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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

CHARACTERIZATION OF ADDISABABA EXPANSIVE SOIL USING UNSATURATED SOIL PROPERTIES

A Thesis in Geotechnical Engineering

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April 2 2024

Addis Ababa, Ethiopia

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

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ABSTRACT

Proper characterization of expansive soils is critical in geotechnical engineering practice for proper design. However, a limited researches were done on unsaturated expansive soil properties in Addis Ababa. The availability of soil suction profiles from in situ and laboratory measurements is currently limited. This research aims to enhance geotechnical site assessments in Addis Ababa's expansive soil regions through combined laboratory testing and long-term field monitoring of unsaturated soil properties. To properly characterize the unsaturated properties of expansive soil laboratory pressure plate analyses were performed on twelve undisturbed soil samples to develop soil-water characteristic curves (SWCC) with two categories four of them from under roadway and eight from excavations for a building purpose with a varying depth and locations coupling with shrinkage curves (SC). The SWCCs were determined using a pressure plate apparatus with a suction range of 0 to 1300kPa. The laboratory-measured data points were then curve-fitted by using the Fredlund and Xing (1994) model. The SC was also determined to evaluate the change in volume of the different soil samples. Experimental results reveal Air Entry Value acquired through consideration of volume change with Degree of Saturation Soil-Water Characteristic Curve (S-SWCC) is higher in magnitude than gravimetric water content soil water characteristic curve (w-SWCC) and a volume change of 74.15-79.8 for soil samples from under roadway and 83.1% - 98.1% for soil samples sampled from excavations for building construction is quantified through void ratio characteristic curves.

Concurrent field monitoring was conducted to capture seasonal matric suction profiles in Addis Ababa using a digital tensiometer and Diviner 2000 probes to directly measure matric suction profiles and volumetric water content. This study implemented direct long-term monitoring of matric suction in situ at multiple depths (140cm,160cm, and 190cm) using digital tensiometer equipment. And coupled with volumetric water content measurements gathered using Diviner 2000 sensors. Integrating the tensiometer data and diviner 2000 from June to October, the soil suction profile with depth and time is shown. Seasonal matric suction measurements from the field showed that temporal pattern of fluctuation with depth. The magnitude of matric suction values ranges from 23 to 83kPa based on the depth of the soil for a volumetric water content ranging from 12-53%. Matric suction profile with depth is found increasing with a magnitude of difference varying based on the soils volumetric water content for the depth of investigation.

Keyword: Air Entry Value, Matric Suction, Shrinkage curve, Soil-water characteristic curve

ACKNOWLEDGMENT

Firstly, I want to express my gratitude to the Almighty God for granting me success in this study. I would like to express my sincere gratitude and appreciation to my advisor, Dr. Tezera Firew Azmatch, for his continuous help, valuable guidance, and encouragement throughout the entire process of this work. Working under his supervision was a rewarding experience.

I would also like to extend my gratitude to Wollo University, KiOT for the opportunity to learn this MSc Program at Addis Ababa Institute of Technology.

Finally, I would like to thank my parents for their support and encouragement throughout my journey.

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ACCRONYMS

Ac	Activity
AEV	Air Entry Value
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
e-CC	Void Ratio Characteristics Curve
FS	Free Swell
Gs	Specific Gravity
HAED	High-Air-Entry Disk)
IAEG	International Association of Engineering Geology
IS	Indian Standard
kPa	Kilopascal
LL	Liquid Limit
LS	Linear Shrinkage
NMC	Natural Moisture Content
PL	Plastic Limit
PI	Plasticity Index
PPA	Pressure Plate Apparatus
PVC	Potential Volume Change
S-SWCC	Degree of Saturation Soil-Water Characteristic Curve
SC	Shrinkage Curve
SF	Scaled Frequencies
SL	Shrinkage Limit
SMC	Saturated Moisture Content
SWCC	Soil-Water Characteristic Curve
TP	Test Pit
USCS	Unified Soil Classification System
USPF	Unsaturated Soil Property Functions
w-SWCC	Gravimetric Water Content Soil-Water Characteristic Curve
θr	Residual Volumetric Water Content
θs	Saturated Volumetric Water Content
θ-SWCC	Volumetric Water Content Soil-Water Characteristic Curve

CHAPTER 1 INTRODUCTION

1.1 Background of The Study

Unsaturated soils are partially filled with water, leaving air in the remaining pore spaces. Unsaturated soil mechanics studies the behavior of these soils, which differs significantly from that of fully saturated soils. It is now an important part of geotechnical engineering practice, especially in the areas of expansive, collapsible soils and geo-environmental engineering. The ability to assess soil suction and the development of laboratory and field-testing tools for unsaturated soils have made it possible to use unsaturated soil mechanics.

The use of the soil-water characteristic curve (SWCC) is the key to the implementation of unsaturated soil mechanics into engineering practice (Fredlund, 2009). The SWCC is broadly defined as the relationship between the amount of water in a soil and soil suction (Fredlund and Xing, 1994). The SWCC can then be used for the estimation of unsaturated soil property functions (USPF). (Fredlund 2000). Consequently, a variety of "estimation techniques" for unsaturated soil property functions have been forthcoming from research studies in various countries (Fredlund, 2000a, Vanapalli et al., 1996a). The SWCC constitutes the primary soil information required for the analysis of seepage, shear strength, volume change, airflow, and heat flow problems involving unsaturated soils.

Numerous techniques have been proposed and studied for the assessment of the soil-water characteristic curves. These techniques range from direct laboratory measurement to indirect estimation from grain-size curves and knowledge-based database systems.

This thesis employs laboratory and field-based suction measurements together with the volumetric water content of Addis Ababa's expansive soils. It utilizes a pressure plate apparatus for controlled laboratory measurements of soil suction and digital tensiometers for in-situ field monitoring together with Diviner 2000 to determine the volumetric water content of the soils.

Expansive soil is generally defined as soil which is found in arid and semiarid areas that has the potential to increase in volume under increasing water content. Much of Ethiopia, including Addis Ababa, has expansive soils that can shrink or swell, often causing significant damage to structures built on them. In Ethiopia, more than 13.8 million hectares of land, or 12.5% of the total area, are covered by expansive soils (Negawo et al., 2017). Problems associated with expansive soils are the result of changes in soil moisture caused by environmental influences and human activities. When the moisture condition changes in expansive soils, a differential soil movement occurs (Mitchell 1979).

Any geotechnical study of a building or road on expansive soils must include an assessment of the shrinkage and swelling properties of the soil as well as the environmental conditions that contribute to soil moisture flow (Nelson and Miller, 1997). The shrink-swell properties of expansive soils are controlled by soil suction. The theory of soil suction has been used by geotechnical engineers for solving the problems caused by expansive soils for many years.

In Ethiopia engineering characteristics of expansive soil are determined based on the approaches for saturated soils even though most of the structures are found in unsaturated zones, soil investigation results carried out mainly defining the saturated engineering behavior of soil. Therefore, this research mainly aims to determine the behavior of unsaturated soil properties by developing SWCC of expansive soils of Addis Ababa and conducting field measurement of soil suction which can be used for determination of unsaturated properties like volume change, seepage, shear strength and permeability functions.

Environmental conditions have significant impacts on saturated and unsaturated soils. Moisture flow between the atmosphere and the ground surface is an important component of many problems related to soil mechanics and geoengineering (Fredlund et al. 2012). A better understanding of the interactions of the environment with the soil can provide solutions to various geotechnical problems. Many pavement and foundation structures cannot be designed without evaluating moisture flow at the soil surface (Wilson et al. 1997). Water movement significantly influences the soil profile, especially the expansive soil profile.

This thesis presents and interprets the long-term soil suction measurements made using digital tensiometer and volumetric water content using diviner 2000 between July 2023-october 2023 on field at Jemo, Addis Ababa.

1.2 Statement of The Problem

Most infrastructures in engineering practices are built on unsaturated soil zones, despite the fact that most conventional methods based on saturated soil ideas are used to predict their behavior.

Plasticity index, activity, percent of swell, and swell pressure have long been investigated in expansive soils that exhibit significant volume change linked with changes in water contents, either in the form of swell or shrinkage. However, knowing the influence of matric suction on the properties of expansive soils is critical for determining the suitable volume change, unsaturated shear strength and permeability functions encountered in practice.

Because the technology necessary to directly measure unsaturated soil property functions is expensive and time-consuming, it is unsuitable for most routine engineering applications. Consequently, the need arises for practical solutions for the determination of unsaturated soil property function. As a result, using soil water characteristic curves as an estimating approach for producing unsaturated soil property functions has proven to be both feasible and sufficient. By constructing a SWCC for expansive soils in Addis Ababa, this work aims to shorten and simplify the lengthy and expensive procedures for assessing the features of unsaturated soils.

The increase and decrease in pore water pressure in the soil increases and decreases the matric suction and bearing capacity of the soil, which depends on climatic parameters. It is therefore necessary to study the seasonal changes in the distribution of the matric suction in the soil and with depth. For this reason, long term field measurements of suction force starting from (June to October 2023) and its relationship with volumetric water content were carried out in this study.

1.3 Objective

1.3.1 General Objective

The general objective of this study is to develop a SWCC for expansive soils in Addis Ababa and conduct long-term field measurements of suction volumetric water content and to investigate their relationship with climatic parameters and/or season.

1.3.2 Specific Objective

1. Identifying the index properties and classifying soil samples appropriately.
2. Conducting laboratory tests necessary for developing SWCCs.
3. Determining shrinkage curve (SC) using digital Caliper and degree of saturation soil-water characteristic curve (S-SWCC).
4. Evaluating volume change properties of the soil samples using Void ratio characteristics curve (e-CC).
5. Quantifying variation of matric suction with depth within the soil profile.
6. Quantifying variation of matric suction with season within the soil profile.
7. Comparing field measurements of matric suction using digital tensiometers against laboratory measurements obtained using pressure plates.

1.4 Scope of The Study

To properly characterize the unsaturated expansive soils of Addis Ababa, laboratory and field tests are employed.

1. Pressure plate test: Using this instrument the water content of the soil at the following suction pressures (33,200,400,800,1300kPa) is measured.
2. This study focuses on drying front of SWCC for undisturbed soil samples from 12 test pits.
3. This research investigates expansive soils sampled from Addis Ababa, Ethiopia.
4. Field tests are carried out to measure the field soil suction and volumetric water content, using digital tensiometer and Diviner 2000 respectively starting from June to October 2023.

The laboratory test program was carried out at the geotechnical research laboratory of Addis Ababa institute of technology and Debre Zeit Institute of Agricultural Research and the field test is done at Jemo around Nasew real state. The data obtained from these tests are then used to develop SWCCs and soil suction profile with depth and season. These SWCCs and profiles are then used to assess the behavior of the soils under various conditions.

1.5 Significance of The Study

This study characterizes unsaturated soil properties of Addis Ababa's expansive soils by providing, w-SWCC, s-SWCC, e-CC for determination of unsaturated soil properties such as, volume change, seepage, shear strength and permeability functions. The results of this study can also be used as input data by professionals looking for these characteristics.

In this study, field measurements of suction force and its relationship to volumetric water content were carried out from June to October 2023 using a digital Tensiometer and Diviner 2000, respectively to 2m depth from original ground level. Results are then used to show how tightly water is bound within the soil at various depths and how these changes with seasons climatic condition to the depth the study is done.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews previous works on expansive soils and unsaturated soil mechanics in engineering practice. It covers the following topics:

- The properties, origins, identification, classification, and distribution of expansive soils are discussed.
- The nature and behavior of the soil-water characteristic curve and shrinkage curve for expansive soils are examined. which are used to describe the water retention and volume change properties of unsaturated soils.
- The different curve fitting models and methods for predicting and measuring the SWCC and SC in the laboratory.
- Field measurement techniques for suction and in situ water content using various sensors on the field are explored.
- Previous studies on field suction measurements for expansive soil are discussed.

Understanding these processes from an unsaturated soil mechanics perspective can lead to improved characterization, modeling, and mitigation strategies.

2.2 Expansive Soil

Soils that tend to change their volume as a result of changes in their moisture content are known as expansive soils. Expansive soil is a term generally applied to any soil or rock material that has a potential for shrinking or swelling under changing moisture conditions (Jhon and Debora, 1992). The black cotton soil, which is grey to black in color and gets its name from India, where these soils are ideal for cultivating cotton, is the most well-known example of expansive soil (Alemayehu and Mesfin, 1999). Soils with a high percentage of swelling clay have a very high affinity for water partly because of their small size and partly because of their positive ions (R. Day 1999). The swelling behavior is generally attributed to montmorillonite, a lattice clay mineral that expands in expansive soils.

Expansive soils are formed by a mixture of smectite clay minerals, such as montmorillonite and bentonite. Expansive soils are distributed all over the world, in the United States, Egypt, Australia, China, South Africa, etc. (EI-Garhy and Wray 2004). Water molecules consist of two hydrogen atoms and one oxygen atom. Within a single water molecule, the electrical charges are not evenly distributed. The two positively charged hydrogen atoms are grouped on one side of the negatively charged oxygen atom. The electrical structure of water molecules enables them to become attached to the clay crystals (Foundation Repair Guide 2007).

The montmorillonite has a stronger hydrophilic ability compared to other clay minerals (Shi et al. 2014). Therefore, the expansive soils that contain a high amount of montmorillonite can shrink or swell up to 1.5 to 2 times their original volume after changing the moisture content.

2.3 Distribution of Expansive Soils in Ethiopia

Areal coverage of expansive soils in Ethiopia is estimated to be 24.7 million acres or 40% of area coverage according to (Bantayehu Uba, 2017) and 12.5% or 13.8 million hectares of land according to (Negawo et al., 2017). Expansive soils are observed in areas such as central Ethiopia, following the major trunk roads like Addis Ababa - Ambo, Addis Ababa - Weliso, Addis Ababa – Debre-Birhan, Addis Ababa - Gohatsion, Addis Ababa - Mojo. Also, it covers areas like Mekelle, Bahirdar, Gambela, Arba Minch, and the Southern, southwest, and southeast parts of the capital Addis Ababa area in which the most major recent construction is being carried out.

According to (Alemayehu T. And Solomon Y. 1986), the black and grey soils found in the eastern and southern parts of Addis Ababa are highly expansive and there is no distinction between the heaving characteristics of the grey and black soils. The clay content of the soil is found to be as high as 80% and the amount of montmorillonite in Addis Ababa's expansive soil is 70-80%. These soils can hold a significant amount of water that affects the shear strength, as well as shrinkage and swelling characteristics of the soil (Luelseged A, 1990).

Most of the area is covered with thick expansive soil. Based on the available drilling geotechnical data the thickness of expansive soil ranges from 3m to 16m in the study area with a high swelling potential (Berhane G, 2021).

2.4 Damages from Expansive Soils

The damage of expansive soils causes a range of risks and impacts on the structures, particularly pavements and foundations of light buildings. One-story buildings are more subjected to the damages of expansive soils than multi-story buildings, which are heavy enough to sustain swelling pressures. However, if multi-story buildings are constructed on wet expansive soils, they may be damaged by the shrinkage of soils due to moisture loss such as evaporation. The problems of expansive soils are usually overlooked since they take several years to cause damage (Buhler and

Cerato 2007). In the United States, the damages of expansive soils to the structures cost $2.3 billion each year, which is more than twice the damages from other hazards, such as floods, hurricanes, tornadoes, and earthquakes (Kerrane 2004).

The formation of cracks is a key problem to expansive soils. Many geotechnical constructions are affected directly or indirectly by the cracks in drying soils. When the expansive soils lose water and shrink, cracks will form because the tensile stress increases to exceed the tensile strength of the soil particles. Cracks destroy the stability and integrity of soils by decreasing soil bearing capacity. Two main factors can affect crack development. The montmorillonite content in expansive soil and the combined effect of environmental conditions, such as temperature, precipitation, wind speed, solar radiation, and evaporation. It should be emphasized that cracks are more prone to form in lightly loaded structures than in heavily loaded buildings, as the former is simpler to move vertically due to underlying expansion soil pressure. (Hussein, 2010).

Geotechnical engineers have developed a variety of theories and models to predict the volume changes of expansive soils. The incorporation of soil suction into soil stress can be used to predict the direction and rate of moisture flow as well as the volume change of expansive soils. The analysis of soil suction is highly involved in the studies of cracks in expansive soils (Auvray et al. 2014; Morris et al. 1992). The suction variation cycles in response to the wetting and drying cycles of the environment influence the formation of cracks. Once the variations of soil suction have been predicted, they can be used to analyze soil-structure interaction and moisture flow in soil (Lytton 1977).

2.5 Identification of Expansive Soil

The methodologies for identifying and classifying expansive soils are classified into two categories: field identification and laboratory identification.

2.5.1 Field Identification

Some of the important field identification methods that indicate the potential for expansiveness of soil which are explained by (Chen 1966,) are the following: -

- A shiny surface is easily obtained when a partially dry piece of the soil is polished with a smooth object such as the top of a fingernail.
- The wet sample of the soil is sticky, and it is relatively difficult to clean the soil from the hands.
- The appearance of cracking in nearby structure.
- They usually have a color of black and grey.

- In the regions where there is seasonal moisture variation there is a presence of joint or similar discontinuity, slickenside (highly polished or glossy fissure surface) and shattering or micro-shattering, (presence of fissures forming granular fragments of clayey soils) may observed.

Chen, (1966) stated that expansive soils can be recognized by using mineralogical identification, indirect index property tests or direct expansion potential tests and expansively of a soil is governed by the type and proportion of clay minerals it contains. Also, knowing the type and proportion of the clay mineral in a soil gives a clue on the swelling potential.

2.5.2 Laboratory Identification

By using laboratory identification methods expansive soils can be identified in three different methods-

- Direct measurement
- Mineralogy
- Indirect measurement

2.5.2.1 Direct Measurement

It is a convenient and more reliable test because it immediately tells the likely in situ response of the ground for moisture variations since it directly measures the force per unit area that a swelling soil exerts on any structure resting on it. The test can be done using a conventional one-dimensional consolidometer (Chen, 1988; Nelson and Miller, 1992).

2.5.2.2 Mineralogy

There are mineralogical identification methods by using the mineralogy of clay particles, such as: X-ray diffraction, Differential thermal analysis, Dye absorption, Electron microscope, cation exchange capacity, and so on (Chen, 1988; Nelson and Miller, 1992). Nevertheless, they are not suited for routine testing as they are time consuming, require expensive test equipment and, the results are interpreted by specially trained technicians.

2.5.2.3 Indirect Measurements

This method is used to investigate the swelling potential of expansive soils by examining other parameters, which indirectly gives information about the soil properties (Asuri, 2016). Indirect property tests (Grain Size Analysis, Atterberg Limit, linear shrinkage and Free Swell tests) are some, among the routinely conducted index property tests. The other tests the cation exchange capacity (CEC) and the potential volume change (PVC) are included in this method.

Table 2-1 Indirect Method of Expansive Soil Identification

Tests	**Properties investigated**
Atterberg limit	Liquid limit (LL), Plastic limit (PL), Plasticity index (PI) and Shrinkage limit (SL)
Potential volume change (PVC)	Free swell (FS) $=\left(\frac{V_F-V_I}{V_I}\right)*100$ VF Final volume in water and VI initial volume in water
Activity method	$Activity(Ac) = \frac{Plasticity\ Index}{(\%\ by\ weight\ finer\ than\ 0.002mm)}$

2.6 Classification of Expansive Soils

A systematic method of categorizing soils into various groups and subgroups according to their engineering behavior is known as soil classification. The systems that are quite popular amongst engineers are the American Association of State Highway and Transportation Officials (AASHTO), the Unified Soil Classification System (USCS), and the International Association of Engineering Geology (IAEG). The USCS and IAEG are commonly used methods for geotechnical investigation (Murthy, 2002). On this work USCS classification system is used.

Table 2-2 Classification of expansive soil based on (Asuri K 2016)

Free swell (%)	**Swell potential**
<50	Low
50-100	Medium
100-200	High
>200	Very High

Table 2-3 Classification of expansive soil based on Skempton method

Degree of activity	Activity
Inactive clay	<0.75
Normal clay	0.75-1.25
Active clay	>1.25

Table 2-4 Classification of Expansive soils according to Chen (1988).

The percentage passing No.200 sieve	Plasticity index (%)	Percentage of swell	Swelling pressure(kPA)	Degree of expansion
>95	>55	>10	>1000	Very high
60-95	20-55	3-10	250-100	High
30-60	10-35	1-5	150-250	Medium
<30	0-15	<1	50	Low

Table 2-5 Shrinkage limits and Degree of Expansion according to Altmeyer (1955).

Shrinkage limit (%)	Linear Shrinkage (%)	Degree of Expansion
<10	>8	Critical
10-12	5-8	Marginal
>12	0-5	Non-Critical

2.7 Soil Suction Theory and Typical Soil Suction Profiles

2.7.1 Soil Suction Theory

Soil suction is defined as the free energy of the soil water (Fredlund 1993). Which is the energy required to remove a unit volume of water from the soil. Typically expressed in units of kPa. It represents the thermodynamic potential of pore water relative to free water, where free water is defined as water with no dissolved solutes (Lu 2004).

The theory of soil suction is highly involved in the engineering practice of unsaturated soil, such as foundation design, soil movement prediction, soil volume change, etc. The movement of expansive soil is usually associated with suction change near the soil surface (Lytton 1994). As a result, it is necessary to evaluate soil suction in engineering practice.

The total suction (free energy) of soil has two components. Osmotic suction and matric suction. Osmotic suction originates from dissolved solutes in the pore water and matric suction resulting from the combined effects of capillary tension and short-range adsorption forces (Lu, 2004).

The total suction in unsaturated soil has two components: matric suction and osmotic suction. Matric suction is defined as the difference between the pore air pressure and pore water pressure (ua-uw). Osmotic suction results from the forces exerted on water molecules from the dissolved salts in the pore fluid. In most geotechnical practice, osmotic forces in the soil are fairly constant and there is no significant change in osmotic suction. Therefore, changes in total suction are mainly due to changes in matric suction (Nelson and Miller 1992).

Matric suction is the parameter of primary interest for Geotechnical engineering as it influences many phenomena and processes in unsaturated soil. It has been proved that matric suction is a stress state variable controlling the mechanical behavior of unsaturated soil (Fredlund 1992). Matric suction can be affected by several factors, such as environmental and moisture conditions, ground surface conditions, the depth of the water table, and soil permeability. Matric suction is generally high in dry seasons and low in wet seasons. Hence, the moisture flow through soils is from a state of low suction (high moisture content) to a state of high suction (low moisture content).

The matric suction beneath an uncovered surface varies greater between wet and dry seasons than that beneath a covered surface. The depth of the water table can also affect the magnitude of the matric suction. The equilibrium matric suction near the surface is higher when the water table is deeper (Durkee 2000).

It is critical to gain a better understanding of how unsaturated soil behaves and works. The water table divides the world of soil mechanics for the sake of simplicity. Effective stress (σ - uw) governs soil behavior below the water table, whereas two separate stress factors, net normal stress (σ - ua) and matric suction (ua – uw), influence soil behavior above the water table (Jennings and Burland, 1962; Fredlund and Morgenstem, 1977). The soil is at or near saturation condition and behaves as if it is saturated at low matric suctions, where the suction is less than the air-entry value (AEV) of the soil. The soil begins to desaturate at matric suctions greater than the soil's AEV (Thamer et al., 2006).

2.7.2 Seasonal Variation of Matric Suction

Climatic variation has a significant impact on the water content of the soil near the ground surface. While rainfall and other forms of precipitation induce a downward flux, evaporation and evapotranspiration from the ground surface cause an upward flux. The pore water pressure of the soil is determined by the difference between these two processes. A net upward flux causes the soil mass to gradually dry, crack, and desiccate, whereas a net downward flux eventually saturates the soil mass. The net surface flux, among other things, influences the depth of the water table. According to (Fredlund and Rahardjo 1993), arid and semi-arid areas have a deep groundwater table.

Mitchell (1979) analyzed seasonal soil suction variation in expansive soils. He pointed out that the climate, drainage, and vegetation type controlled the moisture flow at soil surface. Mitchell’s research indicated that the suction change as a periodic function of time.

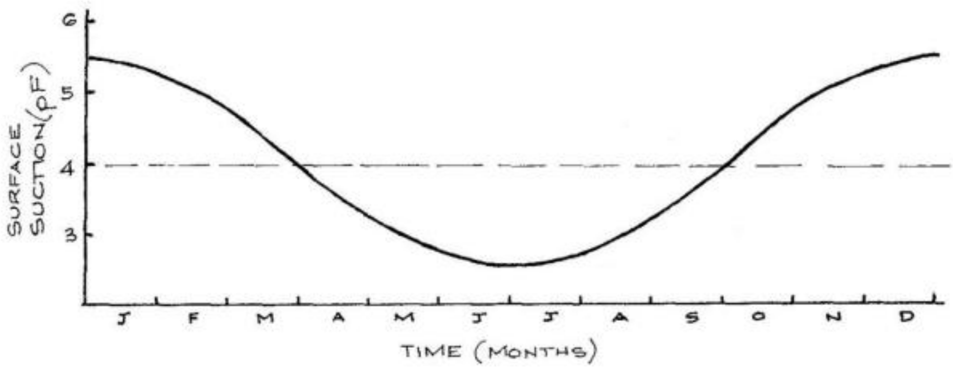


Figure 2-1 Seasonal suction variation at soil surface (Mitchell 1979)

M Bardanis (2023). Worked on Long-term measurements of suction in the field and their relation to climatic parameters for high plasticity soils. By using three suction and volumetric water content monitoring stations in Greece. This work indicates that suction variation with depth and climate (time) as shown on Figure 2-2.

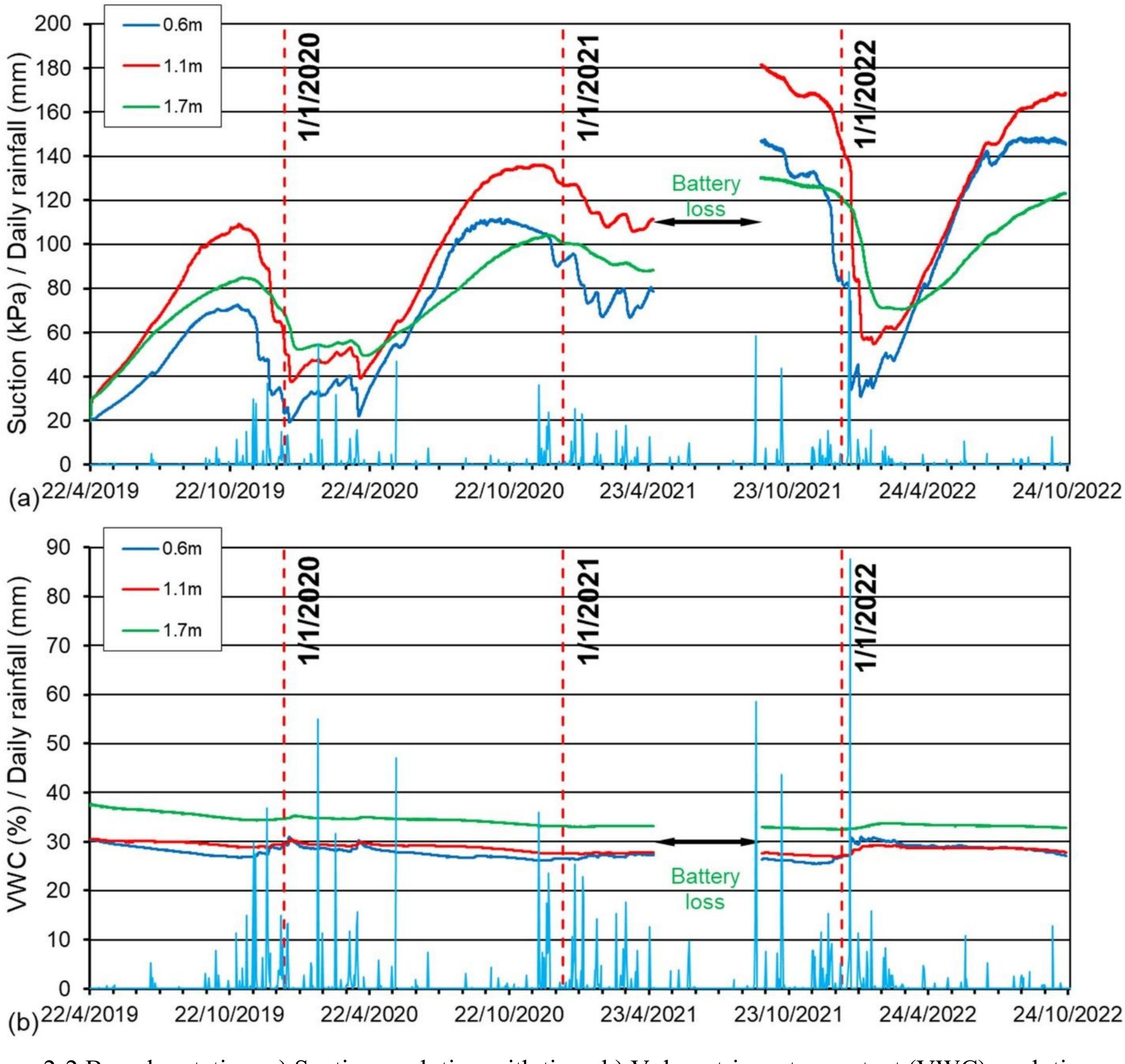


Figure 2-2 Bassales station: a) Suction evolution with time. b) Volumetric water content (VWC) evolution with time. Light blue solid line in both diagrams corresponds to daily rainfall.

