WETTING AND DRYING UNSATURATED SOIL DIFFUSIVITY MEASUREMENTS IN LABORATORY

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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, 2010

WETTING AND DRYING UNSATURATED SOIL DIFFUSIVITY MEASUREMENTS IN LABORATORY

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ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my academic advisor, Dr. Rifat Bulut, for his guidance, support and generosity. Dr. Bulut taught me how to research and write academic papers. Without his persistent help this thesis would not have been possible.

I would like to thank Dr. Stephen Cross and Dr. Gregory Wilber for serving on my thesis committee. Dr. Cross encouraged and provided me with knowledge in pavement materials and design. Additionally, Dr. Gregory Wilber generously provided some of the tools I needed to perform experiments.

Last, but not least, I thank all the members of my family for their unconditional support and encouragement to pursue my interests.

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INTRODUCTION

1.1 Problem Statement

Reliable estimates of soil water diffusivity are important in describing and predicting the movement of water in unsaturated soils. The diffusion of moisture through unsaturated soils is governed by the total suction gradient within the soil profile; with moisture travelling from regions of low total suctions to regions of high total suctions (Mitchell 1979). The unsaturated moisture diffusion coefficient controls transient moisture flow conditions within a soil mass in response to suctions or fluxes imposed at the boundaries of the mass.

Most of the approaches used to determine soil water diffusivity properties in the laboratory are based on the pressure plate method proposed by Gardner (1956) and the horizontal infiltration method proposed by Bruce and Klute (1956). These methods are based on water content measurements. Gardner's approach is based on measuring outflow of water with time from a soil specimen subjected to changes in matric suctions. In the Bruce-Klute method, water is introduced at one end of the soil column and measurements of water content distribution along a horizontal soil column are performed. These methods are plagued with expensive, difficult, and/or time consuming laboratory procedures and calculations. In addition, the diffusivity models developed based on the pressure plate method yield only the drying (drainage) diffusivity and those based on the horizontal infiltration method yield only the wetting diffusivity. This implies that the hysteresis effect associated with drying and wetting of soils due to seasonal moisture variations has not been thoroughly investigated.

Mitchell (1979) proposed two simple laboratory tests to determine the soil water diffusion coefficient in unsaturated soils, namely the drying (evaporation) test and wetting (soaking) test. Mitchell's method is based on measurement of suction distribution along a soil column. In these tests, the cylindrical surface and one end of the soil column are sealed while the other end is left open and exposed to the atmosphere (drying test) or liquid (wetting test) of known suction. Thermocouple psychrometers inserted into the soil specimens are employed to monitor the distribution of suction at various locations over time as moisture propagates through the soil body. Mitchell's approach provides a simple, economical and reliable framework for determining the wetting and drying diffusivity parameters on a routine basis in the laboratory.

However, Mitchell's study only reported one value for the drying test and one value for the wetting test performed on two different specimens. A study performed by Lytton et al. (2004) and Bulut et al. (2005) made improvements to only the drying diffusion coefficient measurements. In this research study, the drying testing equipment and method have been modified to incorporate the wetting test. The new water bath built at Oklahoma State University was used to perform drying and wetting tests on a number of soil specimens. This research study also proposes a unified testing protocol that permits both drying and wetting tests to be performed in cycles on the same soil specimens. The hysteresis effect on the evaporation and soaking parameters associated with drying and wetting of soils due to seasonal variations was reliably evaluated with this testing method.

1.2 Objective of Research Study

As noted earlier, the most recent improvements to Mitchell's method only dealt with drying diffusion coefficient measurements. Therefore, this research study will:

- Develop an improved and unified testing protocol for measuring both the drying and wetting diffusivity parameters on the same soil specimens.
- Improve the current testing equipment to perform both the drying test and wetting test.
- Evaluate the hysteresis effect on the drying and wetting diffusion parameters associated with drying and wetting of soils due to seasonal moisture variations.

1.3 Organization of the Thesis

Chapter II reviews the concept of soil suction and the techniques used to measure suction in this research study.

Chapter III covers the theoretical background of the most common methods used to determine soil water diffusivity parameters, namely, the pressure plate method, the horizontal infiltration method, and the suction distribution method. The simplified analysis of moisture flow in unsaturated soils based on Mitchell (1979) single diffusivity parameter is described.

Chapter IV includes the test procedures used to study moisture flow within a soil profile during the wetting and drying process. This chapter expounds on how psychrometers are used to measure suction distribution over time and details the improved testing protocol and equipment developed to perform the drying and wetting diffusivity tests.

Chapter V presents the findings from the diffusivity tests and compares the drying and wetting unsaturated soil parameters.

Chapter VI concludes this research study.

CHAPTER II

SUCTION IN UNSATURATED SOILS

2.1 Total Soil Suction

Soil suction or soil water potential is one of the fundamental physical properties used to describe the hydromechanical behavior of unsaturated soils. In general, soil suction refers to the measure of the energy or stress that attracts and holds soil water in the pores of an unsaturated soil mass. Total soil suction quantifies the thermodynamic potential of soil pore water relative to a reference potential of free (or pure) water (Lu and Likos 2004). The thermodynamic relationship between total suction and its partial vapor pressure of the soil pore water is described by Kelvin's equation (Sposito 1981):

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

where h_t = total suction (kPa); R = universal gas constant (8.31432 J $\mathrm{mol^{-1}\ K^{-1}}$); T = absolute temperature [i.e., T = (273.16 + t^o) (K)]; t = temperature (^{o}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 = partial pressure of pore water vapor (kPa); and P_0 = saturated pressure of water vapor over a flat surface of pure water at the same temperature (kPa). Noting that (P/P_0) is the relative humidity, Eq. [2.1] can be rewritten as:

$$h_t = \frac{RT\rho_w}{M_w} \ln(RH) \qquad [2.2]$$

where RH = relative humidity (expressed as a decimal). If Eq. [2.2] is evaluated at a reference temperature of 25^{o}C, the relationship between total suction and relative humidity can be written as follows:

$$h_t = 137194\ \ln(RH) \qquad [2.3]$$

Figure 2.1 shows a plot of Eq. [2.3]. From Figure 2.1, it can be seen that the total suction is 0 kPa when relative humidity is 100% and increases when relative humidity is less than 100%. At completely dry conditions (i.e., oven-dried conditions), a soil has a suction of 1,000,000 kPa (Fredlund and Xing 1994).

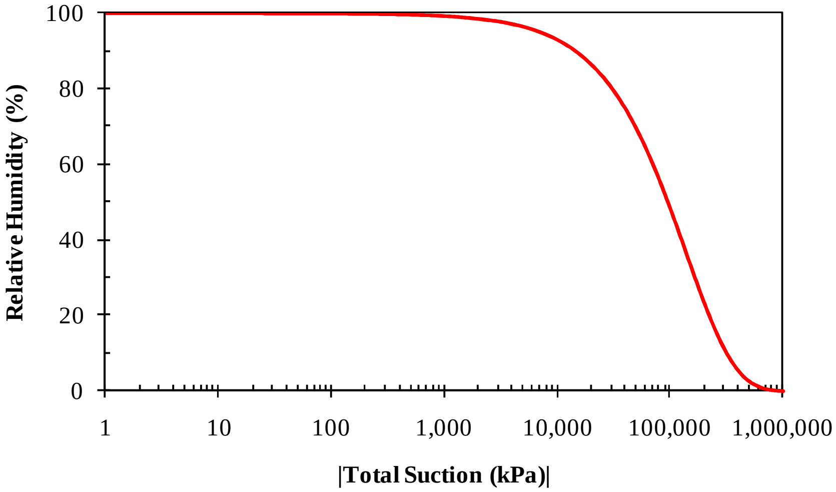


Figure 2.1. Relationship between Total Suction and Relative Humidity.

2.1.1 Components of Soil Suction

Soil suction is comprised of two primary components, namely, matric suction and osmotic suction. The matric component of suction is associated with capillary phenomenon, texture, and surface adsorptive forces of a soil. Matric suction is typically measured in an apparatus that employs a high air-entry (HAE) disk, such as pressure plate or pressure membrane. By artificially raising the air pressure (u_a) experienced by an unsaturated soil while maintaining the pore water pressure (u_w) at a reference value; the pressure difference ($u_a - u_w$) obtained is referred to as matric suction and can be expressed as (Fredlund and Rahardjo 1993):

$$h_m = (u_a - u_w) \qquad [2.4]$$

where h_m = matric suction; u_a = applied air pressure; and u_w = pore water pressure. As the soil moisture content increases, matric suction will decrease and vice-versa. The other devices that can be employed to measure matric suction include contact filter paper method, tensiometer, and thermal conductivity sensor. The osmotic component of suction arises from the presence of dissolved solutes in the pore water. The presence of dissolved ions in soil water decreases the vapor pressure (relative humidity), which then increases the osmotic suction. The osmotic suction of electrolyte solutions, which are usually employed in the calibration of psychrometers and filter papers, can be calculated using the relationship between osmotic coefficients and osmotic suction for different salt solutions (Bulut et al. 2001). The osmotic suctions for different salt solutions can be calculated using Eq. [2.5] (Lang 1967; Bulut et al. 2001):

$$\phi = -\frac{\rho_w}{vmM_w}\ln\left(\frac{P}{P_0}\right) \qquad [2.5]$$

where ϕ = osmotic coefficient; v = number of ions from one molecule of salt (i.e., v = 2 for NaCl, KCl, NH_4Cl and v = 3 for Na_2SO_4, $CaCl_2$, $Na_2S_2O_3$, $MgCl_2$, etc.); and m = molality, moles solute per 1000 grams of solvent. Table 2.1 shows osmotic coefficients for different salt solutions at 25°C. If Eq. [2.1] and Eq. [2.5] are combined, osmotic suctions for different salt solutions can be calculated as follows (Bulut et al. 2001):

$$h_\pi = -vRTm\phi \qquad [2.6]$$

where h_π = osmotic suction. Table 2.2 shows osmotic suctions for different salt solutions at 25°C. The algebraic sum of matric and osmotic suction is called total suction. In a simplified equation form, this can be written as:

$$h_t = h_m + h_\pi \qquad [2.7]$$

Soil suction within a soil mass is dependent on the soil's water content. The soil-water characteristic curve describes the constitutive relationship between water content and soil suction (Lu and Likos 2004). Typically, this relation is described in terms of matric suction or total suction.

2.1.2 Units of Suction

The suction in soils can be expressed in the usual units of pressure e.g., *kPa* or *psf* or *head of water (cm or ft).* However, because of the large values of suction encountered,

Table 2.1. Osmotic Coefficients for Several Salt Solutions (Bulut et al. 2001).

Osmotic Coefficients at 25°C							
Molality (m)	**NaCl**	**KCl**	**NH_4Cl**	**Na_2SO_4**	**$CaCl_2$**	**$Na_2S_2O_3$**	**$MgCl_2$**
0.001	0.9880	0.9880	0.9880	0.9608	0.9623	0.9613	0.9627
0.002	0.9840	0.9840	0.9840	0.9466	0.9493	0.9475	0.9501
0.005	0.9760	0.9760	0.9760	0.9212	0.9274	0.9231	0.9292
0.010	0.9680	0.9670	0.9670	0.8965	0.9076	0.8999	0.9106
0.020	0.9590	0.9570	0.9570	0.8672	0.8866	0.8729	0.8916
0.050	0.9440	0.9400	0.9410	0.8229	0.8619	0.8333	0.8708
0.100	0.9330	0.9270	0.9270	0.7869	0.8516	0.8025	0.8648
0.200	0.9240	0.9130	0.9130	0.7494	0.8568	0.7719	0.8760
0.300	0.9210	0.9060	0.9060	0.7262	0.8721	0.7540	0.8963
0.400	0.9200	0.9020	0.9020	0.7088	0.8915	0.7415	0.9206
0.500	0.9210	0.9000	0.9000	0.6945	0.9134	0.7320	0.9475
0.600	0.9230	0.8990	0.8980	0.6824	0.9370	0.7247	0.9765
0.700	0.9260	0.8980	0.8970	0.6720	0.9621	0.7192	1.0073
0.800	0.9290	0.8980	0.8970	0.6629	0.9884	0.7151	1.0398
0.900	0.9320	0.8980	0.8970	0.6550	1.0159	0.7123	1.0738
1.000	0.9360	0.8980	0.8970	0.6481	1.0444	0.7107	1.1092
1.200	0.9440	0.9000	0.8980	…	…	…	…
1.400	0.9530	0.9020	0.9000	…	…	…	…
1.500	…	…	…	0.6273	1.2004	0.7166	1.3047
1.600	0.9620	0.9050	0.9020	…	…	…	…
1.800	0.9730	0.9080	0.9050	…	…	…	…
2.000	0.9840	0.9120	0.9080	0.6257	1.3754	0.7410	1.5250
2.500	1.0130	0.9230	0.9170	0.6401	1.5660	0.7793	1.7629

Table 2.2. Osmotic Suctions for Several Salt Solutions (Bulut et al. 2001).

Osmotic Suctions at 25°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	5880	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	6615	6261	6247	…	…	…	…
1.5000	…	…	…	6998	13391	7994	14554
1.6000	7631	7179	7155	…	…	…	…
1.8000	8683	8104	8076	…	…	…	…
2.0000	9757	9043	9003	9306	20457	11021	22682
2.5000	12556	11440	11366	11901	29115	14489	32776

suction can be represented in *pF* units [i.e., suction in *pF* = $\log_{10}$ (|*suction in cm of water*|)] or in *log kPa* units [i.e., suction in *log kPa* = $\log_{10}$ (|*suction in kPa*|)]. The relationship between *pF* and *log kPa* units is given by the expression *log kPa ≈ pF – 1*.

2.1.3 Measurement of Suction

The magnitude of soil suction can range from 0 to 1,000,000 kPa (Fredlund and Xing 1994). Table 2.3 shows various devices available for measuring total suction and matric suction in a soil and their typical ranges. In this study, thermocouple psychrometers and filter paper method were employed to measure suction.

Table 2.3. Soil Suction Devices (Bulut and Leong 2008; Lu and Likos 2004).

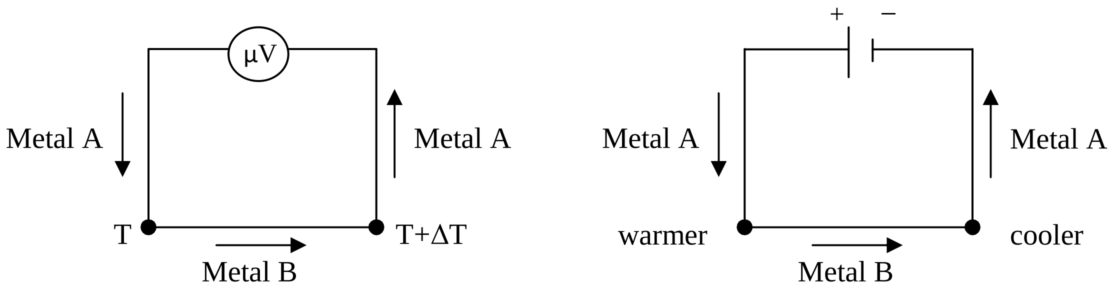
Suction Component Measured	Device/Sensor	Range (kPa)
Total	Thermocouple psychrometer	300-7,000
	Noncontact filter paper method	500-30,000 (or higher)
	Chilled-mirror hygrometer	500-30,000 (or higher)
Matric	Contact filter paper method	entire range
	Axis translation technique	0-1,500
	Tensiometer	0-100
	Thermal conductivity sensor	0-1,500

2.1.3.1 Peltier Thermocouple Psychrometers

Thermocouple psychrometers are used to determine total soil suction in the field or laboratory by measuring the relative humidity of the vapor in equilibrium with the soil water. The relative humidity is related to total suction as expressed in Eq. [2.2]. Spanner (1951) introduced the use of Seebeck effect and Peltier effect in thermocouple psychrometers to measure suction (Ng and Bruce 2007).

When two dissimilar metals or wires are joined to form a closed loop, electrical current will flow through the wires whenever their junctions are at different temperatures [i.e., T and ($T+\Delta T$)] as illustrated in Figure 2.2a. The magnitude of the voltage (μV) measured by a microvoltmeter installed in the circuit, is dependent on the temperature difference (ΔT) between the two junctions. This phenomenon which permits two different wires (i.e., a thermocouple) to generate an electrical current due to change in temperature between two different junctions is referred to as the Seebeck effect (Fredlund and Rahardjo 1993; Lu and Likos 2004).

When a current is passed through a closed loop consisting of two dissimilar metals or wires, one of the junctions becomes warmer, while the other junction becomes cooler as indicated in Figure 2.2b. When the current is reversed, the thermal conditions for both junctions are reversed. This phenomenon, which permits two junctions in a circuit comprised of two different wires (i.e., a thermocouple) to be cooled or warmed, depending on the direction of the applied electrical current, is referred to as the Peltier effect (Fredlund and Rahardjo 1993; Lu and Likos 2004).



(a) (b)

Figure 2.2. Electrical Circuit to Illustrate (a) Seebeck Effect, and (b) Peltier Effect.

A typical Peltier thermocouple psychrometer commonly used to measure soil suction in geotechnical engineering practice is shown in Figure 2.3. For relative humidity measurements, the Peltier and Seebeck effects are used to create and measure respectively, the temperature difference between the measurement junction and the reference junction (Ng and Bruce 2007). Initially, the Peltier effect is used to cool the measuring junction to dewpoint temperature corresponding to the surrounding temperature using an electrical current, which results in moisture condensation on the junction. Upon termination of the passing current, the condensed moisture starts to evaporate to the surrounding atmosphere causing further reduction in temperature, leaving a temperature difference between the junction and the surrounding atmosphere. The Seebeck effect is then employed to measure the current, which is a function of the temperature difference.

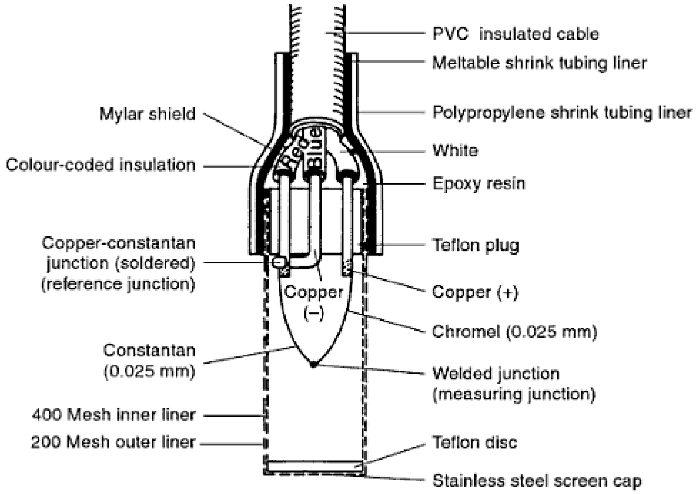


Figure 2.3. Peltier Thermocouple Psychrometer (Fredlund and Rahardjo 1993).

Thermocouple psychrometers can reliably measure suction values between approximately 3 and 5 pF. Psychrometers from Wescor, Inc. used in this study had stainless steel screen protective covers around the thermocouple wires (Figure 2.3). A CR7 datalogger manufactured by Wescor, Inc. and Campbell Scientific, Inc. was used to measure the voltage generated during the evaporation and condensation process. Before suction measurements are taken, the psychrometers are calibrated by suspending them in salt solutions of known water potential to develop a relationship between the microvolt output and total suction (see Chapter 4 and Appendix A). Psychrometers are very sensitive to temperature fluctuations, and therefore temperature control should be provided to maintain a constant temperature environment during suction measurements.

2.1.3.2 Filter Paper Method

The filter paper method developed in the soil science discipline has long been used to measure soil suction. Many soil science and engineering researchers have had interest in the filter paper method because of its advantages over other suction devices. The filter paper method is low cost, relatively simple laboratory test method, and can measure both total and matric suction over the entire range of soil suction.

Basically, the filter paper is used as a sensor and is assumed to come to either water vapor equilibrium (total suction measurement) or liquid equilibrium (matric suction measurement) with soil having a specific suction. When an initially dry filter paper disc is suspended above a soil specimen (i.e., no direct contact with the soil for total suction measurement), water vapor is transferred from the unsaturated soil to the paper until equilibrium is reached (Figure 2.4). When an initially dry filter paper disc is sandwiched between the soil specimen (i.e., in direct contact with the soil for matric suction measurement), water liquid will flow from the soil to the paper until equilibrium is achieved (Figure 2.4). After equilibrium is established between the filter paper and the soil, the water content is determined.

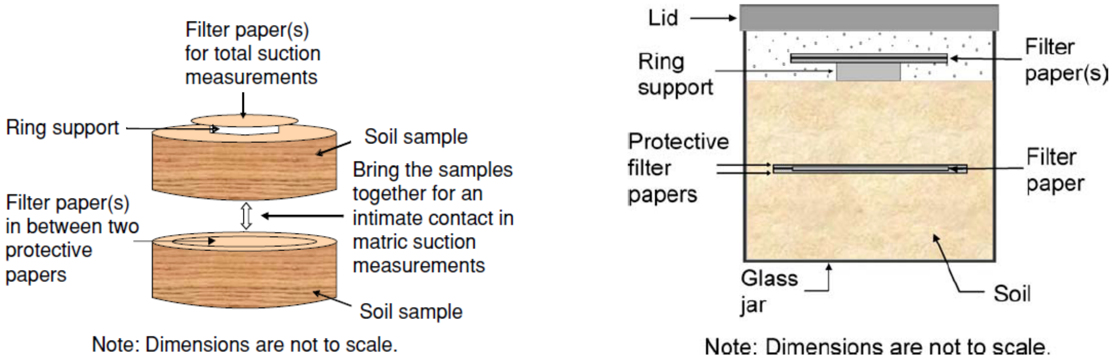


Figure 2.4. Suction Measurement using Filter Paper Method (Bulut and Wray 2005).

Prior to soil suction measurements, filter papers are calibrated to determine the relationship between equilibrium water content and suction. Bulut et al. (2001) developed both wetting and drying calibration curves for Schleicher & Schuell No. 589 – White Hard (WH) filter paper discs (Figure 2.5). The wetting filter paper calibration curve was developed by suspending initially dry filter papers over salt solutions with known water potential. The drying filter paper calibration curve was developed using initially wet filter papers sandwiched between soil specimens in pressure plate or pressure membrane apparatus. An equilibration period of 2 weeks (for wetting curve) and 3 to 7 days (for drying curve) was employed.

It can be seen from Figure 2.5 that the drying calibration curve is above the wetting curve. This is due to the hysteresis effect between wetting and drying process for both total and matric suction values. The wetting filter paper calibration curve developed from salt solutions can be adopted for both total and matric suction measurements. This is because the amount of water an initially dry filter paper would absorb would be the same for both the noncontact (i.e., total suction) and contact (i.e., matric suction) measurements, if enough time is allowed for thermodynamic equilibrium (Bulut and Wray 2005). In this research study, the wetting calibration curve and Schleicher & Schuell No. 589 – White Hard (WH) filter paper discs were employed. A detailed summary of several different soil suction measurement techniques is given in Bulut and Leong (2008).

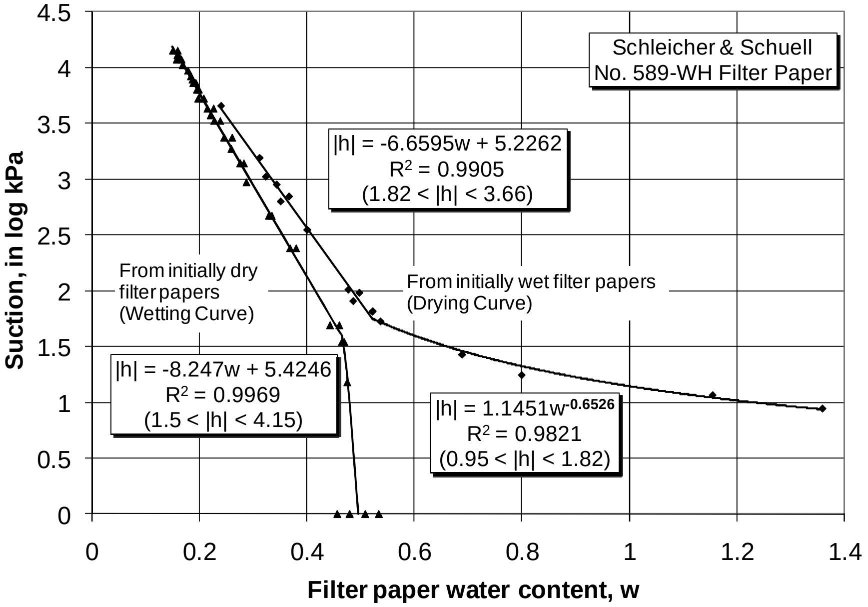


Figure 2.5. Wetting and Drying Filter Paper Calibration Curves (Bulut et al. 2001).

CHAPTER III

MEASUREMENT OF SOIL WATER DIFFUSIVITY

Reliable estimates of soil water diffusivity are important in describing and predicting the movement of water in unsaturated soils. The most commonly preferred laboratory methods of determining soil water diffusivity in unsaturated soils include: (1) pressure plate outflow method which was first proposed by Gardner (1956) based on volumetric outflow measurements of water with time from a soil sample subjected to changes in matric suction; (2) horizontal infiltration method which was first proposed by Bruce and Klute (1956) based on the Boltzmann transformation and measurements of the water content distribution along a horizontal soil column; and (3) Mitchell (1979) method based on inducing transient flow in a soil column and measuring the resulting suction profiles with time.

3.1 Pressure Plate Outflow Technique

The pressure plate outflow technique is typically a multistep flow experiment or one-step flow experiment.

3.1.1 Multistep Outflow Method

In this experiment, a soil sample of known dimensions is placed inside a pressure plate apparatus on top of a saturated porous plate or membrane. Usually the test is initiated with the sample near saturation. A small increment of pressure applied in the chamber and maintained constant. This induces water flow from the soil through porous plate or membrane to an outflow measurement system. The outflow of water released from the sample is recorded with time until it ceases (i.e., until suction equilibrium is achieved). At equilibrium, another small increment of pressure is applied and outflow volume measured as a function of time. This process is repeated until the desired suction range of interest is covered. Outflow measurements can be performed by attaching the pressure plate apparatus to an automatic weighing system or a burette can be used for outflow collection. This outflow method utilizes several small pressure increments to induce water flow in unsaturated soils and is sometimes referred to as the multistep outflow method.

For one-dimensional vertical flow, neglecting gravity, the equation describing water movement in unsaturated soils can be written as (Gardner 1956):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(\theta)\frac{\partial P}{\partial z}\right] \qquad [3.1]$$

where $k(\theta)$ = unsaturated coefficient of permeability as a function of volumetric water content (θ); P = soil water pressure; z = distance; and t = time. Gardner (1956) considered a soil sample of volume (V), cross-sectional area (A), and height (L) situated on a saturated porous plate or membrane. Let P_i be the initial pressure in the chamber for which water in the soil sample is in hydraulic equilibrium with the water in the outflow measuring system. If at time $t = 0$ a small increment in pressure (ΔP) is imposed in the chamber, the final pressure being: $P_f = P_i + \Delta P$; water will flow out of the soil until hydraulic equilibrium is attained once again. Gardner (1956) solved Eq. [3.1] by assuming that: (i) permeability, hence diffusivity, is constant over each small pressure increment; (ii) the water content versus suction relation is linear over each small pressure increment and relation taken to be:

$$\theta(P) = a + bP \qquad [3.2]$$

where a and b are constants; and that (iii) flow impedance of the porous plate or membrane is negligible compared to the impedance in the soil sample. Substituting Eq. [3.2] into Eq. [3.1] yields (Gardner 1956):

$$\frac{\partial P}{\partial t} = D(\theta)\frac{\partial^2 P}{\partial z^2} \qquad [3.3]$$

with $D(\theta) = \frac{k(\theta)}{b}$

where $D(\theta)$ = soil water diffusivity as a function of volumetric water content (θ); $b = \partial\theta/\partial P$ = specific water capacity. Eq. [3.3] is difficult to solve analytically because it is a non-linear differential equation. However, assumptions can be made to linearize the equation and make its solution possible. Assuming boundary conditions:

$$upper\ boundary: \quad \left(\frac{\partial P}{\partial z}\right)_{z=L} = 0$$

$$lower\ boundary: \quad P(0,t) = 0$$

$$inital\ boundary: \quad P(z,0) = \Delta P \quad 0 \leq z \leq L \quad t = 0$$

where *upper boundary* refers to the top of the soil sample (i.e., $z = L$); and *lower boundary* refers to soil boundary in contact with the plate or membrane (i.e., $z = 0$). Gardner (1956) derived an analytical solution to the diffusion problem using method of separation of variables and Fourier series as:

$$Q(t) = Q_0\left[1 - \frac{8}{\pi^2}\sum_{n=1}^{n=\infty}\frac{1}{n^2}exp\left(-\left(\frac{n\pi}{2L}\right)^2 Dt\right)\right] \quad (n = 1,3,5,7,\ldots) \qquad [3.4]$$

where $Q(t)$ = amount of water extracted from the sample at any time (t); Q_0 = total amount of water extracted from sample for a pressure increment (ΔP); L = sample height; and D = soil water diffusivity. Neglecting all but the first term of Eq. [3.4], rearranging, and taking the logarithms of both sides of the equation gives (Gardner 1956):

$$ln[Q_0 - Q(t)] = ln\left(\frac{8Q_0}{\pi^2}\right) - \frac{\pi^2}{4L^2}Dt \qquad [\ 3.5\ ]$$

Eq. [3.5] can be used to determine D from experimental data. If experimental values of $[Q_0 - Q(t)]$ versus t are plotted on semi-log paper, a straight line graph is obtained (see Figure 3.1) with slope (S) and intercept given by Eqs. [3.6] and [3.7] respectively:

$$S = -\frac{\pi^2}{4L^2}D \qquad [3.6]$$

$$Intercept = ln\left(\frac{8Q_0}{\pi^2}\right) \qquad [3.7]$$

Eq. [3.6] can be rewritten as:

$$D = S\frac{4L^2}{\pi^2} \qquad [3.8]$$

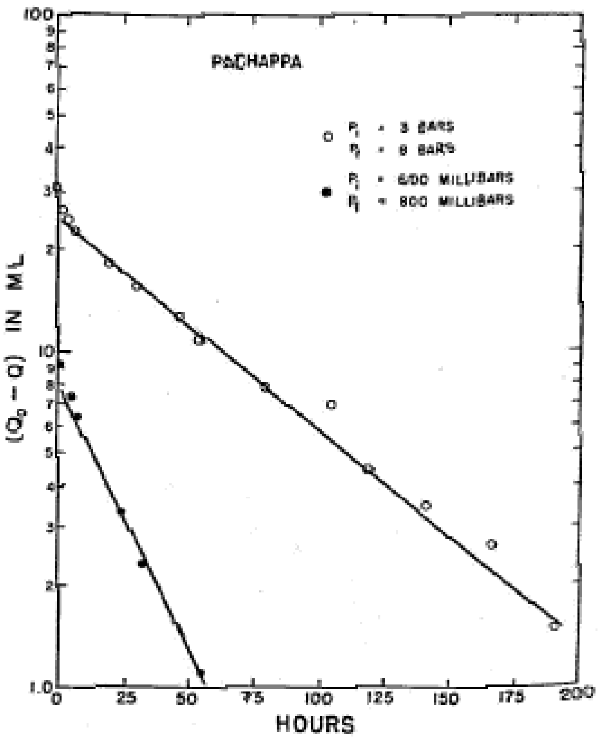


Figure 3.1. Water Outflow versus Time (Gardner 1956).

It is important to note that the pressure increments chosen must be small enough to meet the assumption of constant permeability and water capacity over the increment, but large enough to provide a measurable volume of outflow (Klute 1972; Tindall and Kunkel 1999). The method first proposed by Gardner (1956) was originally an outflow method to determine the drying (drainage) diffusivity. However, if provision is made to maintain a supply of water in contact with the lower surface of the porous plate or membrane, the wetting diffusivity can be obtained (Klute 1972).

The multistep outflow method was subsequently refined by Miller and Elrick (1958), Rijtema (1959), Kunze and Kirkham (1962), Richards (1965), and others to account for flow impedance of the plate and contact impedance between plate and soil. Bruce and Klute (1963), Jackson et al. (1963), and Davidson et al. (1966) examined the outflow methods and observed that even with accurate consideration of plate and contact impedance, the methods show poor agreement between experimental data and theory, particularly in the high water content range. In addition, it is extremely difficult to obtain replicate results (Jackson et al. 1963). Although the pressure plate technique is relatively easy to apply, the multistep outflow method in the form proposed by Gardner (1956) has two major experimental and theoretical problems:

I. Pressure increments of sufficiently small size to validate the assumption of constant D, yet large enough to provide a measurable volume of outflow appear impractical. This is because small pressure increments require high measurement precision and necessitate a large number of increments to cover a given range of water contents which can be time consuming. (Davidson et al. 1966; Jackson et al. 1963).
II. Because of the dependence of the soil water content-pressure relation on the rate at which a given pressure becomes established, the observed transient flow is not often compatible with the appropriate theory (Bruce and Klute 1963; Davidson et al. 1966).

