DETERMINATION OF MOISTURE DIFFUSION COEFFICIENT AT LOW SUCTIONS USING THERMAL CONDUCTIVITY SENSORS

By

SRUTHI MANTRI

Bachelor of Science in Civil Engineering

Jawaharlal Nehru Technological University

Kakinada, India

2011

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

DETERMINATION OF MOISTURE DIFFUSION COEFFICIENT AT LOW SUCTIONS USING THERMAL CONDUCTIVITY SENSORS

Thesis Approved:

Dr. Rifat Bulut

Thesis Adviser

Dr. Avdhesh Tyagi

Dr. Xiaoming Yang

ACKNOWLEDGEMENTS

Firstly, I would like to express my gratitude to my adviser, Dr. Rifat Bulut, for giving me the opportunity to work on this research. Dr. Bulut taught me how to proceed in a research and believed in me. I am also grateful to Dr. Xiaoming Yang and Dr. Avdhesh Tyagi for agreeing to be my committee members.

I would like to thank my fellow researchers Yi Tian, Omar Amer and Lizhou Chen for helping me when I need anything in my experiments. My deepest Gratitude goes to my family and friends for their love and encouragement. My best friend Spandana Annamraju has always be there for me in everything I needed.

I would like to thank God for helping me to make this possible.

Name: SRUTHI MANTRI

Date of Degree: DECEMBER, 2014

Title of Study: DETERMINATION OF MOISTURE DIFFUSION COEFFICIENT AT LOW SUCTIONS USING THERMAL CONDUCTIVITY SENSORS

Major Field: CIVIL ENGINEERING

Abstract:

The main aim of this research is to determine the drying and wetting moisture coefficients in unsaturated soils at low suctions using thermal conductivity sensors. The performance of a geotechnical structure can be strongly influenced by the moisture conditions in the soil. The movement of water in unsaturated soils can be described by determining the diffusion coefficient of the soil. The diffusion coefficient can be determined by the analysis of suction changes with time in the soil. The suction measurements can be made using different techniques. In this research study, the suction measurements were conducted using thermal conductivity sensors and thermocouple psychrometers. Mitchell (1979) proposed an approach to determine the diffusion coefficient of the soil. Mitchell's proposal of one dimensional analysis using rate of moisture flow through soil provides a simple, economical and reliable framework for determining the drying and wetting diffusion coefficients in a geotechnical laboratory. The calibration and the operation of the thermal conductivity sensors and the thermocouple psychrometers are explained in detail in this research study. Using the two devices, the drying and wetting diffusion coefficients were determined and the comparison study has been conducted between the two approaches. With the reliable estimate of the diffusion coefficient, the moisture movement can be predicted in a soil mass.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

1.1 Problem Statement:

There are significant changes in the field of soil mechanics during the past few decades. Some of these changes are due to the rapid development in unsaturated soil mechanics (Leong et al. 2001). The performance of any geotechnical structure is influenced by the moisture movement in the subgrade soils. The movement of water in unsaturated soils can be described by determining the soil water diffusion coefficient. The most important parameter on which the soil water diffusivity depends is soil suction. The reliable estimate of soil water diffusivity is important for predicting the moisture movement in the unsaturated soil.

The moisture diffusivity measurements in unsaturated soils strongly depend on reliable suction measurement techniques. There are many ways to determine the soil suction (Hupan et al. 2010). The soil suction has two components, namely matric suction and osmotic suction. There are different measurement devices available to determine the matric suction component of the soil and total suction of the soil independently (Fredlund and Rahardjo 1993). There are direct and indirect ways to measure the suction. Direct suction measurement techniques mainly include axis transition technique and tensiometer. Indirect matric suction measurement techniques are divided into categories, namely, measurement techniques of matric suction and total suction. Indirect matric suction measurement techniques include electrical conductivity sensors, thermal conductivity sensor (TCS) and in-contact filter paper technique. Indirect total suction measurement techniques include psychrometer technique, relative humidity sensor, chilled-mirror hygrometer technique and non-contact filter paper method.

Mitchell (1979) recommended experimental determination of diffusion coefficient by wetting (soaking) test and drying (evaporating) test. The main assumption is the suction gradient can be maintained in a soil column by keeping an open end allowed to atmospheric suction and all the other ends sealed. This laboratory testing method of suction measurements is a reliable and simple method. Lytton et al. (2005) made significant improvements to the drying part of testing. Mabirizi et al. (2010) developed a unified protocol for both drying and wetting tests using thermocouple psychrometers. The hysteresis effect on the drying and wetting cycles was also discussed by Mabirizi et al. (2010). The thermocouple psychrometers which have a reliable suction range of 3.5 – 4.5 pF were used to determine the diffusion coefficient of the soil. In this research study, the laboratory testing methods for the determination of both drying and wetting diffusion coefficients have been modified for a lower suction range using thermal conductivity sensors. The tests have been conducted using both thermal conductivity sensors and thermocouple psychrometers.

1.2. Objectives of Research Study:

Thermal conductivity sensors can measure a suction range of 0 -1000 kPa (Fredlund et al. 1989). Thermocouple psychrometers to have a reliable measured range of suction from 300 to 7000 kPa (Bulut and Leong 2008). Both thermal conductivity sensors and thermocouple psychrometers have been used together on a single soil specimen to measure a wider suction range. As noted earlier, the determination of the drying and wetting diffusion coefficients were performed for a higher suction range by Mabirizi et al. (2010) using thermocouple psychrometers. Hence, this study accomplishes the following

1. To develop an improved testing protocol for the purpose of using thermal conductivity sensors in drying and wetting tests.
2. To determine diffusion coefficients using both thermal conductivity sensors and thermocouple psychrometers together for a wider suction range.
3. To evaluate the comparison between the drying and wetting diffusion coefficients at different suction ranges.

1.3. Organization of Thesis:

Chapter 2 reviews the concept of soil suction and the different devices available for the determination of suction.

Chapter 3 reviews the phenomenon of moisture diffusion through unsaturated soil and the Mitchell’s approach for the determination of diffusion coefficients in the laboratory soil specimens.

Chapter 4 discusses the laboratory testing protocol for improved suction measurements on soil specimen using both thermal conductivity sensors and thermocouple psychrometers.

Chapter 5 presents the outcomes of the laboratory testing and the comparison of the results of the suction measurements and the diffusivity parameters.

Chapter 6 concludes the research study with some recommendations.

CHAPTER II

SUCTION IN UNSATURATED SOILS

2.1. Overview

This chapter discusses the soil suction and its components. The different devices that can measure total suction and the matric suction independently were given. The working principle and the reliable range of the devices were also included in this chapter. The drawbacks and the improvements of each device have also been discussed.

2. 2. Total Suction

Soil suction can be defined as the force with which water is held in the pores between the soil particles. It is one of the fundamental properties in explaining the mechanical behavior of the unsaturated soils (Fredlund et al. 2012). The soil suction is mainly influenced by the pore size and the water content of the soil. The soil suction theory was mainly developed in relation to the soil-water-plant system (Fredlund et al. 2012)

Total soil suction can also be defined in terms of the free energy or the relative vapor pressure (relative humidity) of the soil moisture. The thermodynamic equation for measuring the soil suction in terms of partial vapor pressure is given by Kelvin's equation:

$$h_t = \frac{RT}{V} ln\left(\frac{P}{P_0}\right) \tag{2.1}$$

where, h_t is the total suction, R is the universal gas constant, T is the absolute temperature, V is the molar volume of the water, P is the partial pressure of the water vapor and P_o is the saturation pressure of water vapor over a flat surface at the same temperature. Soil suction is usually represented in pF units (Schofield 1935). Suction in pF = Log_{10} (Suction in cm of water).

2.3. Components of Total Suction

The Total Soil suction can be subdivided into two components namely matric suction and osmotic suction. Matric suction is the negative gauge pressure relative to the external gas pressure on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with soil water (Krahn et al. 1972). A meniscus forms at the soil-air interface due to the surface tension. This results in the reduction of vapor pressure above the water. The decreased water pressure becomes negative thus defines the matric suction of the soil. The matric suction pressure increases as the radius of curvature of the meniscus decreases. The size of the soil pores decrease with a decrease in soil particle size which then affects the radius of curvature and consequently the matric suction pressure (Fredlund and Rahardjo 1993). Matric suction can be described as the partial pressure of the water vapor in equilibrium with soil water relative to the partial pressure of the vapor in equilibrium with a solution identical in composition with soil water (Fredlund et al. 2012).

The osmotic suction is the negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with a pool containing a solution identical in composition with the soil water (Krahn et al. 1972). The presence of dissolved ions in the soil water decreases the vapor pressure which results in the osmotic suction of soil (Fredlund and Rahardjo 1993). Osmotic suction can be described as the partial pressure of the water vapor in equilibrium with a solution identical in composition with soil water relative to the partial pressure of the water vapor in equilibrium with free pure water (Fredlund et al. 2012).

The total suction is the negative gauge pressure relative to the external gas pressure on the soil water to which a pool of pure water must be subjected in order to be in equilibrium through a semi permeable membrane with the soil water. The sum of matric and osmotic suction equals to the total suction (Krahn et al. 1972). Total suction can be described as the partial pressure of the water vapor in equilibrium with soil water relative to the partial pressure of the water vapor in equilibrium with free pure water (Fredlund et al. 2012). The schematic diagram explain the total suction is given in Figure 2.1

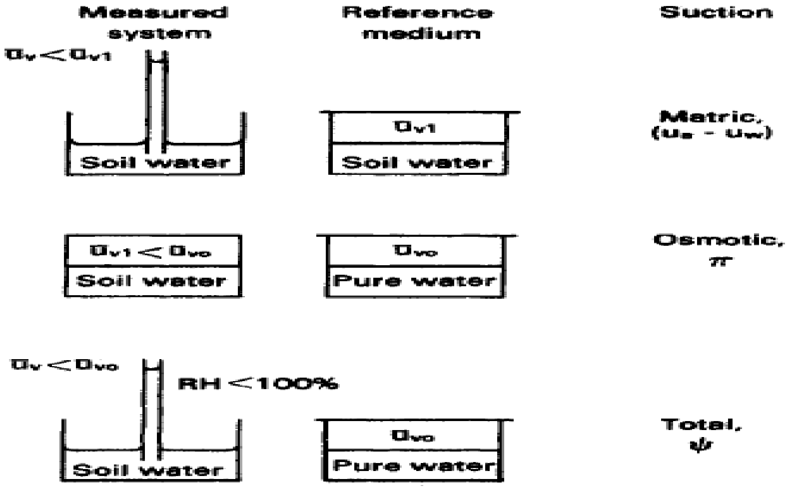


Figure 2.1 Schematic Diagrams for Total, Matric and Osmotic suctions (Fredlund et al. 1989)

2.4. Measurements of Suction

2.4.1. Direct measurements of suction

Matric suction is the measurement of negative pressure that results due to the capillarity in the soil matrix. The direct measurements are done by separation of water and air phase by means of a ceramic material.

Axis-translation Technique

Axis translation technique works on the principle of maintaining the pore water pressure of the soil sample at a positive reference pressure by artificially raising the atmospheric air pressure.

The difference between the air pressure and pore water pressure is taken as the matric suction in the axis translation technique. Since water pressure in the water compartment is maintained as close as possible at a zero value, the technique is called null-type axis-translation technique (Fredlund, 1989).

In this technique, a ceramic plate is saturated and the soil sample is placed on the ceramic plate. The air pressure is kept constant until the soil reaches suction equilibrium. After the soil sample reaches the suction equilibrium, the air pressure in the pressure cell is to be changed until equilibrium is reached again. The difference between the applied air pressure and the water pressure is taken as the matric suction. This technique is adopted for a suction range which is less than 1500 kPa (i.e., the air entry value of the porous disk). The range of axis translation technique to measure the matric suction is limited by two factors, namely, the maximum air pressure which can be imposed on the experiment system and the air entry value of the ceramic disk. The main limitation is that the occluded air bubbles in the soil might result in the over estimation of the matric suction. (Pan et al. 2010).

Figure 2.2. GCTS Soil Water Characteristic Curve Device (www.gcts.com)

Tensiometer

Tensiometer is normally used for directly measuring the negative pore-water pressure of soil. The basic principle is that the pressure of water contained in a high air entry material will come to equilibrium with the soil water pressure making it possible to measure negative soil water pressures.

A small ceramic cup is attached to a tube filled with de aired water which is connected to a pressure measuring device like a pressure gauge. The first step in the procedure for measuring the matric suction is to saturate the ceramic cup and tube by filling with water and applying a vacuum to the tubing. After saturation, the ceramic cup is allowed to dry to reduce the water pressure in the sensor and the air bubbles formed should be removed. After inserting the ceramic tip in the soil directly, the air bubbles appeared in the tubing need to be removed. This procedure does not require any calibration but for a check for elevation between the pressure gauge and the ceramic tip. Tensiometers do not work in dry soil because the pores in the ceramic cup drain and air is sucked in through them breaking the vacuum seal between the soil and the gauge on the top of the tensiometer (Pan et al. 2010).

The limitation is that air in the sensor will result in erroneous or less negative measurements of the pore water pressure for the following reasons: a) Air in the soil can diffuse through the ceramic material. b) Water vaporizes as the soil water pressure approaches the vapor pressure of the water at the ambient temperature (Pan et al. 2010). c) Air comes out of solution as the water pressures decrease (Pan et al. 2010). A schematic drawing of a tensiometer is given in Figure 2.3 in which the phenomenon of soil sucking the water from the tensiometer and creating a vacuum is shown. The vacuum gauge indicates the measure of the matric suction of the soil.

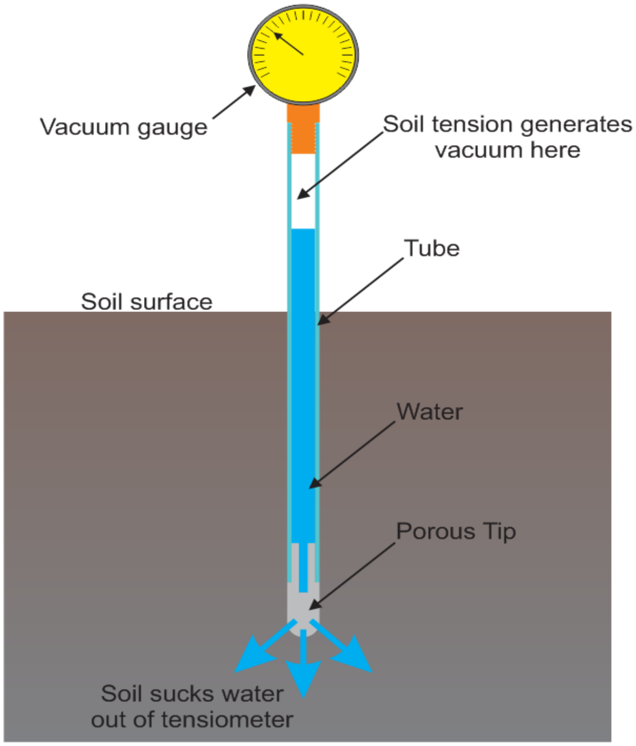


Figure 2.3. Working of Tensiometer (www. soil moisture equipment corporation.com)

2.4.2. Indirect measurements of suction

Indirect measurements of suction involve estimating the suction of the soil by means of another parameter like thermal conductivity, electrical conductivity or relative humidity. The measurement is usually performed by equilibrating the sensor with the moisture content of the soil which controls the suction. There are means to measure matric suction and total suction separately. The suction ranges and the equilibrium times for each kind of measurement are given in Table 2.1.

2.4.2.1. Matric Suction

Electrical conductivity sensors

The electrical conductivity sensor works on the principle that electrical conductivity increases as the moisture content increases. As matric suction is related to the water content in the soil. The measure of electrical resistance gives an estimate of the water content in the soil and thereby the matric suction. The electrical conductivity sensor consists of two concentric electrodes embedded inside a porous block. The porous block is usually made of gypsum which is found be the most suitable as it takes the shortest time to saturate and respond fastest in the measurement of matric suction (Buoyoucos and Mick 1940). The unintended effect of using gypsum as the porous block is that it eventually dissolves completely into the soil solution (Yu and Drnevich 2004). The equilibration times of the gypsum electrical conductivity sensors were found to vary with matric suction ranging from 6 h for a matric suction of 50 kPa to 50 h for a matric suction of 1,500 kPa. Besides, the electrical resistance, the electrical conductivity of the porous block is also dependent on the salt concentration of the soil solution and may not be a direct indication of the moisture content of the porous block. These shortcomings have led to a diminished use of electrical conductivity sensor for matric suction measurement even in the agricultural industry (Skinner *et al.* 1997).

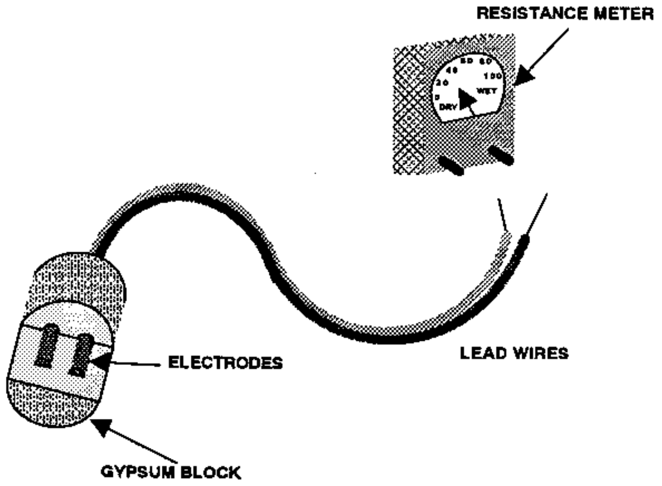


Figure 2.4. Electrical Conductivity sensor (Evans et al. 1996)

Thermal Conductivity sensor

Thermal conductivity sensors work on the principle that matric suction can be indirectly measured by the temperature rise in the sensor. The working principle is depicted in Figure 2.5. It consists of a ceramic block as a medium to measure matric suction indirectly. The thermal conductivity of the porous block is due to the change in water content in the voids of the porous block. As the moisture content of the porous block increases, the thermal conductivity of the block increases. The moisture content of the block is measured by heating the porous block with a heater embedded in the center of the porous block and measuring the temperature rise during heating. The temperature rise, which is a measure of the thermal conductivity of the porous medium and the moisture content, can be used to determine the matric suction of the soil. The equilibration time depends on the difference in temperature and the hydraulic conductivity of the surrounding soil and the porous medium (Fredlund and Wong 1989).

Gorden Conwell Theological Seminary (GCTS) manufactures Fredlund Thermal Conductivity sensors (FTC). These FTC sensors are used in this study. It has a GCTS data logger to record the temperature differences and the suction measurements. As shown in Figure 2.6, the FTC sensor uses a standardized ceramic block as the porous media. Using a miniature heating element, the heat is provided to the element and the temperature is recorded using a digital temperature sensor. If the block is wet, more heat will be dissipated when the heat pulse is applied, resulting a lower temperature rise than if the block is dry. Sending a constant electric current to the sensor for 60 seconds to the ceramic block gives two different results when the stone is wet and dry. These two readings represent the upper and lower bounds of the possible suction measurements. They have a reliable measurement range of 0 to 1000 kPa. Before using the FTC sensors, they need to be calibrated by applying a known matric suction and finding corresponding temperature rise. The calibration data should be used to determine the suction measurements. The calibration data is presented in terms of calibration curves. Sensors should be installed such that the ceramic tips are in good contact with the surrounding soil.

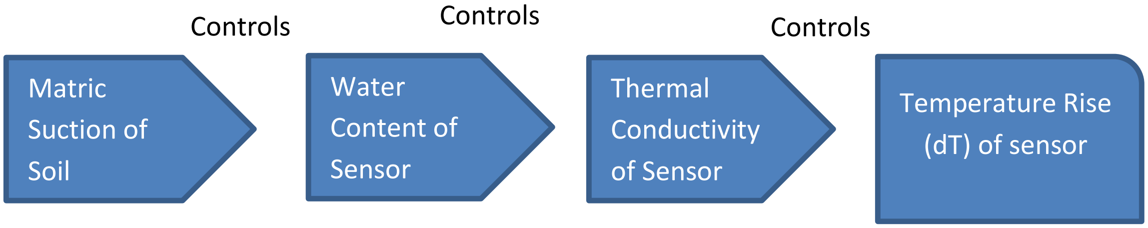


Figure 2.5. Matric Suction Measurement in FTC sensors

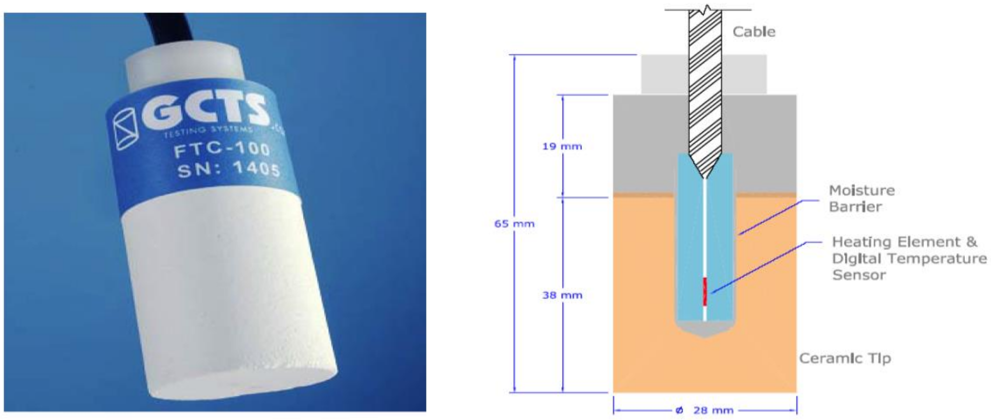


Figure 2.6. Fredlund Thermal Conductivity Sensor (www. gcts.com)

Filter paper technique

The filter paper method is another indirect method for measuring the suction of the soil. Both total and matric suction can be obtained from this method. It is one of the easiest and relatively inexpensive methods of all the suction measurement methods. The filter paper method is the only method that covers practically the whole range of the suction. However, this will take around one week time to give the correct suction measurement. Basically, the principle involved in the filter paper testing is that the filter paper comes into equilibrium with either the water vapor for total suction or with the liquid water in the soil for matric suction measurement (Bulut et al. 2001). Therefore, after the equilibrium is established, the water content of the filter paper is measured and by using the calibration curve of the filter paper, the suction value can be computed. If the fundamental principles are followed strictly, then the filter paper method is considered to be very reliable suction measurement technique (Houston et al. 1994; Bulut et al. 2001; Bulut and Leong 2008).

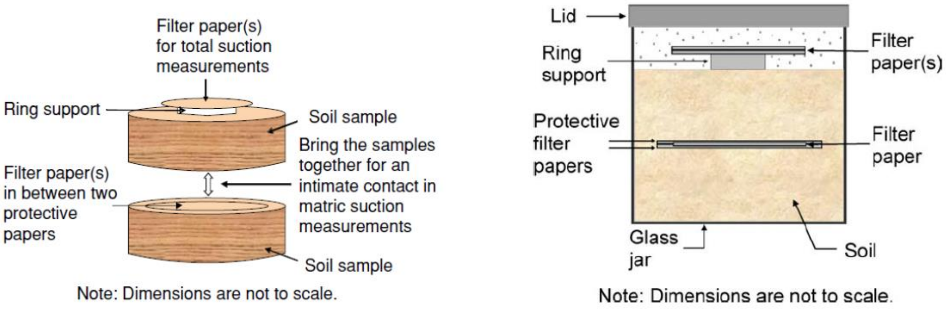


Figure 2.7. Suction Measurement Using Filter Paper Method (Bulut and Wray 2005)

2.4.2.2. Total Suction Measurement

Psychrometer technique

Thermocouple psychrometers are used to determine the total suction indirectly by means of measuring the relative humidity of the vapor of the soil water. Spanner (1951) introduced the use of Seebeck effect and Peltier effect for the measurement of suction using thermocouple psychrometers. The relation between relative humidity and the total suction is given by Kelvin's equation given in Equation 2.1. Seebeck effect is referred as when two dissimilar wires are joined to form a closed loop, flow of current occurs when the two metals are at different temperatures. The amount of the flow of voltage is dependent on the temperature difference between them (Fredlund and Rahardjo 1993, Lu and Likos 2004).

Figure 2.8. Wescor Thermocouple Psychrometers (Mabirizi 2010)

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. When the current is reversed, the temperature differences for both junctions are reversed. This phenomenon, which allows two junctions in a circuit consisting of two different wires to be cooled or heated, depending on the direction of the applied electrical current, is referred to as the Peltier effect (Fredlund and Rahardjo 1993, Lu and Likos 2004). They have a reliable measurement range of 300 to 7000 kPa. A CR7 data logger manufactured by Wescor, Inc. and Campbell Scientific Inc. was used to measure the voltage generated by condensation and evaporation processes.

Chilled-mirror psychrometer technique

A chilled mirror psychrometer uses the chilled mirror dew point technique to infer total suction under isothermal conditions in a closed container. Decagon Devices manufactures WP4 dew point potentiameter which works on the chilled mirror technique. The principle involved in measuring the total suction with WP4 is based on equilibrating the liquid phase of the water in the soil with the vapor phase in the air above the soil sample in a closed chamber (Bulut and Leong 2008). In the chilled mirror equipment, there is a Peltier cooling device to cool the mirror until dew forms and then to heat the mirror to remove the dew. For detecting the dew formed on the mirror, an optical sensor is utilized. An infrared thermometer is used to measure the temperature of the soil sample. The dew point temperature is measured by the thermocouple attached to the chilled mirror. A small fan is also employed to circulate the air in the sensing chamber and speed up vapor equilibrium. Relative humidity is then determined using the dew point and soil sample temperature above the soil sample in the closed temperature (Lu and Likos 2004). The soil suction can be obtained by using the relative humidity of the sample by Equation 2.1. This instrument is for rapid measurement of total suction. The time taken for the measurement of the suction is less than 10 minutes.

Figure 2.9 . WP4 Dew Point Potentiameter (www. Decagondevices.com)

The performance of the WP4 devices might be different from each other even though the principle involved in the measurement of the suction is same. The proposed one point calibration check by the manufacturer might not be sufficient to determine the capability of the device. The capability of the particular device is determined by developing the characteristic curve of the instrument using several salt solutions (Mantri and Bulut 2014).

Table 2.1. Summary of Suction Measurement Techniques (Fredlund, 1989; Pan et al. 2010; Fredlund and Wong 1989; Bulut et al. 2001; Mantri and Bulut 2014)

		Technique	Theoretical Suction Range (kPa)	Equilibrium Time
Direct Measurements of Suction	Matric Suction	Axis translation technique	0-1500	Hours
		Tensiometer	0-100	
Indirect Measurements of Suction	Matric Suction	Electrical conductivity sensor	50-1500	6 – 50 Hours
		Thermal conductivity sensor	0-1000	2- 3 Hours
		Filter paper method	Whole range	7 – 14 days
	Total Suction	Thermocouple psychrometer technique	300-7000	2- 3 Hours
		Filter paper method	Whole range	7 – 14 days
		Chilled mirror psychrometer	>100	10 minutes

CHAPTER III

MOISTURE DIFFUSION THROUGH CLAY

3.1. Overview

As the water penetrates into and evaporates out of the soil, there will be changes in the suction. These suction changes lead to the changes in the strength, volume and permeability of the soil. In saturated soils, the analysis for the movement of moisture is relatively easy compared to unsaturated soils. The relationship between moisture content and the suction is nonlinear in the case of unsaturated soils. Mitchell (1979) proposed an approach by analyzing the change of suction in logarithmic form and assuming the linearity to solve the diffusivity parameters. Moisture flow through an unsaturated soil is influenced by the permeability and the moisture retention properties of the soil. This chapter discusses the parameters used for the derivation of diffusion equation and the empirical relations for the calculation of diffusivity parameters.

3.2. Evaluation of the Moisture Diffusion Coefficient

3.2.1. Unsaturated permeability parameter

Darcy's law for saturated soil states that discharge per unit area is directly proportional to the head difference and inversely proportional to the lengh of the soil column.The proportainality constant is considered as the saturated permeability parameter (k).

$$v = \left[- k \left(\frac{\Delta H}{L}\right)\right] \tag{3.1}$$

Richards (1931) modified the Darcy's law for unsaturated porous medium and came up with the following equation:

$$v = \left[- k(h) \left(\frac{dh}{dx}\right)\right] \tag{3.2}$$

where v = discharge per unit area; *k*(*h*) = coefficient of unsaturated permeability, which is considered as a function of soil suction (*h*); and *dh/dx* = suction gradient in the x direction. H = total head

Laliberte and Corey (1967) gave the nonlinear permeability-suction relationship as:

$$k(h) = k_0 \left(\left(\frac{h_0}{h}\right)^n\right), h > h_0 \tag{3.3}$$

where k_0 = saturated permeability of the soil, h_0 = suction of the soil in saturated state and *n* = material constant, which for clays is close to 1 (Mitchell 1979).

Mitchell (1979) considered the following steps in the derivation of the diffusion equation. A cubical element with dimensions $\Delta x, \Delta y \; and \; \Delta z$ is considered for the moisture flow. The rate of flow of the source of the water into the soil element is assumed to be f(x, t). The net flow in one dimension which is considered in the x direction is given by (Mitchell 1979).

$$\Delta Q = v_x \Delta x \Delta y \Delta z \, \Delta t - v_{x+\Delta x} \Delta x \Delta y \Delta z \, \Delta t + f(x,t) \Delta x \Delta y \Delta z \Delta t \tag{3.4}$$

Substituting the rate of flow in Equation 3.4: (3.5)

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

$$\Delta Q = k(h) \Delta x \Delta y \Delta z \, \frac{\left(\frac{\partial u}{\partial x}\right)_{x+\Delta x} - \left(\frac{\partial u}{\partial x}\right)_x}{\Delta x} \Delta t + f(x,t) \Delta x \Delta y \Delta z \Delta t \tag{3.6}$$

As $\Delta x \to 0$, The flow in the body becomes:

$$Q = k(h) \Delta x \Delta y \Delta z \left(\frac{\partial^2 u}{\partial x^2}\right) \Delta t + f(x,t) \Delta x \Delta y \Delta z \Delta t \tag{3.7}$$

The amount of water stored in the element is as follows:

$$\Delta Q' = -\Delta x \Delta y \Delta z \Delta \theta \tag{3.8}$$

Where θ the volumetric water content that can be defined as the product of gravimetric water content (w) and the ratio of the dry density of the soil (γ_d) and unit weight of water. (γ_w)

$$\Delta Q' = -\Delta x \Delta y \Delta z \left(\frac{\gamma_d}{\gamma_w}\right) \Delta w \tag{3.9}$$

The slope of the soil water characteristic curve is considered as c = $\frac{\Delta w}{\Delta u}$ (Mitchell, 1979):

$$\Delta Q' = -\Delta x \Delta y \Delta z \left(\frac{\gamma_d}{\gamma_w}\right) c \Delta u \tag{3.10}$$

The net flow in the soil element should be equal to the water stored:

$$k(h) \Delta x \Delta y \Delta z \left(\frac{\partial^2 u}{\partial x^2}\right) \Delta t + f(x,t) \Delta x \Delta y \Delta z \Delta t = -\Delta x \Delta y \Delta z \left(\frac{\gamma_d}{\gamma_w}\right) c \Delta u \tag{3.11}$$

$$k(h) \left(\frac{\partial^2 u}{\partial x^2}\right) \Delta t + f(x,t) \Delta t = \left(\frac{\gamma_d}{\gamma_w}\right) c \Delta u \tag{3.12}$$

$$k(h) \left(\frac{\partial^2 u}{\partial x^2}\right) + f(x,t) = \left(\frac{\gamma_d}{\gamma_w}\right) c \frac{\Delta u}{\Delta t} \tag{3.13}$$

$$\left(\frac{\partial^2 u}{\partial x^2}\right) + \frac{f(x,t)}{k(h)} = \left[\left(\frac{\gamma_d}{\gamma_w}\right) \frac{c}{k(h)}\right] \frac{\Delta u}{\Delta t} \tag{3.14}$$

$$\left(\frac{\partial^2 u}{\partial x^2}\right) + \frac{f(x,t)}{k(h)} = \frac{1}{\alpha} \frac{\Delta u}{\Delta t} \tag{3.15}$$

Where α = $\left(\frac{\gamma_w}{\gamma_d}\right) \frac{k(h)}{c}$, u = total soil suction in pF , x = the distance; $f(x,t)$ = the rate of flow of source of moisture per unit volume, $k(h)$ = the unsaturated permeability coefficient, c = slope of the SWCC, γ_w = unit weight of water, γ_d = dry unit weight of soil, α = diffusion coefficient.

