A STUDY OF MEASUREMENT OF SOIL SUCTION AND SOIL WATER CHARACTERISTIC CURVE OF UNSATURATED SOILS

A dissertation submitted in partial fulfillment of the requirement for the award of degree of

MASTERS OF TECHNOLOGY
IN
GEOTECHNICAL ENGINEERING

BY

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CERTIFICATE

This is to certify that the Dissertation Report titled **"A Study of Measurement of Soil Suction And Soil Water Characteristic Curve of Unsaturated Soils"** is a bonafide work carried out by **Ms. Salonee Srivastava (2k14/GTE/17)** of M. Tech 2014-16 and submitted to Civil Engineering Department, Delhi Technological University, Bawana Road, Delhi- 110042 in partial fulfillment of the requirement for the award of the Degree of Masters of Technology.

Signature of Guide:

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Place:

Date:

DECLARATION

I, **Salonee Srivastava (2k14/GTE/17),** student of M. Tech. 2014-16 at Department of Civil Engineering, Delhi Technological University, Bawana Road, Delhi- 42 declare that the Dissertation Report titled "**A Study of Measurement of Soil Suction And Soil Water Characteristic Curve of Unsaturated Soils"** submitted in partial fulfillment of Degree of Masters of Technology, is the original work conducted by me. The information and data given in the report is authentic to the best of my knowledge. This Report has not been submitted to any other University for award of any other Degree, Diploma and Fellowship.

Salonee Srivastava

Place:

Date:

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ABSTRACT

Unsaturated soil mechanics is an important topic to deal with at the post graduate level because textbooks cover the theories related to soils in a completely dry or a completely saturated condition. Recently, it has been shown that attention must be given to soils that do not fall into these common categories. Many of these soils can be classified as unsaturated soils. As a geotechnical expert, we have to encounter soils which are in a state of partial saturation. And it becomes necessary to understand the basic behavior of these kinds of soils in order to carry out any construction activity on them. Engineering related to unsaturated soils has typically remained empirical due to the complexity of their behaviour. An unsaturated soil consists of more than two phases and therefore the natural laws governing its behaviour are changed and the principle of soil suction comes into action.

So, a basic understanding about the concept of soil suction, its components, its representation, various methods with their relative advantages and limitations and a detailed description of filter paper method to measure soil suction has been presented in this report. An experimental setup has been designed which can be used in the laboratory. The procedure to obtain a calibration curve required to obtain the results has also been provided, along with the models of various researchers to obtain soil water characteristic curve and unsaturated hydraulic conductivity. The effect of compaction on these parameters has also been dealt with.

At last, due references have been mentioned.

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LIST OF SYMBOLS

T = absolute temperature (°K)

g = acceleration due to gravity

ρ_w = density of water

S_e = effective degree of saturation.

w = gravimetric water content

h_c = height of capillary rise

R = ideal gas constant (8.314 J/mol-°K)

e = irrational constant equal to 2.71828.

w = molecular mass of water

m = molality

M_v = molar volume of water ($1.8 \times 10^{-5} m^3/mol$)

v = number of ions from one molecule of salt

Ø = osmotic coefficient

π = osmotic suction

u_a = pore air pressure

n = pore size parameter

u_w = pore water pressure

r = radius of meniscus

K_s = saturated hydraulic conductivity

θ_s= saturated volumetric water content

Ψ = soil suction

Ts = surface tension

a_f, n_f , m_f = three fitting parameters of Zapata model

Θ = volumetric water content

θ = volumetric water content

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CHAPTER 1
INTRODUCTION

1.1. Introduction

Unsaturated soil mechanics is often applied to geotechnical problems such as embankments, dams, pavements, foundations, landfills, slopes, nuclear waste disposals, etc. Analyzing such problems requires information about soil suction variations in such soil. This explains why significant effort has been made from all over the world on suction measurement techniques under field conditions.

1.2. Soil Classification

Soil can broadly be classified into two main categories, which is shown in Figure 1.

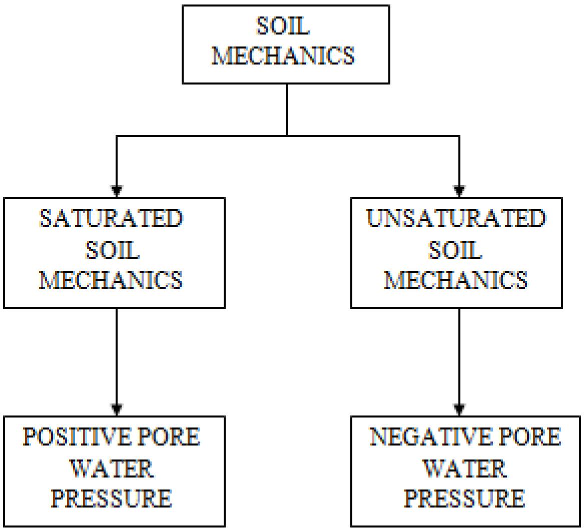

Figure 1 Soil classification [Fredlund and Rahardjo (1993)]

1.3. Introduction to the Soil Suction

The water particles present in soil voids below the water table is normally continuous. The soil can either be saturated, with all the voids filled completely with water or may have occluded or trapped air bubbles present in the soil matrix along with water. Pore pressures at various depths from the ground below the water table are the result of an effective combination of the total weight of the water lying above the given height and the drainage conditions existing below.

If the water present in the voids of a soil is subjected to no force other than that due to gravity, the soil present above the water table would be perfectly dry. However, there exist very strong molecular and physio-chemical forces acting at the boundary between the soil particles and the water, causing the water to be either drawn up into the otherwise empty void spaces of the soil or to be held there without drainage following infiltration from the surface. This attraction that the soil exerts on the water is termed as soil suction.

The magnitude of this attractive force that soil present above the water table exerts on water is governed by the size of the voids in manner similar to the way that the diameter of a small bore glass tube governs the height to which water will rise inside the tube when it is immersed in water. The smaller the void, greater is the force of attraction and harder it is to remove the water from the void.

Fredlund and Rahardjo (1993) in their literature emphasized on the fact that the meniscus formed between adjacent particles of the soil by soil suction creates a normal force between the soil particles, which thus bonds them in a temporary way. Thus soil suction, if relied upon, can enhance the stability of earth structures. However soil suction also provides an attractive force for free water, which can result in a loss of stability in loosely compacted soils or swelling in densely compacted soils, which might ultimately lead to failure of the soil matrix.

1.4. Objective and Scope of the Project

Unsaturated soil mechanics turns out to be a complex area of study mainly because of the fact that the engineers have a least idea about the mechanisms occurring in these types of soils. The existing concepts and theories are needed to be made as simple as possible for the engineers to easily understand the principles of their application.

Soil suction being the basic phenomenon occurring in unsaturated soils, is an important concept to be dealt with at post graduate level. Measurements of suction values help in plotting the soil characteristic curve, from which various other properties like hydraulic conductivity, shear strength, volume changes, etc. of unsaturated soils can be obtained using suitable models available.

Unsaturated soils are encountered in case of landfills, expansive soils, stability of temporary excavations, to name a few. Knowledge about them gives a better understanding of the phenomenon involved with the geotechnical problem thus providing

- Safer design.
- Economy.
- Follow up of the behavior of structures.

1.5. Components of Soil Suction

(a) Total Suction

Total soil suction is defined by Kelvin's equation in terms of the relative vapour pressure or relative humidity of the soil moisture

$$\Psi = (-RT / M_v) * \ln (RH) = -135055 \ln (RH) \quad (1)$$

where,

Ψ = total suction in ka

RH = relative humidity (%) = $\frac{P}{P_0}$

T = absolute temperature (°K)

R = ideal gas constant (8.314 J/mol-°K)

M_v = molar volume of water ($1.8 \times 10^{-5} m^3/mol$)

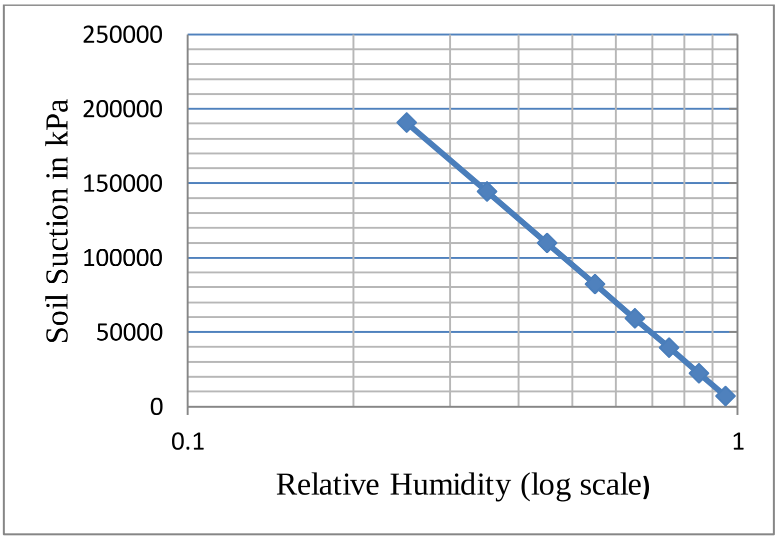

Figure 2 Total suction versus relative humidity

There is an inverse relationship between total suction and relative humidity at a constant temperature (i.e., Eq. (1)). Figure 2 is obtained by plotting Kelvin's equation for 25^{o}C temperature. From the relationship, total suction is equal to zero when relative humidity is 100 percent (i.e., fully saturated condition). On the other hand, total suction becomes very large when relative humidity decreases, but the change in relative humidity is very small with respect to the change in total suction.

The total suction consists of two components, matric suction (u_a - u_w) and osmotic suction (π) and is given as:

$$\Psi = (u_a - u_w) + \pi$$

Both components are due to differences in relative humidity of the soil vapour.

(b) Matric Suction (u_a-u_w)

Matric suction is the suction exerted by the soil material (matrix) that induces water to flow in unsaturated soil. It is a negative pressure that results from the combined effects of adsorption and capillarity due to the soil matrix. Water flows in a soil from low matric suction (a wet soil) to soil with a high matric suction (a dry soil).

At the soil-air interface, due to the surface tension, the meniscus formed results in reduced vapor pressure in the water. The vapour pressure decreases, becomes more negative, and the matric suction pressure increases as the radius of curvature of the meniscus decreases.

The size of the pores of soil decreases with a decrease in soil particle size which then affects the size of the radius of curvature and consequently the matric suction pressure. The vapor pressure decreases as the degree of saturation decreases.

(c) Osmotic Suction (π)

The presence of dissolved ions in water in the voids decreases the soil vapor pressures and relative humidity, which then increases the value of total soil suction.