3.1.2 One-step Outflow Method

Instead of applying several small increments of air pressure, a single large pressure increment (typically 100 kPa) is imposed in the chamber and the rate of outflow of water is continuously measured. This single equilibrium pressure plate technique was employed by Doering (1965) who named it the one-step outflow method. The one-step outflow concept is based on the approximate solution to Richards (1931) equation presented by Gardner (1962) that does not involve the assumptions (i) and (ii) of the multistep outflow method. By assuming that (i) plate and boundary impedance is negligible; and (ii) water content at any given time during the outflow process does not vary appreciably with sample depth (i.e., diffusivity is a constant over the length of the sample at any time); Gardner (1962) showed that diffusivity can be calculated directly from instantaneous flow rate, average water content, and dimensions of the sample with the expression:

$$D = -\frac{4L^2}{\pi^2(\bar{\theta} - \theta_f)}\frac{d\bar{\theta}}{dt} \qquad [3.9]$$

where D = soil water diffusivity; L = sample length; $\bar{\theta}$ = average volumetric water content over the entire sample; θ_f = final volumetric water content, which is obtained by gravimetric means; and $d\bar{\theta}/dt$ = instantaneous outflow rate, plotted and evaluated.

The one-step laboratory procedure was first described by Doering (1965) who utilized Eq. [3.9] to analyze one-step flow data. Doering (1965) concluded that the diffusivity estimates are as reliable as those produced by the multistep method. However, Gupta et al. (1974) found that Doering's method could be in error by as much as a factor of three. Gupta et al. (1974) presented an alternative method of analyzing one-step outflow data that makes no assumption of constant diffusivity either over the pressure increment or over the length of the soil. Gupta et al.'s method estimates a weighted mean diffusivity (Eq. [3.10]) from experimental outflow data using finite difference technique. The weighted mean diffusivity is then used with Eq. [3.11] given by Crank (1956) to obtain the soil water diffusivity function:

$$\bar{D} = -\frac{2L^2}{2-\pi}\left[\frac{\Theta_L - \bar{\Theta}}{{\Theta_L}^2}\right]\frac{d\bar{\Theta}}{dt}, \qquad \Theta = \frac{\theta - \theta_f}{\theta_i - \theta_f} \tag{3.10}$$

$$\bar{D} = \frac{1.85}{\left(\theta_i - \theta_f\right)^{1.85}}\int_{\theta_f}^{\theta_i} D(\theta)(\theta_i - \theta)^{0.85}d\theta \tag{3.11}$$

where $\bar{D}$ = weighted mean diffusivity; $D(\theta)$ = soil water diffusivity as a function of volumetric water content (θ); L = sample length; θ_i = initial volumetric water content; θ_f = final volumetric water content; Θ = relative water content; $\bar{\Theta}$ = average relative water content; and Θ_L = relative water content at the upper boundary $z = L$. Gupta et al.'s method provided better diffusivity estimates than those of Doering (1965) or multistep outflow procedures; however, the computations required are too complicated for routine use in a laboratory (Passioura 1976; Jaynes and Tyler 1980).

Passioura (1976) presented another method for calculating diffusivity from one-step outflow data that can be routinely applied in the laboratory and yields values of diffusivity close to those of Gupta el al. (1974). Passioura's method is based on the assumption that the rate of change of water content is effectively uniform throughout the draining column of soil at any time (i.e., $\partial\theta/\partial t$ is assumed constant throughout the soil column). Passioura's procedure determines soil water diffusivity as a function of soil water content at position $z = L$, which is the top end of the soil column, using Eq. [3.12]:

$$D(\theta_L) \cong \frac{L^2}{2}\frac{dF}{dW} \qquad [3.12]$$

where $D(\theta_L)$ = soil water diffusivity at water content θ_L (i.e., θ at $z = L$); L = sample length; F = rate of outflow; and W = amount of water remaining in the soil at any time. dF/dW in Eq. [3.12] cannot be directly measured but can be calculated using (Jaynes and Tyler 1980):

$$\frac{dF}{dW} = -\left(\frac{d^2M}{dt^2}\right)\Big/\left(\frac{dM}{dt}\right) \qquad [3.13]$$

with $M + W = T$

where M = cumulative outflow of water; T = total amount of water initially present in the soil at the beginning of outflow; and t = time.

The one-step outflow method based on Passioura (1976) analysis uses simple computer techniques that can be routinely applied in the laboratory to determine soil water diffusivities. However, this method has some limitations arising from the theoretical assumptions inherent in Passioura's method and measurement errors which may be difficult to eliminate. The drawbacks may include (Green et al. 1998):

I. The $D(\theta)$ calculation is sensitive to the method used to obtain the second derivative of the flow data. Any smoothing of the data by fitting functions through the flow data (F versus W) may add to the measurement error. Jaynes and Tyler (1980) and Borcher et al. (1987) employed different methods for estimating derivatives than those used by Passioura (1976) but they do not always give good fits at later stages of outflow and still have problems with non-monotonic $D(\theta)$ behavior.

II. Incomplete contact of the soil sample with the porous plate potentially causes error, the size of which is difficult to establish.

III. In some clay soils the 100 kPa pressure step might not drain a sufficiently large portion of the total pore space to give reliable diffusivity measurements from outflow experiments.

IV. The use of a single 100 kPa pressure step induces large gradients and large initial water flow rates. This might induce flow processes not completely representative of what occurs in the field (van Dam et al. 1992).

3.2 Horizontal Infiltration Experiment

Based on Richards (1931) equation for horizontal infiltration, one-dimensional movement of water through a horizontal semi-infinite unsaturated soil column is defined as (Klute 1952; Bruce and Klute 1956):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right] \qquad [3.14]$$

where $D(\theta)$ = soil water diffusivity, which is dependent on volumetric water content (θ); x = horizontal distance; and t = time since start of test. The column must be sufficiently long to be regarded as semi-infinite length. The boundary conditions to the system are:

$$\theta(x,t) = \theta_i, \quad x > 0, \quad t = 0$$
$$\theta(x,t) = \theta_s, \quad x = 0, \quad t \geq 0$$

where θ_i = initial moisture content of the system; and θ_s = saturated (inlet) water content. By introducing the Boltzmann transformation

$$\lambda(\theta) = xt^{-0.5}, \qquad [3.15]$$

Bruce and Klute (1956) converted Eq. [3.14] into the ordinary differential equation:

$$-\frac{\lambda}{2}\frac{d\theta}{d\lambda} = \frac{d}{d\lambda}\left[D(\theta)\frac{d\theta}{d\lambda}\right] \qquad [3.16]$$

Integrating Eq. [3.16] with respect to λ yields:

$$D(\theta) = -\frac{1}{2}\left(\frac{d\lambda}{d\theta}\right)\int_{\theta_i}^{\theta} \lambda d\theta \qquad [3.17]$$

If time (t) is fixed at some point, then using Eq. [3.15] in [3.17] yields:

$$D(\theta) = -\frac{1}{2t}\left(\frac{dx}{d\theta}\right)\int_{\theta_i}^{\theta} x d\theta \qquad [3.18]$$

where θ = volumetric water content at the distance x along the column. Eq. [3.18] proposed by Bruce and Klute (1956) calculates the soil water diffusivity function from water content versus position data at a fixed time in a horizontal flow system.

Bruce and Klute (1956) presented a laboratory-based transient flow experiment to determine $D(\theta)$. Water is applied at one end of a horizontal long tube of air-dry or partially wet soil at a small but constant pressure and allowed to move into the soil column for a measured period of time. Eq. [3.18] is then evaluated using the following procedure (Bruce and Klute 1956):

(a) Plot θ versus x curve from the experimental data, i.e., θ as a function of x at a constant value of t. This yields a moisture content distribution curve.

(b) From the plot, evaluate the derivative by measuring the slope of the moisture content distribution curve and evaluate the integral by estimating the area under the curve using approximate methods at a series of values of θ versus x.

(c) Calculate D at the values of θ used in step (b), thereby obtaining $D(\theta)$.

The original Bruce-Klute test method relies on evaluating slopes of the water content distribution curves and the area under the curves. However, application of Eq. [3.18] is problematic for mainly two reasons:

I. The experimental data exhibits natural scatter (see Figure 3.2), thus making it difficult to accurately measure the slopes (Warrick 1994; Tyner and Brown 2004). This is apparent especially at the inlet and wetting front resulting in a tendency to obtain the least reliable results due to large θ where the slope tends to be very small. Because accurate determination of the slope is very difficult, errors arise also in the determination of soil water diffusivity.

II. The estimated $D(\theta)$ values are not necessarily consistent with measured $\lambda(\theta)$ data from the Bruce-Klute test (Tyner and Brown 2004). In other words, the $D(\theta)$ function may not accurately predict the measured $\lambda(\theta)$ data in some soil types.

To remedy these problems, several researchers have suggested fitting the data with explicit functions that can be integrated and differentiated analytically to determine the appropriate areas and slopes along the fitted curves. Others have developed diffusivity functions that ensure the estimated *D*(*θ*) values will accurately predict the measured *λ*(*θ*) data. Some of the proposed analytical models include those of Clothier et al. (1983), McBride and Horton (1985), Warrick (1994), Wang et al. (2004), Tyner and Brown (2004), and many others.

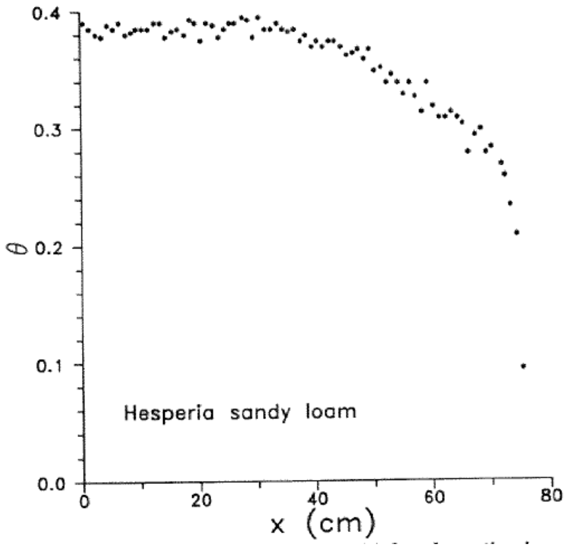


Figure 3.2. Water Content versus Distance (Warrick 1994).

3.2.1 Clothier et al. Model

Clothier et al. (1983) proposed a method of fitting the experimental data obtained from the Bruce-Klute test with a function from expressions derived by Phillip (1960). This made the derivation of a *D*(*θ*) function possible from the fitted expression circumventing the need to differentiate experimental data in which there is scatter. Clothier et al. (1983) selected a function of the form:

$$\lambda(\Theta) = \frac{(p+1)S}{(\theta_s - \theta_i)}(1-\Theta)^p \quad p > 0 \qquad [3.19]$$

with $S = (\theta_s - \theta_i)\int_0^1 \lambda \, d\Theta$ and $\Theta = \frac{\theta - \theta_i}{\theta_s - \theta_i}$

where Θ = normalized water content; $\lambda(\Theta)$ = normalized adsorption similarity profile; p =

curve fitting parameter; θ_s = saturated water content; θ_i = initial water content; and S = sorptivity, which is a measure of the ability of a porous medium to absorb or desorb a liquid. The authors suggest that several other functions proposed by Phillip (1960) could be used to achieve a similar result. Substituting Eq. [3.19] in Eq. [3.17] yielded the following diffusivity function:

$$D(\Theta) = \frac{p(p+1)S^2\{(1-\Theta)^{p-1} - (1-\Theta)^{2p}\}}{2(\theta_s - \theta_i)^2} \tag{3.20}$$

The diffusivity values from Eq. [3.20] fitted to the experimental data are shown in Figure 3.3. All experimental data used was for fine-textured sand; therefore, one drawback to this method of fitting functions is that it may not apply to all soils (Wang et al. 2004).

3.2.2 McBride and Horton Model

McBride and Horton (1985) introduced an empirical function (using linear least squares regression) that yields a curve that fits the water distribution data obtained from a Bruce-Klute test. The proposed empirical equation to fit the water distribution is given by:

$$log\left(log\frac{\theta'_s}{\theta'}\right) = b(\lambda_i - \lambda)^{\frac{1}{2}} \tag{3.21}$$

Substituting Eq. [3.21] in Eq. [3.17] yields a diffusivity function to predict experimental data:

$$D(\theta) = D(\theta') = -\left[\frac{log\left(log\frac{\theta'_s}{\theta'}\right)}{5.30b^2(\theta')\,log\frac{\theta'_s}{\theta'}}\right]\int_{\theta'_i}^{\theta'}\left[\lambda_i - \left(\frac{log\left(log\frac{\theta'_s}{\theta'}\right)}{b}\right)^2\right]d\theta' \quad [\,3.22]$$

where θ' = volumetric water content adjusted by a constant; b = single unknown parameter; and λ_i = transformed distance to wetting front at the conclusion of infiltration. The definite integral can be evaluated using numerical techniques. McBride and Horton (1985) stated that their method to determine $D(\theta)$ from a Bruce-Klute test compares quite favorably to that of Clothier et al. (1983) as shown in Figure 3.4. However, McBride and

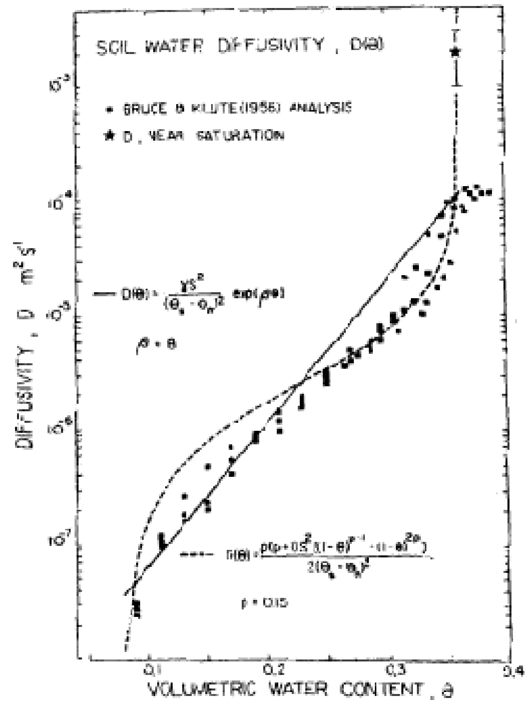


Figure 3.3. Diffusivity Data and Predicted Function (Clothier et al. 1983).

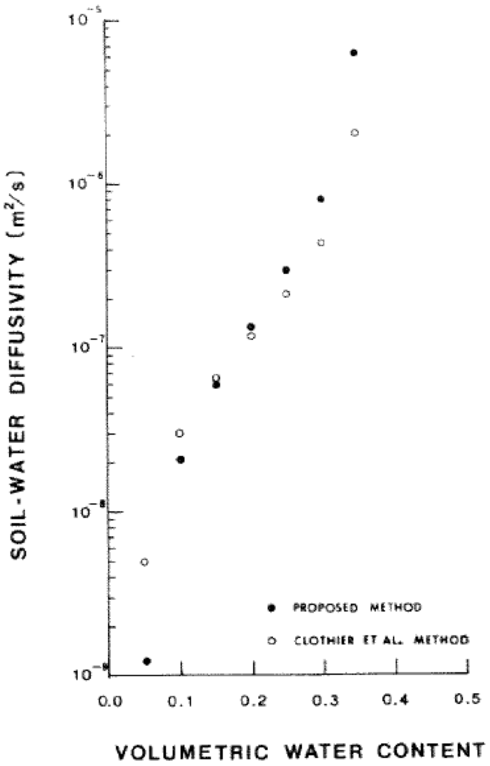


Figure 3.4. Soil Water Diffusivity Values (McBride and Horton 1985).

Horton (1985) did not fit their *D*(*θ*) function to the measured *λ*(*θ*) data thus neglecting to show how their analytical solution predicts the measured data like Clothier et al. (1983) in Figure 3.3 and others.

3.2.3 Warrick Model

Warrick (1994) chose to fit the experimental adsorption data with scaled forms of several commonly used *D*(*θ*) functions. The *D*(*θ*) functions included those of van Genuchten (1980), Fujita (1952) as extended by Broadbridge and White (1987), and Gardner (1958) as extended by Russo (1988). The scaled form of the soil water diffusivity is given by (Warrick 1994):

$$D^{*}(\theta) = D(\theta)\frac{\alpha(\theta_s - \theta_r)}{k_s} \qquad [3.23]$$

where $D^*(\theta)$ = scaled form of the soil water diffusivity D(θ); k_s = saturated coefficient of permeability; θ_s = saturated water content; θ_r = residual water content; and α = fitting parameter. Warrick's procedure uses the *λ*(*θ*) function proposed by Phillip (1969) to obtain the optimum theoretical *λ*(*θ*) values used to fit the measured data. This method requires sufficiently accurate estimates of parameters k_s, θ_s, θ_r, and α. However, measurement of k_s, θ_s, and θ_r require laboratory procedures that are difficult, expensive and time-consuming using traditional techniques such as permeameters, hanging water column and pressure plates (Tyner and Brown 2004).

3.2.4 Wang et al. Model

Wang et al. (2004) developed a diffusivity expression based on hydraulic expressions provided by Brooks and Corey (1964) and the assumption of constant water flux proposed by Parlange (1971). Wang et al. used the observed data of cumulative infiltration versus time, the changes of infiltration rate, and wetting front distance with time to estimate the soil water diffusivities using the expression:

$$D = \frac{k_s h_d}{n(\theta_s - \theta_i)}\left(\frac{\theta - \theta_i}{\theta_s - \theta_i}\right)^{\frac{m-n-1}{n}} \qquad [3.24]$$

where D = soil water diffusivity; k_s = saturated coefficient of permeability; h_d = air-entry suction; θ_s = saturated water content; θ_r = residual soil water content; θ_i = initial water content; m and n = fitting parameters. The assumption of constant water flux is a good approximation only when soil water content is close to saturation, and so far, a limited number of soils have been used to test the assumption (Evangelides et al. 2010; Ma et al. 2009).

3.2.5 Tyner and Brown Model

Tyner and Brown (2004) used van Genuchten (1980) diffusivity expression (Eq. [3.25]) to estimate diffusivity.

$$D(\Theta) = \frac{k_s(1-m)}{\alpha m(\theta_s - \theta_r)} \Theta^{\left(\frac{1}{2}-\frac{1}{m}\right)} \left[\left(1-\Theta^{\frac{1}{m}}\right)^{-m} + \left(1-\Theta^{\frac{1}{m}}\right)^{m} - 2\right] \qquad [3.25]$$

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1+(\alpha\psi)^n}\right]^m, \quad m = 1 - \frac{1}{n}, \quad 0 < m < 1$$

where Θ = normalized water content; ψ = matric potential; and α, m, and n, are fitting parameters. The authors used the $\lambda(\theta)$ expression provided by Phillip and Knight (1974) to obtain the optimum theoretical $\lambda(\theta)$ values to fit the measured data. However, the Tyler-Brown method has problems of convergence and parameter uniqueness (Ma et al. 2009).

Several approaches have been developed to estimate water diffusivity in pressure plate and horizontal infiltration experiments. However, the intensive calculations involved in these procedures, time-consuming measurement of soil parameters, and diffusivity functions not being applicable to all soils limit their application. In addition, the literature review shows that the proposed pressure plate models yield only the drying (drainage) diffusivity and the horizontal infiltration models yield only the wetting diffusivity. Thus, the researchers have not measured both the drying and wetting diffusion coefficients using both the outflow and horizontal infiltration methods.

Mitchell (1979) proposed an alternative approximate linear expression for characterizing unsaturated soil behavior based on measurement of suction in a soil column instead of water content as seen in the other approaches. Laboratory methods based on Mitchell’s approach have the advantage of simple boundary conditions and characterize moisture flow using a single diffusivity parameter with a relatively high degree of confidence. In addition this approach can be used to determine both the drying and wetting diffusivity parameters unlike the pressure plate and horizontal infiltration experiments.

3.3 Mitchell’s Test Method

As noted earlier in this chapter, Mitchell’s approach is based on measurement of suction distribution in a soil column, with moisture travelling from regions with low suction levels to regions with high suction levels (Mitchell 1979; Fredlund and Rahardjo 1993). This section presents two linear approximate solutions proposed by Mitchell (1979) that can be used to describe and predict moisture movement. Moisture flow through an unsaturated soil is influenced by the permeability and moisture retention properties of the soil as will be discussed in the following sections.

3.3.1 Unsaturated Permeability Parameter

Darcy’s law describing one-dimensional flow was extended to unsaturated porous medium by Richards (1931) and can be written as:

$$v = -k(h)\frac{dh}{dx} \qquad [3.26]$$

where v = discharge per unit area or flux density; $k(h)$ = unsaturated coefficient of permeability, which is a function of soil suction (h); and dh/dx = total suction gradient in the x direction. Eq. [3.26] is nonlinear due to the dependence of permeability on suction in the soil. Laliberte and Corey (1967) defined the nonlinear permeability-suction relationship as:

$$k(h) = k_0\left(\frac{h_0}{h}\right)^n, h > h_0 \qquad [3.27]$$

where k_0 = saturated (reference) permeability; h_0 = total suction corresponding to the reference state; and n = material constant, which for clays is close to 1 (Mitchell 1979). Substituting Eq. [3.27] into Eq. [3.26] for a special case of n = 1:

$$v = -k_0 \frac{h_0}{h} \frac{dh}{dx} \tag{3.28}$$

Soil suction in pF units is defined as:

$$u = \log_{10} h \; (cm \; H_2O) \tag{3.29}$$

where u = soil suction (in pF units); and h = soil suction (in cm of water)
Eq. [3.29] can be written as:

$$u = \frac{1}{log_e 10} log_e h = 0.434 \, log_e h \tag{3.30}$$

Differentiating both sides with respect to x, Eq. [3.30] becomes:

$$\frac{du}{dx} = \frac{0.434}{h} \frac{dh}{dx} \tag{3.31}$$

Combining Eq. [3.29] and [3.31], the rate of moisture movement through an unsaturated soil becomes:

$$v = -\frac{k_0 h_0}{0.434} \frac{du}{dx} \tag{3.32}$$

Mitchell (1979) expressed this equivalency as:

$$v = -p \frac{du}{dx} \tag{3.33}$$

with $p = \frac{k_0 h_0}{0.434}$

where p = unsaturated permeability parameter, which is taken as a constant.

3.3.2 Moisture Characteristic

The soil-water characteristic curve (SWCC) defines the relationship between soil suction and the amount of water in an unsaturated soil. The slope of the SWCC defines the moisture storage term of unsaturated soils. The amount of moisture in the soil can be expressed as gravimetric water content, volumetric water content, or degree of saturation.

Mitchell (1979) defines the moisture characteristic (c) as the amount of moisture a soil gains or losses ($\varDelta w$) per unit change of soil suction ($\varDelta u$) expressed in pF. The moisture characteristic is the slope of the SWCC and is expressed as:

$$c = \frac{\Delta w}{\Delta u} \qquad [3.34]$$

Pressure plate devices (i.e., axis translation technique) can be used to obtain SWCC's in the laboratory. Lu and Likos (2004) define axis translation as the practice of elevating pore air pressure while maintaining pore water pressure at a reference value through the pores of a saturated high air-entry (HAE) disk, thus affording direct control of matric suction ($u_a - u_w$). SWCC's can be employed to predict other unsaturated soil properties such as the coefficient of permeability and shear strength with respect to suction. The shape of a SWCC is influenced by type of soil, grain size distribution and void ratio of the soil. Figure 3.5 shows a typical SWCC of an unsaturated soil.

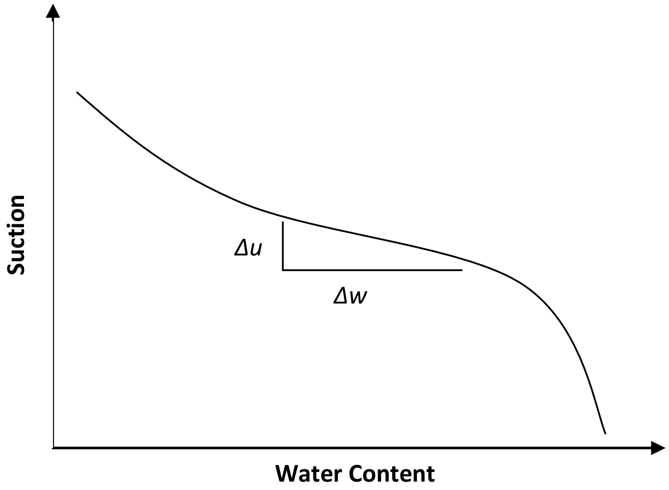


Figure 3.5. Typical Soil-Water Characteristic Curve.

3.3.2.1 Hysteresis of Soil-Water Characteristic Curve

In this research study, soil samples were subjected to wetting and drying processes as described in Section 3.3.4 of this chapter. When soils are wetted and dried, considerable hysteresis may occur in the SWCC as illustrated in Figure 3.6. The drying (desorption) curve is obtained by starting with a saturated sample and increasing the suction in a step-wise manner, to gradually dry the soil while taking successive measurements of wetness versus suction at equilibrium; whereas the wetting (adsorption) curve is obtained by gradually wetting an initially dry soil sample while reducing the suction incrementally (Ng and Menzies 2007). At a particular suction level, the water content or degree of saturation will be different for the drying and wetting process (Figure 3.6).

The hysteresis effect may be attributed to several causes (Hillel 1998; Tindall and Kunkel 1999):

- *Geometric Pore Non-Uniformity*: Variations in the geometric sizes and shapes of soil pores will cause geometric hysteresis. Soil pores are generally irregular and are connected by narrow passageways of various sizes.
- *Contact Angle Effect*: The contact angle and radius of curvature of the soil water on the pore wall are greater in the case of an advancing (wetting) meniscus than a receding (drying) meniscus. This results in a tendency for drying process to exhibit higher suction values than wetting process for a given water content. However, contact angle hysteresis can also be attributed to presence of solutes, particle and pore size, surface roughness, and other factors.
- *Entrapped Air*: In wetting process, the water displaces soil air in the pores. However, considerable amount of entrapped air will remain in the system because of dead-end or occluded pores. The presence of entrapped air further reduces the water content of a newly wetted soil and accentuates the hysteresis effect.
- *Shrinkage and Swelling*: Alternate drying and wetting of soils can cause both shrinkage and swelling. This can cause differential changes in soil structure, accompanied by changes in pore space, depending on drying and wetting history of the soil (Hillel and Mottes 1966). Subsequent dissolution and release of soil air during the drying and wetting process may cause significant changes in size and distribution of pores resulting in variations in water content, hence hysteresis.

The difference between the drying and wetting branches of the SWCC maybe as much as one to two orders of magnitude (Fredlund 2002). For example, a particular water content may correspond to soil suction ranging from 10 to 1,000 kPa. The hysteresis effect is in general more pronounced in coarse-textured soils in the low suction range, where pores may empty at an appreciably larger suction than that at which they fill (Hillel 1998).

It was noted in Section 3.3.2 that the SWCC is defined by the moisture characteristic (c). The c value is obtained from the linear portion of the SWCC. When drying and wetting process occurs due to seasonal variations, both drying and wetting branches of the SWCC will exhibit different c values due to the above-mentioned factors. Since the parameter, c is also used in Mitchell's diffusion model to define moisture storage (see Section 3.3.3); there will inevitably be a difference between the Mitchell's drying and wetting diffusion coefficients due to the influence of hysteric c values.

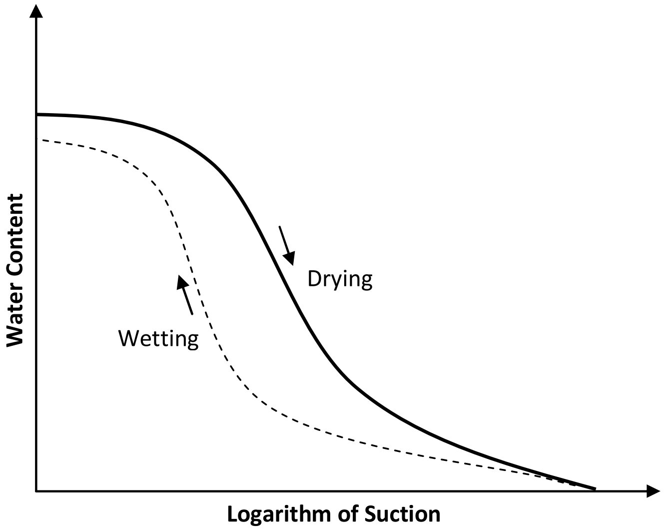


Figure 3.6. Hysteresis Effect in SWCC's.

3.3.3 Derivation of Mitchell's Diffusion Equation

Mitchell (1979) considered an incremental soil element with dimensions Δx, Δy, and Δz that has a source of moisture generated in the soil at a rate per unit volume defined by $f(x,t)$. The moisture flow was assumed to be in the x direction (Figure 3.7) for the case of one-dimensional flow. Net flow into the soil body is given by (Mitchell 1979):

$$\Delta Q = v_x \Delta y \Delta z \Delta t|_x - v_x \Delta y \Delta z \Delta t|_{x+\Delta x} + f(x,t)\Delta x \Delta y \Delta z \Delta t \qquad [3.35]$$

Substituting v_x from Eq. [3.26] into Eq. [3.35] we get:

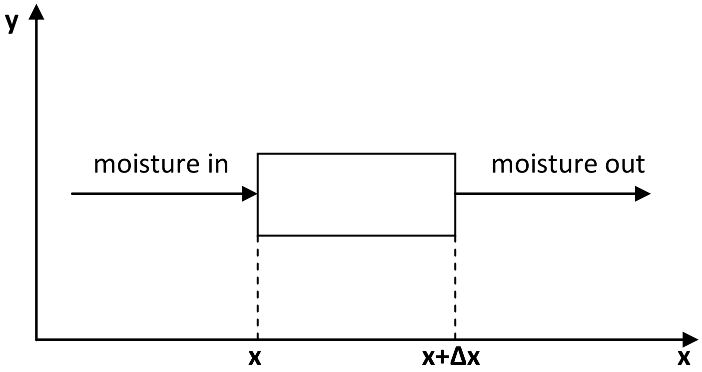


Figure 3.7. Flow of Moisture (Mitchell 1979).

$$\Delta Q = -p\Delta y\Delta z\left(\frac{\partial u}{\partial x}\right)_x \Delta t - \left\{-p\Delta y\Delta z\left(\frac{\partial u}{\partial x}\right)_{x+\Delta x} \Delta t\right\} + f(x,t)\Delta x\Delta y\Delta z\Delta t \quad [3.36]$$

$$\Delta Q = p\Delta y\Delta z\Delta x\,\frac{\left(\frac{\partial u}{\partial x}\right)_{x+\Delta x} - \left(\frac{\partial u}{\partial x}\right)_x}{\Delta x}\Delta t + f(x,t)\Delta x\Delta y\Delta z\Delta t \quad [3.37]$$

As Δx → 0, net flow into a soil body given by Eq. [3.37] becomes:

$$\Delta Q_{x\to 0} = p\Delta x\Delta y\Delta z\left(\frac{\partial^2 u}{\partial x^2}\right)\Delta t + f(x,t)\Delta x\Delta y\Delta z\Delta t \quad [3.38]$$

The amount of moisture stored ($\Delta Q'$) can be defined as:

$$\Delta Q' = \Delta v = -\Delta x\Delta y\Delta z\,\Delta\theta \quad [3.39]$$

where θ = volumetric water content = $(\gamma_d/\gamma_w)w$; γ_d = dry density; γ_w = unit weight of water; and w = gravimetric water content. Hence, when θ and Eq. [3.34] are substituted into Eq. [3.39], the amount of moisture stored becomes:

$$\Delta Q' = \Delta x\Delta y\Delta z\left(\frac{\gamma_d}{\gamma_w}\right)\Delta w = \Delta x\Delta y\Delta z\left(\frac{\gamma_d}{\gamma_w}\right)c\Delta u \quad [3.40]$$

The net flow in the soil body given by Eq. [3.38] is equal to the amount of moisture stored expressed by Eq. [3.40], hence (Mitchell 1979):

$$p\frac{\partial^2 u}{\partial x^2}+f(x,t)\underset{\substack{\Delta x\rightarrow 0\\ \Delta y\rightarrow 0\\ \Delta z\rightarrow 0\\ \Delta t\rightarrow 0}}{\Longrightarrow}\frac{\gamma_d c}{\gamma_w}\frac{\partial u}{\partial t} \qquad [3.41]$$

or $$\frac{\partial^2 u}{\partial x^2}+\frac{f(x,t)}{p}=\frac{\gamma_d c}{\gamma_w p}\frac{\partial u}{\partial t} \qquad [3.42]$$

or $$\frac{\partial^2 u}{\partial x^2}+\frac{f(x,t)}{p}=\frac{1}{\propto}\frac{\partial u}{\partial t} \qquad [3.43]$$

with $\propto=\frac{\gamma_w p}{\gamma_d c}$

where u = total soil suction (in pF); x = distance; $f(x,t)$ = rate of moisture inflow per unit volume; t = time; p = unsaturated permeability parameter; c = moisture characteristic; γ_d = dry density; γ_w = unit weight of water; and α = diffusion coefficient. Considering three-dimension flow, Eq. [3.43] becomes (Mitchell 1979):

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}+\frac{f(x,y,z,t)}{p}=\frac{1}{\propto}\frac{\partial u}{\partial t} \qquad [3.44]$$

Eq. [3.44] is a diffusion equation that defines the distribution of suction throughout the soil profile as a function of space and time. Because of the dependence of permeability on suction and the nonlinearity of the moisture-suction relationship, the analytical formulation of flow through an unsaturated soil is highly nonlinear (Aubeny et al. 2003). However, Mitchell (1979) proposed linear approximations for Eq. [3.44] as discussed in the following sections. These analyses provide a practical basis for measuring soil moisture diffusion characteristics in the laboratory.