If the flow is taken for the three dimensions (Mitchell 1979):

$$\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\frac{f(x,y,z,t)}{k(h)}=\frac{1}{\alpha}\frac{\Delta u}{\Delta t} \tag{3.16}$$

The above equation gives the diffusion of moisture flow and the suction distribution as a function of time and distance.

3.2.2 Determination of Diffusivity Parameters

The diffusivity parameters of unsaturated soil can be determined using two testing methods in the laboratory. Mitchell (1979) proposed these two laboratory testing methods, for a drying soil column where the soil is exposed to air for evaporation and the other is a wetting test where the soil is kept in contact for soaking. The diffusion coefficient can be measured using the rate of change of suction in the prepared Proctor compacted soil specimen using thermal conductivity sensors and thermocouple psychrometers. These tests can be performed on a soil specimen to determine the soil water diffusivity parameters.

3.2.2.1. Drying test:

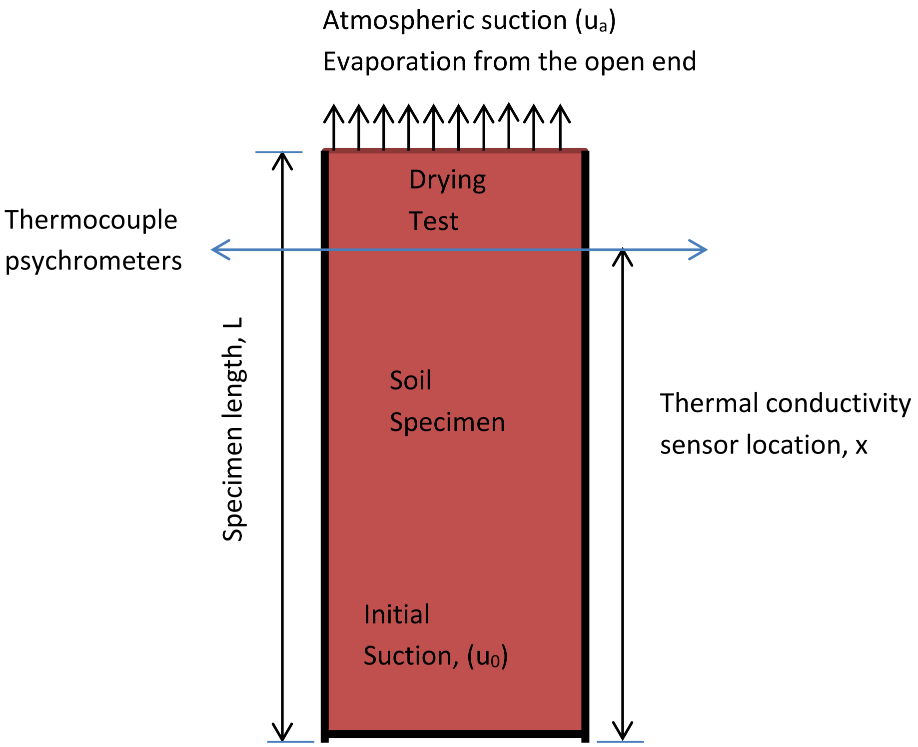


Figure 3.1. Boundary Conditions for Drying Test

A standard Proctor compacted sample is prepared with optimum moisture content and maximum dry density. The sample is saturated and then it is sealed all the sides leaving an open surface to the known atmospheric suction as shown in Figure 3.1. This test reflects the evaporation of moisture at the soil surface. Mitchell (1979) reports a constant which relates a suction gradient at the surface. The suction gradient represents the difference between the atmospheric suction (u_a) and the suction at the soil surface (u_l).

$$\left(\frac{du}{dx}\right)_{x=L} = h_e(u_a - u_l) \tag{3.17}$$

where h_e is the evaporation constant which is assumed to be independent of the state of suction. The value of the constant is given as 0.54 cm^{-1} (Mitchell, 1979). The solution to the given drying problem considers the following boundary conditions.

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

The initial suction of the soil at time zero should be known.

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

There should be constant suction at the sealed boundary. The change in suction with time at the sealed boundary should be zero.

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

Where u = total suction of the soil, u_0 = Initial total suction of the soil, u_a = Atmospheric suction

x = Suction sensor’s distance from closed end, L = length of the soil specimen

Mitchell (1979) found a solution to the drying diffusion problem by using separation of variables and properties of orthogonal functions. The solution is

$$u(x,t) = u_a + \sum_{n=1}^{\infty} \frac{2(u_0 - u_a)\sin z_n}{z_n + \sin z_n \cos z_n}\, e^{-\left(\frac{z_n^2 \propto t}{L^2}\right)} \cos\left(\frac{z_n x}{L}\right) \tag{3.18}$$

Where u(x, t) = suction as a function of location and time, z_n = solution of cot $z_n = z_n / h_e L$,

h_e = evaporation coefficient which is assumed to be 0.54 cm^{-1} based on Mitchell (1979) and

α_{dry} = drying diffusion coefficient.

3.2.2.2 Wetting Test

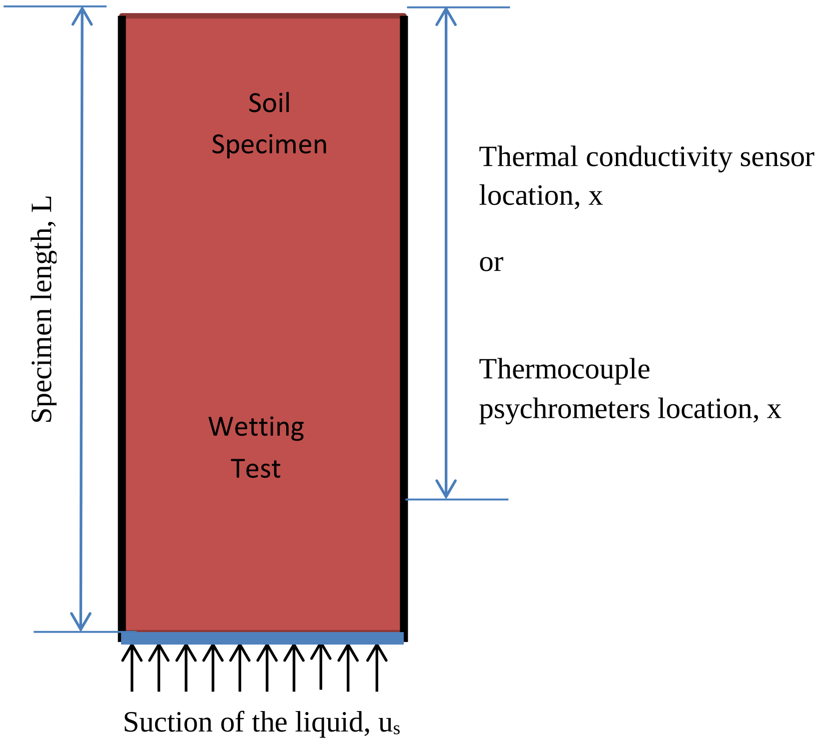


Figure 3.2. Boundary Condition for Wetting Process

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 3.2. The solution to the wetting soil column problem considers the following boundary conditions (Mitchell 1979), as depicted in Figure 3.2:

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

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

Open Boundary: $\frac{\partial u(L,t)}{\partial x} = u_s$

Mitchell (1979) found a solution to the wetting diffusion problem by using Laplace transforms:

$$u(x,t)= u_s + \frac{4(u_s-u_o)}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{2n-1} e^{\left(\frac{-(2n-1)^2\pi^2\, t\alpha_{wet}}{4L^2}\right)} \cos\left(\frac{(2n-1)\pi t}{2L}\right) \tag{3.19}$$

Tang et al. (2003) conducted several diffusion tests on high plasticity clays and showed that an assumption of n equals 1 in equation 3.3 gives adequate agreement between theoretical and experimental measurements in majority of the cases.

The simplified approach proposed by Mitchell has two main advantages (Aubeny et al. 2003):

- The coefficient of moisture diffusion can be determined easily from simple laboratory tests.
- Analytical solutions are possible with the linearization formulation for cases with simple boundary conditions. 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 (Mabirizi 2010). The moisture flow at any location can be specified by a single diffusivity parameter if the total suction as a function of length and time is known. This approach provides a practical basis for simple, economical, and relatively rapid laboratory measurements of unsaturated soil water diffusivity characteristics.

3.3. Empirical Correlations for Diffusion Coefficient

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

$$\propto = -S\,p\,\frac{\gamma w}{\gamma d} \tag{3.20}$$

where γ_w = unit weight of water, γ_d = dry unit weight of soil, and S = slope of suction (in pF) versus gravimetric water content curve i.e, Soil water characteristic curve, p = $\frac{h_0 k_0}{0.4343}$

h_0 = suction at which the soil saturates, approximately 200 cm, k_0 = saturated permeability of the soil. Jayatilaka and Lytton (1997) presented an empirical equation for estimating field moisture diffusivity from soil index properties given by

$$\propto_{\text{field}} = 0.0029 - 0.000162\ S - 0.0122\ \gamma_h \qquad (3.21)$$

Where S = slope of the soil water characteristic curve and γ_h = volume change coefficient. Texas Jayatilaka and Lytton 1997 gives an empirical equation for the determination of the parameter S.

$$S = -\ 20.29 + 0.155\ (LL\ \%) - 0.117\ (PI\ \%) + 0.0684\ (F) \qquad (3.22)$$

Where LL = liquid limit, PI = plastic limit and F = Percentage of particle sizes passing # 200 sieves on a dry weight basis.

CHAPTER IV

LABORATORY TESTING PROTOCOL

4.1 Overview

Using the Fredlund thermal conductivity sensors, matric suction changes in a soil sample can be measured overtime and using thermocouple psychrometers total suction changes can be determined overtime in the laboratory. These suction changes are observed in cylindrical soil samples that are compacted and then saturated for the drying test. The flow of moisture is one dimensional as all the boundaries are sealed except one which is exposed to the atmospheric suction in the laboratory in the drying test. For the wetting test, the open boundary is in contact with the surface of a liquid water. This approach of measuring the suction changes with time was developed at Oklahoma State University. Using the thermal conductivity sensors and thermocouple psychrometers, both drying and wetting diffusion tests can be conducted on the same soil specimens over a wide suction range.

Analytical methods for the determination of the diffusion coefficients were proposed by Mitchell (1979). Lytton et al. (2005) made advancements to the testing approach and produced drying diffusion coefficients on high plastic Texas soils. Mabirizi et al. (2010) developed a unified testing protocol for the drying test and the wetting test. In this research study, the testing protocol developed by Mabirizi (2010) was used for determining the wetting and drying diffusion coefficients using thermal conductivity sensors.

The diffusion tests are performed after calibrating the thermal conductivity sensors. The calibration is performed using the Fredlund thermal conductivity cell. After developing the calibration curve, the suction measurements are taken to determine the diffusion coefficients.

The atmospheric suction is also determined in the laboratory using the relative humidity and temperature measurements from a thermo hygrometer device. Kelvin’s equation was used to calculate the atmospheric suction.

This chapter includes the testing procedures for the determination of drying and wetting diffusion coefficients using thermal conductivity sensors. Calibration of the thermal conductivity sensors and thermocouple psychrometers is also discussed in this chapter.

4.2. Calibration of Fredlund Thermal Conductivity Sensors

The Fredlund thermal conductivity sensors work on the principle that the thermal conductivity of a porous media increases with increase in water content. The measurement of thermal conductivity of a standard porous block which is in equilibrium with the soil can be used to measure the suction of the soil. The water content of the ceramic tip is dependent on the matric suction of the soil. Hence the thermal conductivity of the sensor can be calibrated against the matric suction.

According to the operating instructions of the Fredlund thermal conductivity sensors, calibration is conducted for only one sensor in a batch of 24 sensors. The same calibration curve is used for all the sensors in the batch. The calibration curve for a sensor represents the response of a sensor under several applied matric suctions. The responses are measured as a temperature rise in the sensor when a specific quantity of heat that is 160 mA for 60 seconds is applied to the ceramic.

Fredlund et al. (1989) proposed a procedure for calibrating the thermal conductivity sensors.

Before the calibration, the ceramic tip of the sensor is saturated for two days. After saturation, the sensor is introduced in to a pressure chamber which can be connected to the air pressure. The temperature measurements are taken when the sensor is totally dry and another measurement is taken when the sensor is in saturated condition. The temperature readings are noted after applying air pressures of 50, 500 and 1000 kPa.

Using the following equation, the sensor calibration parameters are determined.

$$\varphi = \left[\frac{b\ (\Delta t - a)}{c - \Delta t}\right]^{d} \tag{4.1}$$

Where φ = applied matric suction in kPa, Δt = raise in temperature and a, b, c and d are the calibration parameters that should be given to the datalogger.

After the drying calibration curve, again the pressures are applied in a decreasing manner and the temperature measurements are collected. In this manner, the wetting calibration curve is obtained. Hysteresis can be observed from the calibration curve, hence two different sets of calibration parameters are to given to the data logger to determine the suction values. The calibration curve obtained for the sensors is given in Figure 4.1. The same calibration curve that was developed from one sensor was used for all the other sensors. (as suggested by the manufacturer). The ΔT values against saturation read from each sensor were all different in the calibration. Hence, there could be discrepancies in the wetting test of the soil using thermal conductivity sensors. If each sensor is calibrated separately and have a separate calibration curve, then the accuracy in measuring suction would be probably high.

According to the GCTS manual, the same calibration curve is utilized for all the sensors. Theoretically, all the sensors in a batch should give the same value when they are saturated however that is not the case based on laboratory test results. Therefore, the sensors whose values are relatively close to the calibrated sensor are used for the measurement of suction for the purpose of increasing the accuracy. The temperature values of the sensors at the time of saturation are given in the next chapter.

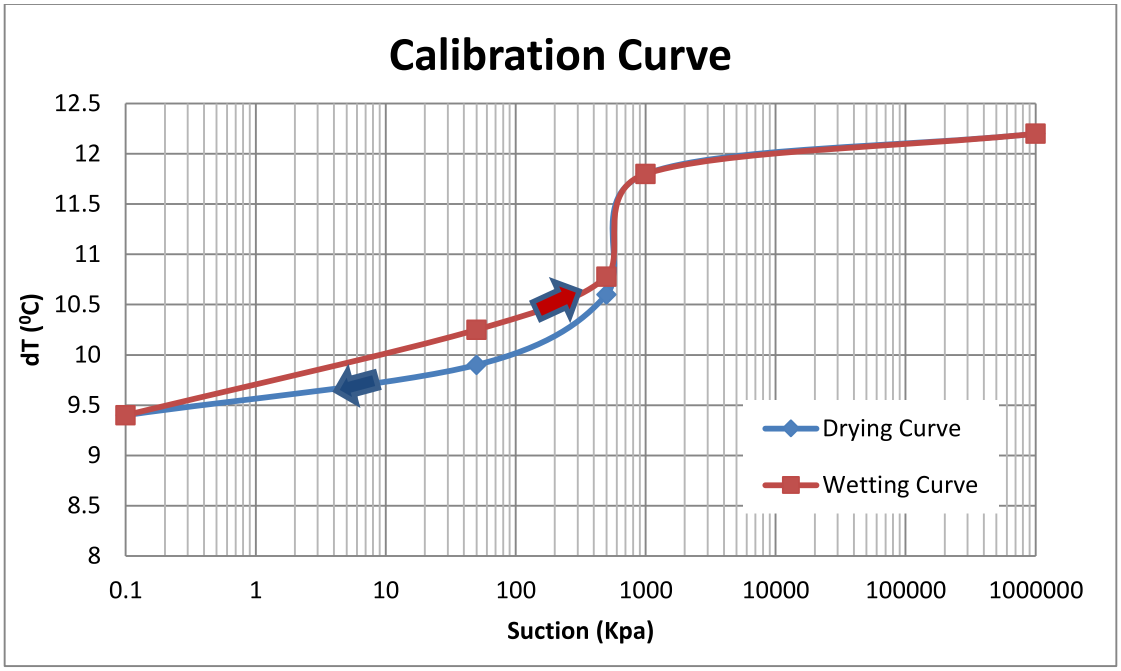


Figure 4.1. Calibration curve for Thermal Conductivity Sensors

4.3 Calibration of Thermocouple Psychrometers

Before the diffusion tests were performed, thermocouple psychrometers were calibrated to measure the total suction. Thermocouple psychrometers are the total suction measurement devices that work on the principle of changes in relative humidity as the moisture infiltrates or evaporates from the soil. The psychrometer is subjected under different total suctions and the output in terms of microvolt is obtained to develop a calibration curve. Different molalities of sodium chloride (NaCl) solutions with known water potentials were used to calibrate the psychrometers. Glass jars were employed to calibrate a number of psychrometers at one time. The calibration was performed by immersing the psychrometers in different molalities of NaCl salt solutions. The osmotic suction values of different molality solutions are given in Table 4.1. The calibration setup is shown in Figure 4.2.

Table 4.1. Osmotic Suction Values of the NaCl and KCl Solutions at 25°C (Hamer and Wu 1972, Bulut et al. 2001)

Sodium Chloride (NaCl)			Potassium Chloride (KCl)		
Molality (m)	**Osmotic Coefficient (ϕ)**	**Osmotic Suction (pF)**	**Molality (m)**	**Osmotic Coefficient (ϕ)**	**Osmotic Suction (pF)**
0.000	1.00000	0.00	0.000	1.00000	0.00
0.001	0.98840	1.69	0.001	0.98800	1.69
0.002	0.97604	1.99	0.002	0.98400	1.99
0.005	0.96804	2.39	0.005	0.97600	2.39
0.010	0.96804	2.68	0.010	0.96700	2.68
0.020	0.95832	2.98	-	-	-
0.050	0.94357	3.37	0.050	0.94000	3.37
0.100	0.93250	3.67	0.100	0.92700	3.67
0.200	0.92387	4.14	0.200	0.91300	3.96
0.400	0.92106	4.27	0.400	0.90200	4.26
0.500	0.92224	4.36	-	-	-
0.600	0.92427	4.44	-	-	-
0.700	0.92691	4.51	0.800	0.89800	4.56
1.000	0.93729	4.57	1.000	0.89800	4.65
1.200	0.94567	4.75	1.200	0.90000	4.73
1.500	0.95980	4.86	-	-	-
2.000	0.98657	4.99	2.000	1.01638	4.96
2.200	0.99818	5.04	-	-	-

Figure 4.2. Calibration of Thermocouple Psychrometers

A CR7 data logger 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 4.3.

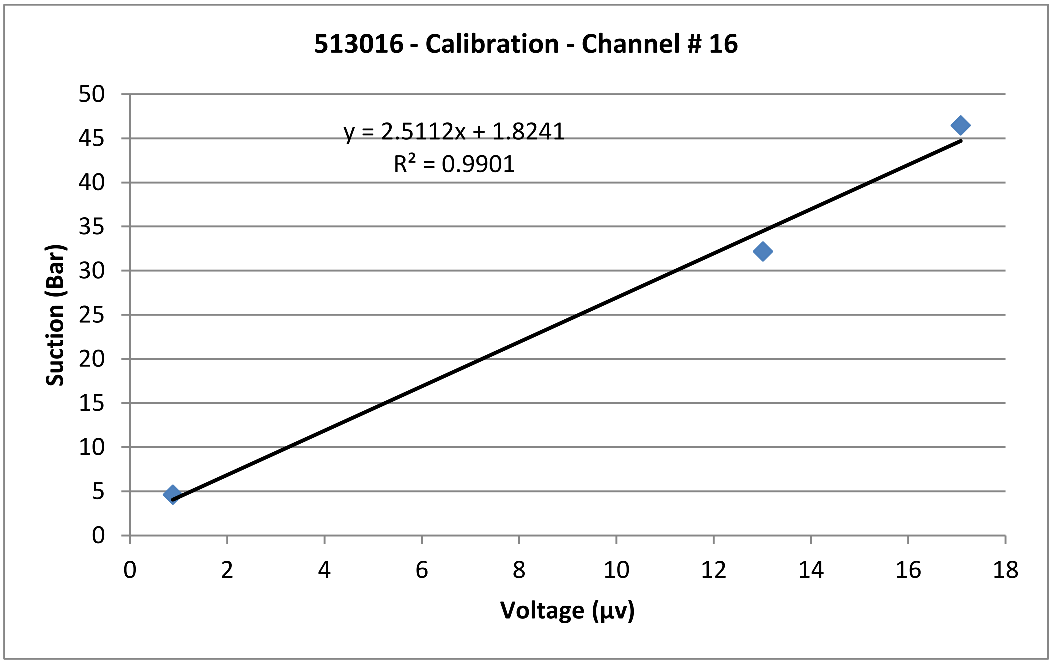


Figure 4.3. Calibration Curve for Thermocouple Psychrometer

4.4. Measurement of Soil Water Diffusion Coefficients

Analytical methods for the determination of the diffusion coefficients were proposed by Mitchell (1979). A detailed testing methodology was not provided by Mitchell however Aubeny et al. (2005) made advancements to the testing approach and produced drying diffusion coefficient values for a number of Texas soils. Mabirizi et al. (2010) developed a unified testing protocol for the drying and wetting tests. By constructing a new water bath for temperature equilbrium, the tests were performed on several soil specimen using thermocouple psychrometers. The hysteresis effect on the evaporation and soaking parameters were also evaluated by Mabirizi et al. (2010). In this research study, the same protocol was used for determining the wetting and drying diffusion coefficients using thermal conductivity sensors. The diffusion values from thermal conductivity sensors are compared with the values that are obtained from thermocouple psychrometers.

4.4.1. Sample preparation

In this research study, the diffusivity coefficients were measured on Proctor compacted samples of 160 cm long and 90 cm in diameter. The samples were compacted to the maximum dry density and optimum moisture content and then they were saturated by wetting the samples for the drying tests. The wetting was performed by wrapping the specimen with a wet cloth. After the sample is saturated, it is taken and wrapped all around tightly with an electric tape. After the sample is cured for the suction equilibrium, it is wrapped all around except one end for the drying and wetting tests. The thermal conductivity sensor tip is 65 mm long and 28 mm in diameter. A hole is made on the side of the specimen for inserting the sensor as shown in Figure 4.4. The hole is made carefully not to disturb the specimen. The distance from the open surface to the hole is noted. To have a shorter testing time, the distance from the open end should be shorter. At the same level, but at a different location, a calibrated psychrometer is inserted into the soil sample as shown in Figure 4.4. It is very important to ensure that no artificial

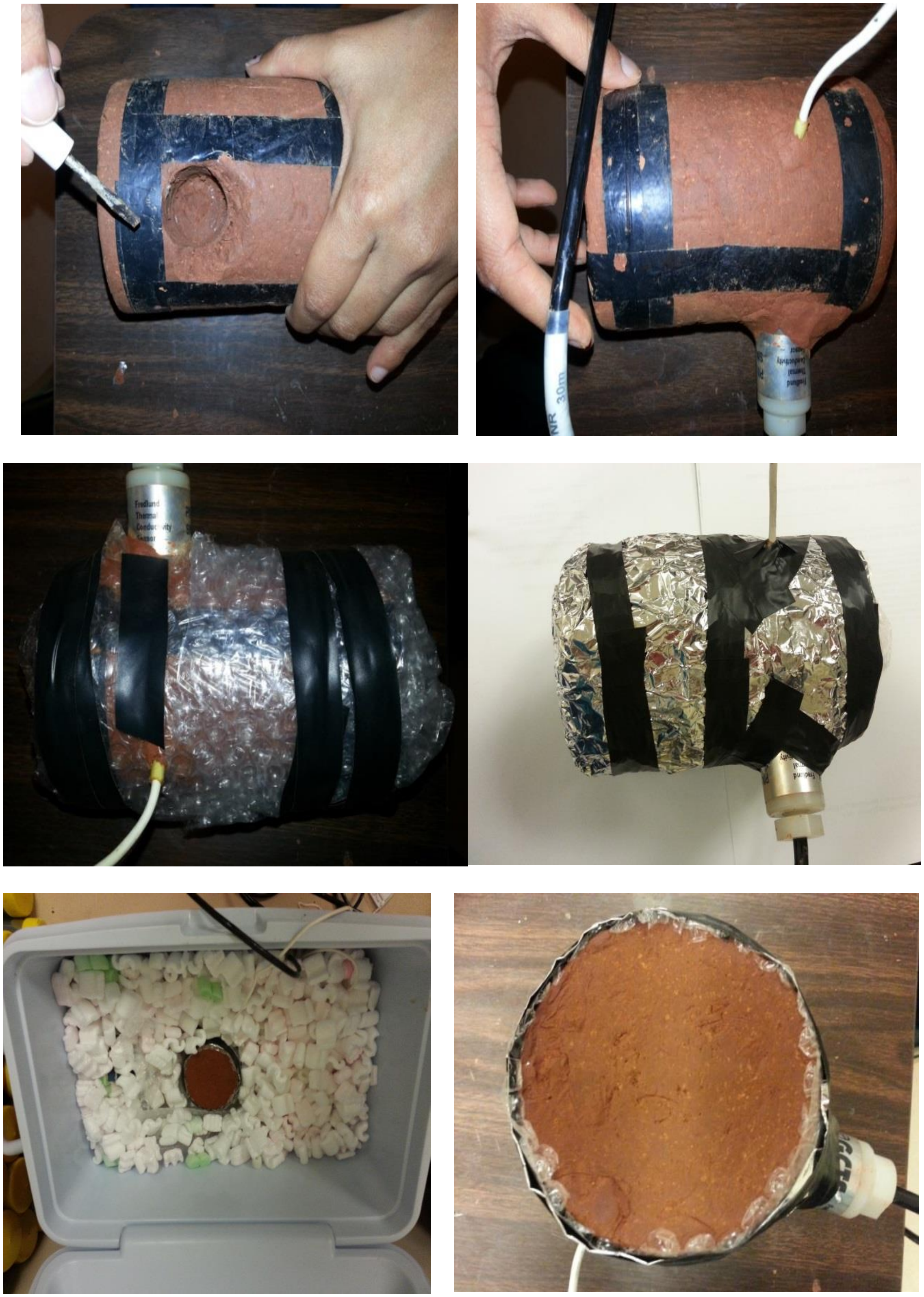


Figure 4.4. Testing set up and Sample Preparation for Drying Diffusion Coefficient

cracks are induced when making holes in the specimen. The hole should be tightly and carefully sealed to keep the thermal conductivity sensor and the psychrometer from moving and to avoid any loss or gain of moisture through the holes. After the sensors are inserted securely, the specimen should be sealed completely against any moisture loss or evaporation. To prevent the loss or gain of moisture, the specimen should be carefully sealed with plastic wrap and aluminum foil except the end that is selected to expose to the atmosphere of known suction for the drying test or liquid for the wetting test. The diffusivity tests are started by keeping the specimen in an ice chest and fill the spaces in the ice chest with plastic bubble wraps for temperature control.

4.4.2. Drying and wetting tests

For the drying test, the soil specimen which is wrapped up with plastic wrap and aluminum foil is placed in the ice chest with the open end of the specimen exposed to the atmosphere of the testing room. The space remained in the ice chest is covered with the plastic bubble wraps to maintain the temperature control. The ice chest has to be placed on a level ground where the level is flat to maintain stability.

For the wetting test, the samples are rested on the ceramic stones in a bowl filled with water. A piece of cloth is placed between the ceramic stones and the sample to maintain intimate contact. The level of water in the bowl should always be kept constant so that the sample just touches the surface of water as shown in Figure 4.5. The duration of the test can be 7-10 days for either wetting or drying test. A step by step procedure for the testing protocol is given in Appendix A.

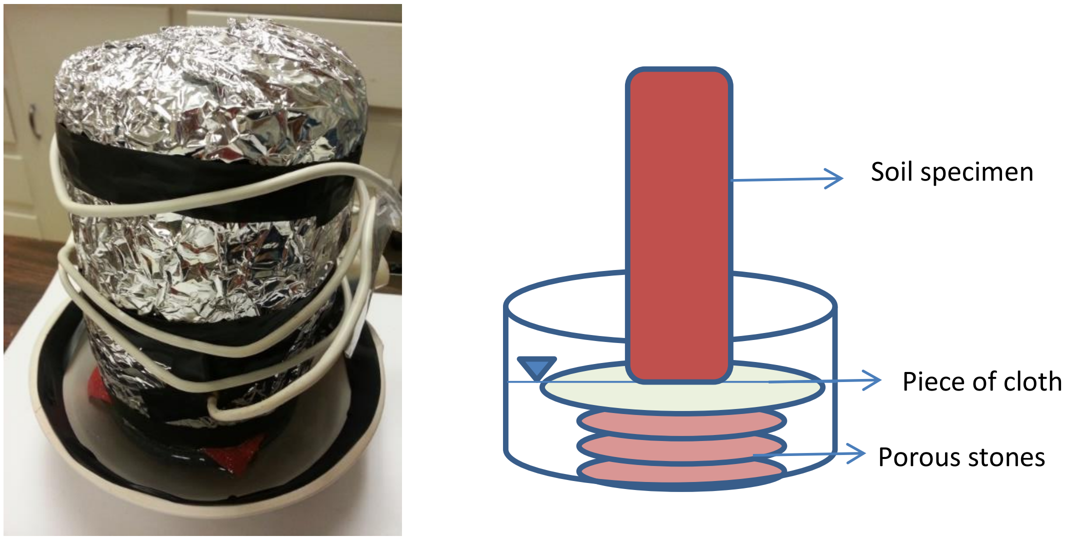


Figure 4.5. Testing Setup for Wetting Diffusion Coefficient

4.5 Measurement of Atmospheric Suction

The atmospheric suction can be determined using the relative humidity measurements of the room 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:

$$u_a = \frac{RT\,\rho_W}{M_W}\, ln(RH) \qquad (4.2)$$

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. 6. Interpretation of Data

The unsaturated drying and wetting diffusion coefficients can be determined using the suction measurements and corresponding time data from the drying and wetting processes. After determining the diffusion coefficient using a Matlab program, the theoretical and experimental values are plotted. The plot is given in Figure 4.6.

The parameters that are needed for the calculation of the diffusion coefficient are the length of the specimen, the location of the psychrometer or the sensor from the closed end of the specimen and the atmospheric suction that the open end of the soil specimen was exposed in the time of testing. The initial suction of the soil specimen is also needed. The initial suction was obtained from the first measured value from the thermal conductivity sensor. The evaporative coefficient is taken as 0.54 cm^{-1} (Mitchell, 1979).

