ASSESSMENT OF SOIL-WATER RETENTION PROPERTIES OF LIME AND CEMENT TREATED CLAYS

by

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ABSTRACT

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The soil-water characteristic curve (SWCC) of unsaturated soils has considerable importance in the analysis of geotechnical engineering problems involving soils that remain under partially saturated conditions throughout any given year. The SWCC reflects the behavior of unsaturated soils with regard to its hydraulic conductivity, shear strength, and volume change behavior.

Numerous investigations have been undertaken in recent decades to extend the unsaturated soil mechanics principles into conventional engineering practice. The soil-water characteristic curve (SWCC) has become a widely used experimental means for assessing fundamental properties of unsaturated soils for a wide range of suction values. However, a limited number of studies have focused on soil-water retention properties of natural and chemically treated expansive soils via the SWCC. The present work is motivated by the lack of experimental evidence of this type.

The soil-water characteristic curves of expansive soil from south Arlington, Texas were measured under both natural and treated conditions using pressure plate (suction range of 0-690 kPa) and filter paper (suction range 690-1,000,000 kPa) techniques. The measured results were then analyzed using Fredlund and Xing‟s (1994) SWCC model equation. In addition, correlations were developed between basic soil and stabilizer properties, such as optimum moisture content, dry density, liquid limit, plastic limit, and stabilizer dosage and type, and Fredlund and Xing‟s model constants via multiple regression analysis.

The multiple regression analysis shows that higher coefficients of correlations can be achieved by using six or more independent soil properties. The comparisons between the predicted and measured volumetric water contents are within 15%.

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CHAPTER 1

INTRODUCTION

1.1 Background and Importance

Expansive soils can be found almost anywhere in the world. Countries in which most severe expansive soil problems have been reported include Argentina, Australia, Burma, Canada, China, Cuba, Ethiopia, India, Iran, Israel, Ghana, Mexico, Rhodesia, Spain, South Africa, Turkey, and USA. In the United States, nearly all 50 states contain deposits of expansive soils with the highest concentration being in Texas, Colorado, Oklahoma, Virginia, North Dakota, and Montana. Expansive soils have inherent property of shrinking when they are dried and swelling when water is absorbed. These soils exhibit moderate to high plasticity, low to moderate strength and high swell and shrinkage characteristics (Holtz and Gibbs, 1956; Sherwood, 1962; Aitcheson et al., 1973; Lytton, 1981; Chen, 1988), undergoing large volumetric changes even due to small fluctuation in water content. The volumetric changes are very large in magnitude and they are responsible for the partial or total distress of structures. The amount of damage caused by expansive soils is alarming. Structural damages from instability of these expansive soils run into the billions of dollars; the estimated nationwide damage last year was reported to be $10-billion.

Swell response of expansive soils has been investigated by researchers since the early 1950‟s based on Atterberg limits, index properties, and other soil tests carried out in the laboratory (Holtz and Gibbs, 1956; Seed et al., 1962; Vander Merwe, 1964; Richards et al., 1984). These studies have been, on one hand, successful in exploring numerous properties of these soils, but they have failed to determine the associated engineering properties. This is mainly because different soils that have same Atterberg limits can exhibit different volume change behavior and shear strength characteristics as many parameters such as soil structure, chemical composition and minerals present in the soil can influence their behavior.

The SWCC describes the relationship between gravimetric water content ω, or volumetric water content θ, or degree of saturation vs. matric suction ($u_a - u_w$) for a single soil specimen, where u_a = pore air pressure and u_w = pore water pressure. The SWCC reflects the behavior of unsaturated soils with regard to its hydraulic conductivity, shear strength, and volume changes (Leong and Rahardjo, 1997). These unsaturated soil properties vary as the soil suction changes and these changes can be related to the amount of water present in the soil pores. The SWCC can provide with approximate estimates of the above mentioned properties. These approximations may be satisfactory for geotechnical engineering practice (Fredlund and Rahardjo, 1993). Therefore, because of its importance, the soil-water characteristic should be considered as a standard test for unsaturated soils.