3.3.4 Determination of Mitchell's Diffusivity Parameters

Mitchell (1979) proposed two laboratory methods that can be performed to determine the diffusivity parameters of an unsaturated soil; namely drying (evaporation) test and wetting (soaking) test. In both tests the diffusion coefficient of the soil can be measured by determining the rate of change of suction with time in the Shelby tube soil specimen using thermocouple psychrometers. The drying and wetting test can be performed on disturbed and undisturbed soil columns to determine soil water diffusivity of unsaturated soils.

3.3.4.1 Drying Test

A soil specimen originally at a known initial suction, is sealed at one end and the curved surface and allowed to lose moisture to atmosphere of known suction from one open end as shown in Figure 3.8. This test considers the evaporation of moisture at the soil-air interface as a boundary condition. From tests performed on undisturbed clay samples in Australia, Mitchell (1979) reports a constant which relates suction gradient at the surface to the difference between the atmospheric suction (u_a) and the suction at the soil surface (u_ℓ) by:

$$\left(\frac{du}{dx}\right)_{x=L} = h_e(u_a - u_\ell) \qquad [3.45]$$

where h_e = evaporation constant, assumed to be independent of the state of suction in a soil profile. Based on the previous work by Mitchell (1979), h_e = 0.54 cm^{-1}. The solution to the drying problem (Eq. [3.46]) considers the following boundary conditions (Mitchell 1979), as shown in Figure 3.8:

$$\textit{inital suction}: \qquad u(x,0) = u_0$$

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

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

where u = total suction; u_0 = initial total suction of the soil; u_a = atmospheric suction; t = elapsed time since start of test; x = psychrometer distance from closed end; and L = length of the soil specimen. Mitchell (1979) found a solution to Eq. [3.44] to solve the drying diffusion problem by using separation of variables and properties of orthogonal functions. The solution is:

$$u(x,t) = u_a + \sum_{n=1}^{\infty} \frac{2(u_0 - u_a)\, sin\, z_n}{z_n + sin\, z_n\, cos\, z_n}\, exp\left(\frac{-{z_n}^2 t\alpha_{dry}}{L^2}\right) cos\left(\frac{z_n x}{L}\right) \qquad [3.46]$$

where $u(x,t)$ = suction as a function of location and time; z_n = solution of $\cot z_n = z_n/h_eL$; h_e = evaporation coefficient, which is equal to 0.54 cm^{-1} based on Mitchell (1979) recommendation; and α_{dry} = drying diffusion coefficient.

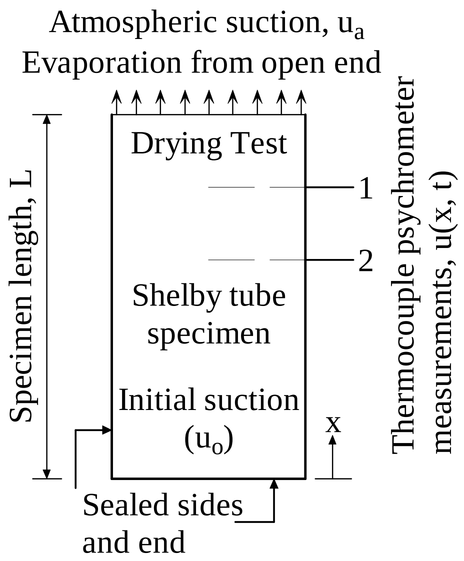


Figure 3.8. Boundary Conditions for Drying Process.

3.3.4.2 Wetting Test

A soil specimen originally at a known suction, is sealed at one end and the curved surface and exposed to a liquid of known suction at the open end as shown in Figure 3.9. The solution to the wetting problem (Eq. [3.47]) considers the following boundary conditions (Mitchell 1979), as depicted in Figure 3.9:

$$\textit{inital suction}: \quad u(x,0) = u_0$$

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

$$\textit{open boundary}: \quad u(L,t) = u_s$$

Mitchell (1979) found a solution to Eq. [3.44] to solve the wetting diffusion problem by using Laplace transforms. The solution is:

$$u(x,t) = u_s + \frac{4(u_s - u_0)}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{2n-1} exp\left(\frac{-(2n-1)^2\pi^2 t\alpha_{wet}}{4L^2}\right) cos\left(\frac{(2n-1)\pi t}{2L}\right) \quad [3.47]$$

where u_s = soaking suction; and α_{wet} = wetting diffusion coefficient. The soaking suction is equal to 2.75 pF based on Mitchell (1979) recommendation. This level of suction is very low and representative of suction energy in the soaking water.

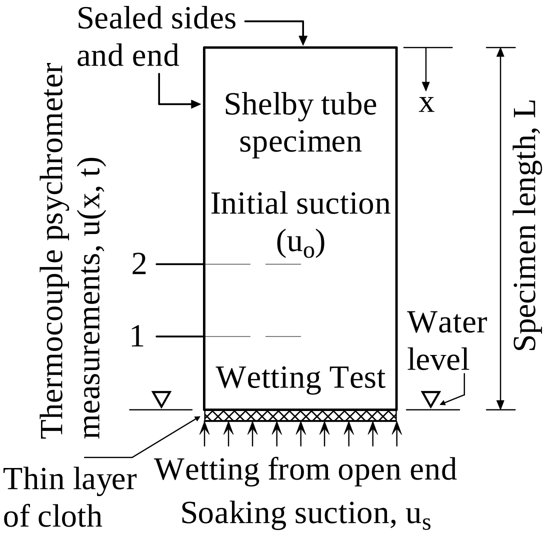


Figure 3.9. Boundary Conditions for Wetting Process.

The limitation to Mitchell's simplified approach is (Aubeny and Lytton 2004):

I. A study by Aubeny et al. (2003) showed that the exponent *n* in Eq. [3.27] is not necessarily equal to unity as assumed by Mitchell (1979). However, Tang (2003) performed diffusion tests on several high plasticity clays and showed that an assumption of $n = 1$ provided adequate agreement between theory and measurements in a majority of cases.

Despite the above limitation, the simplified approach presented by Mitchell has two main advantages (Aubeny et al. 2003):

I. The moisture diffusion coefficient (α) presented as a single parameter can be interpreted with little ambiguity from a relatively simple laboratory test and measurements show a remarkably good conformity to the simplified theory.

II. For cases with simple boundary conditions, analytical solutions are possible with the linearization formulation. Such closed-form solutions can be particularly useful in understanding the basic mechanics of moisture infiltration.

Moisture movement in an unsaturated soil is extremely complex and difficult to model, especially if there are cracks and different permeable soil layers in the soil regime.

However, if total suction as a function of space coordinates and time is defined, then the moisture flow at any location can be specified by a single diffusivity parameter. This approach provides a practical basis for simple, economical, and relatively rapid laboratory measurements of unsaturated soil water diffusivity characteristics.

3.3.5 Empirical Correlations for Diffusion Coefficient

The moisture diffusion coefficient can be determined indirectly by measuring suction changes in a soil column at various locations. The accuracy of the method can be verified by the relation (Aubeny and Lytton 2004):

$$\propto = \frac{k_0 h_0}{c} \frac{\gamma_w}{\gamma_d} \qquad [3.48]$$

where k_0 = saturated permeability of the soil; h_o = suction at which the soil saturates (approximately given by the air-entry value); γ_w = unit weight of water; γ_d = dry unit weight of soil; and c = slope of suction (in pF) versus gravimetric water content curve.

Jayatilaka and Lytton (1997) presented an empirical equation for estimating field moisture diffusivity from soil index properties given by:

$$\alpha_{field} = 0.0029 - 0.000162\, S - 0.0122 \gamma_h \qquad [3.49]$$

where α_{field} = field moisture diffusivity; S = slope of the suction versus water content curve; and γ_h = volume change coefficient. Parameter S can be obtained from the soil-water characteristic curve. It can also be predicted by the empirical equation given by Jayatilaka and Lytton (1997):

$$S = -20.29 + 0.155(LL) - 0.117(PI) + 0.0684(Percent\ Fines) \qquad [3.50]$$

where LL = liquid limit; PI = plasticity index; *Percent Fines* = percentage of particle sizes passing the No. 200 sieve on a dry weight basis.

3.3.6 Recent Studies on Mitchell's Diffusion Coefficient

Bulut et al. (2005) performed one-dimensional water evaporation laboratory tests on soil columns obtained from several locations in Fort Worth, Atlanta, and Austin sites in Texas. All soil samples comprised of 76.2 mm diameter Shelby tube samples obtained at relatively shallow depths from compacted clay highway embankments. The unsaturated soil water diffusivity measurements were performed by following Mitchell (1979) original approach with slight modifications to the drying test proposed by Lytton et al. (2004) and Bulut et al. (2005). A summary of the laboratory drying diffusion coefficients obtained from this study is given in Table 3.1. The diffusion values ranged from 0.0636x10^{-3} to 8.22x10^{-3} cm^2/min for a variety of soils from the Texas sites.

Table 3.1. Moisture Diffusivity at Texas Sites (Bulut et al. 2005).

Texas Site	Sample Depth (m)	Liquid Limit (%)	Plasticity Index (%)	Percent Fines (%)	Initial Suction (log kPa)	Atmospheric Suction (log kPa)	Diffusion Coefficient (x10^{-3} cm^2/min)
Fort Worth	0.0-4.2	36-63	15-36	84-99	2.02-3.76	4.91-5.22	0.0636-8.22
Atlanta	0.3-4.2	37-48	15-26	83-94	1.84-2.99	4.76-5.06	0.738-7.86
Austin	0.3-3.3	33-68	8-35	75-96	2.21-2.77	4.76-4.90	1.09-6.42

Aubeny et al. (2005) compared the laboratory moisture diffusivity values obtained from Fort Worth and Austin sites to field values back-calculated from moisture-suction profiles measured in the field on the same soils. The field diffusion coefficients were estimated using Eq. [3.49] proposed by Jayatilaka and Lytton (1997). Table 3.2 shows the estimated and measured diffusivity values at Fort Worth site. Aubeny et al. (2005) found laboratory measurements on intact specimens (α_{intact}) to be substantially lower than empirical estimates (α_{field}) back-calculated from moisture-suction profiles measured in the field by generally two orders of magnitude. The difference in the diffusivity values was attributed to the formation of crack networks in the field and root-holes in the soil.

Table 3.2. Moisture Diffusivity at Fort Worth Site (Aubeny et al. 2005).

Sample No.	Sample Depth (m)	Liquid Limit (%)	Plasticity Index (%)	Percent Fines (%)	Estimated α_{field} (x10^{-3} cm^2/min)	Measured α_{intact} (x10^{-3} cm^2/min)
A3	2.74-3.04	63	43	93.6	220.2	0.553
B4	3.96-4.26	45	21	99.4	234	1.58
C1	0.61-0.9	62	36	99.7	208.2	1.39
C5	2.13-2.43	42	19	98.2	240.6	1.73

3.3.7 Prediction of Moisture Active Zone

One practical application of the moisture diffusion properties relates to predicting the depth of the moisture active zone and the magnitude of suction variations with the zone. The moisture active zone refers to the shallow regions of unsaturated soil masses where cycles of drying and wetting occur due to seasonal moisture fluctuations at the ground surface. The depth of the moisture active zone and magnitude of suction variations within this zone depend on both the diffusion characteristic of the upper soil region and the amplitude of moisture variation at the surface. Suction within a soil mass decays exponentially as a function of depth and time following the expression (Mitchell 1979):

$$u(z,t) = U_e - U_0 exp\left[-z\left(\frac{\pi f}{\alpha}\right)^{0.5}\right] cos\left[2n\pi t - z\left(\frac{\pi f}{\alpha}\right)^{0.5}\right] \qquad [3.51]$$

where $u(z,t)$ = suction as a function of depth and time; U_e = equilibrium suction value; U_0 = amplitude suction value at the surface; z = depth; f = frequency of seasonal fluctuations in surface suction; α = diffusion coefficient; and t = time. If the cosine term in Eq. [3.51] is set to 1.0 as in Eq. [3.52], the exponential function obtained will generate the extreme dry and wet suction envelopes (Aubeny et al. 2005).

$$u(z,t) = U_e - U_0 exp\left[-z\left(\frac{\pi f}{\alpha}\right)^{0.5}\right] \qquad [3.52]$$

CHAPTER IV

LABORATORY TEST METHODS

The drying and wetting unsaturated soil diffusion coefficients can be determined in the laboratory by measuring total suction over time using thermocouple psychrometers embedded in a Shelby tube soil specimen. These tests can be performed on disturbed or undisturbed cylindrical soil samples in the laboratory. Moisture flow in the cylindrical specimen is induced by sealing all the boundaries except one end which is exposed to the atmosphere of known suction that is higher than the suction in the specimen or liquid of known suction that is lower than the suction in the specimen. In this research study, the approach of measuring total suction over time was enabled by the new testing equipment developed at Oklahoma State University that was utilized to determine both drying and wetting parameters on the same soil specimen.

Mitchell (1979) proposed analytical methods for both the drying and wetting diffusion coefficient measurements; but this study only reported one value for the wetting test and one value for the drying test performed on two different specimens. Lytton et al. (2004) and Bulut et al. (2005) made improvements to only the drying test and reported several diffusivity values. In this research study, the drying testing equipment and method have been modified to incorporate the wetting test. A unified testing protocol is proposed for determining both the drying and wetting diffusion parameters on the same soil specimen. This approach enabled an investigation of hysteresis effects on the evaporation and soaking diffusivity parameters obtained from laboratory measurements. In order to perform both diffusivity tests in a temperature controlled environment, a new water bath was constructed. The water bath was designed to perform both drying and wetting tests on several soil specimens at the same time. The hysteresis effect on the evaporation and soaking parameters associated with drying and wetting of soils due to seasonal variations can be reliably evaluated with this testing method.

Before diffusion tests were performed, the psychrometers were calibrated in salt solutions having known water potential by immersing them in different concentrations of sodium chloride solutions. A relationship between the equilibrium microvolt output from the psychrometers and the corresponding osmotic suction values gave the calibration curve for each psychrometer.

The filter paper method was employed to validate the initial total suction measurements obtained from the first readings given by the psychrometers. This test is warranted for low suction levels at which the reliability of thermocouple psychrometers readings is questionable. The filter paper method gives relatively consistent suction measurements at low suction levels compared to thermocouple psychrometer readings. The laboratory filter paper testing procedure proposed by Bulut et al. (2001) was adopted in this research study.

The atmospheric suction in the laboratory was determined by measuring the relative humidity in the testing room using a thermo-hygrometer. Using the measured relative humidity in the room, atmospheric suction was calculated using Kelvin's equation.

This chapter includes laboratory procedures used to calibrate thermocouple psychrometers, to determine drying and wetting diffusion coefficients, to validate the initial total suction value obtained from psychrometers using the filter paper method, and to measure the atmospheric suction in the testing room.

4.1 Calibration of Thermocouple Psychrometers

Thermocouple psychrometers with stainless screen shields (Figure 4.1) from Wescor, Inc. were employed to monitor changes in total suction over time as moisture evaporates from or a liquid infiltrates a soil specimen through its open boundary as illustrated in Figure 4.6. Before diffusion tests were performed, different molalities of sodium chloride (NaCl) solutions with known water potentials were used to calibrate the psychrometers. Table 4.1 presents osmotic suctions for various NaCl concentrations. Glass jars were employed to calibrate a number of psychrometers at one time. The calibration process was performed by immersing the psychrometers in different molalities of NaCl salt solutions (Figure 4.2). The calibration tests were performed at 25±0.1 ^{o}C for a suitable psychrometer range of suction measurements, typically 3 to 5 pF osmotic suction. Temperature control is extremely important in total suction measurements (Lytton et al. 2004). The new water bath developed to perform diffusivity tests (Figure 4.3) can also be employed to provide a fairly constant temperature environment throughout the testing process. This important tool was employed to provide a constant temperature environment during the calibration process.

A CR7 datalogger (Figure 4.4) manufactured by Wescor, Inc. and Campbell Scientific, Inc. was employed to record the psychrometer microvolt output on a computer. The equilibrium microvolt outputs were plotted against their corresponding osmotic suction values to obtain a calibration curve for each psychrometer. A typical calibration curve for an individual psychrometer is depicted in Figure 4.5. A step-by-step procedure of how salt solutions are prepared and psychrometer calibration is performed is given in Appendix A.

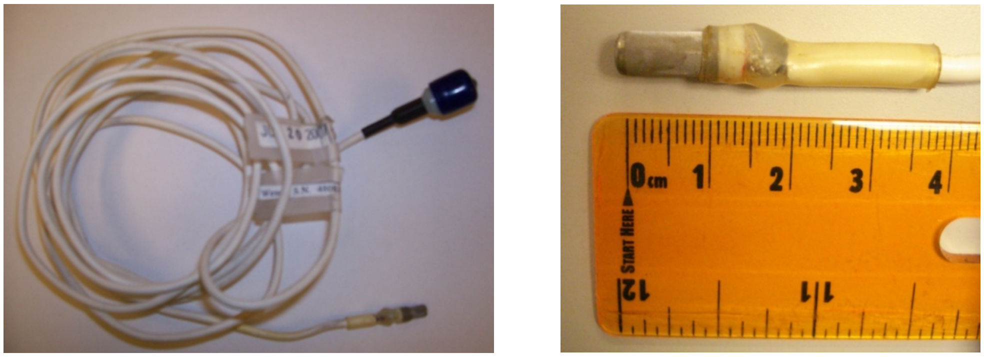


Figure 4.1. Thermocouple Psychrometer from Wescor Inc.

Figure 4.2. Calibration Setup of Thermocouple Psychrometers.

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)	Amount of NaCl (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	18.2658	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	6627.9768	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	3.9398	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

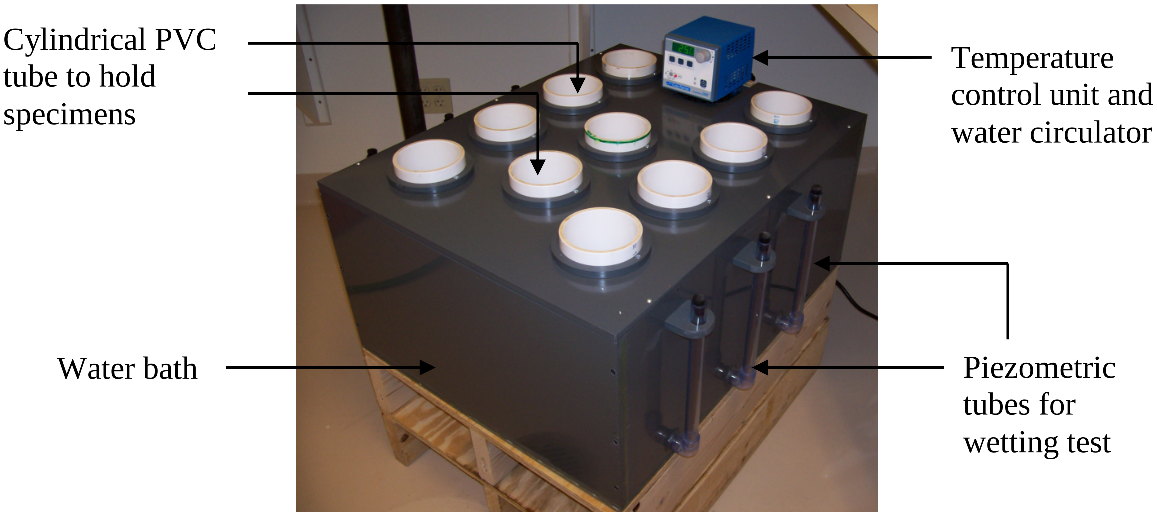


Figure 4.3. Water Bath for Diffusivity Measurements.

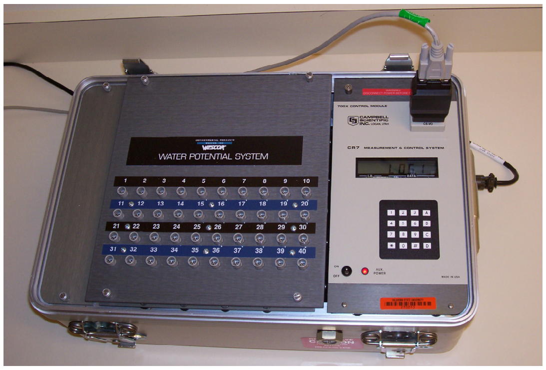


Figure 4.4. CR7 Datalogger from Wescor/Campbell.

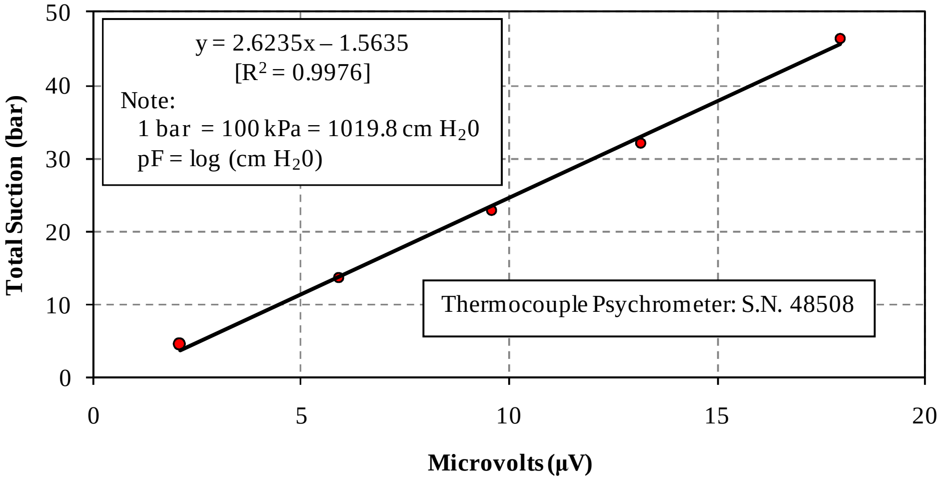


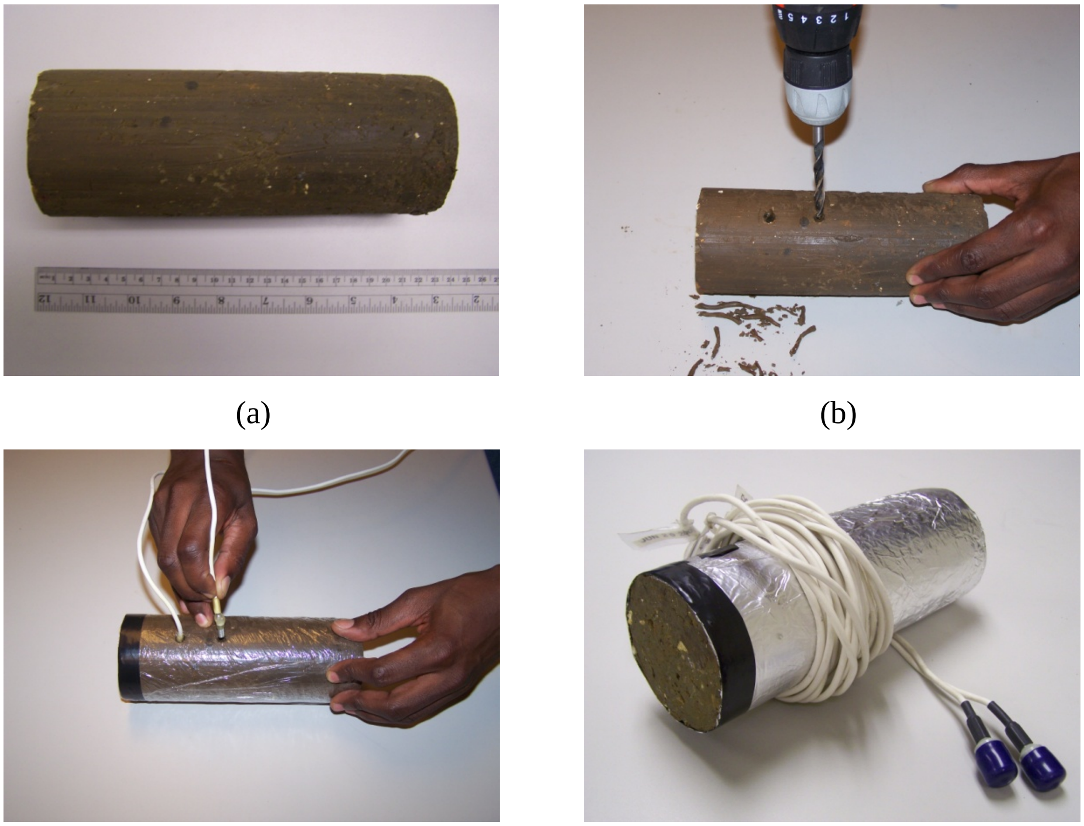
Figure 4.5. Typical Thermocouple Psychrometer Calibration Curve.

4.2 Measurement of Soil Water Diffusion Coefficients

Analytical methods to the drying and wetting diffusivity problem were originally proposed by Mitchell (1979); however, the study only reported one value the drying test and one value for the wetting test performed on two different specimens. Lytton et al. (2004) and Bulut et al. (2005) made improvements to only the drying test. In this research study, the drying testing equipment and method are modified to accommodate the wetting test. The research study proposes a unified testing protocol that permits both drying and wetting tests to be performed in cycles on the same soil specimens. The new testing equipment, built at Oklahoma State University, enables drying and wetting total suction values to be measured continuously and reliably on the same soil specimens. This tool permits reliable comparisons of the evaporation and soaking diffusivity parameters that are associated with alternating testing cycles corresponding to seasonal moisture variations.

4.2.1 Sample Preparation for Diffusion Test

In this research study, the diffusivity tests were performed on 76.2 mm diameter undisturbed Shelby tube specimens. A soil specimen of about 200 mm in length is selected (Figure 4.6a) and its ends carefully trimmed to provide a planar surface. A decision is made as to which end of the specimen will be exposed to both the atmosphere and liquid of known suction. Psychrometer positions are then marked relative to the open boundary along the lateral side of the specimen. The distance from the open end to the first psychrometer and the psychrometer spacing may change depending on the soil type, the insitu moisture state of the soil specimen, and the method used to bore psychrometer


(a) (b)

(c) (d)

Figure 4.6. Diffusion Test Sample Preparation (Mabirizi and Bulut 2010).

holes in the specimens. It is important to note that the closer a psychrometer is to the open end, the shorter the testing time will be.

A drill-bit with slightly larger diameter than that of the psychrometer tips was used in this research to make holes for psychrometer installation. The holes were extended to the center of the soil specimen (Figure 4.6b). It is very important to ensure that no artificial cracks are induced when drilling psychrometer holes into the specimen. The calibrated psychrometers were then inserted into the holes (Figure 4.6c) and each hole was tightly and carefully sealed to keep the psychrometer from moving and to avoid any loss or gain of moisture through the psychrometer holes. After securing the psychrometers in the holes, the whole specimen except the end selected to be exposed to the atmosphere of known suction (drying test) or liquid of known suction (wetting test), is carefully sealed with plastic wrap and aluminum foil (Figure 4.6d) to prevent loss or gain of moisture through its boundaries. The diffusivity tests were performed immediately after the sample was prepared. A step-by-step procedure of how to prepare a Shelby tube specimen for diffusion testing is given in Appendix B.

4.2.2 Drying and Wetting Diffusion Coefficient Measurements

For the drying test, the sealed specimen with the psychrometers is placed in one of the water bath cylindrical tubes without piezometric fittings with its open end exposed to the atmosphere of the testing room (Figure 4.7). The tubes with the piezometric fittings (Figure 4.7) are mainly designed for the wetting test; however, they can also be used for the drying test if needed. The water bath and testing room were maintained at a constant testing temperature of $25\pm0.1\ ^{o}$C and a dehumidifier was used to control the relative humidity of the room where necessary.

For the wetting test, the sealed specimen with the psychrometers is placed in one of the water bath cylindrical tubes with a piezometric tubing system and its open end is turned upside down to make contact with the constant distilled/deionized water front provided through the piezometric tubes (Figure 4.7). The water bath and testing room were maintained at a constant testing temperature of $25\pm0.1\ ^{o}$C.

The water bath (Figure 4.3) developed at Oklahoma State University can provide a controlled temperature environment for reliable suction measurements. This equipment also includes a piezometric tubing system that is used to provide a constant water front during the wetting process. A thin layer of cloth may be placed between the open boundary and porous stones to ensure smooth contact between the planar surface and the water front. A schematic drawing of the water bath and testing setup is shown in Figure 4.8. This water bath was constructed such that it can be used for both the drying and wetting tests on multiple soil specimens at the same time.

The drying test and wetting test can be performed in cycles and on the same soil specimen. This approach is permitted by the diffusion setup developed in Figure 4.7. In this case, the soil specimen is prepared once and either the drying test or wetting test is performed first and then the process is immediately reversed at the end of one test. In other words, after the drying test is completed, for instance, the specimen is turned open end facing down for the wetting test and vice-versa. This enables total suction measurements with time to be collected continuously. In this research, if the drying test is performed first followed by the wetting test; this represents one cycle and is referred to as a drying-wetting cycle. On the other hand, if the wetting test is performed first followed by the drying test, this is a wetting-drying cycle.

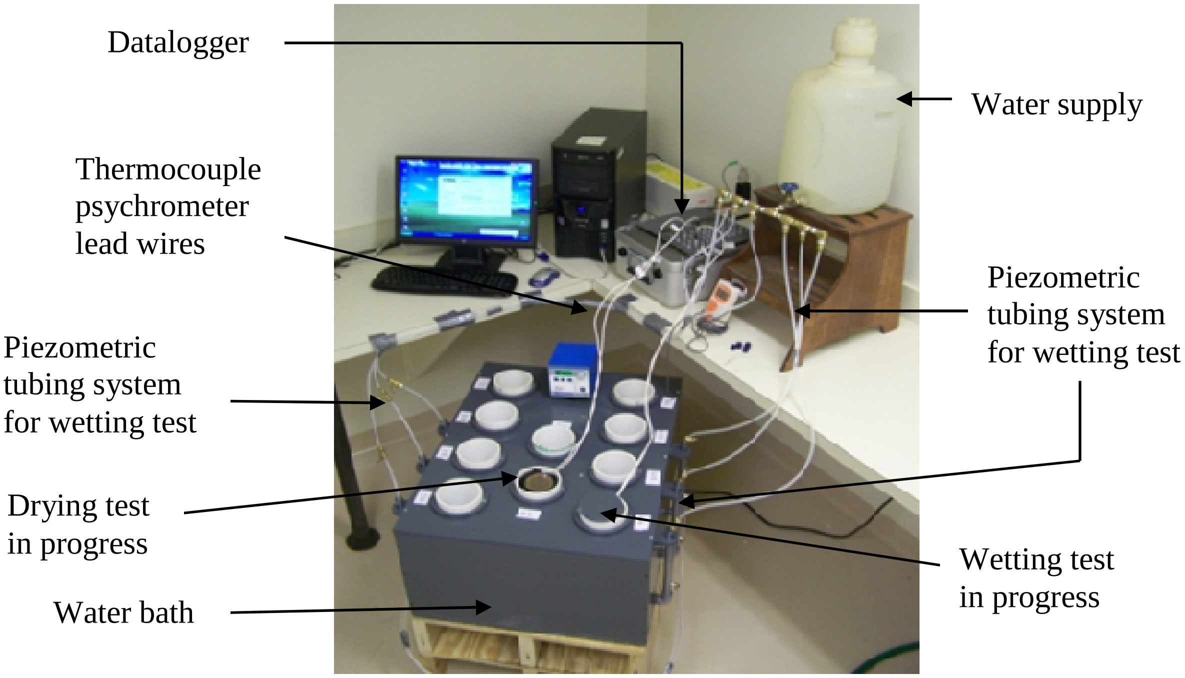


Figure 4.7. Wetting and Drying Diffusion Test Setup.

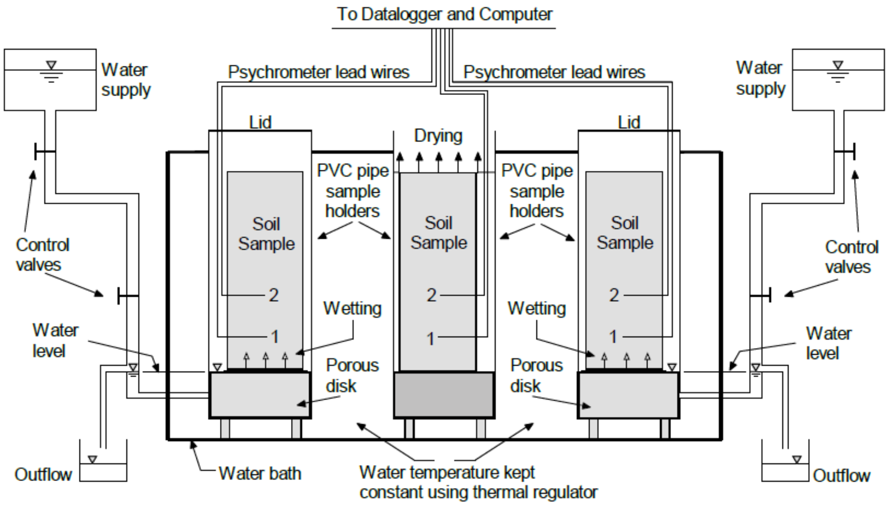


Figure 4.8. Schematic Diagram of Test Equipment (Mabirizi and Bulut 2010).