2.7.3 Phases of Unsaturated Soils

Unsaturated soil contains a complex interplay of three distinct phases (Fredlund and Rahardjo 1993). Solid Phase, liquid phase and gas phase. These phases are not isolated and they interact with each other in complex ways. The water in the liquid phase can be adsorbed on to the surface of soil particles, creating a thin film called the contractile skin. This skin or air-water interface can significantly impact the behavior of the soil, particularly its strength and deformation characteristics and considered as a fourth distinct phase. In a dry soil, a thin film of water is tightly bound to soil particles, and soil air occupies most of the pore space.

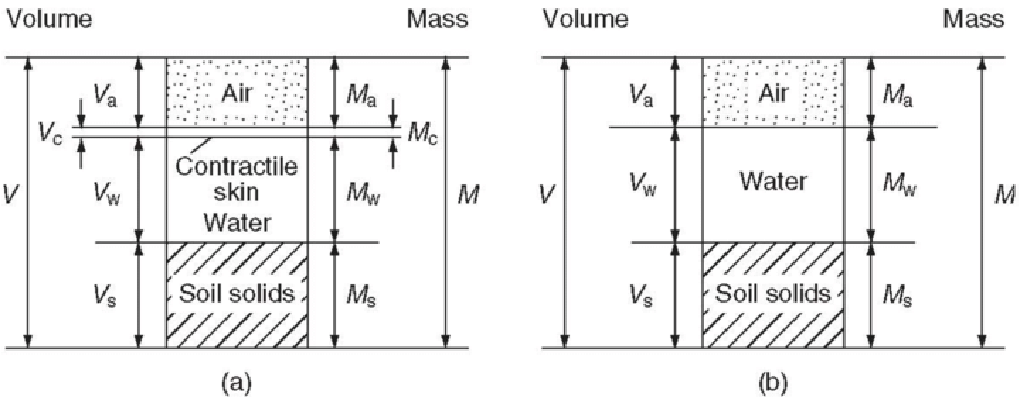


Figure 2-3 Phase diagrams for an unsaturated soil: (a) Rigorous four phase unsaturated soil system; (b) simplified three-phase diagram (Fredlund and Rahardjo, 1993).

2.8 Suction Measurement Techniques

Several measurement techniques are available to measure the suction of a soil sample. The method selected should depend upon the suction desired. Different methods are used to determine the total suction and matric suction respectively. The following measurement techniques, and their applicable range of suction measurements will be described:

Tensiometers, Conductivity Sensors, Pressure Plate Extractors, Psychrometers, and Filter Paper Method.

The following tests described are applicable when determining the matric suction of the soil. Matric suction can be measured direct or indirectly. In the direct measurement method, the negative pore water pressure is measured, however, for indirect methods, thermal or electrical properties of a ceramic are indicators of the matric suction of the soil (Fredlund, 1993). Axis translation technique, Tensiometer, and Suction Probe are examples of direct approaches. Time domain reflectometry, Electrical conductivity sensors, Thermal conductivity sensors, and in-contact filter paper technology are all indirect methods of detecting matric suction.

2.8.1 Tensiometers (0-100kPa)

A tensiometer is a device for measuring, when the soil is not too dry, the soil matric potential. Because the instrument measures tension, it was called a tensiometer. The matric potential is the force that holds water in the soil against gravity. The tensiometer consists of a high air entry porous ceramic cup that is saturated with water and placed in good contact with the soil. In the tensiometer the space behind the ceramic tip is filled with de-aired water and buried in the soil. A vacuum gauge is attached to the top of the cup, and as the soil dries out, water is drawn out of the cup and into the soil. The vacuum gage measures the tension in the water column, which is proportional to matric potential of the soil. (Richards 1949)

A tensiometer consists of a porous, permeable ceramic cup connected through a water-filled tube to a manometer, vacuum gauge, pressure transducer, or other pressure measuring device (Soil Science Society of America, 1997). For this work Electronic tensimeter with hypodermic needle SMS 2500S model is used. Expressed in terms of potential energy per unit volume or bar in the range of 0 – 100kPa.

A matric potential exists in soil when the soil is unsaturated and the water in the soil is under tension. We use a piezometer to measure water in saturated soil. A piezometer is an instrument used to measure pressure. Tensiometers do not measure osmotic potential, because they are not sensitive to the osmotic effects of dissolved salts in the soil solution (Richards, 1965).

Tensiometers provide for direct measurement of the negative pore water pressures in soil within the range of 0-100 kPa. The device usually consists of a tube filled with water containing a high air entry ceramic tip at one end, and a sensor used to measure the negative pore water pressure at the other end (Lu, 2004). Tensiometers are equipped with gauges to read the values of negative pore water pressure. These gauges are typically Bourdon gauges. The tensiometer is inserted into a soil sample. Negative pressure within the soil causes water within the tensiometer to be pulled through the high air entry ceramic tip until an equilibrium condition is reached between the inside of the tensiometer and the surrounding soil. When the stress slowly equalizes between the water tension in the tensiometer and the water tension in the soil pores. That tension is then measured.

2.8.2 Pressure Plate Apparatus (0-1500kPa)

The pressure plate apparatus (PPA) is a closed pressure chamber that can be used to increase the air pressure in the soil pores to the point where the air chases the water out of the pores. A soil sample is placed within the chamber onto a saturated high air entry disk that will only allow for the flow of water through the saturated pore spaces but prevents air up to a rated value (air entry value) of matric suction. The axis translation technique (Hilf, 1956), involves using some variation of a pressurized chamber to apply air pressure to a material while keeping the water pressure at a constant value (usually zero). The air pressure inside of the chamber is elevated to a desired value (decrease in tension). When the water tension becomes equal to zero, the water comes out and at that point, the air pressure is equal to the water tension. This technique is called the axis translation technique. The difference between the applied air pressure and the constant pore water pressure is the matric suction (ua-uw) at the existing water content or degree of Saturation. As the pore air pressure is elevated, water is expelled from the soil sample through the saturated high air entry disk.

Figure 2-4 Conventional 1500kPa pressure plate extractor (Debre Zeit Institute of Agricultural research)

2.8.3 Filter Paper

Soil suction can be measured with filter paper, which is a simple and inexpensive approach. It has sensitive experimental procedure and requires soil-specific calibration. This technique is used to measure total and matric suctions, and the test is carried out in line with ASTM D 5298 – 94. Higher suctions, up to 10^6 kPa, can be measured with filter paper. Filter paper is allowed to absorb moisture from a soil specimen, When the soil and filter paper have reached equilibrium, the suction in the filter paper equals the suction in the soil (Ridley and Wray, 1996).

2.8.4 Water Content

The water content of a soil refers to the amount of water contained in the void spaces between soil particles. Quantitatively water content can be expressed as either a mass ratio which is gravimetric water content (e.g., grams of water per gram of dry solids) or volume ratio which is volumetric water content (e.g., cm^3 of water per cm^3 bulk soil).

Different designations for the amount of water in the soil generate different forms of SWCC, such as gravimetric water content SWCC, volumetric water content SWCC, instantaneous volumetric water content SWCC, and degree of saturation SWCC. The volumetric water content is the water content with the volume of water referenced to the original total volume of the soil specimen.

2.9 Soil Water Characteristic Curve (SWCC)

The soil water characteristic curve (SWCC), is a graphical representation of the mathematical relationship between the matric suction of a soil and either its water content (gravimetric or volumetric) or degree of saturation (S) (Fredlund and Rahardjo 1993). Originally developed by soil and agricultural science, it has gained popularly within the geotechnical engineering community through the research of Fredlund, Vanapalli and others. It represents the water storage (capacity) ability of a given material and allows for the determination of changes in matric suction with respect to changes in water content or degree of saturation.

There are two ways to obtain SWCCs: (1) desorption, by gradually drying the initially saturated sample through applying increasing suction; and (2) sorption, by gradual wetting the initially dry sample through reducing suction (Hillel 2004). Because of the difficulties in measuring sorption (wetting) curve, the desorption (wetting) portion of the curve is usually measured in the laboratory.

Hysteresis is the phenomenon when the drying and wetting curves of the same soil differ.

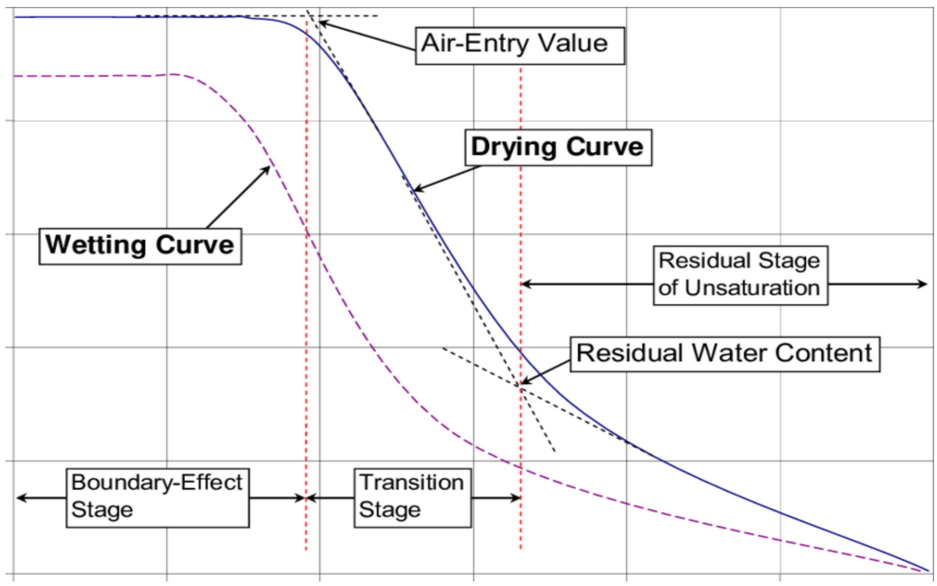
Figure 2-5 Definition of Variables Associated with the Soil Water Characteristic Curve along with wetting and drying curves (modified after Fredlund, 2000)

shows that at a given soil suction, the water content of the drying curve is higher than that of the wetting curve (i.e., the drying curve lies above the wetting curve). The hysteresis effect is caused by (1) irregularly shaped voids in the soil; (2) the contact angle effect; (3) entrapped air in the soil; (4) swelling or shrinking in soil structure (Hillel 2004).

Figure 2-5 Definition of Variables Associated with the Soil Water Characteristic Curve along with wetting and drying curves (modified after Fredlund, 2000)

The saturated volumetric water content (θs), residual volumetric water content (θr), and air-entry value (AEV) are three important features in SWCC. The saturated water content is the maximum amount of water stored in the soil. The residual water content is the water content at which a large matric suction change is required to remove additional water from the soil. The air-entry value is the matric suction at which air starts to enter the largest pores of the soil (Fredlund and Xing 1994)

There are four key parameters on any soil-water characteristic curve (Pham et al. 2003). These are the water content at zero soil suction (i.e., water content of the soil at saturation), the air-entry value, the slope of the curve (particularly between the air-entry and residual points) and the residual water content. Three zones of desaturation can be seen within the curve. The key features on the SWCC are the air-entry value and the residual value for suction and water content



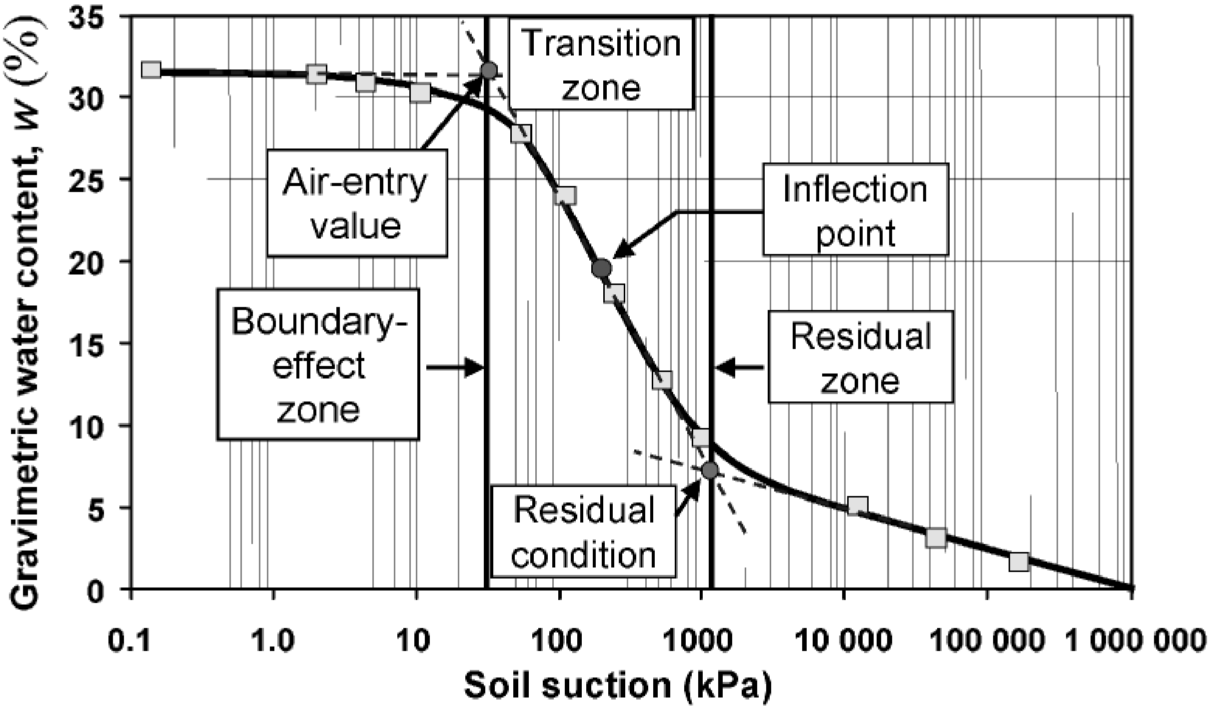


Figure 2-6 Zones of desaturation defined by the desorption branch of the SWCC.

Soil suctions can be found in all ground that lies above the water table. It is one of the most important parameters describing the moisture stress condition of unsaturated soils and laboratory measurements of suction are useful for assessing the quality of the samples, estimating the in situ effective stress and realistic applications of unsaturated soil mechanics. This paper reports on direct soil suction measurement methods both in the laboratory and in the field. Direct suction measurement techniques mainly include axis transition technique, tensiometer and suction probe.

The accuracy of the determination of the SWCC depends on various factors such as: sample preparation technique; initial moisture content of the sample, the water change volume measurement technique; and stress state such as normal stress applied to the specimen during the course of the test. Soil-water characteristic curves generated for soils with different historical stress states are presented in Figure below. The initially slurried soil represents the maximum volume change condition (Fredlund, 2002).

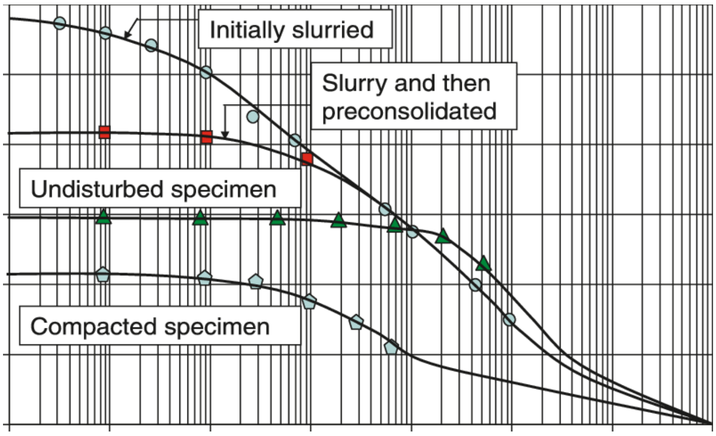


Figure 2-7 Illustration of the influence of initial state on the soil-water characteristic curve (modified from Fredlund 2002).

2.10 Air Entry Value (AEV) of Clays

As explained previously, air-entry value of a soil is defined as the matric suction at which desaturation of the largest pores within the soil begins. The air-entry value of a specific soil is related to the radius of the largest pore (i.e., if the largest pore is relatively small, the air-entry value will be relatively large). Numerous researchers have found that the saturation water content and air-entry value generally increase with the plasticity of the soil (Fredlund and Xing, 1994). Fredlund (2011, 2013) reported that air-entry of soils is generally quite close to their plastic limit. Consequently, the author concluded that there is an approximate correlation between the plastic limit of a soil and its air-entry value. Some other authors, however, reported different degrees of saturation (less than 100%) for soils at plastic limit. Ito and Azam (2010), for example, conducted laboratory experiments on expansive soils and reported degrees of saturation at plastic limit of about 80% and 60% at the shrinkage limit. Upon further drying, another point is reached where the soil dries without any further volume change. This can be referred to as the true “shrinkage limit” of the soil and the gravimetric water content appears to approximately correlate with residual soil conditions.

Li et al. (2009) reported that dry density has a great effect on air-entry value and storage water coefficient of SWCC. Therefore, it can be concluded that AEV for the compacted and slurry specimens can be significantly different. The researchers concluded that AEV of soil samples of lower initial water content is lower and water in soil sample of lower initial water content is excreted easily when AEV is low. They also found that the AEV of soil decreases gradually with consolidation pressure value increasing.

According to Bilsel (2004), the higher the porosity, the lower the air-entry value expected and the faster the desaturation period. The AEV is directly proportional to the plasticity index and inversely proportional to the amount of coarse fraction.

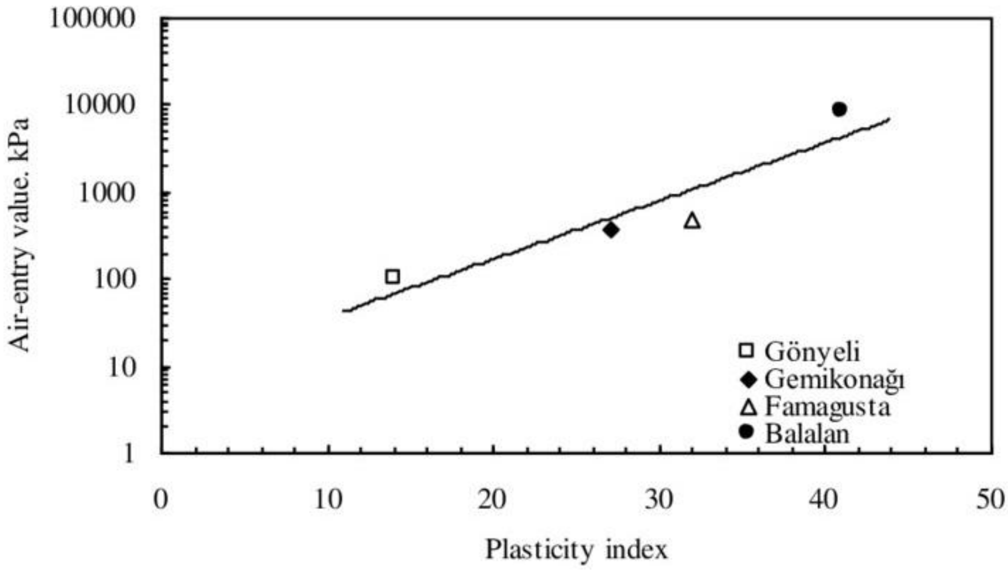


Figure 2-8 Shows the trend of AEV with change in PI of the soil tested by Bilsel (2004).

2.11 Equations to Best-Fit Soil Water Characteristic Curve Data

Numerous equations have been proposed to best-fit SWCC data. Several of these equations are sigmoidal in character and provide a continuous function over the entire soil suction range. These equations have two or more fitting soil parameters. The equations with more fitting parameters are more likely to closely fit the SWCC data obtained from laboratory. The saturated volumetric water content, θs, which is present in numerous SWCC fit equations, is determined by considering porosity of the soil whereas the residual volumetric water content, θr, is not always determined in the laboratory (Chao, 2007).

Various forms of mathematical equations have been suggested to characterize the SWCC. Some of the most common models used to estimate the soil water characteristic curve are. Gardner equation (1958), Brooks and Corey (1964), Brutsaert (1967), Campbell (1974), van Genuchten 1980, McKee and Bumb (1987), Fredlund and Xing (1994) equation and Fredlund and Houston, (2009). Fredlund and Xing (1994) equation is one of the most commonly used SWCC fit equation.

2.11.1 Fredlund and Xing (1994)

The equation proposed by Fredlund and Xing (1994) has been shown to have sufficient flexibility to best-fit laboratory data reasonably well over the entire soil suction range from near zero to 10^6 kPa, provided the material behaves in a mono-modal manner. The form of the Fredlund and Xing (1994) equation written in terms of degree of saturation, (i.e., S-SWCC) is shown in equation 2-1

$$S = \frac{S_o\left(1 - \ln\left(1 + \psi/\psi_r\right) \Big/ \ln\left(1 + 10^6/\psi_r\right)\right)}{\left(\ln\left(exp(1) + \left(\psi/a_f\right)^{n_f}\right)\right)^{m_f}} \qquad 2\text{-}1$$

where ψ is the soil suction. S(ψ) is the degree of saturation at a soil suction of ψ. S_0 is the initial degree of saturation at zero soil suction, and afx, nfx, mf, Ψr are four best-fitting parameters controlling the shape of the SWCC.

The shape of the SWCC (e.g., described by the air-entry value, slope, residual conditions) are influenced by the four fitting parameters (i.e., afx, nfx, mf, and Ψr) in a combined and complex manner. There is no simple one-on-one connection between the fitting parameters and the features of the curve, although afx affects the AEV in a significant way, while nfx significantly influences the slope of SWCC. Bharat and Sharma (2012) studied the validity limits of the Fredlund–Xing parameters and found that small values of Ψr influenced the SWCC near saturation and mf also influenced the residual portion of the SWCC. In other words, these variables affect the shape of SWCC in a coupled manner.

The AEV of the soil is the suction at which air begins to enter the largest pores in the soil (Fredlund and Xing 1994). Vanapalli et al. (1998) proposed an empirical, graphical construction technique to estimate the AEV from the SWCC. The AEV must be determined from the degree of saturation SWCC (Fredlund et al. 2011).

2.12 Shrinkage Curve (SC) Determination

The shrinkage curve is a plot of water content (WC) versus volume change (ΔV) for a soil. It is determined by measuring the change in volume of a soil sample as it is dried from a saturated state.

The shrinkage curve determination for a soil by using the cylindrical ring method is a standardized laboratory test procedure used to determine the relationship between the water content of a soil and its volume change upon drying. This is a technique used to measure a soils shrinkage curve by using a cylindrical ring upon drying by air. Soil specimens are prepared with the same procedure as SWCC specimen preparation.

When determining the SWCC of an expansive soil, it is important to consider the volume change that occurs as the suction changes during the test (Chao et al. 2008). Mbonimpa et al. (2006) extended modified Kovács model which predicts the soil water characteristic curve using basic properties for incompressible soils to clay soils showing suction induced volume change. The authors performed this by introducing the shrinkage curve in the formulation. The authors used previously measured data points for soil water characteristic curve and shrinkage curve from

SOILVISION (Soil Vision Systems Ltd., 1999), Fleureau et al. (1993, 2002), and Biarez et al. (1987) for validating their model.

Ng and Pang (2000) reported the issues related to volume change when determining the SWCC of a sandy silt and clay mixture using a modified pressure plate extractor. The authors proposed to verify the no volume change assumption throughout the drying-wetting processes. They concluded that the conventional assumption of no volume change in the pressure plate tests would lead to inaccurate estimation of the soil properties

Stange and Horn (2005) conducted laboratory experiments on sandy and silty soil samples collected at three sites in Germany in order to determine the SWCC. They measured the gravimetric water contents and the volumes of the samples after each equilibration, which were used to calculate volumetric water contents. The actual soil volume was determined using vernier caliper measurements. The authors found the importance of considering the volume change during the tests.

Chao et al. (2008) conducted experiments on Claystone samples of the Denver and Pierre Shale Formations obtained near Denver, Colorado using the SWC-150 device and the filter paper method. The authors studied the effect of the volume changes on the SWCC of expansive soils. The authors used calipers to measure the height and diameter of the sample in order to determine the volume. Measurements of the weight and volume of the sample at equilibrium were recorded throughout the experiment. The authors reported importance of measuring the volume change during the test and correcting the SWCC for the volume change.

Fredlund and Houston (2013) reported that not correcting SWCC's for soil volume change that occurs during the SWCC test (particularly soils with high volume change potential), can lead to unrealistic results namely the estimated air-entry value of the soils. The authors described the procedure with which the SWCC obtained from laboratory results can be corrected for volume change with the use of a shrinkage curve. The authors suggested two approaches for correcting SWCC's for the volume change, the first one being to use laboratory devices capable of volume change measurement. The next method is to generate shrinkage curves which define the relationship between gravimetric water content and void ratio of the soil tested. For developing the shrinkage curve the authors suggested using digital micrometers for soil volume measurement. Fredlund and Houston (2013) demonstrated the importance of considering the soil volume change (as soil suction changes) by developing SWCC's for oil sands tailings and Regina clay with and without volume change consideration and compared the results (i.e., with particular focus on air-entry value of the soils).

These SWCC's are shown in Figure 2-9. The authors recommended using volume corrected SWCC in terms of degree of saturation for the estimation of the true air-entry value of the soil.

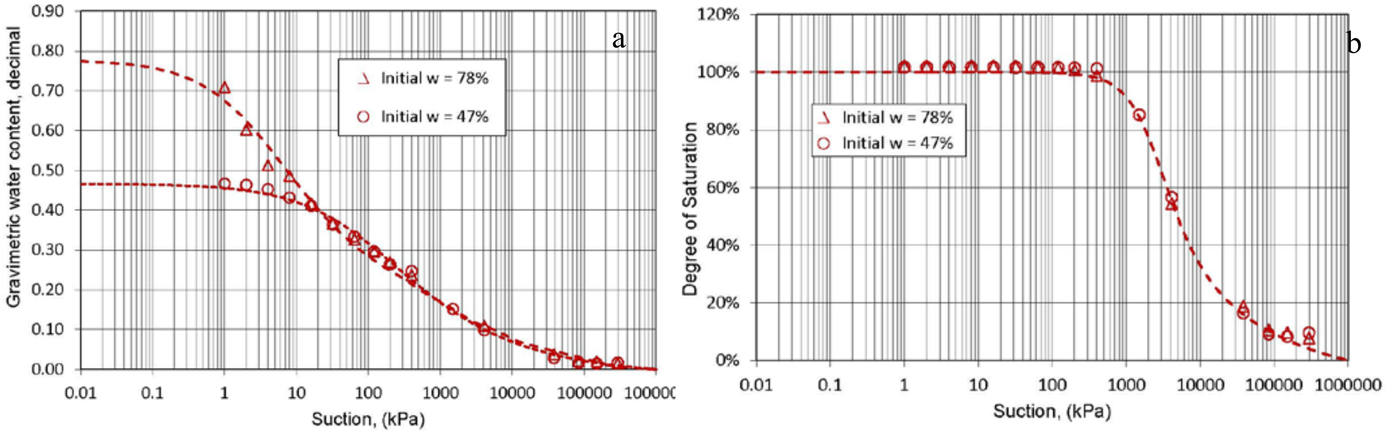


Figure 2-9 a) Gravimetric water content SWCC's measured on the Oil Sands tailings with two initial moisture contents of 78% and 47%, b) SWCC’s plotted as the degree as saturation versus suction for the Oil Sands tailings considering volume change of the soil (After Fredlund and Houston, 2013)

Vazquez and Durand (2011) determined the SWCC of high plasticity clay by running the test, while measuring the dimensions of the sample throughout the test using a caliper. Like many other researchers, the authors found the importance of volume change consideration for obtaining the true SWCC.