Various models have been developed by previous researchers during the last five decades to predict the shape of the SWCC for different types of soils (Sillers, 1996). Most commonly used models to represent SWCC data are Brooks–Corey (1964) model, Fredlund and Xing (1994) four–parameter model, Van Genuchten (1980) model, and Fredlund and Xing (1994) five–parameter model. Of the many formulations proposed, Fredlund and Xing (1994) provide the best fit for most reported experimental data (Leong and Rahardjo, 1997; Sillers et al., 2001).

Many experimental tests have been performed at different conditions to obtained SWCC for different types of soils. The majority of the studies were aimed at unsaturated natural and expansive soils. Very few studies were directed at the behavior of SWCC for stabilized expansive clays. The present work is motivated by the lack of research on this topic.

1.2 Objective and Scope

The main objective of the present work is to study the effects of stabilizer treatment on the SWCC of expansive soil. Two types of treatments were studied using cement and lime. Test results were analyzed and modeled to simulate soil water characteristic curves by using the analytical modeling proposed by Fredlund and Xing (1994). In addition, relationships were established between basic soil and stabilizer properties, such as liquid limit, plastic limit, dry density, and water content, and the Fredlund and Xing‟s model constants via Multiple Regression analysis.

This paper examines SWCC of both natural and stabilized expansive soil from Arlington, Texas. The emphasis is on analyzing the effect of the stabilizer on the SWCC of these treated soils. Two type of treatments were analyzed: Cement (2%, 5%, and 10%), and Lime (2%, 5%, and 10%). Initially, soil-water characteristic curves were obtained following the drying path in the suction range of 0 to 690 kPa via Pressure

Plate Extractor method, whereas from 690 kPa to 1,000,000 kPa suction range the Filter Paper method is employed.

The results were then evaluated using Fredlund and Xing‟s (1994) equation. The three model constants of the Fredlund and Xing‟s equation (i.e. a, n and m) were then correlated with basic soil properties, stabilizer types, and dosage proportions via Multiple Regression Analysis.

1.3 Organization

A brief description of the content of each chapter included in this thesis is presented in the following paragraphs.

Chapter 2 presents a brief review of the concept of soil water characteristic curve. It concludes with a review of recent studies conducted on soil water characteristic curves for stabilized expansive soils using Pressure plate technique.

Chapter 3 is devoted to describing the fundamentals of Pressure Plate apparatus and Filter paper method, including main apparatus components and the step by step testing procedures.

Chapter 4 presents the engineering properties of the testing soil, specimen preparation process and experimental procedures adopted in the present work.

Chapter 5 presents the analysis of all test results obtained from pressure plate and filter paper measurements, along with a multiple regression analysis of the SWCC data.

Chapter 6 includes the summary and the main conclusions of this work, as well as some recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the fundamentals of the soil-water characteristic curve. It begins with a brief description of SWCC. It then describes features of SWCC and different equations proposed for SWCCs followed by different methods used in the lab to determine soil-water retention properties. The chapter concludes with a discussion on previous studies conducted on soil-water characteristic curves for stabilized soils.

2.2 Soil Water Characteristic Curve

The soil water characteristic curve represents the relationship between volumetric or gravimetric water content and matric suction for a soil. The water content can be defined as the amount of water contained within the pores of the soil. In soil science volumetric water content (θ), which is defined as the ratio of volume of water to the total volume of soil is most commonly used (Leong and Rahardjo, 1997). In geotechnical engineering practice, gravimetric water content (ω), which is the ratio of the mass of water to the mass of solids, is most commonly used. Matric suction is the difference between pore air pressure and pore water pressure. For common geotechnical engineering practice pore air pressure is equal to the atmospheric pressure and is considered as zero. For unsaturated soils pore water pressure is always negative (less then atmospheric pressure). This negative pore water pressure is termed as suction.