With this testing approach, cycles of drying-wetting and wetting-drying can be performed numerous times to study moisture flow process in an unsaturated soil by measuring the corresponding diffusivity parameters. The setup presented in Figure 4.7, which is relatively compact and has multiple diffusion testing capabilities, can be easily performed in any geotechnical laboratory. A step-by-step procedure for the unified testing protocol is given in Appendix B. One drying–wetting or wetting–drying cycle was performed in this research to determine the evaporating and soaking diffusivity parameters. The duration of the test was typically 4 to 7 days for either the drying test or soaking test.

4.3 Total Suction Measurement using Filter Papers

The noncontact filter paper method was used to validate initial psychrometer measurements in order to determine the insitu total suction of the soil sample. Filter papers work on the premise that vapor equilibrium will occur between the soil and the paper in a temperature controlled environment; thus the total suction in the soil will be the same as that of the filter paper. Schleicher & Schuell No. 589 – White Hard (WH) filter papers were used in this research. These discs were calibrated in a study by Bulut et al. (2001) and a relationship between the equilibrium filter paper water content and suction was obtained. The wetting calibration curve (Figure 4.9) for this brand of filter paper discs was adopted in this research study. To obtain the wetting curve, dry filter paper discs were suspended over known salt concentrations corresponding to the suction range of interest in a sealed container until equilibrium water content was reached as explained in Chapter 2. In the total suction test setup, the salt solution is replaced by an unsaturated soil; therefore the wetting curve is appropriate for determination of total suction values obtained from the wet filter papers.

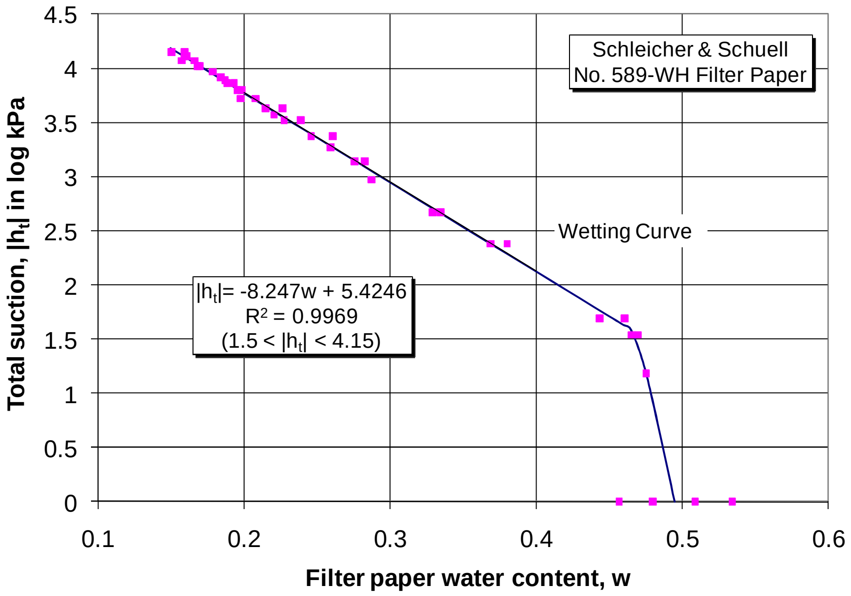


Figure 4.9. Filter Paper Wetting Calibration Curve (Bulut et al. 2001).

The testing procedure proposed by Bulut et al. (2001) was adopted for filter paper total suction measurements. A portion of a Shelby tube specimen for diffusion measurement is trimmed to fill about two-thirds of a glass jar (Figure 4.10). A clean ring-type support is placed on top of the soil specimen to provide a noncontact system between the filter paper and the unsaturated soil in a glass jar. Two filter paper discs, one on top of the other, are placed on the support ring (Figure 4.10). This setup is then tightly sealed to prevent any loss or gain of moisture. The glass jar is placed in an ice chest which is in a temperature controlled room for equilibration to occur. After 7 days of equilibration, the water content of the filter paper discs was measured and Figure 4.9 was used to determine the total suction values. A step-by-step procedure of how to determine total suction using filter paper discs is given in Appendix C.

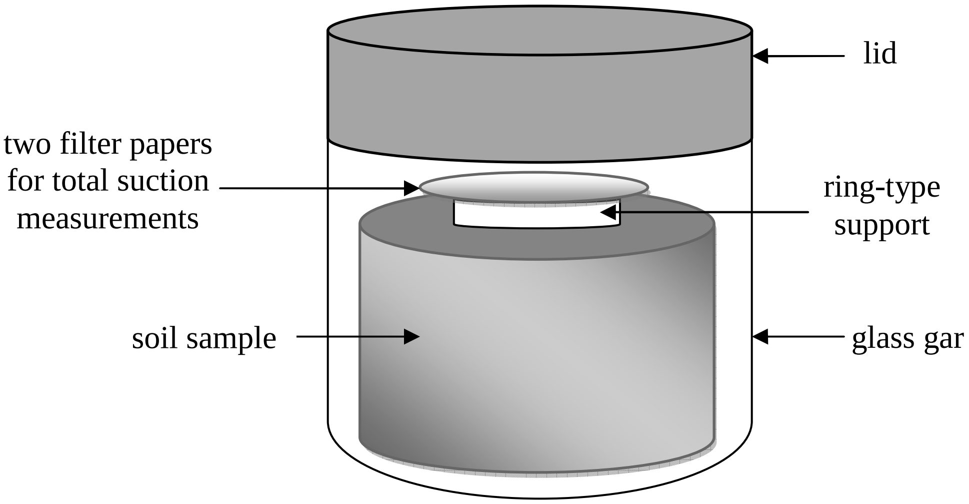


Figure 4.10. Total Suction Measurements using Filter Papers.

4.4 Measurement of Atmospheric Suction

The relative humidity in the testing room was measured and used to determine the atmospheric suction during the testing period. A digital thermo-hygrometer was employed to measure the relative humidity in the laboratory. The relative humidity is recorded several times in the day and an average of the values is obtained for the duration of the diffusion test for every soil specimen. The atmospheric suction was then calculated using Kelvin's equation given by:

$$u_a = \frac{RT\rho_w}{M_w}\ln(RH) \qquad [4.1]$$

where u_a = atmospheric suction in the laboratory; R = universal gas constant; T = absolute temperature; ρ_w = density of water as a function of temperature; M_w = molecular mass of water; and RH = relative humidity.

4.5 Interpretation of Diffusion Test Data

Using the total suction and corresponding time data from the drying and wetting processes, the unsaturated drying and wetting diffusion coefficients can be determined, respectively. The suction versus time data is then fit with a theoretical line (Figure 4.11) predicting suction profile for a given soil specimen (Mitchell 1979). The data required to plot both the drying and wetting theoretical curves includes: u_s = soaking suction, u_0 = initial suction, x = psychrometer distance from closed end, L = sample length, h_e = evaporation constant, u_a = atmospheric suction, α_{dry} = drying diffusion coefficient, and α_{wet} = wetting diffusion coefficient.

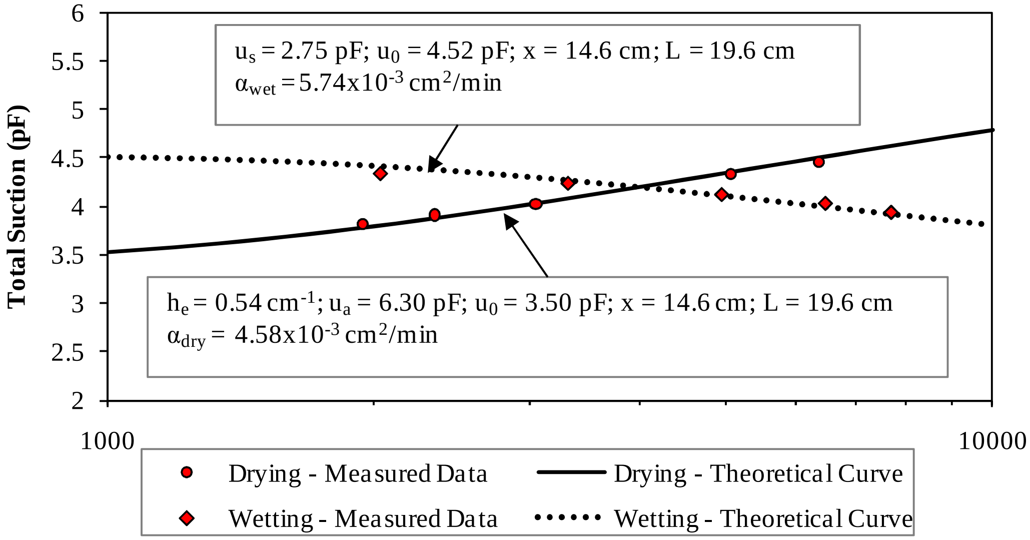


Figure 4.11. Theoretical versus Measured Total Suction Values with Time.

Data interpretation protocol proposed by Lytton et al. (2004) was employed to determine the drying and wetting moisture diffusivity coefficients. The procedure can be summarized as follows:

1. Make an initial estimate of α to compute a theoretical suction value corresponding to each measurement location (x) and measurement time (t) using Eq. [3.46] for drying test or Eq. [3.47] for the wetting test.
2. Compute the error (E) between the theoretical suction values (u_{theo}) and measured suction values (u_{meas}) for drying test or wetting test; so $E = u_{theo} - u_{meas}$.
3. Calculate the sum of squared errors (E_{sum}) for all suction measurements for drying test or wetting test; so $E_{sum} = \Sigma\,(u_{theo} - u_{meas})^2$.

4. Optimize α (from step 1) to minimize E_{sum} for all suction measurements using a trial and error approach for drying test or wetting test.
5. Report the soil diffusivity coefficient values to the nearest 4 decimal places in cm^2/min.

Hand calculations of Eqs. [3.46] and [3.37] is not practical. These equations can simply be programmed using a numerical computing language. Matlab was used to generate the diffusion coefficients and Microsoft Excel was used to plot the measured and theoretical suction data. A typical plot is shown in Figure 4.11.

CHAPTER V

ANALYSIS OF EXPERIMENTAL RESULTS

Soil specimens from six different sites, namely A, B, C, D, E, and F, across Oklahoma were obtained from the Oklahoma Department of Transportation (ODOT). These soils consisted of 7.62 cm diameter Shelby tube samples, which had already been extruded from their sampling tubes and wrapped in plastic wrap.

In this research study, both drying and wetting diffusivity tests were performed on the same specimen to determine the drying diffusion coefficient (α_{dry}) and wetting diffusion coefficient (α_{wet}), respectively. For most soils, one drying-wetting cycle was adopted as described in Chapter IV. In other words, the drying test was performed first by exposing the open end of the specimen to a known atmospheric suction and then the wetting test immediately followed by exposing open end to a liquid of known suction. Two psychrometers were used in each test but the reported results are based on the measurements from the psychrometer closest to the open end. As noted in the previous chapter, the closer the psychrometer is to the open end, the shorter the testing time. Only one psychrometer is sufficient to obtain diffusion parameters. The second psychrometer is utilized in case the first psychrometer fails to obtain suitable values.

5.1 Evaluation of Test Results

The diffusion results for site A, B, C, D, E, and F soils are summarized in Tables 5.1, 5.2, 5.3, 5.4, 5.5, and 5.6, respectively and the curve fits to the measured data are shown in Appendix D. Figure 5.1 shows plots of the diffusivity measurements with depth for site A, B, E, and F soils. In addition, the Atterberg limits and percent minus sieve No. 200 values for the test samples are shown in Table 5.7.

Table 5.1. Drying and Wetting Diffusion Coefficients of Site A Soils.

Sample No.	Depth (cm)	Testing Cycle	Drying Test			Wetting Test		Remarks on Soil Specimens
			^1u_a (pF)	$^2u_0$ (pF)	$^3\alpha_{dry} \times 10^{-3}$ (cm^2/min)	$^2u_0$ (pF)	$^4\alpha_{wet} \times 10^{-3}$ (cm^2/min)	
					Site A			
A1	9.14-38.40	drying-wetting	6.21	4.09	8.1579	4.50	12.7158	Small amount of gravel, silt seams, shrinkage cracks.
A2	38.10-80.77	drying-wetting	6.21	4.09	1.6474	4.50	4.3158	Small amount of gravel, shrinkage cracks.
A3	42.67-79.25	drying-wetting	6.22	4.09	2.3579	4.95	2.7053	Small amount of gravel, silt seams, no visible shrinkage cracks.
A4	7.62-44.20	drying-wetting	6.23	4.13	5.7211	4.74	3.3158	Small amount of gravel, a few root fibers, shrinkage cracks.
A5	44.20-80.77	drying-wetting	6.29	4.13	1.4737	4.52	2.7053	A few root fibers, some gravel, shrinkage cracks.
A6	42.67-79.25	wetting-drying	6.22	3.50	2.7368	4.09	9.5421	A few gravel particles, shrinkage cracks.
A7	0.00-33.53	wetting-drying	6.21	2.85	10.5311	3.55	19.4737	A few root fibers, no visible shrinkage cracks.
A8	56.39-88.39	wetting-drying	6.20	2.83	8.5789	4.01	31.8421	An unintentional crack was induced when drilling psychrometer hole, shrinkage cracks.
A9	0.00-49.68	drying-wetting	6.32	4.00	5.3105	4.68	11.7895	Tiny longitudinal cracks along soil column before testing, shrinkage cracks.

^1u_a = atmospheric suction; $^2u_0$ = initial suction; $^3\alpha_{dry}$ = drying diffusion coeffcient; and $^4\alpha_{wet}$ = wetting diffusion coefficient.

Table 5.2. Drying and Wetting Diffusion Coefficients of Site B Soils.

Sample No.	Depth (cm)	Testing Cycle	Drying Test			Wetting Test		Remarks on Soil Specimens
			$^{1}u_a$ (pF)	$^{2}u_0$ (pF)	$^{3}\alpha_{dry}$ x 10^{-3} (cm^2/min)	$^{2}u_0$ (pF)	$^{4}\alpha_{wet}$ x 10^{-3} (cm^2/min)	
Site B								
B1	0.00-38.40	drying-wetting	6.27	3.09	2.1842	4.50	3.7474	A few small cracks along soil column before testing, small shrinkage cracks after drying test, a few root fibers.
B2	0.00-44.20	drying-wetting	6.21	3.80	5.8316	4.66	8.1842	Several cracks along soil column before testing, small shrinkage cracks after drying test, root fibers.
B3	0.00-39.62	wetting-drying	6.27	3.32	2.7053	4.62	3.7474	A few small cracks along soil column before testing, small shrinkage cracks after drying test, root fibers.
B4	39.62-82.30	drying-wetting	6.26	3.88	1.9053	4.67	6.8737	Several cracks along soil column before testing, no visible shrinkage cracks after drying test.
B5	39.62-82.30	drying-wetting	6.20	3.91	1.3474	4.58	5.3105	A few root fibers, no visible shrinkage cracks after drying process.
B6	38.10-80.77	drying-wetting	6.36	3.97	1.6474	4.64	4.7316	No visible shrinkage cracks after drying process.

$^{1}u_a$ = atmospheric suction; $^{2}u_0$ = initial suction; $^{3}\alpha_{dry}$ = drying diffusion coeffcient; and $^{4}\alpha$wet = wetting diffusion coefficient.

Table 5.3. Drying and Wetting Diffusion Coefficients of Site C Soils.

Sample No.	Depth (cm)	Testing Cycle	Drying Test			Wetting Test		Remarks on Soil Specimens
			^1u_a (pF)	$^2u_0$ (pF)	$^3\alpha_{dry} \times 10^{-3}$ (cm^2/min)	$^2u_0$ (pF)	$^4\alpha_{wet} \times 10^{-3}$ (cm^2/min)	
Site C								
C1		drying-wetting	6.29	3.48	13.2105	4.95	15.2632	Dry, soft, silty, organic soil, easily breaks during sample preparation, no visible shrinkage cracks.
C2		drying-wetting	6.29	3.63	7.1053	4.70	8.9211	Dry, soft, silty, organic soil, easily breaks during sample preparation, no visible shrinkage cracks.
C3		drying-wetting	6.29	3.38	9.2105	4.65	14.7844	Dry, soft, silty, organic soil, easily breaks during sample preparation, no visible shrinkage cracks.
C4		drying-wetting	6.28	3.79	5.5263	4.56	7.6316	Dry, soft, silty, organic soil, easily breaks during sample preparation, no visible shrinkage cracks.

^1u_a = atmospheric suction; $^2u_0$ = initial suction; $^3\alpha_{dry}$ = drying diffusion coeffcient; and $^4\alpha$wet = wetting diffusion coefficient.

Table 5.4. Drying and Wetting Diffusion Coefficients of Site D Soils.

Sample No.	Depth (cm)	Testing Sequence	Drying Test			Wetting Test		Remarks on Soil Specimens
			^1u_a (pF)	$^2u_0$ (pF)	$^3\alpha_{dry}$ x 10^{-3} (cm^2/min)	$^2u_0$ (pF)	$^4\alpha_{wet}$ x 10^{-3} (cm^2/min)	
Site D								
D1		drying-wetting	6.25	2.35	1.016	4.33	1.0026	Wet, hard, clay soil, a few shrinkage cracks.
D2		drying-wetting	6.24	2.27	1.282	4.43	1.0158	Wet, hard, clay soil, no visible shrinkage cracks.
D3		drying-wetting	6.24	2.12	1.584	4.42	1.9316	Wet, hard, clay soil, no visible shrinkage cracks.
D4		drying-wetting	6.25	3.14	0.632	4.43	1.4474	Wet, hard, clay soil, a few tiny roots, one shrinkage crack.
D5		drying-wetting	6.24	2.83	0.937	4.46	1.2421	Wet, hard, clay soil, no visible shrinkage cracks.
D6		drying-wetting	6.24	3.45	0.521	4.36	0.9526	Wet, hard, clay soil, shrinkage crack (about 1mm diameter). Largest crack compared to other specimens.
D7		drying-wetting	6.25	2.90	0.790	4.43	1.5263	Wet, hard, clay soil, a few shrinkage cracks.
D8		drying-wetting	6.24	3.03	1.242	4.47	1.7789	Wet, hard, clay soil, a few shrinkage cracks.
D9		drying-wetting	6.23	2.80	1.053	4.45	1.3874	Wet, hard, clay soil, a few shrinkage cracks.

^1u_a = atmospheric suction; $^2u_0$ = initial suction; $^3\alpha_{dry}$ = drying diffusion coeffcient; and $^4\alpha$wet = wetting diffusion coefficient.

Table 5.5. Drying and Wetting Diffusion Coefficients of Site E Soils.

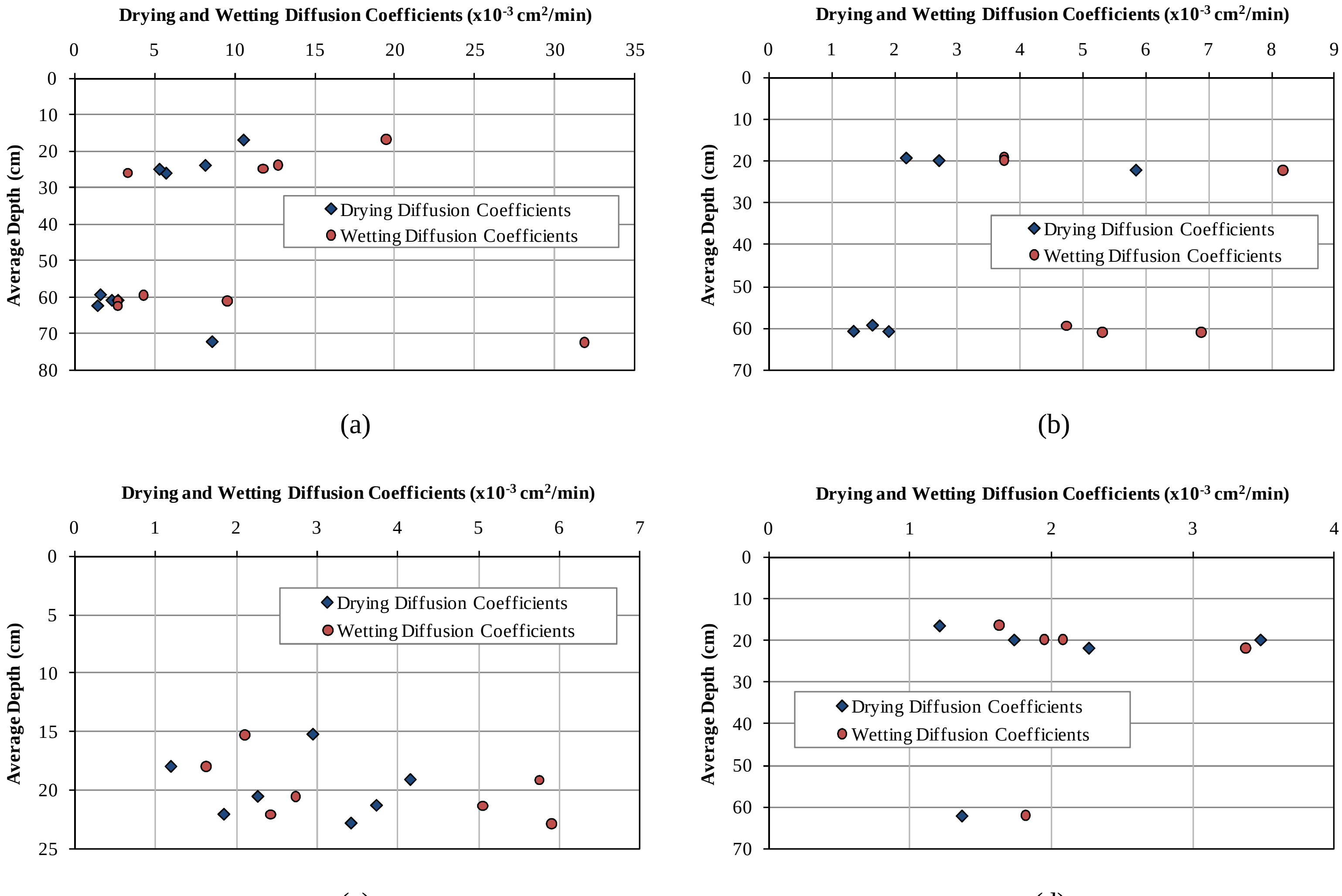
Sample No.	Depth (cm)	Testing Sequence	Drying Test			Wetting Test		Remarks on Soil Specimens
			^1u_a (pF)	$^2u_0$ (pF)	$^3\alpha_{dry}$ x 10^{-3} (cm^2/min)	$^2u_0$ (pF)	$^4\alpha_{wet}$ x 10^{-3} (cm^2/min)	
Site E								
E1	3.05-42.67	drying-wetting	6.30	3.46	3.4211	4.49	5.8947	Gravelly, stiff soil, visible tiny cracks on exposed end before testing, a few shrinkage cracks.
E2	0.00-44.20	drying-wetting	6.23	3.60	1.8421	4.53	2.4211	Gravelly, stiff soil, a few shrinkage cracks.
E3	0.00-42.67	drying-wetting	6.28	3.64	3.7368	4.45	5.0526	Gravelly, stiff soil, a few shrinkage cracks.
E4	0.00-38.25	drying-wetting	6.30	4.35	4.1579	4.52	5.7474	Gravelly, stiff soil, a few shrinkage cracks.
E5	0.00-35.99	drying-wetting	6.24	3.55	1.1842	4.42	1.6316	Gravelly, stiff soil, a few shrinkage cracks.
E6	0.00-30.48	drying-wetting	6.25	2.73	2.9474	4.46	2.1053	Gravelly, stiff soil, a few shrinkage cracks.
E7	1.52-39.62	drying-wetting	6.20	3.03	2.2632	4.37	2.7368	Gravelly soil, a few shrinkage cracks.

^1u_a = atmospheric suction; $^2u_0$ = initial suction; $^3\alpha_{dry}$ = drying diffusion coeffcient; and $^4\alpha wet$ = wetting diffusion coefficient.

Table 5.6. Drying and Wetting Diffusion Coefficients of Site F Soils.

Sample No.	**Depth (cm)**	**Testing Sequence**	**Drying Test**			**Wetting Test**		**Remarks on Soil Specimens**
			$^{1}u_a$ (pF)	$^{2}u_0$ (pF)	$^{3}\alpha_{dry} \times 10^{-3}$ (cm^2/min)	$^{2}u_0$ (pF)	$^{4}\alpha_{wet} \times 10^{-3}$ (cm^2/min)	
Site F								
F1	44.20-79.86	drying-wetting	6.27	3.48	1.3684	4.52	1.8158	Gravelly soil, a few shrinkage cracks.
F2	0.00-39.62	drying-wetting	6.23	3.43	1.7368	4.45	1.9474	Gravelly, stiff soil, no visible shrinkage cracks.
F3	0.00-39.62	drying-wetting	6.28	3.05	3.4737	4.54	2.0789	Gravelly, stiff soil, one relatively big shrinkage crack compared to other specimens.
F4	2.35-41.22	drying-wetting	6.32	2.95	2.2632	4.47	3.3684	Gravelly, stiff soil, a few shrinkage cracks.
F5	0.00-32.86	drying-wetting	6.25	3.42	1.2105	4.39	1.6316	Gravelly, stiff soil, a few shrinkage cracks.

$^{1}u_a$ = atmospheric suction; $^{2}u_0$ = initial suction; $^{3}\alpha_{dry}$ = drying diffusion coeffcient; and $^{4}\alpha$wet = wetting diffusion coefficient.



(a) (b)

(c) (d)

Figure 5.1. Diffusion Coefficients with Depth for (a) Site A, (b) Site B, (c) Site E, and (d) Site F.

Table 5.7. Soil Properties.

Sample No.	Depth (cm)	Atterberg Limits		% Passing No. 200 Seive	Sample No.	Depth (cm)	Atterberg Limits		% Passing No. 200 Seive
		Liquid Limt (%)	Plastic Limit (%)				Liquid Limt (%)	Plastic Limit (%)	
Site A					**Site D**				
A1	9.14-38.40	52.8	26.4	90.9	D1		59.1	25.7	91.7
A2	38.10-80.77	48.6	24.1	93.7	D2		57.7	27.0	92.7
A3	42.67-79.25	62.8	28.2	95.0	D3		48.4	23.5	89.7
A4	7.62-44.20	52.9	27.9	90.3	D4		52.5	23.8	90.1
A5	44.20-80.77	68.8	27.1	93.6	D5		49.8	22.1	90.2
A6	42.67-79.25	58.1	24.7	94.7	D6		54.2	22.3	90.5
A7	0.00-33.53	53.4	25.9	91.4	D7		50.3	21.1	91.0
A8	56.39-88.39	70.2	27.9	95.4	D8		55.5	21.8	89.4
A9	0.00-49.68	57.2	29.1	92.3	D9		47.7	20.9	92.2
Site B					**Site E**				
B1	0.00-38.40	57.4	27.1	83.0	E1	3.05-42.67	53.2	27.6	78.0
B2	0.00-44.20	50.3	27.7	79.1	E2	0.00-44.20	48.8	25.3	79.8
B3	0.00-39.62	53.9	29.1	85.9	E3	0.00-42.67	50.3	25.7	76.2
B4	39.62-82.30	45.6	22.7	86.4	E4	0.00-38.25	51.3	27.1	77.2
B5	39.62-82.30	51.7	27.5	86.9	E5	0.00-35.99	49.6	26.8	79.3
B6	38.10-80.77	46.9	26.1	93.1	E6	0.00-30.48	50.2	24.9	77.8
					E7	1.52-39.62	51.4	27.2	76.0
Site C					**Site F**				
C1		42.9	21.7	93.2	F1	44.20-79.86	34.9	19.3	70.5
C2		38.5	19.9	92.8	F2	0.00-39.62	48.4	24.9	70.0
C3		40.5	20.3	92.5	F3	0.00-39.62	44.8	22.5	76.6
C4		39.9	21.0	91.4	F4	2.35-41.22	36.5	18.6	71.2
					F5	0.00-32.86	42.8	22.5	69.8

5.1.1 Site A Soils

Nine Shelby tube soil specimens were tested. Six of those specimens followed the drying-wetting cycle, and three specimens followed the wetting-drying cycle. Site A soils were obtained from depths of 0.00 to 88.39 cm. The soils had liquid limits, plastic limits, and fine fraction ranging from 48.6-70.2%, 25.1-29.1%, and 90.3-95.4% respectively (see Table 5.7). The soils had initial total suctions ranging from 2.83 to 4.13 pF. The atmospheric suction in the testing room was relatively constant, ranging from 6.20 to 6.32 pF. The length of test samples varied from 11.2 to 19.5 cm depending on the length of soil column provided. Table 5.1 lists the drying and wetting coefficients for Site A soils and Figure 5.1a shows a plot of the diffusivity measurements with depth. The estimated diffusivity coefficients indicate the following:

- α_{wet} values are generally higher than α_{dry} values by a factor of about 1.1-3.7.
- The samples obtained from depths approximately above 45.20 cm have larger differences between α_{wet} and α_{dry} values than those obtained below 45.20 cm.
- Samples from depth above 45.20 cm generally have higher α values compared to those from depth below 45.20 cm.
- The difference between the diffusivity coefficients is larger for drying-wetting cycle than wetting-drying cycle.
- Sample A8 had a crack induced near the psychrometer, probably due to drilling, resulting in α_{wet} values much higher than the other values in this group.
- Generally, for the soil in this group, α_{dry} values were between 1.47-10.53 cm^2/min and α_{wet} values were between 2.70-19.47 cm^2/min.

5.1.2 Site B Soils

Six Shelby tube specimens were tested. Five of those specimens followed the drying-wetting cycle, and one specimen followed the wetting-drying cycle. Site B soils were obtained from depths of 0.00 to 82.30 cm. The soils had liquid limits, plastic limits, and fine fraction ranging from 45.6-57.4%, 22.7-29.1%, and 79.1-93.1% respectively (see Table 5.7). The soils had initial total suctions ranging from 3.09 to 3.97 pF. The atmospheric suction in the testing room was relatively constant, ranging from 6.20 to 6.36 pF. The length of test samples varied from 11.6 to 18.8 cm depending on the length of soil column provided. Table 5.2 lists the drying and wetting coefficients for Site B soils and Figure 5.1b shows a plot of the diffusivity measurements with depth. The estimated diffusivity coefficients indicate the following:

- α_{wet} values are generally larger than α_{dry} values by a factor of about 1.4-3.9.
- The differences between α_{wet} and α_{dry} values for samples obtained above approximately 39.62 cm depth appear to be smaller than for those samples obtained below 39.62 cm. This behavior is the opposite of what was observed in Soil A.

- Samples obtained above 39.62 cm depth appear to have larger α_{dry} values and smaller α_{wet} values compared to those obtained below 39.62 cm.
- B2 and B4 had several cracks along soil column before testing. These cracks may have contributed to the somewhat higher α_{wet} value compared to the other specimens.
- Generally, for the soils in this group, α_{dry} values were between 1.35-5.83 cm^2/min and α_{wet} values were between 3.75-6.87 cm^2/min.

5.1.3 Site C Soils

Four Shelby tube specimens were tested. All the soil specimens tested followed the drying-wetting cycle. Unfortunately information about the sample depth could not be obtained from ODOT. The soils had liquid limits, plastic limits, and fine fraction ranging from 38.5-42.9%, 19.9-21.7%, and 91.4-93.2% respectively (see Table 5.7). The soils had initial total suctions ranging from 3.38 to 3.79 pF. The atmospheric suction in the testing room was relatively constant, ranging from 6.28 to 6.29 pF. The length of test samples varied from 12.9 to 17.4 cm depending on the length of soil column provided. Table 5.3 lists the drying and wetting coefficients for Site C soils. The estimated diffusivity coefficients indicate the following:

- α_{wet} values are generally larger than α_{dry} values by a factor of about of 1.2-1.6.
- The α_{dry} and α_{wet} values are generally much bigger than those of the other soil samples. This soil was much softer, silty/sandy clay soil. It took the least time to run tests on Soil C.
- Generally, for the soils in this group, α_{dry} values were between 5.53-13.21 cm^2/min and α_{wet} values were between 7.63-15.26 cm^2/min.