Liu et al. (2011, 2012) reported that the volume change measurement is essential for obtaining the true degree of saturation at different suction values throughout the SWCC test. The authors measured the vertical (axial) volume change measurement method in which a vertical load is applied to the sample to ensure the contact between the sample and the confining ring. This method, obviously assumes that the full contact of soil and ring is maintained throughout the test, therefore, considerable volume measurement errors may occur for the cases in which the full contact of soil and confining ring is not maintained throughout the test. The authors developed a modified SWCC device which can measure and record volume changes during the test. Liu et al. (2011, 2012) also evaluated the effect of volume change on the SWCC. They found the volume change of the soil to be an important factor in the soil SWCC. The authors reported the case in which the initial volumetric water content of the soil was 0.1. For this case, a volume change of 3% occurred during the test, and not considering it led to 0.3% error in the volumetric water content determination. The authors reported that the errors become larger with larger initial water content values of the soil.

D. Fredlund and M. Fredlund (2020) recommended that test specimens for the SC and w-SWCC tests be made from the same soil sample.

Several equations for fitting SCs have been suggested, as summarized by Leong and Wijaya (2015). When w-SWCC is combined with the SC test, Fredlund's (2000) hyperbolic equation 2-4, provides the best match for the curves (Fredlund, 2019).

$$e(w) = a_{sh}\left(\left(\frac{w}{b_{sh}}\right)^{c_{sh}} + 1\right)^{\frac{1}{c_{sh}}} \qquad 2\text{-}2$$

$$b_{sh} = \left(a_{sh} \cdot S_o\right) / G_s \qquad 2\text{-}3$$

Where:

- a_{sh} = minimum void ratio upon complete drying (i.e., ranging from 0.4 to 1.0).
- b_{sh} variable related to the slope of the drying curve.
- c_{sh} = variable related to the sharpness of curvature as the soil desaturates.
- S_o = initial degree of saturation.

According to Fredlund (2019), the common range of fitting parameters for ash is 0.4 to 1.0, the bsh variable is calculated from the ash variable, and soil csh values vary from 3 to 15. Low compressibility soils have a csh value of 15, whereas soils with a csh value of 1.5 have a far higher compressibility (or undergo considerable volume change) as soil suction is increased.

2.12.1 Phases of A Drying Soil

When a soil dries, it goes through four phases (Bensallam et al., 2012). By creating the SC, these phases can be obtained. Figure 2-10 depicts the volumetric SC stages, the four phases that exist on the soil up until it dries. Structural, normal, residual, and zero shrinkage are the four types. The structural shrinkage stage is defined as when the reduction in soil volume is less than the amount of water taken from the soil. The amount of free water collected from the soil determines the volume reduction in this phase. Clayey soils, on the other hand, lack this phase (Chertkov, 2003). The emptying of the huge inter-aggregate pores and biological tubular pores of the soil happens exclusively in structured well-aggregated soils (Amenuvor et al., 2020). In the normal shrinkage stage, a decrease in water volume causes a proportional decrease in bulk soil volume. This stage is important in the SC because it accounts for 30–80% of total water loss and 64–94% of total volume loss in many soils (Peng and Horn, 2005). Tripathy et al. (2002) also reported that >80% of volume change occurs in this zone. Air enters the intra-aggregate pores during residual shrinkage, and the drop-in water volume upon drying surpasses the decrease in soil bulk volume (Amenuvor et al., 2020). Finally, in the zero-shrinkage stage, the soil particles reach their densest structure, and the volume of the aggregates remains unchanged while the water volume drops (Bronswijk, 1991).

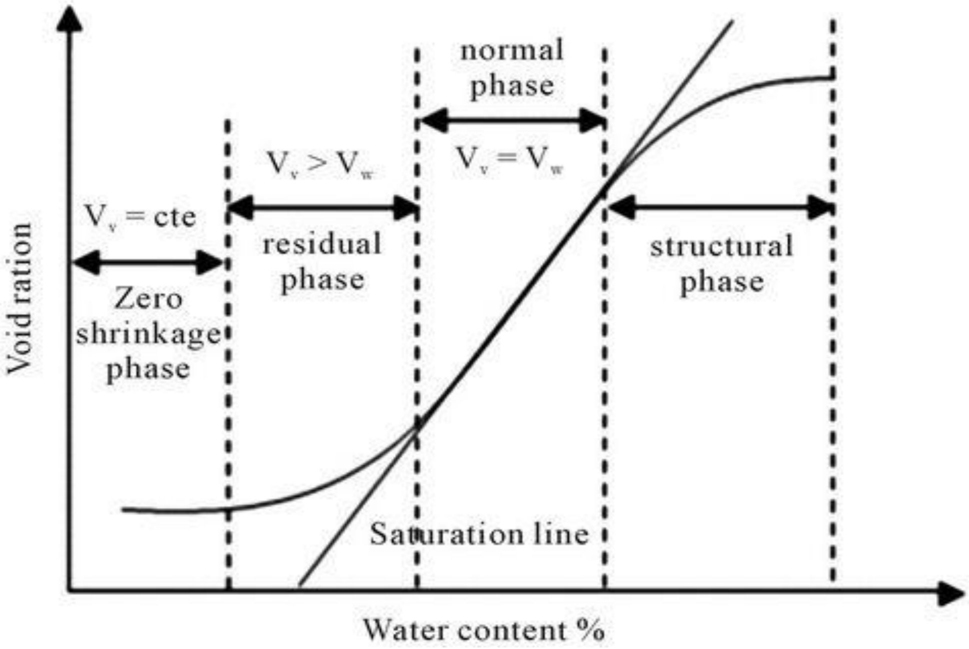


Figure 2-10 Volumetric shrinkage curve. (Bensallam et al., 2012.)

2.13 Methods for Determining Shrinkage Curve (SC)

Different researchers have proposed different ways for determining SC. Mercury, Toluene wax-freezing, Cylindrical-ring, Balloon, and Imaged-based technologies are among them.

1. Mercury Method

The volume of fluid displaced by the soil in mercury was measured in this method to determine the bulk volume of the soil (ASTM, 1990). The mercury method, according to Sibley and Williams (1989), is appropriate for stiff and regularly shaped specimens but cannot specify the whole shrinkage behavior of the soil from the liquid limit to the dried state. Because of its toxicity, using this procedure is no longer encouraged and can result in health complications.

2. Cylindrical Ring Method

Berndt and Coughlan (1976) proposed this strategy, which D. Fredlund and M. Fredlund (2020) have recently used. The bulk soil volume was calculated directly by measuring the diameter and height of a core sample. SC is best defined using this method for undisturbed and compacted samples. This method is utilized to define the SC in this investigation.

3. Balloon Method

The balloon method of estimating the SC was proposed by Tariq and Durnford (1993). An ordinary balloon contains a saturated, undisturbed soil sample. The balloon has an inlet and outlet stopper, and low-pressure air is allowed to pass over the soil sample in the balloon to dry it. After exerting low suction to tightly fit the balloon around the soil, the bulk soil volume is measured at specific periods by displacement of the soil with the balloon in water. In comparison to other ways, this method takes only 2–4 days to generate the shrinkage curve, whereas other methods take weeks.

4. Imaged-based Method

Amenuvor et al. (2020) proposed using image processing to quickly measure the shrinkage curve. In comparison to the existing methods for measuring the soil shrinkage curve, this method is simple and quick. This approach involves filling a cylindrical dish with soil slurry (i.e., soil paste with a water content slightly above the liquid limit) and placing it on an electronic scale with a digital camera set above it to collect periodic photos while the soil dries. The volume of the soil is calculated by multiplying its calculated surface area by its varying thickness, which is calculated using the measured initial and final thicknesses and the assumption that the change in thickness is proportional to the change in surface area or radius at any given stage of drying.

CHAPTER 3 MATERIALS, METHODS AND PROCEDURES

3.1 Introduction

A key difference with conventional soil mechanics is the existence of a negative pore water pressure referred to as suction. Adequately capturing the effect of suction on soil behavior is a complex task that is not commonly used in professional practice. Yet, transportation infrastructures (railways, roads, bridge abutments, etc..) and buildings are commonly constructed on unsaturated soils. Such soils can exhibit large volume variations upon changes in suction and can exert significant swelling pressure on structures, which is problematic and needs to be accounted for in a design process. This research aims to characterize the behavior of unsaturated expansive soils of Addis Ababa.

Unsaturated soil mechanics requires the determination of unsaturated soil properties and these properties along with the saturated soil properties can be used for the estimation of unsaturated soil functions (i.e., shear strength, swelling pressure, and permeability functions). The two unsaturated soil properties determined in this research are: (i) Gravimetric water content versus soil suction, referred to as the soil-water characteristic curve (w-SWCC), and (ii) void ratio versus water content, referred to as the shrinkage curve (SC).

Twelve soil samples from nine locations are used in this work. Four roadway expansive soil samples obtained from two locations during construction work from Lafto Mebrat and Kality area are used. These samples were taken at depths of 2 and 3 meters from roads that have been in service for years. And eight soil samples from various building construction sites in Addis Ababa excavated for construction of building. Among these two soil samples were one location collected from Bole, representing soil from different depths.

Seasonal cycles of soil water content cause shrinking and swelling in clay soils, which can in turn contribute to failure. This research presents and analyses four months of field measurements of soil water content and pore water pressures of Addis Ababa expansive soil by using Digital tensiometer and diviner2000. By using this work variation of matric suction with depth and seasonal variation of matric suction for four consecutive months is shown.

Expansive soils, in general, experience volume changes as a result of soaking and drying. To account for the soil's volume change behavior, the SC must be utilized in conjunction with the SWCC.

3.2 Materials

Both undisturbed and disturbed soil samples were sampled from twelve different test pit locations in Addis Ababa. The locations were chosen based on a review of previous literature and physical tests (Berhane G 2021). The samples were collected at depths ranging from two to nine meters.

The natural soils in this study were named with their locations from where they were taken as follows, by using the Global Positioning System (GPS) tracker software.

Table 3-1 Locations of test pits with GPS Coordinates

Test Pit No.	Location	Depth (m)	Under Roadway/Building	GPS-Coordinates
TP-1	Lafto-Mebrat	2	Under Roadway	Lat: 8.9480033, Long: 38.7344908
TP-2	Lafto-Mebrat	3	Under Roadway	Lat: 8.9480033, Long: 38.7344908
TP-3	Kality	3	Under Roadway	8°54´35´´N 38°45´52´´E
TP-4	Kality	1.5	Under Roadway	8°54´35´´N 38°45´52´´E
TP-5	Megenagna Yeka park	3	Building	Lat: 9.025403 Long: 38.797289
TP-6	Ayat	2	Building	Lat: 8.9916359, Long: 38.7913866
TP-7	Jemo-1	3	Building	Lat: 8.9830713, Long: 38.7801842
TP-8	Bulgaria	5	Building	Lat: 8.995328 Long: 38.751519
TP-9	Tafo	4	Building	Lat: 9.073666 Long: 38.900206
TP-10	Bole	6	Building	Lat: 8.9830713, Long: 38.7801842
TP-11	Bole	9	Building	Lat: 8.9830713, Long: 38.7801842
TP-12	Jemo-2	3	Building	Lat: 8.9830713, Long: 38.7801842

3.3 Soil Sampling and Preparation

By using literatures to identify locations where expansive soils are available soil sampling is carried out. The exact locations of test pits are tracked and recorded. In accordance with ASTM D 4220 AND ASTM D 5079 the samples are transported from their location to the laboratory. The undisturbed samples were covered with a plastic bag and wax to avoid moisture loss. The tests are performed in Addis Ababa institute of Technology and Debre-Zeit Institute of Agricultural research.

Soil sample preparation according to ASTM D 421 – 85 involves exposing soil samples to the air to dry them at room temperature, then breaking up the air-dried soil aggregates with a rubber-covered pestle in the mortar. The dried soils are then sieved to separate them into several laboratory tests, such as: Liquid Limit (LL) and Plastic Limit (PL), Free swell (FS), Specific Gravity (GS) and Linear Shrinkage (LS).

3.4 Laboratory Tests

The laboratory tests were conducted into two phases: phase 1 involved determining the Natural Moisture Content (NMC), Atterberg Limit (LL, PL), Grain Size distribution, Specific Gravity (Gs), Free Swell potential (FS), and Linear Shrinkage (LS). Phase 2 focused on establishing (SWCC) using the Pressure Plate Apparatus and SC using Ring method.

3.4.1 Natural Moisture Content (NMC)

Moisture content is the ratio of the mass of water contained in the pore spaces of soil to the solid mass of particles in that material, expressed as a percentage. A standard temperature of 110 ± 5°C for 24 hours is used to determine the mass of the sample according to ASTM D 2216. The test results are found in Table 4-1.

3.4.2 Specific Gravity

Specific gravity (Gs) of solid particles is defined as the ratio of mass of a given volume of solids to the mass of an equal volume of distilled water at 20°C. The testing procedure conformed to ASTM Standard D584. Specific gravity tests were performed for natural soils. The test results are found in Table 4-1.

3.4.3 Atterberg Limits

Atterberg limits are the most important references in the description of fine-grained soils such as liquid limit (LL), plastic limit (PL), plasticity index (PI), and shrinkage limit. The water content level is capable of making a great difference on the engineering behavior and consistency of soils.

The liquid and plastic limit test procedures are carried out in accordance with ASTM standard D4318. The test results are given in Table 4-1.

3.4.4 Grain Size Analysis

Grain size analysis of disturbed sample was performed in accordance with ASTM D 422-63 and ASTM C136 standard test method. The analysis was conducted in two stages: Sieve analysis and Hydrometer Analysis is used.

Based on the soil retained on each sieve, and hydrometer analysis, the particle size distribution graphs of all test soils were generated, shown in Figure 4-1.

3.5 Soil Index and Classification Test Results

Soil classification

A systematic method of categorizing soils into various groups and subgroups according to their probable engineering behavior without detailed descriptions is known as soil classification.

Free swell

One of the most common easy tests for estimating the swelling capacity of expansive clay is Free-Swell first proposed by Holtz and Gibbs (1956). This test was carried out in accordance with Indian standard 2720 Part XL (ISI 1977).

Several techniques have been used to identify and classify the swelling potential of expansive soils (Snethen et al. 1977). This research used the classification provided by Chen (2012).

Table 3-2 Expansive soil classification (Chen 2012)

Swelling potential	Plasticity index
Low	0-15
Medium	10-35
High	20-55
Very high	35 and above

Linear shrinkage

Linear shrinkage is a measurement of how much a sample shrinks in length upon complete drying, expressed as a percentage of its initial length. The test was carried out in accordance with IS 2718, an Indian standard.

3.6 SWCC Determination

3.6.1 Pressure plate Apparatus

The pressure plate apparatus is used to determine the moisture retention characteristics of the soil. It consists of the following parts.

- A pressure chamber: This is a sealed chamber that contains a ceramic plate.
- A soil sample: This is a sample of soil that is placed on the ceramic plate.
- A pressure regulator: This is a device that controls air pressure in the pressure chamber.
- A water outlet: This is a tube that allows water to flow out of the pressure chamber.
- A ceramic plate: Also known as a high-air-entry disk (HAED) which needs to be water saturated and that selectively allows water to flow through it while preventing air passage. The bottom surface of HAED is exposed to atmospheric pressure, while the top is subjected to the applied matric suction. And ceramic plate is at atmospheric pressure at the bottom and while the top surface is at the applied pressure.

Figure 3-1 a) Pressure plate apparatus b) Ceramic disc c) Soil sample on ceramic plate

SWCCs were determined using pressure plate apparatus with a maximum capacity of 1500kPa. The procedure needs careful placement of the soil sample on the saturated ceramic plate to ensure effective water extraction during pressure application. Method C of ASTM D 6836 was used for applying suction to the soil sample by raising the pore gas pressure through the axis translation principle. This test was conducted in the Debre Zeit Institute of Agricultural Research with the equipment shown in Figure 3-1.

3.6.2 Test Procedure of SWCC using Pressure-Plate Apparatus

As a part of this study, SWCC of 12 expansive soils samples were determined. A total of 24 SWCC tests were conducted. To improve reliability duplicate specimens were prepared for each test from the same soil sample. The purpose of running replicate tests was to achieve higher reliability in test results.

Soil was taken from the mold and extracted gently with the soil extractor used for this case which is 5cm in diameter and 1cm in height. In order to have good contact with the ceramic disc specimens are trimmed with sharp-edged tool according to ASTM D 6836. After preparation of undisturbed specimen with the ring size is soaked in water to reach saturation condition for two to three days. In order to avoid soil loss during saturation process a soft towel was used for folding which is able to pass water without disturbing the soil.

And the mass of specimen and ring were recorded immediately. The specimen's mass in the ring was measured and recorded to the nearest 0.01g.

$$p_d = \frac{M_m}{V\left(1 + W_m\right)} \tag{3-1}$$

- Mm - Mass of the moist soil in the retaining ring.
- W_m - Gravimetric water content of the soil.
- V - Volume of the retaining ring.

After measuring the saturated mass of the specimen, the specimen was ready to start the test.

After the sample was saturated the weight of the soil is measured and the saturated water content was calculated with the equation

$$W_{sat} = \frac{M_{sat}\left(1 + w_m\right)}{M_m} - 1 \tag{3-2}$$

- Msat is the mass of soil in the retaining ring after saturation.

Ceramic discs are then saturated by placing it in a water for 3hrs.

The apparatus used for this test is model pressure plate apparatus (soil moisture 505 - 20 bar compressor) for a suction value lower than 1500kPa. This apparatus uses axis translation method to control matric suction. Air pressures are provided by hydraulic pressure system up to 1500kPa to the top of the plate while holding pore water pressure to zero. The axis translation technique is based on the principle of applying a suction gradient to a soil specimen and measuring the resulting water flow. For this work a maximum of 1300kPa were achieved by this method.

The specimens were allowed to equilibrate at each suction value, it took four to five days for each suction point. If the water levels in the tubes do not change for 24 to 36 hours the soil is assumed reaching equilibrium. Water flows from the specimen when the matric suction was applied until the equilibrium water content is reached for the applied suction. And then specimens were weighed immediately.

This method is repeated for all the required suction values, in this case, the following values 33kPa, 200kPa, 400kPa, 800kPa, 1000kPa and 1300kPa.

After applying the final suction value and or 1300kPa the soil is immediately weighed and placed in a drying oven for 24 hours. And the dry specimens were removed from the oven and immediately weighed and gravimetric water contents of the soil specimens were calculated.

By definition gravimetric water content is the ratio of the mass of water to dry mass of soil.

$$w = M_w / M_s \qquad 3\text{-}3$$

3.7 Shrinkage Curve (SC) Determination by Using Cylindrical Ring Method

Soil samples were carefully extracted from the same soil sample holder used for soil water characteristics curve (SWCC) determination. A cylindrical core with a diameter of 50mm and a height of 10mm is used. To improve reliability two to four replicate specimens per soil type is used.

Initial mass of ring and wet soil sample was weighed. Samples were then allowed to air-dry slowly over five to six days during which the change in sample volume was periodically measured. Immediately after measuring its diameter and height the soil specimen is weighed to the nearest 0.01g. This is done until the soil shows no volume change upon drying. In this study, 12 consecutive measurements of sample weight and sample size were performed until the final oven-dried sample. Once the mass stabilized, samples were oven dried at 105°C for over 24 hours.

Soil shrinkage curves were constructed by calculating the gravimetric water content, dry density and void ratio at each drying phase from the measured masses and degree of saturation were computed, and the SCs were fitted using Fredlund (2000) equation.

This procedure was consistently followed for all twelve soil samples tested.

3.8 Combined Test Results of SC and w-SWCC

The combined test results of shrinkage curve and w-SWCC provide a comprehensive understanding of the soils behavior under changing moisture conditions for soils experiencing considerable volume change when soil suction increases.

Fredlund and Houston (2013) reported that not correcting SWCC's for soil volume change that occurs during the SWCC test (particularly soils with high volume change potential), can lead to unrealistic results namely the estimated air-entry value of the soils. The authors described the procedure with which the SWCC obtained from laboratory results can be corrected for volume change with the use of a shrinkage curve, which define the relationship between gravimetric water content and void ratio of the soil tested.

The AEV is a critical SWCC parameter that describes the minimum matric suction at which air begins to enter the largest pores in the soil as it desaturates (Fredlund and Rahardjo, 1993). For soils that do not experience considerable volume change when soil suction increases, the AEV determined using w-SWCC and S-SWCC is the same. However, for a soil that undergoes significant volume change as soil suction increases, the AEV depends on the w-SWCC and SC test results.

For soils changing their volume with moisture AEV is underestimated by the w-SWCC test result. By combining shrinkage curve and w-SWCC valuable insights can be gained into the soil's expansive and shrink-swell properties including identifying true AEV. The void ratio and water content provided by the SC can be used to calculate the degree of saturation, which can then be used to convert the w-SWCC to the S-SWCC (D. Fredlund and M. Fredlund ,2020).

In this work, the SC and w-SWCC tests were conducted independently, and the data were subsequently merged to account for the volume change that occurred as soil suction is increased. This allowed the development of e-CC and s-SWCC which provides a more comprehensive representation of the soil's behavior with varying moisture conditions.

Volume mass variables calculated:

$$Dry\ density,\ \gamma_d = {p}/{(1+w)} \quad 3\text{-}4$$

$$Degree\ of\ Saturation,\ S = \frac{G_s w}{e} \quad 3\text{-}5$$

$$void\ ratio,\ e = \frac{G_s p_w}{p_d} - 1 \quad 3\text{-}6$$

Where:

- P - total density
- w - gravimetric water content
- Gs - specific gravity
- Pw - density of water

The calculated degree of saturation was obtained using equation 3-7 as follows.

$$s(\psi) = \frac{G_s w(\psi)}{e(w(\psi))} \quad 3\text{-}7$$

Where:

- S(ψ) is degree of saturation at any suction.
- w(ψ) is measured gravimetric water content determined using pressure plate.
- e(w(ψ)) is calculated with the following equation.
- Gs - specific gravity

$$e(w) = a_{sh}\left(\left(\frac{w}{b_{sh}}\right)^{c_{sh}} + 1\right)^{\frac{1}{c_{sh}}} \quad 3\text{-}8$$

The degree of saturation over the entire suction was predicted using the Fredlund and Xing (1994) equation as follows:

$$S(\psi) = c(\psi)\,\frac{s_o}{\{\ln\left[e + \left(\psi/a\right)^n\right]\}^m} \quad 3\text{-}9$$

- So is the initial degree of saturation.
- e= irrational constant equal to 2.71828
- a = fitting parameter indicating the inflection point on the curve.
- n= fitting parameter related to the rate of desaturation,
- m = fitting parameter related to the curvature near residual conditions

C (ψ) = correction factor directing the SWCC to 10^6 kPa at zero water content, and given by:

$$C(\psi) = 1 - \frac{\ln\left(1 + \psi/\psi_r\right)}{\ln\left[1 + \left(10^6/\psi_r\right)\right]} \qquad 3\text{-}10$$

Ψ_r is the suction corresponding to the residual water content, ωr.

3.9 Field Matric Suction Determination

3.9.1 Tensiometer

The electronic tensiometer used for this work is a portable, battery powered with a measuring range 0-100 kPa. The electronic tensimeter is a portable pressure sensor in a bag for measurement of the moisture tension in the soil, measured through a tensiometer tube placed in the soil. The measuring device can be moved from tensiometer tube to tensiometer tube allowing an unlimited number of measurements over a short period of time. The hypodermic needle of the tensimeter is fitted on the tensiometer tube through the silicon stopper after which the moisture tension can be read. The meter has a measuring range of 0-100 kPa with an accuracy of less than 2%. Tensiometer tubes are available in various lengths (SMS 2500 S Electronic Tensimeter Users Guide).

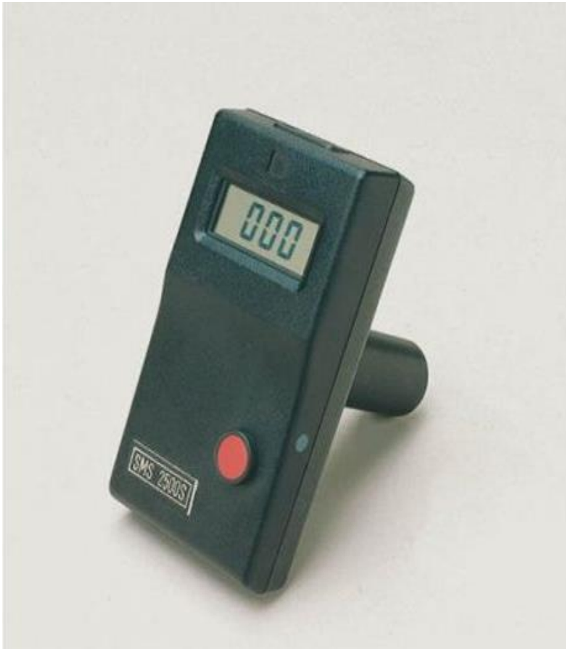


Figure 3-2 Electronic tensimeter

Tensiometers probe

Tensiometers probe is a part of the instrument with ceramic tip that is inserted into the soil to measure soil water tension. The probe is typically made of a porous ceramic material that allows water to enter and exit the tensiometer but not air. As soil water tension increases, water is drawn out of the tensiometer and into the soil creating a negative pressure that is measured with the tensiometer.

In-situ matric suction measurements were conducted at three different depths across various seasons using digital tensiometers for an expansive soil location for the highest volume change located at test pit 12 in the Jemo area, around the Nasew real estate.

Figure 3-3 Electronic Tensiometer and Probes on Field

Test procedure

The technique of measure plug by electronic tensiometer consists in pierce a silicone bung putting on tensiometric tube, by means a hypodermic needle it even connected to a collector of vacuumeter. This type of measure is both very precise and very economic.

1. Preparation of tensiometric tubes: Ensure porous ceramic will be saturated in water for not less than 8 hours in water before to be installed in the soil. Soak the porous ceramic for 8hours in a gasless water container to make sure absolutely no air in the porous ceramic.
2. To exit the tensiometric tube of its container and to make escape the water through the ceramic such that indicated in the sketch below. Never to leave the level of water in the tensiometric tube to reach the porous ceramic. To remake the full as soon as the level declines. Duration of the operation 30 minutes approximately.
3. To fill completely the tensiometric tube with the gasless water. Using syringe preserving porous ceramic in full water container. To pull then on the piston of the syringe, what is going then to create assaults a water entry through the porous ceramic. The senses of the flow go from the water of the container to the interior of the tensiometric tube. Duration of the operation 5 minutes approximately.
4. Locating of installation sites of tensiometric tubes and drilling of holes for the installation of tensiometric tubes. The auger to be used has to be 21.5mm of diameter at least.
5. These tensiometric tubes will be installed and is now functioning.

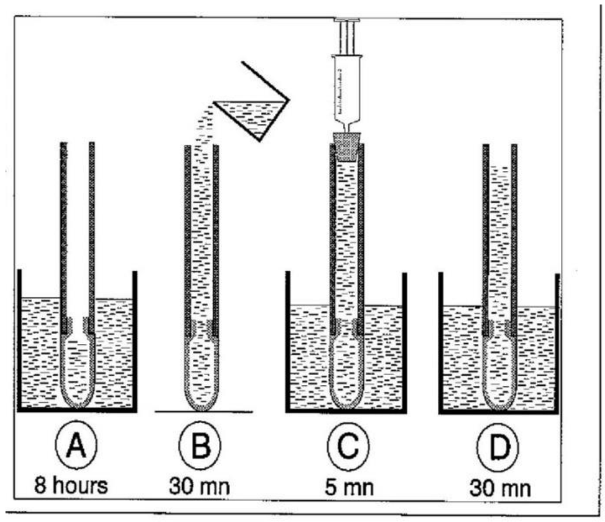


Figure 3-4 Preparation of tensiometer probes

3.9.2 Diviner 2000

Water held in pores of soil in liquid or vaporized form is referred as soil moisture. Soil moisture sensors can be implemented using various techniques like resistive, gravimetric, neutron scattering, capacitive techniques, time domain reflectometry etc. Among these, capacitance is the most widely used electromagnetic method for monitoring soil water content (Gardner et al. 1991). In this paper design of soil moisture sensor based on capacitive technique is used. The basic principle of operation is that the soil is incorporated as part of the capacitor and the variations in the dielectric constant of the combined soil-water-air are used to estimate the soil water content. The dielectric constant of pure water at 20°C is 80.4, whereas that of dry soil oscillates between 3 and 4 and that of air is equal to 1 (Fares and Polyakov 2006).