The initial suction in the case of a wetting test is considered as the final suction value obtained from the drying test. The suction of the liquid for the wetting test was decided after a parametric analysis on the plots of the theoretical curve and the measured values from the wetting test. The suction of the liquid is taken as 1.5 pF.

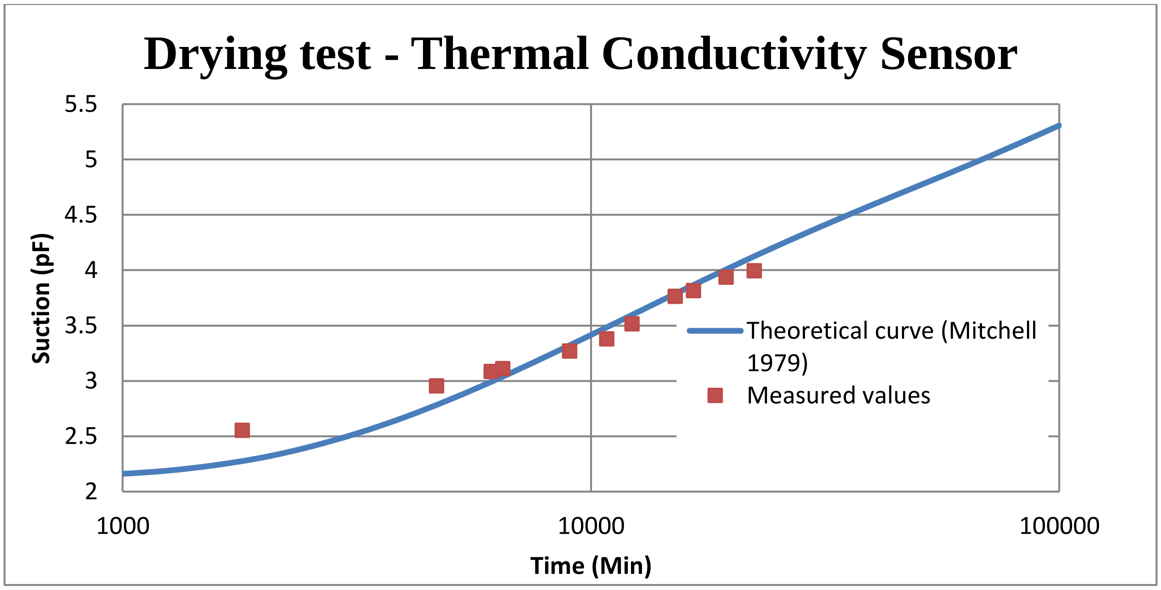


Figure 4.6. Theoretical and Experimental Data Plot

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. Initially, a value of α is assumed to compute the theoretical suction value corresponding to each measurement location x and measurement time t using Equation 3.18 for drying test or Equation 3.19 for the wetting test.

2. Compute the error between the theoretical suction values (theoretical (u)) and measured suction values (measured (u)) for drying test or wetting test (i.e., the error, E= theoretical (u) – measured (u)).

3. Calculate the sum of the squared errors (E_s) for all the measurements of suction for drying test or wetting test, $Es = \Sigma$ (theoretical (u) – measured (u))^2.

4. Optimize α (from step 1) to minimize Es 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 2 decimal places in cm^2/min. Hand calculations of Equation 3.7 is not practical. These equations can simply be programmed using a numerical computing language, i.e., Matlab and Microsoft Excel was used to plot the measured and theoretical suction data. A typical plot is shown in Figure 4. 6.

CHAPTER V

ANALYSIS OF TEST RESULTS

5.1. Overview

Soil specimens from three different sites were obtained from Oklahoma Department of Transportation. Basic soil tests were conducted on these soil specimens for grain size distribution and index properties. Standard Proctor compaction tests were also performed on these soil types to determine the maximum dry density and the optimum moisture content.

Using the optimum moisture content of the soil, standard Proctor compacted soil samples were prepared and used for suction measurement tests. Both drying and wetting diffusion tests were performed on the specimen. The drying test was performed first by exposing the open end of the specimen to the atmosphere and then the wetting test was performed by exposing the open end to the known liquid suction. Both thermal conductivity sensors and thermocouple psychrometers are used to determine the diffusion coefficient values.

The comparison of the drying and wetting diffusion coefficients at different suction ranges from both thermal conductivity sensors and thermocouple psychrometers has been made using the test results.

5.2. Site Description

Oklahoma Department of Transportation (ODOT) conducted the drilling process and sampled the shelby tube soil specimens used in this study. The sites are located in Oklahoma City near Lake Hefner (named as Lake Hefner site), in Norman on Robinson Street (named as Norman site), and along Interstate Highway I-35 in Ardmore (named as Ardmore site) in Oklahoma.

5.3. Calibration data of the Thermal Conductivity Sensors and Thermocouple Psychrometers

Thermal conductivity sensors measure matric suction of the soil. The measurement of matric suction is made indirectly by measuring the raise in the temperature (dT) of the sensor when suction changes. The sensors were calibrated using a FTC cell. The sensors were saturated for two days and dT values were obtained corresponding to the wet sensors from the GCTS software. The values of the dT when the sensors are wet are given in Table 5.1. The calibration curve was developed for sensor number 3. Since the dT value at the time of saturation for the sensors 3, 7 and 8 is relatively close to the sensor that was calibrated, only three sensors were used for this study. The calibration and operation of the thermal conductivity sensors are presented in Appendix A.

Table 5.1. dT Measurements for the Saturated Thermal Conductivity Sensors

Saturated Sensor Number	dT value (^{0}C)
1	9.746
3	9.535
4	9.436
6	8.795
7	9.467
8	9.527
10	11.727

The calibration curve developed for the sensor number 4 is given in Figure 4.1. The values of a, b, c and d parameters for the drying curve are 9.436, 39.7,12.2 and 1.8 respectively and for the wetting curve are 9.436 , 9.33, 12.2 and 2.8 respectively.

The thermocouple psychrometers measure total suction indirectly by measuring the relative humidity of the vapor in equilibrium with the soil water. The suction measurements are given in terms of microvolt readings. The thermocouple sensors were inserted in to the salt solutions with known osmotic potential and the microvolt readings were obtained. The suction measurements against the microvolt readings were plotted for three sensors (i.e., 513016, 513018 and 513013) that were used in this study. The calibration curves for the three thermocouple psychrometers are given in Figures 5.1, 5.2, and 5.3.

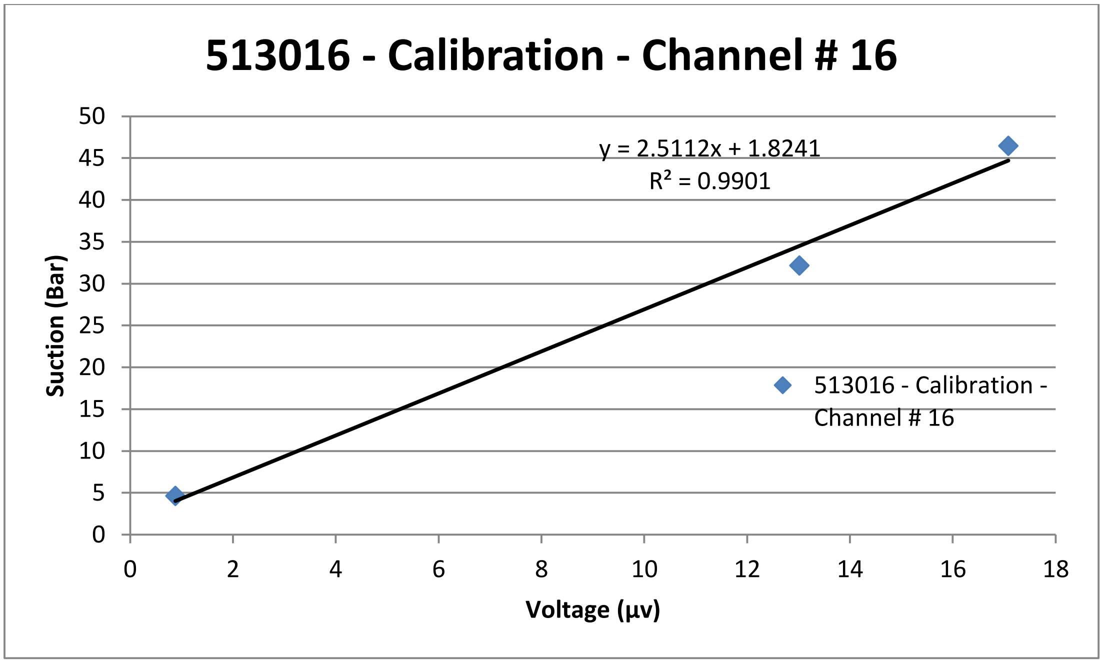


Figure 5.1. Calibration Curve of the Thermocouple Psychrometer 513016

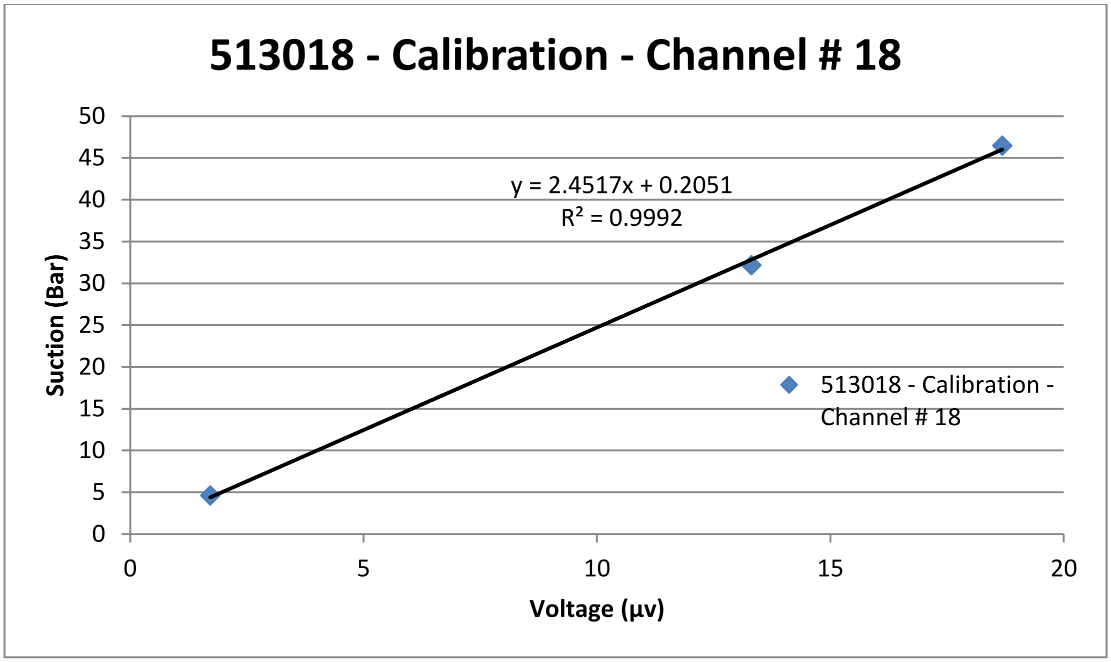


Figure 5.2. Calibration Curve of the Thermocouple Psychrometer 513018

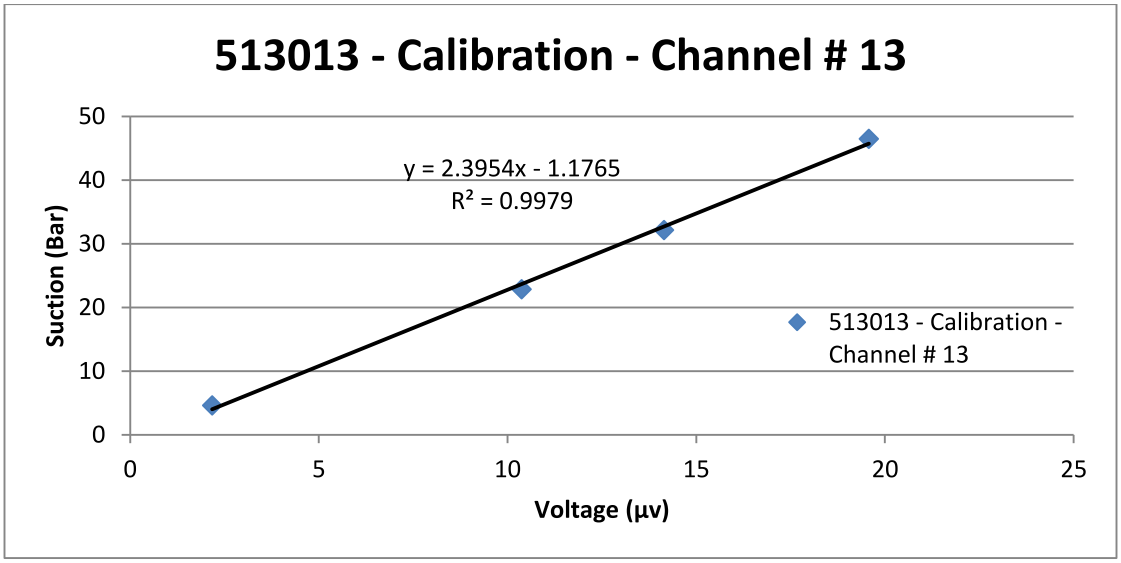


Figure 5.3. Calibration Curve of the Thermocouple Psychrometer 513013

5.4. Evaluation of Test Results

The diffusion coefficient test results for the Norman, Lake Hefner and Ardmore sites are given in Tables 5.2, 5.5 and 5.8, respectively from both thermal conductivity sensors and thermocouple psychrometers. The comparison of the coefficients from both sensor types is given in Table 5.2.

The measured values and the theoretical curves for the determined diffusion coefficients are given in Appendix B. In addition, the basic index properties and the other soil properties are given in Tables 5.3, 5.6, and 5.9 for each site. The comparison of the drying and wetting diffusion coefficients obtained from both thermal conductivity sensors and thermocouple psychrometers for different suction ranges are given in Tables 5.4, 5.7 and 5.10 for each site. The same comparison has been depicted in a plot in Figure 5.4.

5.4.1. Norman site

Table 5.2. Comparison of Diffusion Coefficients from Thermal Conductivity Sensors and Thermocouple Psychrometers for Norman site

Coefficient of moisture diffusion, α (cm^2/ min)		From Thermal Conductivity Sensors	From Thermocouple Psychrometers
Drying	Norman 1	1.2258×10^{-3}	1.9211×10^{-3}
	Norman 2	0.9940×10^{-3}	1.2589×10^{-3}
Wetting	Norman 1	2.1528×10^{-3}	3.9739×10^{-3}
	Norman 2	2.9806×10^{-3}	4.0732×10^{-3}

Table 5.3. Basic Soil Properties of the Norman Site Soil

Properties	Norman site
Liquid Limit (%)	36.5
Plastic limit (%)	16.7
Plasticity Index (%)	19.8
Maximum dry density (pcf)	112.8
Optimum moisture content (%)	17.5
% of soil passing through 200 sieve (%)	82
% of soil passing through # 2 microns (%)	24

Table 5.4. Comparison of diffusion coefficients in different suction ranges for Norman site

		Suction Ranges in pF scale					
		From Thermocouple Psychrometers		From Thermal Conductivity Sensors			
		3.5-4.0	4.0-4.5	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0
		Coefficient of moisture diffusion, $\alpha \times 10^{-3}$ (cm^2/ min)					
Drying	Norman 1	2.4177	1.4244	-	6.4572	3.4773	2.2217
	Norman 2	1.292	1.2258	1.9542	1.4575	0.9609	0.9278
Wetting	Norman 1	1.588	1.3515	-	2.3894	1.5236	2.5697
	Norman 2	1.689	1.3921	3.1130	3.1130	1.6893	1.6562

Two standard Proctor compacted specimens were tested from the Norman site (i.e., Norman 1 and Norman 2). First the samples were tested for the drying cycle and then the wetting test was followed. The soil has a liquid limit of 36.5 % and plastic limit of 16.7 %. The atmospheric suction in the testing room was relatively constant ranging between 6.24 to 6.27 pF. The length of the Norman 1 and Norman 2 specimens were 14.5 and 15 cm respectively. Table 5.2 lists the diffusion coefficient values from both thermal conductivity sensors and thermo couple psychrometers. The measured diffusion coefficients indicate the following:

- $\propto_{wet}$ values are higher than the $\propto_{dry}$ in both the specimens Norman 1 and Norman 2.
- The diffusion coefficient values from thermal conductivity sensors are smaller than from the thermocouple psychrometers in both wetting and drying tests. The higher value of α might be due to the measurement of total suction from thermocouple psychrometers whereas it is matric suction measurement in case of thermal conductivity sensor.
- The samples do not have too many cracks on the surface at the end of the drying test.
- The diffusion coefficient values decrease as the measured range of the suction increases in both drying and wetting case.

5.4.2. Lake Hefner site

Table 5.5. Comparison of Diffusion Coefficients from Thermal Conductivity Sensors and Thermocouple psychrometers

Coefficient of moisture diffusion, α (cm^2/ min)		From Thermal Conductivity Sensors	From Thermocouple Psychrometers
Drying	Lake Hefner 1	0.6629×10^{-3}	0.7622×10^{-3}
	Lake Hefner 2	0.8284×10^{-3}	1.3913×10^{-3}
Wetting	Lake Hefner 1	0.7291×10^{-3}	0.4973×10^{-3}
	Lake Hefner 2	2.2104×10^{-3}	3.9408×10^{-3}

Table 5.6. Basic Soil Properties of the Lake Hefner Site soil

Properties	Lake Hefner site
Liquid Limit (%)	37.6
Plastic limit (%)	23.4
Plasticity Index (%)	14.2
Maximum dry density (pcf)	99.0
Optimum moisture content (%)	26
% of soil passing through 200 sieve (%)	63
% of soil passing through # 2 microns (%)	20

Table 5.7. Comparison of Diffusion Coefficients in Different Suction Ranges for Lake Hefner site

		Suction Ranges in pF scale					
		From Thermocouple Psychrometers		From Thermal Conductivity Sensors			
		Coefficient of moisture diffusion, $\alpha \times 10^{-3}$ (cm^2/ min)					
		3.5-4.0	4.0-4.5	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0
Drying	Lake Hefner 1	1.196	0.7953		1.8548	1.0602	1.0271
	Lake Hefner 2	1.6562	1.1595	0.5967	0.7291	0.8946	0.8946
Wetting	Lake Hefner 1	0.398	0.4973	3.1130	3.1130	1.6893	1.6562
	Lake Hefner 2	1.6692	1.4839		2.6350	2.3598	1.6584

Two standard Proctor compacted specimens were tested from the Lake Hefner site (i.e., LakeHefner1 and Lake Hefner 2). First, the samples were tested for the drying cycle and then the wetting test was followed. The soil has a liquid limit of 37.6 % and plastic limit of 23.4 %. The compaction test was conducted using a optimum moisture content of 26% obtained from standard Proctor compaction test. The atmospheric suction in the testing room was relatively constant ranging between 6.24 to 6.27 pF. The length of the Lake Hefner 1 and Lake Hefner 2 specimens were 15 and 16 cm respectively. Table 5.5 lists the diffusion coefficient values from both thermal conductivity sensors and thermocouple psychrometers. The determined diffusion coefficients indicate the following:

- $\propto_{wet}$ values are larger than the $\propto_{dry}$ in the Lake Hefner 2 specimen. The $\propto_{wet}$ value is smaller in the Lake Hefner 1 specimen when measured with thermocouple psychrometers.
- The diffusion coefficient values from thermal conductivity sensors are smaller than from the thermocouple psychrometers in Lake Hefner 2 and the value from thermal conductivity sensor is larger than the diffusion coefficient value from thermocouple psychrometer in Lake Hefner 2 specimen. The increase in the value of α might be due to the measurement of total suction from thermocouple psychrometers whereas it is matric suction measurement in the case of thermal conductivity sensor.
- The samples do not have too many cracks on the surface at the end of the drying test.
- The diffusion coefficient values decrease as the range of the suction increases in both drying and wetting case as shown in Table 5.7

5.4.3. Ardmore site

Table 5.8. Comparison of Diffusion Coefficients from Thermal Conductivity Sensors and Thermocouple Psychrometers

Coefficient of moisture diffusion, α (cm^2/ min)		From Thermal Conductivity Sensors	From Thermocouple Psychrometers
Drying	Ardmore 1	2.2853×10^{-3}	-
	Ardmore 2	0.5304×10^{-3}	0.8284×10^{-3}
Wetting	Ardmore 1	5.9605×10^{-3}	-
	Ardmore 2	1.8217×10^{-3}	-

Table 5.9. Basic Soil Properties of the Ardmore Site Soil

Properties	Ardmore site
Liquid Limit (%)	52.6
Plastic limit (%)	27.0
Plasticity Index (%)	25.6
Maximum dry density (pcf)	105.2
Optimum moisture content (%)	14
% of soil passing through 200 sieve (%)	42
% of soil passing through # 2 microns (%)	12

Table 5.10. Comparison of Diffusion Coefficients in Different Suction Ranges for Ardmore site

		Suction Ranges in pF scale					
		From Thermocouple Psychrometers		From Thermal Conductivity Sensors			
		Coefficient of moisture diffusion, α × 10^{-3} (cm^2/ min)					
		3.5-4.0	4.0-4.5	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0
Drying	Ardmore 1	-	-		3.1462	2.0866	1.2920
	Ardmore 2	0.9278	0.6298	2.2522	0.6960	0.6298	0.4973
Wetting	Ardmore 1				2.3541	1.6587	1.4235
	Ardmore 2				1.2866	0.994	0.7622

Two standard Proctor compacted specimens were tested in Ardmore site (i.e., Ardmore 1 and Ardmore 2). First the samples were tested for the drying cycle and then the wetting test was followed. The soil has a liquid limit of 52.6 % and plastic limit of 27 %. The compaction test was performed using the optimum moisture content of 14 % obtained from standard Proctor compaction test. The atmospheric suction in the testing room was relatively constant ranging between 6.24 to 6.27 pF. The length of the both Ardmore1 and Ardmore 2 specimens was 16 cm. Table 5.8 lists the diffusion coefficient values from both thermal conductivity sensors and thermocouple psychrometers. The measured diffusion coefficients indicate the following:

- $\propto_{Wet}$ values are higher than the $\propto_{dry}$ in Ardmore 1 sample. The $\propto_{wet}$ value is smaller in the other sample, Ardmore 2.
- The diffusion coefficient values from thermal conductivity sensors are smaller than from the thermocouple psychrometers in Ardmore 2 specimen. The increase in the value of α might be due to the measurement of total suction from thermocouple psychromerts whereas it is matric suction measurement in case of thermal conductivity sensor.
- The samples have too many cracks on the surface at the end of the drying test.
- The diffusion coefficient values decrease as the range of the suction increases in both drying and wetting case
- The psychrometers inserted into the specimen were not working well to obtain a diffusion coefficient from them.

The comparison of the diffusion coefficients from thermal conductivity sensors and thermocouple psychromerts were plotted in Figure 5.5. The points that are above the 1:1 line indicate a larger alpha value with thermocouple psychrometers. The wetting and drying diffusion coefficients were also compared in Figure 5.6 which shows that 65% of the data lies on the upper side of the 1:1line. The wetting diffusion coefficient values are larger than the drying diffusion coefficient values in 65% of the cases.

In Figure 5.7, the diffusion coefficient values obtained from the thermal conductivity sensors against the lowest range of the suction measured were plotted. Each line in the plot represents each specimen. As the suction increases, the diffusion coefficient value decreases in most of the cases. In Figure 5.8, the diffusion coefficient values obtained from the thermocouple psychrometers against the lowest range of the suction measured were plotted. Each line in the plot represents each specimen. As the suction increases, the diffusion coefficient value decreases in most of the cases.

Figure 5.9 and Figure 5.10 represent a good fit and a bad fit respectively between theoretical line and measured values. The remaining plots for each test are given in Appendix B. Figure 5.11 is the change of suction with time using thermal conductivity sensors and thermocouple psychrometers. The plots of all the suction versus time are given in Appendix C.

Figure 5.10 indicates that the behavior of the theoretical curve for the wetting test given by Mitchell (1979) is distinctively different from the behavior of the test results using thermal conductivity sensors. At very low suction less than 2 pF, the change in suction is very high with time as the moisture content of the soil increases. Similar trends have been observed for different porous media (Bulut and Wray 2005) and in the calibration curve of Schleicher & Schuell No.589-white hard Filter Paper (Bulut et al. 2002) as shown in Figure 5.4. However, Mitchells approach does not follow the experimental trend.

In Appendix D, A parametric analysis was performed on Mitchell’s equation for the determination of wetting coefficient. All the plots from the parametric study are given in Appendix D. The behavior of the curve is observed by changing a parameter keeping all the other parameters constant. The behavior of the curve is different from the behavior of the experimental values in all the possible plots. Based on the experimental results, It is believed that Mitchell’s equation for the wetting test should be evaluated carefully.

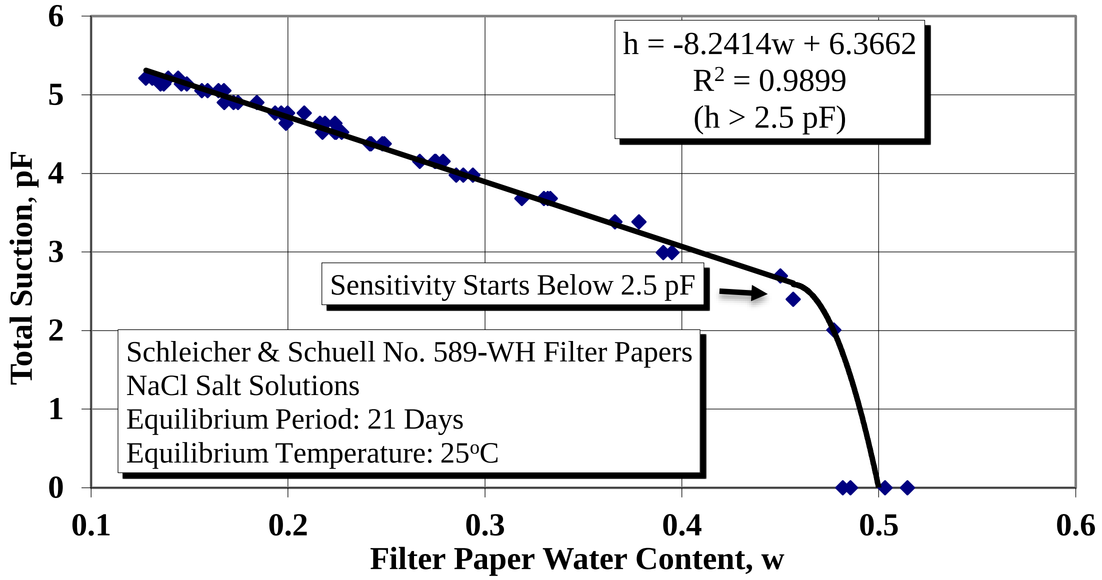


Figure 5.4. Calibration curve of Schleicher & Schuell No.589-white hard Filter Paper at 25oC (Bulut et al. 2002).