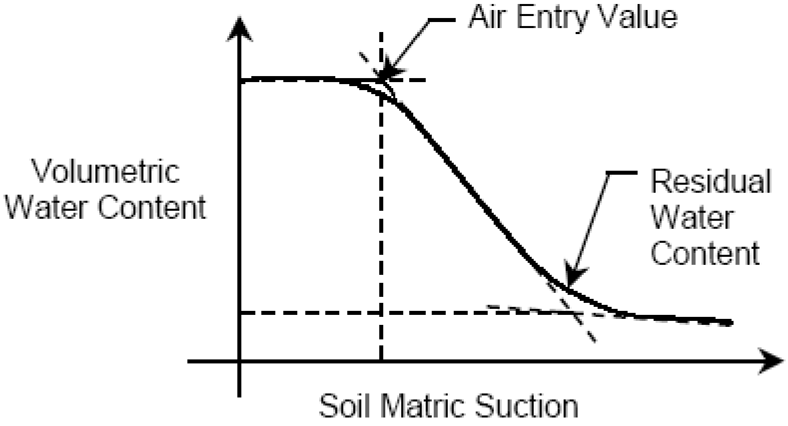

Fig 2.1 Typical Soil Water Characteristic Curve.

SWCC exhibits similarity relationship between particular soil and properties of unsaturated soils as concluded through laboratorial studies (Fredlund and Rahardjo, 1993). It has become an acceptable procedure to predict empirically the permeability function for an unsaturated soil by using the saturated coefficient of permeability and the soil-water characteristic curve (Marshall, 1958; Mualem, 1986; University of Saskatchewan, 1984). Similar procedures have been suggested for the shear strength properties of an unsaturated soil (Fredlund and Rahardjo, 1993). Since the soil-water characteristic curve is used as the basis for the prediction of other unsaturated soil parameters, such as the permeability and shear-strength functions, it is important to have a reasonably accurate characterization of the soil-water characteristic curve (Fredlund Xing, 1994).

2.2.1 Features of SWCC

The SWCC is a plot of volumetric water-content on the y-axis against soil-suction on the x-axis; the graph is semi-log in nature with the soil-suction plotted on a logarithmic scale.

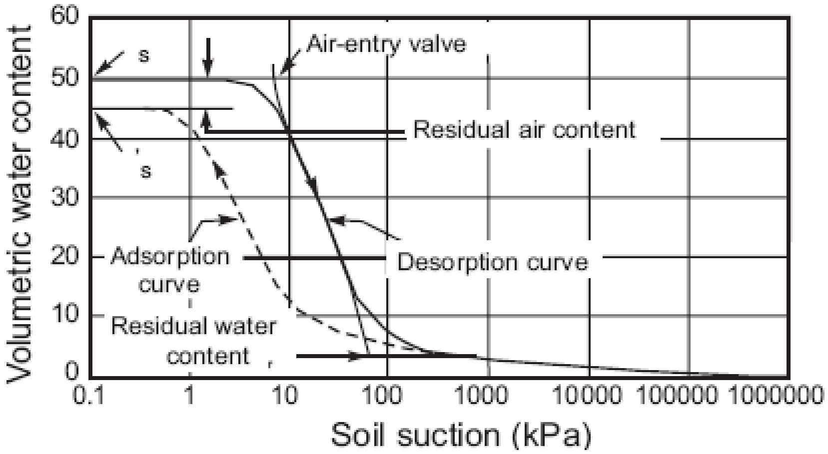

Fig 2.2 Typical Soil Water Characteristic Curve for a Silty Soil
(Fredlund and Xing, 1994).

Figure 2.2 shows the typical relationship between volumetric water-content and matric suction. At zero matric suction the volumetric water-content is called the saturated volumetric water-content and is representative of the total capacity of the soil pores to hold water (Fredlund and Xing, 1994).

The main curve shown in figure 2.2 is a desorption curve; the adsorption curve differs from the former due to hysteresis. The hysteresis in the SWCC is caused due to non-uniformity of pore-size distribution in the soil. During the wetting and drying process, the soil water-content differs at any given matric suction (Fredlund and Rahardjo, 1993).