Changes in osmotic suction have effects on mechanical behavior of the soil, causing a change in the shear strength and overall volume of the soil. Changes in osmotic suction become important to deal with when there is significant amount of soil contamination.

Osmotic changes are generally less significant. The change of total suction corresponding to changes in osmotic suction when water content is varied does not come out to be much and hence osmotic suction is neglected in this study.

CHAPTER 2

LITERATURE SURVEY

2.1 Capillary Model

According to **Millington and Quirk (1961)**, soil matric suction is described in terms of capillary forces, i.e., capillary rise, acting in soil. Capillary rise is caused by surface tension and the attractive forces between the soil ions and the water molecules in the adsorbed water.

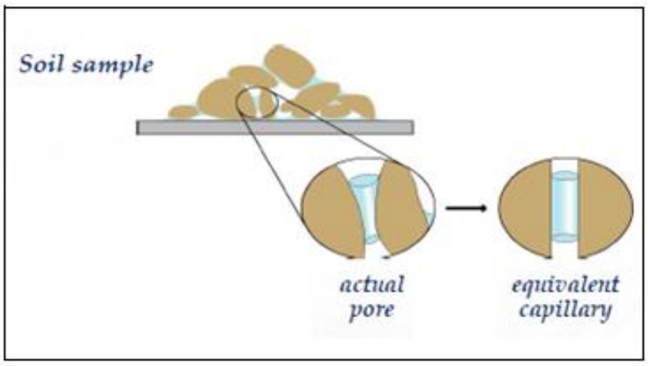

Figure 3 Capillarity in soils [Millington and Quirk (1961)]

The rise in a capillary tube is computed by setting the total upward forces due to surface tension equal to the downward force due to the weight of the water in a tube, as shown in the equation (2):

$$2\pi r T_s \cos\alpha = \pi r^2 h_c \rho_w g \quad (2)$$

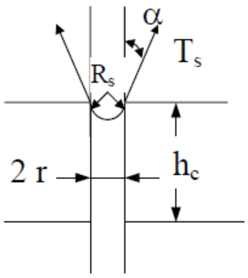

Figure 4 Illustration of capillary rise

height of capillary rise, h_c, is obtained by assuming α=0 (for water angle of contact is generally 0).

$$h_c = 2T_s / \rho_w g r \quad (3)$$

The matric suction pressure can then be given as

$$(u_a-u_w) = \rho_w g h_c = 2T_s / r \quad \textbf{(4)}$$

Since the pores sizes in soil which are comparable to the parameter r in equation (4) are indeterminate so it is not possible to calculate pore water pressure directly. Moreover, the variation in pore sizes and the orientation of particles within the soil system lead to the variation in properties of soil thus making it difficult to do the direct calculations.

In an unsaturated soil system, the surface tension may have a component of force perpendicular and a component in parallel direction to the surface which results in the soil particles being acted upon by compressive forces.

2.2 Different Methods to Determine Soil Suction

There are numerous ways of measuring the soil suction value for a given unsaturated soil sample. **Sreedeep and Singh (2011)** gave a brief description of few important methods:

a) Psychrometers

(i) Basic Principle: The principle used in psychrometers is that the difference in temperature between a non evaporating and an evaporating surface depends upon on the relative humidity.

(ii) Description: A thermocouple which is an electrical circuit with two dissimilar conductors is used to determine the relative humidity of the air inside a sealed chamber.

(iii) Methodology: A very small current flow causes an increase and decrease in the temperature at the junctions of a thermocouple which is explained by Peltier Effects. Condensation and subsequent evaporation takes place at the junction which is cooled to the dew point. The evaporation causes a cooling of the junction. An electromotive force gets induced due to the difference in temperature at the two junctions which is due to Seebeck Effects. The voltage measured (in micro volts) is a function of the difference in temperature which in turn is a function of the relative humidity.

(iv) Calibration Procedure: The instrument is calibrated using known values of osmotic suction pressures of solutions and the output from the sensor.

(v) Sensor Calibration: It can be used to measure the total suctions values from 100 to 8000 kPa.

(vi) Sensor Limitations: The response time for sensors can create certain limitations. Since relative humidity is dependent on temperature, the use of pshycrometers requires constant temperature during measurements.

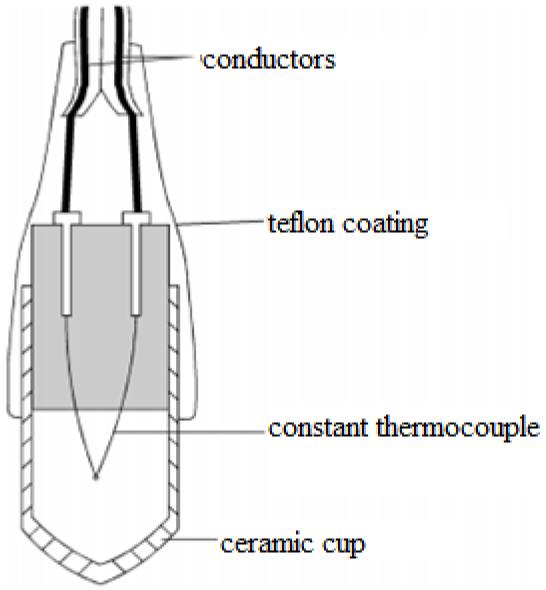

Figure 5 Cross section of a thermocouple psychrometer contained in an air-filled ceramic and used to measure the $\psi_m + \psi_0$ of the soil water in situ. [Sreedeep and Singh (2011)]

b) Filter Paper Method

(i) Basic Principle: The basic principle that is used in filter paper method for soil suction measurement is that the moisture content of a filter material will reach equilibrium according to the surrounding environment, i.e., the soil medium.

(ii) Description: The initially dry filter paper of known mass and size is calibrated using salt solution to give total or matric suction.

(iii) Methodology: In this method, the dry filter paper is placed in contact with the soil to measure matric suction or suspended above the soil to measure its total suction, in a closed container and is allowed to come to equilibrium with the soil vapor or the water pressure. The water content of the filter paper after an equilibrium period of 7 days is indicative of the suction pressure.

(iv) Calibration Procedure: For calibration, the filter paper water contents is calibrated with some salt of known osmotic coefficient which ultimately gives us total suction values of solutions.

(v) Range Measured: It is used to measure all the range of suction pressures.

(vi) Method's Limitations: The response time of 7 days may provide limitations. Also the filter may not be in good contact with the soil.

c) Tensiometers

(i) Basic Principle: The basic principle used in tensiometer method for soil suction measurement 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

(ii) Description: It consists of a small ceramic cup which is attached to a tube filled with de-aired water which is then connected to a device for measuring pressure, like pressure gauge or a transducer, or a manometer.

(iii) Methodology: The ceramic cup and the tube is saturated by filling it with water and then applying a vacuum to the tubing. The ceramic tip is then allowed to dry up in order to reduce the pressure of water in the sensor and remove any air bubbles that may appear. The sensor is then installed with ceramic tip being in direct contact with the soil and the air bubbles being removed as they appear in the tube.

(iv) Sensor Capabilities: It can be used to measure the suction pressures even up to -90 kPa.

(v) Sensor Limitations: Any air trapped in the sensor will lead to wrong measurement of the pore water pressure values. Air may accumulate because of:

- air coming out of the solution with the decrease in water pressures;
- air in soil may diffuse through the material of the ceramic cup;
- water may vaporize causing cavitation as the soil water pressure approaches the value of vapor pressure of the water at ambient temperature.

d) Pressure Plate Extract:

(i) Basic Principle: The basic principle used in pressure plate extractor for soil suction measurement is that it uses the technique of axis-translation in which the reference air pressure is reversed from atmospheric to above atmospheric thus causing the change in pore water pressure as it comes to equilibrium with the pore air pressure.

(ii) Description: In a closed system the air pressure and the soil water pressure is varied by the same amount so that the matric suction remains constant. In such case no water flow occurs and this behavior is used to verify whether this technique is valid or not.

For an open system, the high value of pore air pressure forces the water to flow from the soil to the ceramic disk until the value of soil pore water pressure which is equal to the pressure in the disk, comes to an equilibrium with the air pressure of the soil.

(iii) Methodology: A ceramic plate is saturated and a soil sample is placed on the ceramic plate and the soil is allowed to reach the desired state of equilibrium. The air pressure is then varied in the pressure cell until an equilibrium is reached again. The soil matric pressure is equal to the difference between the applied air pressure and the water pressure where the water pressure is usually close to atmospheric pressure. Then the soil moisture content is determined by either of the two ways:

- By measuring the volume of flow of water, or
- By quickly removing the soil from the cell and measuring its water content.

(iv) Calibration Procedure: Knowledge about the response time of the ceramic plate helps in interpreting the results.

(v) Sensor Capabilities: The sensor can measure matric suction up to 15 bars and can be used to investigate matric suction-moisture relationships of the soil sample.

(vi) Sensor Limitations: The presence of occluded air bubbles in soil result in overestimation of matric suction, i.e., lower measured water pressure. Diffusion of air through the plate can lead to the underestimation of matric suction in case a pressure gauge is used to determine the value of water pressure and ultimately results in an erroneous calculation of the volume of the flow of water.

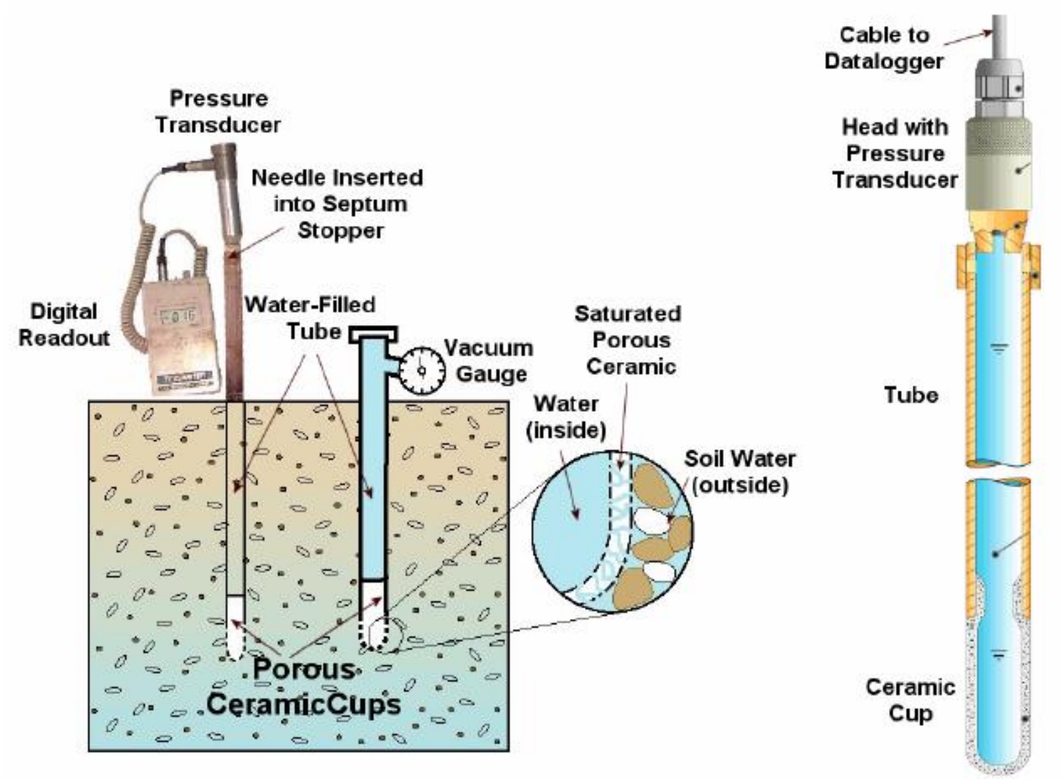

Figure 6 Illustration of tensiometers for matric potential measurement using vacuum gauges and electronic pressure transducers. [Sreedeep and Singh (2011)]

e) Moisture Blocks

(i) Basic Principle: The basic principle used in pressure plate extractor for soil suction measurement is that a porous material block along with an electrical sensor is placed in soil sample and the water pressure of the block is allowed to come to an equilibrium with the soil water pressure. The thermal or electrical conductivity properties of the block are dependent on the amount of water present in the block.