Diviner 2000 measures soil water every 10cm down through the soil profile in only few seconds. Measurement range oven dry to saturation. It comprises a data display unit and a portable probe. The display unit can log many data with high precision. Custom calibration equations can be created and installed for specific soil types.

Volumetric soil moisture content is measured by responses to changes in the dielectric constant of the soil. Dielectric constant, is an electromagnetic property of a material that describes its ability to store electrical energy. The dielectric constant of soil varies significantly with its moisture content. Dry soil has a dielectric constant typically between 3 and 5, while water has a dielectric constant of around 80. It utilizes the principle that the capacitance between two electrodes immersed in a medium change with the dielectric constant of the medium.

The probe is light weight and portable with 70cm,1m or 1.6m length. Each depth reading is taken automatically by swiping the sensor down the access tube, so that a whole profile can be read in seconds. The portable probe measures soil moisture content at regular intervals of 10 cm down through the soil profile. Readings are taken through the wall of a PVC access tube.

In one swipe and go action with the probe, Diviner 2000 records data from all levels in the soil profile to the depth of the probe, i.e., 0.7 meters, 1 meter or 1.6 meters.

The access tubes Diviner 2000 are installed into the ground using specialized installation tools and techniques to ensure minimal site disturbance and maintenance of site integrity. Correct installation requires good access tube to soil contact to avoid preferential path flow of water down the side of the tube. (Diviner-2000-User-Guide-V1.5)

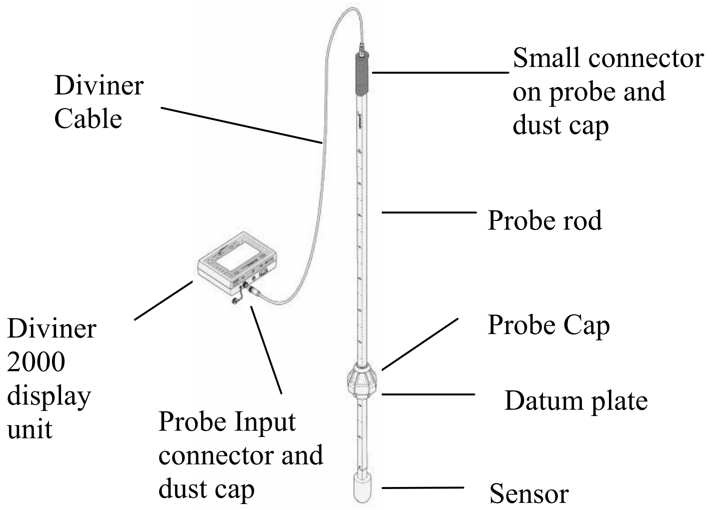


Figure 3-5 Components of the Diviner 2000 display unit and probe.

3.10 Calibration of Diviner 2000

As capacitance is an indirect method for estimating soil water content, it is necessary to carry out specific calibrations for each location in which it is utilized, to ensure that the estimates of soil water content it produces are accurate (Paltineau and Starr 1997; Baumhardt et al. 2000; Leib et al. 2003; Fares et al. 2004; Groves and Rose 2004). The capacitance probe used in this study was the Diviner 2000 (Sentek Pty Ltd, Adelaide, SA).

Calibration of a measuring instrument is typically made by aligning the readings of that instrument against values determined by a method that is long established and accepted as a standard method for measuring the same value.

Calibration of the Soil Moisture Sensors is made by comparing Scaled Frequency readings from an access tube installed in the field or in a container in the laboratory with values of volumetric water content determined gravimetrically from immediately adjacent to the tube.

When these values are plotted on a graph, they form a relationship that is described by a mathematical equation. In this way the moisture levels sent from the sensor are directly related to real values determined in the soil.

As well as calibrating the soil, each sensor must be normalized in water and air to establish the water and air counts for the scaled frequency calculation.

The use of tools such as the Probes offers a non-destructive and less tedious method of measuring soil water content than traditional methods (Fares & Alva, 2000). It must be remembered that any site-specific calibration equation cannot be accurately extended to other sites to yield absolute soil water content, and is only representative of an area of the same soil properties that immediately surround that site.

The Soil Moisture Sensors are calibrated by comparing sensor readings (Scaled Frequencies) with actual soil water content values over a range of soil moisture contents. Gravimetric sampling, in conjunction with determination of bulk density, enables the volumetric soil water content to be derived.

The relationship between Scaled Frequencies and independently determined volumetric soil water content values provides a calibration curve. In fact, this relationship can be a straight line or curve and is described mathematically by a calibration equation. Calibrations can be performed either in the laboratory or in the field.

3.10.1 Normalization procedure

The Diviner 2000 is normalized using the "Normalization tube Diviner 2000" and a 9-liter bucket of water, to set the air and water counts. This is necessary because each sensor responds slightly differently to air and water.

To set the air count

1. Normalization tube is Positioned in air.
2. Probe is placed inside the sealed normalization tube.
3. Hold the probe and normalization tube in the air, clear of all solid objects.
4. The reading is taken over a 10-second interval and the probe must be held in the air for this period.

To set the water count

1. Probe head is put into the Diviner 2000 Normalization tube, and inserted into a 10-liter bucket of water.
2. Use the arrow keys to move the cursor to the Water Count field. The Water count function is highlighted.
3. Probe is inserted into the sealed normalization tube.
4. Wait until the measurement is complete.

3.10.2 Field Calibration Technique

Step-1

Install approved PVC access-tubes in an appropriate site. Ensure there are no air gaps around the access tubes. Six access tubes are used to perform a calibration. A minimum of two tubes should be placed in wet soil, two in moist soil and two in dry soil. The replicates should be at least two meters apart and the different treatments at least five meters apart, but in the same general area.

Figure 3-6 Installation of Access tubes

Step 2

Sufficient time is allowed to prepare the soil with variation of soil water content. Sufficient time is allowed to make difference between calibration points for wet, moist and dry soil for a good site preparation. Probes are installed prior to site preparation, and then sufficient time allowed for adequate wetting and drying.

Step 3

Three raw count readings at each selected depth level are collected.

Step 4

Immediately after obtaining readings, a trench is dig beside the tube to the depth of the deepest Diviner 2000 Probe length, which is 40 cm far enough from the access tube to avoid disturbance of the soil being measured and sampled.

Figure 3-7 Digging Trench

Step 5

Three thin-walled metal rings are used to sample soil water and bulk density from each depth. Each core is trimmed with care using a spatula, without compressing the soil.

Step 6

Aluminum foil caps are placed on the top and bottom of the ring. Each of the samples weighed to obtain the wet mass of the soil core (Mw) immediately. After weighing, samples dried at 105ºC to constant weight and reweighed to obtain the dry mass of the soil core (Md).

Step 7

These steps are followed for each of the other tubes and the following calculations are Performed:

$$w = \frac{M_w - M_d}{M_d} \quad 3\text{-}11$$

$$V = \pi\left(\mathrm{ID}/2\right)^2 \cdot \mathrm{h} \quad 3\text{-}12$$

$$P = M_d / V \quad 3\text{-}13$$

$$\theta_v = W \cdot p \quad 3\text{-}14$$

Where:

Mw = Wet Mass (g)	W = gravimetric water content,
Md = Dry Mass (g)	V = Volume of the core sampler,
ID = internal diameter of the ring (cm)	ρ = bulk density of each sample
h = height of ring (cm)	$\boldsymbol{\theta}_v$ = volumetric water content of each sample.

RESULTS

A calibration equation is a mathematical relationship between Diviner 2000 scaled frequency readings and real volumetric soil water content. It is determined by gravimetric sampling, this mathematical relationship is described by an equation which has 'A', 'B', and 'C' values.

For the calibration, four PVC access pipes (0.5 m length, 56.5-mm interior diameter) were inserted into the soil 2 m apart, performing no physical nor chemical changes, because the existing soil condition should be evaluated. Three sets of moisture content were created dry and moist with two replicates per set, sets were separated by 6m.

In each sampling tube, three readings were made from 0.1m down to 0.6m depth. Immediately after obtaining the readings with the probe, a ditch was dug to the maximum depth of measurement (0.5 m) and 0.3 m away from the pipes so that the soil around them would not be disturbed. In this ditch, two samples were taken using metal cylinders (height, diameter) by each replicate pipe and at each measuring depth, while ensuring that the sample was taken within the radius of influence of the sensor (3 cm away from the access tube). The water content of soil samples was determined gravimetrically and the soil's apparent density by the cylinder.

$$SF = (FA - FS) / (FA - FW) \qquad \text{Eq 3-15}$$

- FA = raw count in the PVC access tube while suspended in air (Air Count) 17947;
- FW = raw count in the PVC access tube in a water bath or normalization container (Water Count) 147368;
- FS = raw count in the PVC access tube in the soil at each particular depth level (Field Count

Table 3-3 Calculation of Volumetric Water Content and Scaled frequencies

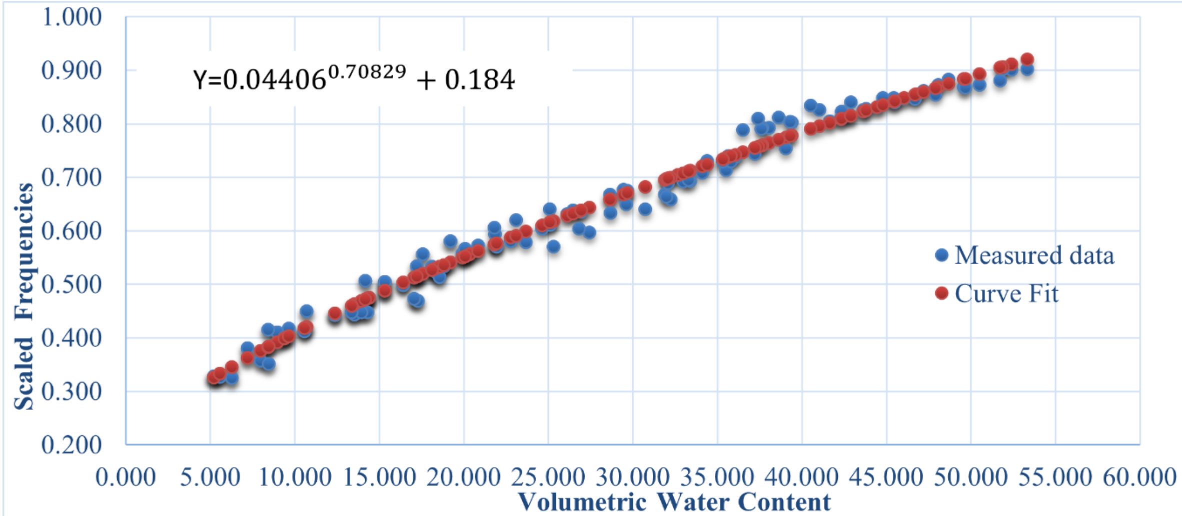


Figure 3-8 Calibration Equation for Volumetric Water Content by Using Diviner 2000

From the calibration equation derived, assign A, B, and C coefficients to enter into the Diviner 2000 display unit. These must match the equation format $SF = Ax^B + C$. If the derived calibration equation is linear, the B coefficient will be 1. For this research by conducting a study, the values of A, B, and C are determined by using Excel solver. Based on the analysis, the values are 0.04406,0.70829 and 0.184.

3.11 Measurement Technique

Volumetric soil moisture content is measured by responses to changes in the dielectric constant of the soil. The capacitance of soil increases considerably with an increase in the number of soil water molecules, which are free to relax as their electric dipoles respond to the capacitor sensors field reversal. This measurement is proportional to capacitance and is also called specific polarization or electric dipole moment per unit volume. With the advent of microelectronics, it is possible to measure the responses of capacitance sensors within a soil profile and correlate it very highly to the dynamics of volumetric soil moisture content.

At a single depth level, the probe records moisture from a soil volume outside the access tube, which has a sphere of influence of 10cm vertical height and 5-10cm radial distance from the outer wall of the access tube. Volumetric water units if the probe reads one millimeter that means there is one millimeter of water content in a 100 mm thick soil slice on a volume basis. This amounts to a volumetric soil moisture content of 1%.

Figure 3-9 Measurement of volumetric water content using Diviner 2000

3.12 Variations in Matric Suction with Moisture and Time Obtained from Tensiometers and Diviner 2000

Each day for four months long term matric suction data is measured for two different seasons rainy and dry seasons on expansive soil with high volume changing property by using digital tensiometer and diviner 2000 for measuring matric suction of a soil and volumetric water content of a soil. For a varying depth of a soil by using three different length probes by using ASTMD6836 for basic procedures.

A field study was conducted to assess the volumetric water content and long-term matric suction response in an expansive clay soil under varying seasonal conditions. Digital tensiometer and advanced capacitance sensors were used to get high resolution suction and volumetric water content profiles. Testing spanned for four months containing both rainy and dry seasons in order to quantify hydrological changes related to expansive soil's shrink/swell behavior.

Measurements were taken daily at multiple depths of 1.4m, 1.6m and 1.9m from original ground level using sensor probes in order to obtain matric suction distribution with depth and season aligned with standard test method. The variation in soil suction and soil moisture throughout wetting and drying season for expansive soil is also tracked.

CHAPTER 4 RESULTS AND DISCUSSION

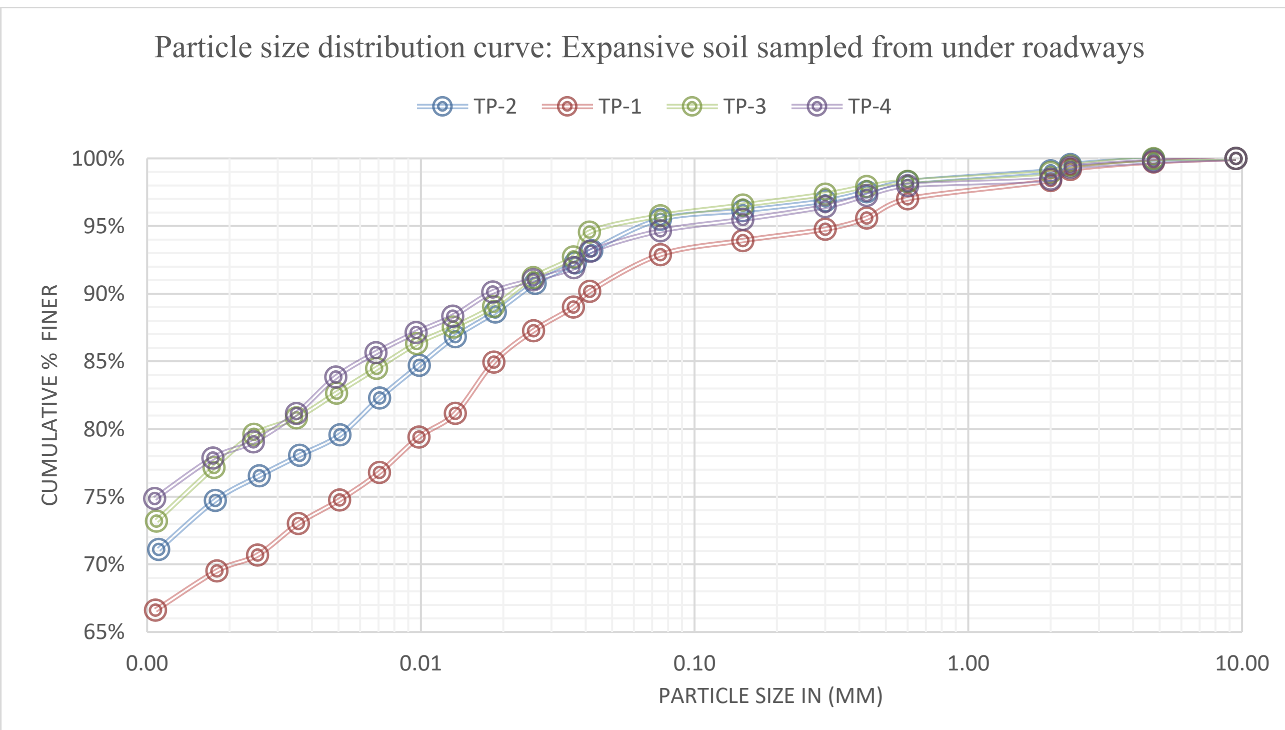
4.1 Introduction

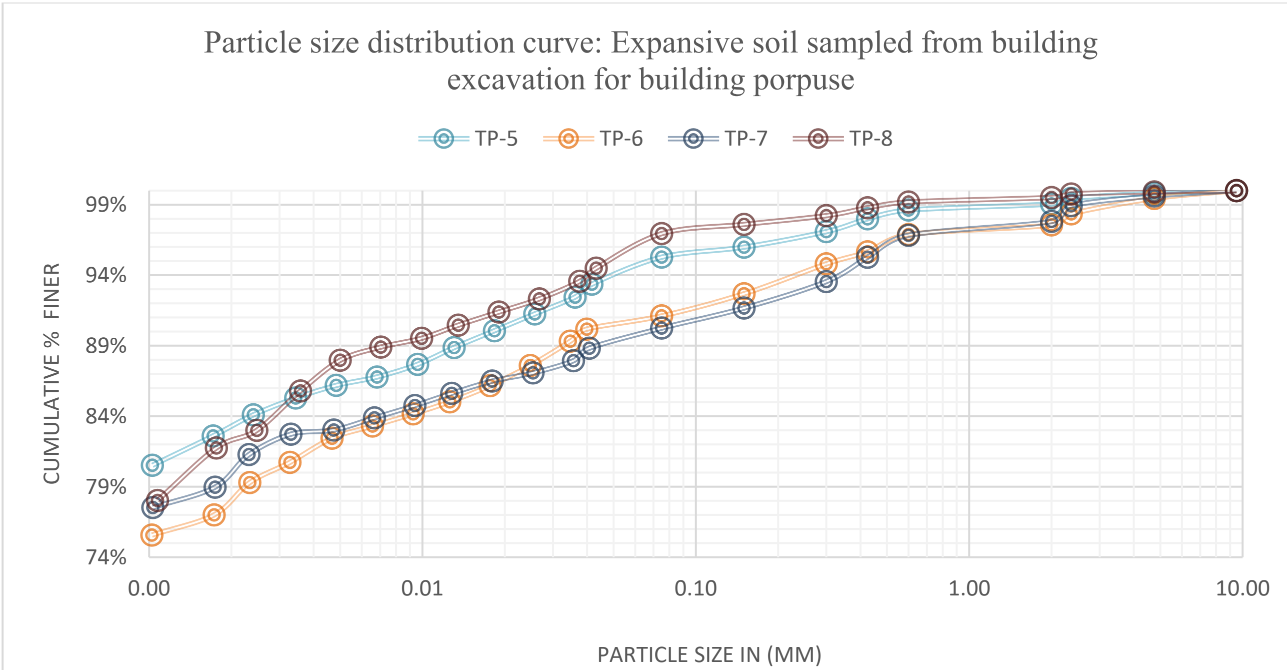
A comprehensive suite of field and laboratory tests on disturbed and undisturbed soil samples was performed to characterize properties thoroughly. Laboratory tests include basic index, classification, FS test, LS test, SWCC tests, and SC tests while field tests include matric suction and volumetric water content measurements. All tests were performed following the ASTM standard. For each laboratory and field test conducted, a brief description is included and its importance is explained. The findings are meticulously discussed, and a comparison with previous research findings is drawn to establish a broader context for the current study.

4.2 Laboratory Test Results

4.2.1 Soil Index and Classification Test Results

Figure 4-1 shows the particle size distribution curves of the twelve soil samples. Sieve analysis and hydrometer test were conducted to determine the particle size distribution of the twelve soil samples. The percentage of sand, silt, and clay in each soil sample is presented in Table 4-1.





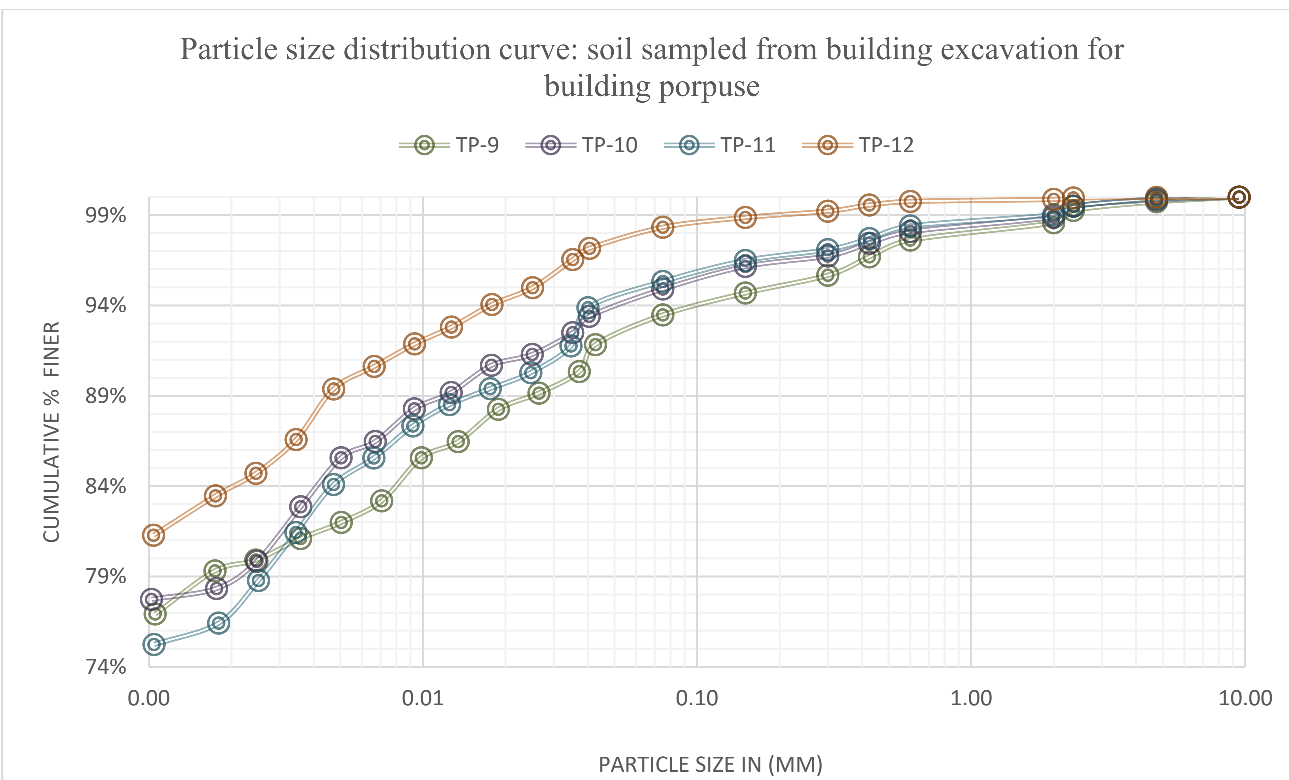


Figure 4-1 particle size determination curve for twelve expansive soils in the study area

Table 4-1 Results of Natural Moisture Content, Saturated Moisture Content, Atterberg Limits, Specific Gravity, Free Swell and Linear Shrinkage

Sample Notation	NMC (%)	SMC (%)	Gs	FS (%)	Atterberg limit Test			LS (%)	According to Chen 1988
					LL (%)	PL (%)	PI (%)		
TP-1	31.4	51.3	2.77	155%	89.46%	30.55%	58.91%	15.7%	Very high swelling potential.
TP-2	32.4	49.1	2.71	160%	89.63%	33.61%	56.02%	14.3%	Very high swelling potential.
TP-3	27.4	48.8	2.69	170%	87.76%	39.70%	48.06%	18.6%	Very high swelling potential.
TP-4	33.4	49.1	2.72	160%	81.43%	36.79%	44.64%	22.9%	Very high swelling potential.
TP-5	32.7	43.1	2.74	135%	88.65%	38.24%	50.41%	15.7%	Very high swelling potential.
TP-6	27.7	48.9	2.75	125%	88.55%	36.77%	51.79%	25.0%	Very high swelling potential.
TP-7	34.2	42.7	2.70	115%	80.56%	37.63%	42.94%	17.9%	Very high swelling potential.
TP-8	36.8	41.7	2.66	112%	87.76%	47.17%	40.59%	18.6%	Very high swelling potential.
TP-9	36.7	44.0	2.68	130%	89.22%	39.11%	50.12%	14.3%	Very high swelling potential.
TP-10	35.0	49.6	2.70	105%	85.06%	38.19%	46.87%	19.3%	Very high swelling potential.
TP-11	33.3	45.3	2.73	115%	86.85%	39.43%	47.41%	21.4%	Very high swelling potential.
TP-12	33.8	47.8	2.71	110%	84.12%	34.99%	49.13%	16.4%	Very high swelling potential.

4.3 Soil Classification

Twelve soil samples are categorized according to USCS and results are shown in table 4.1.

The plotted data point determined falls within the "CH" high plasticity clay zone, indicating the soil is potentially expansive.

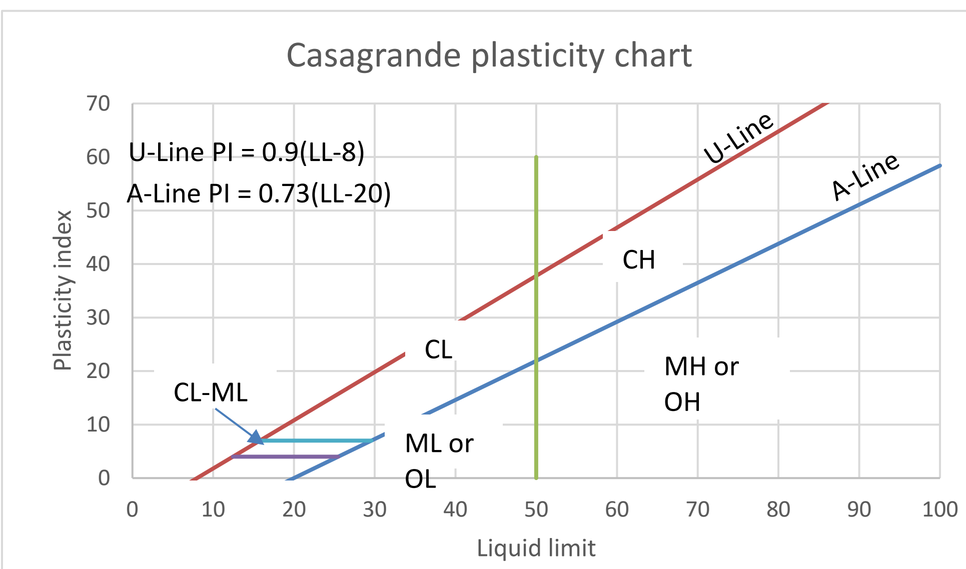


Figure 4-2 Casagrande's Plasticity Chart

Table 4-2 Soil Classification

Test Pit No.	P_{200} (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Activity of Soils	USCS
1	92.9	0.0	7.11%	18%	75.19%	58.91%	CH
2	95.5	0.0	4.50%	17%	78.79%	56.02%	CH
3	95.8	0.0	4.24%	14%	81.47%	48.06%	CH
4	94.7	0.0	5.35%	12%	82.73%	44.64%	CH
5	95.3	0.0	4.72%	7%	87.93%	46.76%	CH
6	91.1	0.0	8.89%	5%	85.65%	42.94%	CH
7	90.3	0.0	9.75%	2%	87.81%	51.79%	CH
8	97.0	0.0	3.05%	12%	84.75%	40.59%	MH/OH
9	93.5	0.0	6.52%	8%	85.07%	49.13%	CH
10	94.9	0.0	5.09%	12%	83.06%	45.55%	CH
11	95.3	0.0	4.67%	13%	82.46%	44.36%	CH
12	98.3	0.0	1.67%	13%	85.33%	46.82%	CH

4.4 SWCC and Shrinkage Curve Determination

The two unsaturated soil properties determined in this research are: (i) Gravimetric water content versus soil suction, referred to as the soil-water characteristic curve (w-SWCC) and (ii) void ratio versus water content, referred to as the shrinkage curve (SC). In this research, SWCCs were determined for suction ranges from 0-1300 kPa using pressure plate test apparatus and the SC was determined using cylindrical ring method.