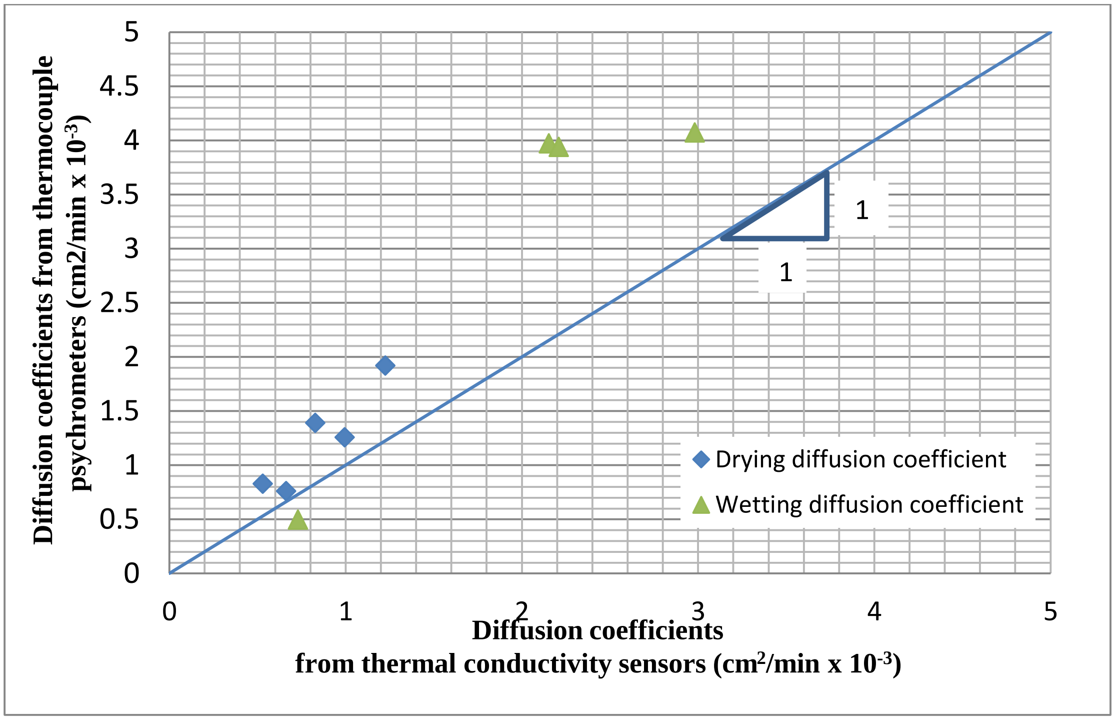


Figure 5.5. Comparison of Diffusion Coefficients from Thermal Conductivity Sensors and Thermocouple Psychrometers

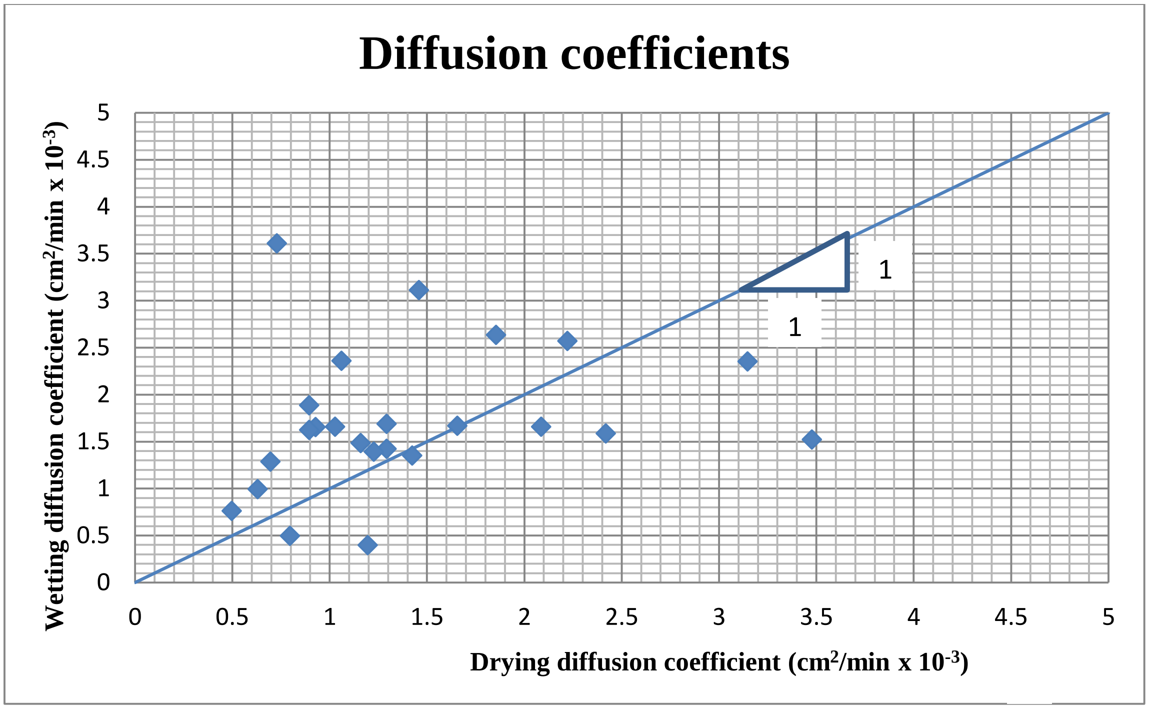


Figure 5.6. Comparison of Wetting and Drying Diffusion Coefficients

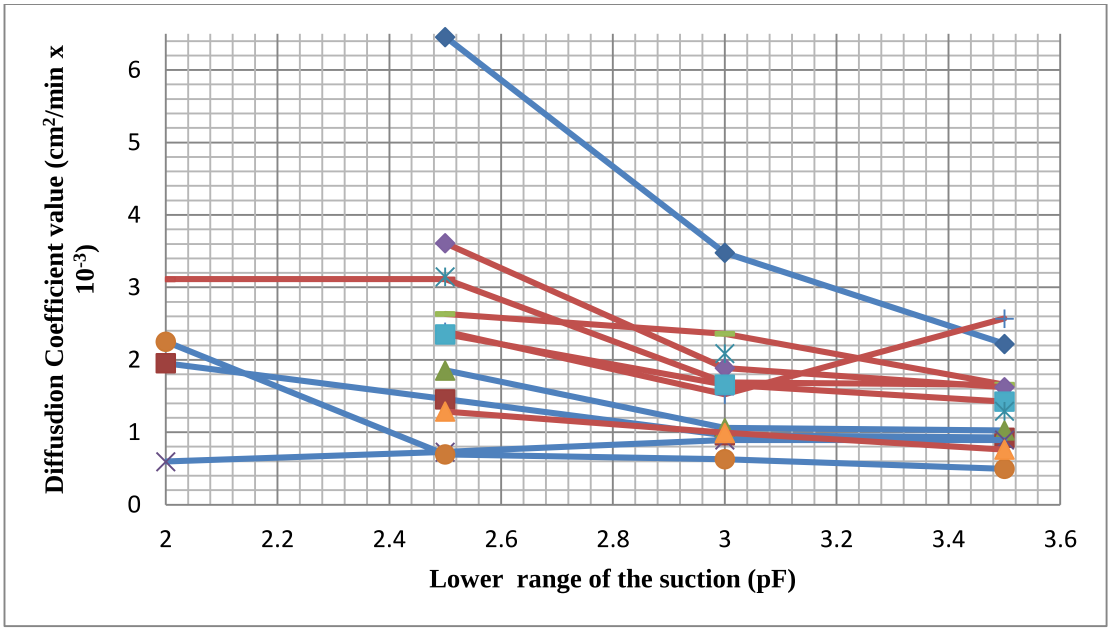


Figure 5.7. Comparison of Wetting and Drying diffusion Coefficients at Different Suction Ranges from Thermal Conductivity Sensors

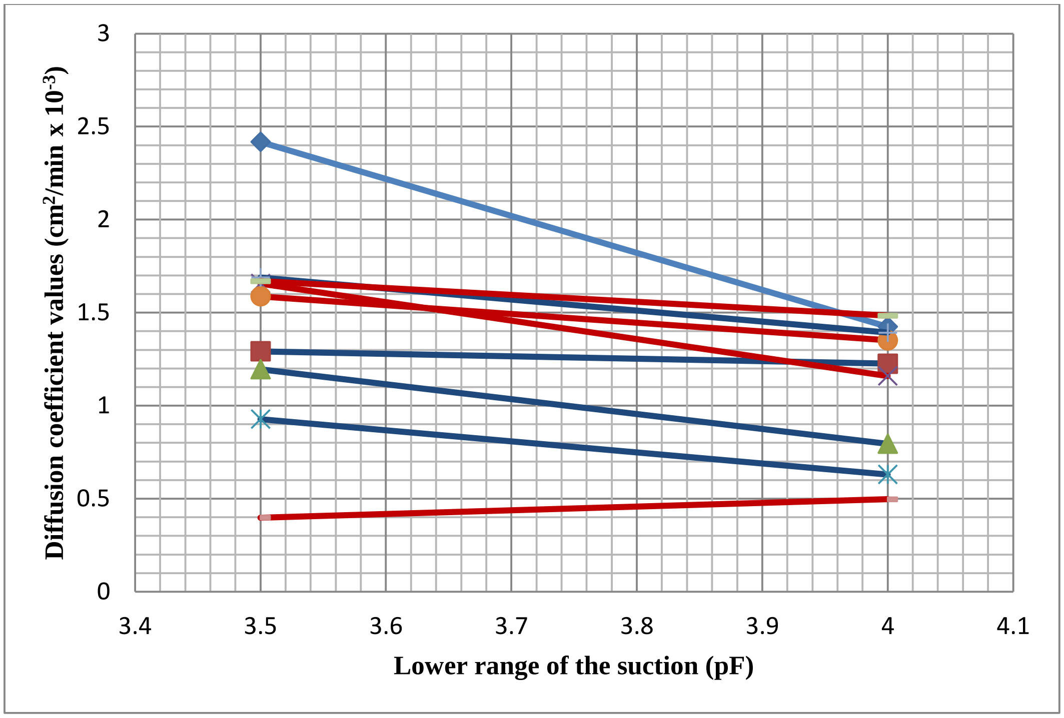


Figure 5.8. Comparison of Wetting and Drying Diffusion Coefficients at Different Suction Ranges from Thermocouple Psychrometers

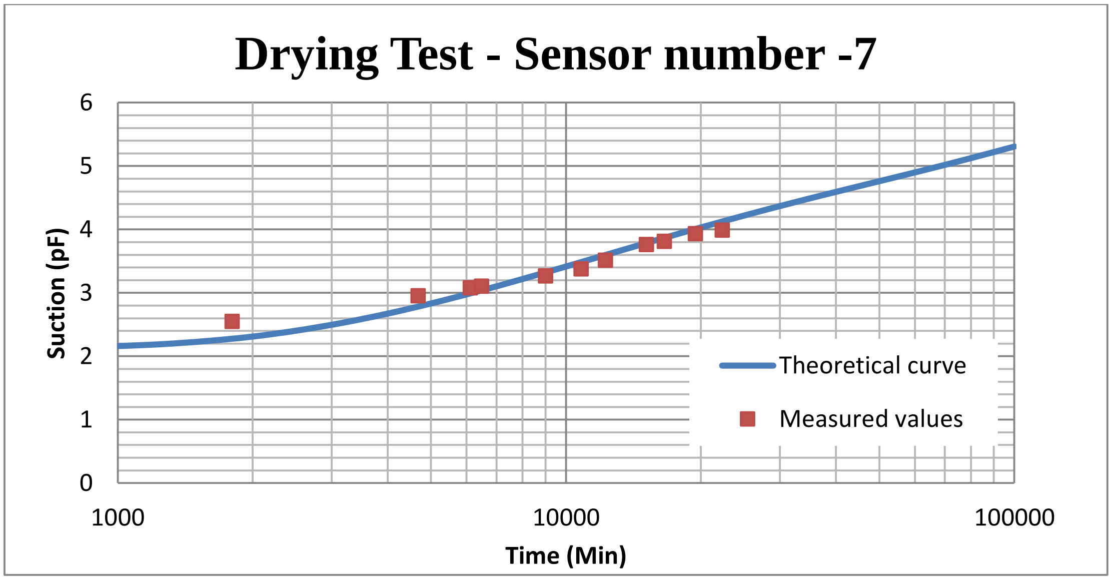


Figure 5.9. Good fit Between Theoretical and Measured Values from Thermal Conductivity Sensor

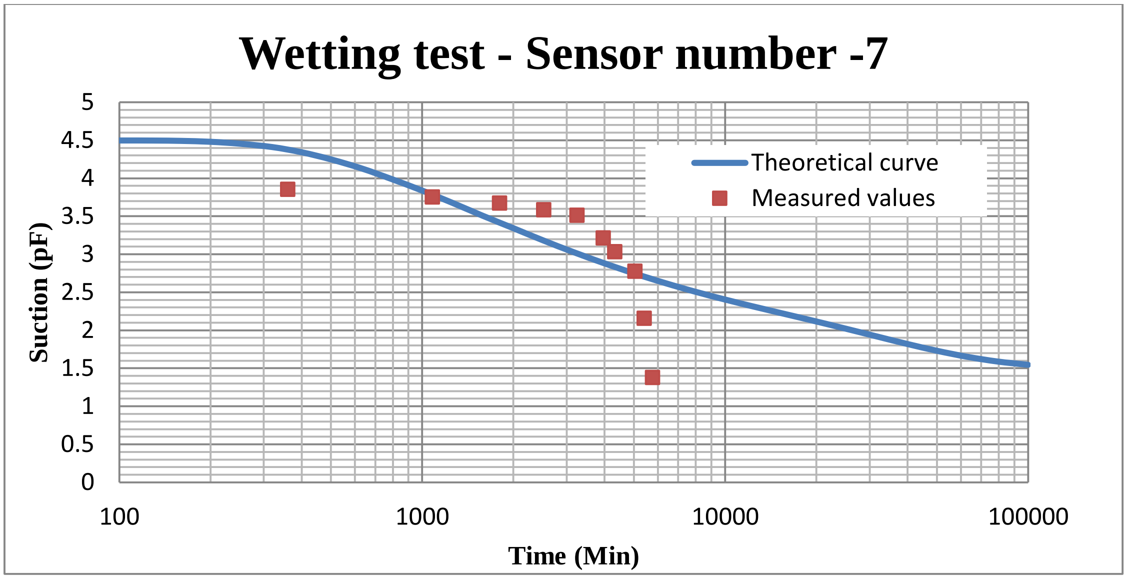


Figure 5.10. Bad Fit between Theoretical and Measured Values from Thermal Conductivity Sensor

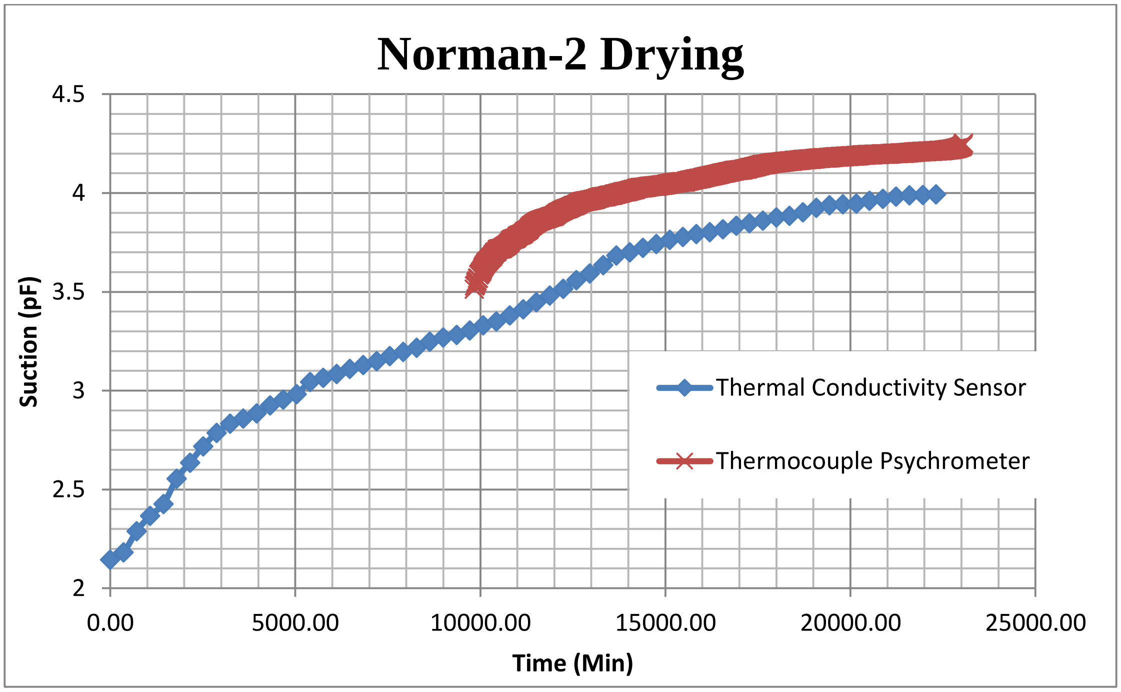


Figure 5.11. Change in Suction with Time

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The measurements of total suction with time can be obtained from thermocouple psychrometers and the matric suction measurements with time can be obtained from thermal conductivity sensors. The wetting and drying coefficients of moisture diffusion can be determined in the laboratory using both the devices by inserting them into the soil specimen. Mitchell’s (1979) proposal of one dimensional analysis using rate of moisture flow through soil provides a simple, economical and reliable framework for determining the drying and wetting diffusion coefficients in a geotechnical laboratory.

Thermal conductivity sensors can reliably measure matric suctions within the range of 0 kPa to about 1000 kPa (Fredlund et al. 1989). Thermocouple psychrometers can measure total suctions within the range of about 300 kPa to about 7000 kPa (Bulut et al. 2008). Both thermal conductivity sensors and thermocouple psychrometers have been used together on a single soil specimen to measure a wider suction range. In this study, both drying and wetting tests are conducted on multiple specimens at the same time in a controlled temperature environment. The analysis of hysteresis has also been performed on a soil specimen. Since the analysis in this study was utilized on a wider range of the suction, the change of the diffusion coefficient with the measured range of suction can also be observed.

With a collective testing protocol, determination of wetting and drying diffusion can be done in a very simple and economical way on a routine basis. The following are the conclusions that can be drawn from this study:

- A new testing protocol was developed for determining moisture diffusion coefficients using thermal conductivity sensors
- For most of the soil specimens, the diffusivity coefficients measured from thermocouple psychrometers based on total suction are larger than the diffusivity measured from thermal conductivity sensors based on matric suctions. This difference could be either due to the difference in the approach of measurement.
- The wetting diffusion coefficient is larger than the drying diffusion coefficient in most of the cases using both thermal conductivity sensors and thermocouple psychrometers
- The value of the drying diffusion coefficient decreases as the measurement range of the suction increases.
- The value of the wetting diffusion coefficient decreases as the measurement range of the suction increases.
- Mitchell’s approach for determining wetting moisture diffusion coefficient at low suctions has proved inadequate based on the experimental results.

6.2. Recommendations for Future Research

- In this research, only one drying-wetting cycle was considered to determine the drying and wetting diffusion coefficients. Further study is required to analyze the effects of multiple cycles of drying and wetting on diffusion coefficients.
- The cracking of the soil starts at a specific range of the suction which could be captured using a device that can measure a lower suction range like thermal conductivity sensor. This analysis of the relation between suction and the initiation of cracks need to be

studied. Observing the suction at the initiation of the cracks and the effect of cracks on the diffusion coefficient can be studied.

- Though this study covered a wider range of suction from 2 to 4.5 pF. More study is needed to determine the relation between the diffusivity of the soil and the suction on a wider range.
- Each thermal conductivity sensor should be calibrated individually and a calibration curve needs to be developed for each sensor separately before using for the measurement of matric suction.

REFERENCES

1. Aubeny, C., Bulut, R., and Lytton, R.L. (2005). " Laboratory versus field values of unsaturated soil diffusivity", *Proceedings of an International Symposium on Advanced Experimental Unsaturated Soil Mechanics*, Trento, Italy, June 27-29, pp. 495- 500.
2. Aubeny, C., and Lytton, R.L. (2004). "Shallow Slides in Compacted High Plasticity clay Slopes," *Journal of Geotechnical and Geoenvironmental Engineering*; Vol.130, pp. 717-727.
3. Aubeny, C., Lytton, R.L., and Tang, D. (2003). "Simplified analysis of moisture flow through unsaturated Soil," *Transportation Research Record*; Journal of the Transportation Research Board, No. 1821, pp. 75-82.
4. Buoyoucos, G. J., and Mick, A. H. (1940). "An electrical resistance method for the continuous measurement of soil moisture under field conditions", Techn. bull. 172, Michigan Agric. Exp. Stn., East Lansing, MI.
5. Bulut, R., Hineidi, S.M., and Bailey, B. (2002). " Suction measurements with filter paper and chilled mirror psychrometer", Proceedings of the Texas Section, *American Society of Civil Engineers,* Fall Meeting, Waco. 2-5 October.
6. Bulut, R. and Leong, C. (2008). " Indirect measurements of suction", Special Issue on Laboratory and Field Testing of Unsaturated Soils, *Journal of Geotechnical and Geological Engineering*, Vol.26, pp. 633-644.
7. Decagon Devices, Inc. (1999). WP4 dew point potentiameter operator's manual version 1.0 Pullman, WA. < http://www.decagon.com/wp4 > (Aug.15, 2013).
8. Fredlund, D.G. (1989), "Negative pore-water pressures in slope stability". In Simposio Sur americanode Deslizamiento, Paipa, Columbia, Vol. 1 pp. 1-31.

9. Fredlund, D.G. and Wong, D.K.H. (1989).” Calibration of thermal conductivity sensors for measuring soil suction”, *Geotechnical Journal*, Vol. 12, No. 3, pp. 188-194.

10. Fredlund, D.G. and Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*, John Wiley and Sons, Inc., New York, NY.

11. Hamer, W.J. and Wu, Y.C. (1972). "Osmotic coefficients and mean activity coefficient of uni-univalent electrolytes in water at 25ºC." *Journal of Physics and Chemistry Reference Data*, Vol. 1 (4): 1047-1099.

12. Houston, S. L., Houston, W. N., and Wagner, A. M. (1994). “Laboratory filter paper measurements.” *Geotechnical Testing Journal*, GTJODJ., Vol. 17, No. 2 pp. 185-194.

13. Krahn, J. and Fredlund, D. G. (1972).” On total, matric and osmotic suction”, The Williams and Wilkins Co. *Soil Science*. Vol 4, No. 5, pp 339-348.

14. Jayatilaka, R. and Lytton, R.L. (1997). “Prediction of expansive clay roughness in pavements with vertical moisture barriers,” *Research Report No. FHWA/TX- 98/197-28F*, Texas Transportation Institute.

15. Laliberte, G. E. and Corey, A.T. (1967) “Hydraulic properties of disturbed and undisturbed soils”, *Permeability and Capillarity of Soils*, ASTM Special Technical Publication No. 417. pp 56-71.

16. Leong, E.C., Tripathy, S., and Rahardjo, H. (2003). “ Total suction measurements of unsaturated soils with a device using the chilled mirror dew point technique.” *Geotechnique,* Vol. 53, pp 173-182.

17. Lu, N. and Likos, W.J. (2004). *Unsaturated Soil Mechanics*, John Wiley and Sons, Inc., Hoboken, NJ.

18. Mabirizi, D. and Bulut, R. (2010). “Unified testing method for measuring unsaturated soil drying and wetting diffusion coefficients in laboratory,” *Journal of the Transportation Research Board.* Issue No 217. pp. 109-118.

19. Mabirizi, D. (2010). “Wetting and drying unsaturated soil diffusivity parameters,” Master’s Thesis, Oklahoma State University, USA.

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

21. Pan, H., Qing,Y., and Pei-yong, L. (2010). “Direct and indirect measurements of suction*”, Electronic Journal of Geotechnical Engineering*, Vol. 15, Bundle B.

22. Schofield, R. K. (1935). “The pF of water in soil.” *Transactions of the 3rd International Congress on Soil Science*., Vol. 2, pp. 37-48.

23. Spanner, D.C (1951). “The peltier effect and its use in the measurements of suction pressure.” *Journal of Experimental Botany*, Vol. 2, No. 5, pp. 145-168.

24. Skinner, A., Hignett, C., and Dearden, J. (1997). “Resurrecting the gypsum block for soil moisture measurement.” *Australian viticulture*, October/November1997.

25. Topp, G.C., Davis, J. L., and Annan, A.P. (1980). “Electromagnetic determination of soil water content: Measurements in coaxial transmission lines”. *Water Resources Research*, Vol. 6 No.3, pp. 574-582.

26. Yu, X. and Drnevich, V.P. (2004).” Soil water content and dry density by time domain reflectometry.” *Journal of Geotechnical and Geo environmental Engineering*, Vol. 130 No. 9, pp. 922-934.

APPENDICES

A. LABORATORY DETERMINATION OF SOIL DIFFUSION COEFFICIENTS

The coefficient of moisture diffusion controls the rate of the movement of moisture in a soil profile. The drying and wetting diffusion coefficients are measured using thermal conductivity sensors inserted in a standard Proctor compacted specimen. The testing methodology was originally proposed by Mitchell (1979). Improvements were made by Bulut et al. (2005). The wetting diffusion coefficient testing and a unified testing protocol for the testing were developed by Mabrizi et al. (2010) using thermocouple psychrometers. This research makes changes to determine the wetting and drying diffusion coefficients using thermal conductivity sensors which measure matric suction with a reliable suction range of 0 -1000 kPa.

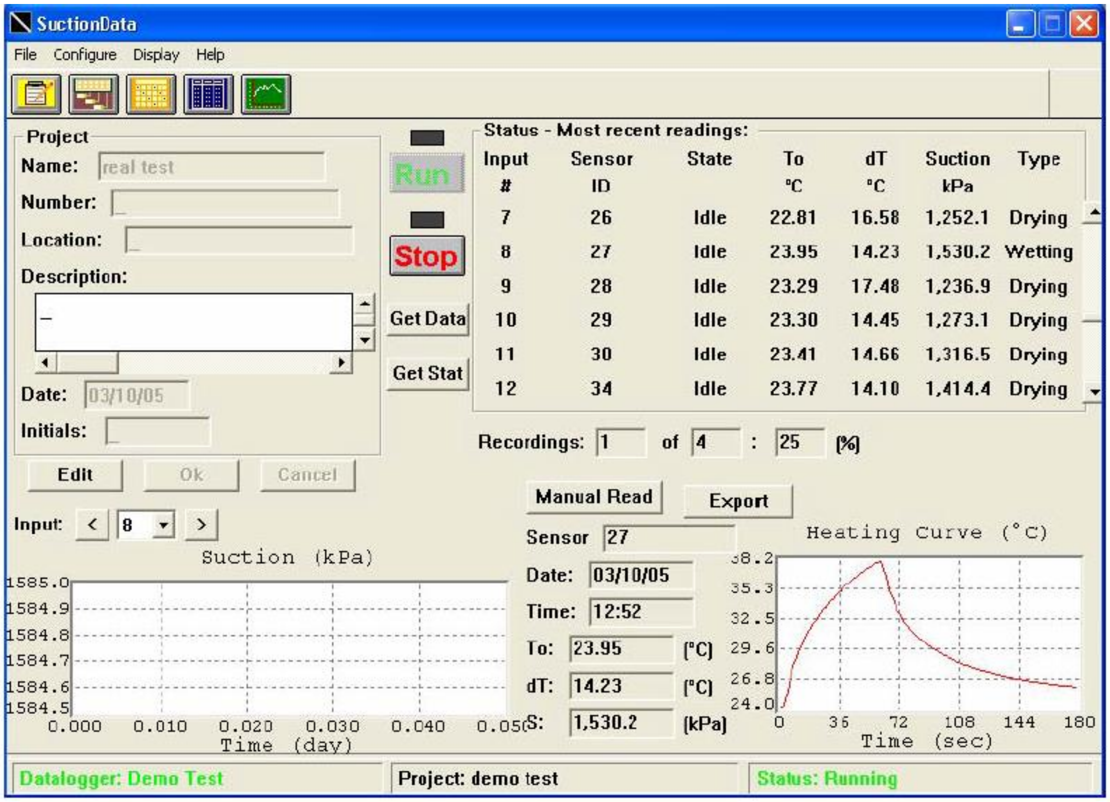
Calibration of Thermal conductivity sensors

The calibration of the sensors can be performed as follows

1. The thermal conductivity sensors are first connected to the data logger which uses GCTS testing software.
2. Using computer interface the value of the change in temperature (dT) can be noted from the software.
3. This is treated as the upper limit of the calibration of the sensor when it is air dry (consider this dT against a suction of 7 pF, as mentioned in the GCTS manual).

4. The thermal conductivity sensors are taken and saturated for two days.
5. After saturation, the sensors while they are still in water should be connected to the data logger.
6. Using computer interface the value of the change in temperature (dT) can be noted from the software.
7. This is treated as the lower limit of the sensor calibration curve when it is saturated. (consider this dT against a suction of 0.1 pF, as mentioned in the GCTS manual)
8. The sensor is taken and inserted in to a FTC cell which is shown in Figure A.1
9. There is an opening for allowing air pressure in to the cell which can be connected to the compressed air cylinder.

Figure A.1 FTC Cell used for Calibration



Project

Name: real test

Number:

Location:

Description:

Date: 03/10/05

Initials:

Input: 8

Status - Most recent readings:

Input #	Sensor ID	State	To °C	dT °C	Suction kPa	Type
7	26	Idle	22.81	16.58	1,252.1	Drying
8	27	Idle	23.95	14.23	1,530.2	Wetting
9	28	Idle	23.29	17.48	1,236.9	Drying
10	29	Idle	23.30	14.45	1,273.1	Drying
11	30	Idle	23.41	14.66	1,316.5	Drying
12	34	Idle	23.77	14.10	1,414.4	Drying

Recordings: 1 of 4 : 25 [%]

Sensor 27

Date: 03/10/05

Time: 12:52

To: 23.95 [°C]

dT: 14.23 [°C]

S: 1,530.2 [kPa]

Datalogger: Demo Test

Project: demo test

Status: Running

Figure A.2 Screenshot for the test data

10. A ceramic stone is in the bottom of the cell which is to be kept in contact with the thermal conductivity sensor during calibration.
11. The ceramic stone needs to be saturated for two days before the insertion of the saturated sensor in to it.
12. After the sensor is inserted, The FTC cell should be closed tightly with the o rings given and using tape so that the air pressure do not leak.
13. The air pressure of 50 kPa is applied to the sensor which is connected to the data logger. The applied air pressure is noted and it should be kept constant for over one week.
14. The value of dT can be obtained against the applied air pressure from the computer interface.

15. The air pressure should be increased for a specific noted value (50, 500, 1000 kPa are used in this study suggested by the manufacturer) and to be applied constant for another week.
16. The dT values against each applied pressure is noted and a calibration curve is plotted as shown in Figure A.3.

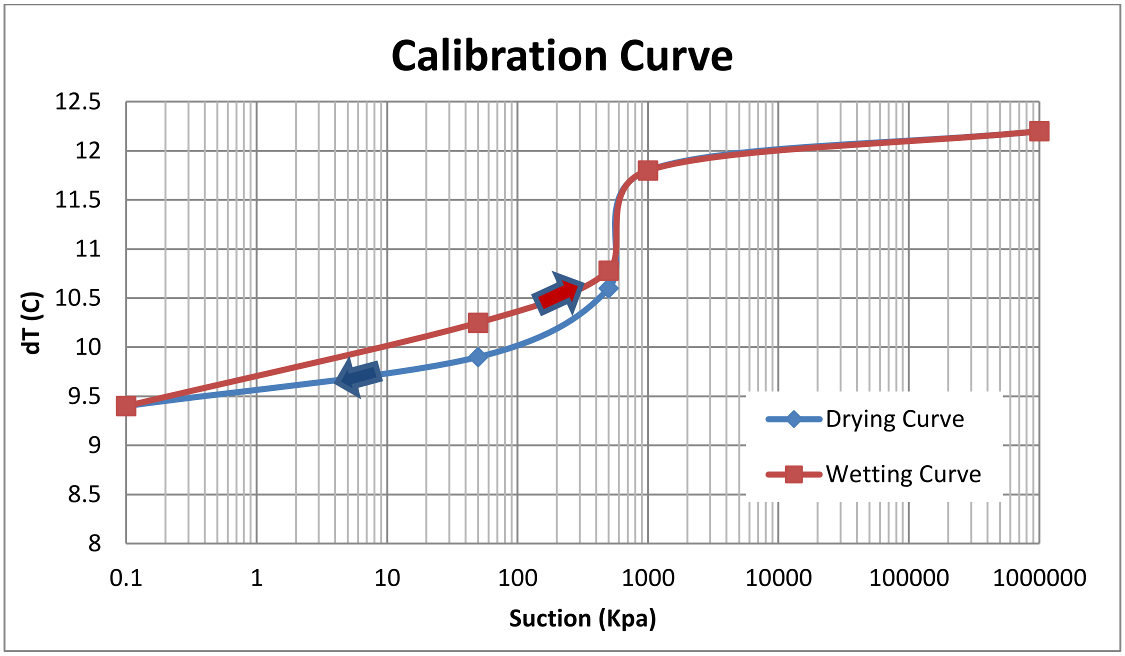


Figure A.3. Calibration curve of the Thermal Conductivity Sensor

17. After the drying curve is plotted, the sensor was taken out and the ceramic stone in the FTC was saturated again for two days.
18. The sensor was installed in to the FTC cell again, a pressure of 1000 kPa is applied for a week and the dT value against the pressure is noted.
19. The pressure is slowly decreased to a value of 500 kPa and kept constant for a week. The dT value against the applied pressure is noted.
20. Again the pressure should be reduced to 50 kPa and kept constant for a week to note the dT value against that pressure.

21. A wetting calibration curve is plotted using all the dT values obtained from applying the pressures as shown in Figure A.3.

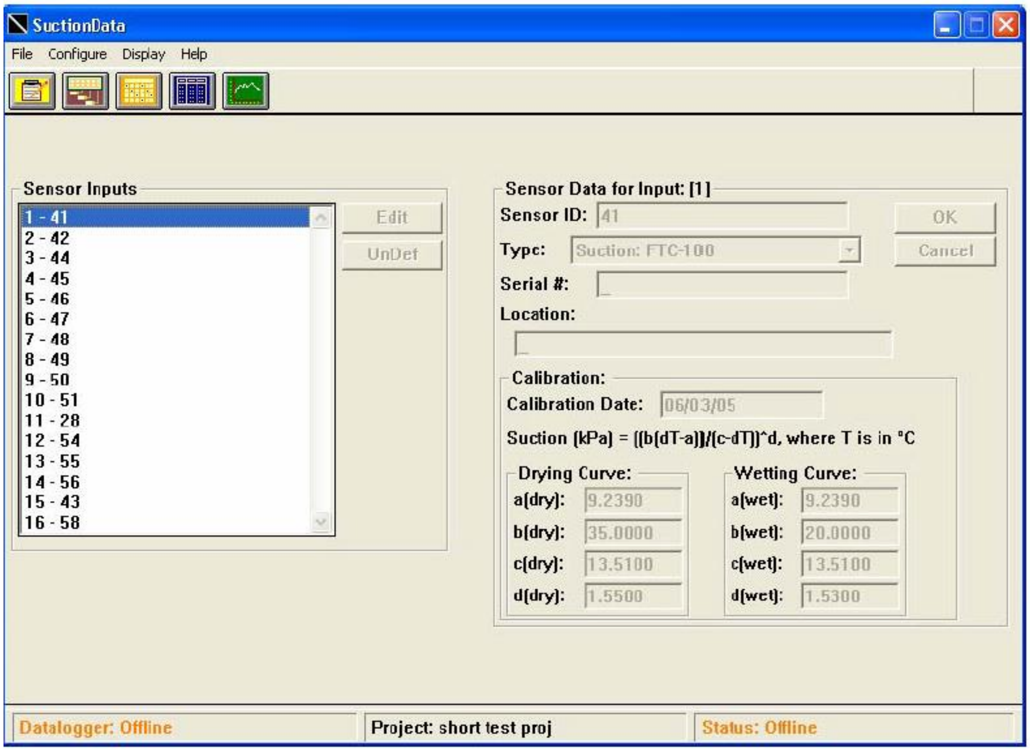
Using the following equation, the sensor calibration parameters are determined using any two points on the calibration curve. Substituting any two suction values and Δt values in the following equation and solving them gives the parameters.

$$\varphi = \left[\frac{b\ (\Delta t - a)}{c - \Delta t}\right]^{d}$$

Where φ the applied matric suction in kPa; Δt is the raise in temperature; a, b, c and d are the calibration parameters that should be given to the data logger. The input of calibration parameters are shown in Figure A.4.