5.1.4 Site D Soils

Nine Shelby tube specimens were tested. All the soil specimens tested followed the drying-wetting cycle. Unfortunately information about the sample depth could not be obtained from ODOT. The soils had liquid limits, plastic limits, and fine fraction ranging from 47.7-59.1%, 20.9-27.0%, and 89.4-92.7% respectively (see Table 5.7). The samples had initial total suctions ranging from 2.12 to 3.45 pF. The atmospheric suction in the testing room was relatively constant, ranging from 6.23 to 6.25 pF. The length of test samples varied from 15.5 to 20.7 cm depending on the length of soil column provided. Table 5.4 lists the drying and wetting coefficients for Site D soils. The estimated diffusivity coefficients indicate the following:

- α_{wet} values are generally larger than α_{dry} values by a factor of about of 0.8-2.3.
- The α_{dry} and α_{wet} values are generally much smaller than those of the other soil samples. This soil was generally wet, stiff clay. It took the most time to run tests on Soil D.
- The differences between α_{wet} and α_{dry} values are significantly smaller for Soil D than the other soil specimens. Soil D is much stiffer clay compared to the other five soils tested.
- Generally, for the soils in this group, α_{dry} values were between 0.63-1.28 cm^2/min and α_{wet} values were between 0.95-1.93 cm^2/min.

5.1.5 Site E Soils

Seven Shelby tube specimens were tested. All the soil specimens tested followed the drying-wetting cycle. Site E soils were obtained from depths of 0.00 to 45.20 cm. The soils had liquid limits, plastic limits, and fine fraction ranging from 48.8-53.2%, 24.9-27.6%, and 76.0-79.8% respectively (see Table 5.7). The samples had initial total suctions ranging from 2.73 to 5.35 pF. The atmospheric suction in the testing room was relatively constant, ranging from 6.20 to 6.30 pF. The length of test samples varied from 16.8 to 19.9 cm depending on the length of soil column provided. Table 5.5 lists the drying and wetting coefficients for Site E soils and Figure 5.1c shows a plot of the diffusivity measurements with depth. The estimated diffusivity coefficients indicate the following:

- α_{wet} values are generally larger than α_{dry} values by a factor of about 0.7-2.3.
- Generally, for the soils in this group, α_{dry} values were between 1.18-5.16 cm^2/min and α_{wet} values were between 1.63-5.89 cm^2/min.

5.1.6 Site F Soils

Five Shelby tube specimens were tested. All the soil specimens tested followed the drying-wetting cycle. Site E soils were obtained from depths of 0.00 to 79.86 cm. The soils had liquid limits, plastic limits, and fine fraction ranging from 34.9-48.4%, 18.6-22.5%, and 69.8-76.6% respectively (see Table 5.7). The samples had initial total suctions ranging from 2.95 to 3.48 pF. The atmospheric suction in the testing room was relatively constant, ranging from 6.23 to 6.32 pF. The length of test samples varied from 16.2 to 19.8 cm depending on the length of soil column provided. Table 5.6 lists the drying and wetting coefficients for Site F soils and Figure 5.1d shows a plot of the diffusivity measurements with depth. The estimated diffusivity coefficients indicate the following:

- α_{wet} values are generally larger than α_{dry} values by a factor of 0.6-1.5.
- Generally, for the soils in this group, α_{dry} values were between 1.21-3.47 cm^2/min and α_{wet} values were between 1.63-3.37 cm^2/min.

5.2 Comparison of Diffusion Results from Various Sources

The diffusivity parameters using Mitchell's approach obtained in this research study have been summarized in Table 5.8. In this section, the values in Table 5.8 will be compared to those from previous research studies shown in Table 5.9. As noted in Section 1.1, the diffusivity models (Table 5.9) based on the pressure plate method yield only drying diffusivity values and those based on the horizontal infiltration method yield only wetting diffusivity values. In addition, previous studies based on Mitchell's approach only dealt with the drying diffusivity coefficients. Comparison of diffusivity values in Table 5.8 and 5.9 indicates the following:

- Aubeny et al. (2005) drying diffusion parameters, together with those obtained by Richards (1965) using Gardner, Rijtema and Richards methods, performed on clay soils are on the lower end of those in Table 5.8 and compare well with those of site D.
- The drying diffusivity parameters for all soils tested in this research are within the range obtained by Bulut et al. (2005).

- The drying and wetting diffusivity values (Table 5.9) obtained using the pressure plate for Bruce and Klute (1963), Klute et al. (1964), and Davidson et al. (1966) and the horizontal infiltration methods are generally not within the range of the values obtained in this research using Mitchell's approach. This is mainly because (i) this research employed clay soils while the other investigators used sand, silt, and/or loam soils; and (ii) the diffusivity tests were conducted at different suction ranges. In general, diffusivity values (both drying and wetting) of coarse-grained soils are much larger than those of fine-grained soils.

It can be noted that for clay soils, the drying diffusivity values obtained in this research are generally close and on the lower end to those obtained using the pressure plate method given in Table 5.9. Therefore, it can be concluded that the diffusivity coefficients obtained in this research using Mitchell's approach method are in reasonable agreement with those of clay soils in the literature. This implies that Mitchell's approach to moisture diffusivity provides a repeatable framework for determining the drying and wetting diffusivity parameters in the laboratory.

Table 5.8. Summary of Diffusion Test Results.

SOIL	**Average Diffusivity Values**	
	Drying Test $x10^{-3}$ (cm^2/min)	**Wetting Test $x10^{-3}$ (cm^2/min)**
A	5.1684	10.9339
B	2.6035	5.4325
C	8.7632	11.6501
D	1.0061	1.365
E	2.7932	3.6556
F	2.0105	2.1684

5.3 Moisture Movement in Unsaturated Soils

As noted in section 3.3.7, one practical application of the moisture diffusion properties relates to predicting the depth of the moisture active zone and the magnitude of suction variations within a soil profile. In other words, the diffusivity parameters can be used to predict the depth to which soil suction variations do not occur due to the effects

Table 5.9. Diffusion Results from Various Sources.

Author/Model	**Diffusivity Values (x10^{-3} cm^{2}/min)**	**Suction Range Studied (pF)**	**Remarks**
	[a]Pressure Plate Method		
*Bruce and Klute (1963)	600-6,000	1.0-2.2	50-250μ sand
	300-12,000		75μ glass beads
	1,200-30,000		Mason county fine sand
*Klute et al. (1964)	2-347	1.3-3.2	Hayden sandy loam
*Davidson et al. (1966)	10-10000	1.6-2.0	Oaklay sand
*Doering (1965)	8.7-174	0-3	Loam
	17.4-219.6		Clay
	1.55-43.8		Clay loam
[¤]Gardner (1956)	0.20-3.55	0-3	Syndal clay
	0.31-0.76	3-3.3	Horsham clay
[¤]Rijtema (1959)	0.61-3.97	0-2.9	Syndal clay
	0.37-1.76	3-3.2	Horsham clay
Richards (1965)	0.16-3.35	0-3	Syndal clay
	0.35-0.86	3-3.3	Horsham clay
*Passioura (1976)	6-189.7	0-2.6	Clay loam
	0.6-60		Non-swelling clay
	[b]Horizontal Infiltration Method		
*Bruce and Klute (1956)	60-600,000	-	75μ glass beads
	600-600,000	-	50-250μ sand
	60-60,000	-	Mason county fine sand
*Clothier et al. (1983)	6-60,000	-	Manawatu fine sandy loam
*McBride and Horton (1985)	0.6-6,000	-	Nicollet sandy clay loam
Wang et al. (2004)	145,000-175,000	-	Yuling sand
	5,510-6,050	-	Shuide loam
	4,160-4,500	-	Xian silt loam
	[a]Mitchell's Method		
Aubeny and Lytton (2004)	0.040-0.147	3-5	Waco clays
Bulut et al. (2005)	0.0636-8.22	3-5	Fort Worth clays
	0.738-7.86		Atlanta clays
	1.09-6.42		Austin clays
Aubeny et al. (2005)	0.553-1.73	3-5	Fort Worth clays

[a]drying diffusivity values, [b]wetting diffusivity values, [¤]values from Richards (1965), and *diffusivity values estimated from plotted graphs

of seasonal moisture changes. The diffusivity values obtained in this research study were employed to predict the depths to constant suction and the results are shown in Table 5.10. The α_{dry} and α_{wet} parameters will generate the maximum and minimum suction envelopes, respectively as shown in Appendix E.

In this analysis, the surface suction was varied between 2.5 and 5 pF. This represents the minimum and maximum suction values, respectively. Two annual weather cycles with frequency f = 1 and f = 2 cycles per year were considered. The depth to constant suction was defined by the point where the difference between the predicted suction value and its corresponding equilibrium suction value was less than 0.01 pF. Overall the following main points are drawn from this analysis:

- The depths to constant suction obtained using α_{wet} values are greater than those obtained using α_{dry} values by a factor of about 1.0 to 1.5.
- The maximum depth to constant suction is obtained when α_{wet} values are used.
- The depths obtained for f = 1 are greater than those obtained for f = 2 by a factor of about 1.4 for both α_{dry} and α_{wet} values.

Table 5.10. Depths to Constant Suction.

Site	**Frequency**	**Dry Envelope**		**Wet Envelope**	
	(cycles/yr)	***α_{dry} x 10^{-3} (cm^2/min)**	**$^{a}z_{cd}$ (cm)**	***α_{wet} x 10^{-3} (cm^2/min)**	**$^{a}z_{cw}$ (cm)**
A	1	5.1684	141	10.9339	209
	2		100		148
B	1	2.6035	100	5.4325	147
	2		71		104
C	1	8.7632	184	11.6501	215
	2		130		152
D	1	1.0061	63	1.365	74
	2		44		53
E	1	2.7932	104	3.6556	121
	2		74		86
F	1	2.0105	88	2.1684	93
	2		63		66

[a] depth to constant suction for drying profile, z_{cd} and wetting profile, z_{cw}

*average diffusivity values for the sites

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The drying and wetting diffusivity coefficients can be determined in the laboratory using total suction measurements with time obtained from thermocouple psychrometers embedded in Shelby tube soil specimens. Mitchell's (1979) approach of describing the rate of moisture flow through a soil in terms of a single diffusivity parameter provided a simple, economical and reliable framework for determining the wetting and drying diffusivity parameters on a routine basis in a geotechnical laboratory.

The water bath built at Oklahoma State University can be used to run multiple tests for measuring both drying and wetting diffusion parameters at the same time under a controlled temperature environment. This provides a strong tool to study the hysteresis between the drying and wetting process in a soil profile. The unified drying and wetting testing protocol proposed in this study provides a very simple and relatively rapid framework for experimental measurement of diffusion properties on an economical and routine basis.

The following can be concluded from the search study:

- For most soil specimens tested, α_{wet} values are generally higher than α_{dry} values by a factor of about 1 to 2.
- Hard/stiff clay soils (i.e., site D soils) tend to have smaller diffusivity values than silty/ sandy clay soils (i.e., site C soils).
- Soils with significant amount of cracks have much larger α_{wet} values than those with few cracks.
- It has been noted that cracks in the soil and vegetative influence such as root fibers, lead to the wetting diffusion parameters being much greater than the drying diffusion parameters.

- Soil specimens from deeper ground depths tend to have smaller hysteresis effect between drying and wetting parameters than the soils obtained from shallower depths.

6.2 Recommendations for Future Research

- In this research, one drying-wetting or wetting-drying cycle was considered to determine the drying and wetting unsaturated diffusivity parameters. Further study is required into the drying and wetting diffusivity processes and hysteresis effects from multiple cycles on the same soil specimen.
- Thermocouple psychrometer can reliably measure soil suction values between approximately 3 and 5 pF. The entire pF scale ranges from 1 to 7. Thus the suction range of 1 to 3 pF and 5 to 7 pF were not considered in this study due to psychrometer measurement limitations. More research is required to determine the drying and wetting diffusivity properties and hysteresis effects of unsaturated soils with suction values ranging from 1 to 3 pF and 5 to 7 pF using Mitchell's approach. This will present diffusivity coefficients for the entire pF scale.

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APPENDIX A

CALIBRATION OF THERMOCOUPLE PSYCHROMETERS

Thermocouple psychrometers were employed to monitor changes in total suction over time as moisture evaporates from or a liquid enters into a soil specimen through its open end. The psychrometers were calibrated at 25±0.1 ^{o}C using different concentrations of sodium chloride (NaCl) solutions with known water potential for a suitable psychrometer range of suction measurements, typically 3 to 5 pF osmotic suction. The solute solutions were prepared and used shortly after preparation. The new water bath developed at Oklahoma State University was employed to provide a constant temperature environment. The psychrometer microvolt outputs and corresponding suction values were plotted to obtain a calibration curve for each psychrometer.

A.1 Calibration Apparatus

The following apparatus is required for thermocouple psychrometer calibration:

- Stainless steel wire-shield thermocouple psychrometers from Wescor Inc.
- Sodium Chloride (NaCl) salt.
- Balance with at least 0.0001 g accuracy.
- Distilled/deionized water to make salt solutions.
- Measuring cylinder to determine amount of distilled water required.
- Plastic bottles to store the salt solutions.
- Glass jars to calibrate a number of psychrometers at one time.
- Measuring plastic bowls, spatulas, rubber stoppers with lengthwise hole, silicon sealant, and electrical tape.
- CR7 datalogger from Wescor/Campbell.
- Water bath with cylindrical tubes to hold specimen and temperature control unit.
- Temperature controlled room.

A.2 Preparation of Salt Solutions

The salt solutions were prepared as follows:

1. Use Table A1 to determine the amount of NaCl salt to be used depending upon the suction value and quantity of solution (in liters) required.
2. Weigh the salt on the balance. Seal the bottle containing the salt shortly after use to prevent the salt from forming clumps if exposed to the atmosphere.
3. Pour the salt and required amount of distilled/deionized water in a plastic bottle.
4. Seal the plastic bottle with electrical tape and shake vigorously to dissolve the salt.
5. Repeat steps 1 to 4 for all salt concentrations.

Table A1. Osmotic Suctions for NaCl (Bulut et al. 2001).

Molality of NaCl (m)	**Osmotic Suction (bar)**	**Osmotic Suction (kPa)**	**Osmotic Suction (log kPa)**	**Osmotic Suction (pF)**	**Amount of NaCl (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	18.2658	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	6627.9768	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	3.9398	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

A.3 Thermocouple Psychrometer Calibration Procedure

The psychrometers are calibrated as follows:

1. Make holes, depending on the size of the rubber stoppers, in the lid of a glass jar to be used in calibration process.
2. Place each psychrometer wire in the lengthwise hole of a rubber stopper and tightly fit them into holes made in the lid while providing sufficient length of wire that will enable all the psychrometer tips to be wholly suspended in the salt solution in the glass jar during calibration.
3. Put silicon sealant on the contact areas between the psychrometers and stoppers as well as contact area between the rubber stoppers and lids to prevent loss or gain of moisture during calibration. Allow sealant to dry for at least half an hour.
4. Pour prepared salt solution into glass jar enough to immerse the psychrometer tips into the solution. Place the lid with psychrometers onto the glass jar and seal it with electrical tape to prevent loss or gain of moisture (Figure A1).

Figure A1. Thermocouple Psychrometer Calibration Setup.

5. Place the glass jar in one of the water bath cylindrical tubes (Figure A2) and maintain the water bath at constant temperature of 25±0.1 ^{o}C using temperature control unit. Leave the setup for an hour for thermal and vapor equilibrium of the psychrometers.
6. Connect psychrometers to the CR7 datalogger to collect total suction readings obtained by the psychrometers for at least an hour.
7. After calibration, clean the psychrometers by vigorously rinsing them in distilled/deionized water and allow them to air dry for at least one hour.

8. Repeat steps 4 to 7 for salt solutions with different suction values for all the psychrometers.
9. For each psychrometer, plot the equilibrium microvolt values obtained from the psychrometers against their corresponding suction values for all the different salt solutions. A typical calibration curve obtained from this process is shown in Figure A3.

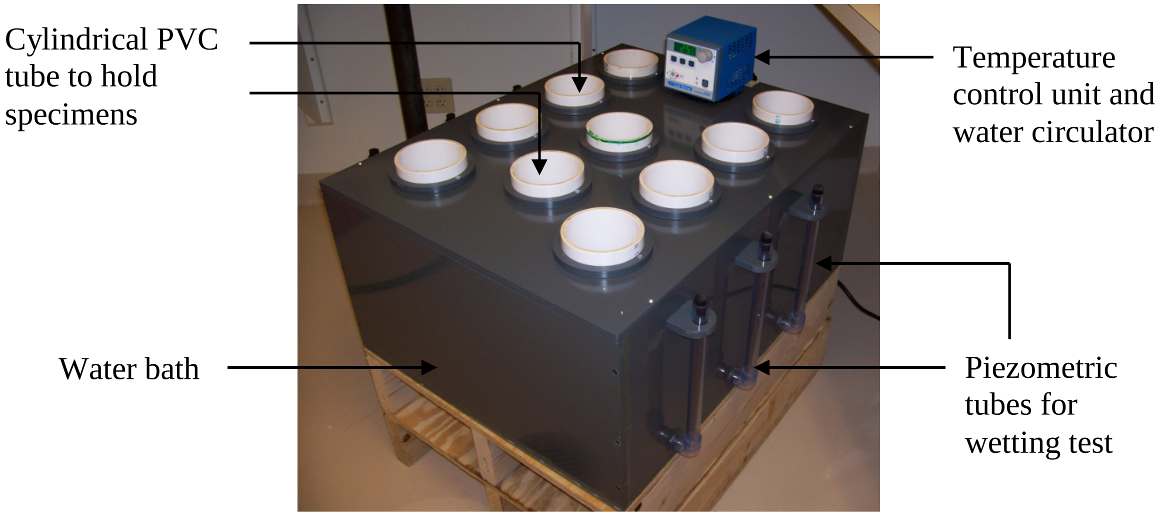


Figure A2. Water Bath used for Temperature Control.

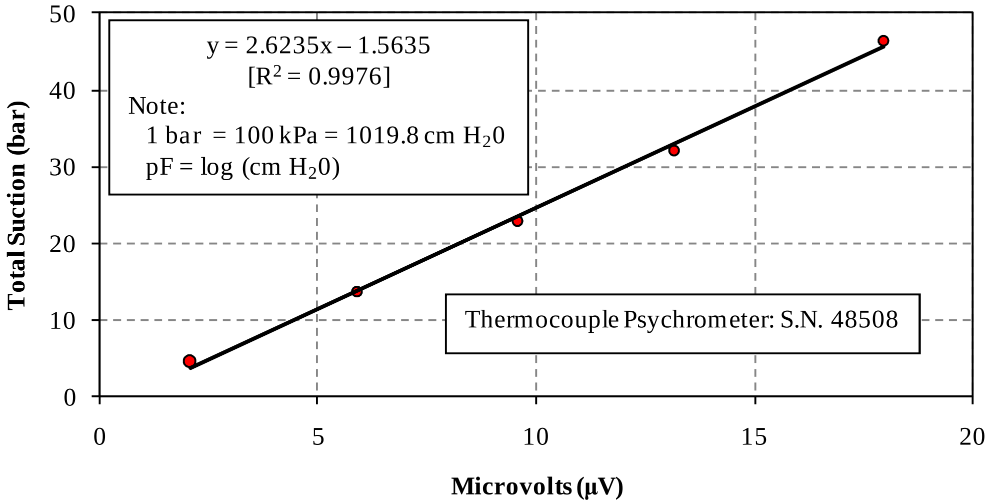


Figure A3. Typical Thermocouple Psychrometer Calibration Plot.

APPENDIX B
LABORATORY DETERMINATION OF SOIL DIFFUSION COEFFICIENTS

The diffusion coefficient controls the rate of infiltration of moisture into a soil mass. The drying and wetting unsaturated soil diffusion coefficients can be determined by measuring total suction with time using calibrated thermocouple psychrometers embedded in a Shelby tube specimen. The drying and wetting diffusivity test was originally proposed by Mitchell (1979). Improvements were made to the drying test by Lytton et al. (2004) and Bulut el al. (2005). This research makes improvements to the wetting test and proposes a unified testing protocol that allows drying and wetting tests to be performed in cycles and on the same soil specimen.

B.1 Diffusion Test Apparatus

The following apparatus are required to perform total suction measurements using thermocouple psychrometers:

- Stainless steel wire-shield thermocouple psychrometers from Wescor Inc.
- Drill-bit to drill holes into the soil specimen.
- Measuring ruler, plastic wrap, aluminum foil, and scissors.
- CR7 datalogger from Wescor/Campbell.
- Water bath with cylindrical tubes to hold specimen and temperature control unit.
- Temperature controlled room.
- Dehumidifier to control the relative humidity.

B.2 Sample Preparation for Diffusion Test

The sample preparation is outlined as follows:

1. Select a soil specimen of about 20 cm long and trim the ends to provide a planar surface. Record the length (L) of the specimen.

2. Choose which end of the specimen will be the open boundary and mark psychrometer positions relative to the open end along the lateral side of the specimen. Mark the first psychrometer position about 5 cm from the exposed side and provide 2 to 4 cm spacing between psychrometers. The first psychrometer position and psychrometer spacing may be changed depending on the soil type, soil moisture condition, and/or method of making psychrometer holes in the specimens.
3. Use a drill-bit to make holes for psychrometer installation and extend the depth of the holes to approximately halfway the diameter of the soil specimen. The diameter of the holes should be large enough for psychrometers to fit precisely.
4. Insert calibrated psychrometers into the holes and tightly seal the holes on the surface of the specimen with small pieces of soil cuttings obtained from the specimen in step 1 to prevent loss or gain of moisture. Record the psychrometer number and distance from the closed end (*x*) for each psychrometer.
5. Seal the whole specimen; except the one end that will be exposed to the atmosphere and liquid of known suction, with plastic wrap and aluminum foil to prevent loss or gain of moisture (Figure B1).
6. Repeat steps 1 to 5 for each soil specimen.

Figure B1. Preparation for Diffusion Test (Mabirizi and Bulut 2010).

B.3 Drying and Wetting Diffusion Coefficients Measurements

The drying and wetting diffusivity tests are performed immediately after the sample is prepared. The drying test may be performed first followed by the wetting test (i.e., in drying-wetting cycles) or the wetting test may be performed first followed by the drying test (i.e., in wetting-drying cycles). The diffusivity tests are performed in a temperature and humidity controlled environment.

To perform drying-wetting cycles do the following:

1. Place the sealed specimen in one of the water bath tubes without piezometric fittings with its open boundary exposed to the atmosphere to perform the drying test (Figure B2). Maintain the water bath and testing room at 25±0.1 ^{o}C throughout the testing period. Use a dehumidifier to control the relative humidity in the room when necessary.
2. Connect psychrometers to the datalogger and collect total suction values with time until the drying process is completed.
3. At the end of the drying test, immediately place the specimen in one of the water bath tubes with piezometric tubing with its open end facing down to make contact with the constant distilled/deionized water front to perform the wetting test (Figure B2). Provide a thin layer of cloth between the soil specimen and porous disk too ensure that the entire soil surface is in contact with the water front during the wetting process. Use the piezometric tubing system to provide a constant water level. Keep the water bath and testing room at 25±0.1 ^{o}C throughout the testing period.
4. Continue to collect total suction values with time until wetting test is completed.
5. At the end of the wetting test, a drying-wetting cycle will be competed. Remove the water left in the cylindrical tube after a wetting cycle is complete. Thoroughly clean the tube before adding fresh distilled/deionized water for the next wetting test. This will ensure that the water used in the wetting test is not contaminated with the soil water from the previous test.
6. Repeat steps 1 to 5 for each soil specimen and for any number of cycles.

To perform the wetting-drying cycles do the following:

1. Place the sealed specimen in one of the water bath tubes with piezometric tubing with its open end facing down to make contact with the constant distilled/deionized water front to perform the wetting test (Figure B2). Provide a thin layer of cloth between the soil specimen and porous disk too ensure that the

entire soil surface is in contact with the water front during the wetting process. Use the piezometric tubing system to provide a constant water level. Keep the water bath and testing room at 25±0.1 ^{o}C throughout the testing period.

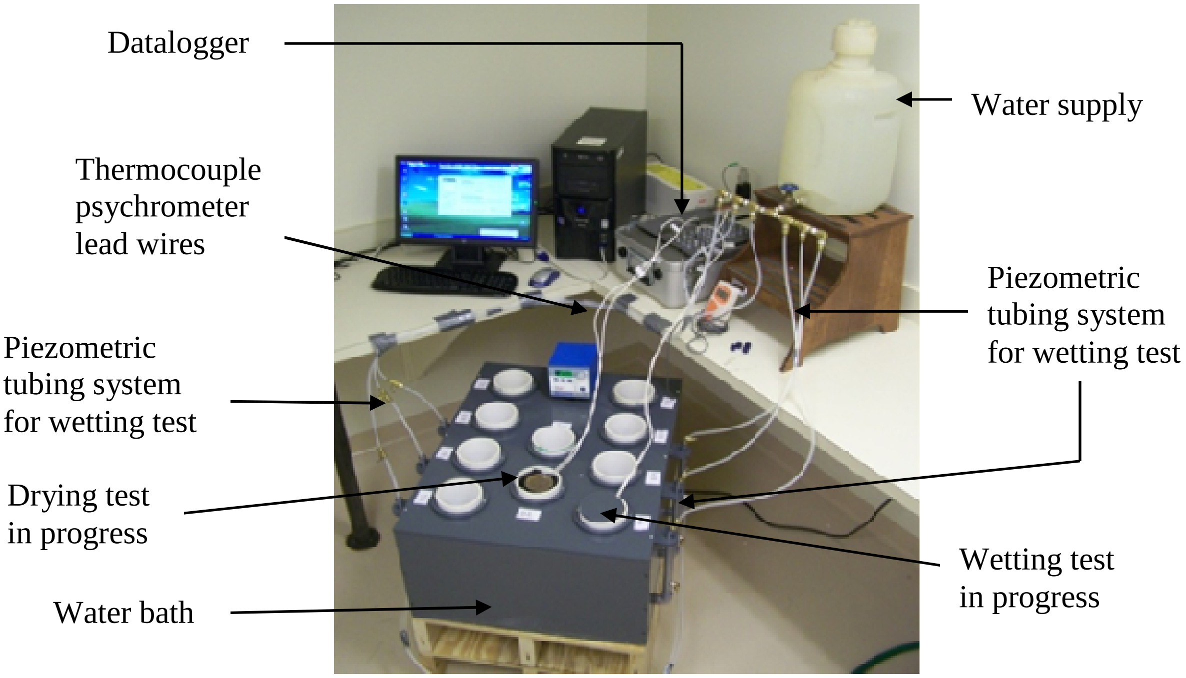


Figure B2. Evaporation and Soaking Diffusion Test Setup.

2. Connect psychrometers to the datalogger and collect total suction values with time until the wetting test is completed.
3. At the end of the wetting process, immediately place the specimen in one of the water bath tubes without piezometric fittings with its open boundary exposed to the atmosphere to perform the drying test (Figure B2). Maintain the water bath and testing room at 25±0.1 ^{o}C throughout the testing period. Use a dehumidifier to control the relative humidity in the room when necessary.
4. Continue to collect total suction values with time until drying test is completed.
5. Remove the water left in the cylindrical tube after a wetting cycle is complete. Thoroughly clean the tube before adding fresh distilled/deionized water for the next wetting test. This will ensure that the water used in the wetting test is not contaminated with the soil water from the previous test.

6. At the end of the drying test, a wetting-drying cycle will be competed. Repeat steps 1 to 5 for each soil specimen and for any number of cycles.

With this testing approach, cycles of drying-wetting or wetting-drying can be performed numerous times on different soil specimens at the same time to study the hysteresis between the evaporation and soaking process.

APPENDIX C

TOTAL SUCTION MEASUREMENT USING FILTER PAPERS

The noncontact filter paper method was used to validate initial psychrometer measurements in order to determine the initial total suction of the soil sample. The laboratory procedure proposed by Bulut et al. (2001) was adopted in this research for total suction measurements using Schleicher & Schuell No. 589 – White Hard (WH) filter papers discs.

C.1 Filter Paper Total Suction Measurement Apparatus

The following apparatus are required to perform a filter paper total suction test:

- Schleicher & Schuell No. 589 – White Hard (WH) filter papers.
- Glass jars to perform total suction filter paper test.
- Oven at 110±5 ^{o}C to dry the filter paper.
- Balance with at least 0.0001 g accuracy.
- Aluminum moisture tins, ring-type supports, tweezers, latex gloves, electrical tape, aluminum block, ice chest, knife, and spatula.
- Constant temperature room.

C.2 Procedure for Initial Total Suction Measurement

Procedure for determining total suction using filter papers is as follows:

1. Cut a portion of Shelby tube soil specimen to fill about two-thirds of the glass jar (Figure C1).
2. Insert the sample in a glass jar and place some soil cuttings from step 1 in the sides of the jar to ensure that the sample does not move in the glass jar.
3. Place a clean ring-type support on top of the soil specimen to provide a noncontact space between the filter paper and the soil. The diameter of the ring is

smaller than that of the filter paper while its height leaves sufficient room for filter papers inside the jar. Ensure that filter papers do not make contact with the glass lid or soil specimen.

4. Place two filter papers, one on top of the other on the ring-type support using tweezers. Make sure the filter papers do not make contact with soil or the glass jar (Figure C1).
5. Place the lid and seal tightly with electrical tape. This helps prevent any loss or gain of moisture that might occur.
6. Carry the glass jar to the ice chest which is in a temperature controlled room for equilibration to occur.
7. Repeat steps 1 to 6 for each soil specimen.

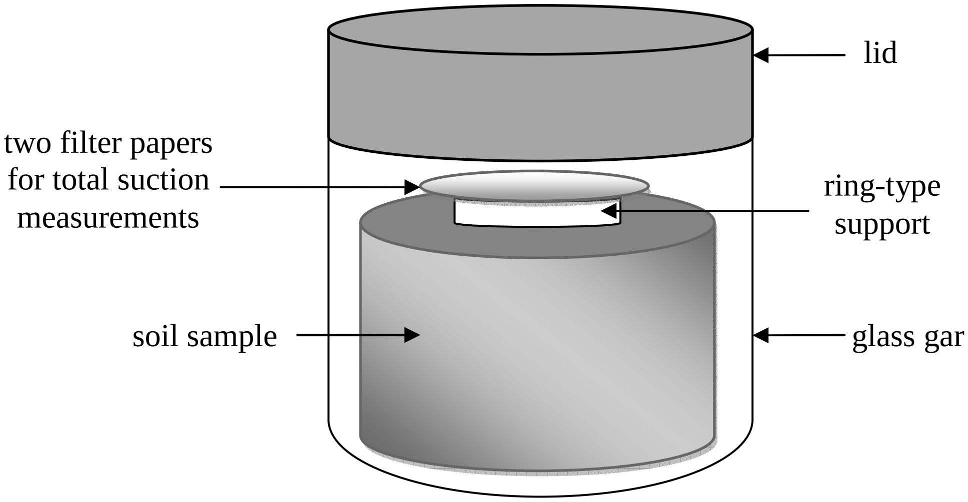


Figure C1. Total Suction Measurements using Filter Papers.

Equilibration period of 7 days was adopted in this study. At equilibrium, the suction of the soil and filter papers will be the same. After equilibration, the wet filter papers are measured to determine their water content as follows:

8. Wear latex gloves before touching any filter paper apparatus.
9. From a temperature controlled room, determine the number of cans to be used for water content measurements. For each tin, record (in Table C1) the cold tare mass (*Tc*) and corresponding moisture tin number.
10. Pick one glass jar from the ice chest in the temperature controlled room.

11. Open the glass jar and use tweezers to place the filter papers into separate moisture tins and close the lids. This process should take not more than a few seconds.
12. Immediately place each can onto the balance and quickly record (in Table C1) the mass of cold tare can plus wet filter paper ($M1$). Record whether it is a top or bottom filter paper.
13. Make a record of all the information pertaining to the soil specimen such as boring number, sample number, sample depth in the worksheet.
14. Repeat steps 10 to 13 for every glass jar.
15. Place all the tare cans inside the oven with their lids half open to allow thermal evaporation. Keep oven temperature at 110±5 °C and allow filter papers to dry for at least 10 hours.

Perform measurements of the dry filter papers as follows:

1. Wear latex gloves before touching any filter paper apparatus.
2. Close the cans with their lids while still in the oven and allow equilibration to occur for about 5 minutes.
3. Pick one can from the oven and place it on an aluminum block for about 20 seconds to cool down.
4. Immediately place the can on the balance and record the mass of hot tare plus dry filter paper ($M2$) in Table C1.
5. Take the filter paper out of the tare can and immediately record the hot tare can mass (Th) in Table C1.
6. Repeat steps 18 to 20 for all the hot tare cans in the oven.

Complete Table C1 by determining the water content of each filter paper using the following calculations:

Mass of dry filter paper, $Mf = M2 - Th$

Mass of water in filter paper, $Mw = M1 - M2 - Tc + Th$

Water content of filter paper, $W_f = Mw / Mf$

Soil suction calculations are performed on every filter paper to obtain the total suction values using the wetting calibration curve (Figure C2) as follows:

Total Suction (log kPa), $h_1 = -8.247W_f + 5.4246$ ($h_1 >$ 1.5 log kPa)

Total Suction (pF), $h_2 = -8.247W_f + 6.4246$ ($h_2 > 2.5$ pF)

Report the total suction values to the nearest two decimal places in log kPa or pF.

Table C1. Worksheet for Filter Paper Suction Measurements.