The volume-mass properties of the w-SWCC and SC test specimens were independently measured at the beginning of each of the tests. The results of the two tests were then combined for the calculation of other volume-mass soil-water characteristic curves, such as θ-SWCC, S-SWCC and e-CC. Each of the volume-mass SWCC relationships plays an independent role in the estimation of USPFs.

4.4.1 Pressure Plate Test Results and Gravimetric Soil Water Characteristic Curves

In this study, the SWCCs are plotted with matric suction on the x-axis (log-scale) against gravimetric water content, or degree of saturation, or void ratio on the y-axis. Two specimens were tested and the average was taken for each sample. The suctions can readily be measured using the soil specimen is also placed into a pressure plate the data generally shows a smooth curve throughout the entire suction range (33, 200, 400, 800, 1000, 1300kPa). The fitting parameters are obtained using the EXCEL Solver function. The data points represent measured experimental data points. The solid lines in Figure 4-3 represent the best-fit curves using Fredlund and Xing's (1994) equation.

Table 4-3 Summary of Measured and Predicted Gravimetric Water Content for w-SWCC of soil samples

The SWCCs are plotted with matric suction on the x-axis (log scale) against gravimetric water content on the y-axis for undisturbed expansive soil samples. Results shown in Figure 4-3 and Table 4-3 discussed as follows:

- SWCC shows the relationship between soil water content (w) and soil water suction (ψ). As suction increases, water content decreases as water drained from the soil.

- The soil AEV, which is the matric suction at which air begins to enter the largest pores in the soil, is connected to the air-entry parameter.

  - AEVs of expansive soil samples sampled from under roadways are as follows 270,300,150 and 120kPa.
  - AEVs of expansive soil samples sampled from excavations for building are as follows 200,160,110,160, 120,170,120, and 80kPa.

- The AEV of under-roadway soil samples from Kality and Lafto Mebrat increased by 30 kPa for 1m to 1.5m increase in depth. These soil samples were obtained from a single excavated pit in the Kality and Lafto Mebrat areas, at depths 1.5/2 and 3 meters below the OGL.

- Soil samples obtained from a single excavated pit (TP 10 and TP 11) the shallower depth from OGL showed a lesser AEV of 120kPa from a 6m depth and 170kpa for a soil sampled from 9m depth, despite having relatively similar particle size distribution and plasticity index with an increasing depth AEV of a soil is found increasing. This is due to an increase over burden pressure which decreases pore spaces and pore sizes which increases AEV.

- A soil with a higher PI value shows the highest AEV while soils with lower PI shows a lower AEV, this is due to soils with higher PI have smaller pore spaces between particles and higher cohesion which makes it harder for air to enter the pores (have a higher resistance to AEV) and therefore have higher AEVs. A soil sample with 58.91% PI results AEV of 270kPa and with 42.94% results 110kPa. And TP-3 and TP-4 with different plasticity index 48.06% and 44.64% test pits sampled from under roadway and the same area results with 150 and 120kPa.

- afx – Curve fitting parameter which is related to the AEV of the soil. The afx parameter shifts the SWCC curve horizontally and defines the AEV. The afx values are higher for soil samples with higher AEV like soils under road way and soils sampled from a relative higher depth reaching as high as 1007.7 for a soil with AEV of 280kPa and as low as 158.6 for 80kPa AEV. afx is usually greater than or equal to the AEV.

- nfx - This parameter controls the slope of the curve around the inflection point where the rate of water loss vs suction is greatest. Higher nfx values will make this middle section of the curve less steep, indicating a more gradual desaturation span over a wider range of corresponding suctions. Lower nfx makes the inflection slope more vertical, showing rapid drainage across a narrow suction range.

- mfx - The mfx parameter is related to modeling the residual saturation level of the soil. Higher mfx values will maintain a higher degree of saturation out towards the end of the curve. Lower mfx approaches zero saturation at lower suctions.

- The residual water content, which is the water content above which a considerable increase in suction is accompanied by a slight change in water content, corresponds to the residual suction (Fredlund et al., 2011). According to Table 4-3, the residual suctions for under roadways are way higher than other soil samples reaching up to 2898.8kPa this is due to the higher density rearrangement of soil particles and pore space from heavy compaction alters water retention mechanics to elevate residual suction parameters.

- And residual soil suction is higher for soils sampled at a greater depth as indicated on Table 4-3 a soil sampled from bole at 6m depth and 9m depth a soil from a 9m depth results a higher residual suction valued 1890.9kPa and 2845.07kPa respectively.

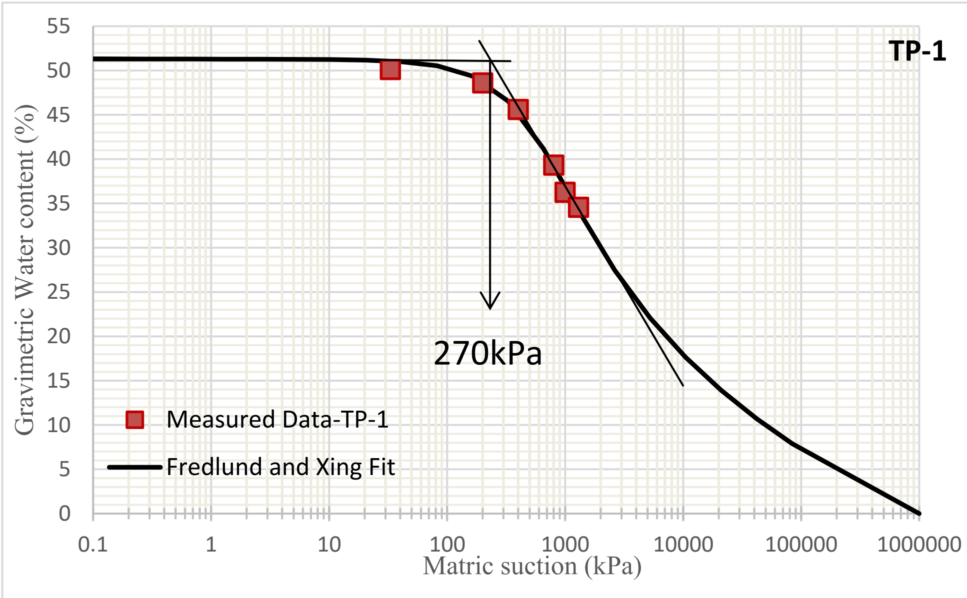


Figure 4-3 w-SWCC of Expansive Soil Samples Test Pit one

4.5 Shrinkage Curve (SC) Determination

The SC test provides data on the relationship between volume change (in terms of changes in the void ratio) and gravimetric water content as the soil suction is increased under evaporative conditions, from near-zero conditions to completely dry conditions (Leong and Wijaya ,2015). To develop this curve, successive measurements of dimension for the specimen was done using digital caliper up on drying and the gravimetric water content was measured with reference to the oven dried specimen. The SC is plotted as void ratio in the y-axis and gravimetric water content (%) in x-axis. According to D. Fredlund and M. Fredlund (2020), the true AEV is determined from the S-SWCC, which is constructed by combination of w-SWCC and SC. In this study, the AEV from w-SWCC and S-SWCC are determined and results are compared.

In this study the SC for undisturbed soil sample is developed by using four specimens to one soil sample and average is used.

Figure 4-4 Shrinkage curve (SC) determination using Digital Caliper

The results are presented in Figure 4-5 and **Error! Reference source not found.**. The data points in **Error! Reference source not found.** represent laboratory-measured values. The solid and dashed lines in Figure 4-5 represent the best-fit lines fitted using Equation 2-2, and the fitting parameters (ash, bsh, and csh) are obtained using the EXCEL Solver function.

- The water content at which the soil transitions from a semi-solid to a solid condition is known as the shrinkage limit (SL). With additional drying of the soil sample, the volume of the soil mass stops changing at this moisture content. The SL for the expansive soil sample is created manually by drawing two tangent lines, as seen in Figure 4-5. Drawing the first straight tangent line that touches the curve at or near the initial saturation point and the second straight line that touches the curve at or near the fully dry point. By extending both tangent lines until they intersect, the point of intersection represents the SL. The SL value of undisturbed soil is 18,19,16.5,17.5,16,18,18,16,18,16,14 and 15.

- For an undisturbed expansive soil sample allowed to fully dry out, its measured minimal void ratio was found to be 0.49 and a maximum of 0.6. The fitting parameter ash in the Fredlund and Xing model directly corresponds to the minimum void ratio that a soil can attain upon complete drying.

- Equation 2-2 is used to get the fitting parameter bsh, which depends on (ash, So, and Gs), and is related to the slope of the drying curve. The csh values ranges in between 0.172 - 0.214 defines the magnitude of the maximum volume change that can occur when the soil desaturates from an initially saturated state to completely dry conditions.

- csh represents the water content at which shrinkage ceases. csh is used to define the lower bound of the soil's volumetric water content (θ) as it dries. The csh values ranges in between 1.87 - 2.63 and it tells mainly the lower bound of soils volumetric water content (θ) as it dries. It sets the point at which the curve flattens out and no further shrinkage occurs.

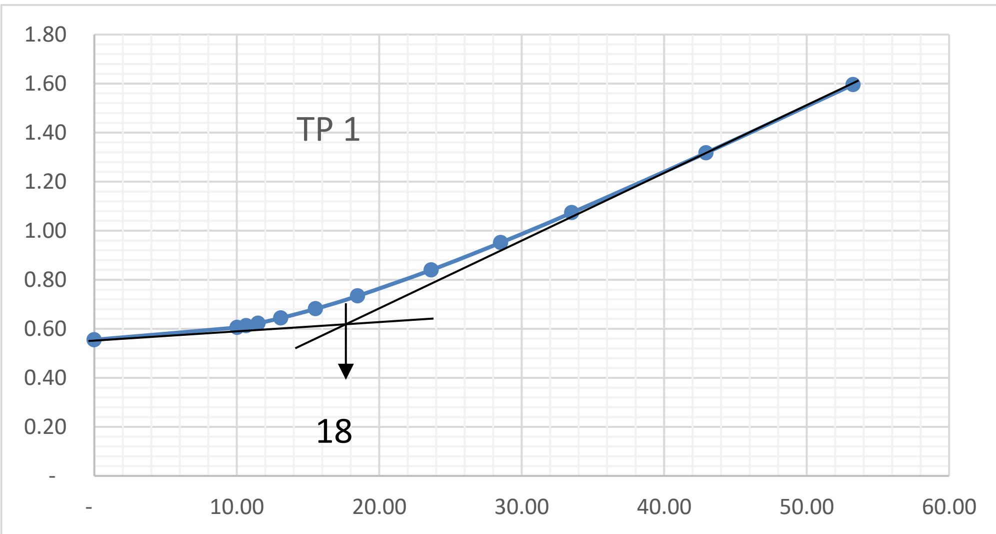


Figure 4-5 Shrinkage Curves of Soil Samples

4.5.1 Combined Test Results of SC and w-SWCC

In this study, the SC and w-SWCC tests are determined independently and then the two test results are merged to determine S-SWCC in order to account the volume change as the soil suction increases. It was found that the errors associated with the SWCC of expansive soils that are not volume-corrected are clear. AEV is wrong if volume change corrections are not made, and so is the slope of the SWCC in the transition zone. It was also found that in order to find the true air-entry value and slope of the SWCC, the volume-corrected SWCC in terms of degree of saturation should be used.

Figure 4-6 Measured and predicted degree of saturations for s-SWCC determination

Suction (kPa)	Calculated degree of saturation	Predicted degree of saturation	Calculated degree of saturation	Predicted degree of saturation	Calculated degree of saturation	Predicted degree of saturation	Calculated degree of saturation	Predicted degree of saturation
	TP -1		TP -2		TP -3		TP -4	
33	92.375	92.796	86.675	87.206	85.839	86.436	85.694	86.081
200	92.086	91.707	86.134	85.909	84.969	84.996	84.207	83.802
400	91.421	90.746	84.991	84.502	83.646	83.546	82.016	81.880
800	89.530	89.086	82.612	82.061	81.382	81.075	79.361	78.850
1000	88.257	88.332	80.502	80.986	80.317	79.995	76.945	77.582
1300	87.416	87.272	79.262	79.519	79.184	78.524	75.879	75.896
So (%)	96.68		95.16		92.81		93.95	
a	1300.00		1316.932		1316.897		2855.856	
n	0.07		0.000		0.019		0.068	
m	0.18		0.309		0.263		0.388	
Ψr	3800.00		1640.449		1640.437		1267.616	
R2	0.9954		0.995		0.996		0.998	
	TP -5		TP -6		TP -7		TP -8	
33	89.178	89.975	92.432	92.935	87.270	87.712	91.466	92.046
200	88.352	88.008	91.304	91.256	85.345	84.875	90.088	89.856
400	86.773	86.000	90.064	89.491	82.123	82.191	88.477	87.638
800	83.127	82.729	87.111	86.517	78.790	78.156	84.455	84.082
1000	80.776	81.356	84.614	85.238	76.280	76.558	81.864	82.609
1300	79.196	79.534	83.285	83.515	74.058	74.504	80.536	80.669
So (%)	93.95		96.60		95.56		98.46	
a	2396.151		2396.151		2406.248		1473.723	
n	0.006		0.005		0.002		0.000	
m	0.145		0.130		0.290		0.228	
Ψr	1016.170		1299.313		591.157		890.427	
R2	0.998		0.997		0.999		0.998	
	TP -9		TP -10		TP -11		TP -12	
33	86.194	86.752	86.669	86.931	88.065	88.1012	88.3675	88.3739
200	84.884	84.581	85.773	85.766	87.012	86.8587	86.3934	86.2180
400	82.976	82.402	84.513	84.502	85.592	85.6797	84.3961	84.4461

800	79.362	78.943	83.000	82.279	83.668	83.6447	81.2873	81.4949
1000	77.301	77.521	81.168	81.289	82.486	82.7354	79.8329	80.2366
1300	75.120	75.656	79.482	79.924	81.672	81.4748	79.0468	78.5506
So (%)	90.56		90.22		93.24		94.759	
a	1451.173		1121.147		1121.146		1121.678	
n	0.000		0.006		0.042		0.003	
m	0.137		0.128		0.224		0.262	
Ψr	831.810		1920.505		2438.138		1187.493	
R2	0.999		0.998		1.000		0.999	

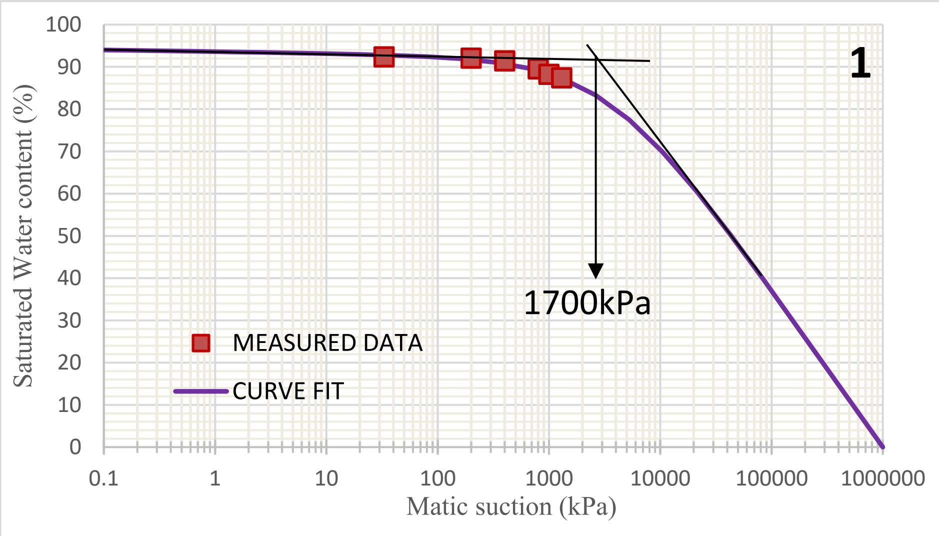


Figure 4-7 s-SWCC of soil samples

The following are discussions of the Combined SC and w-SWCC results of natural soil samples shown on Figure 4-7 and **Error! Reference source not found.**:

- The AEV is significantly higher for the S-SWCC compared to the w-SWCC for all soil samples. As shown in **Error! Reference source not found.**, the fitting parameter "a" which is indicative of the AEV, has much greater numerical values for the S-SWCC data sets. For the TP-1 (under roadway soil), "a" equals 1396.15 kPa on the S-SWCC versus 457kPa on the w-SWCC. Similarly, for the other soil samples as shown on the table there is a big numerical difference. This order-of-magnitude difference in the fitting parameter "a" leads to a pronounced rightward shift and higher air entry pressures shown on the S-SWCC plots when compared against the corresponding w-SWCC data.

- TP-10 and TP-11 were sampled from one location with different depths. Higher depth is found to have a higher AEV based on s-SWCC. TP-11 soil sample from 9m depth results 2000kPa and TP-10 with 1900kPa from 6m depth based on s-SWCC.

- Expansive soil samples obtained from a depth of 3m at test pit locations TP-6 and TP-7 exhibited PI values of 51.79% and 42.94%, respectively. These PI values corresponded to AEV of 1100 kPa for TP-

6 and 600 kPa for TP-7. The results indicate that a higher PI of the soil sample correlates with a higher AEV.

- As shown on the table below soil samples extracted from a similar depth with a varying plasticity index values exhibited, increment in AEV with increasing PI values. Specifically, soil samples from TP-5 and TP-7 collected at 3m depth, results a difference of 400kPa with a difference of 7.5% PI value.

TP	5	7
Depth(m)	3	3
PI (%)	50.40	42.94
AEV (kPa)	1000	600

- The “n” values obtained from the w-SWCC function are much steeper, reaching up to 1.67, compared to the n values from the S-SWCC function, which range from 0.001 to 0.076 as shown in the **Error! Reference source not found.**. The S-SWCC data shows that these soil samples desaturate slowly compared to what the w-SWCC fits predicted.

- The “m” values are found to be lower for S-SWCC compared with w-SWCC. Lower values of "m" indicate moderate SWCC slopes. S-SWCC curves exhibit more gradual, moderate slopes compared to the steeper w-SWCC curve slopes for these soil samples. This suggests the soils retain saturation over a larger suction range before undergoing rapid desaturation, as depicted by the S-SWCC behavior.

4.6 Void Ratio Versus Soil Suction (e-CC)

The relationship of void ratio versus soil suction for Addis Ababa expansive soil is obtained by combining the w-SWCC and the shrinkage curve is shown in Figure 4-8. The void ratio as a function of water content is calculated by substituting the gravimetric water content obtained from w-SWCC into Equation 2-4.

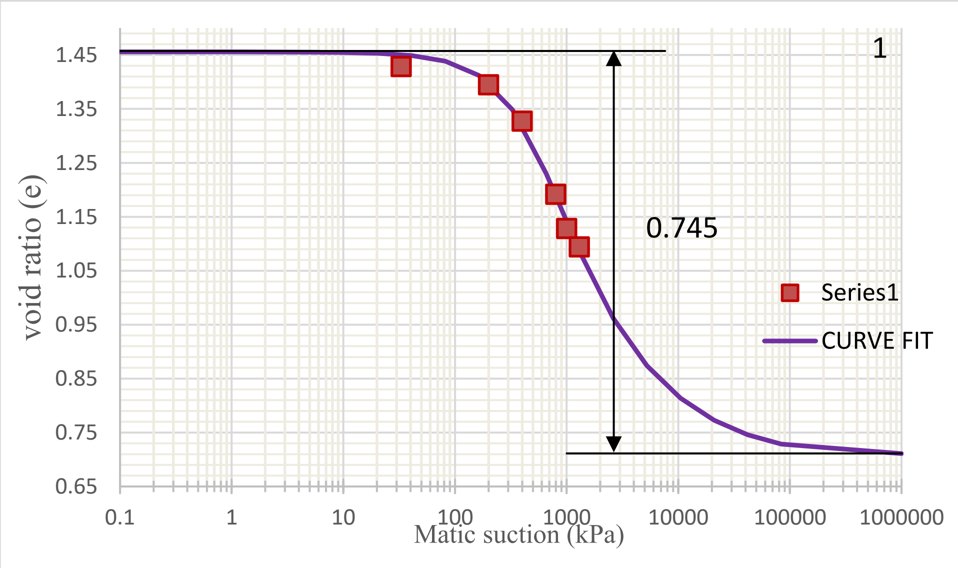


Figure 4-8 e-CC of Test pit 1

The following are discussions of the e-CC results shown in Figure 4-8 and **Error! Reference source not found.**:

- By looking at the relationship between void ratio and soil suction for twelve different soil samples as shown in Figure 5-2. Up to a suction value of 40-70 kPa, there is minimal change in volume for soil sampled from building excavations and it goes up to 130-200 kPa for soil sampled from under roadways. This suggests that the material being studied can resist deformation or compression up to this suction level. Beyond 40-70 kPa and/or 130-200kPa, a significant increase in volume change is observed. This implies that the material's structure or properties are altered beyond these suction values, leading to noticeable deformation or expansion.

- As quantified through e-CC, volume change ranges from 74.15%-79.8% for soil samples from under the roadway and 83.1% - 98.1% for soil samples sampled from excavations for building construction.

- Sample depth impacts the expansive potential and volume change behavior. An expansive soil sample taken from a 9m depth showed a 73.7% maximum volume change and a shallower near-surface expansive soil sample from a 6m depth showed 81.28% maximum volume change. There is a 7.6% difference in maximum volume change between the 9m deep sample (TP-11) and the 6m shallow sample (TP-10). This is due to expansive soils at greater depths that tend to be denser and more confined.

Depth from OGL	6m	9m
Volume Change	81.28%	73.68%

- Soils with relatively very similar plasticity index values exhibit markedly different maximum volume change percentages. TP-5 and TP-12, two soils with plasticity indexes of 46.76% and 46.82% (a difference of just 0.15%) showed 83.88% and 90.6% maximum volume change, respectively. Despite having nearly identical PI, the maximum volume change differed by 7%. This indicates that the PI alone is not a reliable predictor of volume change behavior, and highlights the need for additional testing and characterization to accurately model the volume change potential of soils intended for construction use.

- Compared to other samples, soil samples taken from under roadways (TP-1, TP-2, TP-3, and TP-4) exhibited a significantly lower relative volume change. Specific values were 74.5%, 79.5%, 76.8%, and 79.77%, respectively. This indicates that the soils from building excavations experienced more swelling and shrinkage in response to changes in soil suction compared to the roadway soil.

- As shown from the graph once residual suction is surpassed, volumetric change in the soil is reduced severely. This is due to the immobilization of the remaining water films adhered around clay particles in fine pores and larger soil pores have drained before reaching residual suction value.

4.7 Interpretations of Measured Insitu Matric Suctions and Volumetric Water Content

This section provides interpretation and discussions of in situ matric suction variation with depth and with respect to climatic conditions and/or season.

4.7.1 Seasonal Variation of Soil Matric Suction

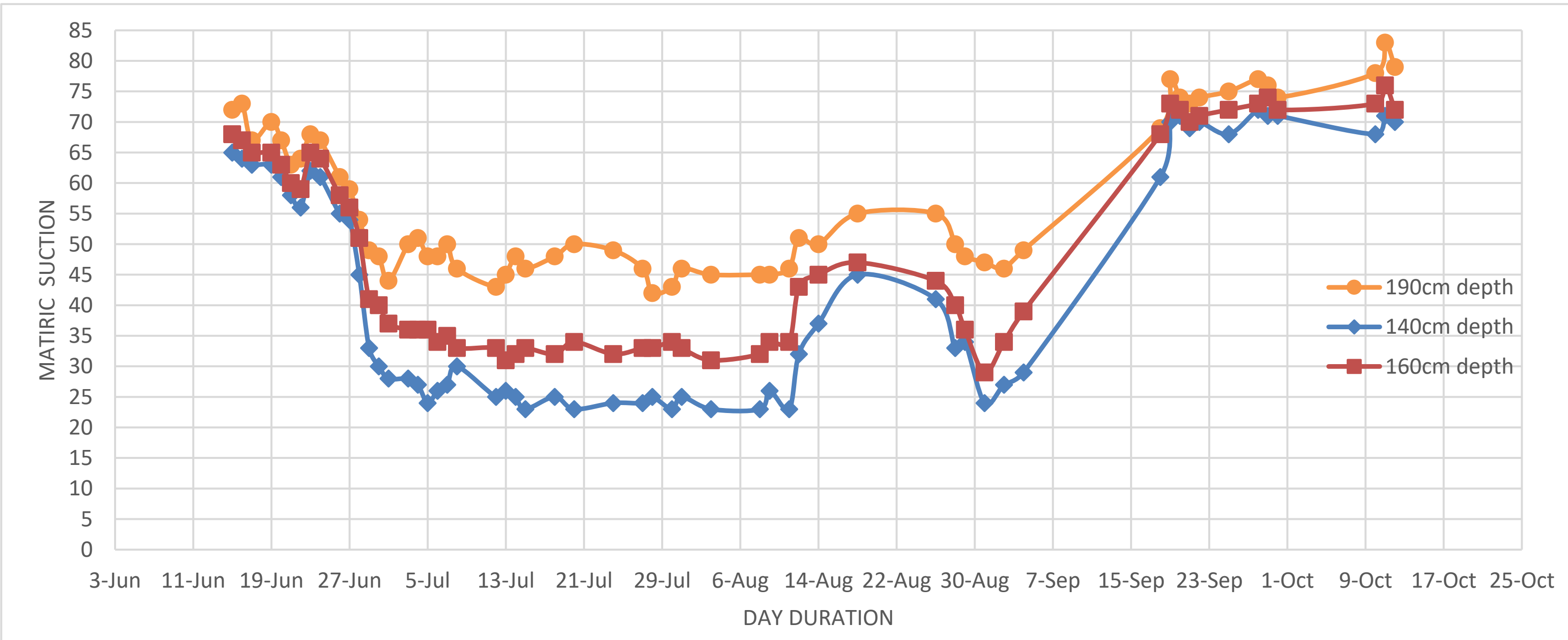


Figure 4-9 Variation of Matric Suction with Season and Depth for Addis Ababa Expansive Soil

As shown in Figure 4-9, the vertical axis shows the matric suction of a soil using digital tensiometer and the horizontal axis shows the day length from June 2023 to the end of October. During this work, heavy rains occurred in large parts of the country, including Addis Ababa from midway of June to starting of September. With a heavy rainfall in July while October was dry with no rainfall at all.

Variation of matric suction with time (climatic conditions)

Key factors influencing matric suction over time include precipitation, temperature, vegetation, and soil properties. Precipitation added moisture from rain will reduce matric suction while periods without precipitation allow suction to increase as soil moisture depletes by evapotranspiration. Higher temperature promotes evapotranspiration drying out soils which increases matric suction and lower temperature slows the rate of drying. Vegetation – transpiration from plant roots contributes to moisture loss from soils over time which allows matric suction to increase. Soil properties – finer textured soils like clays retain more water versus sandy soils, which influences moisture retention.

- The overall pattern of matric suction variation with season is similar for the given location and soil type at different depths.

- The seasonal matric suction measurements at the study site showed an overall consistent temporal pattern of fluctuation across the different monitoring depths in the soil profile. Over the annual cycle spanning wet and dry periods, increases and decreases in suction correlated with drying and wetting trends for the four months this work is done.

- Matric suction in the soil undergoes seasonal fluctuations, with minimum values occurring after rainfall in July and maximum values found during the dry month of October. There is a difference of 40-50 kPa between the minimum and maximum matric suction values at respective soil depths. This indicates that soil moisture levels increase in response to rainfall and infiltration in July, decreasing to low levels as water evaporates during the dry conditions in October. The magnitude of the seasonal matric suction difference, which ranges from 40 to 50 kPa, suggests that soil moisture varies considerably, likely impacting soil properties and behaviors at different times of the year.

Depth	Lower Matric Suction	Higher Matric Suction
140cm	23kPa	71kPa
160cm	29kPa	76kPa
190cm	42kPa	83kPa

- During the rainy month in July matric suction values of 20-30 kPa for 140cm, 30-40 kPa for 160cm, and 40-50 kPa for a depth of 190cm are found.

4.7.2 Field-measured Soil matric suction and volumetric water content

In-situ monitoring of soil moisture was conducted by simultaneously measuring matric suction and volumetric water content at varying depths within the soil profile. Digital tensiometers and moisture probes (Diviner 2000) were installed at the field site to acquire continuous matric suction and volumetric water content data.