Preparation of soil sample

1. A standard Proctor compacted sample is prepared using the optimum moisture content of the soil.
2. The sample is kept for saturation using wet clothes wrapped around it and kept in a closed ice chest for a week.
3. After the sample is assumed to be saturated, it is wrapped tightly with a tape to avoid breaking of the sample.
4. The sample is carefully handled to make a hole sufficient for the insertion of the thermal conductivity sensor.
5. The diameter of the sensor is 28mm and the height is 65 mm. The hole should be made so carefully to avoid the cracks.



Sensor Inputs

1 - 41
2 - 42
3 - 44
4 - 45
5 - 46
6 - 47
7 - 48
8 - 49
9 - 50
10 - 51
11 - 28
12 - 54
13 - 55
14 - 56
15 - 43
16 - 58

Sensor Data for Input: [1]

Sensor ID: 41
Type: Suction: FTC-100
Serial #:
Location:

Calibration:

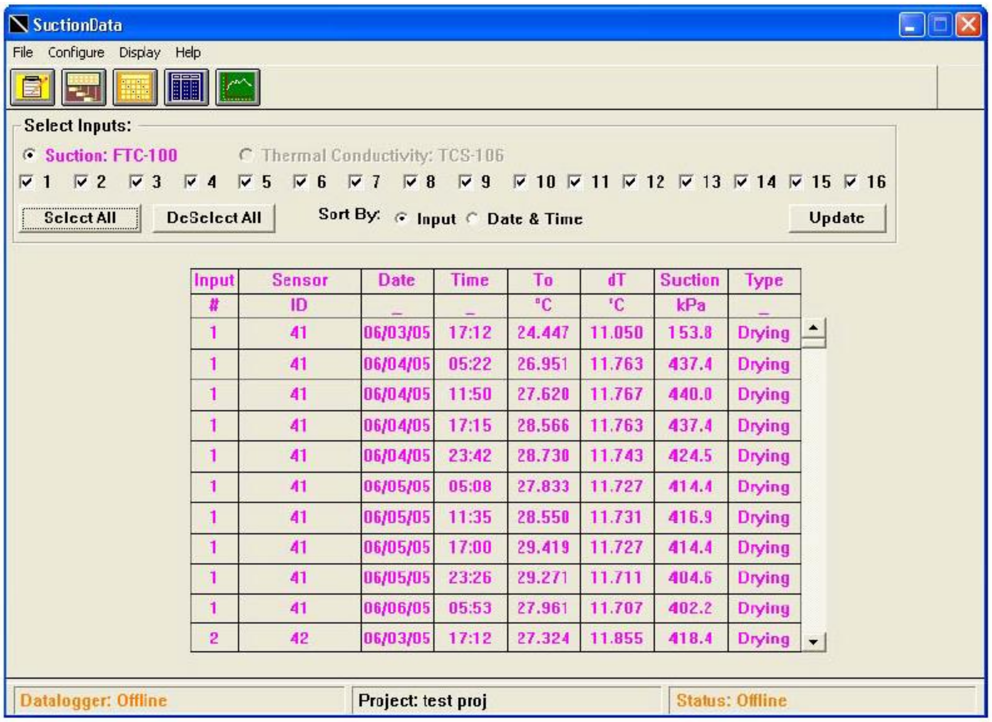
Calibration Date: 06/03/05

Suction (kPa) = [(b(dT-a)]/(c-dT)]^d, where T is in °C

Drying Curve:		Wetting Curve:	
a[dry]:	9.2390	a[wet]:	9.2390
b[dry]:	35.0000	b[wet]:	20.0000
c[dry]:	13.5100	c[wet]:	13.5100
d[dry]:	1.5500	d[wet]:	1.5300

Datalogger: Offline
Project: short test proj
Status: Offline

Figure A.4. Parameters of the Calibration Curve



Select Inputs:

● Suction: FTC-100 ○ Thermal Conductivity: TCS-106

☑ 1 ☑ 2 ☑ 3 ☑ 4 ☑ 5 ☑ 6 ☑ 7 ☑ 8 ☑ 9 ☑ 10 ☑ 11 ☑ 12 ☑ 13 ☑ 14 ☑ 15 ☑ 16

Sort By: ● Input ○ Date & Time

Input	Sensor	Date	Time	To	dT	Suction	Type
#	ID	_	_	°C	°C	kPa	_
1	41	06/03/05	17:12	24.447	11.050	153.8	Drying
1	41	06/04/05	05:22	26.951	11.763	437.4	Drying
1	41	06/04/05	11:50	27.620	11.767	440.0	Drying
1	41	06/04/05	17:15	28.566	11.763	437.4	Drying
1	41	06/04/05	23:42	28.730	11.743	424.5	Drying
1	41	06/05/05	05:08	27.833	11.727	414.4	Drying
1	41	06/05/05	11:35	28.550	11.731	416.9	Drying
1	41	06/05/05	17:00	29.419	11.727	414.4	Drying
1	41	06/05/05	23:26	29.271	11.711	404.6	Drying
1	41	06/06/05	05:53	27.961	11.707	402.2	Drying
2	42	06/03/05	17:12	27.324	11.855	418.4	Drying

Datalogger: Offline
Project: test proj
Status: Offline

Figure A.5. Suction values from the thermal conductivity sensors

Figure A.6 Preparation of the sample for diffusivity measurements

Figure A.7 Testing Setup for the diffusivity measurements

6. The sample is then wrapped with a plastic bubble wrap as tightly as possible and with a aluminum foil to have a controlled temperature.
7. For drying test, one end of the soil sample is exposed to the open air and the other sides should be closed tightly which provides one dimensional moisture movement.
8. After the insertion of the thermal conductivity sensor and the sample wrapping, The sample should be kept in an ice chest with all the plastic wraps surrounding the sample for temperature equilibrium.
9. The sensor is connected to the data logger. The data logger is connected to the computer interface which has GCTS software that collects the suction information.
10. The suction measurements for every 6 hours along with the change in temperature values can be obtained. The suction measurements from the software are given in Figure A.5.
11. For the wetting test, one end of the sample should be kept in contact with water level and the other ends should be tightly sealed.

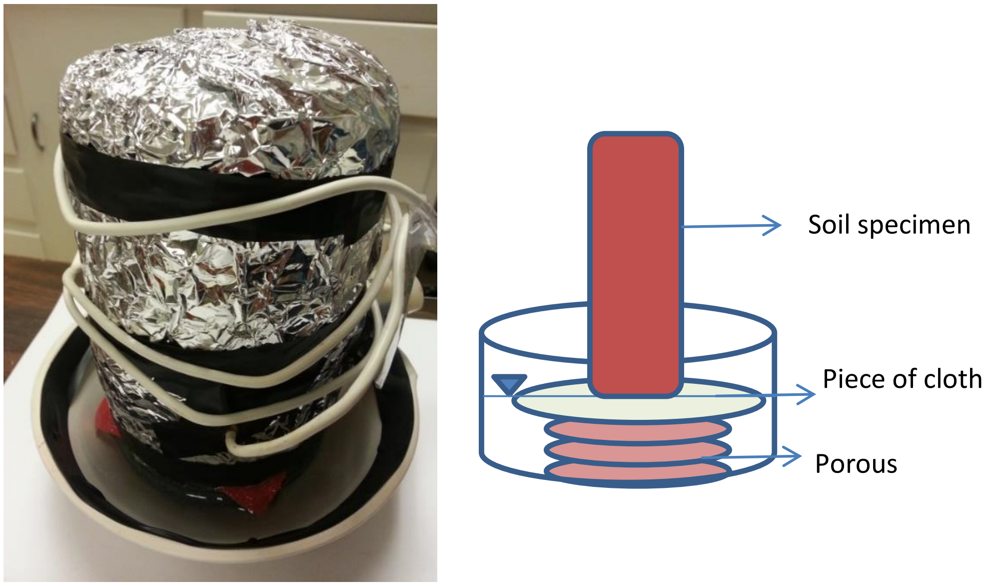


Figure A.8 Test set up for Wetting Diffusivity Measurements

12. A bowl with a constant water level is taken and porous stones and a piece of cloth is to be kept in the bowl on which the soil sample will be rested.
13. The sample should just touch the water level and the whole setup is to be kept in an ice chest to maintain controlled temperature.
14. The suction measurements for every 6 hours along with the change in temperature values can be obtained for wetting test.
15. The matric suction measurements with time can be obtained from thermal conductivity sensors.
16. Using The Matlab software Program, wetting and drying diffusion coefficients can be determined.

B. **Parameters for the determination of Diffusion Coefficient for each site with the plots of theoretical and measured values**

Table B.1. Norman Site: Drying 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.24	pF
Initial Suction (Uo)	2.55	pF
Psychrometer Location (x)	11	cm
Sample Length (L)	14.5	cm
FTC sensor number used	7	

Drying Diffusion Coefficient, $\alpha_{dry} = 1.2258 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
59	2.57
587	2.83
1775	3.03
2959	3.19
5316	3.45
9502	3.62
10691	3.64
12037	3.66
13222	3.72
14562	3.82

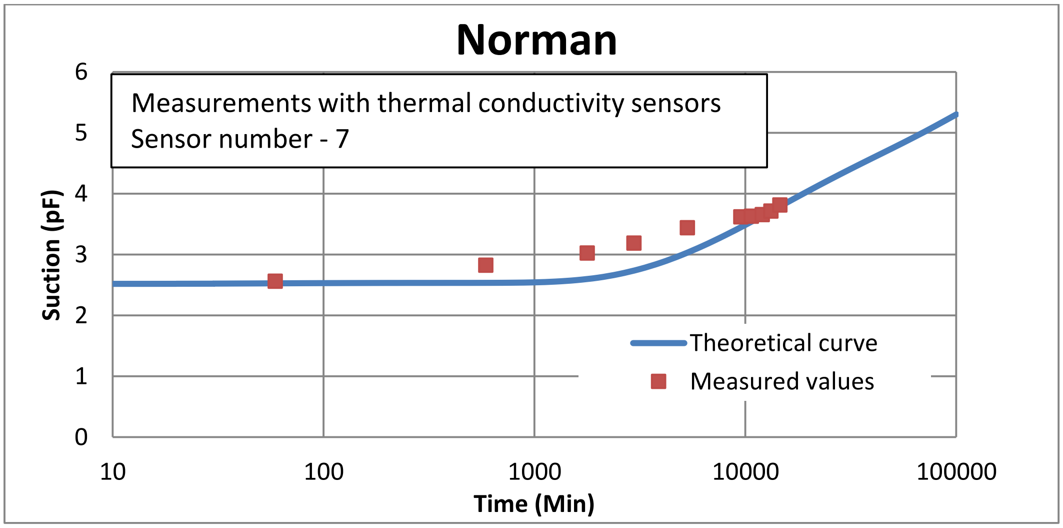


Figure B.1. Norman Site: Drying 1

Table B. 2. Lake Hefner Site: Drying 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.24	pF
Initial Suction (Uo)	2.60	pF
Psychrometer Location (x)	12.5	cm
Sample Length (L)	15	cm
FTC sensor number used	8	

Drying Diffusion Coefficient, $\alpha_{dry} = 0.6629 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
59	2.63
587	2.72
1775	2.98
2959	3.11
5316	3.35
9502	3.63
12037	3.70
13222	3.75
14562	3.81
20132	3.97

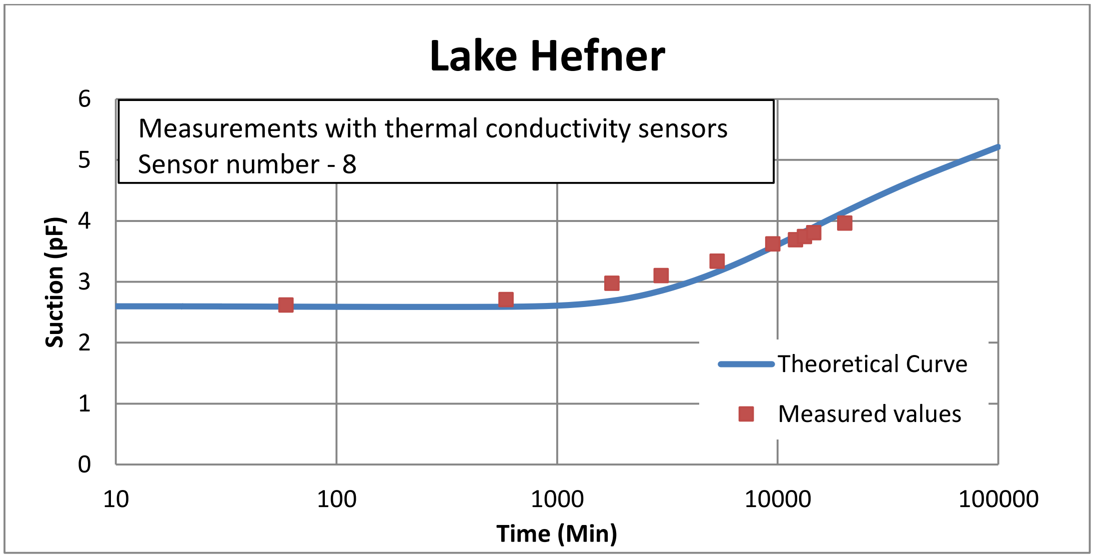


Figure B. 2. Lake Hefner Site: Drying 1

Table B.3. Ardmore Site: Drying 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.24	pF
Initial Suction (Uo)	2.70	pF
Psychrometer Location (x)	11.5	cm
Sample Length (L)	16	cm
FTC sensor number used	3	

Drying Diffusion Coefficient, $\alpha_{dry} = 2.2853 \times 10^{-3}\ cm^2/\ min$

Laboratory Suction Measurements

Time	**Suction**
min	pF
59	2.72
587	2.94
1775	3.29
2959	3.43
4158	3.53
5316	3.69
9502	3.82
10691	3.83
12037	3.87
13222	3.93

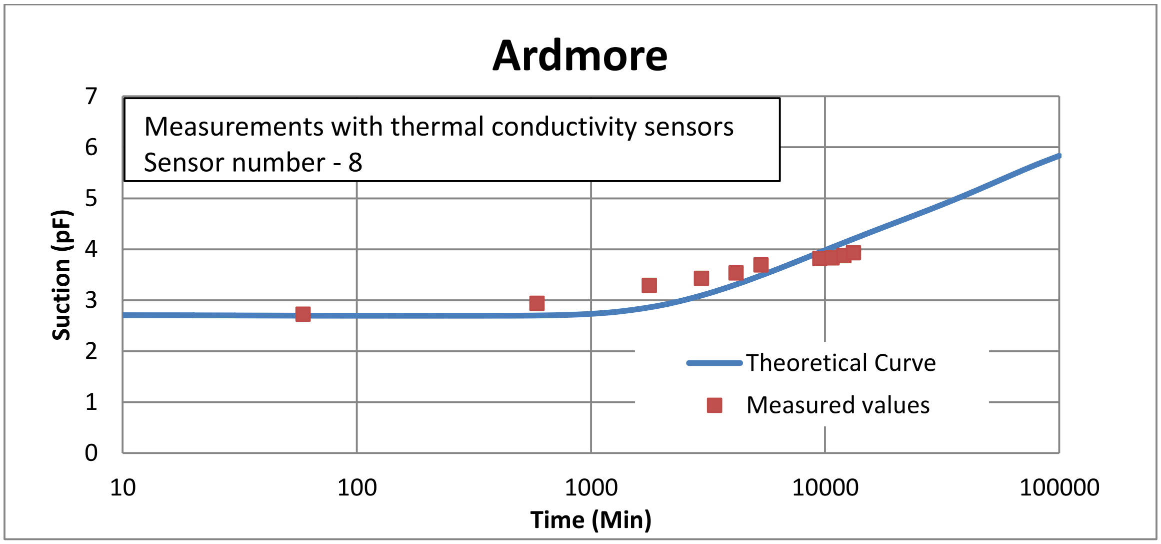


Figure B.3. Ardmore Site: Drying 1

Table B.4. Norman Site: Wetting 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	1.5	pF
Initial Suction (Uo)	4.5	pF
Psychrometer Location (x)	11	cm
Sample Length (L)	14.5	cm
FTC sensor number used	7	

Wetting Diffusion Coefficient, $\alpha_{wet} = 2.1528 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
720	3.93
2160	3.86
3240	3.39
3960	3.28
5760	3.19
7200	3.13
7920	3.05
9720	2.73
10440	2.57
11520	2.30

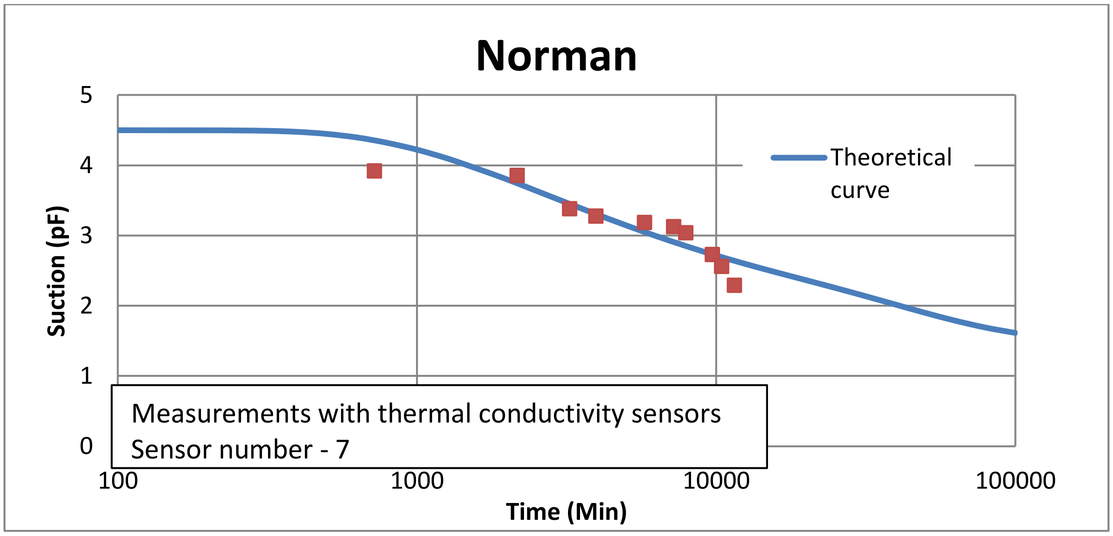


Figure B.4. Norman Site: Wetting 1

Table B.5. Lakehefner Site: Wetting 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	1.5	pF
Initial Suction (Uo)	4.5	pF
Psychrometer Location (x)	12.5	cm
Sample Length (L)	15	cm
FTC sensor number used	8	

Wetting Diffusion Coefficient, α_{wet}= 0.7291 x 10^{-3} cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
720	3.93
1800	3.82
5760	3.58
7200	3.50
8280	3.40
9720	3.27
11520	3.14
12960	2.82
14040	2.29
15120	1.92

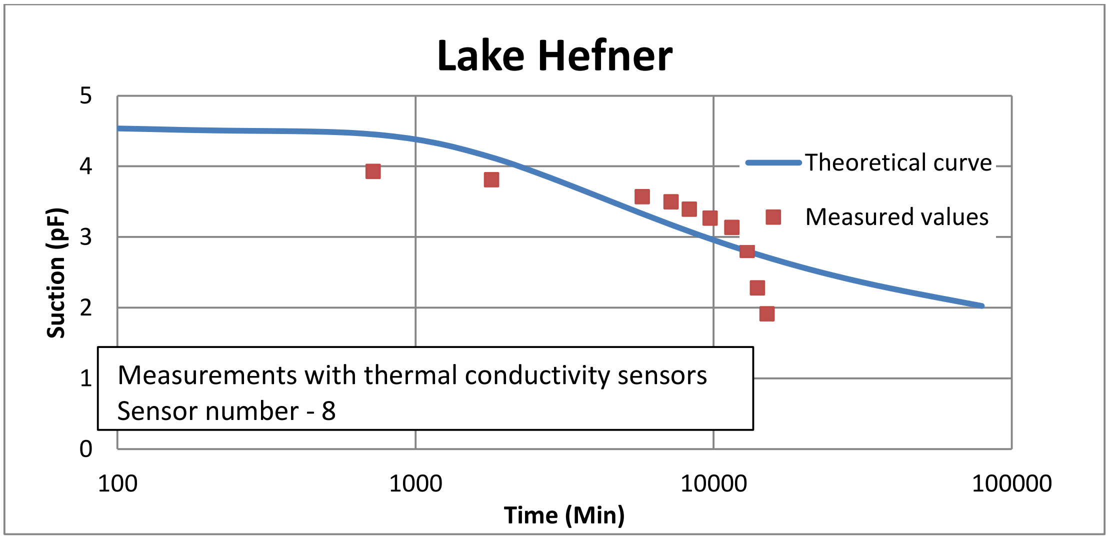


Figure B.5. Lakehefner Site: Wetting 1

Table B.6. Ardmore Site: Wetting 1

Parameter	Value	Units
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	1.5	pF
Initial Suction (Uo)	4.5	pF
Sensor Location (x)	11.5	cm
Sample Length (L)	16	cm
FTC sensor number used	3	

Wetting Diffusion Coefficient, $\alpha_{wet} = 5.9605 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	Suction
min	pF
720	3.92
1080	3.89
1440	3.84
2160	3.74
2520	3.72
3240	3.53
3960	3.27
4680	2.86
5400	2.41
6120	1.08

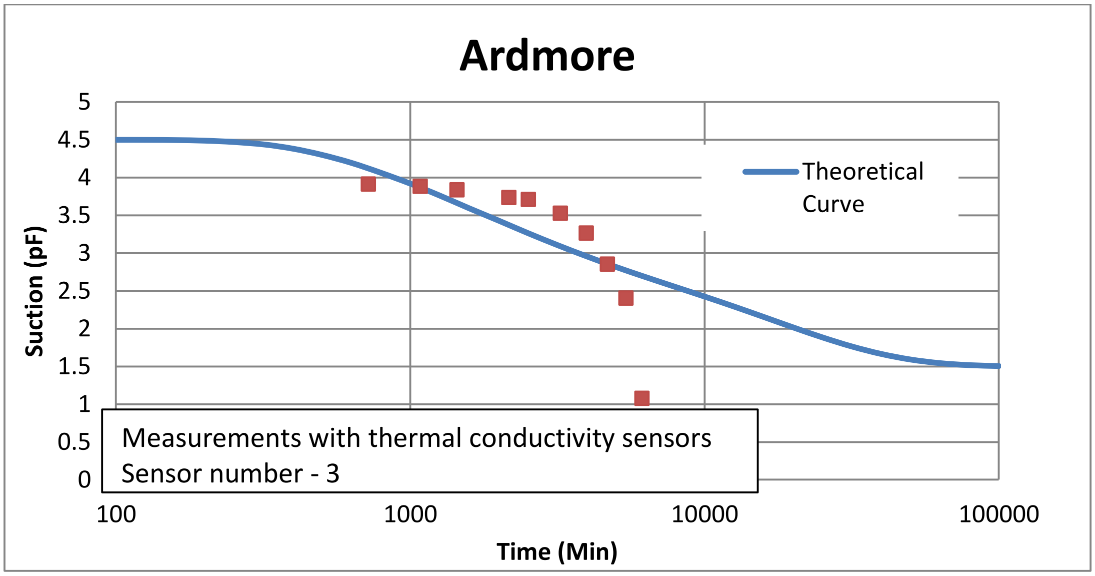


Figure B.6. Ardmore Site: Wetting 1

Table B.7. Norman Site: Drying 2

Parameter	Value	Units
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.27	pF
Initial Suction (Uo)	2.14	pF
Sensor Location (x)	12	cm
Sample Length (L)	15	cm
FTC sensor number used	7	

Drying Diffusion Coefficient, $\alpha_{dry} = 0.994 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	Suction
min	pF
1800	2.56
4680	2.96
6120	3.09
6480	3.12
9000	3.27
10800	3.38
12240	3.52
15120	3.77
16560	3.82
19440	3.94
22320	3.40

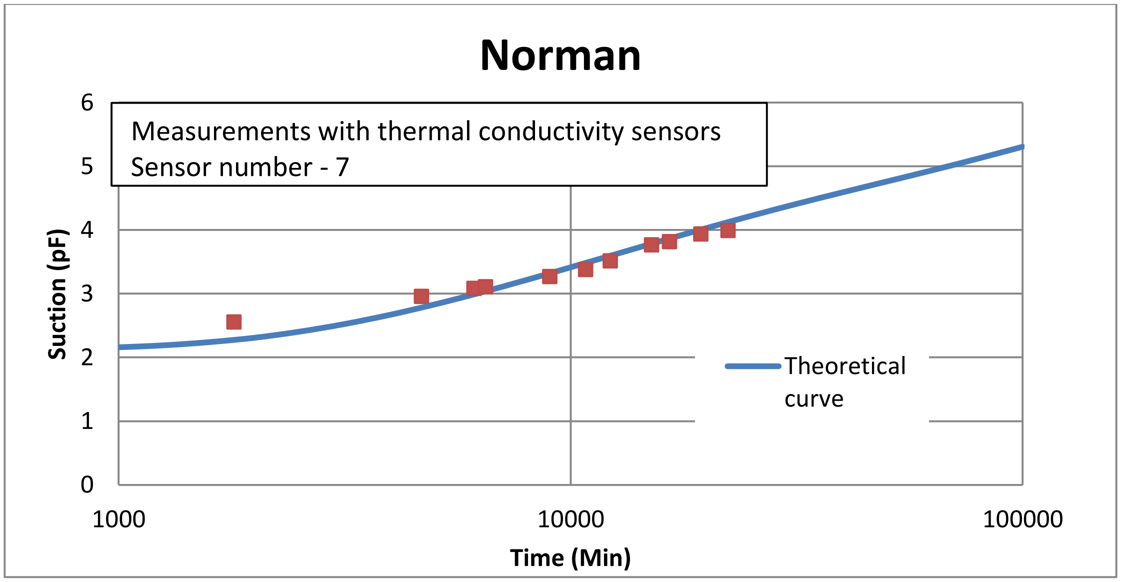


Figure B.7. Norman Site: Drying 2

Table B.8. Lake Hefner Site: Drying 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.27	pF
Initial Suction (Uo)	1.73	pF
Sensor Location (x)	13	cm
Sample Length (L)	16	cm
FTC sensor number used	8	

Drying Diffusion Coefficient, $\alpha_{dry} = 0.8284 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
360	1.76
1440	1.92
3240	1.98
5760	2.21
10080	2.85
12600	3.28
14760	3.45
18720	3.64
21600	3.70
24480	3.85
26640	3.40

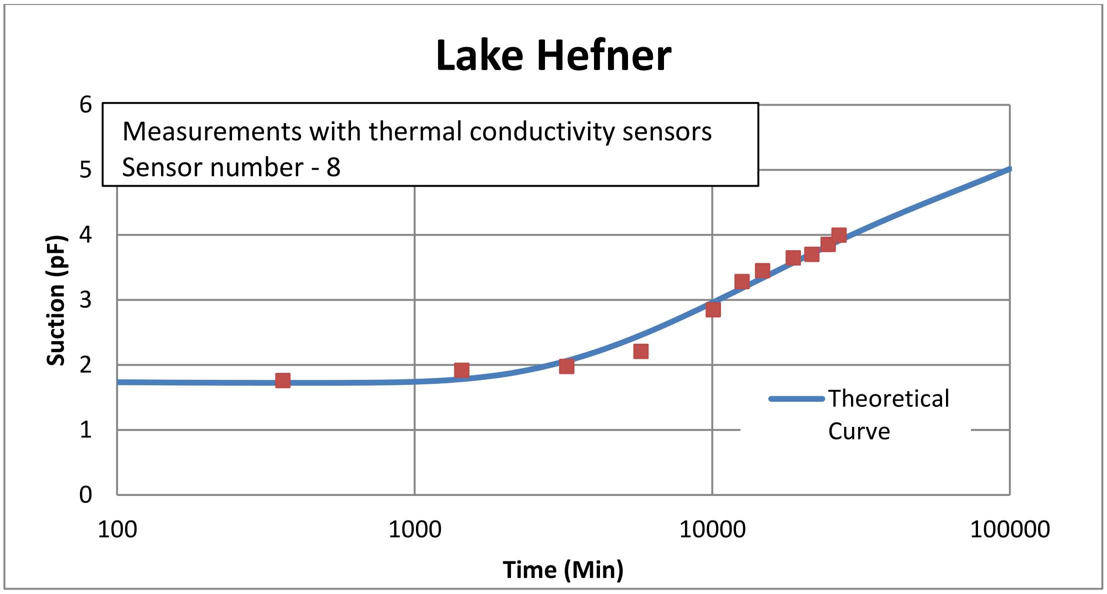


Figure B.8. Lake Hefner Site: Drying 2

Table B.9. Ardmore Site: Drying 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.27	pF
Initial Suction (Uo)	2.22	pF
Sensor Location (x)	14.5	cm
Sample Length (L)	16	cm
FTC sensor number used	3	

Drying Diffusion Coefficient, $\alpha_{dry} = 0.5304 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
2160	2.80
3240	2.90
4320	3.15
5400	3.37
6840	3.51
8280	3.62
10080	3.73
12600	3.82
14760	3.89
16920	3.93
19080	3.98

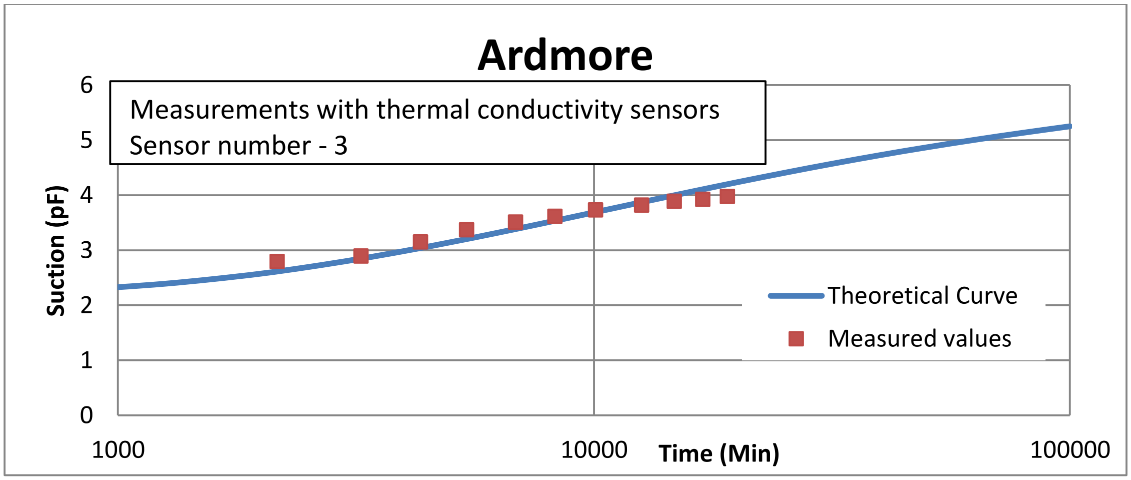


Figure B.9. Ardmore Site: Drying 2

Table B.10. Norman Site: Wetting 2

Parameter	Value	Units
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	1.5	pF
Initial Suction (Uo)	4.5	pF
Sensor Location (x)	12	cm
Sample Length (L)	15	cm
FTC sensor number used	7	