(ii) Description: For moisture blocks, the electrical resistivity of the soil moisture blocks is measured. For thermal conductivity sensors (TCS), the difference in voltage across an electronic sensor, which is temperature-sensitive, is used to indicate the thermal conductivity of ceramic.

(iii) Methodology: The electrical output is measured directly from moisture block sensor. For the new types of thermal conductivity sensors, the difference in voltage across an electrical sensor present in the block is recorded immediately before and after applying a prescribed amount of heat. The difference between the values of the two voltage differences indicates the thermal conductivity of the block.

(iv) Sensor Capabilities: Thermal conductivity sensors and moisture blocks can be used to measure matric suction up to the values of 400 kPa or larger.

(v) Sensor Limitations: The moisture blocks are sensitive to dissolved salts. But the thermal conductivity sensors are neither sensitive to dissolved salts nor to the temperature. It cannot measure the matric suction of frozen soil because the properties of ice are not same as that of water.

2.3 Ranges in which different methods work:

The tabular form of the range of suction values (in kPa) in which various techniques work are listed in tabular form in Table 1.

Table 1 Ranges and equilibration time for different methods [Pan et Al. (2010)]

		Technique (Method)	**Equilibration time**	**Suction range (kPa)**
Direct suction measurement	Matric suction	**(i)** Axis- transition technique	Hours	0-1500
		(ii) Tensiometer	Hours	
		(iii) Suction probe	Minutes	

Indirect suction measurement	Matric suction	**(i)** Time domain reflectometry	Hours	0-1500
		(ii) Electrical conductivity sensor	6-50 hours	50-1500
		(iii) Thermal conductivity sensor	Hours to days	0-1500
		(iv) In –contact filter paper	7-14 days	all
	Osmotic suction	**(i)** Squeezing technique	Days	0-1500
	Total suction	**(i)** Psychrometer technique	1 h	100-10000
		(ii) Relative humidity sensor	Hours to days	100-8000
		(iii) Chilled- mirror hygrometer	10 min	150-30000
		(iv) Non-contact filter paper	7-14 days	all

2.4 Significance of Use of Filter Paper Method

The filter paper method of evaluating soil suction is quite simple and economical with an effective range from 10 to 100 000 kPa i.e., 0.1 to 1000 bars. Moreover, the equipments required for the test are easy to procure and the experiment can start without huge initial investment. Also, the calibration curve which is used in this method can be easily obtained by conducting a simple experiment in the laboratory by following the step by step procedure mentioned in the ASTM D5298 manual for filter paper method. The calibration curve helps us in increasing the effectiveness and accuracy of our experimental work, thus eliminating the possibility of error that might otherwise accumulate while using a pre defined calibration curve. Moreover the authenticity of the experimental work is also easy to maintain.

2.5 The Soil Water Characteristic Curve (SWCC)

Fredlund and Xing (1994) and Barbour (1998) gave the concept of Soil Water Characteristic Curve (SWCC) which describes the functional relationships between soil water content (θ or w) and matric/total potential under equilibrium conditions. The SWCC is an important soil property related to pore space distribution i.e., sizes, inter-connectedness, etc. which is strongly affected by texture, structure and other factors such as organic content. The SWCC is a primary hydraulic property required for modeling water flow in porous materials. The SWC function is highly nonlinear and relatively difficult to obtain accurately.

The convenient idealization of soil pore space enables a linkage between the soil pore size distribution and the SWCC based on capillary rise equation:

$$\mathbf{h_i = \frac{2T}{\rho\, g\, r}} \qquad \textbf{(3)}$$

a) Designation of Water Content

The amount of water in the soil can be defined using more than one variable. Variables used to define the amount of water in the soil are

(i) Gravimetric water content, w

It is the most common parameter for defining the water content which is given as:

$$\mathbf{w = \frac{m_w}{m_s}}$$

where m_w = mass of water , m_s = mass of soil.

(ii) Volumetric water content, θ

This parameter is generally preferred to be used in agriculture, soil physics, soil sciences, etc. Moreover, when a volume change occurs in soil sample, volumetric water content is more accurate a parameter to be used. It is given as:

$$\boldsymbol{\theta = \frac{V_w}{V_s+V_v}}$$

where V_w = Volume of water, V_v = Volume of solids, and V_s = Volume of solids.

(iii)Degree of saturation, S

It refers to the volume of water in reference to the volume of voids, which is given as:

$$\mathbf{S = \frac{V_w}{V_v}}$$

b) SWCC, General Definitions

(i) The air-entry value of the soil is the value of the matric suction where air starts to displace water in the largest pores in the soil.

(ii) The residual water content is the water content where a larger suction is required to remove additional water from the soil. In other words, it is the point on the graph where there is a change in the rate at which water can be possibly extracted from the soil.

(iii) Boundary effect zone is the zone upto air entry value (AEV) where the soil behavior can be described using the principles of saturated soil mechanics.

(iv) **Transition Zone** stretches from air entry value upto the residual water content value, and is described using unsaturated soil mechanics theories.

(v) **Residual Zone** as the name suggest, is the extension of the soil water characteristic curve beyond residual water content, which is relatively difficult to be obtained graphically.

c) Identification of the Zones on the SWCC

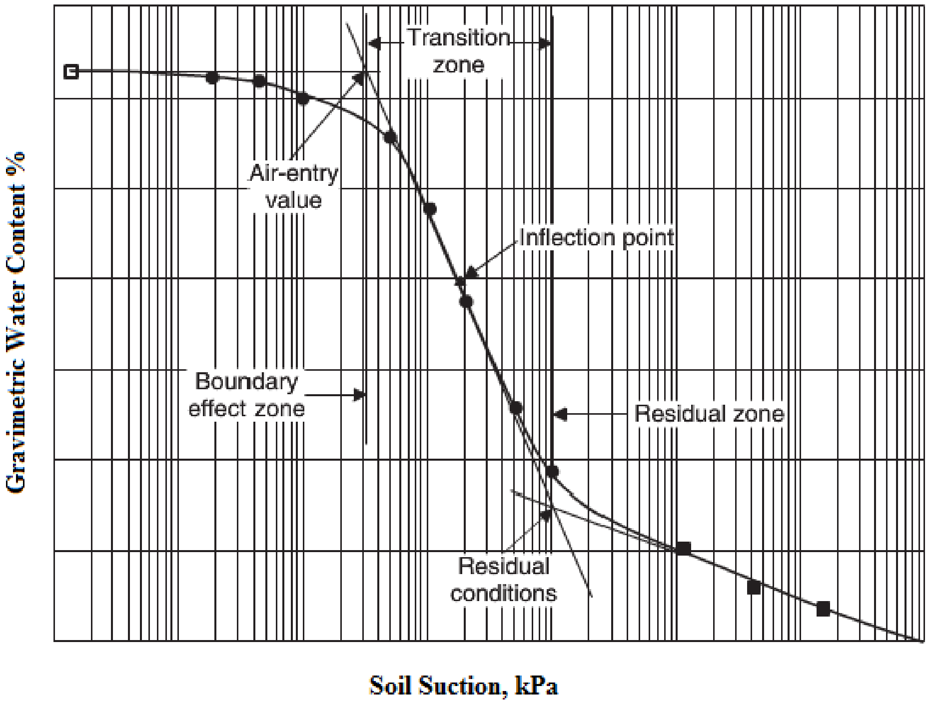

Figure 7 Different zones of SWCC [Fredlund (2002)]

d) SWCC Model

Fredlund and Xing (1994) proposed the following relationship between volumetric water content and soil suction:

$$\theta = \theta_s * \left[\frac{1}{\ln\left[e + (\Psi/a_f)^{n_f}\right]}\right]^{m_f} \quad \textbf{(5)}$$

θ = Volumetric water content

θ_s= Saturated volumetric water content, and

e = Irrational constant equal to 2.71828.

Ψ= Soil suction

a_f , n_f , m_f = Three fitting parameters,

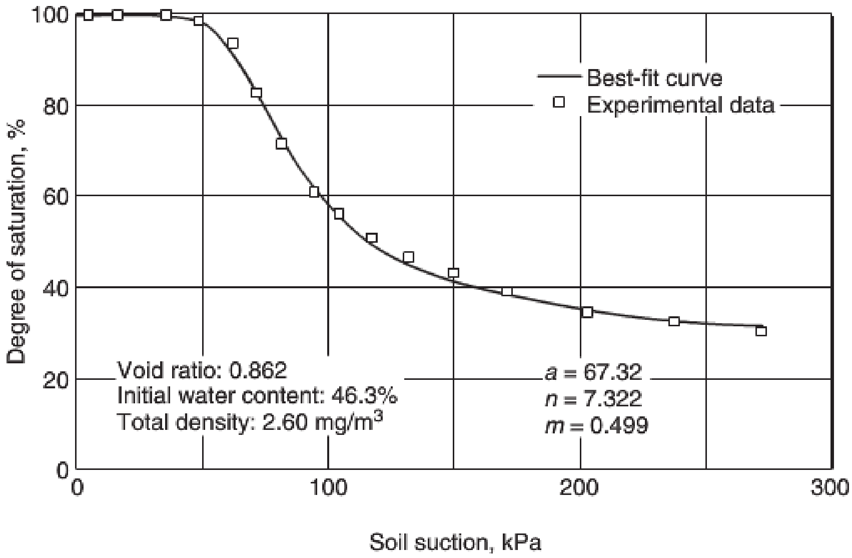

Figure 8 Fredlund and Xing's experimental result [Fredlund and Xing (1994)]

e) Typical SWCC for Soils of Different Texture

The soil of different texture shall have different sizes of voids, different water retaining properties and hence different values of soil suction at same water content. This will lead to different shapes of soil water characteristic curves for different classes of soil.