FILTER PAPER METHOD SUCTION MASUREMENTS WORKSHEET																			
Tested by:																			
Date Tested:																			
Date Sampled:																			
Borimg No.																			
Sample No.																			
Depth																			
Moisture Tin No.																			
Total or Matric Suction (circle)		Total	Matric	Total	Matric	Total	Matric	Total	Matric	Total	Matric	Total	Matric	Total	Matric	Total	Matric	Total	Matric
Top or Bottom Filter Paper (circle)		Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott	Top	Bott
Cold Tare Mass, g	Tc																		
Mass of Wet Filter Paper + Cold Tare Mass, g	M1																		
Mass of Dry Filter Paper + Hot Tare Mass, g	M2																		
Hot Tare Mass, g	Th																		
Mass of Dry Filter Paper, g (M2-Th)	Mf																		
Mass of Water in Filter Paper, (M1-M2-Tc+Th)	Mw																		
Water Content of Filter Paper, (Mw / Mf)	W_f																		
Suction, log kPa (Bulut et al., 2001)	h_1																		
Suction, pF (Bulut et al., 2001)	h_2																		
Average Suction																			

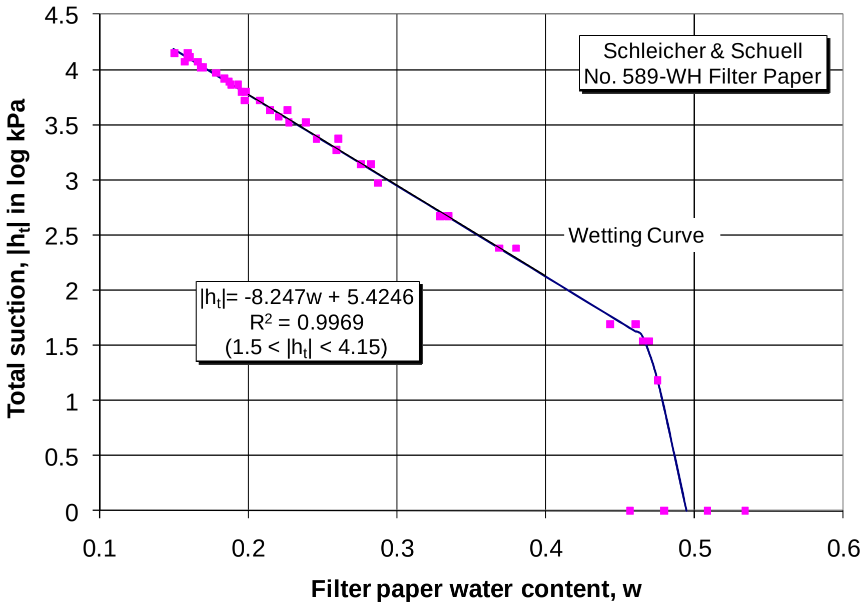


Figure C2. Filter Paper Wetting Calibration Curve (Bulut et al. 2001).

APPENDIX D

DIFFUSION COEFFICIENT VALUES AND CURVES

Specimen No.: **SOIL A1**

Drying Test

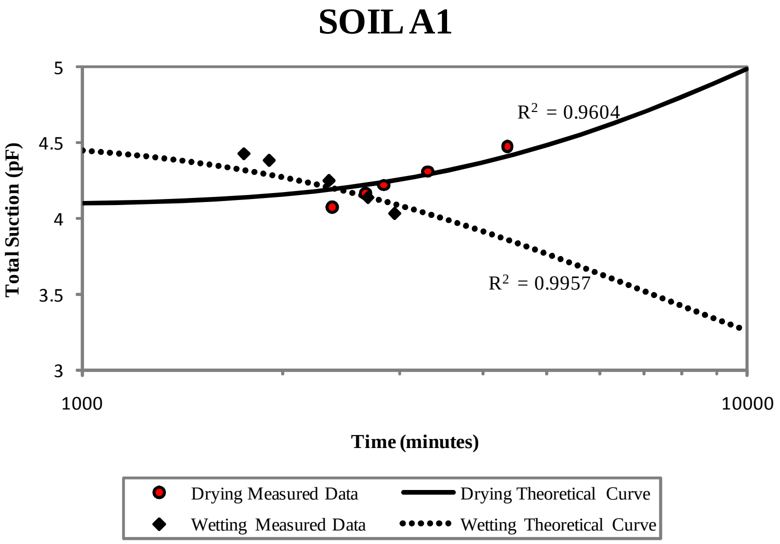
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.21 pF	
Initial Suction:	4.09 pF	
Psychrometer Location:	4.0 cm	
Sample Length:	15.0 cm	
Suction Measurements:	Time (min)	Suction (pF)
	2380	4.074
	2670	4.164
	2840	4.220
	3310	4.309
	4360	4.474

Drying Diffusion Coefficient: **8.16x10^{-3} cm^{2}/min**

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.50 pF	
Psychrometer Location:	4.0 cm	
Sample Length:	15.0 cm	
Suction Measurements:	Time (min)	Suction (pF)
	1750	4.430
	1910	4.387
	2350	4.253
	2690	4.142
	2950	4.037

Wetting Diffusion Coefficient: **12.72x10^{-3} cm^{2}/min**



Specimen No.: **SOIL A2**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.21 pF
Initial Suction:	4.09 pF
Psychrometer Location:	8.0 cm
Sample Length:	15.0 cm

Suction Measurements:

Time (min)	Suction (pF)
3140	3.905
4290	4.081
4770	4.162
5680	4.269
6250	4.333

Drying Diffusion Coefficient: **1.65×10^{-3} cm^2/min**

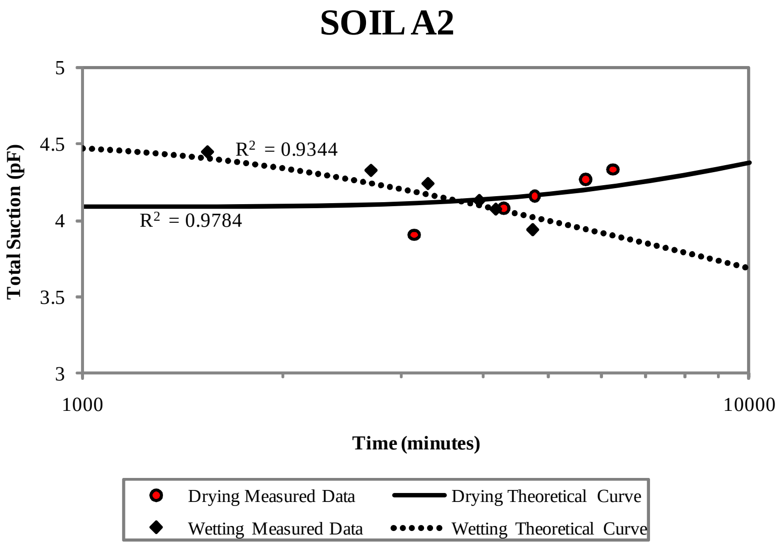
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.50 pF
Psychrometer Location:	8.0 cm
Sample Length:	15.0 cm

Suction Measurements:

Time (min)	Suction (pF)
1540	4.448
2710	4.327
3300	4.240
3940	4.130
4170	4.074
4740	3.939

Wetting Diffusion Coefficient: **4.32×10^{-3} cm^2/min**



Specimen No.: **SOIL A3**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.22 pF
Initial Suction: 4.09 pF
Psychrometer Location: 13.9 cm
Sample Length: 18.9 cm
Suction Measurements:

Time (min)	Suction (pF)
2500	3.954
2610	4.079
3110	4.368
3370	4.456
3790	4.579
4200	4.678

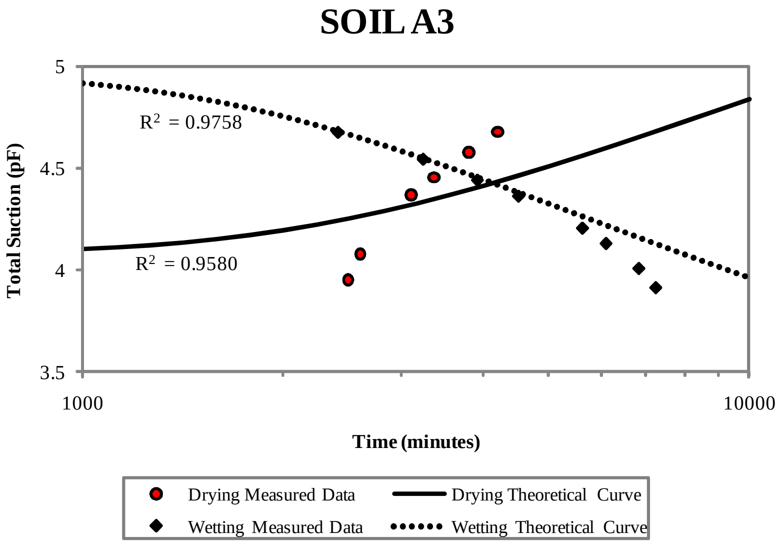
Drying Diffusion Coefficient: **2.36x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.95 pF
Psychrometer Location: 13.9 cm
Sample Length: 18.9 cm
Suction Measurements:

Time (min)	Suction (pF)
2410	4.676
3240	4.544
3910	4.441
4510	4.362
5630	4.205
6110	4.130
6850	4.007
7260	3.913

Wetting Diffusion Coefficient: **2.71x10^{-3} cm^2/min**



Specimen No.: **SOIL A4**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.23 pF
Initial Suction: 4.13 pF
Psychrometer Location: 13.4 cm
Sample Length: 18.4 cm
Suction Measurements:

Time (min)	Suction (pF)
1810	4.395
2040	4.484
2370	4.581
2910	4.694

Drying Diffusion Coefficient: **$5.72\text{x}10^{-3}\ \text{cm}^2\text{/min}$**

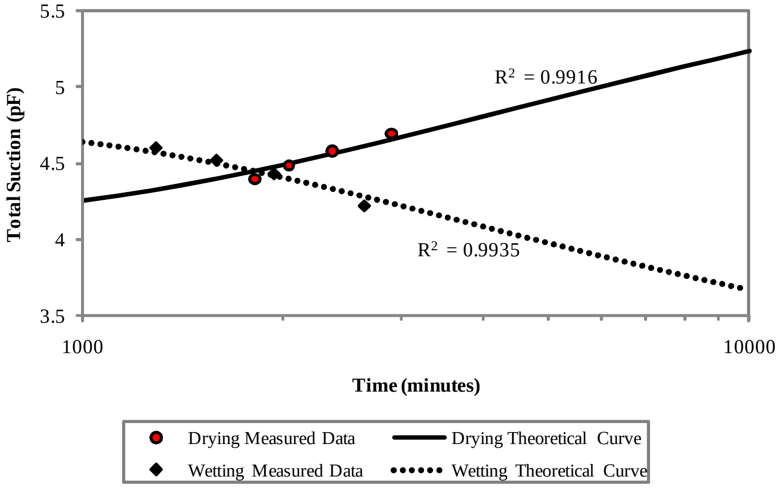
Wetting Test

Soaking Suction: 4.75 pF
Initial Suction: 4.74 pF
Psychrometer Location: 13.4 cm
Sample Length: 18.4 cm
Suction Measurements:

Time (min)	Suction (pF)
1290	4.605
1590	4.522
1940	4.433
2650	4.222

Wetting Diffusion Coefficient: **$3.32\text{x}10^{-3}\ \text{cm}^2\text{/min}$**

SOIL A4



Specimen No.: **SOIL A5**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 4.29 pF
Initial Suction: 4.13 pF
Psychrometer Location: 14.1 cm
Sample Length: 19.1 cm
Suction Measurements:

Time (min)	Suction (pF)
2810	4.099
2970	4.159
3360	4.274
3790	4.373
4020	4.421

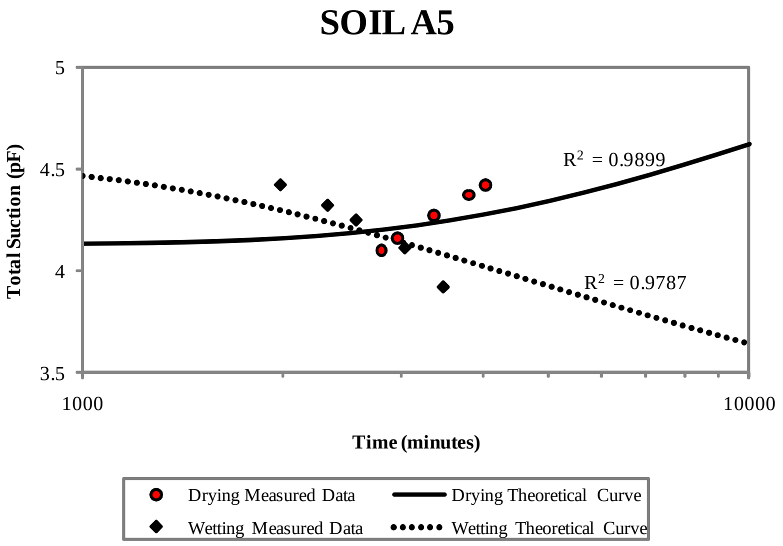
Drying Diffusion Coefficient: **1.47x10^{-3} cm^{2}/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.52 pF
Psychrometer Location: 14.1 cm
Sample Length: 19.1 cm
Suction Measurements:

Time (min)	Suction (pF)
1980	4.422
2330	4.321
2570	4.249
3040	4.112
3470	3.919

Wetting Diffusion Coefficient: **2.71x10^{-3} cm^{2}/min**



Specimen No.: **SOIL A6**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.22 pF
Initial Suction:	3.50 pF
Psychrometer Location:	11.4 cm
Sample Length:	15.4 cm

Suction Measurements:

Time (min)	Suction (pF)
4310	4.061
4690	4.176
5210	4.277
5830	4.388
6490	4.476
7270	4.557
8860	4.679

Drying Diffusion Coefficient: **2.74x10^{-3} cm^{2}/min**

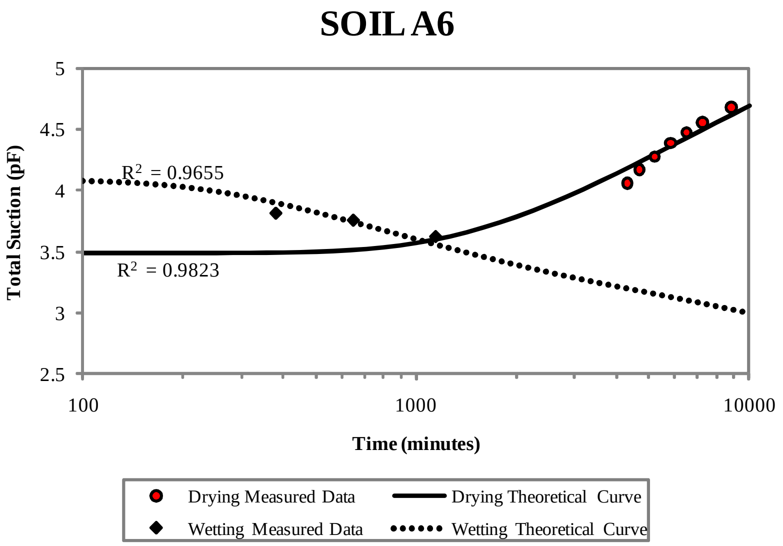
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.09 pF
Psychrometer Location:	11.40 pF
Sample Length:	15.4 cm

Suction Measurements:

Time (min)	Suction (pF)
380	3.818
650	3.761
1150	3.627

Wetting Diffusion Coefficient: **9.54x10^{-3} cm^{2}/min**



Specimen No.: **SOIL A7**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.21 pF
Initial Suction: 2.85 pF
Psychrometer Location: 10.2 cm
Sample Length: 14.2 cm
Suction Measurements:

Time (min)	Suction (pF)
2460	4.274
2710	4.373
2950	4.446
3430	4.522

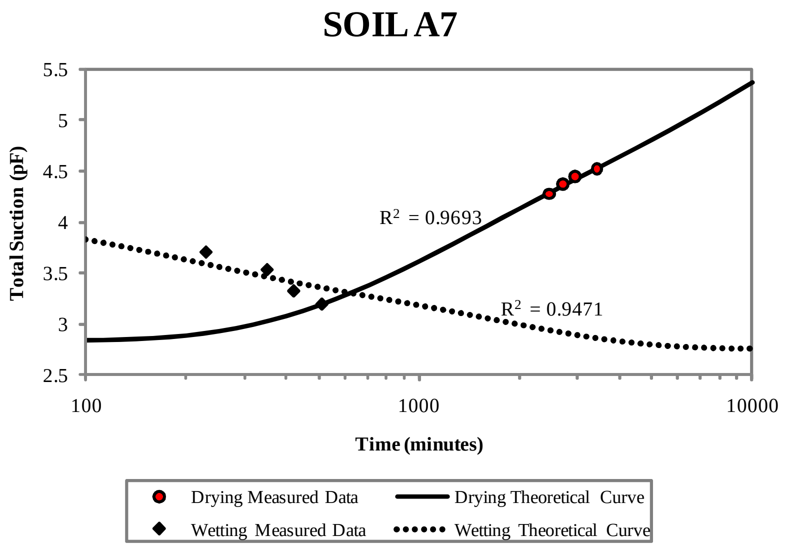
Drying Diffusion Coefficient: **10.53x10^{-3} cm^{2}/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 3.55 pF
Psychrometer Location: 10.2 cm
Sample Length: 14.2 cm
Suction Measurements:

Time (min)	Suction (pF)
230	3.703
350	3.534
420	3.327
510	3.199

Wetting Diffusion Coefficient: **19.47x10^{-3} cm^{2}/min**



Specimen No.: **SOIL A8**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.20 pF
Initial Suction: 2.83 pF
Psychrometer Location: 7.7 cm
Sample Length: 11.2 cm
Suction Measurements:

Time (min)	Suction (pF)
1910	3.994
2090	4.124
2290	4.237
2620	4.378
2880	4.460
3290	4.562
4280	4.688

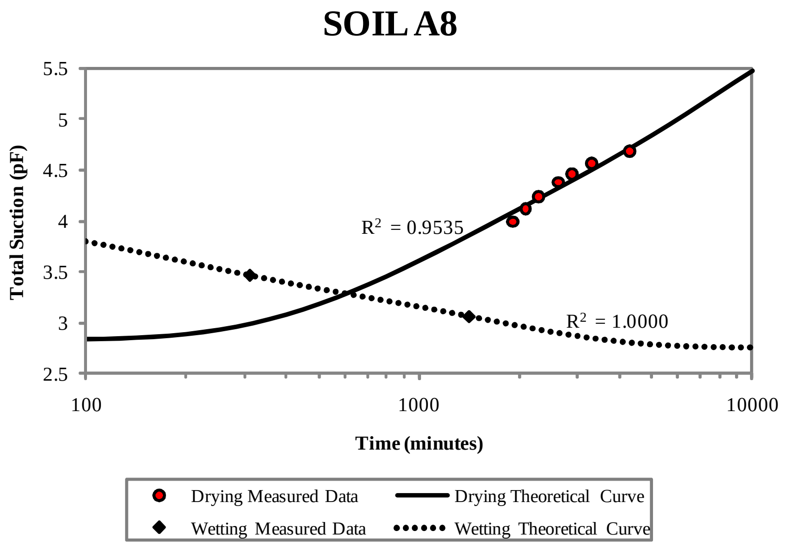
Drying Diffusion Coefficient: **8.58x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.01 pF
Psychrometer Location: 7.7 cm
Sample Length: 11.2 cm
Suction Measurements:

Time (min)	Suction (pF)
310	3.467
1410	3.060

Wetting Diffusion Coefficient: **31.84x10^{-3} cm^2/min**



Specimen No.: **SOIL A9**

Drying Test

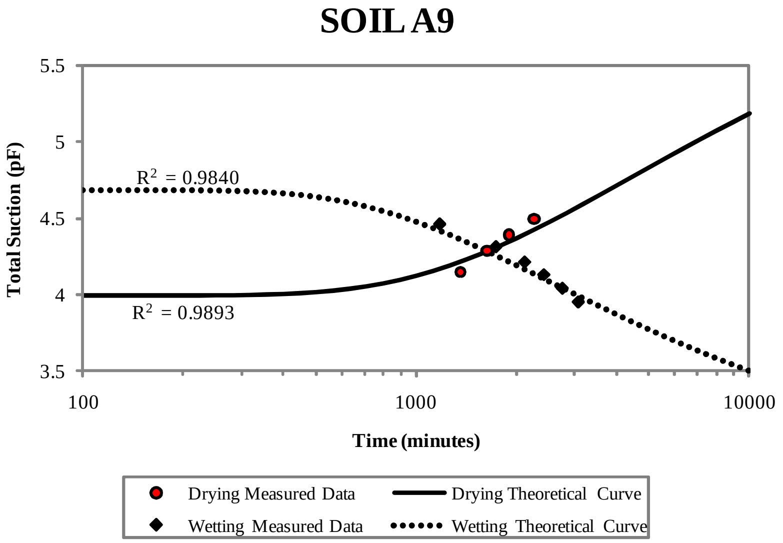
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.32 pF	
Initial Suction:	4.00 pF	
Psychrometer Location:	14.5 cm	
Sample Length:	19.5 cm	
Suction Measurements:	Time (min)	Suction (pF)
	1360	4.148
	1630	4.287
	1900	4.389
	2260	4.494

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.68 pF	
Psychrometer Location:	14.5 cm	
Sample Length:	19.5 cm	
Suction Measurements:	Time (min)	Suction (pF)
	1180	4.462
	1740	4.313
	2120	4.213
	2420	4.131
	2750	4.042
	3070	3.953

Drying Diffusion Coefficient: **5.31x10^{-3} cm^{2}/min**

Wetting Diffusion Coefficient: **11.79x10^{-3} cm^{2}/min**



Specimen No.: **SOIL B1**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.27 pF
Initial Suction:	3.09 pF
Psychrometer Location:	11.1 cm
Sample Length:	15.1 cm

Suction Measurements:

Time (min)	Suction (pF)
8020	4.072
8650	4.188
9300	4.271
10520	4.391
10920	4.417

Drying Diffusion Coefficient: **2.18×10^{-3} cm^2/min**

Wetting Test

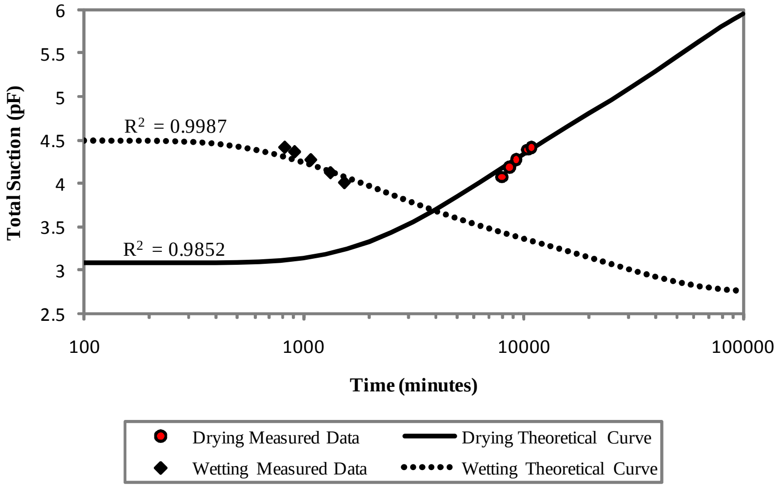
Soaking Suction:	2.75 pF
Initial Suction:	4.50 pF
Psychrometer Location:	11.1 cm
Sample Length:	15.1 cm

Suction Measurements:

Time (min)	Suction (pF)
820	4.411
910	4.359
1080	4.267
1330	4.120
1540	4.007

Wetting Diffusion Coefficient: **3.75×10^{-3} cm^2/min**

SOIL B1



Specimen No.: **SOIL B2**

Drying Test

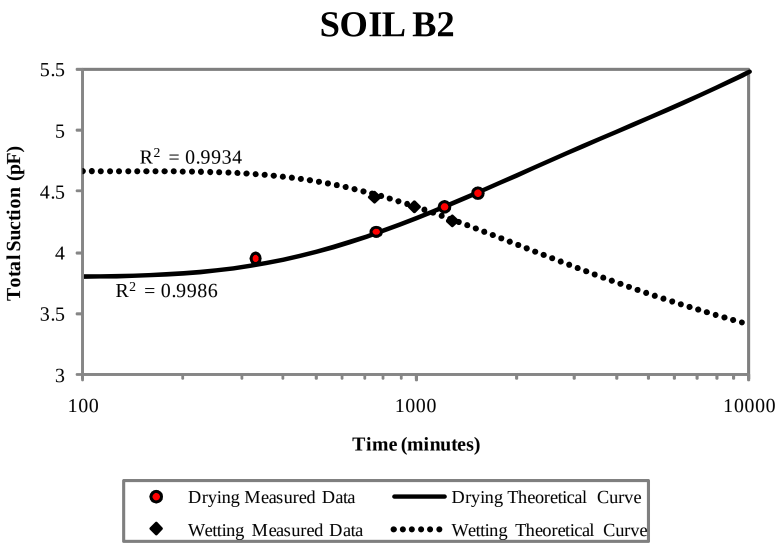
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.21 pF	
Initial Suction:	3.80 pF	
Psychrometer Location:	8.6 cm	
Sample Length:	11.6 cm	
Suction Measurements:	Time (min)	Suction (pF)
	330	3.955
	760	4.171
	1220	4.376
	1530	4.489

Drying Diffusion Coefficient: **5.83x10^{-3} cm^{2}/min**

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.66 pF	
Psychrometer Location:	8.6 cm	
Sample Length:	11.6 cm	
Suction Measurements:	Time (min)	Suction (pF)
	750	4.457
	990	4.376
	1290	4.257

Wetting Diffusion Coefficient: **8.18x10^{-3} cm^{2}/min**



Specimen No.: **SOIL B3**

Drying Test

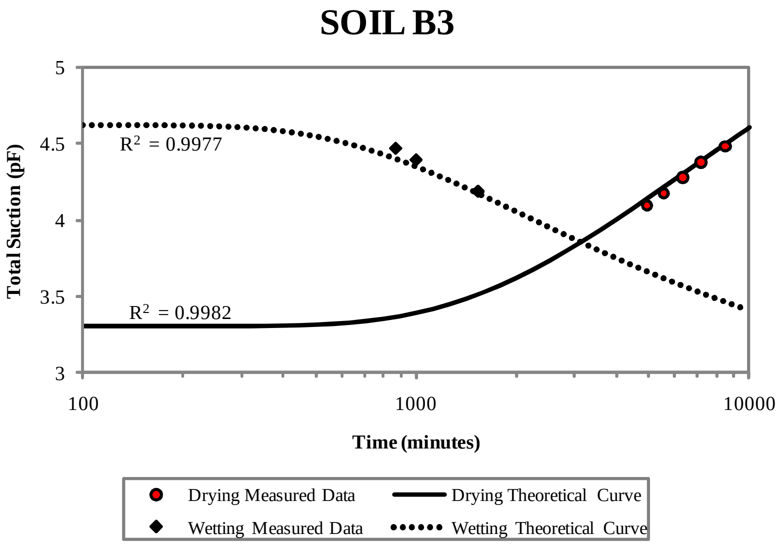
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.27 pF	
Initial Suction:	3.32 pF	
Psychrometer Location:	10.8 cm	
Sample Length:	14.8 cm	
Suction Measurements:	Time (min)	Suction (pF)
	4950	4.093
	5550	4.174
	6310	4.279
	7190	4.376
	8480	4.481

Drying Diffusion Coefficient: **2.70x10^{-3} cm^{2}/min**

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.62 pF	
Psychrometer Location:	10.8 cm	
Sample Length:	14.8 cm	
Suction Measurements:	Time (min)	Suction (pF)
	870	4.467
	1000	4.392
	1530	4.187

Wetting Diffusion Coefficient: **3.57x10^{-3} cm^{2}/min**



Specimen No.: **SOIL B4**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.26 pF
Initial Suction:	3.88 pF
Psychrometer Location:	13.8 cm
Sample Length:	18.8 cm

Suction Measurements:

Time (min)	Suction (pF)
1790	3.734
2690	3.916
3760	4.090
5020	4.228
6830	4.374
8070	4.451
9540	4.518

Drying Diffusion Coefficient: **1.90x10^{-3} cm^2/min**

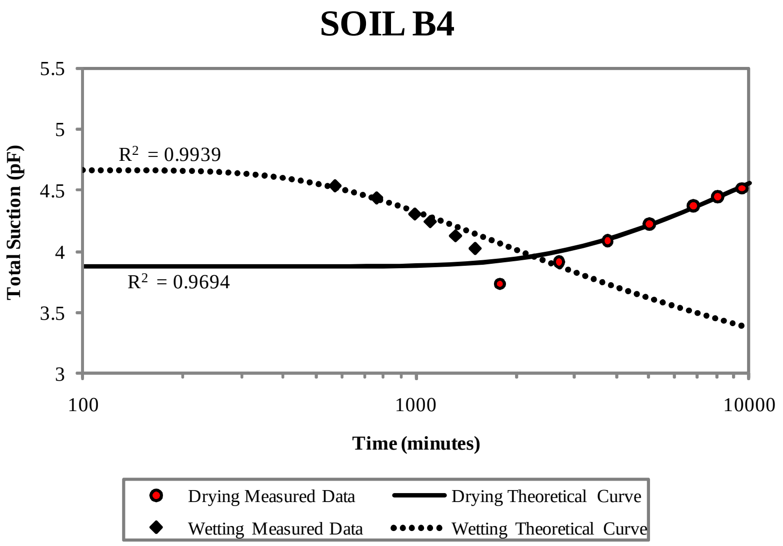
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.67 pF
Psychrometer Location:	13.8 cm
Sample Length:	18.8 cm

Suction Measurements:

Time (min)	Suction (pF)
570	4.544
760	4.445
990	4.312
1100	4.250
1310	4.134
1500	4.030

Wetting Diffusion Coefficient: **6.87x10^{-3} cm^2/min**



Specimen No.: **SOIL B5**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.20 pF
Initial Suction:	3.91 pF
Psychrometer Location:	9.1 cm
Sample Length:	14.1 cm

Suction Measurements:

Time (min)	Suction (pF)
4500	3.939
5340	4.078
6160	4.179
6950	4.261
8130	4.366
9610	4.451

Drying Diffusion Coefficient: **1.35x10^{-3} cm^2/min**

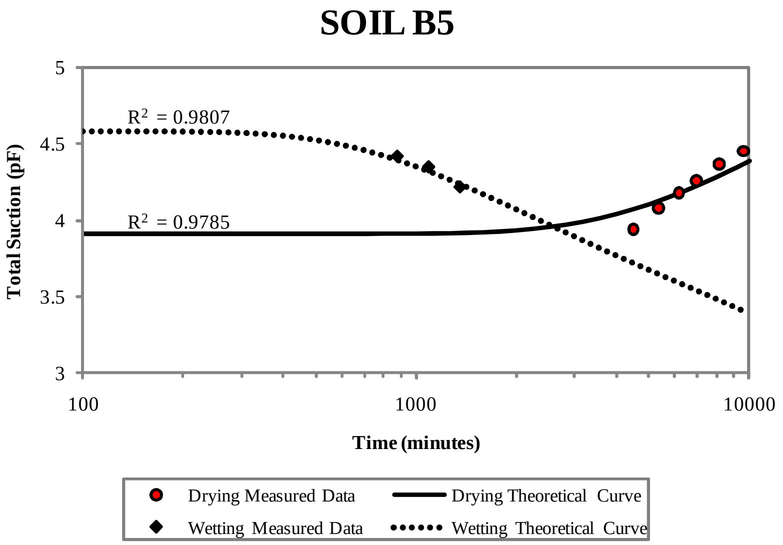
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.58 pF
Psychrometer Location:	9.1 cm
Sample Length:	14.1 cm

Suction Measurements:

Time (min)	Suction (pF)
880	4.416
1090	4.347
1350	4.217

Wetting Diffusion Coefficient: **5.31x10^{-3} cm^2/min**



Specimen No.: **SOIL B6**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	5.21 pF
Initial Suction:	6.21 pF
Psychrometer Location:	13.6 cm
Sample Length:	18.6 cm

Suction Measurements:

Time (min)	Suction (pF)
3910	4.032
4220	4.118
4950	4.262
5800	4.369
6960	4.473

Drying Diffusion Coefficient: **1.65×10^{-3} cm^2/min**

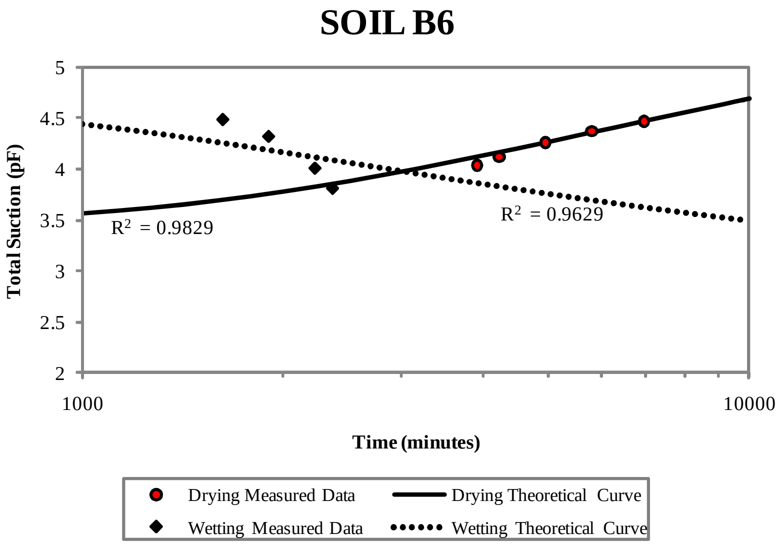
Wetting Test

Soaking Suction:	5.21 pF
Initial Suction:	6.21 pF
Psychrometer Location:	13.6 cm
Sample Length:	18.6 cm