Matric suction values ranging between 23 kPa and 83 kPa were recorded across the unsaturated zone with sensors embedded at depths of 140 cm, 160 cm, and 190 cm from the surface. Additionally, volumetric moisture content was logged as a percentage at levels of 10% up to 50% using Diviner 2000.

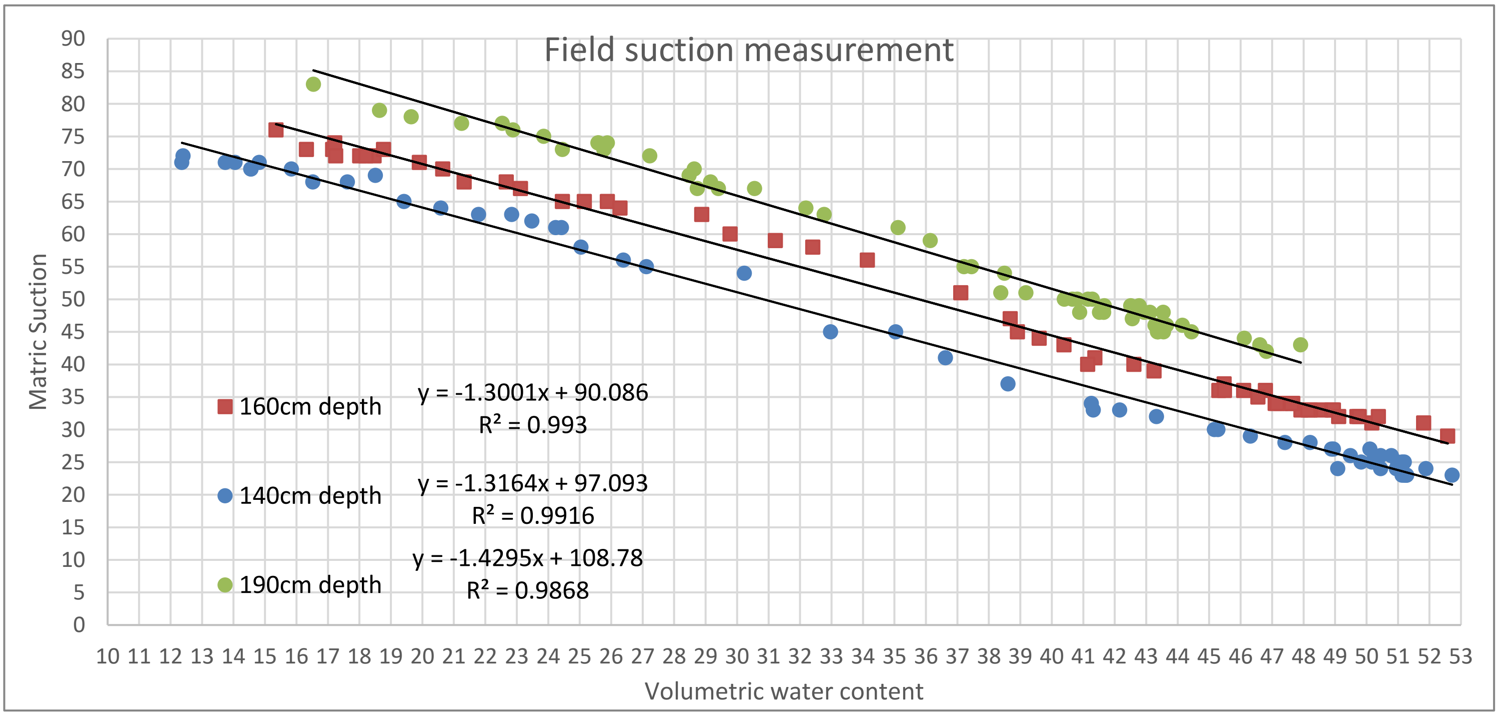


Figure 4-10 In-situ measurements of suction and volumetric water content in the field (Addis Ababa) and their relation to depth

This is a result shown by a graph with the volumetric water content horizontally and soil matric suction vertically.

- Matric suction was measured at various depths using tensiometers installed in the soil profile. Additionally, volumetric water content was measured at corresponding depths using a Diviner 2000 capacitance probe. The matric suction showed a general trend of increasing with depth, at the same time. Specifically looking at one-point for a 47.91 volumetric water content, matric suction ranged from 28kPa at a depth of 140 cm to 34 kPa at 160cm and 43kPa at 190 cm. These matric suction variations with depth align with the volumetric moisture content measurements from the Diviner 2000, which showed volumetric water contents decreasing from 46.59 at 190cm depth to 39.6 at 160cm and 35.04 at 140cm depth for a specific matric suction of 43kPa.The increment in matric suction values for the same volumetric water content at greater depths reflects the generally confined soil conditions with increasing depth.

- This shows that for the same moisture content, the matric suction was higher at greater depths, while at the same matric suction, the moisture content decreased with depth. This trend can be attributed to overburden pressure exerted by the weight of the soil leading to greater suction stresses at depths despite similar moisture levels.

- With the depth of the soil the sensors show that there is a difference in matric suction of the soil as big as 20kPa in August and where the rainfall is slightly higher and as slow as 3-5kPa in June the lower rainfall time. For example, on October 11-2023, matric suction values were found to be 68kPa,73kPa, and 78kPa for 140cm,160cm, and 190cm depth from the ground. Which shows a 5kPa difference, and on August 8 23kPa,32kPa, and 45kPa for 140cm,160cm, and 190cm depth from the ground with a 22kPa difference. This indicates variation of matric suction with depth is lower in a drier season and higher with depth for a wet season with a generally increasing matric suction with depth.

4.8 Volumetric Water Content Soil Water Characteristic Curve (ɵ-SWCC)

The relationship of volumetric water content versus soil suction for Addis Ababa expansive soil is obtained by combining the w-SWCC and Equation 4-5.

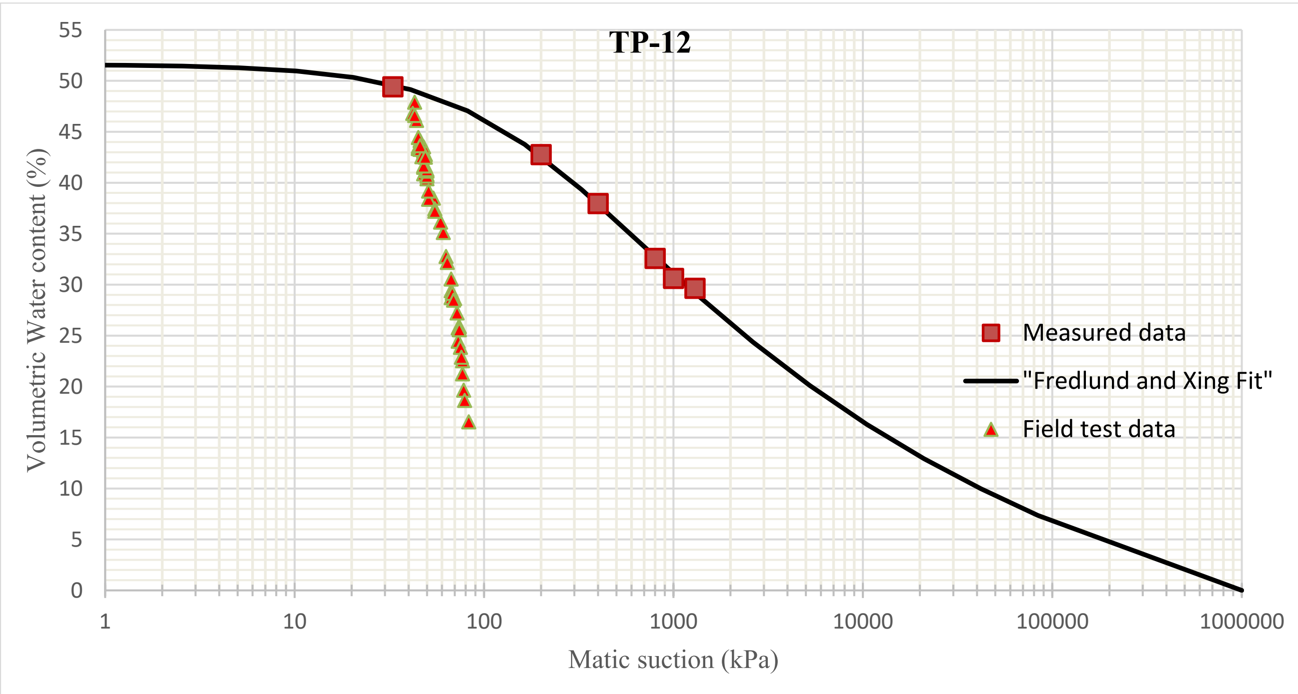


Figure 4-11 Comparison of field measurements of soil suction with laboratory measurement

- As shown in Figure 4-11 at a lower matric suction value for the larger volumetric water content the matric suctions obtained from the sensors show similar values to those estimated matric suction from the SWCC obtained in the laboratory. This is due to soil sampling season since the soil was sampled in a wet season, the natural volumetric moisture content of the soil sample was 44.76% for the matric suction values in this area laboratory data fits with the field test data as shown in Table 4-4 and for the lower volumetric water content region, there is a difference in the matric suction values determined in the laboratory and the field as the soil dries in comparison.

Table 4-4 Comparison of field soil suction and estimated matric suctions from SWCC at a higher VWC.

	Depth from the surface	Volumetric water content (%)	Matric suction (kPa)
Field Test From sensors	1.9m	46.82	42kPa
Laboratory Test From SWCC	2m	45.45	42kPa
Field Test From sensors	1.9m	47.91	43kPa
Laboratory Test From SWCC	2m	48	43kPa
Field Test From sensors	1.9m	46.12	44kPa
Laboratory Test From SWCC	2m	45.35	44kPa

Equation for changing gravimetric water content to volumetric water content.

$$\theta_v = \frac{wp_b}{p_w} \quad 4\text{-}1$$

- θv - Volumetric water content.
- w - Gravimetric water content.
- ρb - Bulk density of the soil.
- ρw - Density of water. (1 g/cm^3)

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusions

1. As matric suction increases, more water tends to drain from the soil. However, at any suction level, soil samples from shallower depths will retain a higher water content compared to deeper soil samples.

2. AEV is significantly higher for the S-SWCC compared to the w-SWCC for all soil samples. Soil samples from the shallower depth from OGL showed a lesser AEV, with an increasing depth AEV of a soil increase. A soil with a higher PI value shows the lowest AEV while a lower PI shows a higher AEV. Soil samples extracted from a similar depth with a varying PI value exhibited an increment in AEV with increasing PI values.

3. Based on e-CC curves up to a suction value of around 40-70 kPa, there is minimal change in volume for the soil sampled from building excavations, and for under-roadway soils, it goes up to 200kPa. This suggests that the material being studied is able to resist deformation or compression up to this suction level. Beyond that, a significant increase in volume change is observed. This implies that the material's structure or properties are altered beyond this suction threshold, leading to noticeable deformation or expansion.

4. Based on the void-ratio characteristics curve, the volume change of natural undisturbed expansive soils collected from different locations in Addis Ababa at different depths shows within the range of 73-98%.

5. Based on field tests matric suction showed a general trend of increasing with depth, with a range of increments depending on the climate at the same time. Variation of matric suction with depth is lower in a drier season and higher with depth for a wet season in magnitude. For the same moisture content, the matric suction was higher at greater depths, while at the same matric suction, the moisture content decreased with depth.

6. Matric suctions obtained from the sensors show similar values to the estimated matric suction from the SWCC obtained in the laboratory at a lower matric suction value.

7. Matric suction values ranging between 23 kPa and 83 kPa with a corresponding volumetric water content ranging between 10% up to 50% were recorded across the unsaturated zone with sensors embedded at depths of 140 cm, 160 cm, 190 cm from the surface. Starting from June to the end of October 2023.

8. The matric suction variations with depth, indicate fluctuation with weather conditions. During rainfall, the matric suction variation with depth reaches up to 20 kPa in August and in when the rainfall is slightly higher. Conversely, in June the lower rainfall time, it gets as slow as 3-5kPa.

5.2 Recommendations

Based on the results of this study, the following recommendations for future research are offered:

1. Under a hysteresis framework, this study used a drying process in developing SWCC curves. It is recommended to make a similar study using wetting curves.
2. In this study a digital caliper is used for measuring shrinkage curves. To accurately measure the volume changes in soil samples it is recommended to use measurement devices that can accurately measure the volume change of soil with suction applied.
3. There are many works in developing regression models to predict USPF including bearing capacity, swelling pressure, permeability, and shear strength using SWCC parameters in other countries, it is recommended to develop USPFs using soil properties here in Ethiopia.
4. In this study a four-month suction measurement is used in the field, it is recommended further studies on Long-term measurements of suction in the field and their relation to climatic parameters.
5. It is recommended to study, the effect of climate change and/or matric suction on the environment, infrastructure, and historic monuments through unsaturated soil behaviors.
6. This study used electronic Tensimeter and Diviner 2000 for field measurements, it is recommended to make studies using Advanced suction and water content measurement sensors, especially in the field.

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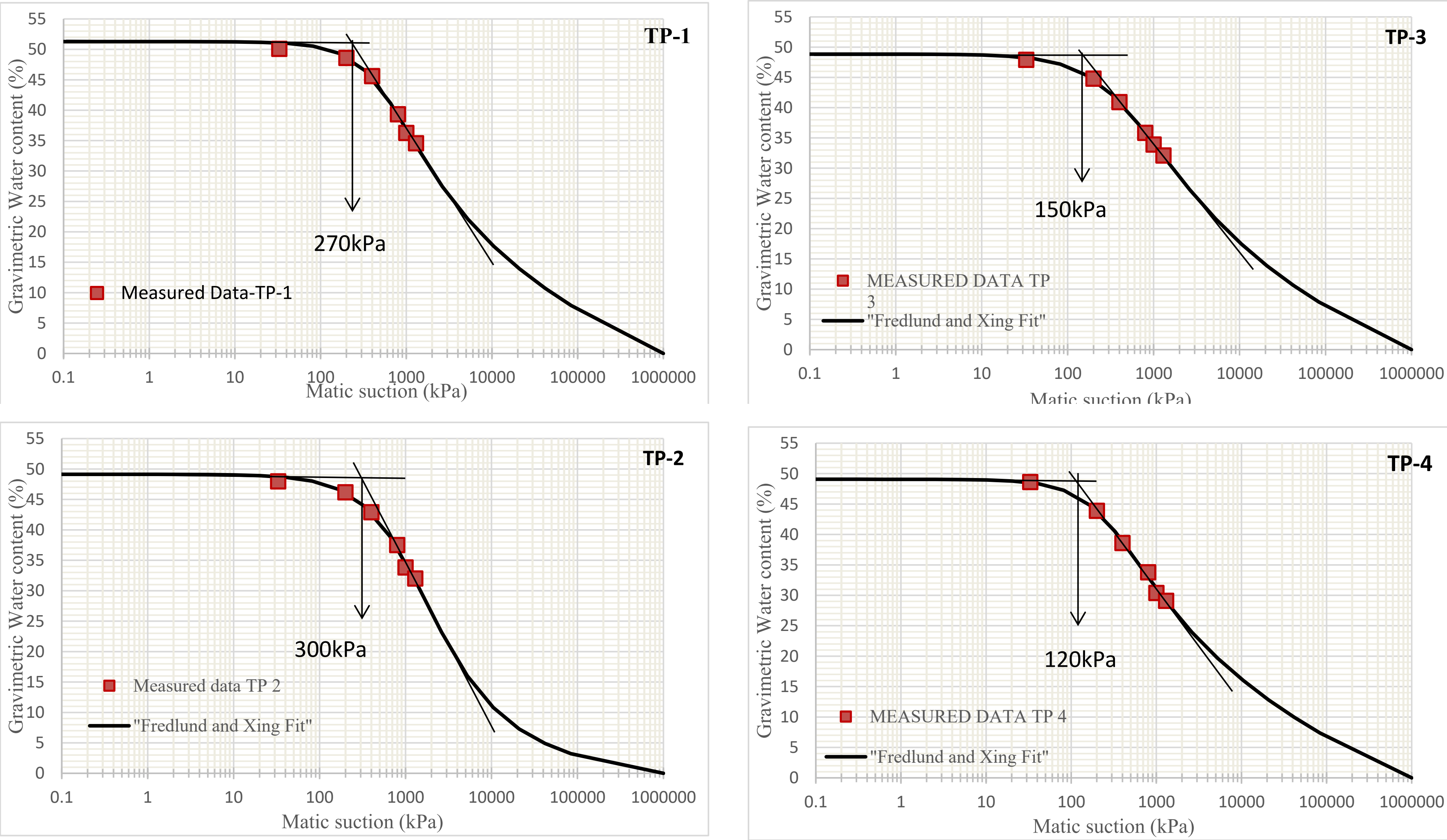
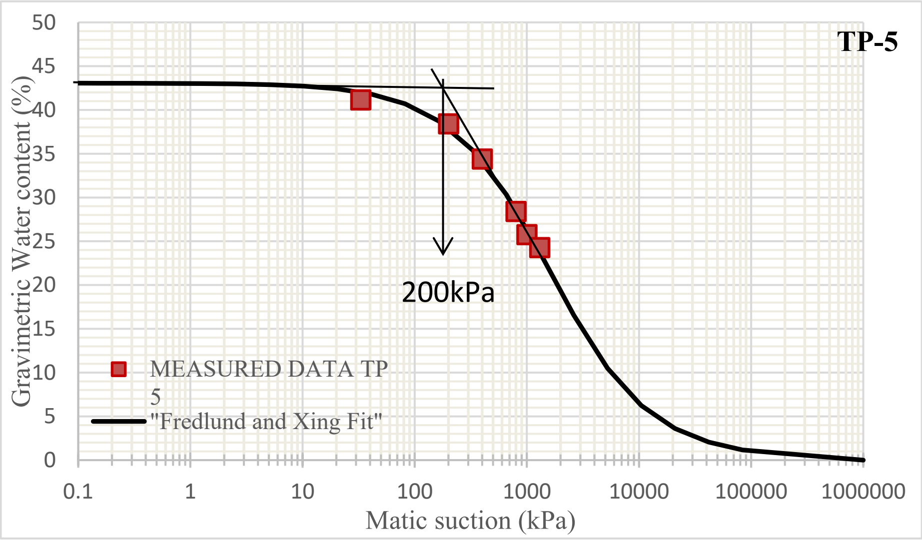
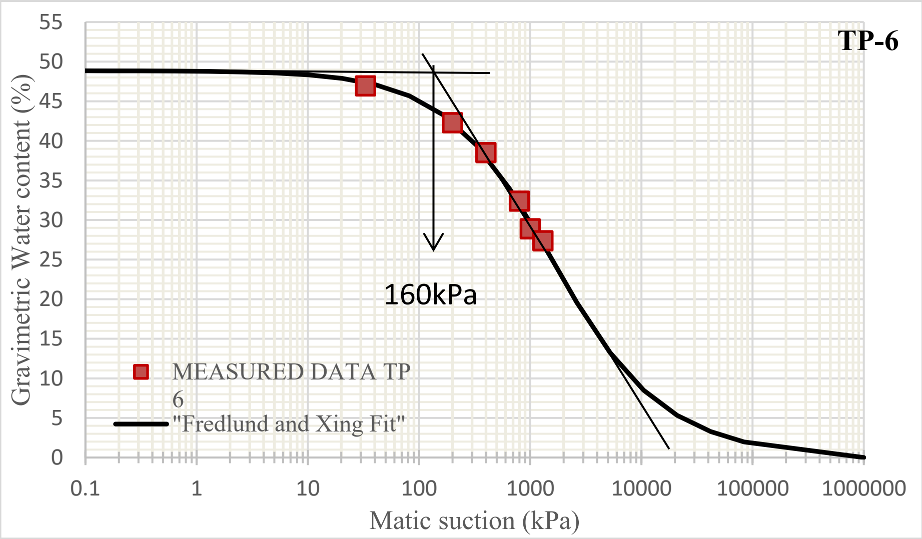
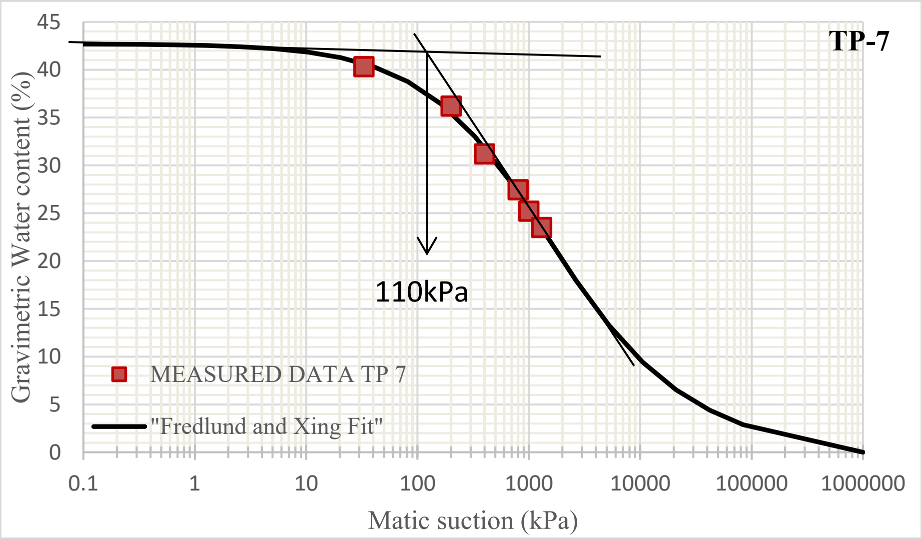
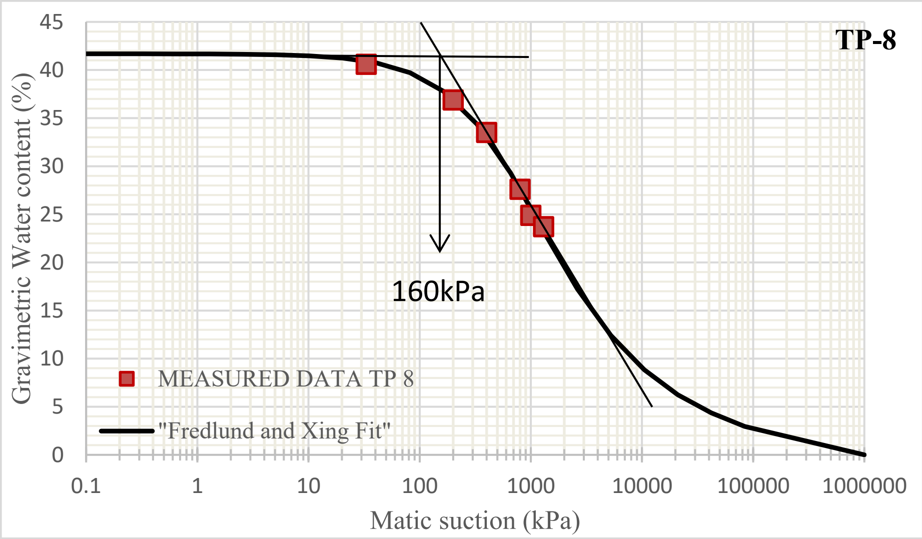
w-SWCC Test Results of Addis Ababa Expansive Soil

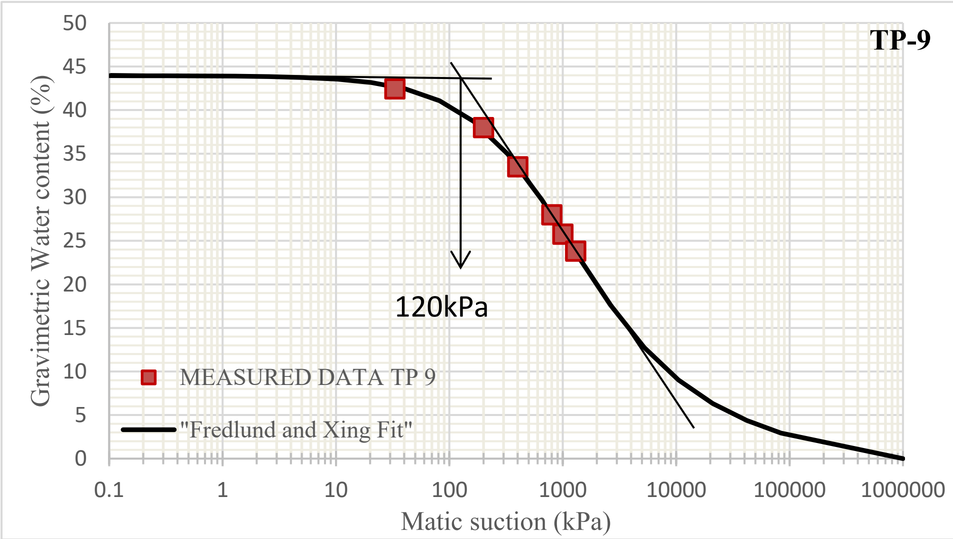


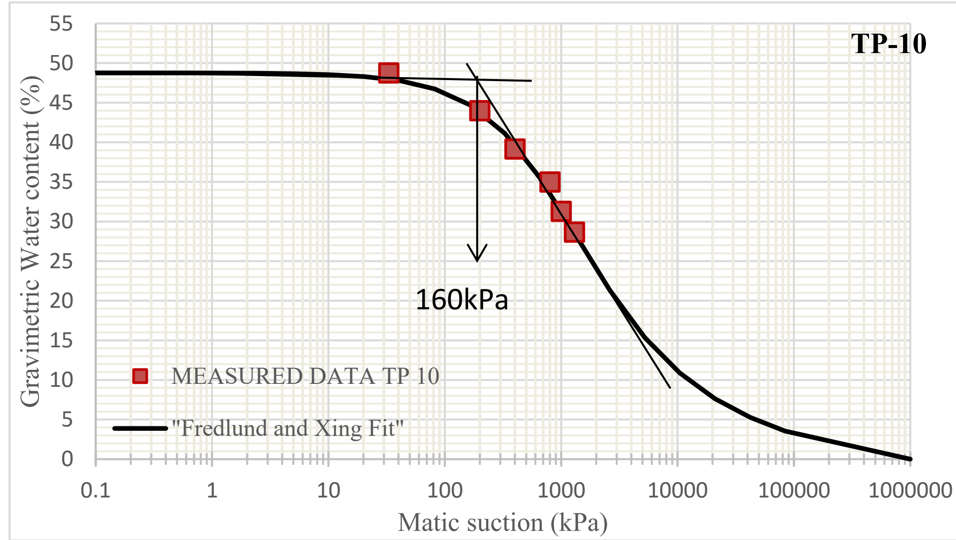

TP-5
Gravimetric Water content (%)
Matic suction (kPa)
200kPa
MEASURED DATA TP 5
"Fredlund and Xing Fit"

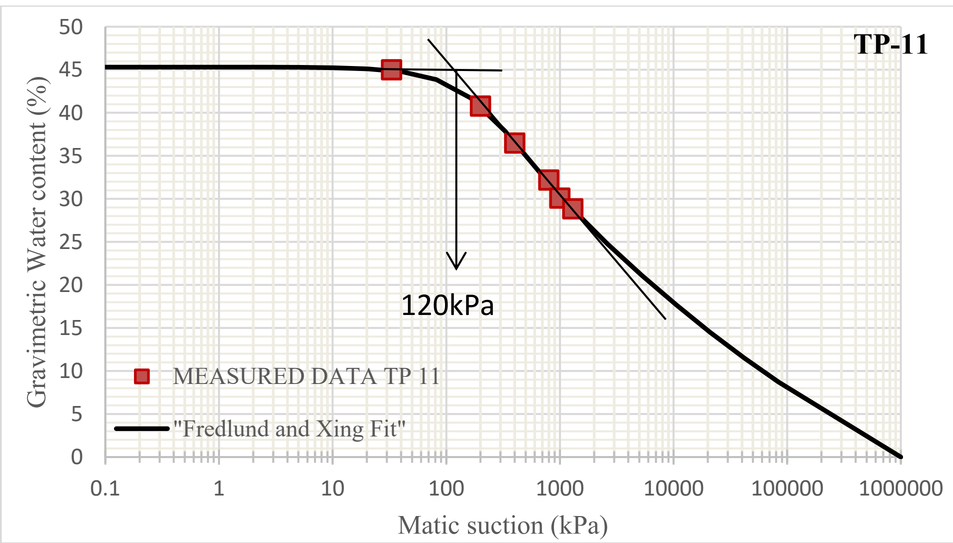

TP-6
Gravimetric Water content (%)
Matic suction (kPa)
160kPa
MEASURED DATA TP 6
"Fredlund and Xing Fit"