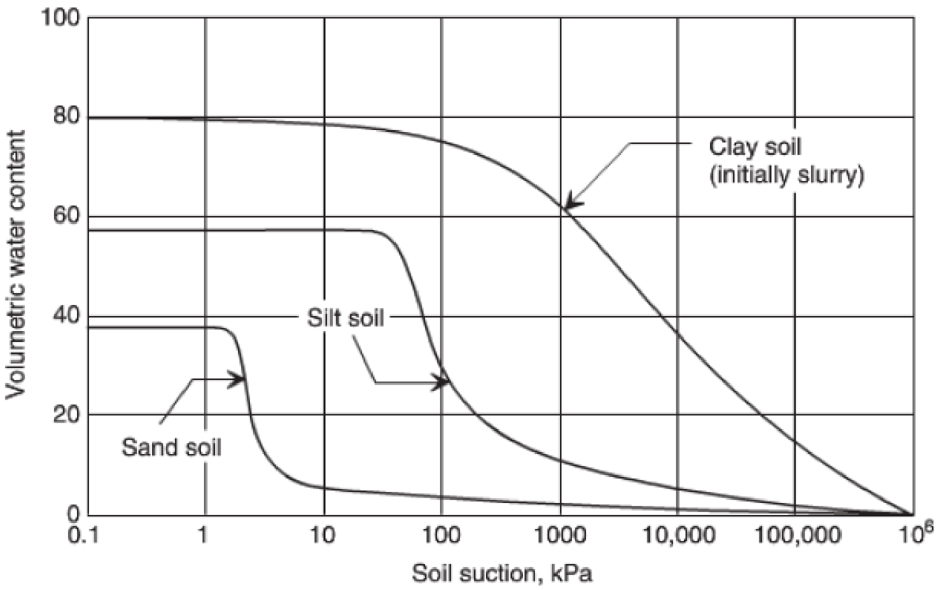

Figure 9 SWCC for soils of different textures [Barbour (1998)]

f) Relationship between Void Ratio and Soil Suction

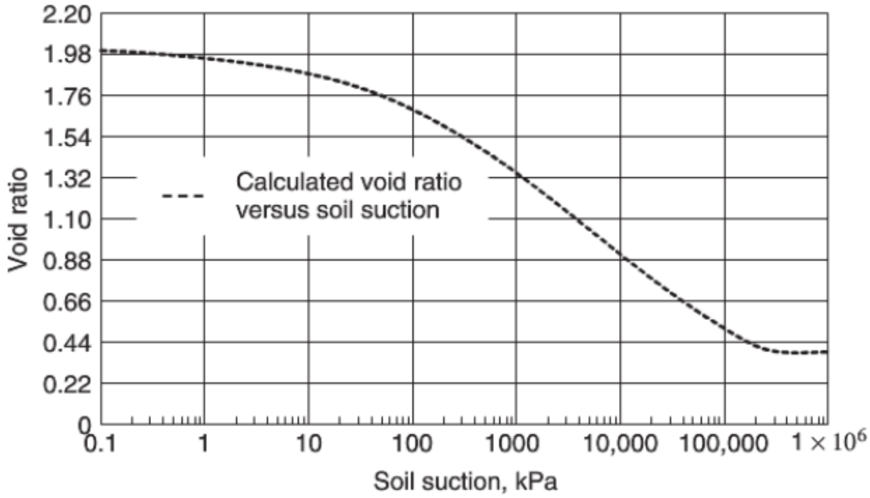

Figure 10 Graph showing variation of soil suction with void ratio [Fredlund et Al. (1997)]

2.6 Estimation of the Model Parameters

Zapata et Al. (1999) provided a set of equations in order to define the three fitting parameters of the Fredlund and Xing equation by a database of approximately 190 soils collected from previously published data. Below mentioned are some important points from his study.

(i) The soils collected were divided into two categories: plastic and non-plastic soils.

(ii) The database consisted of approximately 70 plastic soils and 120 non-plastic soils.

(iii) The data collected for the plastic soils consisted of the percentage passing the No. 200 sieve and the Atterberg limits, in particular, the plasticity index.

(iv) The grain-size diameter D_{60} was used to represent non-plastic soils.

(v) Each soil used in the statistical correlation had a measured and well-defined SWCC.

(vi) The weighted value of PI, which is the percentage passing the No. 200 sieve (used as a decimal value) multiplied by the plasticity index (i.e., w_pPI) was used to characterize the plastic soils. The correlation study yielded a family of SWCCs for both plastic and non-plastic soils.

a) Family of SWCCs for Plastic Soils Based on Zapata Model

(i) $a_f = 0.00364*(wPI)^{3.35} + 4(wPI) + 11$

(ii) $m_f = 0.0514*(wPI)^{0.465} + 0.5$

(iii) $n_f = m_f*[-2.313(wPI)^{0.14} + 5]$

(iv) $h_r = a_f*(32.44e^{0.0186(wPI}\ )$

2.7 Effect of compaction on SWCC

For the purpose of studying the effects that the variation in compactive effort and water content has on the soil suction values for compacted clayey soils, **Tinjum et Al. (1997)** and **Miller et Al. (2002)** conducted a study. The soils they used had varying amounts of clay fraction with plasticities which ranged from high to low values. The behavior of unsaturated soil was further investigated for various conditions, thereby covering a range of water contents and compactive efforts. They then used the experimental data so obtained in four commonly used models of water content-soil suction relationship. Each model used provided a satisfactory result to the experimental data. They conclude that the soil water characteristic curves were more susceptible to changes in compactive effort than the changes in compaction water content. They also concluded that at almost same water contents, the soil suction values increased with the increase in the compaction effort for different compaction condition and soil type considered.

2.8 HCF (Hydraulic Conductivity Function)

Darcy's law is equally applicable to variably saturated soils. However, **Genuchten (1980)** said that the hydraulic conductivity K for unsaturated soils can no longer be a constant value and is typically portrayed as a function of either the degree of saturation or h_m (pore water pressure head).This functional relationship is called the hydraulic conductivity function (HCF). Graph is obtained showing variation in magnitude and dependence of hydraulic conductivity on saturation for representative soils.

Mualem (1976) proposed the following model to describe the variation of hydraulic conductivity K with the effective degree of saturation S_e.

$$\mathbf{K = K_s*S_e^{0.5}*[\ 1 - S_e\ (S_e^{n/(1-n)} - 1)^{(n-1)/n}\ ]^2} \qquad \textbf{(6)}$$

where ,

n = pore size parameter;

K_s = saturated hydraulic conductivity;

S_e = effective degree of saturatio

CHAPTER 3

DESIGN OF EXPERIMENTAL SETUP

3.1 Introduction

The method of filter paper is a technique of soil suction measurement. It is a laboratory method, and is inexpensive and simpler than various other methods. It is also said to be the only method known that covers the full range of suction values. With this filter paper method, both total suction and matric suction values can be measured easily. If the filter paper is allowed to absorb water through vapor flow, i.e., non-contact method, then only the total suction gets measured. However, if the filter paper is allowed to absorb water through fluid flow, i.e., contact method, then only matric suction gets measured. With a consistent technique for soil suction measurement, the soil suction profiles can be obtained for the given soil, the samples being taken at convenient depth from ground. The change in soil suction values with seasonal change in moisture movement is an important information for applications in many engineering problems.

3.2 Discussion

Matric suction results from the surface adsorption and capillarity forces present in the soil whereas osmotic suction results from the presence of salts in the soil pore water.

(a) Working Principle:

The working principle of the filter paper method as mentioned in **ASTM D 5298** is that the filter paper placed in soil sample for some duration will come to equilibrium with the soil moisture content, either through vapor flow or liquid flow, and after the end of equilibrium period, the suction value of the filter paper and the soil will become the same. In this filter paper method, the filter paper is brought to equilibrium either by contact with soil specimen and thus measuring matric suction or by a non-contact mechanism thus measuring total suction values, while keeping the setup in a constant temperature environment. Once the equilibrium is established between the filter paper and soil specimen, the water content of the filter paper used in the experiment is measured. Then, by using a filter paper calibration curve for water content versus suction, the corresponding suction values are tabulated from the curve. So the filter paper method is an indirect method of measuring soil suction.

(b) Representation of Suction

In engineering practice, soil suction is generally represented in log kPa unit system **(Fredlund and Rahardjo 1993)** which is given as:

$$\text{Suction in log kPa} = \log_{10} (\text{suction value expressed in kPa})$$

However, soil suction is also sometimes represented in cm of negative head and is calculated in pF units **(Schofield 1935)** which is given as:

$$\text{Suction in pF} = \log_{10} (\text{suction value expressed in cm of water})$$

The relationship existing between these two systems of units is approximately given as:

$$\text{Suction in pF} = \text{Suction in log kPa} + 1$$

The conversion from kPa to cm is 1 kPa = 10,198 cm.

3.3 Calibration

In order to obtain the calibration curve for our set of filter papers we need an electrolytic salt solution of known molality whose osmotic coefficient is known (**ASTM D 5298)**. Molality is defined as the number of moles of NaCl molecule that are present in 1000 ml volume of distilled water. For example, one mole of NaCl weighs 58.5 gm (which is equal to its molecular weight). Thus, 2 molal NaCl solution means 2 times 58.5 gm i.e. 117 gm NaCl in 1000 ml volume of distilled water. The osmotic suction of the electrolyte solutions that is employed in the calibration procedure of filter papers used is calculated using the relationship between osmotic suction and osmotic coefficients. The values of osmotic coefficients are readily available in various literatures for different salt solutions. Table 2 gives the values of osmotic coefficients for several salt solutions. Osmotic coefficients can also be obtained from the following relationship **(Lang 1967)**:

$$\text{Ø} = -\frac{\rho_w}{vmw} \ln \left(\frac{P}{P_0}\right) \qquad \textbf{(7)}$$

Where:

Ø = osmotic coefficient,

m = molality,

w = molecular mass of water,

v = number of ions from one molecule of salt (i.e., v = 2 for NaCl, KCl, NH_4Cl and v = 3 for Na_2SO_4, $CaCl_2$, $Na_2S_2O_3$, etc.), and

ρ_w = density of water.

The combination of Eq. (1) and Eq. (7) gives a relationship that can be used to calculate the values of osmotic suctions for different salt solutions:

$$h_\pi = -\nu RTm\, Ø \qquad (8)$$

3.4 Apparatus required

(a) For Calibration of Filter Paper

(i) Whatman No. 42 type filter papers.