Wetting Diffusion Coefficient, $\alpha_{wet} = 2.9806 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	Suction
min	pF
360	3.86
1080	3.76
1800	3.68
2520	3.59
3240	3.52
3960	3.22
4320	3.04
5040	2.78
5400	2.16
5760	1.38

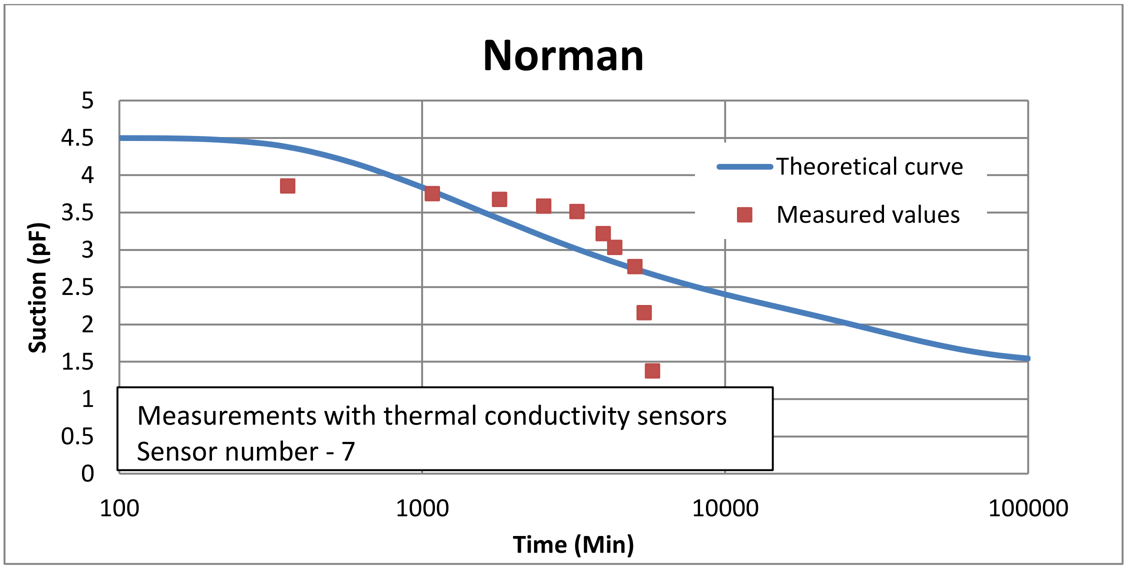


Figure B.10. Norman Site: Wetting 2

Table B.11. Lake Hefner Site: Wetting 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	1.5	pF
Initial Suction (Uo)	4.5	pF
Sensor Location (x)	13	cm
Sample Length (L)	16	cm
FTC sensor number used	8	

Wetting Diffusion Coefficient, $\alpha_{wet} = 2.2104 \times 10^{-3}$ cm^2/min

Laboratory Suction Measurements

Time	**Suction**
min	pF
360	3.95
1080	3.89
1800	3.80
2520	3.73
3240	3.34
3600	3.08
4680	2.63
5400	2.32
6120	2.02
6840	0.91

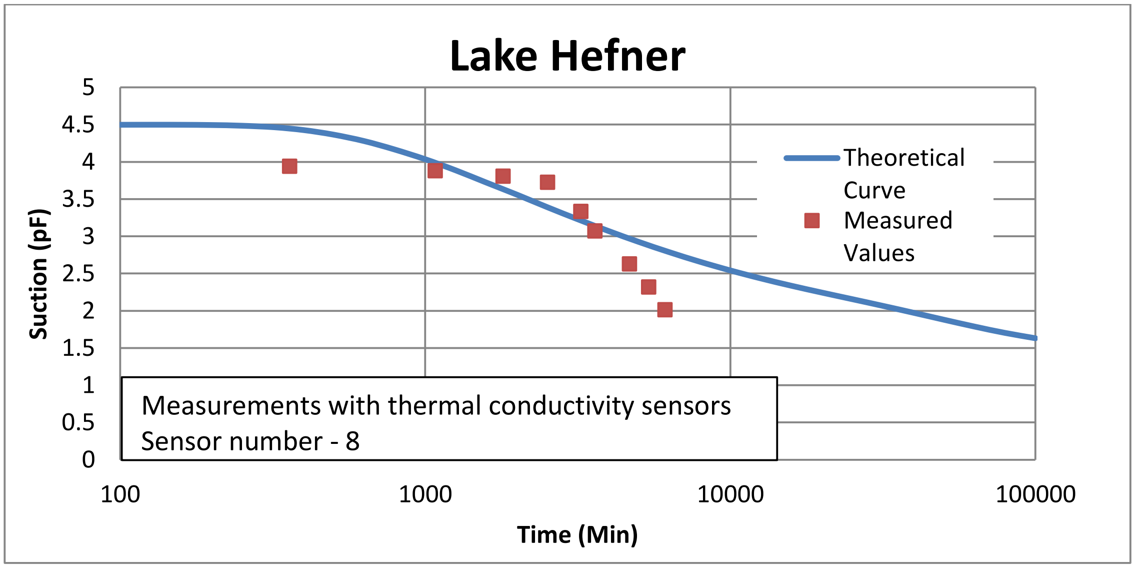


Figure B.11. Lake Hefner Site: Wetting 2

Table B.12. Ardmore Site: Wetting 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	1.5	pF
Initial Suction (Uo)	4.5	pF
Sensor Location (x)	14.5	cm
Sample Length (L)	16	cm
FTC sensor number used	3	

Wetting Diffusion Coefficient, $\alpha_{wet} = 1.8217\text{x } 10^{-3}$ cm^2/min

Laboratory Suction Measurements

Time	**Suction**
min	pF
360	3.96
720	3.76
1080	3.62
1440	3.45
1800	3.20
2160	2.89
2520	0.34

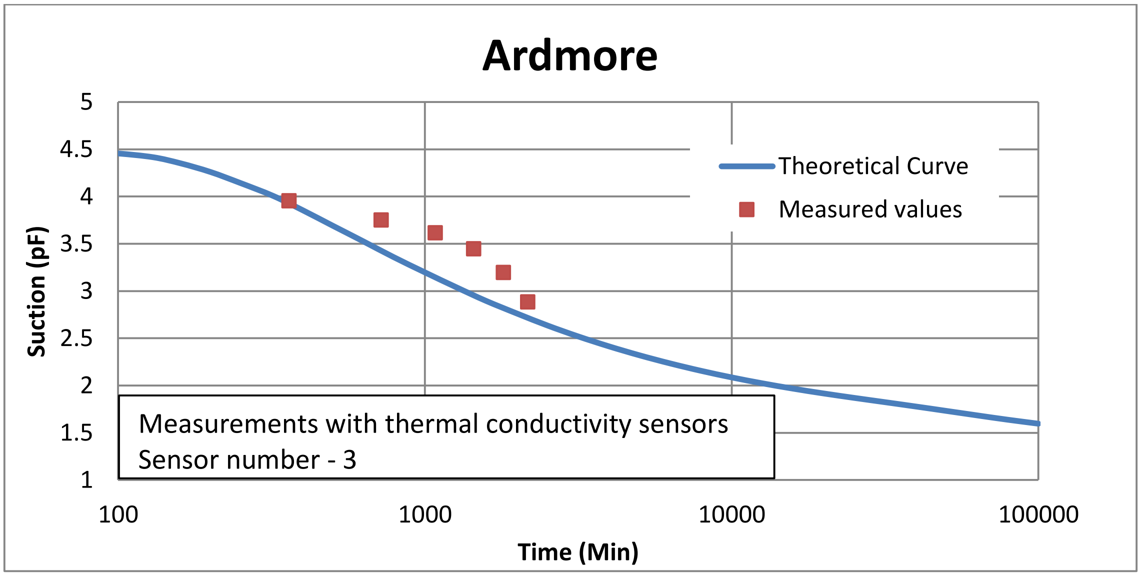


Figure B.12. Ardmore Site: Wetting 2

Table B.13. Norman Site : Drying 1

Parameter	Value	Units
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.24	pF
Initial Suction (Uo)	2.55	pF
Psychrometer Location (x)	11	cm
Sample Length (L)	14.5	cm
Psychrometer number used	513016	

Drying Diffusion Coefficient, $\alpha_{dry} = 1.9211 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	Suction
min	pF
9920	3.61
10040	3.70
10160	3.89
10340	3.99
10580	4.13
10940	4.30
11420	4.36
12020	4.42
12620	4.46
14240	4.50

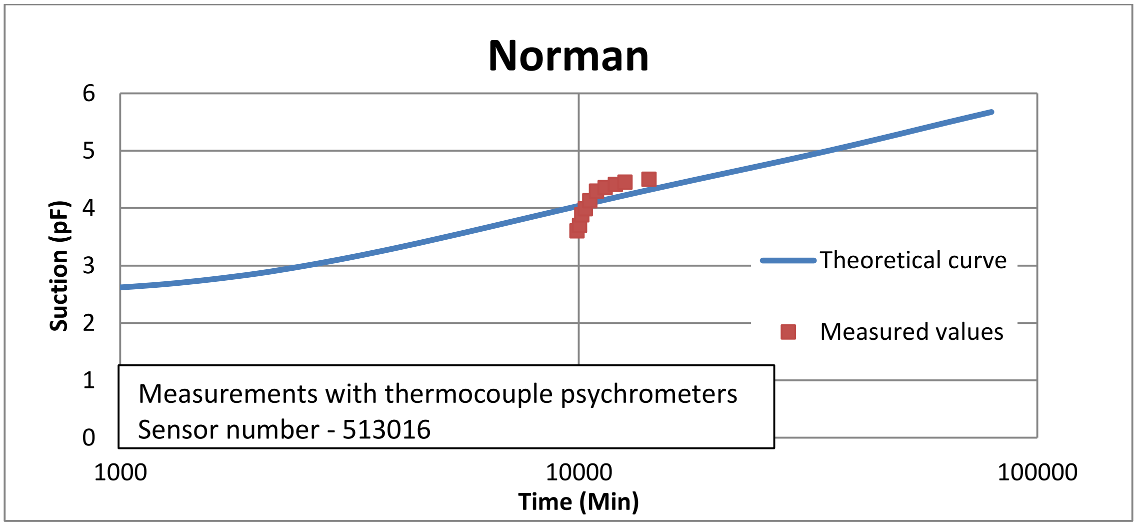


Figure B.13. Norman Site : Drying 1

Table B.14. Lake Hefner Site: Drying 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.24	pF
Initial Suction (Uo)	2.60	pF
Psychrometer Location (x)	12.5	cm
Sample Length (L)	15	cm
Psychrometer number used	513018	

Drying Diffusion Coefficient, $\alpha_{dry} = 0.7622 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
13030	3.75
13130	3.88
13290	3.91
14170	3.94
14430	3.97
14690	4.00
15130	4.07
15310	4.11
15550	4.14

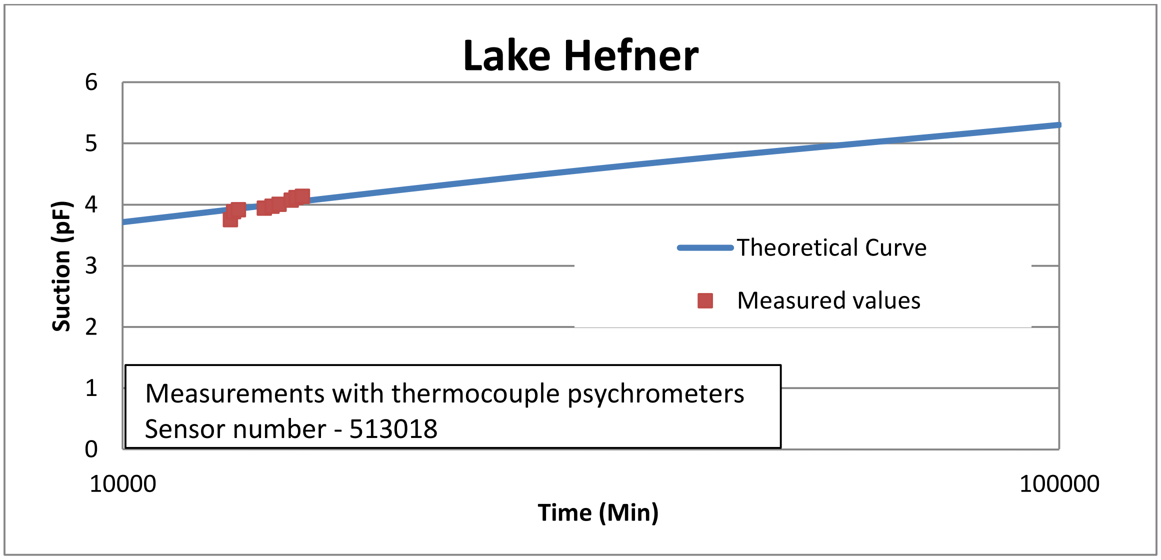


Figure B.14. Lake Hefner Site: Drying 1

Table B.15. Norman Site: Wetting 1

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	2.75	pF
Initial Suction (Uo)	4.5	pF
Psychrometer Location (x)	11	cm
Sample Length (L)	14.5	cm
Psychrometer number used	513016	

Wetting Diffusion Coefficient, $\alpha_{wet} = 3.9739 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
500	4.46
860	4.40
1120	4.26
1220	4.13
1420	3.92
1600	3.83
1900	3.74
2560	3.61
3080	3.50

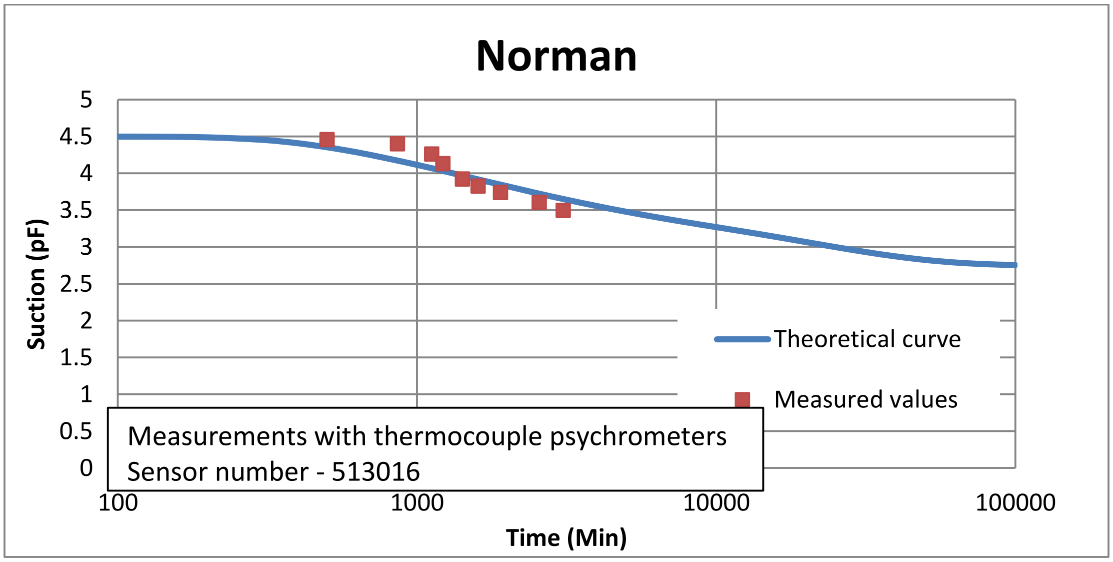


Figure B.15. Norman Site: Wetting 1

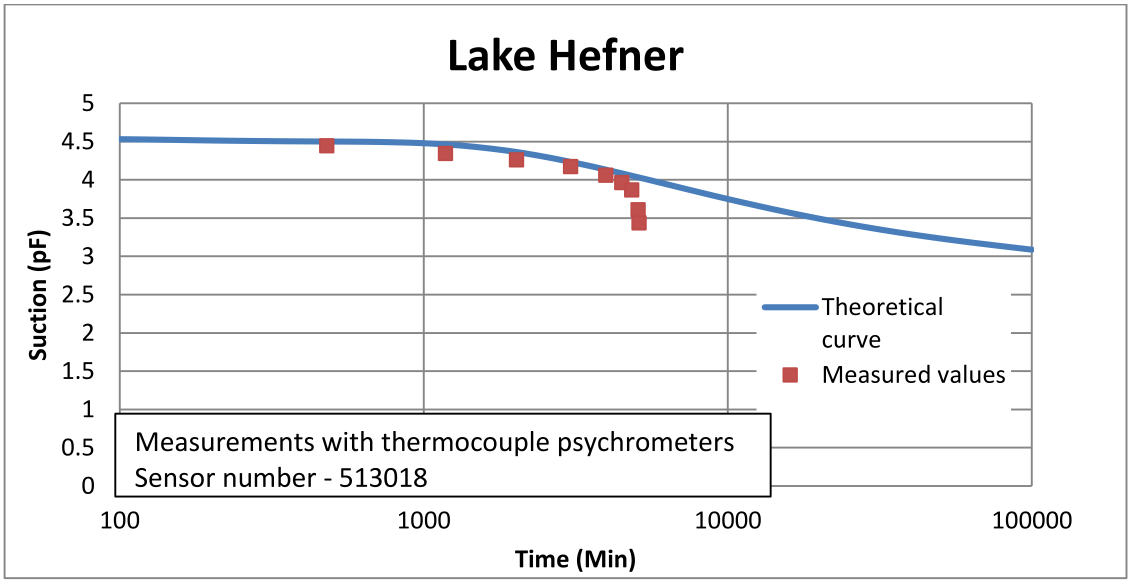
Table B.16. Lakehefner Site: Wetting 1

Parameter	Value	Units
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	2.75	pF
Initial Suction (Uo)	4.5	pF
Psychrometer Location (x)	12.5	cm
Sample Length (L)	15	cm
Psychrometer number used	513018	

Wetting Diffusion Coefficient, α_{wet}= 0.4973 x 10^{-3} cm^2/ min

Laboratory Suction Measurements

Time	Suction
min	pF
480	4.44
1180	4.34
2020	4.26
3040	4.17
3970	4.06
4490	3.96
4840	3.87
5070	3.61
5110	3.44



Measurements with thermocouple psychrometers
Sensor number - 513018

Figure B.16. Lakehefner Site: Wetting 1

Table B.17. Norman Site: Drying 2

Parameter	Value	Units
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.27	pF
Initial Suction (Uo)	2.14	pF
Psychrometer Location (x)	12	cm
Sample Length (L)	15	cm
Psychrometer number used	513016	

Drying Diffusion Coefficient, $\alpha_{dry} = 1.2589 \times 10^{-3}$ cm^2/ min

Laboratory Suction Measurements

Time min	Suction pF
9840	3.51
10060	3.61
10550	3.72
11260	3.81
12200	3.91
14030	4.01
16820	4.11
21010	4.20
22900	4.23
23060	4.25

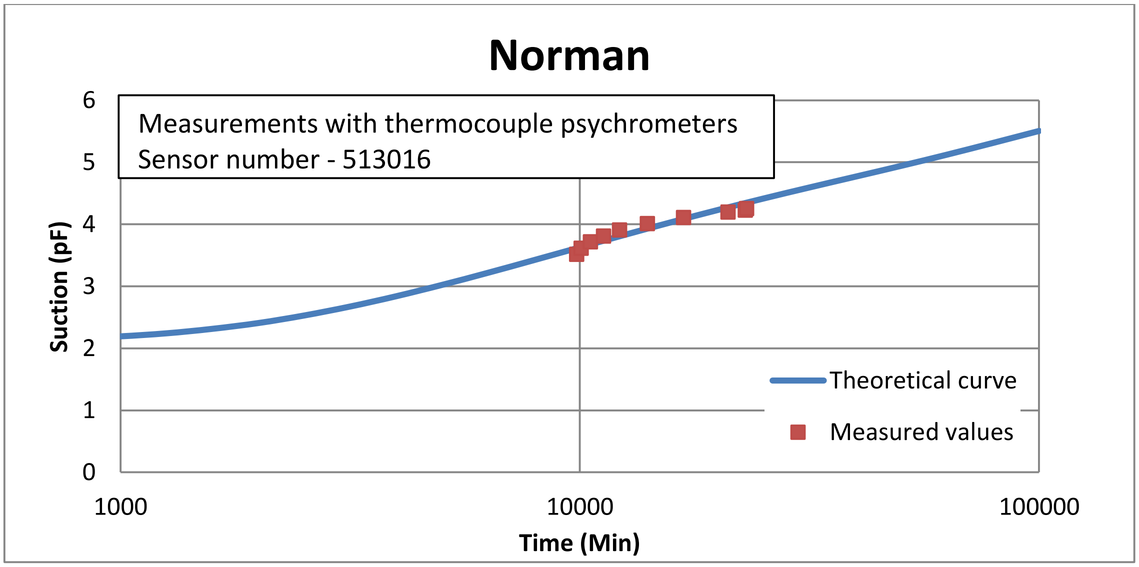


Figure B.17. Norman Site: Drying 2

Table B.18. Lakehefner Site: Drying 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.27	pF
Initial Suction (Uo)	1.73	pF
Psychrometer Location (x)	13	cm
Sample Length (L)	16	cm
Psychrometer number used	48084	

Drying Diffusion Coefficient, $\alpha_{dry} = 1.3913 \times 10^{-3}$ cm^2/min

Laboratory Suction Measurements

Time	**Suction**
min	pF
14560	3.53
15150	3.61
15590	3.73
15880	3.83
16310	3.92
17870	4.06
18500	4.14
19210	4.21
19940	4.31
21270	4.41
22990	4.50

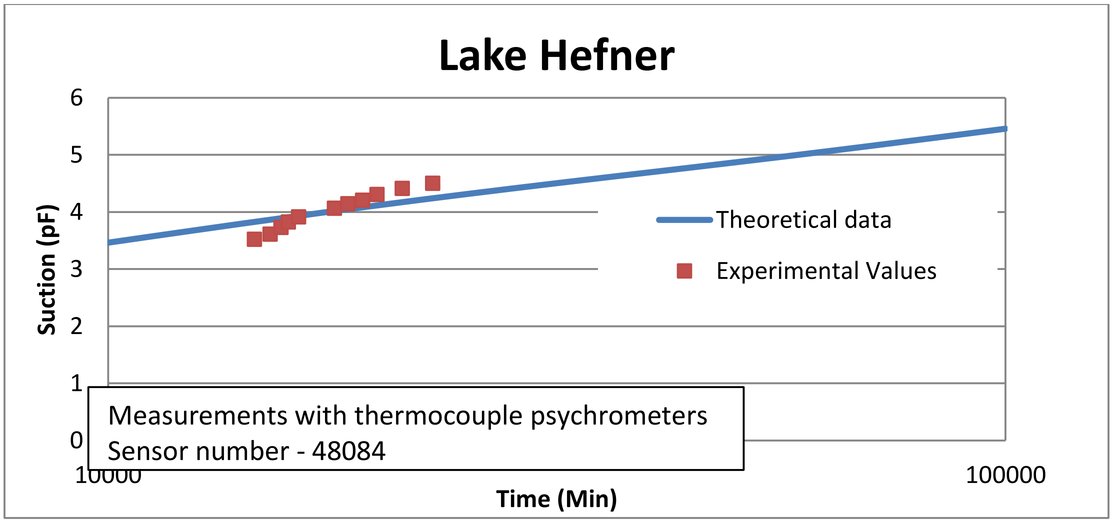


Figure B.18. Lakehefner Site: Drying 2

Table B.19. Ardmore Site :Drying 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Atmospheric Suction (Ua)	6.27	pF
Initial Suction (Uo)	2.22	pF
Psychrometer Location (x)	14.5	cm
Sample Length (L)	16	cm
Psychrometer number used	513018	

Drying Diffusion Coefficient, α_{dry} = x 10^{-3} cm^2/ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
4680	3.54
4790	3.61
5150	3.69
5550	3.75
6280	3.81
7980	3.90
10150	3.98
11360	4.01
14120	4.11
19010	4.20
19510	4.24

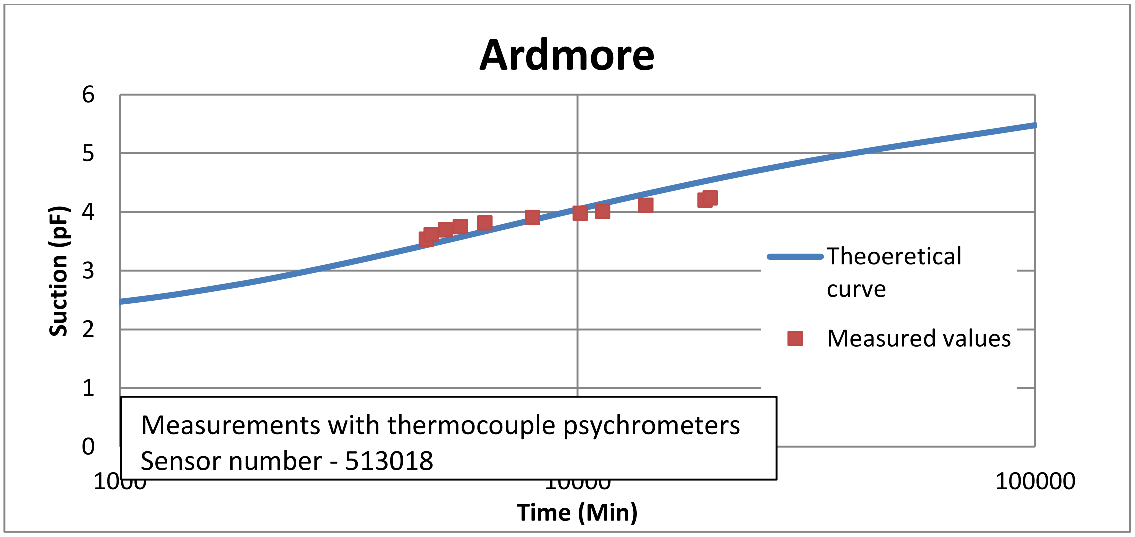


Figure B.19. Ardmore Site : Drying 2

Table B.20. Norman Site: Wetting 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	2.75	pF
Initial Suction (Uo)	4.5	pF
Psychrometer Location (x)	12	cm
Sample Length (L)	15	cm
Psychrometer number used	513016	

Wetting Diffusion Coefficient, $\alpha_{wet} = 4.0732 \times 10^{-3}$ $cm^2/$ min

Laboratory Suction Measurements

Time	**Suction**
min	pF
240	4.29
390	4.10
470	4.04
600	3.95
1010	3.82
1190	3.76
1560	3.68
1920	3.58
2170	3.50
240	4.29

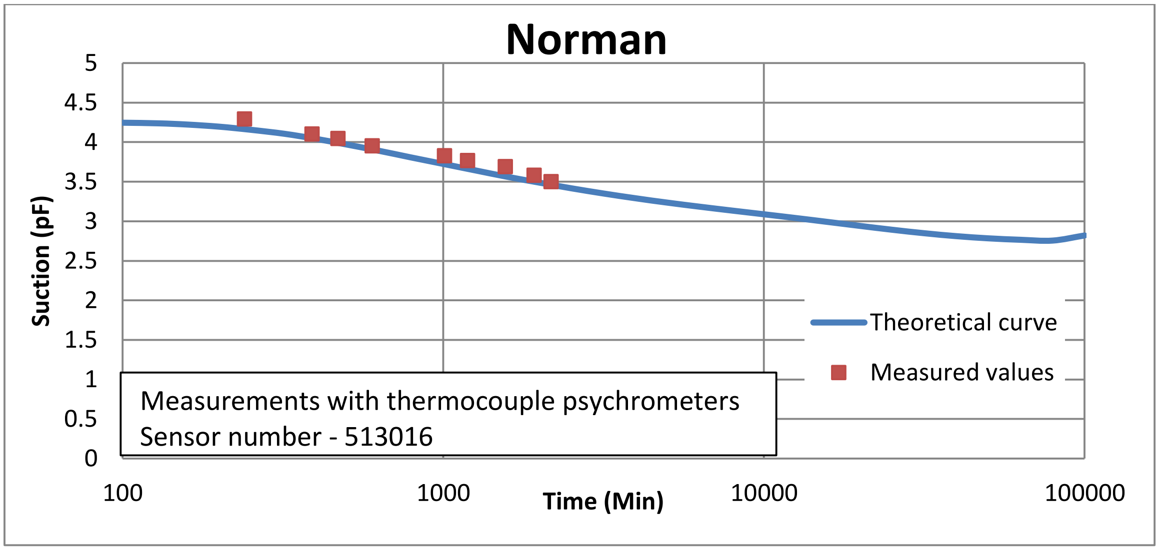


Figure B.20. Norman Site: Wetting 2

Table B.21. Lake Hefner Site: Wetting 2

Parameter	**Value**	**Units**
Evaporation Coefficient (he)	0.54	cm^{-1}
Suction of the Liquid (Us)	2.75	pF
Initial Suction (Uo)	4.5	pF
Psychrometer Location (x)	13	cm
Sample Length (L)	16	cm
Psychrometer number used	48084	

Wetting Diffusion Coefficient, $\alpha_{wet} = 3.9408 \times 10^{-3}$ cm^2/min

Laboratory Suction Measurements

Time	**Suction**
min	pF
560	4.37
600	4.23
710	4.04
900	3.97
1640	3.87
1860	3.79
2240	3.68
2500	3.61
2730	3.54
2860	3.50

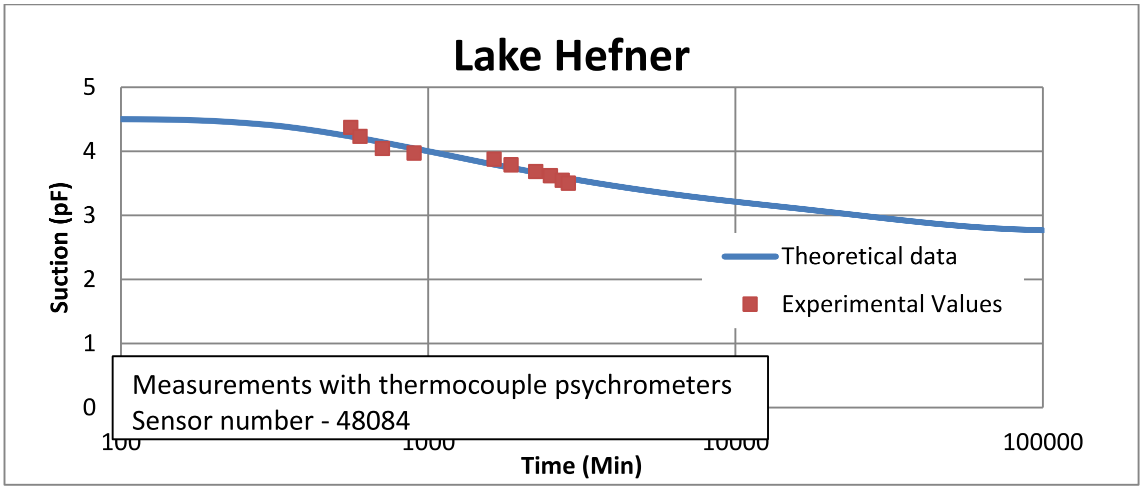


Figure B.21. Lake Hefner Site: Wetting 2

C. Suction versus Time plots of the Thermal Conductivity Sensors and Thermocouple Psychrometers

The suction measurements against time are taken and plotted. All the total suction measurements from thermocouple psychrometers and matric suction measurements from thermal conductivity sensors are plotted on the same graph.