Looking at the figure 2.2, it is evident that the ending point of the adsorption curve differs from the starting point of the desorption curve; this is due to the air being trapped in the soil (Fredlund and Xing, 1994). The ratio between change in soil matric suction and water content is representative of the soil storage potential. The steepness of the slope over a range of soil suctions is representative of the soil storage potential (Leong and Rahardjo, 1997).

Air-entry value is the measure of the soil matric suction which corresponds to the draining of soil pores. As the suction increases the specimen desaturates. After the air-entry value the water-content at which the SWCC starts to flatten is referred to as the residual water-content. To remove additional water from the soil increase in suction is required beyond the residual water-content level. Sillers (1997) described residual water-content as the water-content where water goes from being held by capillary action in the soil to the adsorptive properties of the soil, at zero water-content the soil matric suction is at 1,000,000 kPa (Fredlund et al., 1994).

Since the definition of residual water-content remains vague, Vanapalli et al. (1998) formulated a technique to quantify the relationship. Figure 2.2 shows the technique involved first drawing a tangent from the point of inflection on the straight-line portion of the SWCC, a second line was drawn from the point at 1,000,000 kPa, tangent to the original curve. The point of intersection of these two lines defines the residual volumetric water-content.

2.2.2 Behavior of SWCC

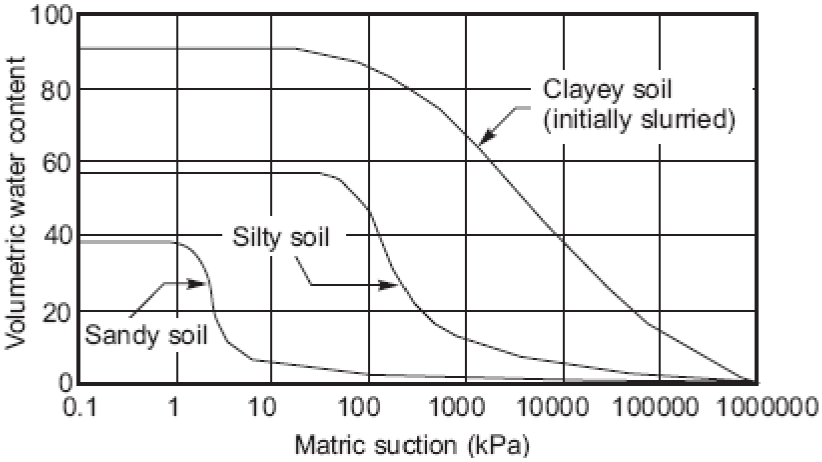

Fig 2.3 Soil Water Characteristic Curve for a Sandy Soil, Silty Soil and Clayey Soil (Fredlund and Xing, 1994).

Figure 2.3 depicts normal SWCCs for sandy, silty, and clayey soils on a semi-logarithmic scale. Saturated water-content and the air-entry value increases with the plasticity, and percentage fines of the soil. With increase in fines of a soil, the rate of desaturation decreases. Thus a soil with high plasticity has a capacity of holding water even at higher matric suctions. Initial water-content, density, stress history, soil state and soil structure, pore size distribution also affects the shape of the SWCC (Fredlund and Xing, 1994).

2.2.3 SWCC Models

In order to develop SWCC for a particular soil, it requires several tests and it‟s a time consuming process to obtain all the necessary information. In order to facilitate this problem, several equations or models are developed in the last four decades. Most SWCC equations or models are empirical in nature, and are based according to the shape of the SWCC. However, it may be seen that even though most SWCCs are sigmoidal in nature, the equations do not produce sigmoidal curves (Leong and Rahardjo, 1997). Most commonly used models are described in the following sections.

Brooks and Corey (1964) Model:

Brooks and Corey are the first to propose equation for SWCC, and the curve is assumed to be exponentially decreasing function of water content at soil suctions greater then the air-entry value and remains the same for suction less than the air-entry value. In addition model is not suitable for degree of saturation less than residual value (Brooks and Corey, 1964). Based on the above conclusions the model is more suitable for coarse grained soils than fine-grained soils (Fredlund and Xing, 1994). The equation is given as:

$$\frac{\quad_{r}}{\quad_{s}\quad_{r}} \qquad \frac{}{a}^{\,n} \text{ when } \quad > a \qquad (2.1)$$

$$1 \text{ and } \qquad _{s} \text{ when } \quad < a \qquad (2.2)$$

where, : Normalized water content; : Soil suction; : Volumetric water content; $_r$: Residual volumetric water content; $_s$: Saturated volumetric water content; „a‟ and „n‟: equation parameters.