(ii) Salt solution of sodium chloride (NaCl) with molality ranging from 0 i.e., distilled water upto 2.5 molal solution.

(iii) Glass jars of 200 - 250 ml volume with properly working lids.

(iv) Small aluminum plates which are used to carry filter papers during moisture content measurements.

(v) A balance with an accuracy to the nearest 0.001 gm for measuring weight of the filter papers.

(vi) An oven for moisture content determination of the filter papers by leaving them in it for 10 hours at a temperature of 105 ± 5^0C in the aluminum moisture cans.

(vii) An incubator in which the fluctuations of the temperature are kept below $\pm 1^o$C in order to be used to keep the samples during equilibrium period.

(viii) Tweezers, latex gloves, scissors, plastic tapes, and a knife for setting up the test.

(b) For Soil Suction Measurements

(i) Whatman No. 42 type filter papers.

(ii) Glass jars of 200 - 250 ml volume with properly working lids.

(iii) Small aluminum plates which are used to carry filter papers during moisture content measurements.

(iv) A balance with an accuracy to the nearest 0.001 gm for measuring weight of the filter papers.

(v) An oven for moisture content determination of the filter papers by leaving them in it for 10 hours at a temperature of 105 ± 5^0C in the aluminum moisture cans.

(vi) An incubator in which the fluctuations of the temperature are kept below $\pm 1^o$C in order to be used to keep the samples during equilibrium period.

(vii) Tweezers, latex gloves, scissors, plastic tapes, and a knife for setting up the test

3.5 Procedure

(a) Filter Paper Calibration

(i) NaCl solutions are prepared from 0 to 2.4 molality.

(ii) A glass jar is filled with approximately 150 ml of a solution of NaCl of known molality and is labeled with the molality value used for that jar.

(iii) Then, a small plastic support is inserted into the glass jar and filter paper is kept on that support in order to interact with salt solution and absorb water from the air of the closed jar. The setup is shown in Figure 10**.** The lid of glass jar is sealed tightly with plastic tapes to ensure air tightness.

(iv) The filter paper and salt solution setups in the sealed containers were put in a constant temperature environment for equilibrium. Temperature fluctuations were kept as low as possible during a two week equilibration period.

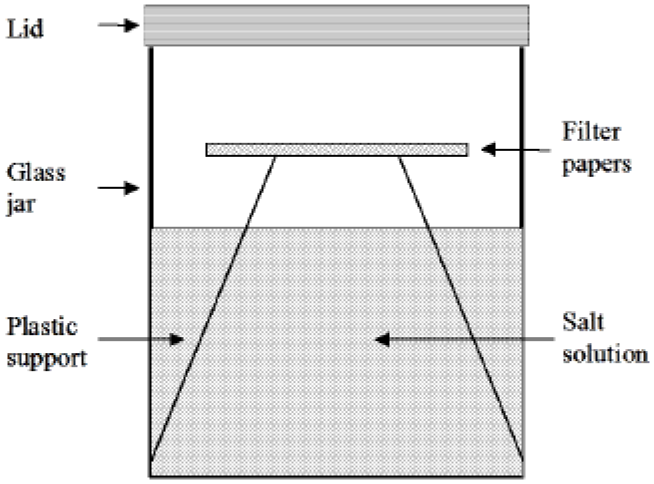

Figure 11 Total suction calibration test configuration

After two weeks of equilibrating time, the procedure followed for the measurement of filter paper water content is as follows:

(i) All the aluminum cans are weighed and their values are recorded.

(ii) Transfer the filter paper, using tweezers, into the aluminum can as quickly as possible.

(iii) Then, the weight of each can with filter paper is measured to the nearest 0.0001 g.

(iv) Steps (ii) and (iii) are followed for every glass jar.

(v) Then, all the filter papers are kept in oven at a temperature of 105± 5°C for 24 hours which is the standard test method for soil water content measurements. However, for filter paper it is only necessary to keep the filter paper for at least 10 hours.

(vi) After that, the can with dry filter paper is weighed to the nearest 0.001 g.

(vii) Step (vi) was repeated for every can.

(viii) Calculate the suction value of the filter paper for different molality values of different soil solutions by using equation (8).

(ix) Plot the graph between filter paper water content and corresponding values of suction.

(x) Obtain a generalized equation of the curve which is further used for calculating the soil suction value of the soil specimen.

(b) Total Suction Measurements

(i) The sampler of the triaxial setup is used to take the sampler. The smaller is the empty space in the glass jar, the smaller will be the time period that the soil system and the filter paper require to come to equilibrium.

(ii) A small ring type support of about 1cm in height is put on top of the soil to place a filter paper on it in order to provide a non-contact system between the soil and filter paper as shown in Figure 12(upper portion).

(iii) A filter paper is then inserted on the ring using tweezers. It should be kept in mind that the filter paper should not touch the soil, underneath the lid in any way, and the inside wall of the jar. Refer to Figure 12.

(iv) Then the lid of the glass jar is sealed tightly using plastic tape.

(v) Step (i), (ii), (iii) and (iv) are repeated for the entire soil sample.

(vi) Then the containers are put into an incubator in a temperature controlled environment for a duration of one week.

(c) Matric Suction Measurements

(i) A filter paper is sandwiched between the soil sample at half of the height of the soil specimen.

(ii) After that, this prepared soil sample with embedded filter papers is put into the glass container. (refer to Figure 12)

(iii) Then the glass container is sealed up tightly using electrical tape.

(iv) Steps (i), (ii) and (iii). are repeated for all the soil sample.

(v) The prepared containers are then put into an incubator for a temperature controlled environment for a period of one week.

A typical setup for measurement of both the total and matric suction is shown in Figure 12 and Figure 13.

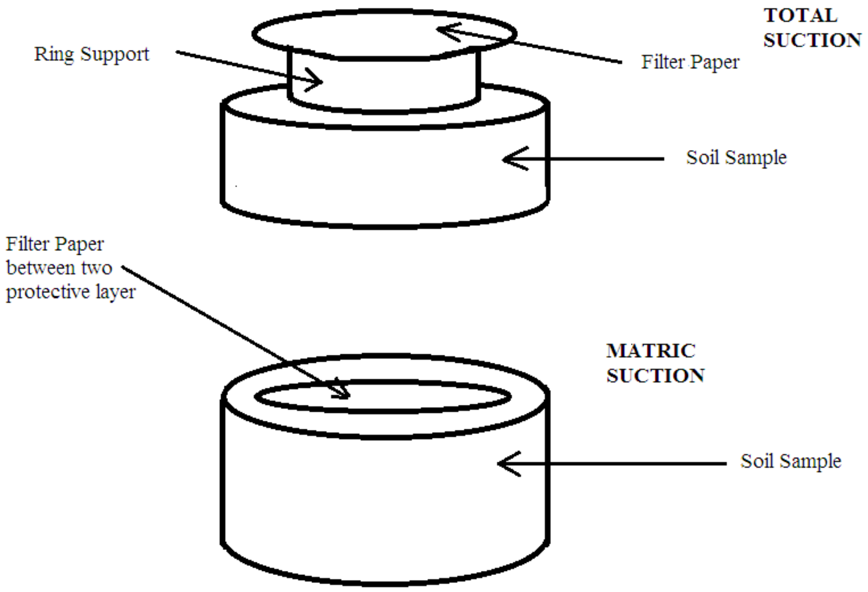

Figure 12 Placing of the filter paper in soil sample

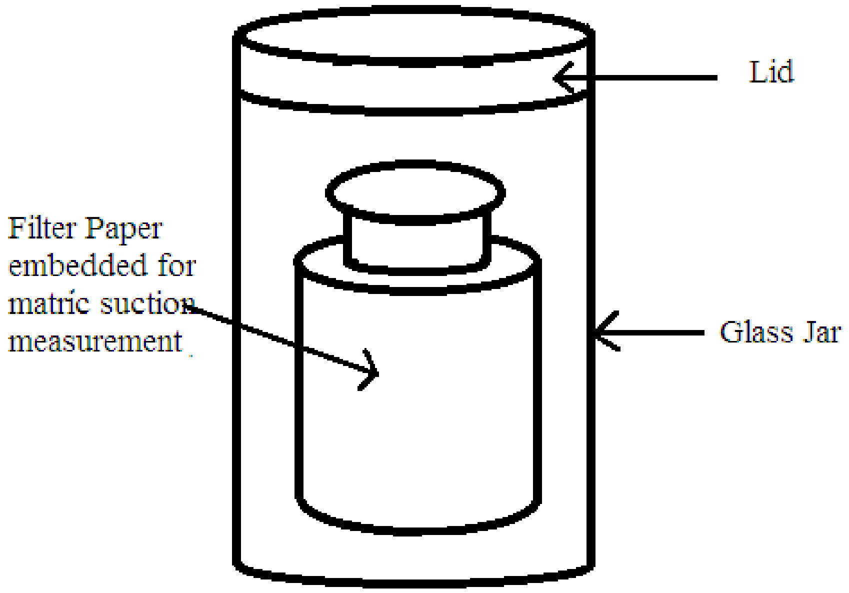

Figure 13 Experimental setup for measuring soil suction

After the equilibrium period, the procedure adopted for the measurement of the filter paper water content is as follows:

(i) All the aluminum cans are weighed and their values are recorded.

(ii) Transfer the filter paper, using tweezers, into the aluminum can as quickly as possible.

(iii) Then, the weights of each can with filter papers is measured to the nearest 0.001 g.

(iv) Steps (ii) and (iii) are followed for every glass jar.

(v) Then, all the filter papers are kept in oven at a temperature of 105± 5^{o}C for 24 hours which is the standard test method for soil water content measurements. However, for this method it is only necessary to keep the filter paper for at least 10 hours.

(vi) After that, the can with dry filter paper is weighed to the nearest 0.001 g.

(vii) Step (vi) was repeated for every can.

(viii) Record all the values of filter paper water content under the proper heading of total and matric suction.

Using the generalized equation obtained from the calibration method, obtain the soil suction value of the soil specimen.

3.6 Laboratory work

(a) Sampler Description

Figure 14 Sampler used for taking sample

(b) Sample Collection

Figure 15 Sample collection from field

(c) Experimental Setup

Figure 16 Modeling of experimental setup in laboratory

(d) Placing Sample in glass Jar

Figure 17 Sample kept in jar

CHAPTER 4
OBSERVATION AND ANALYSIS

4.1 For Calibration Curve

For the purpose of calibration of filter paper I have used NaCl salt solution from molality ranging from 0 to 2.5. Calculation of osmotic coefficient for salt solution is an entirely different experiment in itself. However **Golberg and Nutall (1978)** gave the osmotic coefficient values for different salt solutions.