Suction Measurements:

Time (min)	Suction (pF)
1620	4.486
1900	4.322
2230	4.011

Wetting Diffusion Coefficient: **4.73×10^{-3} cm^2/min**



Specimen No.: **SOIL C1**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.29 pF
Initial Suction: 3.48 pF
Psychrometer Location: 12.4 cm
Sample Length: 17.4 cm
Suction Measurements:

Time (min)	Suction (pF)
890	4.119
1380	4.258
1650	4.341
2020	4.447
2620	4.602
3170	4.691

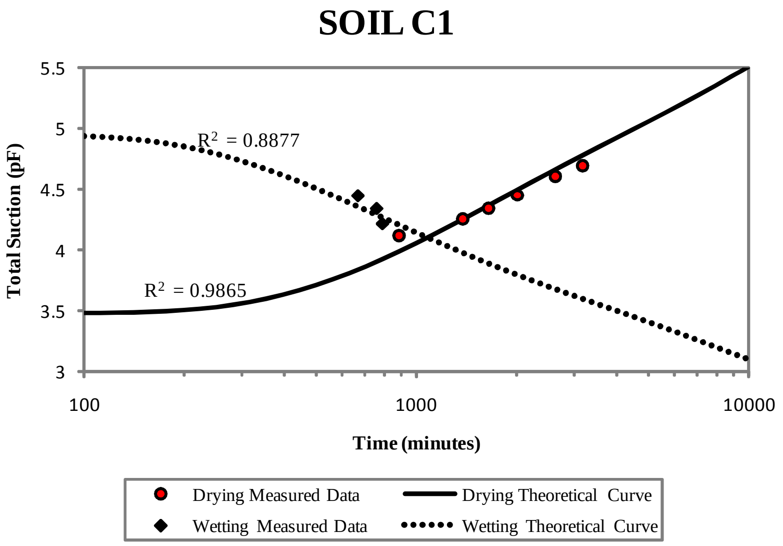
Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.95 pF
Psychrometer Location: 12.4 cm
Sample Length: 17.4 cm
Suction Measurements:

Time (min)	Suction (pF)
670	4.450
760	4.343
790	4.215

Drying Diffusion Coefficient: **13.21×10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **15.26×10^{-3} cm^2/min**



Specimen No.: **SOIL C2**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.29 pF
Initial Suction:	3.63 pF
Psychrometer Location:	8.9 cm
Sample Length:	12.9 cm

Suction Measurements:

Time (min)	Suction (pF)
1710	4.368
2030	4.465
2890	4.642

Drying Diffusion Coefficient: **$7.11\text{x}10^{-3}$ cm^2/min**

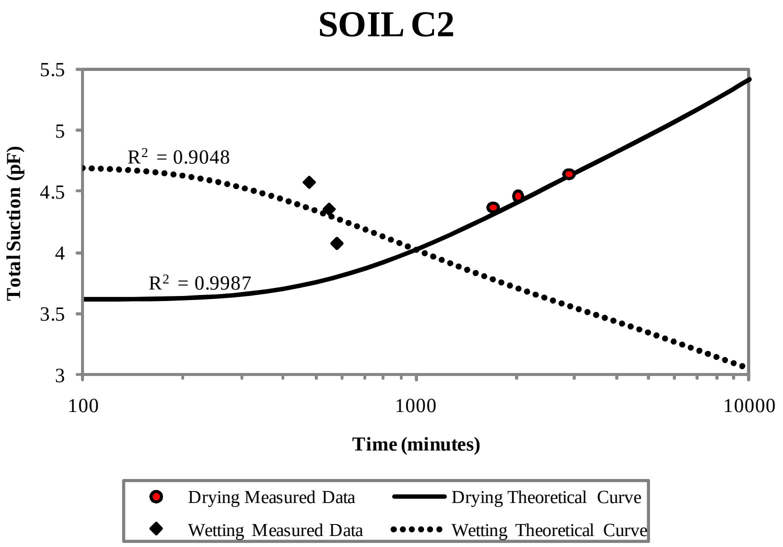
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.70 pF
Psychrometer Location:	8.9 cm
Sample Length:	12.9 cm

Suction Measurements:

Time (min)	Suction (pF)
480	4.569
550	4.352
580	4.074

Wetting Diffusion Coefficient: **$8.92\text{x}10^{-3}$ cm^2/min**



Specimen No.: **SOIL C3**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.29 pF
Initial Suction:	3.38 pF
Psychrometer Location:	11.5 cm
Sample Length:	16.5 cm

Suction Measurements:

Time (min)	Suction (pF)
2050	4.164
2420	4.269
2760	4.354
3120	4.466
3590	4.573

Drying Diffusion Coefficient: **9.21×10^{-3} cm^2/min**

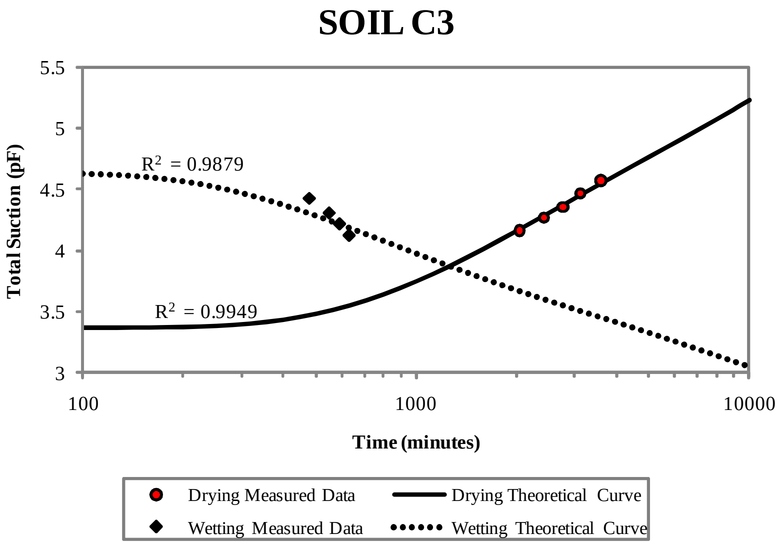
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.65 pF
Psychrometer Location:	11.5 cm
Sample Length:	16.5 cm

Suction Measurements:

Time (min)	Suction (pF)
480	4.428
550	4.307
590	4.218
630	4.122

Wetting Diffusion Coefficient: **14.21×10^{-3} cm^2/min**



Specimen No.: **SOIL C4**

Drying Test

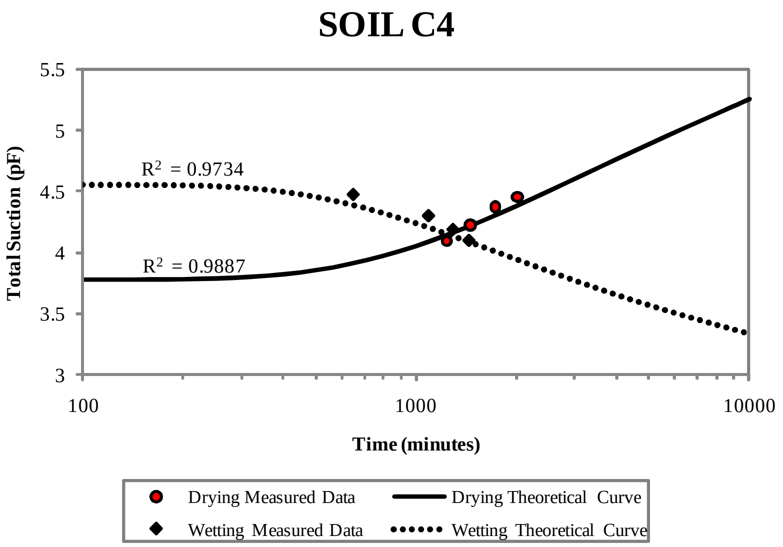
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.28 pF	
Initial Suction:	3.79 pF	
Psychrometer Location:	11.1 cm	
Sample Length:	15.1 cm	
Suction Measurements:	Time (min)	Suction (pF)
	1240	4.096
	1460	4.228
	1730	4.371
	2010	4.457

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.56 pF	
Psychrometer Location:	11.1 cm	
Sample Length:	15.1 cm	
Suction Measurements:	Time (min)	Suction (pF)
	650	4.475
	1090	4.303
	1290	4.192
	1440	4.103

Drying Diffusion Coefficient: **5.53x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **7.63x10^{-3} cm^2/min**



Specimen No.: **SOIL D1**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.25 pF
Initial Suction: 2.35 pF
Psychrometer Location: 14.6 cm
Sample Length: 19.6 cm
Suction Measurements:

Time (min)	Suction (pF)
34810	3.943
36260	4.021
38130	4.104
40130	4.202
43470	4.306

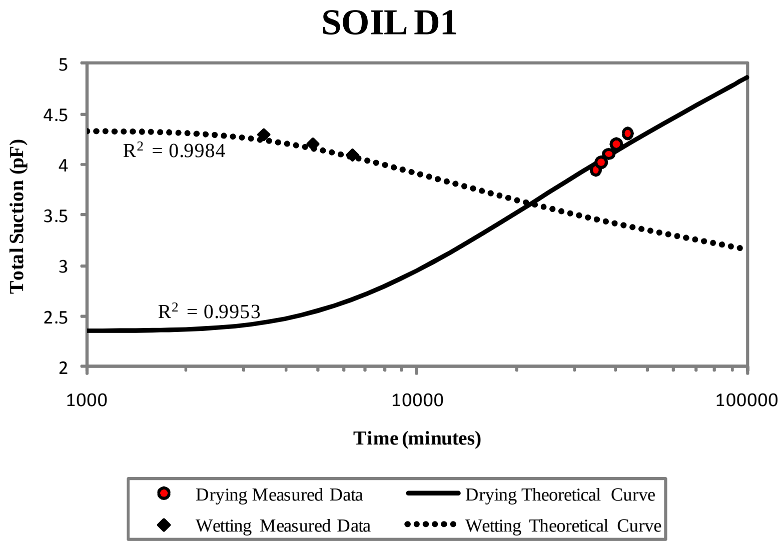
Drying Diffusion Coefficient: **1.02×10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.33 pF
Psychrometer Location: 14.6 cm
Sample Length: 19.6 cm
Suction Measurements:

Time (min)	Suction (pF)
3440	4.290
4850	4.198
6390	4.089

Wetting Diffusion Coefficient: **1.00×10^{-3} cm^2/min**



Specimen No.: **SOIL D2**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.24 pF
Initial Suction: 2.27 pF
Psychrometer Location: 13.7 cm
Sample Length: 18.7 cm
Suction Measurements:

Time (min)	Suction (pF)
27870	3.909
32060	4.062
34070	4.109
37690	4.213
41630	4.333
44440	4.405

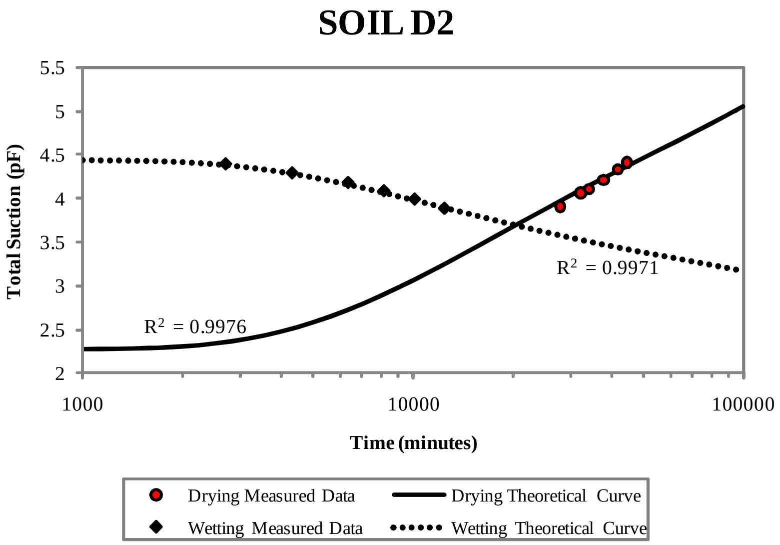
Drying Diffusion Coefficient: **1.28x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.43 pF
Psychrometer Location: 13.7 cm
Sample Length: 18.7 cm
Suction Measurements:

Time (min)	Suction (pF)
2710	4.397
4310	4.295
6370	4.185
8180	4.093
10130	3.998
12480	3.894

Wetting Diffusion Coefficient: **1.02x10^{-3} cm^2/min**



Specimen No.: **SOIL D3**

Drying Test

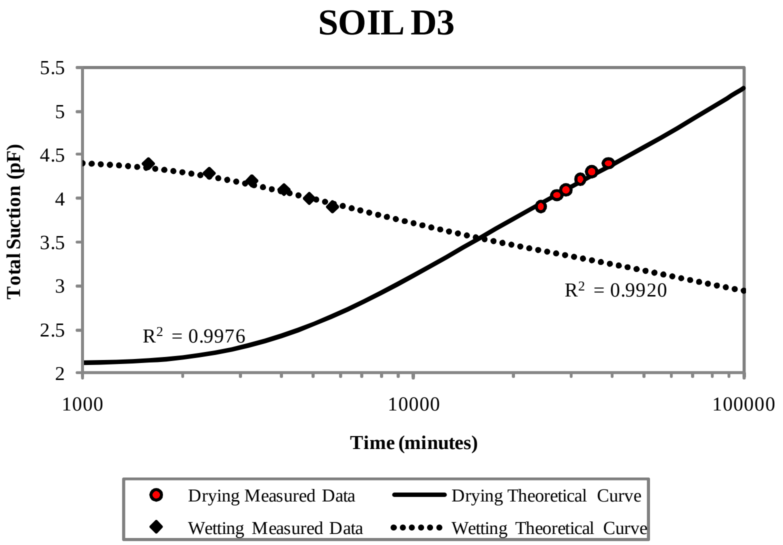
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.24 pF	
Initial Suction:	2.12 pF	
Psychrometer Location:	12.5 cm	
Sample Length:	17.5 cm	
Suction Measurements:	Time (min)	Suction (pF)
	24290	3.908
	27230	4.040
	29010	4.101
	32030	4.217
	34640	4.305
	38850	4.402

Drying Diffusion Coefficient: **1.58x10^{-3} cm^2/min**

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.42 pF	
Psychrometer Location:	12.5 cm	
Sample Length:	17.5 cm	
Suction Measurements:	Time (min)	Suction (pF)
	1580	4.398
	2410	4.287
	3240	4.199
	4050	4.098
	4830	3.995
	5670	3.898

Wetting Diffusion Coefficient: **1.93x10^{-3} cm^2/min**



Specimen No.: **SOIL D4**

Drying Test

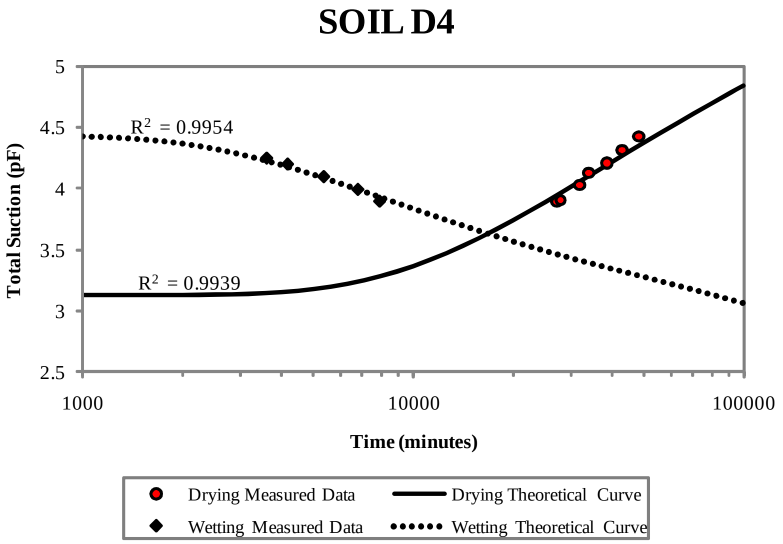
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.25 pF	
Initial Suction:	3.14 pF	
Psychrometer Location:	13.9 cm	
Sample Length:	18.9 cm	
Suction Measurements:	Time (min)	Suction (pF)
	27110	3.895
	27910	3.905
	31890	4.029
	33810	4.129
	38380	4.211
	42760	4.314
	47900	4.425

Drying Diffusion Coefficient: **0.632×10^{-3} cm^2/min**

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.43 pF	
Psychrometer Location:	13.9 cm	
Sample Length:	18.9 cm	
Suction Measurements:	Time (min)	Suction (pF)
	3600	4.244
	4170	4.196
	5370	4.093
	6820	3.989
	7940	3.892

Wetting Diffusion Coefficient: **1.45×10^{-3} cm^2/min**



Specimen No.: **SOIL D5**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.24 pF
Initial Suction:	2.83 pF
Psychrometer Location:	12.5 cm
Sample Length:	17.5 cm

Suction Measurements:

Time (min)	Suction (pF)
24160	3.832
27050	3.973
28200	4.012
31830	4.161
33120	4.212
37330	4.322
39840	4.410

Drying Diffusion Coefficient: **0.937x10^{-3} cm^2/min**

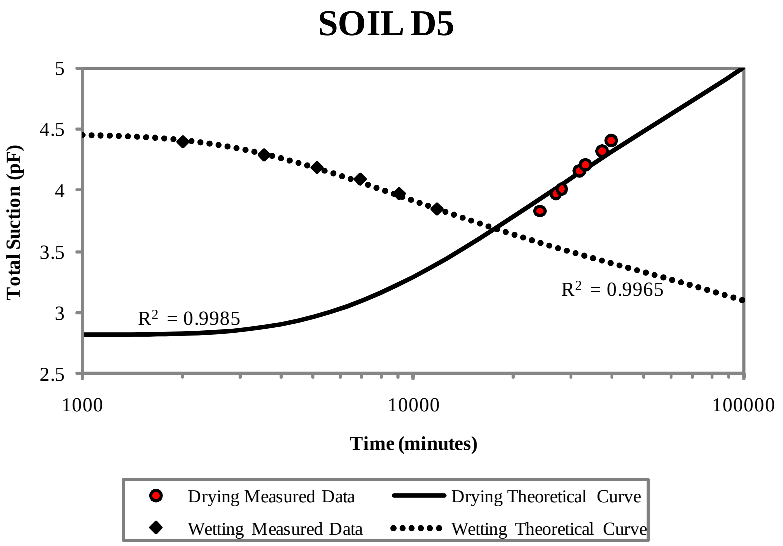
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.46 pF
Psychrometer Location:	15.5 cm
Sample Length:	17.5 cm

Suction Measurements:

Time (min)	Suction (pF)
2010	4.397
3540	4.289
5120	4.186
6920	4.091
9080	3.973
11820	3.847

Wetting Diffusion Coefficient: **1.24x10^{-3} cm^2/min**



Specimen No.: **SOIL D6**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.24 pF
Initial Suction: 3.45 pF
Psychrometer Location: 10.5 cm
Sample Length: 14.5 cm
Suction Measurements:

Time (min)	Suction (pF)
15350	3.838
16640	3.913
20320	4.116
22860	4.223
25410	4.315

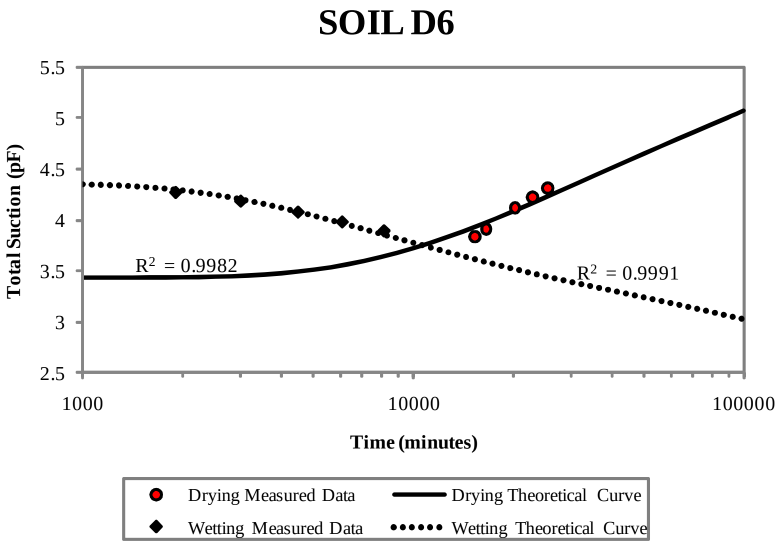
Drying Diffusion Coefficient: **0.521x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.36 pF
Psychrometer Location: 10.5 cm
Sample Length: 14.5 cm
Suction Measurements:

Time (min)	Suction (pF)
1910	4.273
3000	4.186
4470	4.079
6070	3.983
8120	3.896

Wetting Diffusion Coefficient: **0.953x10^{-3} cm^2/min**



Specimen No.: **SOIL D7**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.25 pF
Initial Suction:	2.90 pF
Psychrometer Location:	12.5 cm
Sample Length:	17.5 cm

Suction Measurements:

Time (min)	Suction (pF)
25800	3.839
29350	3.955
32920	4.065
37240	4.178
41480	4.285
44770	4.357
47230	4.412

Drying Diffusion Coefficient: **0.789x10^{-3} cm^2/min**

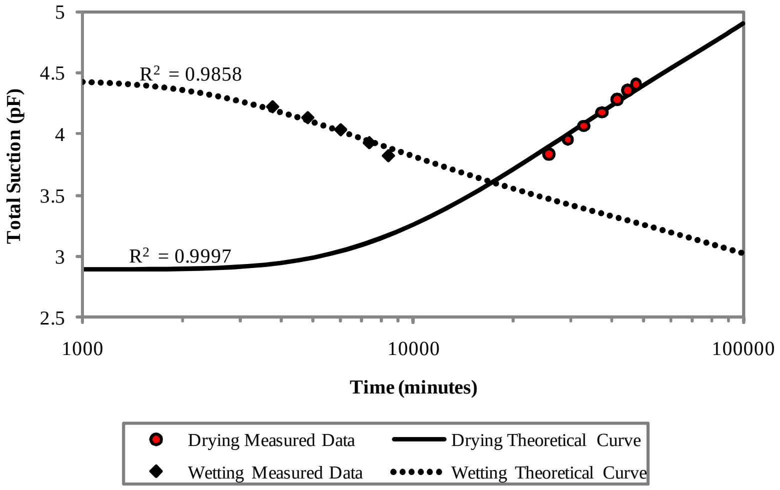
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.43 pF
Psychrometer Location:	12.5 cm
Sample Length:	17.5 cm

Suction Measurements:

Time (min)	Suction (pF)
3770	4.230
4820	4.141
6060	4.042
7400	3.935
8450	3.828

Wetting Diffusion Coefficient: **1.53x10^{-3} cm^2/min**


SOIL D7

Specimen No.: **SOIL D8**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.24 pF
Initial Suction:	3.03 pF
Psychrometer Location:	15.4 cm
Sample Length:	20.4 cm

Suction Measurements:

Time (min)	Suction (pF)
16110	3.886
19950	4.096
21620	4.173
24320	4.275
27070	4.367

Drying Diffusion Coefficient: **1.24×10^{-3} cm^2/min**

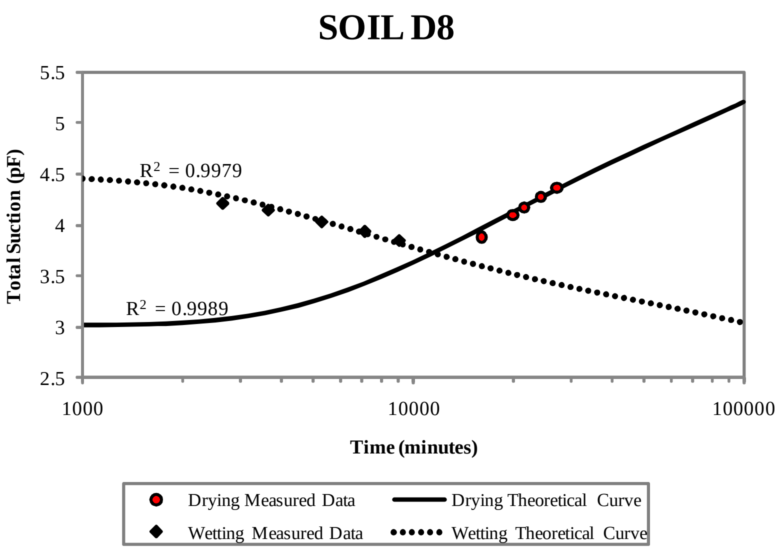
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.47 pF
Psychrometer Location:	15.4 cm
Sample Length:	20.4 cm

Suction Measurements:

Time (min)	Suction (pF)
2650	4.213
3640	4.145
5280	4.029
7120	3.934
9050	3.844

Wetting Diffusion Coefficient: **1.78×10^{-3} cm^2/min**



Specimen No.: **SOIL D9**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.23 pF
Initial Suction: 2.80 pF
Psychrometer Location: 15.7 cm
Sample Length: 20.7 cm
Suction Measurements:

Time (min)	Suction (pF)
23360	3.894
25410	3.988
27920	4.085
30180	4.172
32620	4.260
36470	4.369

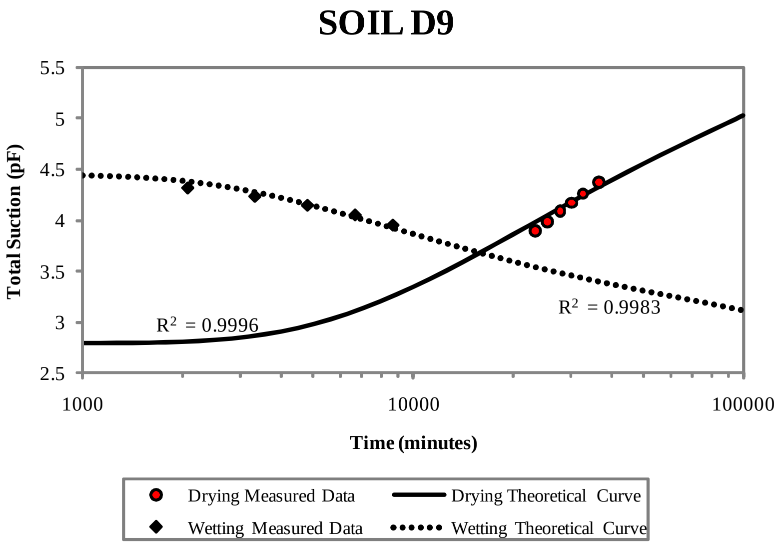
Drying Diffusion Coefficient: **1.05x10^{-3} cm^{2}/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.45 pF
Psychrometer Location: 15.7 cm
Sample Length: 20.7 cm
Suction Measurements:

Time (min)	Suction (pF)
2080	4.322
3320	4.237
4790	4.147
6670	4.050
8680	3.948

Wetting Diffusion Coefficient: **1.39x10^{-3} cm^{2}/min**



Specimen No.: **SOIL E1**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.30 pF
Initial Suction:	3.46 pF
Psychrometer Location:	12.0 cm
Sample Length:	17.2 cm

Suction Measurements:

Time (min)	Suction (pF)
2820	3.840
3130	3.923
3850	4.048
4370	4.126
7160	4.357
9600	4.475

Drying Diffusion Coefficient: **3.42x10^{-3} cm^{2}/min**

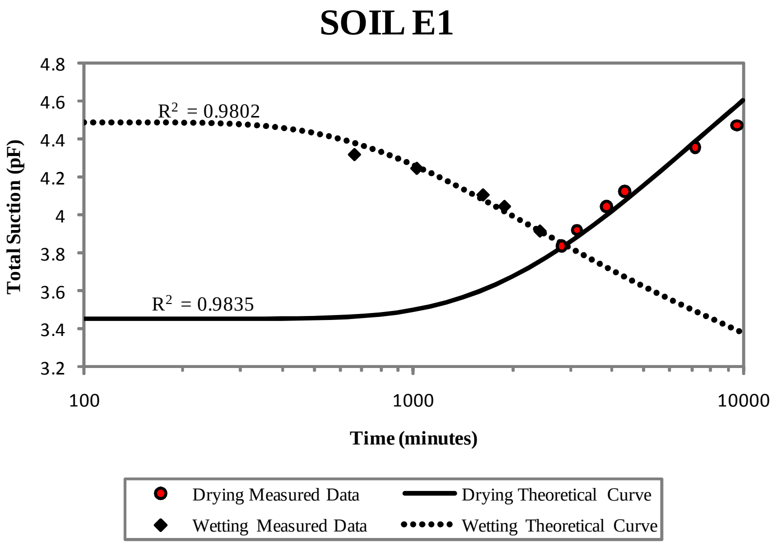
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.49 pF
Psychrometer Location:	12.0 cm
Sample Length:	17.2 cm

Suction Measurements:

Time (min)	Suction (pF)
660	4.320
1020	4.247
1620	4.107
1880	4.046
2410	3.915

Wetting Diffusion Coefficient: **5.89x10^{-3} cm^{2}/min**



Specimen No.: **SOIL E2**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.23 pF
Initial Suction: 3.60 pF
Psychrometer Location: 13.8 cm
Sample Length: 18.8 cm
Suction Measurements:

Time (min)	Suction (pF)
4990	3.866
5540	3.953
6630	4.094
7440	4.181
8790	4.289
9610	4.348
11540	4.474

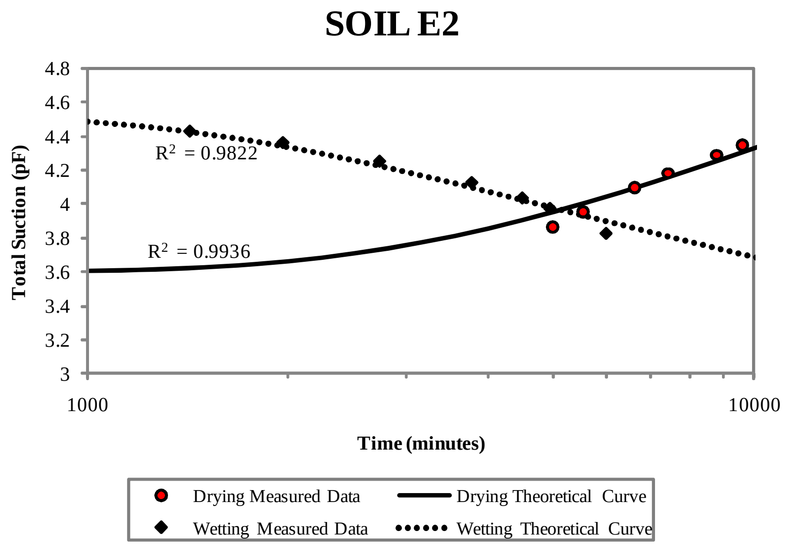
Drying Diffusion Coefficient: 1.84x10^{-3} cm^2/min

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.53 pF
Psychrometer Location: 13.8 cm
Sample Length: 18.8 cm
Suction Measurements:

Time (min)	Suction (pF)
1420	4.432
1960	4.365
2740	4.254
3770	4.128
4490	4.037
4940	3.975
6000	3.827

Wetting Diffusion Coefficient: 2.42x10^{-3} cm^2/min



Specimen No.: **SOIL E3**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.28 pF
Initial Suction:	2.64 pF
Psychrometer Location:	14.9 cm
Sample Length:	19.9 cm

Suction Measurements:

Time (min)	Suction (pF)
6320	3.880
7190	3.979
7870	4.054
9160	4.167
10950	4.284
13100	4.394
14330	4.429

Drying Diffusion Coefficient: **3.74x10^{-3} cm^{2}/min**

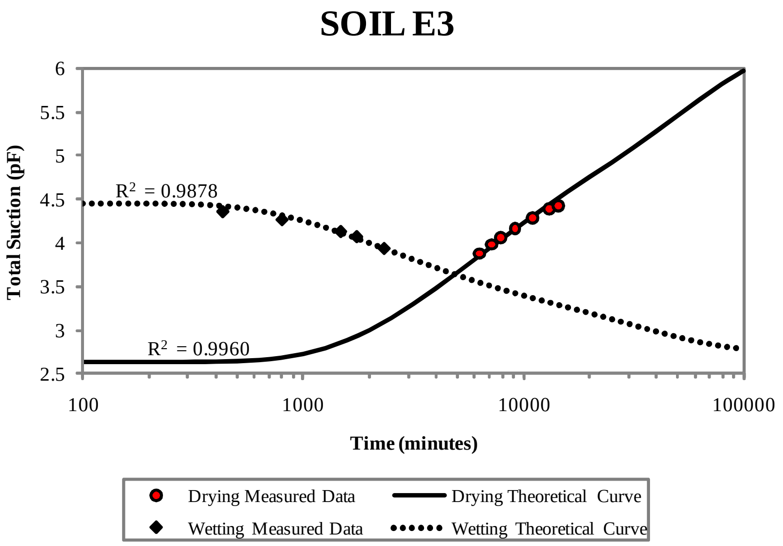
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.45 pF
Psychrometer Location:	14.9 cm
Sample Length:	19.9 cm