Here „a‟ is related to the air-entry value, which is the suction required to remove water from the largest pores or matric suction for which air starts to enter largest pores in the soil. „n‟ is related to the pore size distribution of the soil. Larger the value of „n‟ more uniform the pore sizes in the soil and also steeper is the SWCC within the desaturation zone.

Van Genutchen (1980) Model:

This model is widely used model in modeling and understanding the unsaturated soil behavior. The model is continuous and fits the SWCC over the entire range of soil suction, having fitting parameters as a, n, and m respectively. The model is given as:

$$\frac{\qquad {}_{r}}{{}_{s} \qquad {}_{r}} \qquad \frac{1}{1 \qquad \frac{}{a}^{\,n}}^{\,m} \tag{2.3}$$

where, : Normalized water content; : Soil suction; : Volumetric water content; $_r$: Residual volumetric water content; $_s$: Saturated volumetric water content; a, n, and m: Equation parameters.

Here, the „a‟ parameter is related to the air-entry value which is the suction required to remove water from the largest pores or matric suction for which air starts to enter largest pores in the soil, „n‟ parameter is related to the pore size distribution of the soil, „m‟ parameter is related to the asymmetry of the model. Soils with steeper slope are characterized by smaller „n‟. Also, the soils with higher plasticity index have higher air-entry suction and larger „n‟, which corresponds to an SWCC with shallower slope.

Fredlund and Xing (1994) Model:

This model is similar to the Van Genutchen (1980) model. Using the assumption that soils contain a series of interconnected pores distributed randomly across the surface of the soil, Fredlund and Xing (1994) suggested an equation which explains the entire curve over the full range of the soil-suction, from 0 kPa to 1,000,000 kPa. The model is given as:

$$_{v} \qquad \frac{_{s}}{\ln e \quad \frac{\quad}{a}^{\;n \quad m}} \tag{2.4}$$

where $_{v}$: Volumetric water content; $_{s}$: Volumetric water content at suction = 0 kPa; : Matric suction in kPa; a, n, and m: Model parameters = 2.71828 (natural number).

Here the model parameters have the same meaning as mentioned in Van Genutchen (1980). Detailed studies by Sillers et al., (2001) showed that Fredlund and Xing (1994) equation is well fitted for experimental data for various soils over a wide range of suction and requires less iterations to coverage to the best–fit parameters than Van Genutchen (1980).

2.3 Determination of SWCC

Laboratory determination of the Soil water characteristic curve is generally performed by either increasing or decreasing the soil suction and measuring the resulting soil water content, ω after equilibrium is reached. Soil suction can be determined either by direct or indirect method. Direct methods include pressure plates, suction plates, pressure membranes, and tensiometers. Indirect methods include filter paper, moisture blocks, heat dissipation sensors and phychrometers. A brief description of some of the methods is presented in the following sections.

2.3.1 Pressure Plate Technique

The technique works on the principle of axis translation, which involves increasing the soil matric suction (u_a-u_w) in different steps and measuring the resulting water content, ω after equilibrium is reached at each step. Pressure plates can measure up to a suction range of 1,000 kPa. More detailed explanation about pressure plate is given in chapter 3.