Once the value of osmotic coefficient at different molality value is obtained, using equation (8) I have calculated the value of osmotic suction for the corresponding values of molality (which in case of salt solution is equal to the total suction value).

$$h_{\pi} = -\nu RTm\, Ø \qquad (8)$$

where:
Ø = osmotic coefficient,
m = molality,
v = number of ions from one molecule of salt i.e., v = 2 for NaCl and KCl,
R = ideal gas constant (8.314 J/mol-°K)
T = absolute temperature in °K = (28^{o}C + 273) = 311^{o}K

The calculated values are shown in Table 2. The values have been calculated for KCl salts as well because sometimes they can also be used in place of NaCl salt solution.

Table 2 Osmotic coefficients and osmotic suctions of two salt solutions [Golberg and Nutall (1978)]

Molality (m)	Osmotic Coefficients (Ø)		Osmotic Potential (h_{π}) (in kPa)	
	NaCl	KCl	NaCl	KCl
0.001	0.9880	0.9880	4.895	5.109
0.002	0.9840	0.9840	9.751	10.177
0.005	0.9760	0.9760	24.181	25.236
0.010	0.9680	0.9670	47.965	50.007
0.020	0.9590	0.9570	95.039	98.979

0.050	0.9440	0.9400	233.882	243.052
0.100	0.9330	0.9270	462.314	479.380
0.200	0.9240	0.9130	915.710	944.281
0.300	0.9210	0.9060	1369.106	1405.562
0.400	0.9200	0.9020	1823.492	1865.807
0.500	0.9210	0.9000	2281.843	2327.089
0.600	0.9230	0.8990	2744.156	2789.404
0.700	0.9260	0.8980	3211.924	3250.684
0.800	0.9290	0.8980	3682.663	3715.067
0.900	0.9320	0.8980	4156.375	4179.451
1.000	0.9360	0.8980	4638.015	4643.835
1.200	0.9440	0.9000	5613.187	5602.478
1.400	0.9530	0.9020	6611.153	6530.327
1.600	0.9620	0.9050	7626.957	7488.054
1.800	0.9730	0.9080	8678.439	8451.986
2.000	0.9840	0.9120	9751.723	9432.466
2.400	1.0130	0.9230	12548.9	11741.868

After obtaining the above values of total suction (which is same as osmotic suction in this particular case), we carry out the procedure mentioned in 3.5(a) and obtain the values of filter paper water content for salt solutions at different values of molality which is presented in tabular form in Table 3.

Table 3 Filter paper water content for corresponding values of suction.

Suction (kPa)	Suction log(kPa)	Filter Paper WC
4.895	0.689752696	0.485
9.751	0.989049156	0.48
24.181	1.383474257	0.476
47.965	1.680924449	0.45
95.039	1.977901858	0.439

233.882	2.368996799	0.37
462.314	2.664937045	0.334
915.712	2.961758905	0.296
1369.106	3.136437074	0.278
1823.492	3.260903862	0.262
2281.843	3.35828576	0.25
2744.156	3.438408797	0.24
3211.924	3.506765261	0.232
3682.663	3.566161978	0.225
4156.375	3.618714724	0.219
4638.015	3.666332149	0.213
5613.187	3.749209511	0.203
6611.153	3.820277208	0.194
7626.957	3.882351298	0.187
8678.439	3.938441615	0.18
9751.723	3.989081357	0.174
12548.9	4.098605658	0.16

Once these values are obtained, we will plot a graph between filter paper water content on x-axis and suction values in log (kPa) on y-axis.

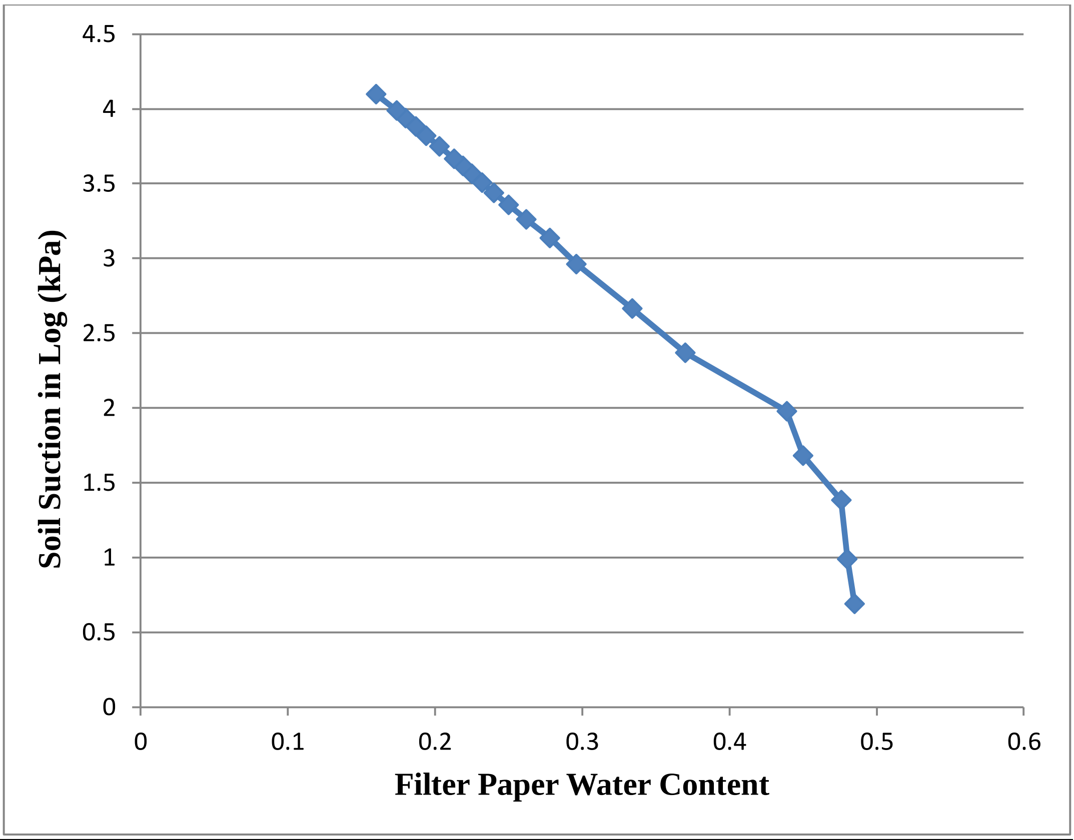

Figure 18 Calibration curve obtained for our filter paper

The above curve obtained needs to have a generalized equation which can be used for all the filter paper measurements. So we will add a trendline to the above graph as shown in the Figure 13 which gives us the equation for soil suction in log (kPa).

The equation obtained is:

$$\mathbf{\Psi = -0.91553w + 5.6298} \quad \mathbf{(9)}$$

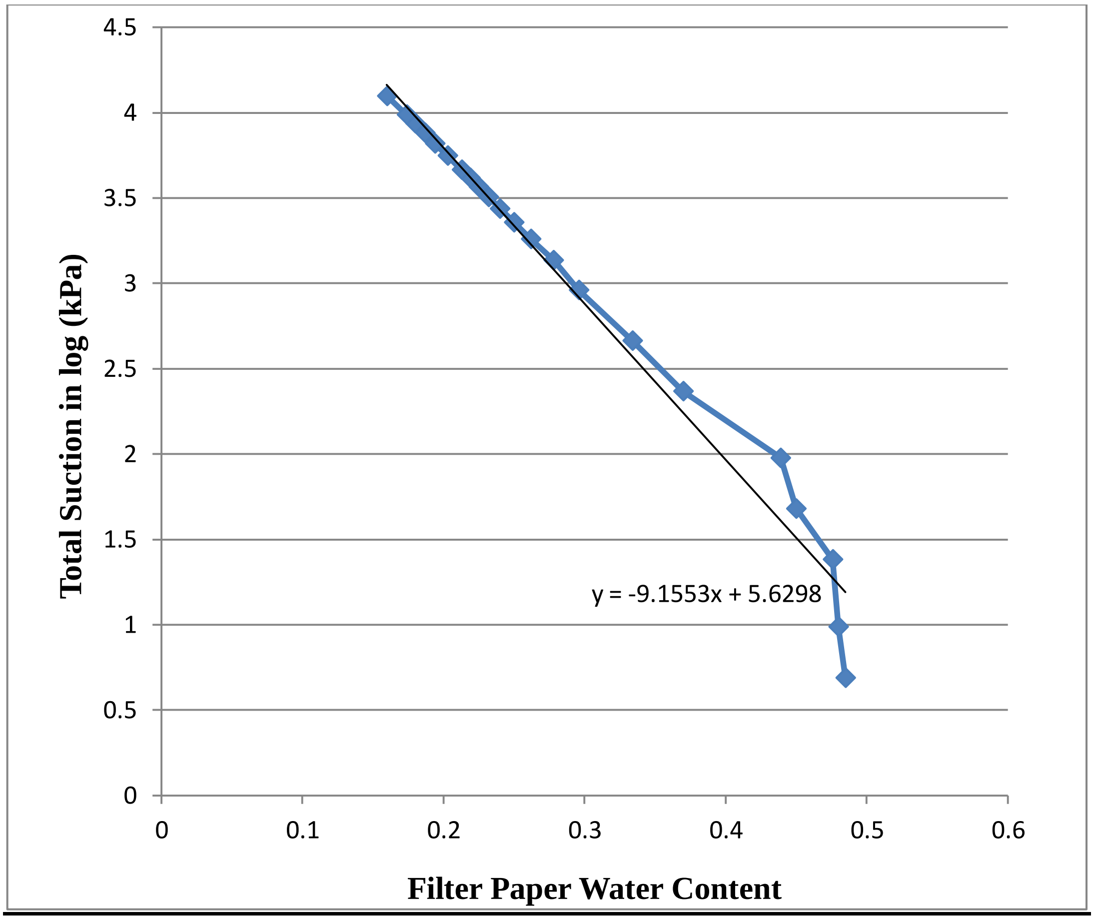

Figure 19 Calibration curve with the trendline for generalized equation

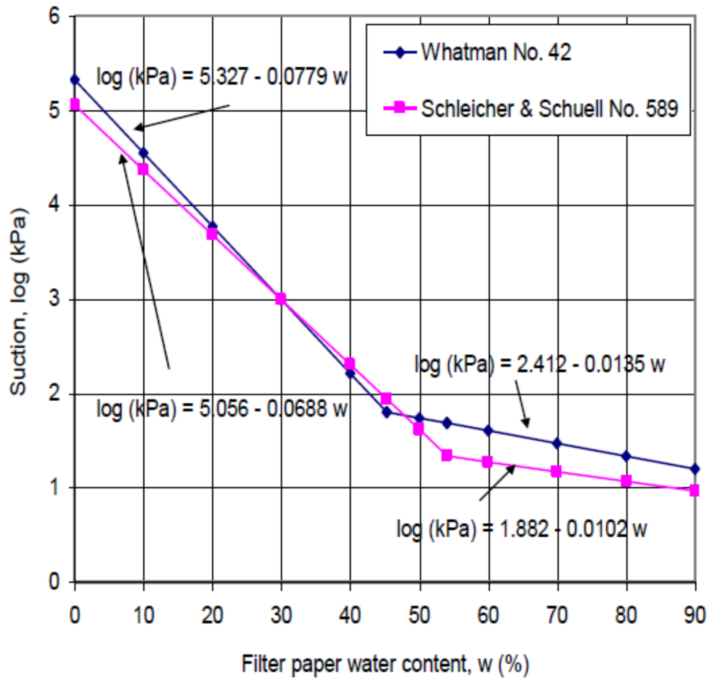

Figure 20 Calibration curves for two types of filter papers [ASTM D 5298)]

The calibration curve which is mentioned in ASTM D5298 is also shown in Figure 14. There are two different equations for two parts of the graph. In calculation of the result for our soil specimen, the results are tabulated from both of these calibration curves and are compared.