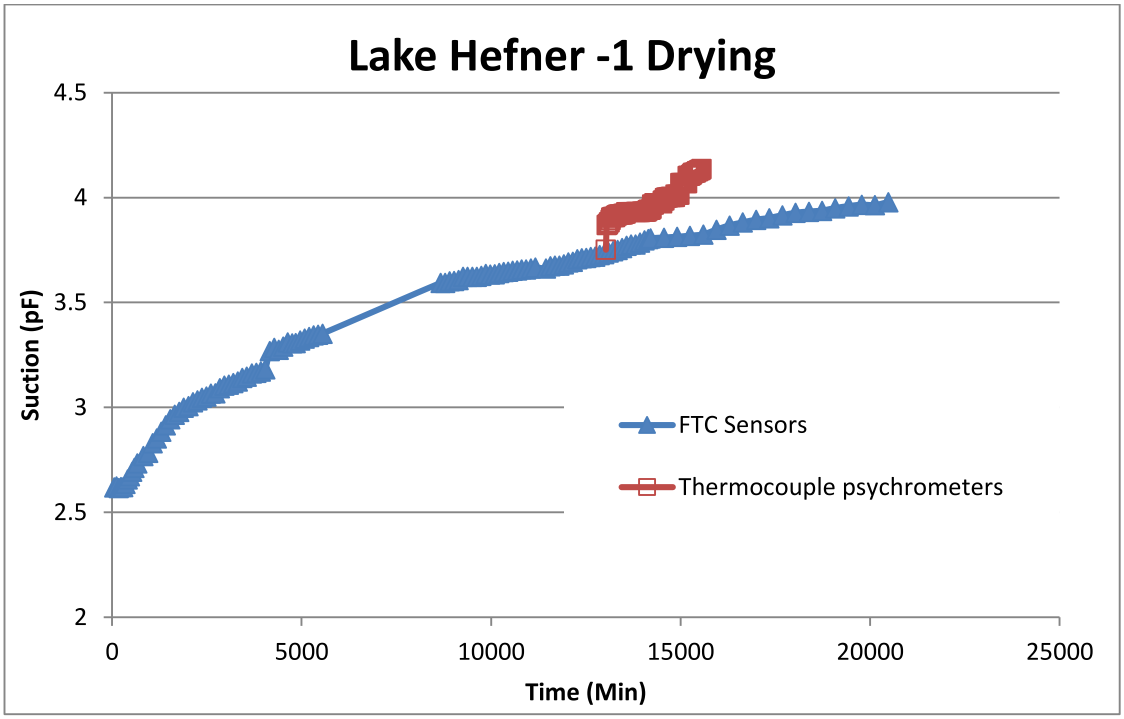


Figure C.1. Lake Hefner 1: Change of Suction with Time in Drying Test

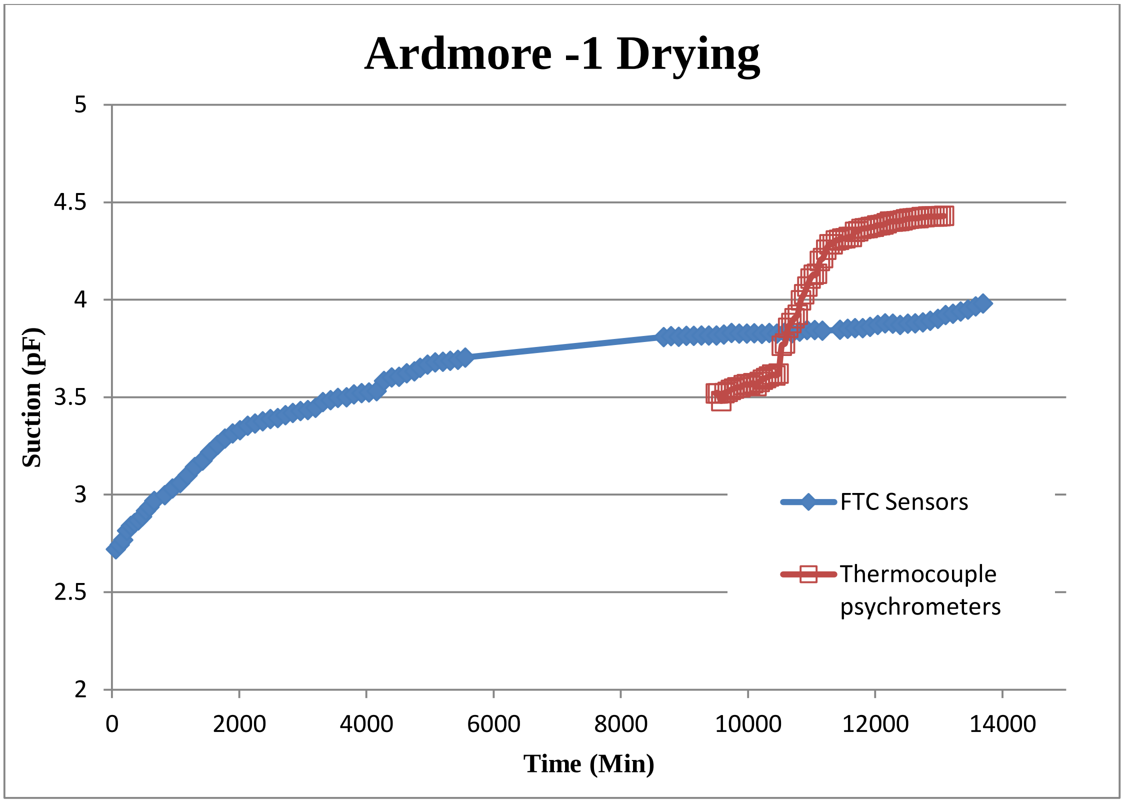


Figure C.2. Ardmore 1: Change of Suction with Time in Drying Test

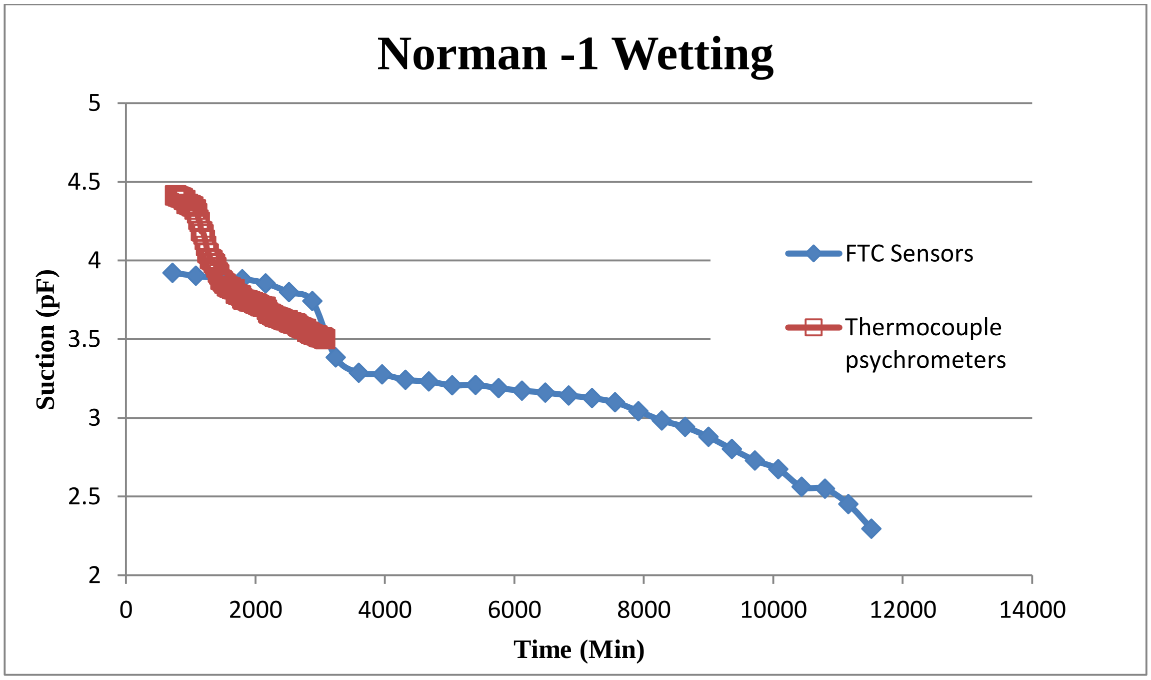


Figure C.3. Norman 1: Change of Suction with Time in Wetting test

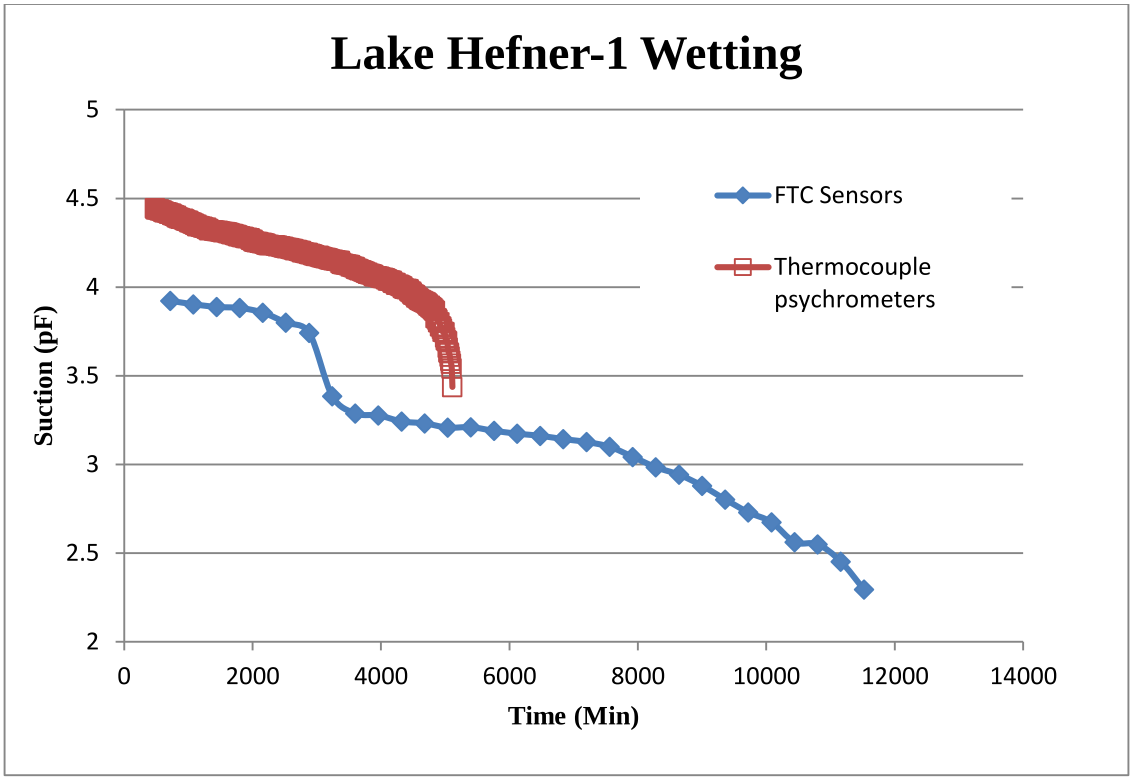


Figure C.4. Lake Hefner 1: Change of Suction with Time in Wetting Test

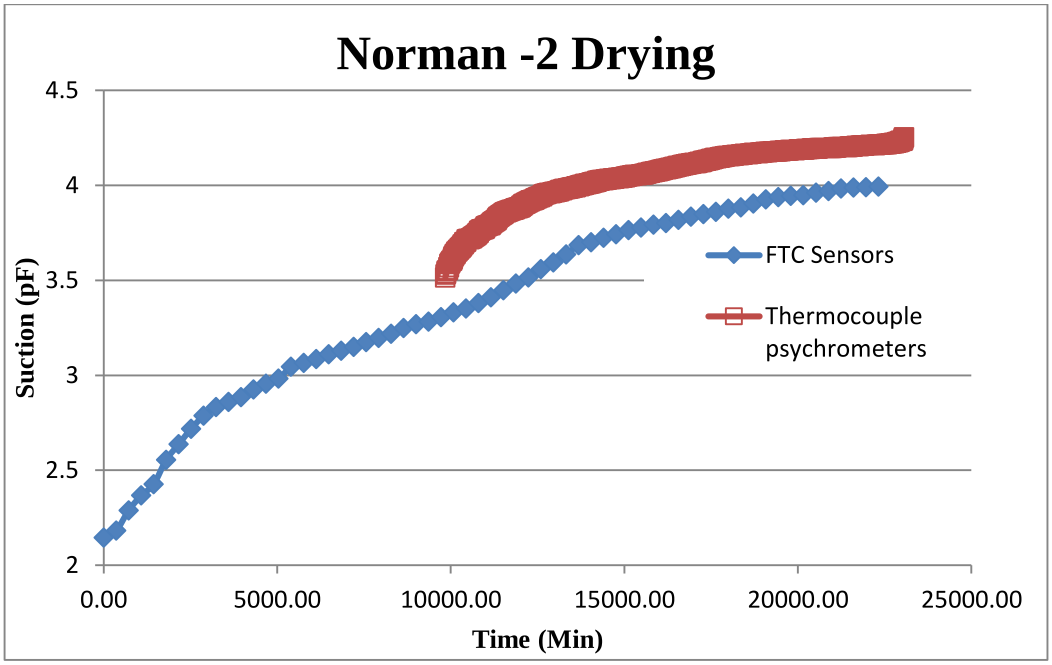


Figure C.5. Norman 2: Change of Suction with Time in Drying Test

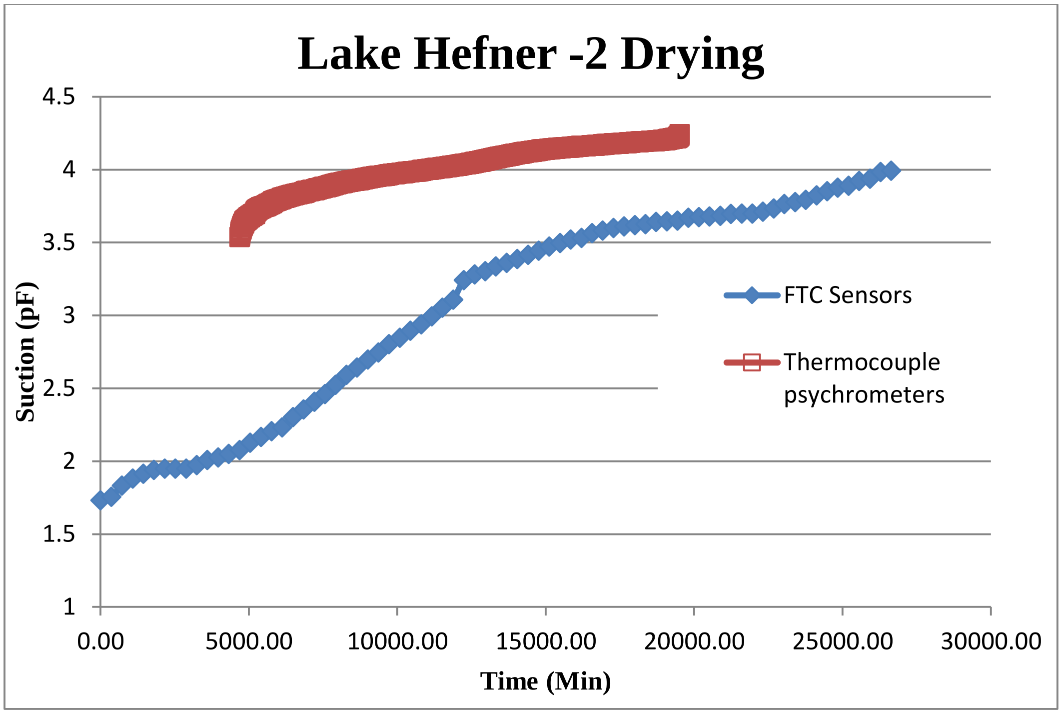


Figure C.6. Lake Hefner 2: Change of Suction with Time in Drying Test

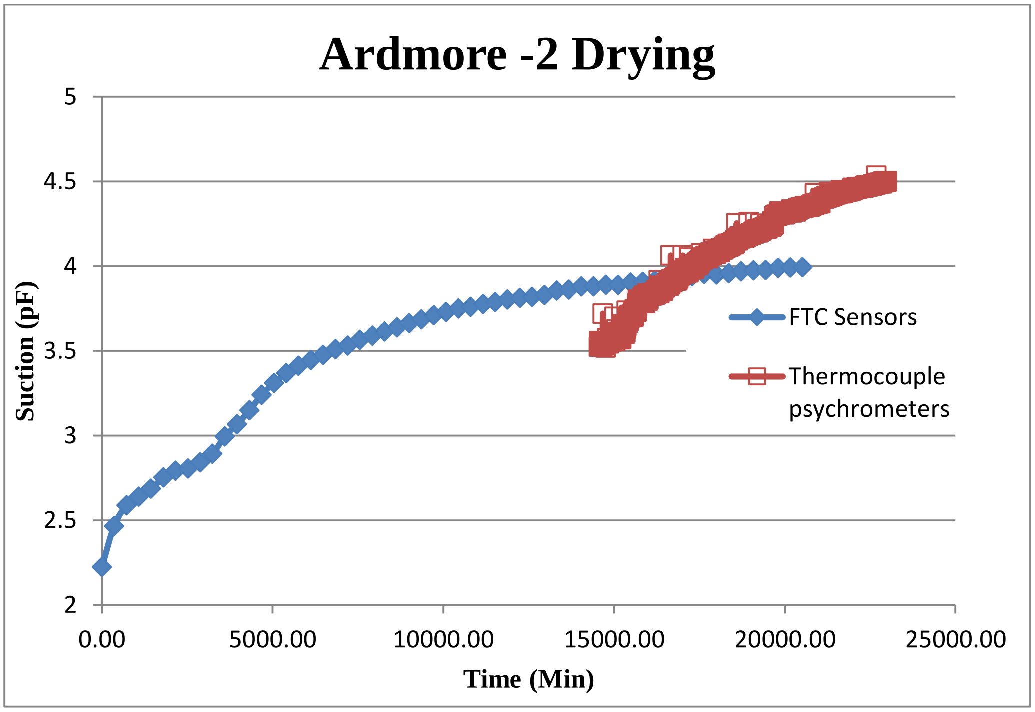


Figure C.7. Ardmore 2: Change of Suction with Time in Drying Test

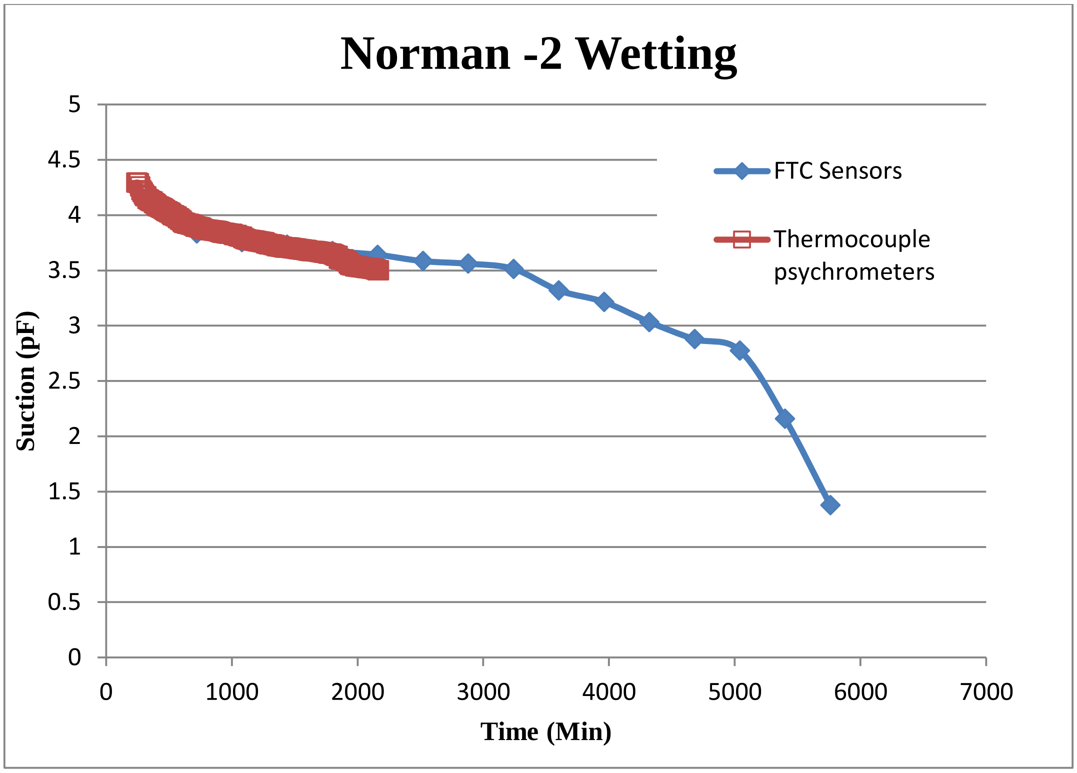


Figure C.8. Norman 2: Change of Suction with Time in Wetting Test

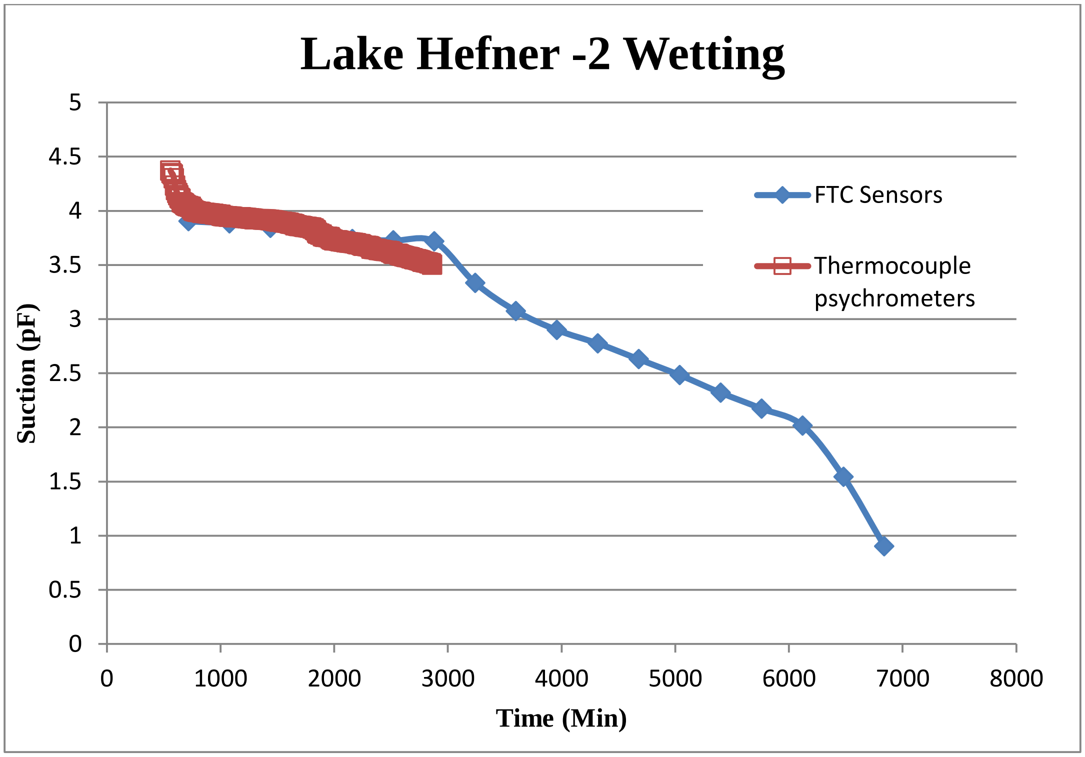


Figure C.9. Lake Hefner 2: Change of Suction with Time in Wetting test

D. Parametric analysis of the Mitchells Equation

In Mitchel's equation for the determination of wetting coefficient, a parametric analysis was performed. The behavior of the theoretical curve was observed by changing one parameter and keeping other parameters constant.

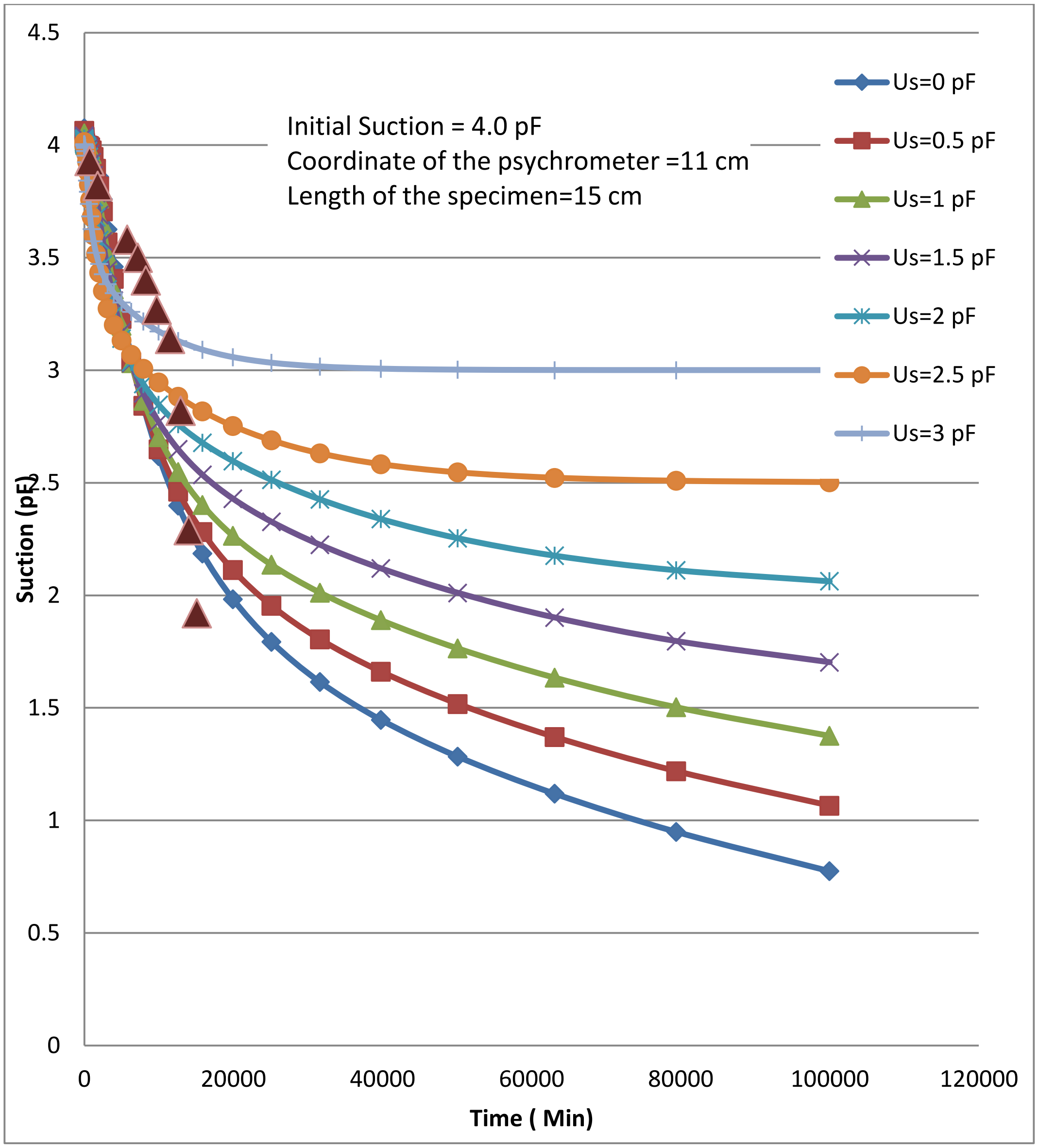


Figure D.1. Change in the suction of the liquid for constant initial suction, Coordinate of the psychrometer and the length of the specimen

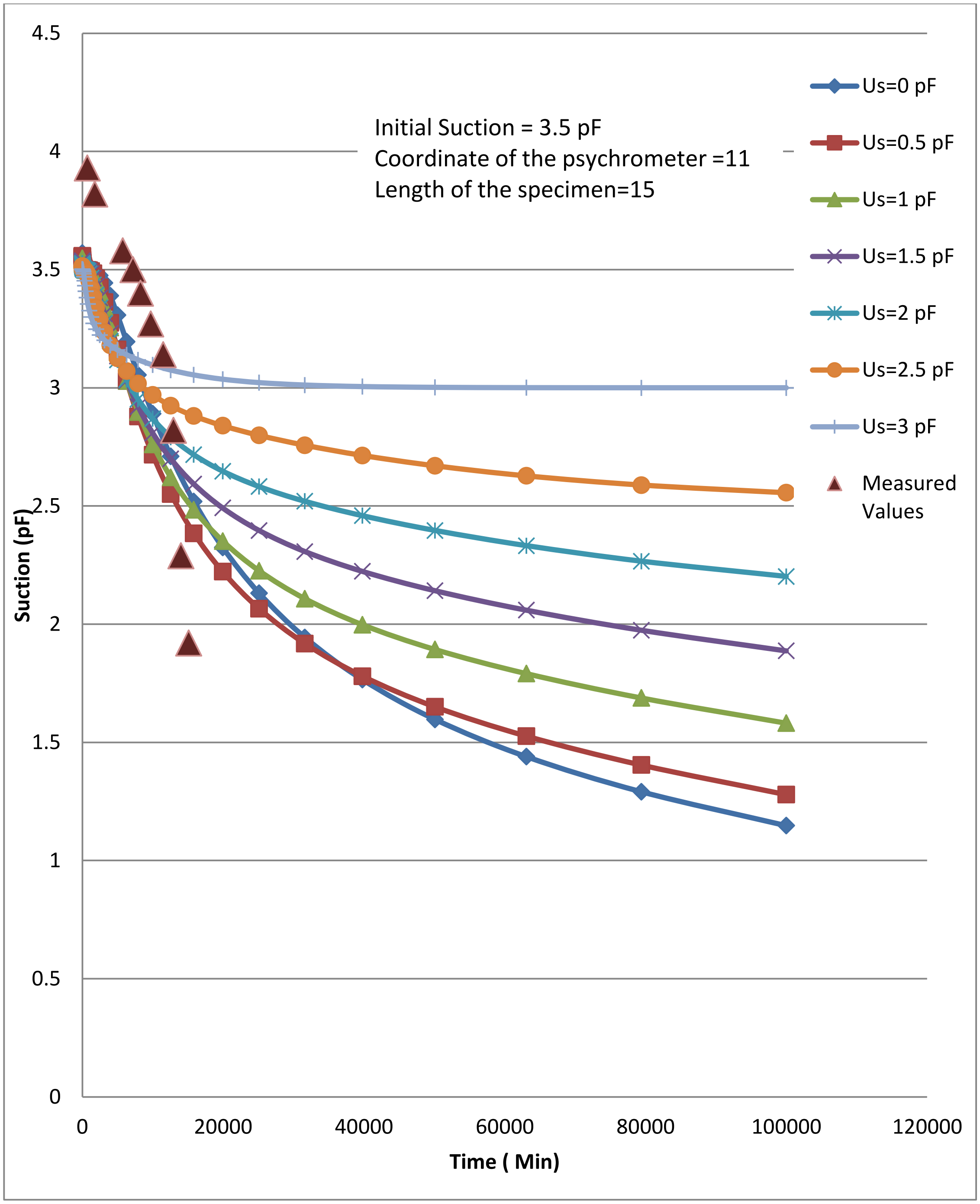


Figure D.2. Change in the suction of the liquid for constant initial suction, Coordinate of the psychrometer and the length of the specimen

