science

Thesis: PREDICTING UNSATURATED SOIL MOISTURE DIFFUSIVITY COEFFICIENT USING SLOPE OF SWCC AND SATURATED PERMEABILITY COEFFICIENT

Major Field: Geotechnical Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Geotechnical Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2014.

Completed the requirements for the Bachelor of Science in Environmental Engineering at Hunan Agriculture University, Changsha, China in 2008.

Experience: None

Professional Memberships: None