4.2 For Soil Suction Measurement:

(a) Soil type:

Soil characterization data are presented in Table 4.

Table 4 Soil characterization

Property		Soil 1	Soil 2
Specific gravity		2.68	2.69
Particle size analysis	% Sand	3	0
	% Silt	38	29
	% Clay	59	42
Soil Classification		CL	CL
Atterberg limits	LL	40	26
	PI	17	24

(b) Observation Tables:

(i) Soil 1 (for total suction):

Table 5 Water content of top filter paper for soil 1

DEPTH	0m	0.25m	0.5m	1.0m
Mass of Aluminum Plate M	6.082	6.079	6.077	6.083
Mass of Aluminum Plate + Wet Filter Paper M_1	6.414	6.404	6.411	6.431
Mass of Aluminum Plate + Dry Filter Paper M_2	6.380	6.365	6.367	6.383
Mass of Dry Filter Paper $M_d = M_2 – M$	0.298	0.286	0.290	0.295
Mass of Water in Filter Paper $M_w = M_1 - M_2$	0.034	0.039	0.044	0.048
Water Content of Filter Paper $w = M_w/M_d$	0.1141	0.1363	0.1517	0.1627

Table 6 Comparison of suction values from two calibration curve

FILTER PAPER WATER CONTENT	From ASTM Calibration Curve		From Experimental Calibration Curve	
	SUCTION [log (kPa)]	SUCTION (kPa)]	SUCTION [log (kPa)]	SUCTION (kPa)
0.1141	4.436	27299.896	4.585	38475.145
0.1363	4.265	18414.174	4.381	24095.315
0.1517	4.145	19971.951	4.241	17415.702
0.1627	4.059	11470.094	4.140	13811.241

(ii) Soil 1 (for matric suction):

Table 7 Water content of bottom filter paper for soil 1

DEPTH	0m	0.25m	0.5m	1.0m
Mass of Aluminum Plate M	6.081	6.079	6.078	6.082
Mass of Aluminum Plate + Wet Filter Paper M_1	6.422	6.416	6.432	6.476
Mass of Aluminum Plate + Dry Filter Paper M_2	6.379	6.368	6.364	6.398
Mass of Dry Filter Paper $M_d = M_2 - M$	0.298	0.289	0.286	0.316
Mass of Water in Filter Paper $M_w = M_2 - M_1$	0.043	0.048	0.068	0.078
Water Content of Filter Paper $w = M_w/M_d$	0.1443	0.1661	0.2378	0.2468

Table 8 Comparison of suction values from two calibration curve

FILTER PAPER WATER CONTENT	From ASTM Calibration Curve		From Experimental Calibration Curve	
	SUCTION [log (kPa)]	SUCTION (kPa)]	SUCTION [log (kPa)]	SUCTION (kPa)
0.1443	4.203	15955.227	4.309	20370.421
0.1661	4.033	10791.480	4.109	12852.867
0.2378	3.474	2982.208	3.453	2837.919
0.2468	3.404	2537.628	3.370	2345.697

(iii)Soil 2 (for total Suction):

Table 9 Water content of top filter paper for soil 2

DEPTH	0m	0.25m	0.5m	1.0m
Mass of Aluminum Plate M	6.081	6.079	6.078	6.080
Mass of Aluminum Plate + Wet Filter Paper M_1	6.41	6.398	6.409	7.027
Mass of Aluminum Plate + Dry Filter Paper M_2	6.380	6.365	6.367	6.978
Mass of Dry Filter Paper $M_d = M_2 - M$	0.295	0.288	0.292	0.295
Mass of Water in Filter Paper $M_w = M_2 - M_1$	0.030	0.033	0.042	0.049
Water Content of Filter Paper $w = M_w/M_d$	0.1017	0.1146	0.1438	0.1661

Table 10 Comparison of total suction values for soil 2

FILTER PAPER WATER CONTENT	**From ASTM Calibration Curve**		**From Experimental Calibration Curve**	
	SUCTION [log (kPa)]	**SUCTION (kPa)]**	**SUCTION [log (kPa)]**	**SUCTION (kPa)**
.1017	4.534	34257.605	4.699	49969.613
.1146	4.432	27035.164	4.581	38071.730
.1438	4.206	16098.967	4.313	20745.795
.1661	4.033	10791.479	4.109	12852.867

(iv) Soil 2 (for matric suction):

Table 11 Water content of bottom filter paper for soil 2

DEPTH	0m	0.25m	0.5m	1.0m
Mass of Aluminum Plate M	6.082	6.079	6.077	6.083
Mass of Aluminum Plate + Wet Filter Paper M_1	6.423	6.419	6.428	7.053
Mass of Aluminum Plate + Dry Filter Paper M_2	6.380	6.365	6.367	6.978
Mass of Dry Filter Paper $M_d = M_2 - M$	0.296	0.287	0.290	0.295
Mass of Water in Filter Paper $M_w = M_2 - M_1$	0.046	0.054	0.061	0.075
Water Content of Filter Paper $w = M_w/M_d$	0.1554	0.1882	0.2103	0.2542

Table 12 Comparison of matric suction values for soil 2

FILTER PAPER WATER CONTENT	From ASTM Calibration Curve		From Experimental Calibration Curve	
	SUCTION [log (kPa)]	SUCTION (kPa)]	SUCTION [log (kPa)]	SUCTION (kPa)
0.1554	4.116	13074.768	4.207	16108.918
0.1882	3.861	7259.756	3.905	8034.753
0.2103	3.689	4883.858	3.704	5063.379
0.2542	3.347	2222.194	3.299	1994.234

4.3 Plotting SWCC:

(a) Soil 1:

Water content w = 22.26%

Plasticity Index = 17%

So, by using Zapata's Equation for plastic soil, we get following values of the three fitting parameter, as shown in Table 13.

Table 13 Soil water characteristic curve fit parameters for soil 1

Model	Parameter	Values
Fredlund and Xing	a_f (kPa)	1576.642
	m_f	1.312
	n_f	0.406