Suction Measurements:

Time (min)	Suction (pF)
430	4.366
800	4.273
1480	4.138
1750	4.077
2330	3.942

Wetting Diffusion Coefficient: **5.05x10^{-3} cm^{2}/min**



Specimen No.: **SOIL E4**

Drying Test

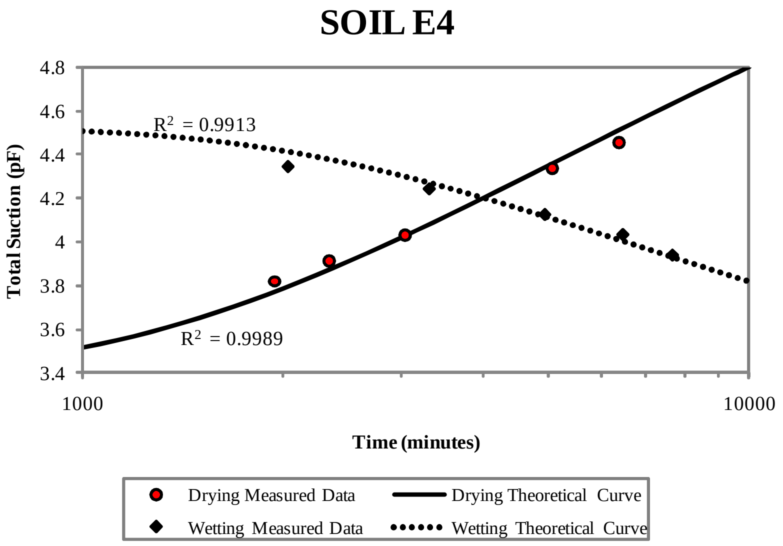
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.30 pF	
Initial Suction:	4.35 pF	
Psychrometer Location:	14.6 cm	
Sample Length:	19.6 cm	
Suction Measurements:	Time (min)	Suction (pF)
	1940	3.818
	2340	3.913
	3050	4.029
	5060	4.337
	6370	4.456

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.52 pF	
Psychrometer Location:	14.6 cm	
Sample Length:	19.6 cm	
Suction Measurements:	Time (min)	Suction (pF)
	2030	4.347
	3310	4.245
	4940	4.128
	6470	4.036
	7680	3.942

Drying Diffusion Coefficient: **4.58x10^{-3} cm^2/min**

Wetting Diffusion Coefficient: **5.74x10^{-3} cm^2/min**



Specimen No.: **SOIL E5**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.24 pF
Initial Suction:	3.55 pF
Psychrometer Location:	12.8 cm
Sample Length:	16.8 cm

Suction Measurements:

Time (min)	Suction (pF)
5780	3.829
6280	3.915
7440	4.079
7980	4.130
9210	4.246
12050	4.385

Drying Diffusion Coefficient: **$1.18\text{x}10^{-3}$ cm^2/min**

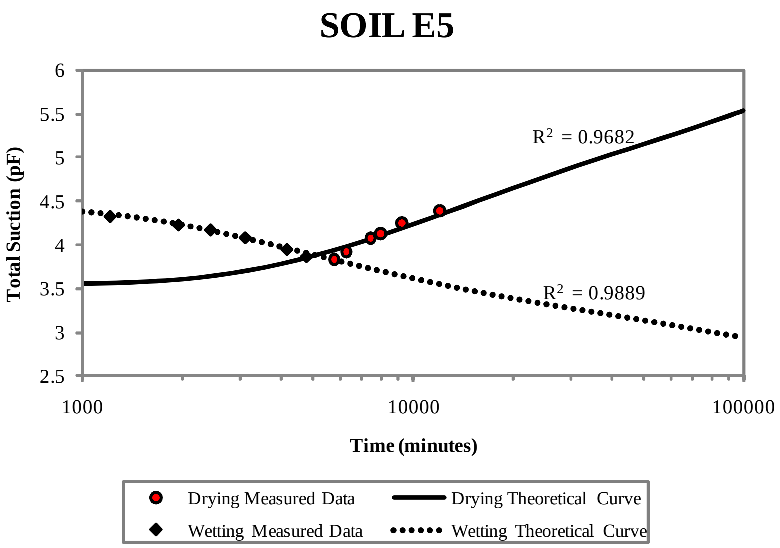
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.42 pF
Psychrometer Location:	12.8 cm
Sample Length:	16.8 cm

Suction Measurements:

Time (min)	Suction (pF)
1210	4.328
1950	4.230
2440	4.172
3110	4.081
4160	3.946
4770	3.862

Wetting Diffusion Coefficient: **$1.63\text{x}10^{-3}$ cm^2/min**



Specimen No.: **SOIL E6**

Drying Test

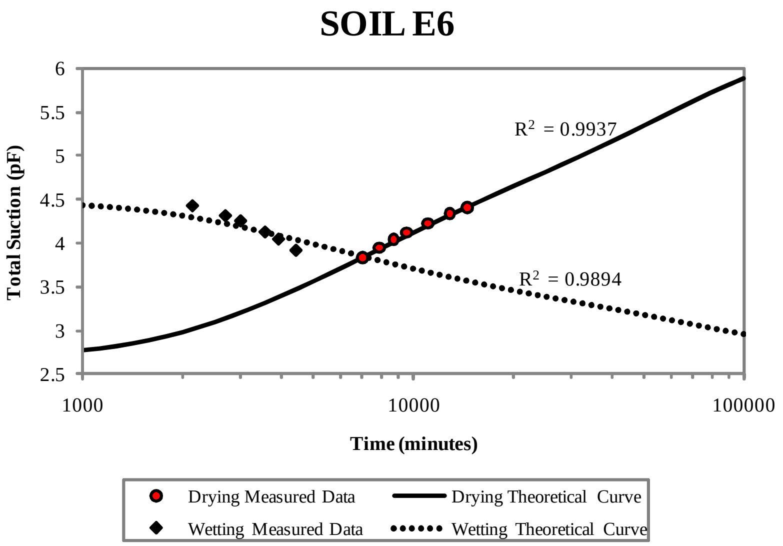
Evaporation Coefficient:	0.54 cm^{-1}	
Atmospheric Suction:	6.25 pF	
Initial Suction:	2.73 pF	
Psychrometer Location:	13.8 cm	
Sample Length:	18.8 cm	
Suction Measurements:	Time (min)	Suction (pF)
	7030	3.836
	7860	3.948
	8730	4.048
	9530	4.121
	11020	4.225
	12870	4.334
	14540	4.410

Drying Diffusion Coefficient: **3.10x10^{-3} cm^2/min**

Wetting Test

Soaking Suction:	2.75 pF	
Initial Suction:	4.46 pF	
Psychrometer Location:	13.8 cm	
Sample Length:	18.8 cm	
Suction Measurements:	Time (min)	Suction (pF)
	2150	4.426
	2700	4.313
	3000	4.252
	3550	4.126
	3900	4.044
	4400	3.916

Wetting Diffusion Coefficient: **4.10x10^{-3} cm^2/min**



Specimen No.: **SOIL E7**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.20 pF
Initial Suction:	3.03 pF
Psychrometer Location:	12.4 cm
Sample Length:	17.4 cm

Suction Measurements:

Time (min)	Suction (pF)
8950	3.954
10020	4.055
11340	4.157
12930	4.254
15660	4.373

Wetting Test

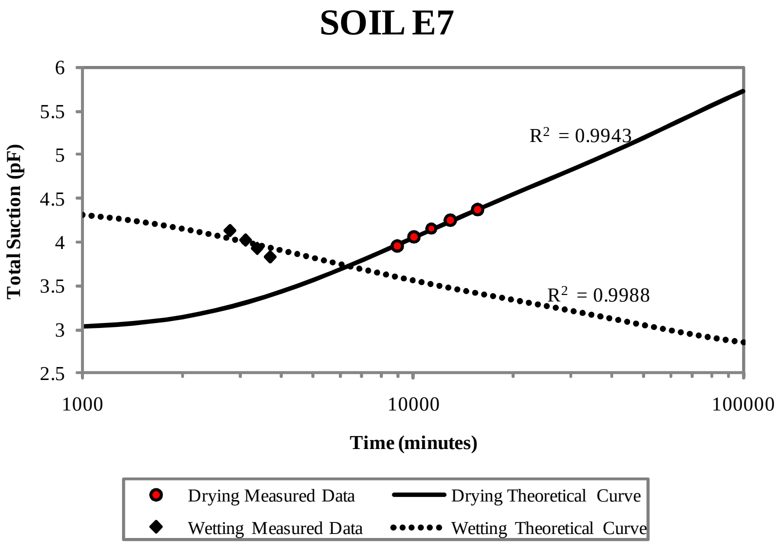
Soaking Suction:	2.75 pF
Initial Suction:	4.37 pF
Psychrometer Location:	12.4 cm
Sample Length:	17.4 cm

Suction Measurements:

Time (min)	Suction (pF)
2780	4.137
3110	4.030
3380	3.934
3710	3.838

Drying Diffusion Coefficient: **2.26x10^{-3} cm^{2}/min**

Wetting Diffusion Coefficient: **2.74x10^{-3} cm^{2}/min**



Specimen No.: **SOIL F1**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}

Atmospheric Suction: 6.27 pF

Initial Suction: 3.48 pF

Psychrometer Location: 14.5 cm

Sample Length: 19.5 cm

Suction Measurements:

Time (min)	Suction (pF)
7030	3.855
8220	3.949
10260	4.092
11210	4.141
13720	4.262
16520	4.370
18740	4.439

Drying Diffusion Coefficient: **1.37×10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF

Initial Suction: 4.52 pF

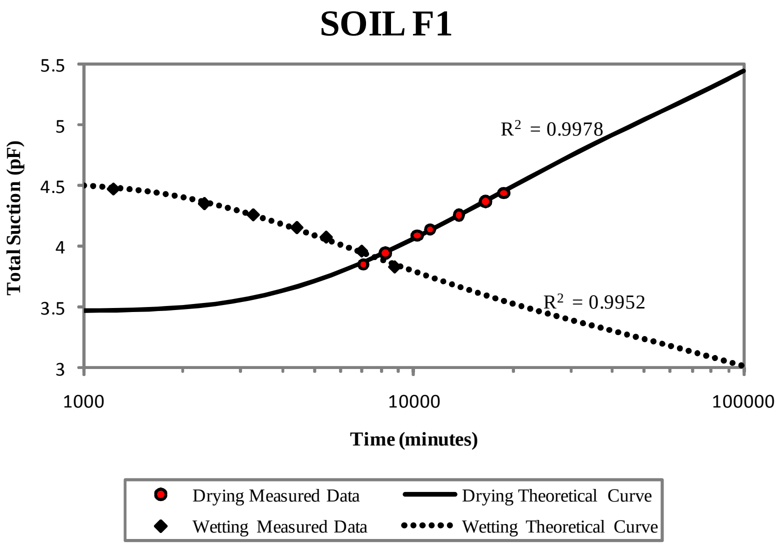
Psychrometer Location: 14.5 cm

Sample Length: 19.5 cm

Suction Measurements:

Time (min)	Suction (pF)
1230	4.478
2320	4.356
3260	4.262
4420	4.156
5420	4.077
6940	3.960
8740	3.828

Wetting Diffusion Coefficient: **1.82×10^{-3} cm^2/min**



Specimen No.: **SOIL F2**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.23 pF
Initial Suction: 3.43 pF
Psychrometer Location: 13.8 cm
Sample Length: 18.8 cm
Suction Measurements:

Time (min)	Suction (pF)
6240	3.804
7340	3.963
8620	4.085
9150	4.132
10400	4.215
13550	4.372
15620	4.442

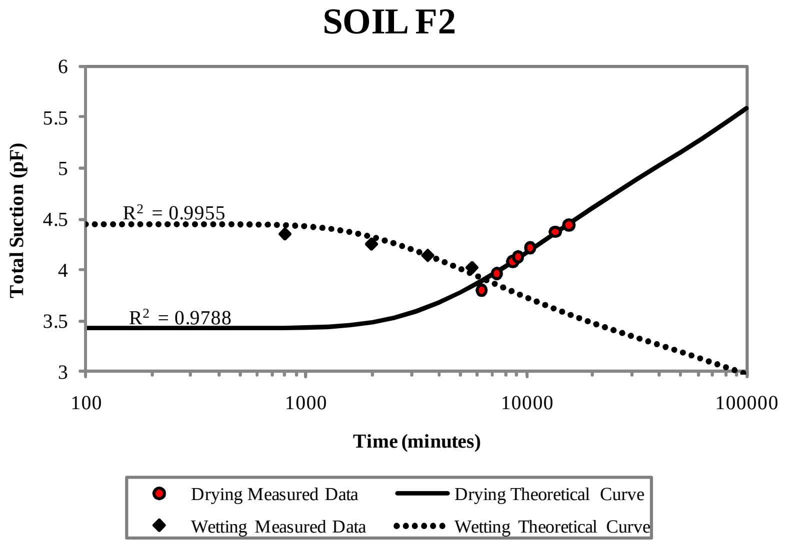
Drying Diffusion Coefficient: **1.74x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.45 pF
Psychrometer Location: 13.8 cm
Sample Length: 18.8 cm
Suction Measurements:

Time (min)	Suction (pF)
800	4.357
1980	4.258
3560	4.148
5660	4.029

Wetting Diffusion Coefficient: **1.95x10^{-3} cm^2/min**



Specimen No.: **SOIL F3**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.28 pF
Initial Suction: 3.05 pF
Psychrometer Location: 14.5 cm
Sample Length: 19.8 cm
Suction Measurements:

Time (min)	Suction (pF)
6410	4.068
7550	4.155
9820	4.296
11140	4.363
13970	4.471

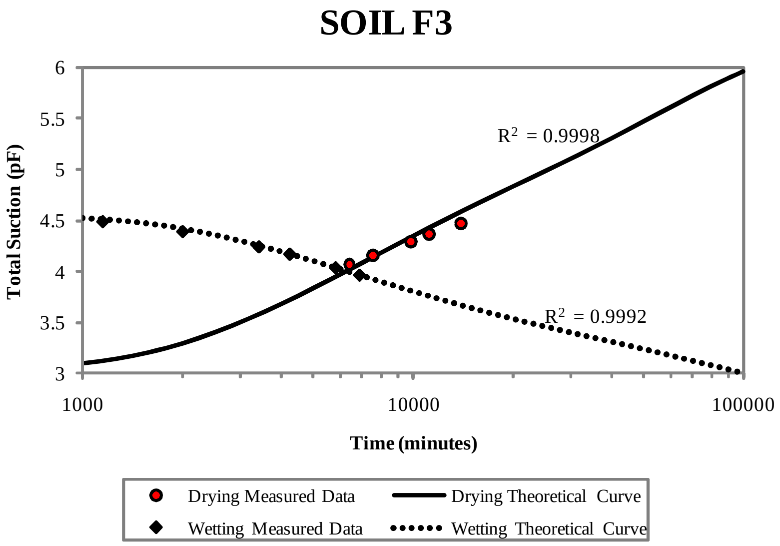
Drying Diffusion Coefficient: **3.47x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.54 pF
Psychrometer Location: 14.5 cm
Sample Length: 19.8 cm
Suction Measurements:

Time (min)	Suction (pF)
1150	4.488
2010	4.391
3420	4.243
4240	4.172
5840	4.040
6900	3.967

Wetting Diffusion Coefficient: **2.08x10^{-3} cm^2/min**



Specimen No.: **SOIL F4**

Drying Test

Evaporation Coefficient:	0.54 cm^{-1}
Atmospheric Suction:	6.28 pF
Initial Suction:	3.05 pF
Psychrometer Location:	14.5 cm
Sample Length:	19.8 cm

Suction Measurements:

Time (min)	Suction (pF)
7470	3.870
8480	3.968
9540	4.036
11860	4.178
14180	4.286

Drying Diffusion Coefficient: **3.47x10^{-3} cm^2/min**

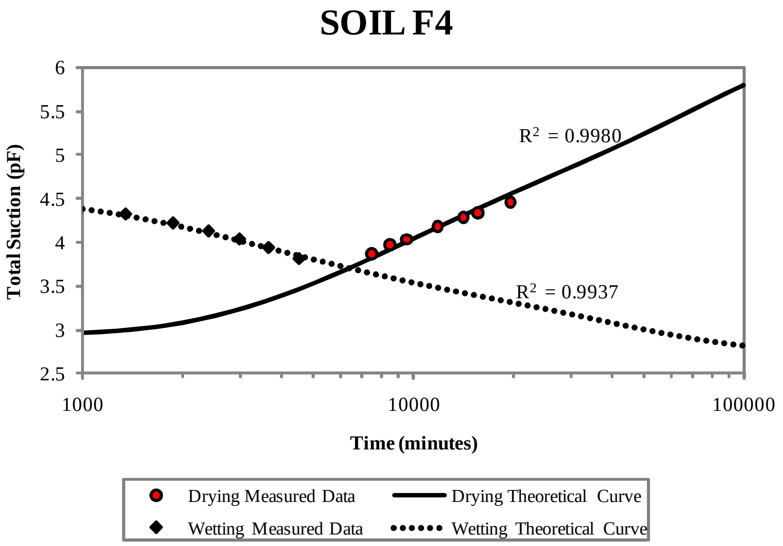
Wetting Test

Soaking Suction:	2.75 pF
Initial Suction:	4.54 pF
Psychrometer Location:	14.5 cm
Sample Length:	19.8 cm

Suction Measurements:

Time (min)	Suction (pF)
840	4.425
1350	4.317
1880	4.214
2410	4.122
2990	4.030
3660	3.933

Wetting Diffusion Coefficient: **2.08x10^{-3} cm^2/min**



Specimen No.: **SOIL F5**

Drying Test

Evaporation Coefficient: 0.54 cm^{-1}
Atmospheric Suction: 6.25 pF
Initial Suction: 3.42 pF
Psychrometer Location: 12.2 cm
Sample Length: 16.2 cm
Suction Measurements:

Time (min)	Suction (pF)
6680	3.880
7190	3.958
8120	4.040
9730	4.174
11220	4.273
13020	4.344

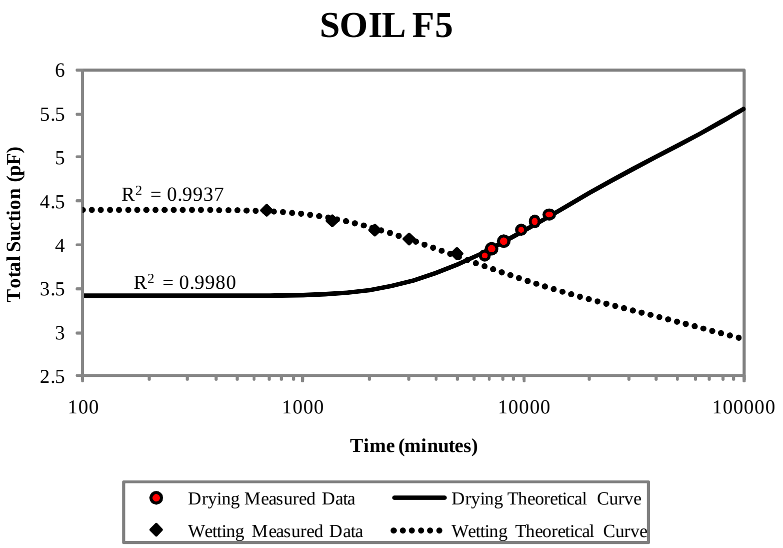
Drying Diffusion Coefficient: **1.21x10^{-3} cm^2/min**

Wetting Test

Soaking Suction: 2.75 pF
Initial Suction: 4.39 pF
Psychrometer Location: 12.2 cm
Sample Length: 16.2 cm
Suction Measurements:

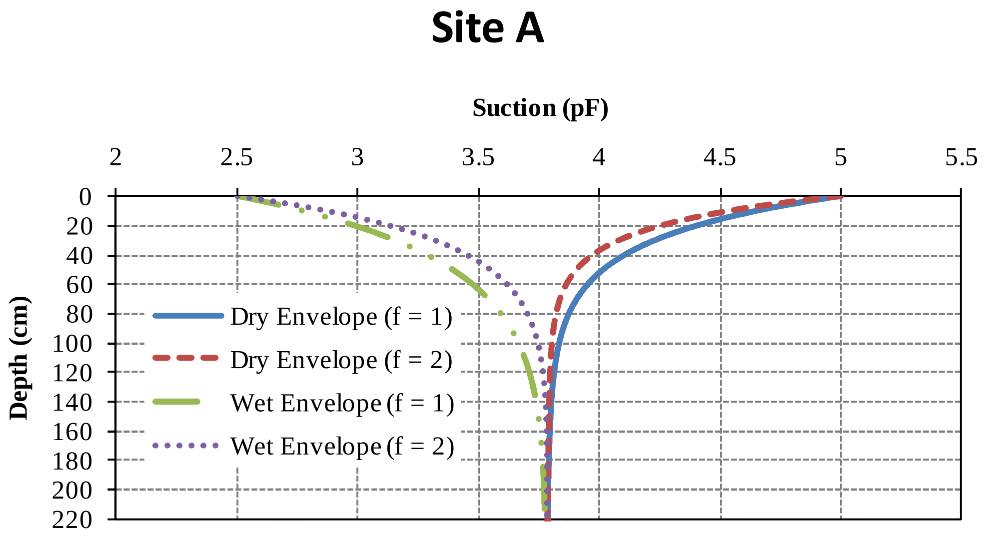
Time (min)	Suction (pF)
680	4.399
1350	4.277
2110	4.168
3020	4.064
4980	3.892

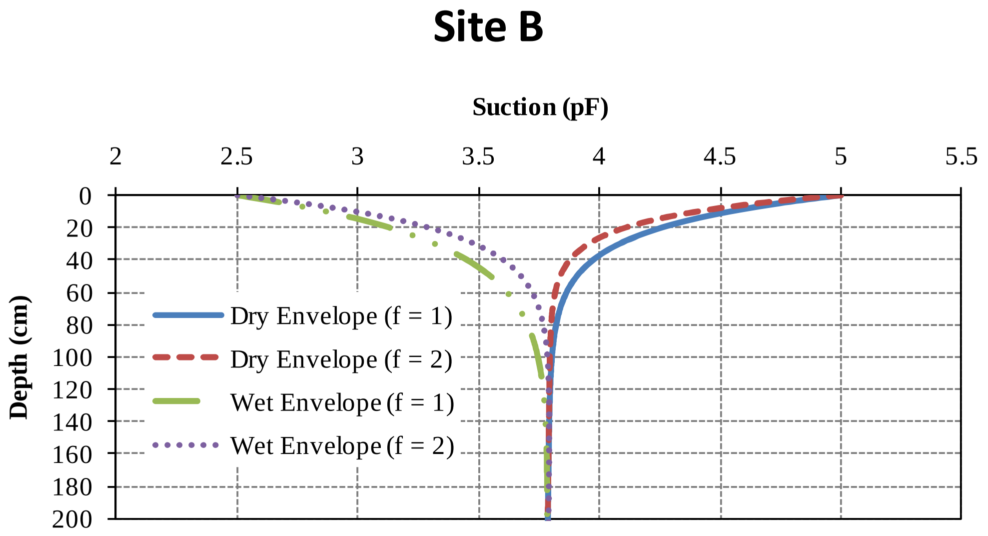
Wetting Diffusion Coefficient: **1.63x10^{-3} cm^2/min**

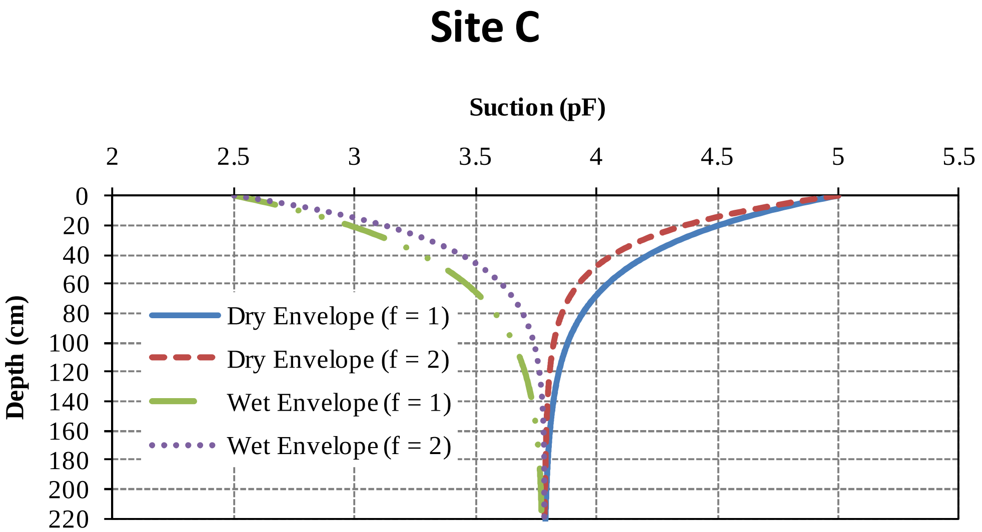


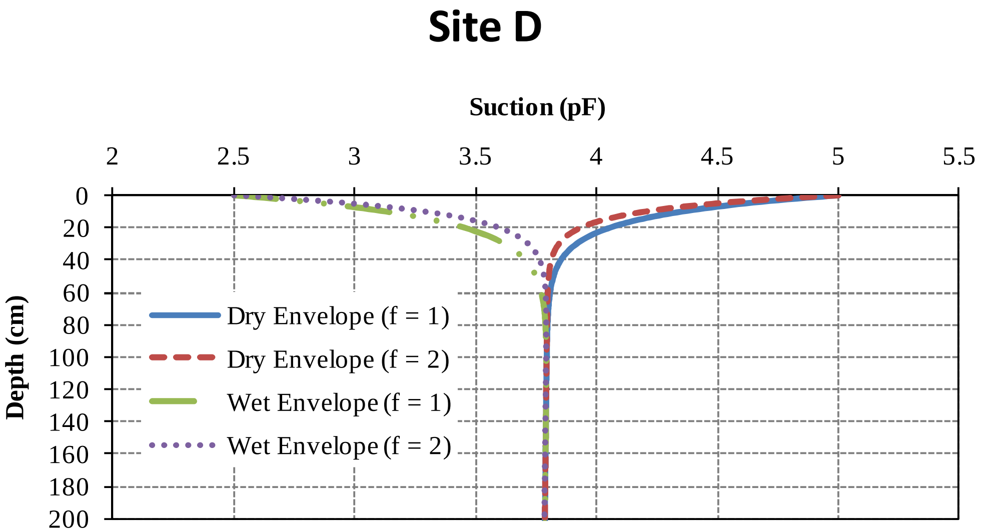
APPENDIX E

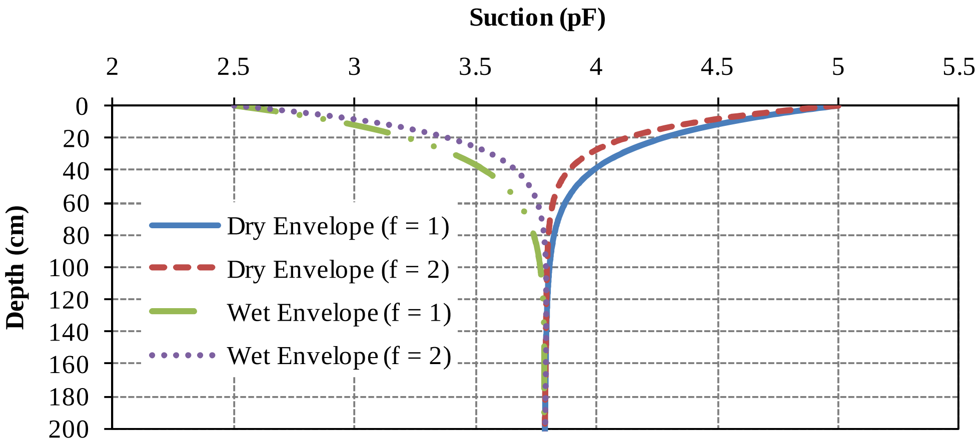
SUCTION PROFILES





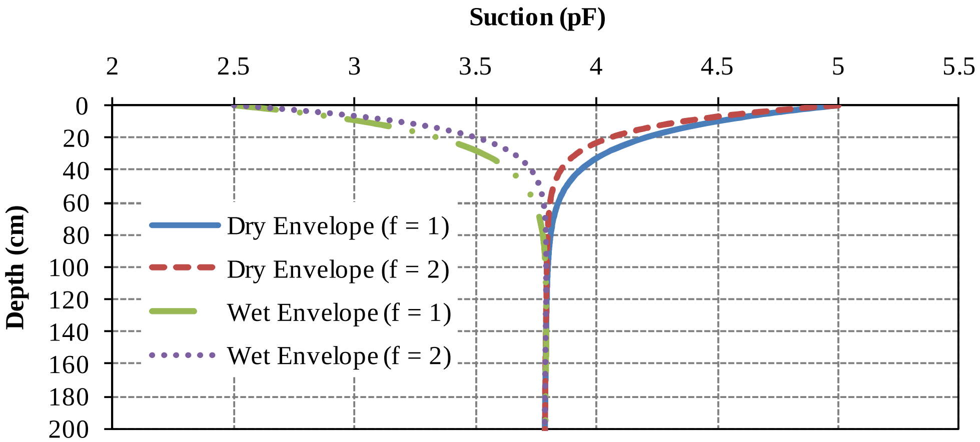

Site C
Suction (pF)
2
2.5
3
3.5
4
4.5
5
5.5
Depth (cm)
0
20
40
60
80
100
120
140
160
180
200
220
Dry Envelope (f = 1)
Dry Envelope (f = 2)
Wet Envelope (f = 1)
Wet Envelope (f = 2)


Site D
Suction (pF)
2
2.5
3
3.5
4
4.5
5
5.5
Depth (cm)
0
20
40
60
80
100
120
140
160
180
200
Dry Envelope (f = 1)
Dry Envelope (f = 2)
Wet Envelope (f = 1)
Wet Envelope (f = 2)



Site E

Suction (pF)
2
2.5
3
3.5
4
4.5
5
5.5
Depth (cm)
0
20
40
60
80
100
120
140
160
180
200
Dry Envelope (f = 1)
Dry Envelope (f = 2)
Wet Envelope (f = 1)
Wet Envelope (f = 2)



Site F

Suction (pF)
2
2.5
3
3.5
4
4.5
5
5.5
Depth (cm)
0
20
40
60
80
100
120
140
160
180
200
Dry Envelope (f = 1)
Dry Envelope (f = 2)
Wet Envelope (f = 1)
Wet Envelope (f = 2)

VITA

Daniel Mabirizi

Candidate for the Degree of

Master of Science

Thesis: WETTING AND DRYING UNSATURATED SOIL DIFFUSIVITY MEASUREMENTS IN LABORATORY

Major Field: Civil Engineering

Biographical:

Education:

Received Bachelor of Science degree in Surveying from Makerere University, Kampala, Uganda in June 2000. Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in December 2010.

Experience:

Employed by Universal Engineering Services, Hoima, Uganda and MBW Consulting Engineers, Fort Portal, Uganda as a surveyor from September 2001 to October 2005 and November 2005 to August 2006 respectively; employed as a graduate teaching and research assistant in the Department of Civil Engineering, Oklahoma State University, Stillwater, Oklahoma from January 2008 to May 2010.

Professional Memberships:

America Society of Civil Engineers; Phi Kappa Phi.

Name: Daniel Mabirizi Date of Degree: December, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: WETTING AND DRYING UNSATURATED SOIL DIFFUSIVITY MEASUREMENTS IN LABORATORY

Pages in Study: 132 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study:

The purpose of this research study was to develop an improved and unified testing protocol for measuring both the drying (evaporation) and wetting (soaking) diffusion coefficients on the same soil specimen in the laboratory. The drying testing equipment and method are modified to accommodate the wetting test. The new testing equipment, built at Oklahoma State University, enabled drying and wetting tests to be performed in cycles on the same soil specimens. One drying-wetting or wetting-drying cycle was adopted in this study. This approach permitted the hysteresis effect on the evaporation and soaking parameters that are associated with seasonal moisture variations to be reliably evaluated.

Findings and Conclusions:

Undisturbed Shelby tube soil specimens from six different sites across Oklahoma were employed in this research study. Generally, the wetting diffusion coefficients were found to be higher than the drying diffusion coefficients by a factor of about one to two. The hysteresis between the diffusivity parameters was attributed to cracks formed in the soil during drying process and root-holes in the soil. Soils obtained from deeper depths from the ground surface tend to have smaller difference between the parameters than those obtained from shallower depths. The new testing equipment provided a strong tool for running multiple tests at the sample time under a temperature controlled environment. The determination of the diffusion coefficient by this method is simple and relatively rapid and can be carried out on a routine basis in a laboratory. The depth to which significant fluctuations in suction occur in a soil mass because of moisture fluctuations depends on the diffusion properties and amplitude of moisture fluctuations at the surface. The distribution of suction with depth within an unsaturated soil surface is greater for wetting diffusion coefficients than for drying diffusion coefficients.

ADVISER’S APPROVAL: Dr. Rifat Bulut