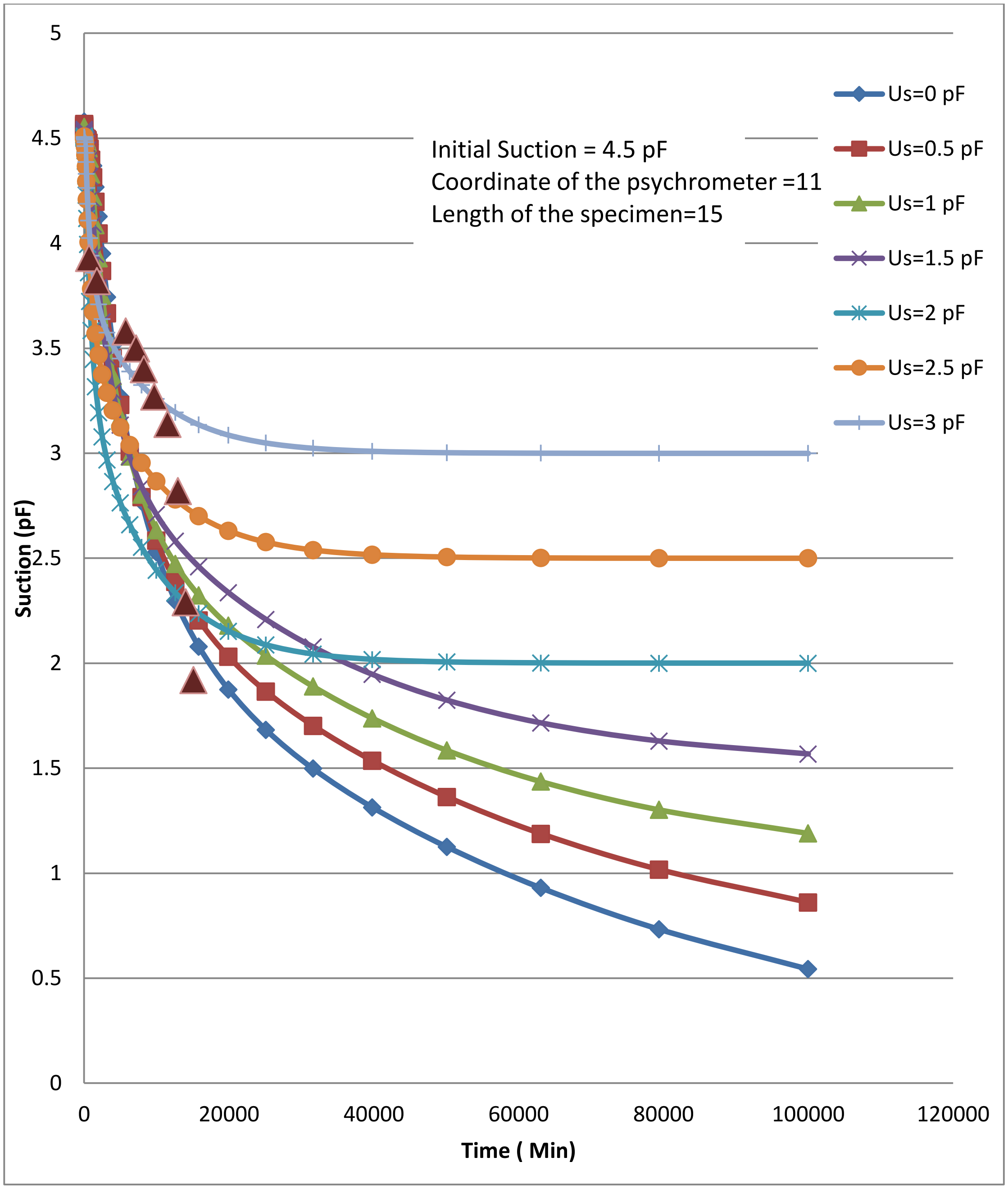


Figure D.3. Change in the suction of the liquid for constant initial suction, Coordinate of the psychrometer and the length of the specimen

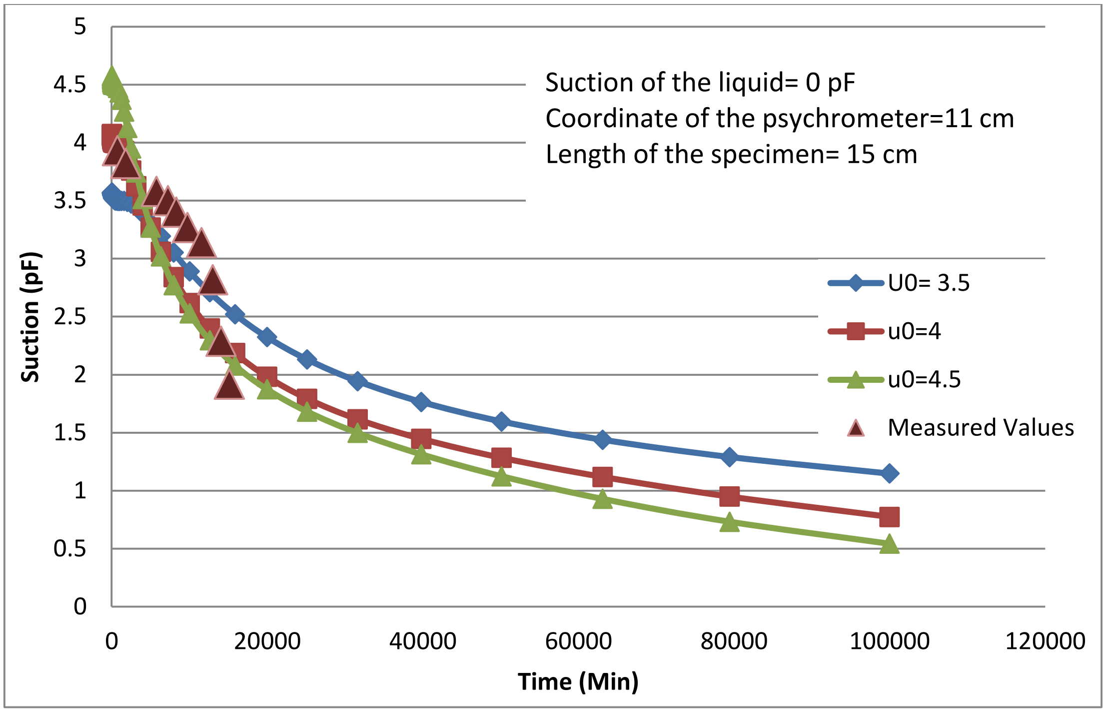


Figure D.4. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

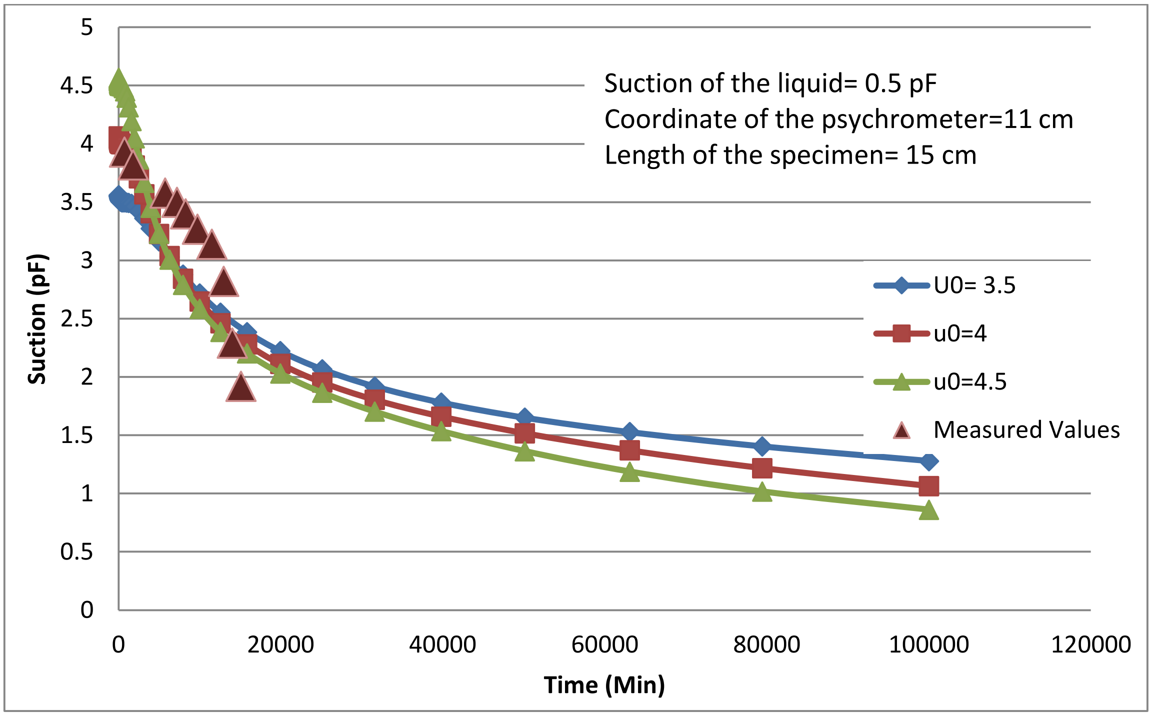


Figure D.5. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

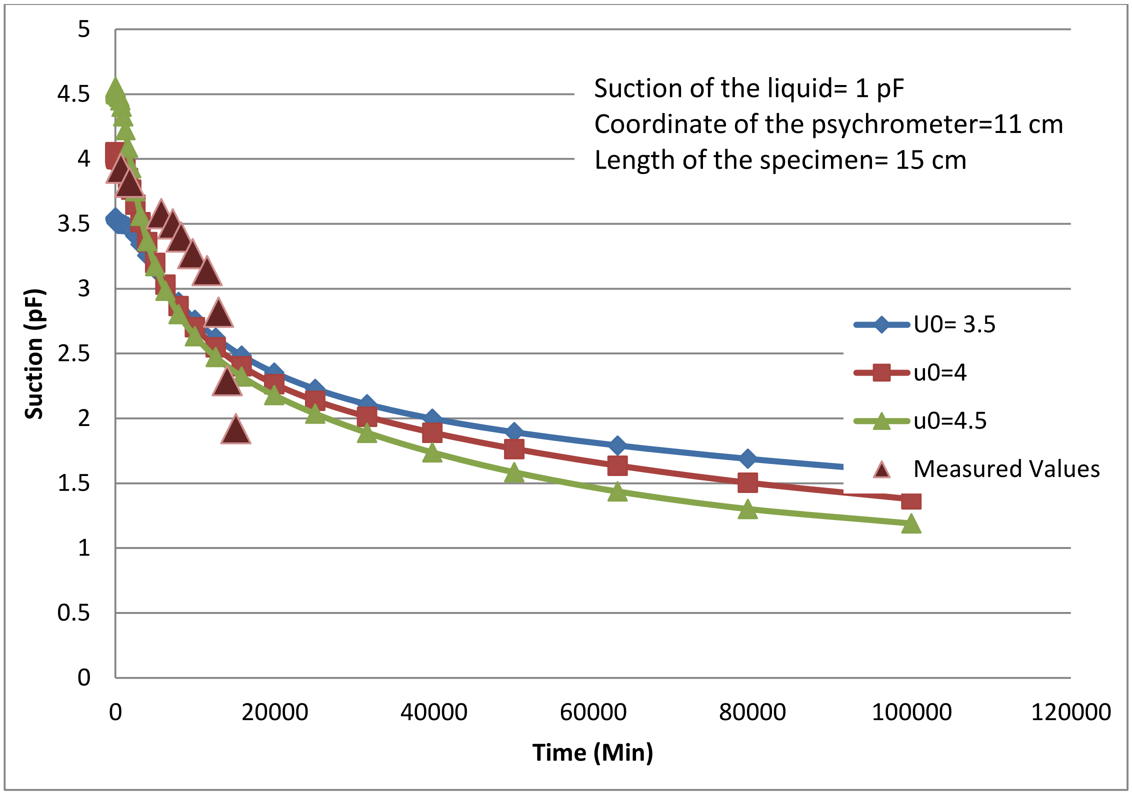


Figure D.6. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

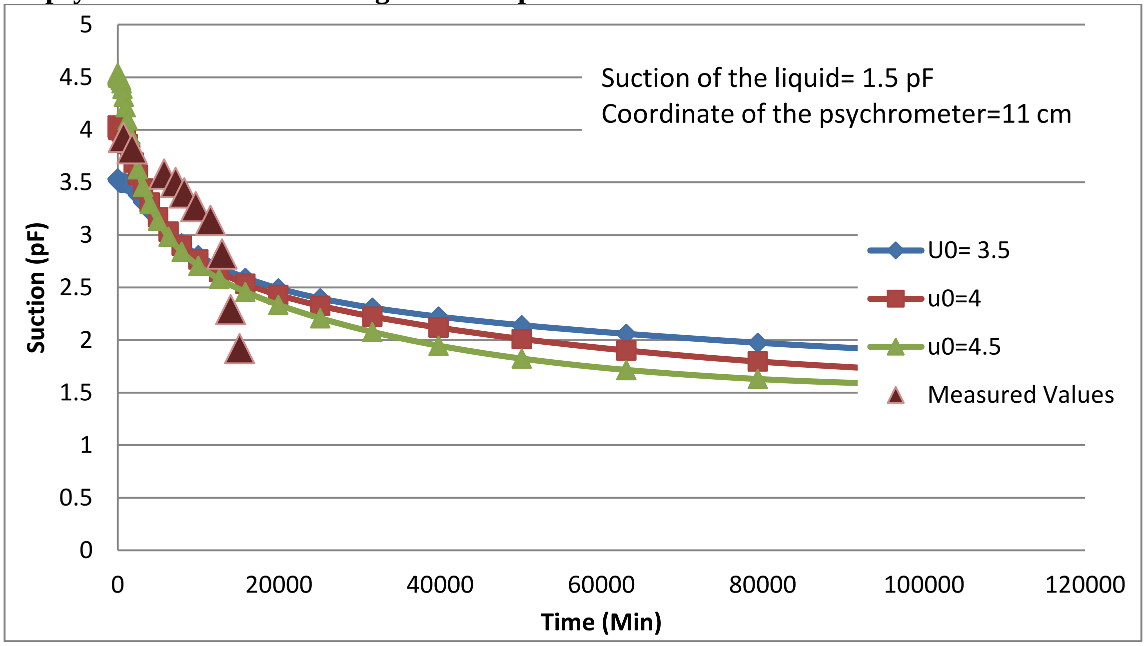


Figure D.7. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

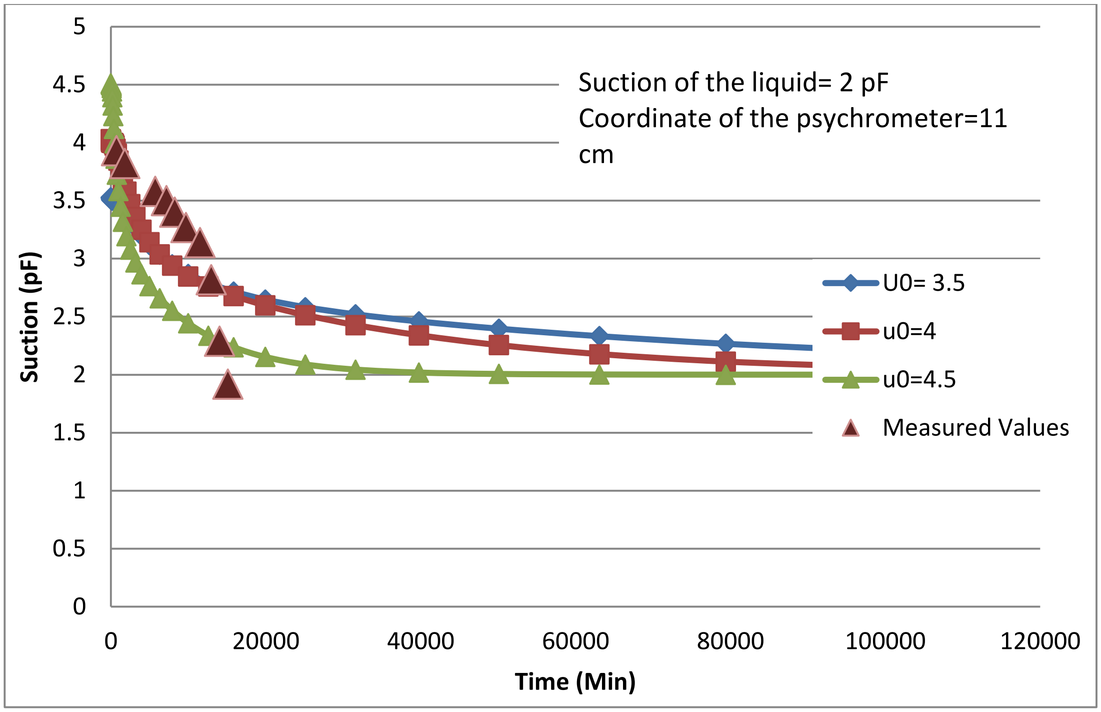


Figure D.8. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

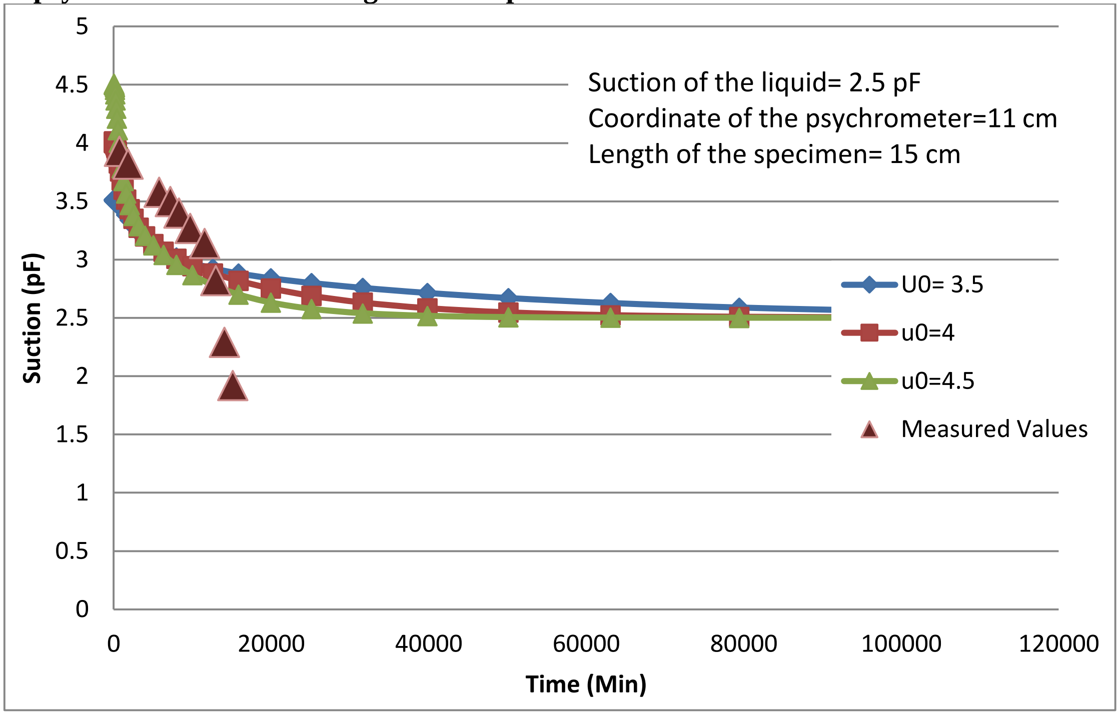


Figure D.9. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

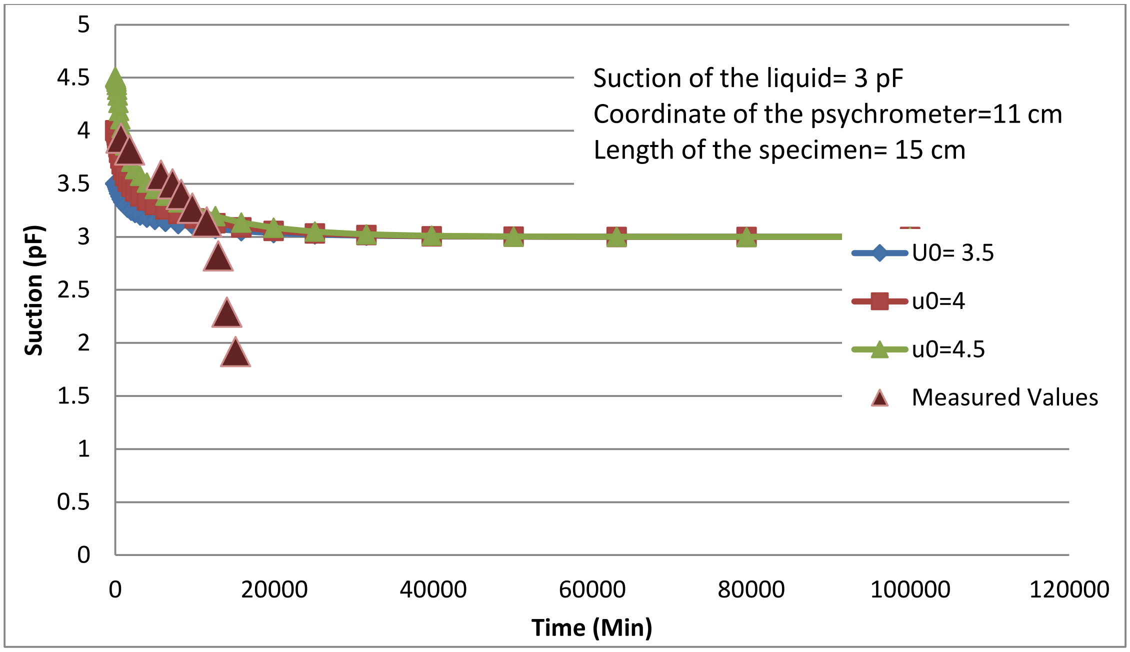


Figure D.10. Change in the Initial suction for Constant Suction of the Liquid, Coordinate of the psychrometer and the Length of the Specimen

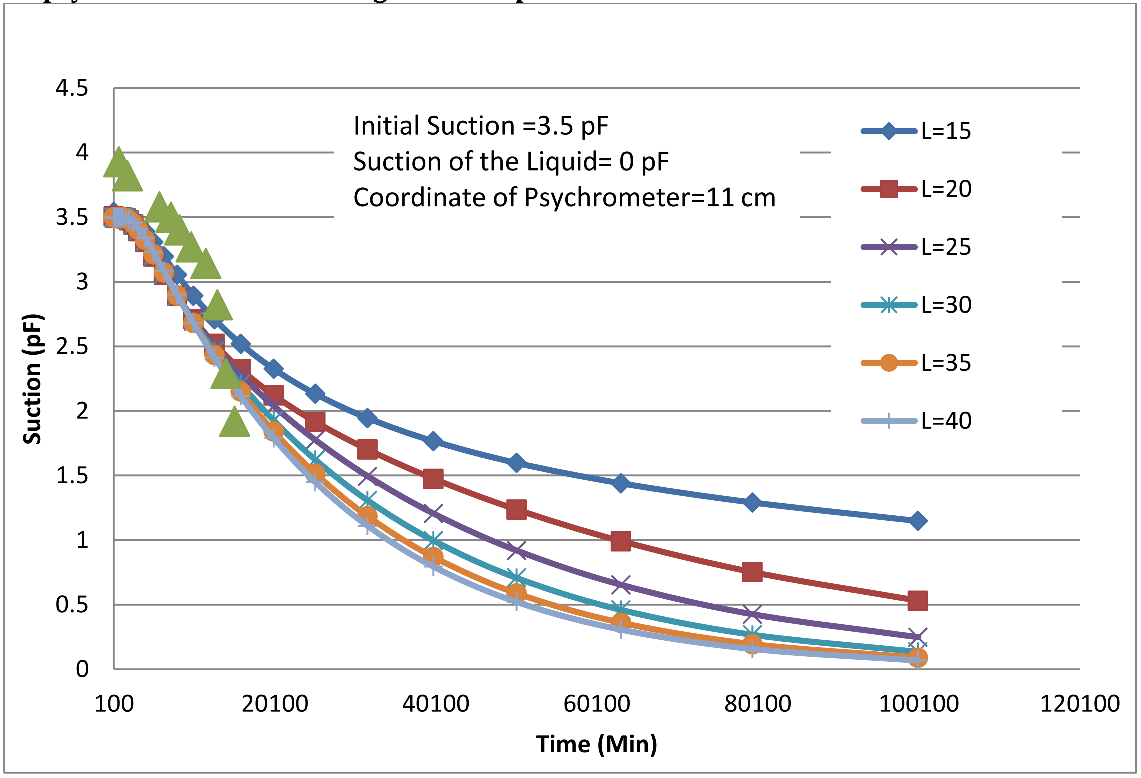


Figure D.11. Change in the Length of the Specimen for Constant Suction of the Liquid, Coordinate of the psychrometer and the Initial Suction

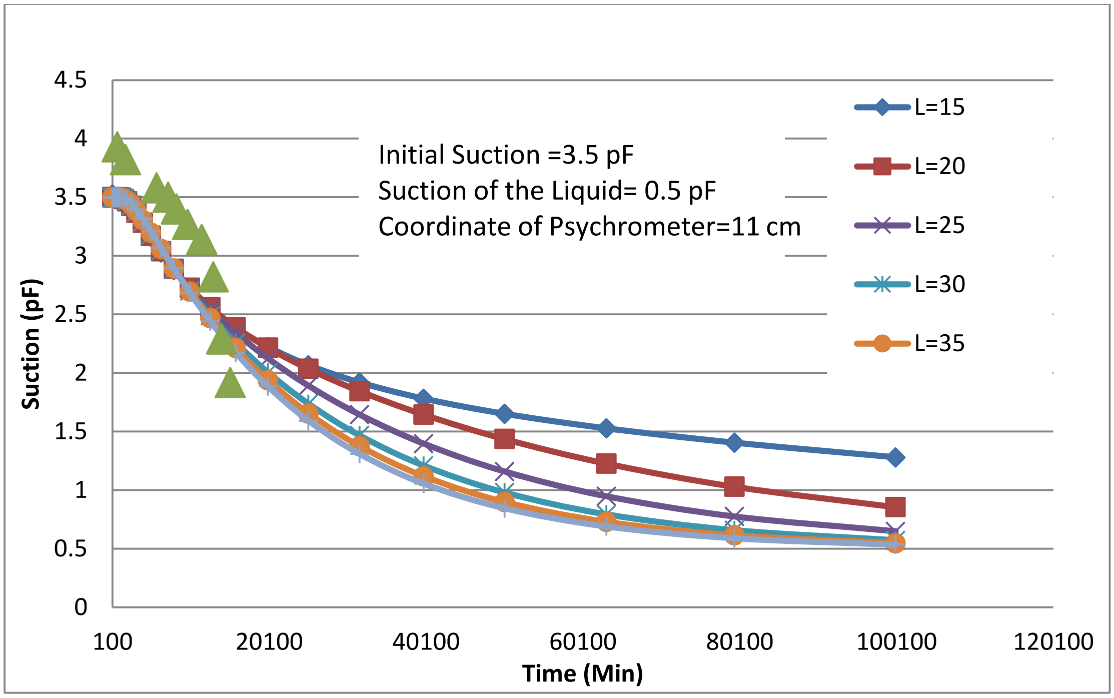


Figure D.12. Change in the Length of the Specimen for Constant Suction of the Liquid, Coordinate of the psychrometer and the Initial Suction

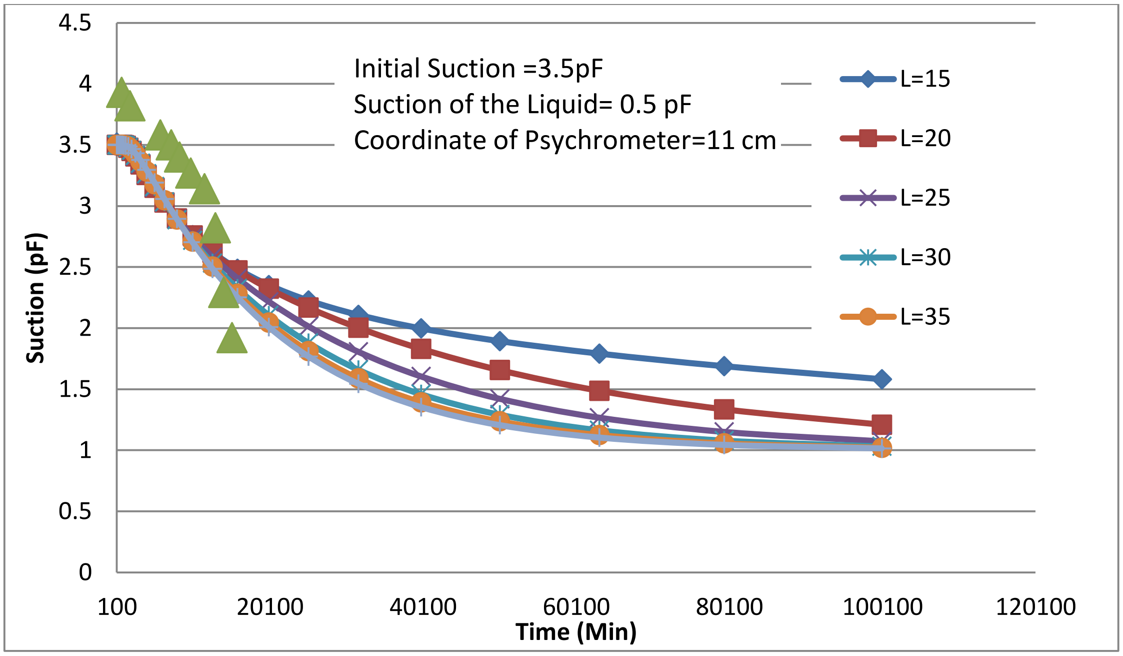


Figure D.13. Change in the Length of the Specimen for Constant Suction of the Liquid, Coordinate of the psychrometer and the Initial Suction

VITA

SRUTHI MANTRI

Candidate for the Degree of

Master of Science

Thesis: DETERMINATION OF MOISTURE DIFFUSION COEFFICIENT AT LOW SUCTIONS USING THERMAL CONDUCTIVITY SENSORS

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in July, 2014. Completed the requirements for the Bachelor of Technology in Civil Engineering at JNTU college of Engineering, Kakinada, India in 2011.

Experience:

Employed as a Research Assistant in Indian Institute of Technology , Bombay from October 2011 to May 2012; Employed as Graduate Research Assistant in Department of Civil Engineering , Oklahoma State University from August 2012 to July 2014.