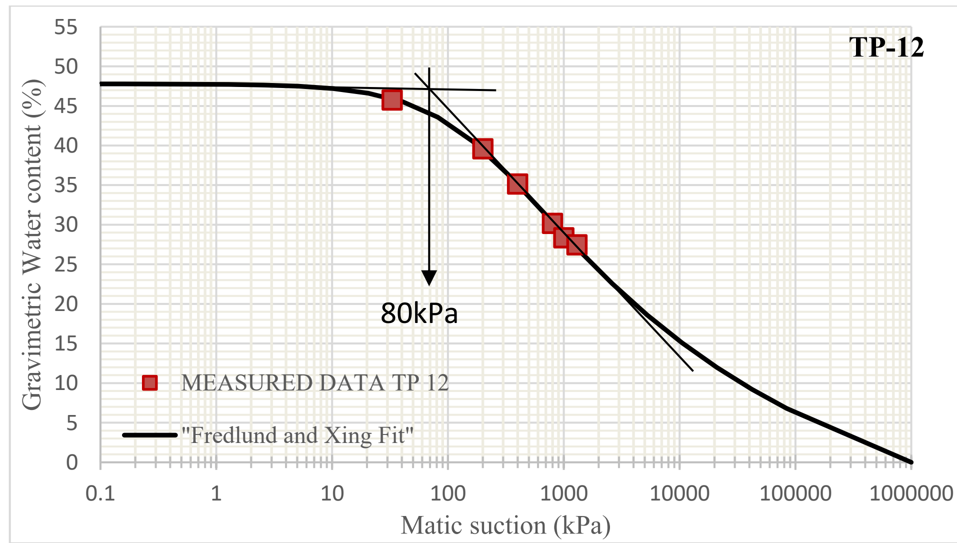

TP-7
Gravimetric Water content (%)
Matic suction (kPa)
110kPa
MEASURED DATA TP 7
"Fredlund and Xing Fit"


TP-8
Gravimetric Water content (%)
Matic suction (kPa)
160kPa
MEASURED DATA TP 8
"Fredlund and Xing Fit"

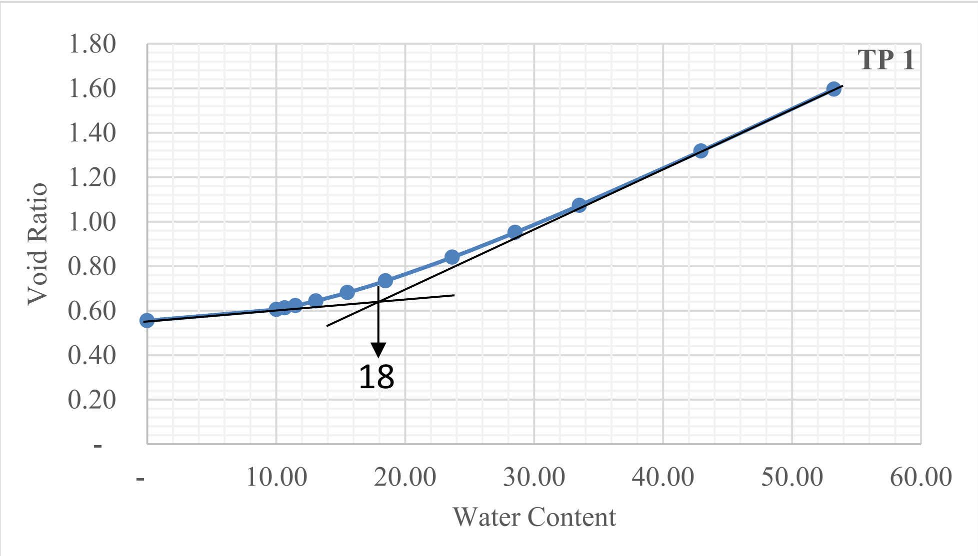

TP-9
Gravimetric Water content (%)
Matic suction (kPa)
120kPa
MEASURED DATA TP 9
"Fredlund and Xing Fit"

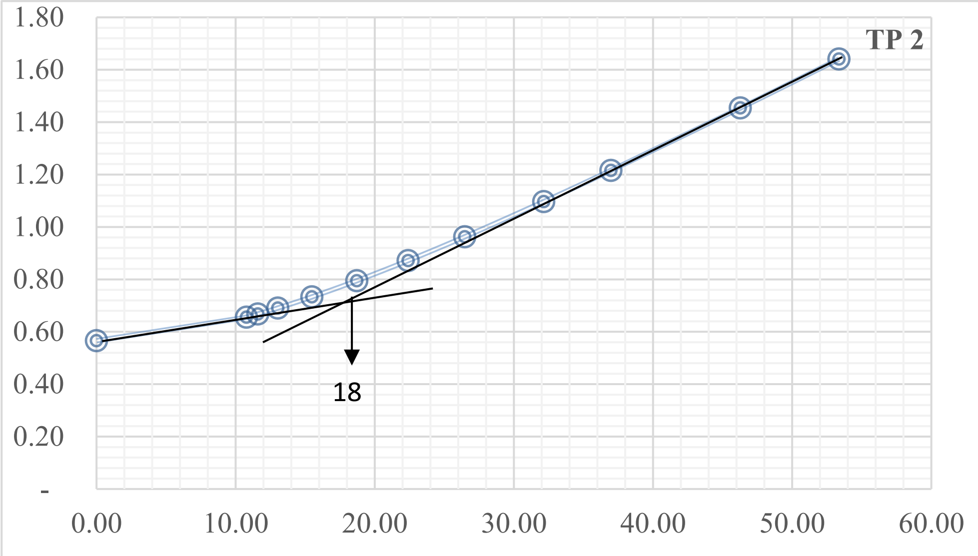

TP-10
Gravimetric Water content (%)
Matic suction (kPa)
160kPa
MEASURED DATA TP 10
"Fredlund and Xing Fit"

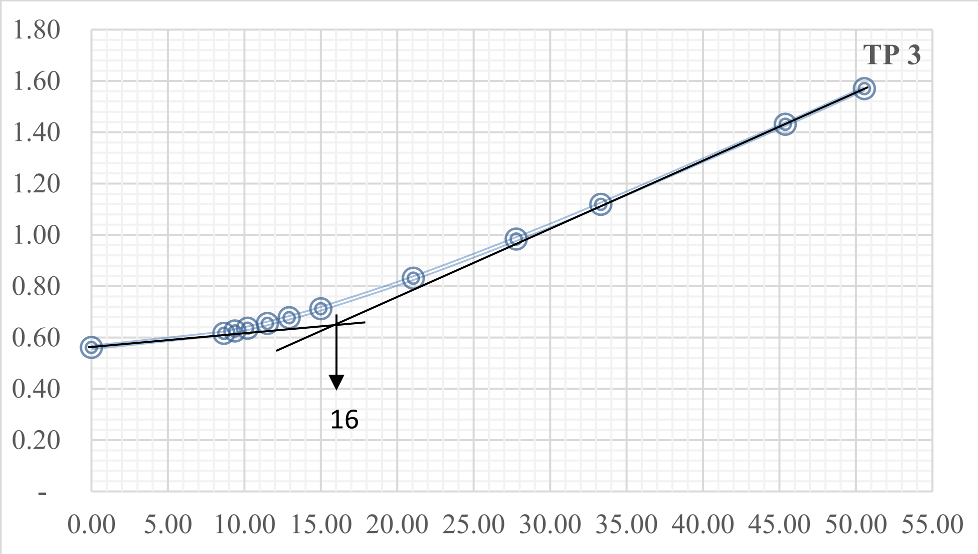

TP-11
Gravimetric Water content (%)
Matic suction (kPa)
120kPa
MEASURED DATA TP 11
"Fredlund and Xing Fit"

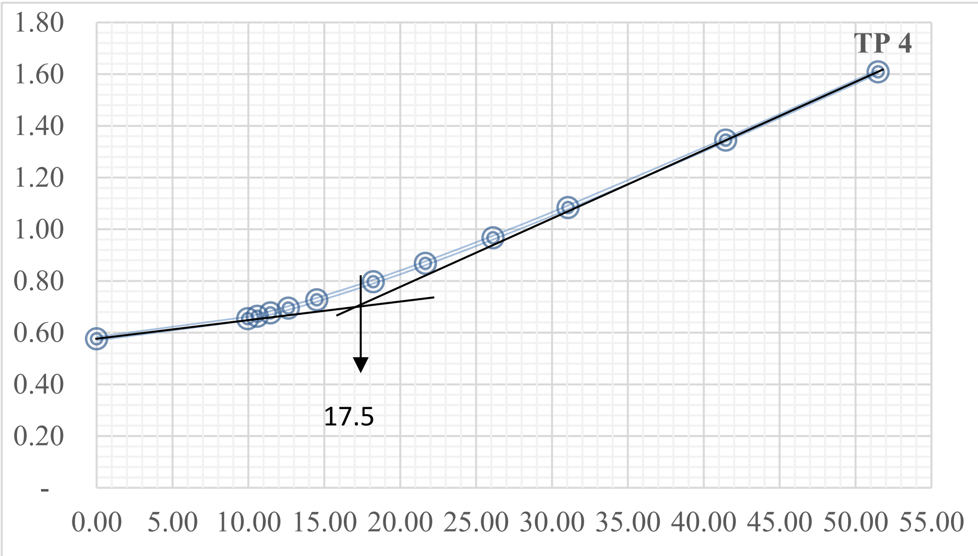

TP-12
Gravimetric Water content (%)
Matic suction (kPa)
80kPa
MEASURED DATA TP 12
"Fredlund and Xing Fit"

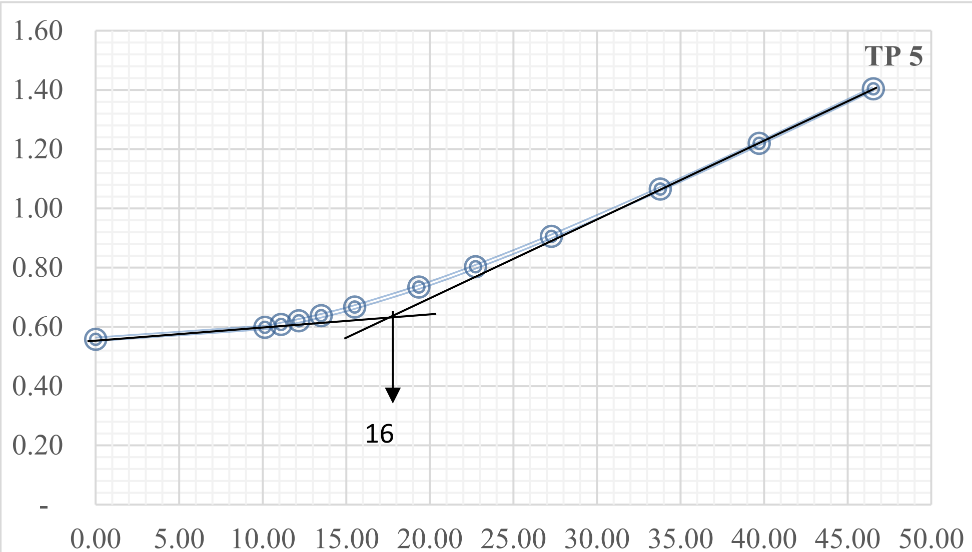
Shrinkage Curve Test Result







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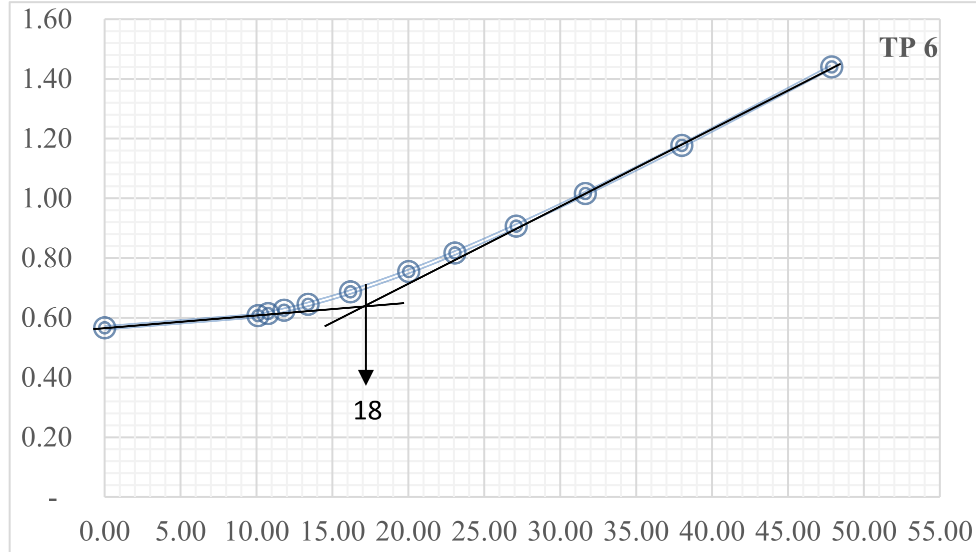
16
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
-
0.00 5.00 10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00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1.60
1.40
1.20
1.00
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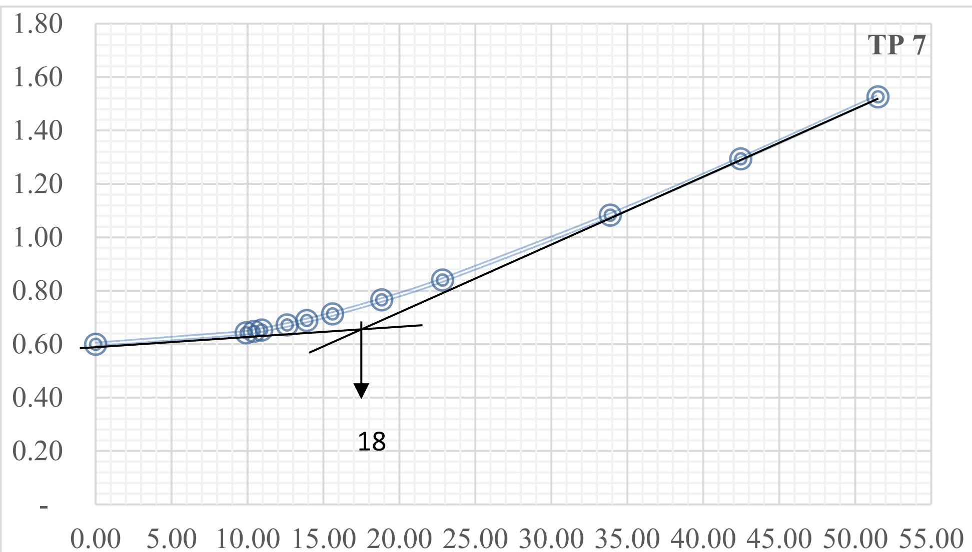
0.60
0.40
0.20
-
0.00 5.00 10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00 55.00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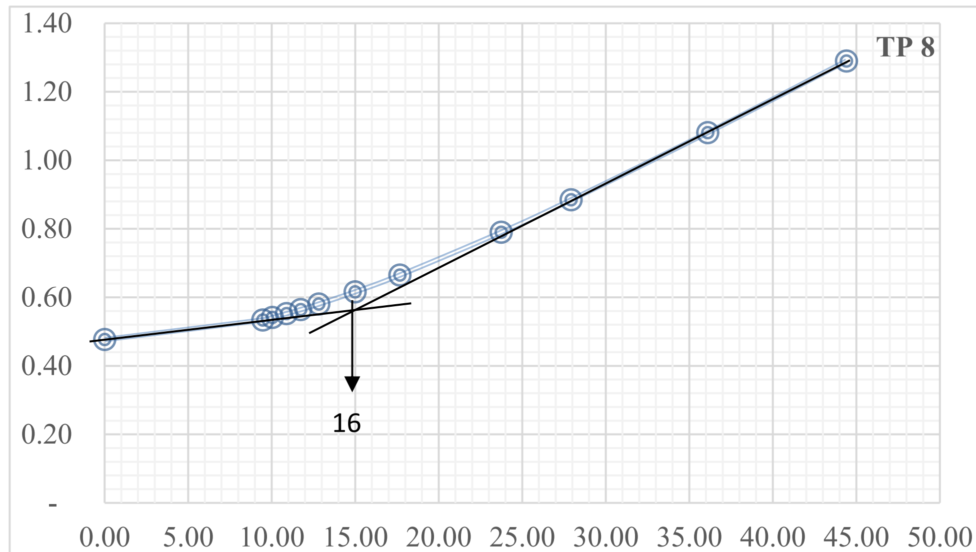
18
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
-
0.00 5.00 10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00 55.00


TP 8
16
1.40
1.20
1.00
0.80
0.60
0.40
0.20
-
0.00 5.00 10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00

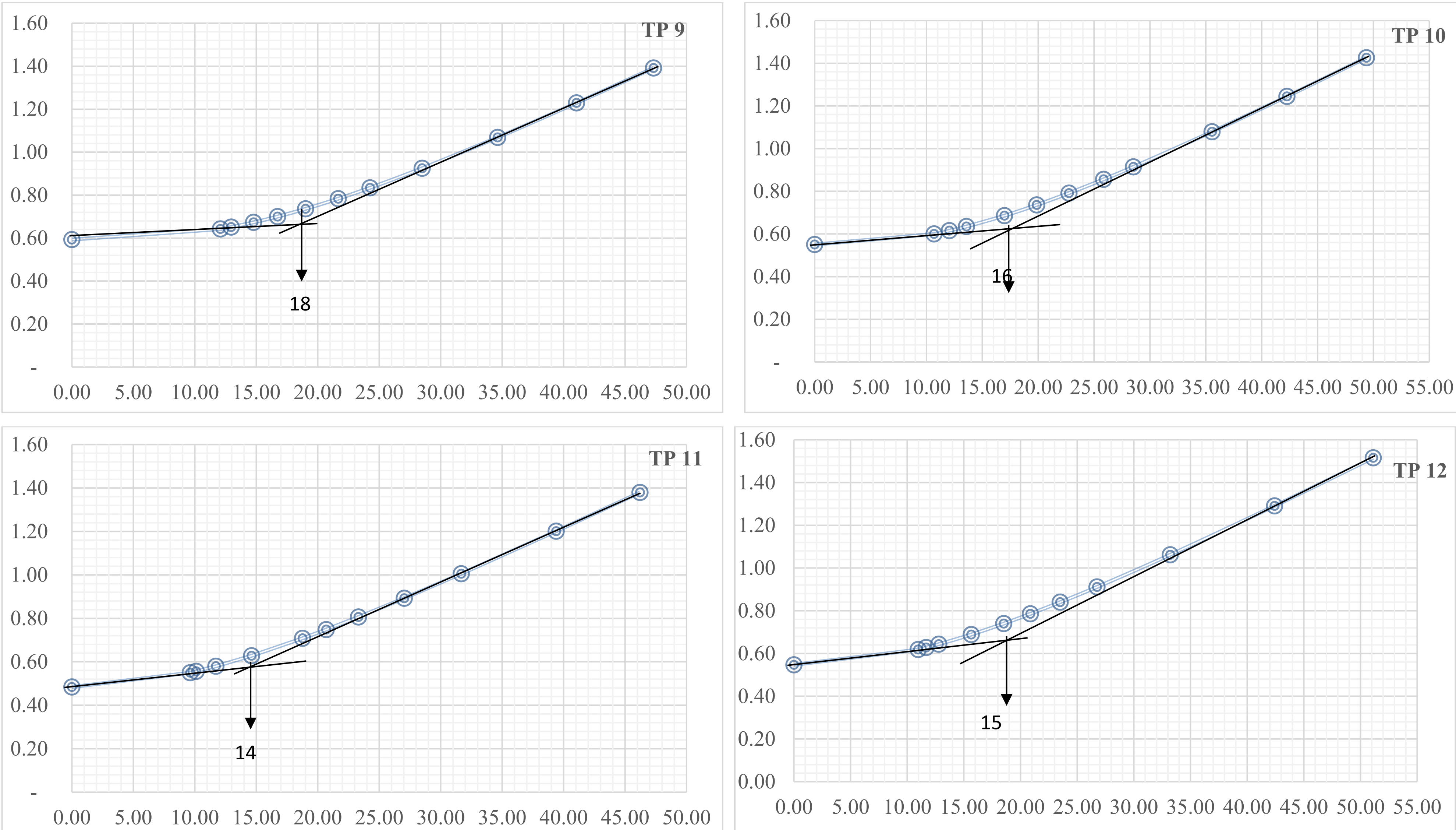
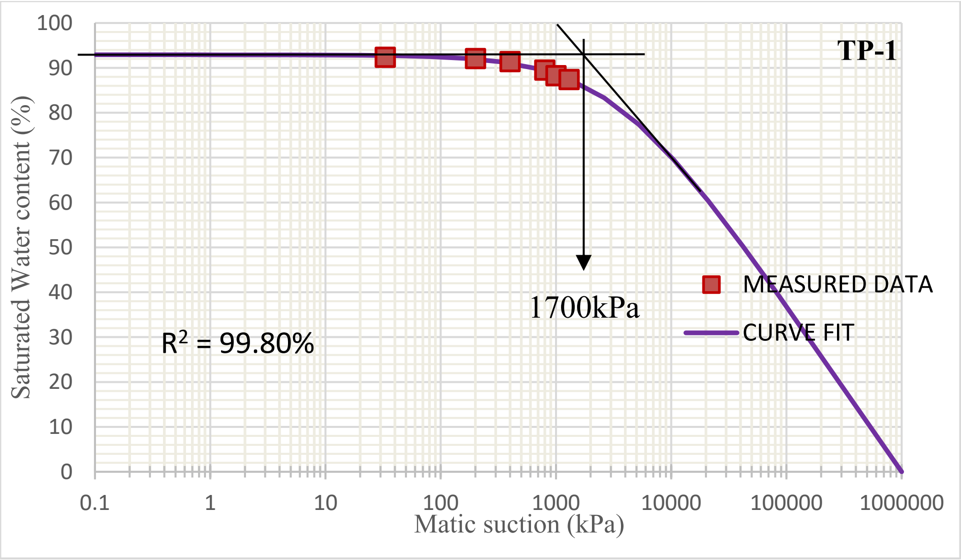
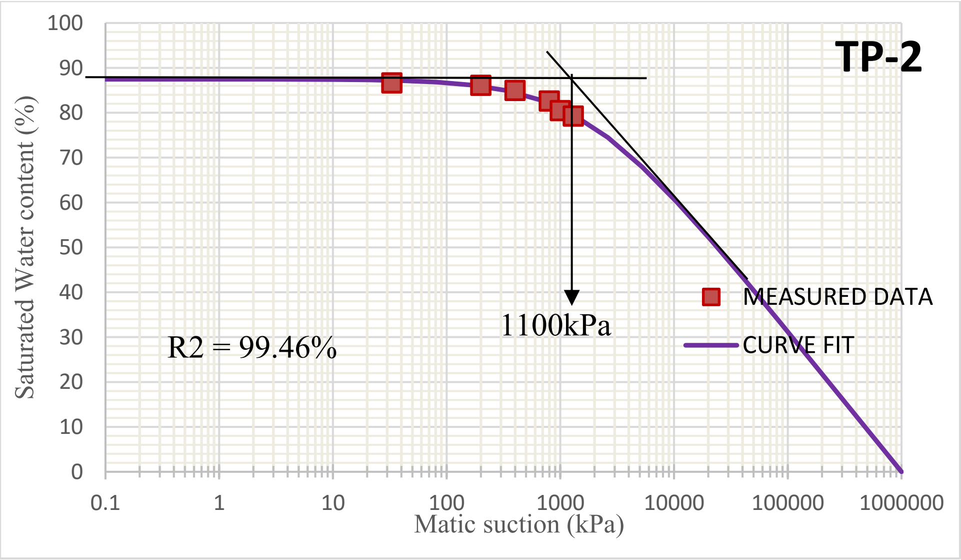
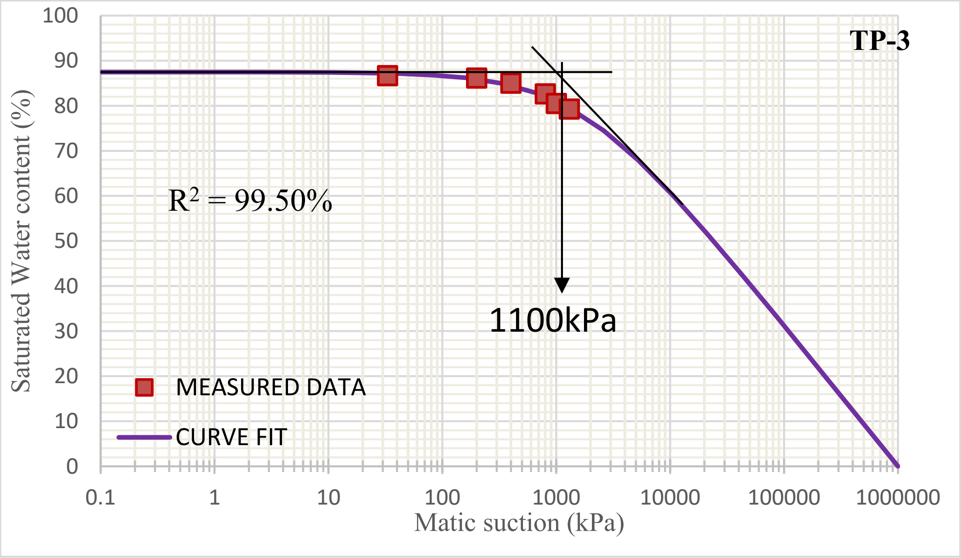


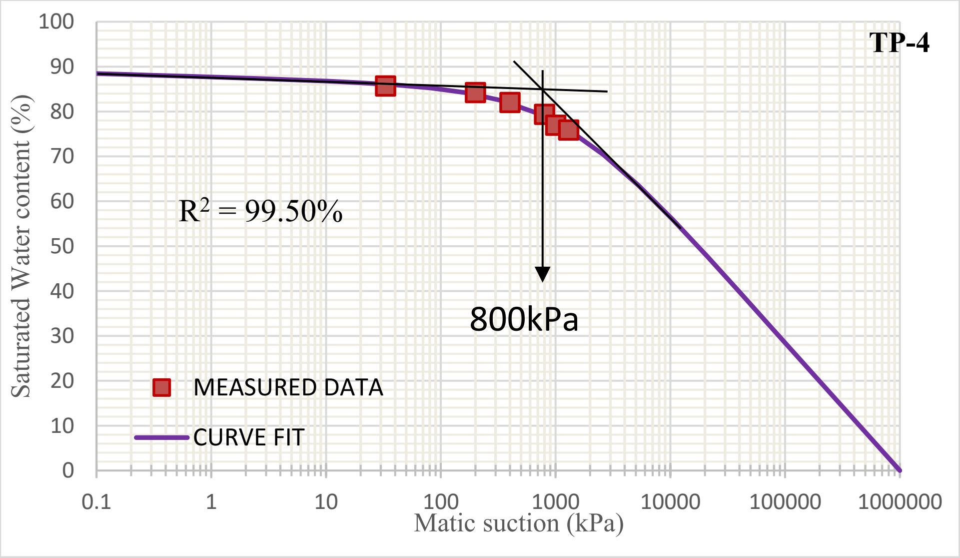
Figure 5-1 SC of Expansive soils samples from Addis Ababa (TP-1 – TP-12)