Using equation (5), plot a graph

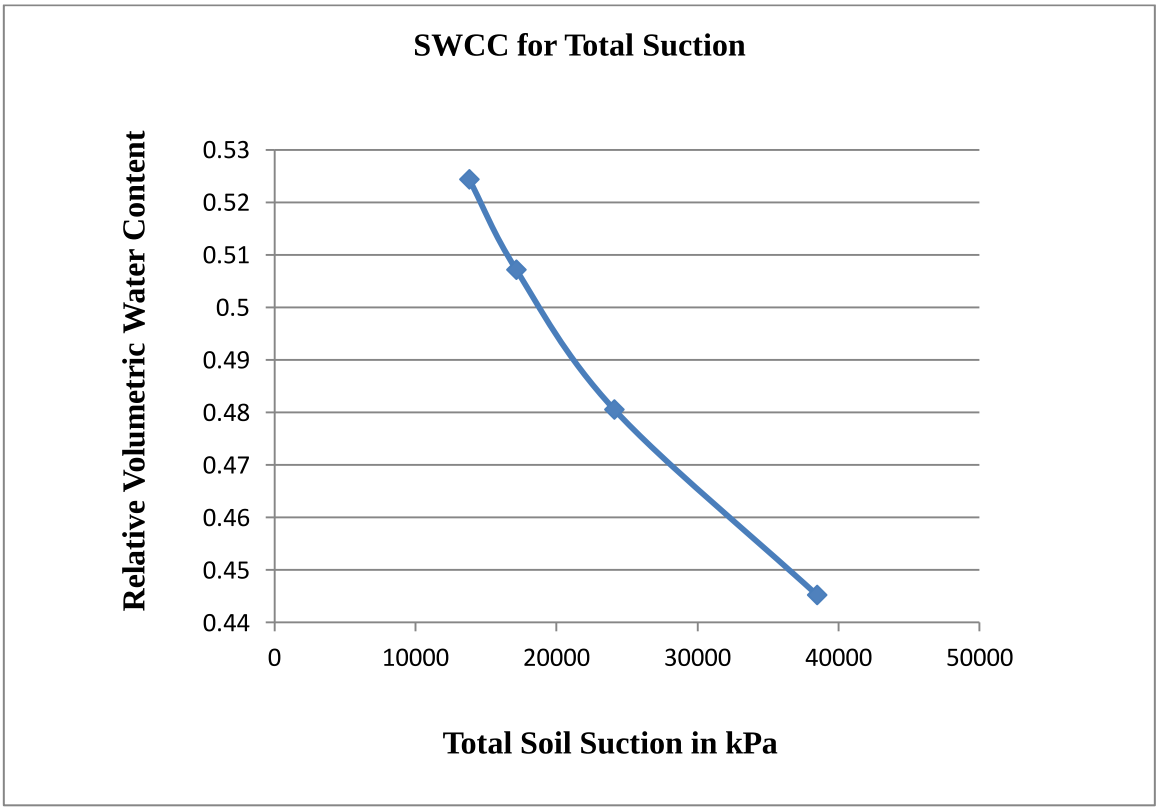

Figure 21 SWCC for total suction for soil 1

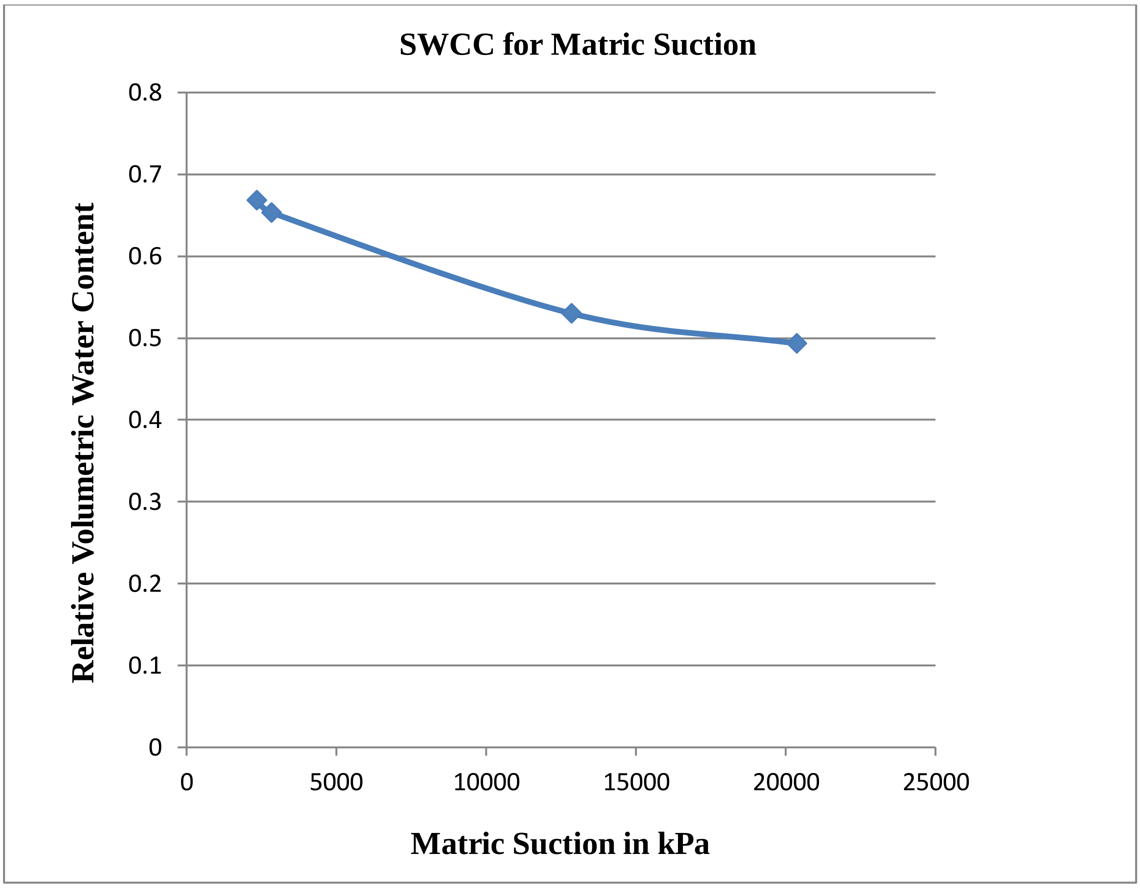

Figure 22 SWCC for matric suction for soil 1

(b) Soil 2

Water content w= 18.29%

Plasticity Index = 24%

So, by using Zapata's Equation for plastic soil, we get following values of the three fitting parameter, as shown in Table 14.

Table 14 Soil water characteristic curve fit parameters for soil 2

Model	Parameter	Standard/dry
Fredlund and Xing	a_f (kPa)	2589.533
	m_f	1.370
	n_f	0.577

Using equation (5) plot a graph.

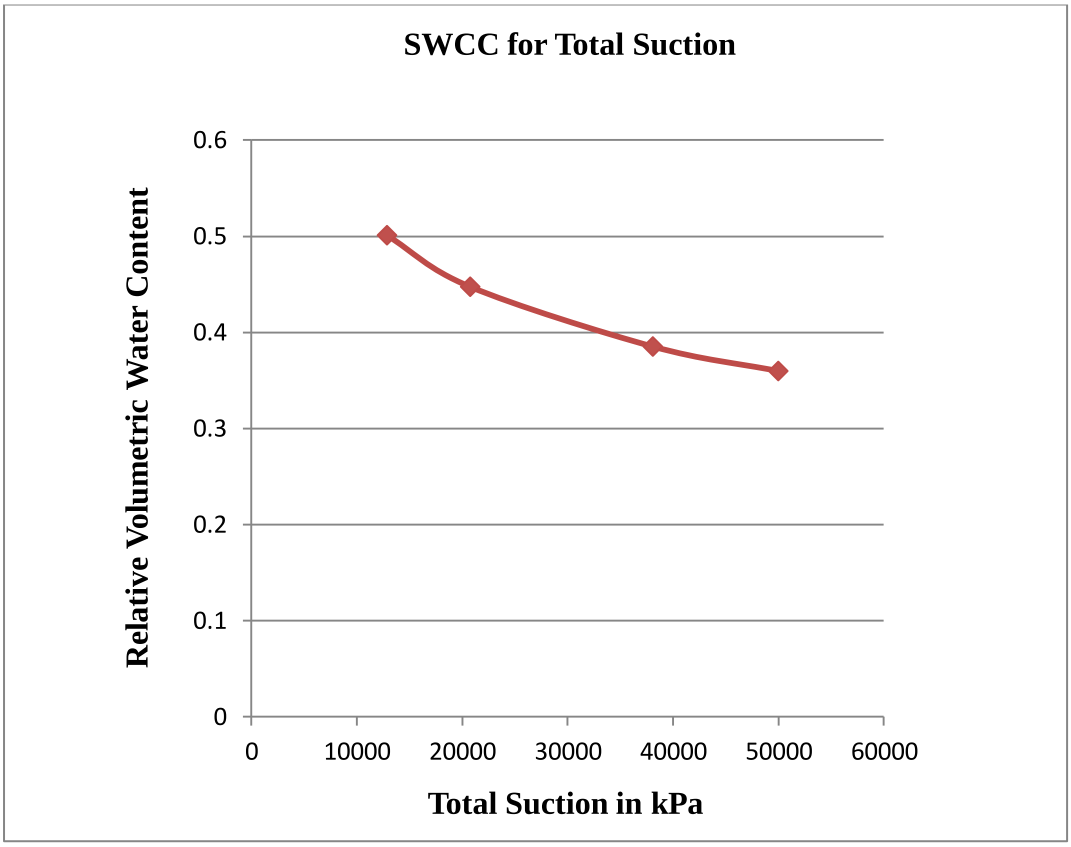

Figure 23 SWCC for total suction for soil 2

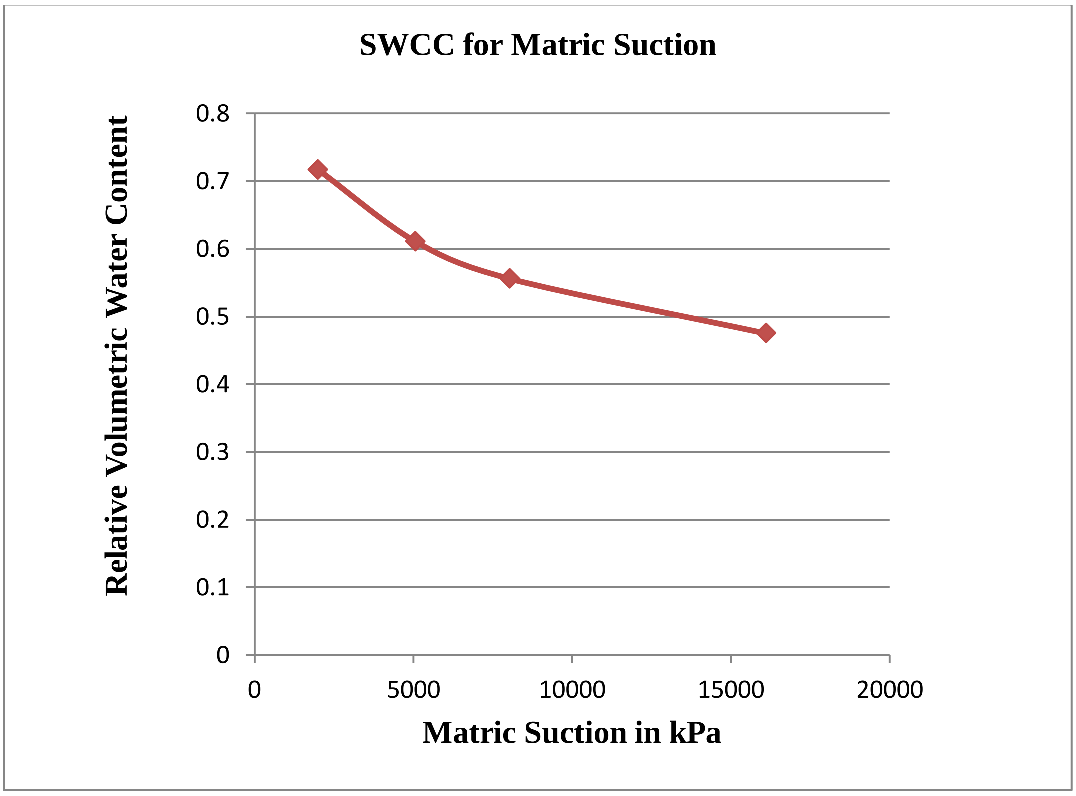

Figure 24 SWCC for matric suction for soil 2

CHAPTER 5
CONCLUSIONS

1. The knowledge of a convenient and economical method for soil suction measurement plotting of the soil water characteristic curve is the first step towards determination of unsaturated soil properties. Even though the unsaturated soil properties cannot be measured very accurately, it is still possible to estimate them in reasonable manner.. The unsaturated soil properties are said to be a function of soil water characteristic curve because variations in properties of unsaturated soil are primarily the function of amount of water in the soil.
2. Soil Water Characteristic Curve shows us the relationship between water content (volumetric or gravimetric or relative) and soil suction values. The values of different parameters once obtained from this curve, is utilized in certain other models to obtain properties like hydraulic conductivity, shear strength, volume changes, etc. In particular, it is the evaluation of the correct air-entry value for the soil that has a significant effect on the estimation of subsequent unsaturated soil properties.
3. The general technique to estimate the properties of unsaturated soil is to express them as a function of saturated soil properties and soil water characteristic curve for unsaturated soils, along with an additional parameter, as shown:

   $$\text{Unsaturated soil properties} = [\text{saturated soil properties}][\text{SWCC}]^{[\text{additional power}]}$$

   For example it has become an acceptable procedure to predict empirically the hydraulic conductivity of unsaturated soils using saturated hydraulic conductivity and SWCC. Similar procedure has been suggested for shear strength of unsaturated soils.
4. Moreover, the SWCC can be used to predict flow of water in soils and thus is used to study the movement of contaminants in the waste disposal system. The contaminants may themselves posses certain osmotic suction values, owing to their chemical contents thereby causing a change in suction value of the landfill.
5. SWCC is also utilized in designing the irrigation system. It is used to predict the soil water storage, water supply to the plants (field capacity) and soil aggregate stability.

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