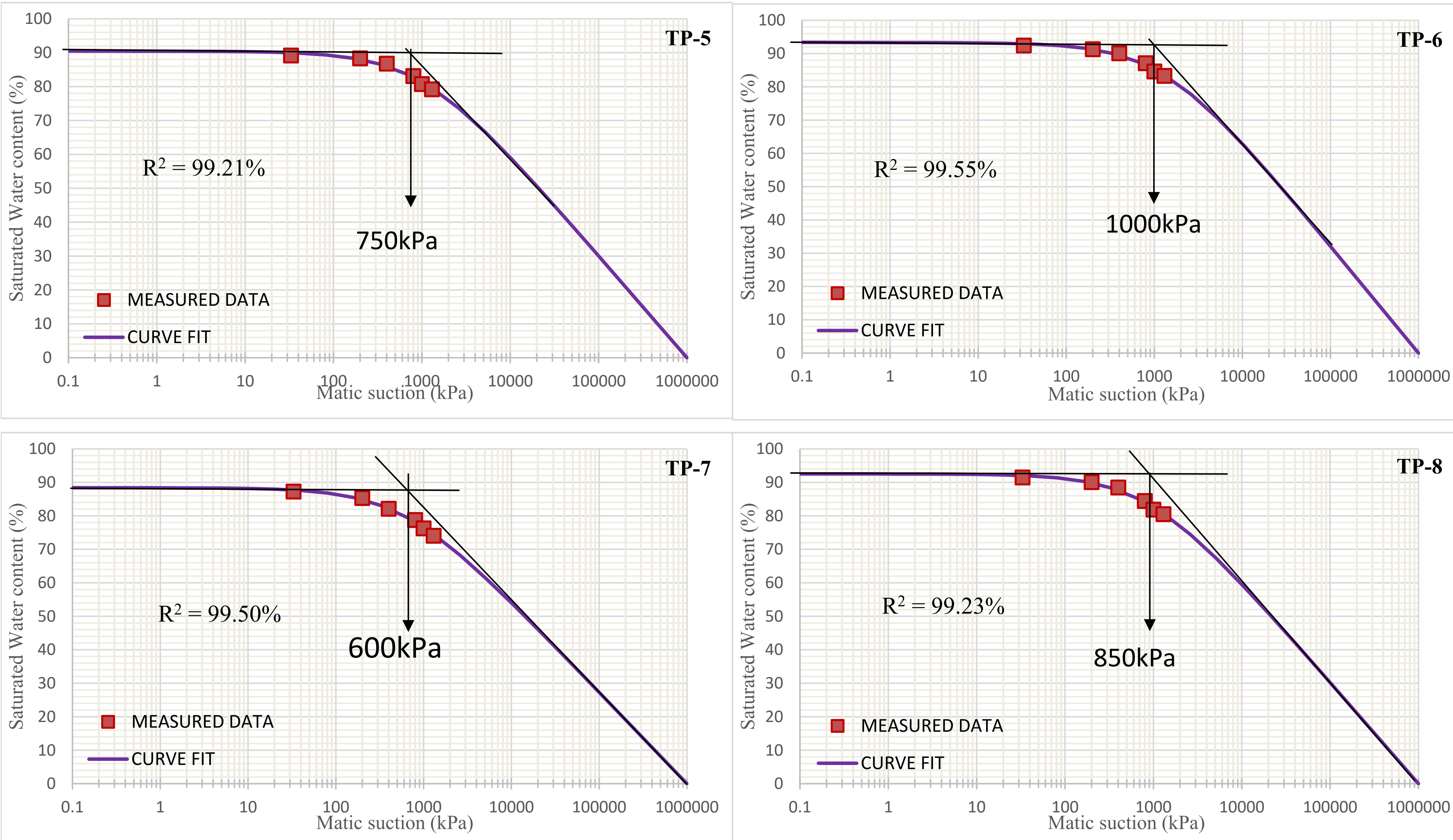
s-SWCC Test Results

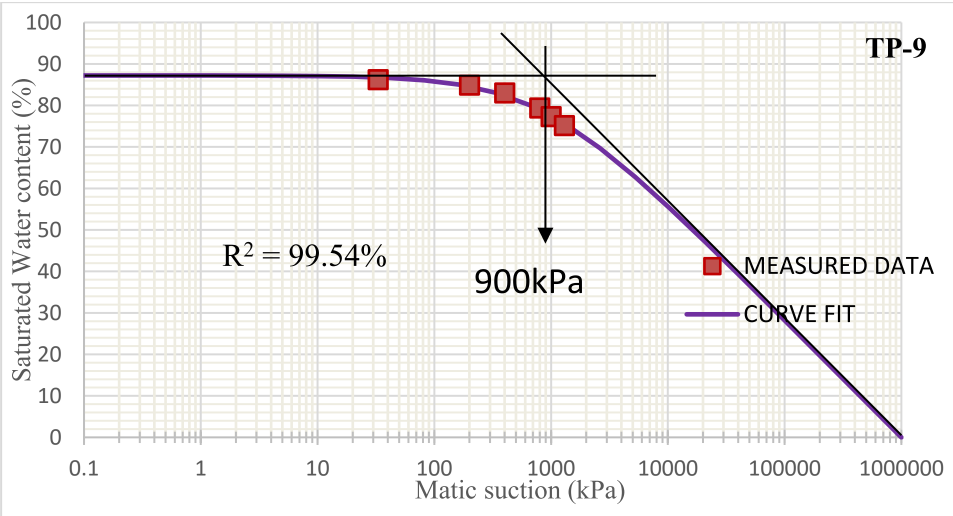


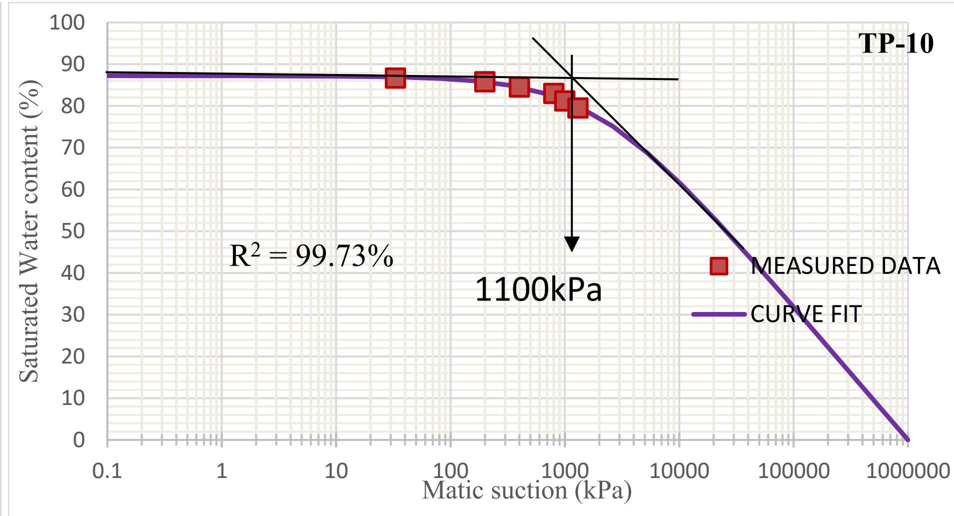


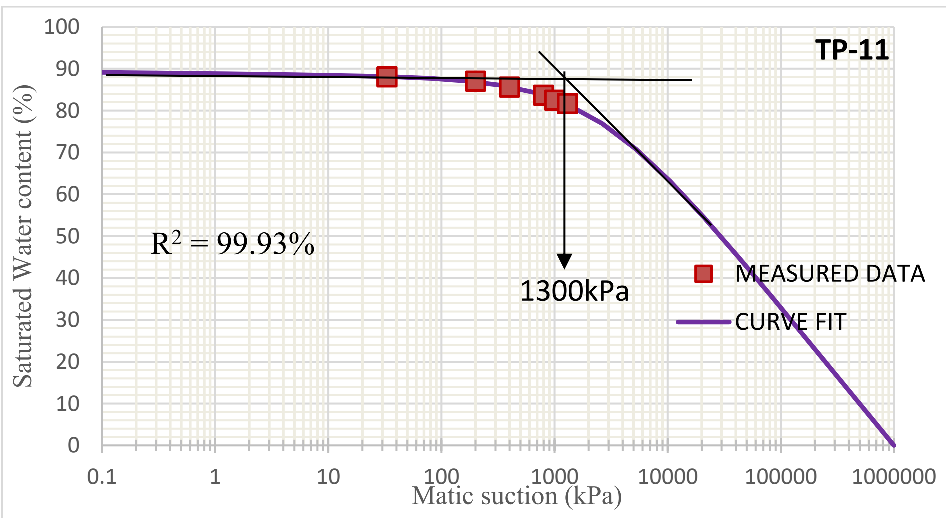


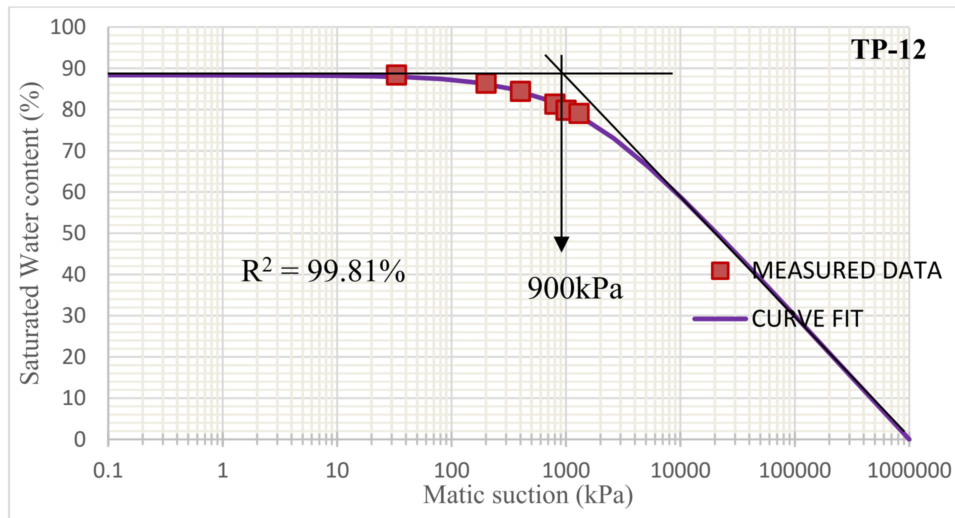



TP-5
R² = 99.21%
750kPa
MEASURED DATA
CURVE FIT
Saturated Water content (%)
Matic suction (kPa)
TP-6
R² = 99.55%
1000kPa
MEASURED DATA
CURVE FIT
Saturated Water content (%)
Matic suction (kPa)
TP-7
R² = 99.50%
600kPa
MEASURED DATA
CURVE FIT
Saturated Water content (%)
Matic suction (kPa)
TP-8
R² = 99.23%
850kPa
MEASURED DATA
CURVE FIT
Saturated Water content (%)
Matic suction (kPa)

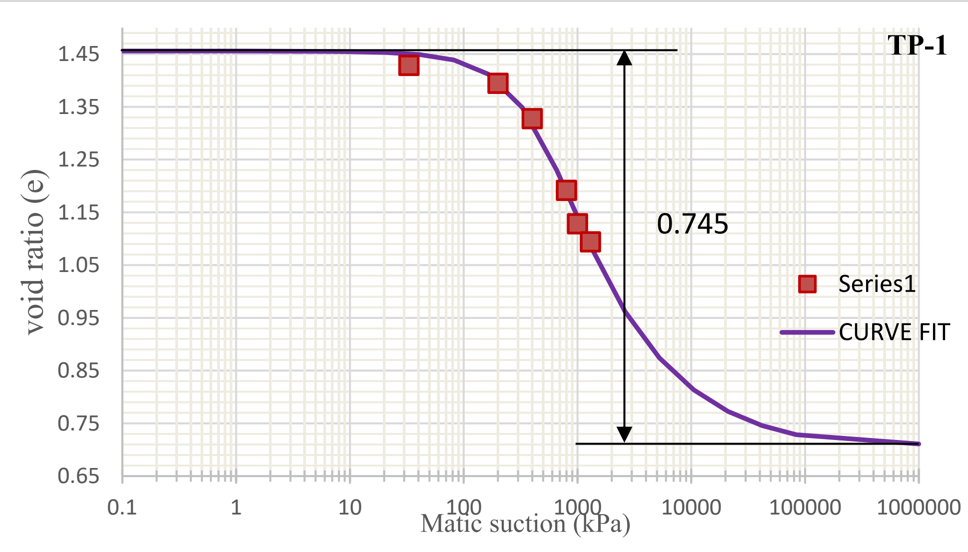

TP-9
Saturated Water content (%)
Matic suction (kPa)
R² = 99.54%
900kPa
MEASURED DATA
CURVE FIT

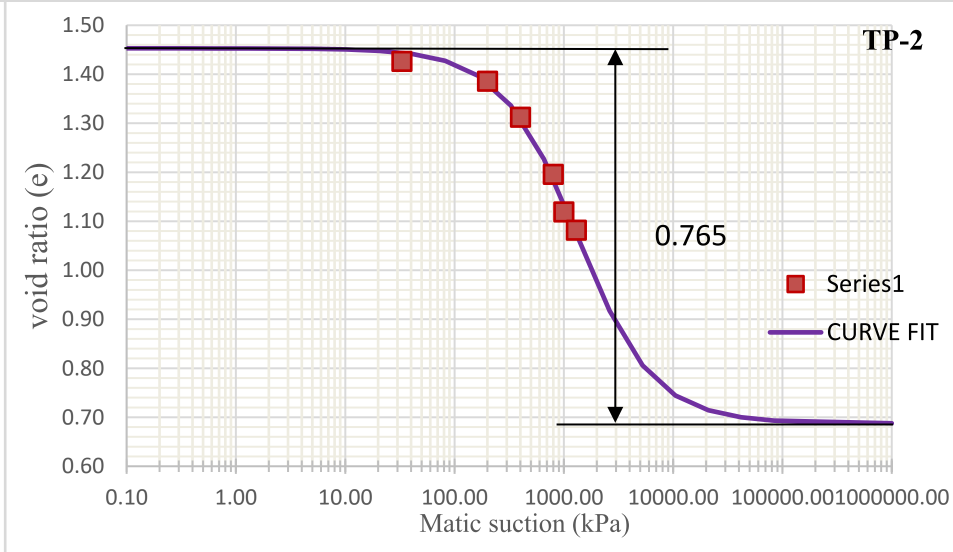

TP-10
Saturated Water content (%)
Matic suction (kPa)
R² = 99.73%
1100kPa
MEASURED DATA
CURVE FIT

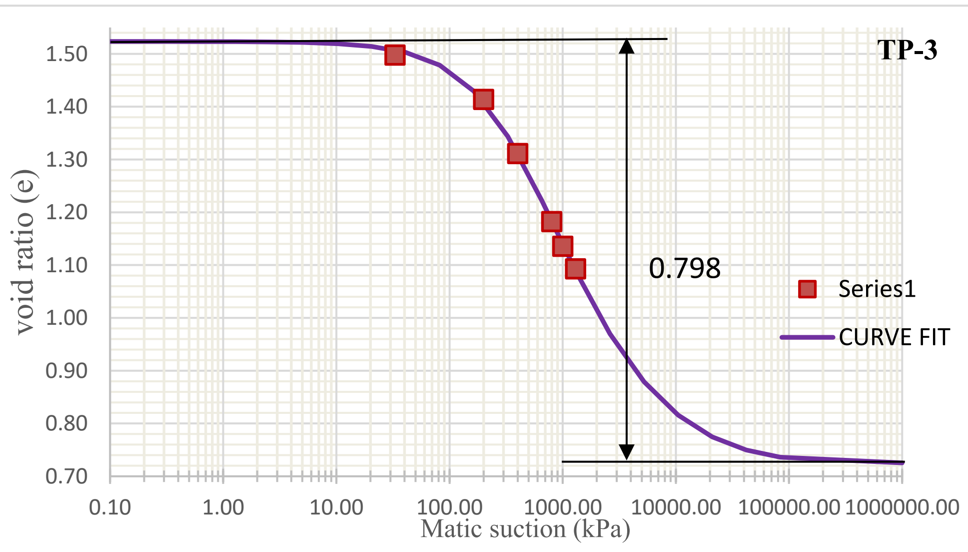

TP-11
Saturated Water content (%)
Matic suction (kPa)
R² = 99.93%
1300kPa
MEASURED DATA
CURVE FIT

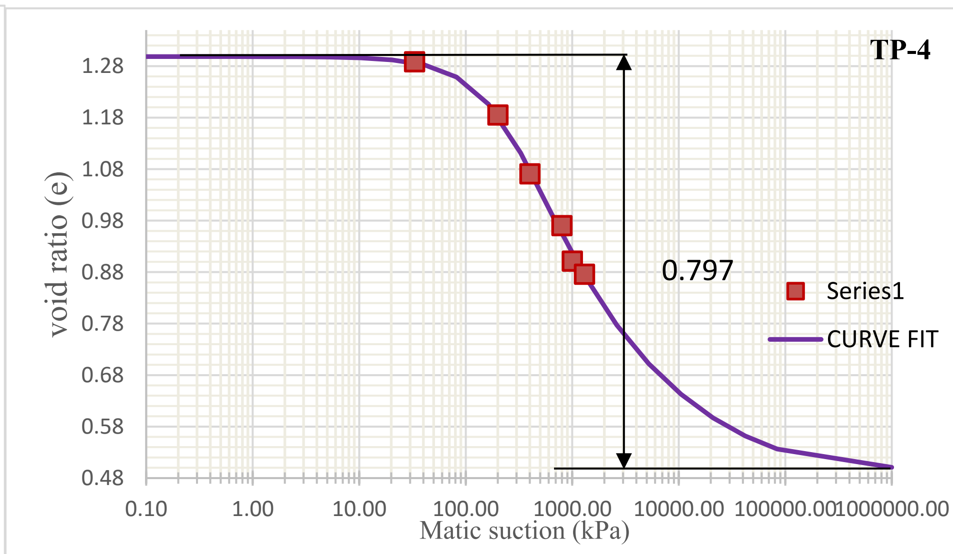

TP-12
Saturated Water content (%)
Matic suction (kPa)
R² = 99.81%
900kPa
MEASURED DATA
CURVE FIT

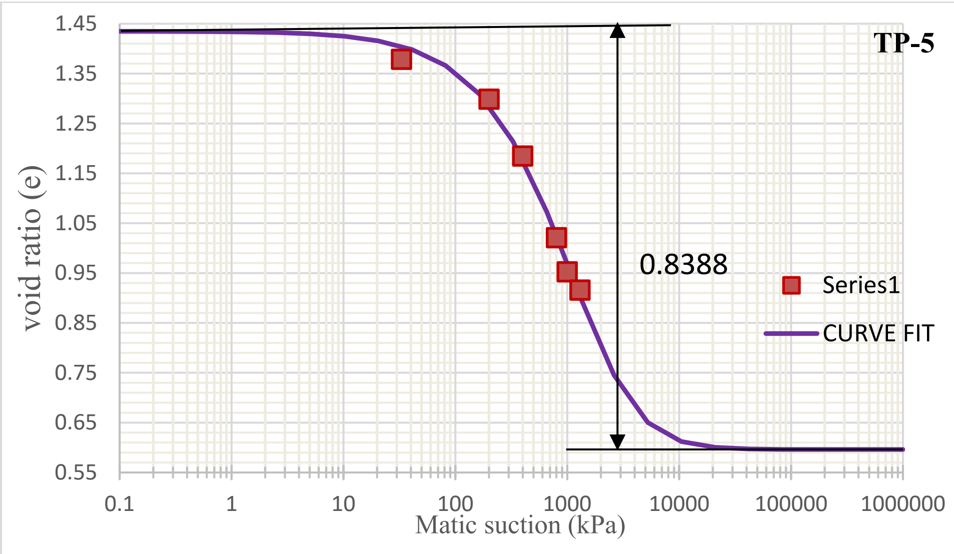
e-CC Test Results

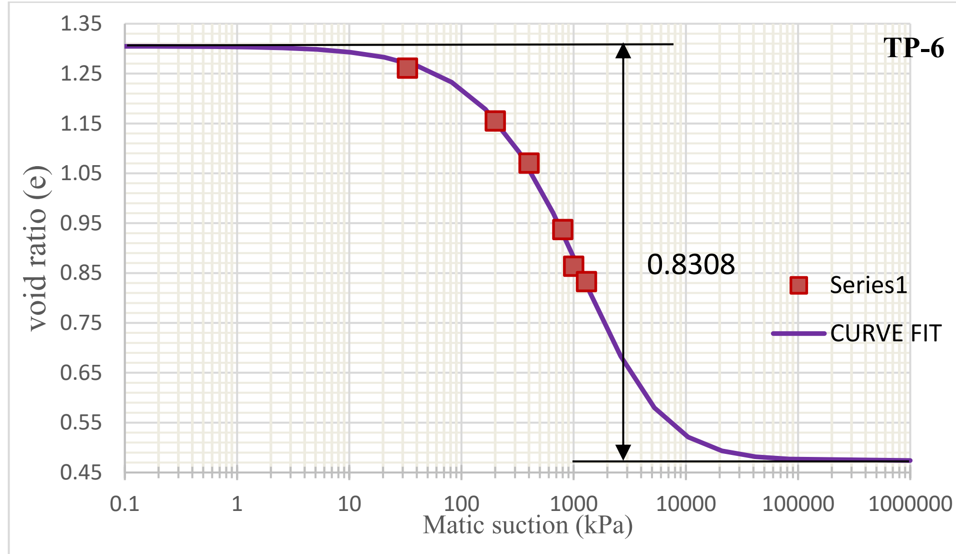


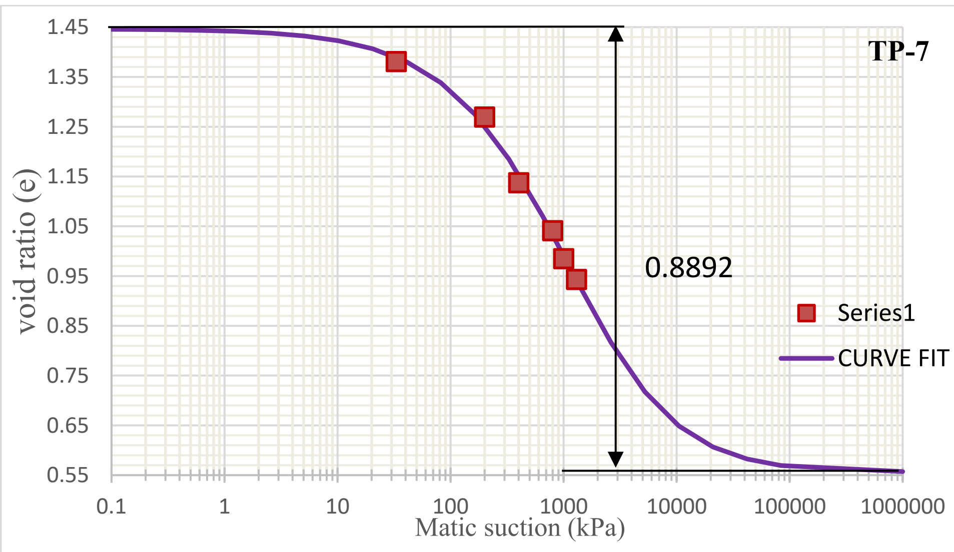


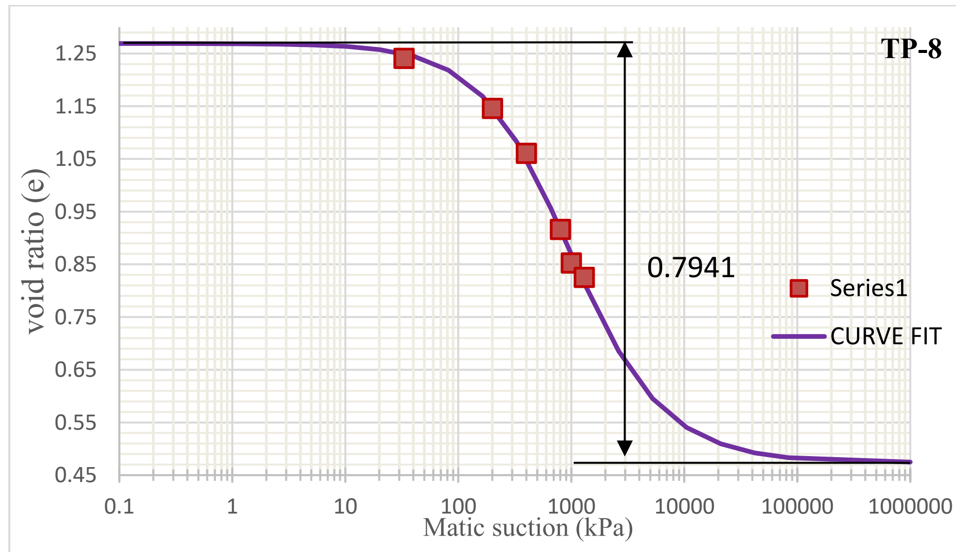





TP-5
void ratio (e)
Matic suction (kPa)
0.8388
Series1
CURVE FIT


TP-6
void ratio (e)
Matic suction (kPa)
0.8308
Series1
CURVE FIT


TP-7
void ratio (e)
Matic suction (kPa)
0.8892
Series1
CURVE FIT


TP-8
void ratio (e)
Matic suction (kPa)
0.7941
Series1
CURVE FIT

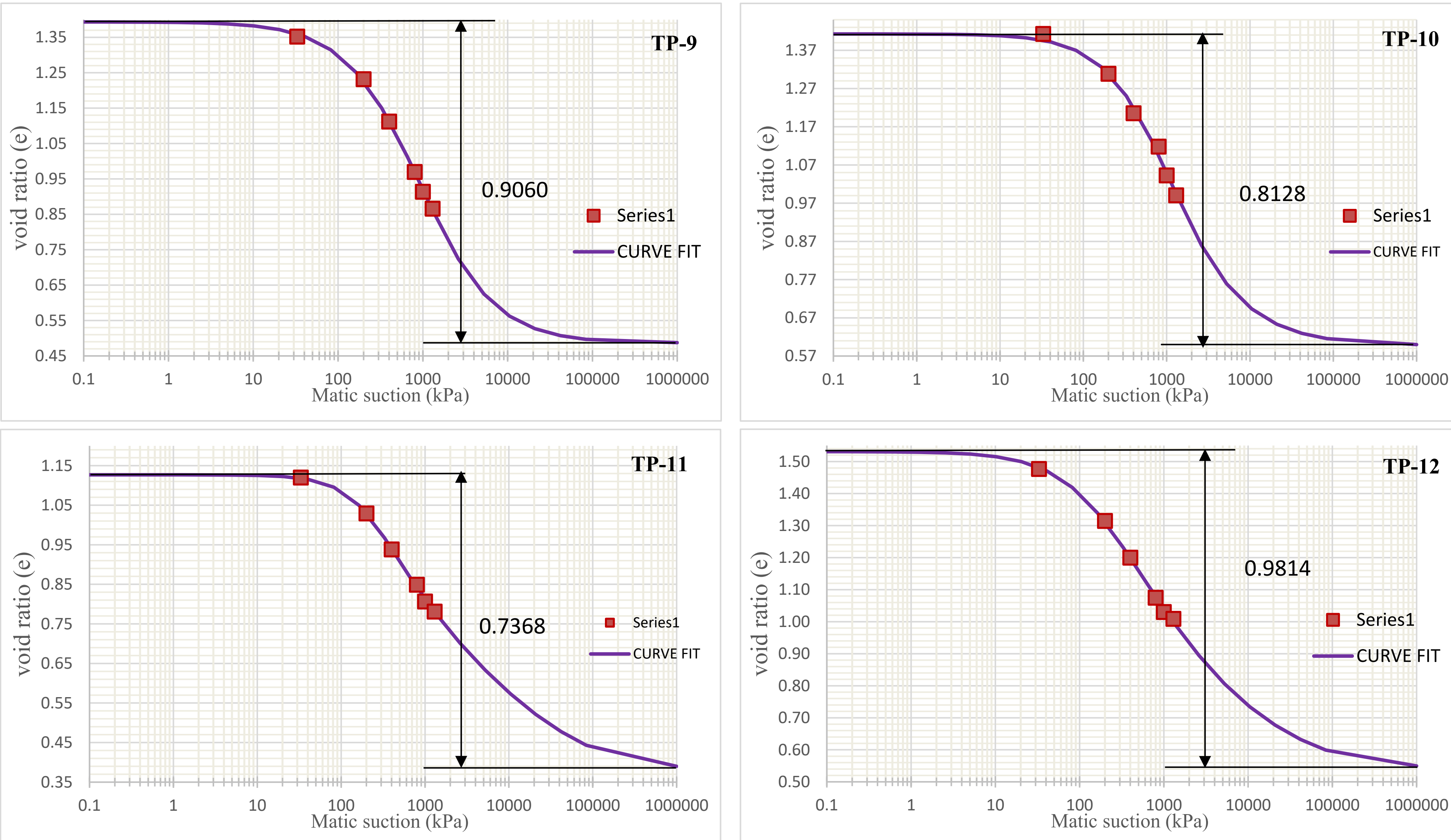


Figure 5-2 e-CC test results of Addis Ababa Expansive soils (TP-1 – TP- 12)