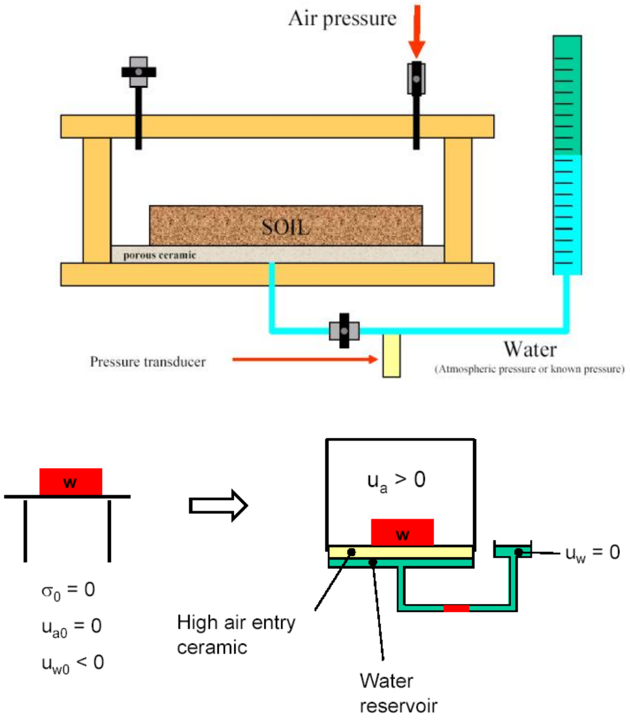

Fig 2.4 Axis Translation Technique (Marinho et al., 2005).

2.3.2 Filter-Paper Technique

Filter paper is simple, inexpensive method to measure soil suction. Total and Matric suctions are measured using this particular technique; the test is conducted in accordance with the ASTM D 5298, ASTM 2000 standards. Filter paper can measure higher suctions up to a range of 1,000,000 kPa. Filter paper is allowed to absorb moisture from a soil specimen, when equilibrium is reached between soil and filter paper, the suction in the filter paper is equal to suction in the soil (Ridley and Wray, 1995). Fig 2.5 shows arrangement of filter paper to measure Total suction (non contact method) and Matric suction (contact method). More detailed explanation is given in chapter 3.

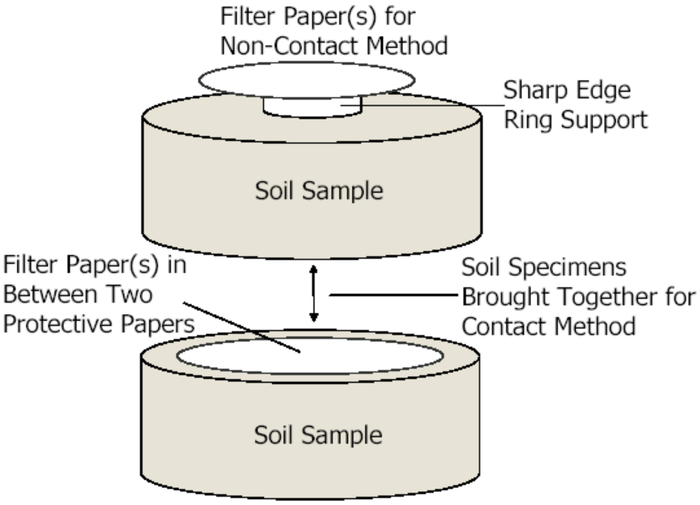

Fig 2.5 Filter Paper Contact and Non Contact Method (Bulut et al., 2001).

2.3.3 The Fredlund Soil Water Characteristic Cell

Fredlund has developed soil water characteristic cell which is more reliable and which would measure SWCC over the entire range suction range for all types of soils. Fig 2.6 shows a picture of the apparatus.

Fig 2.6 The Fredlund Soil Water Characteristic Cell.

This apparatus allows for suction control of up to 1,500 kPa and can handle loading of specimens of up to 75 mm. The equipment is made of stainless steel and consists of hand-operated knobs for fast set-up of specimens. Gauges and pressure panels mounted on the equipment allow for minute measurements at low-pressure ranges.

2.3.4 SWCC from Grain Size Distribution and Volume-Mass Properties

Fredlund et al., (1997) proposed an indirect method to estimate the SWCC from grain size distribution curve and volume-mass properties. To achieve this grain size distribution is divided in to small groups of uniformly sized particles. For each group of particles packing porosity and SWCC is assumed and after that incremental SWCC is summed to produce final SWCC.

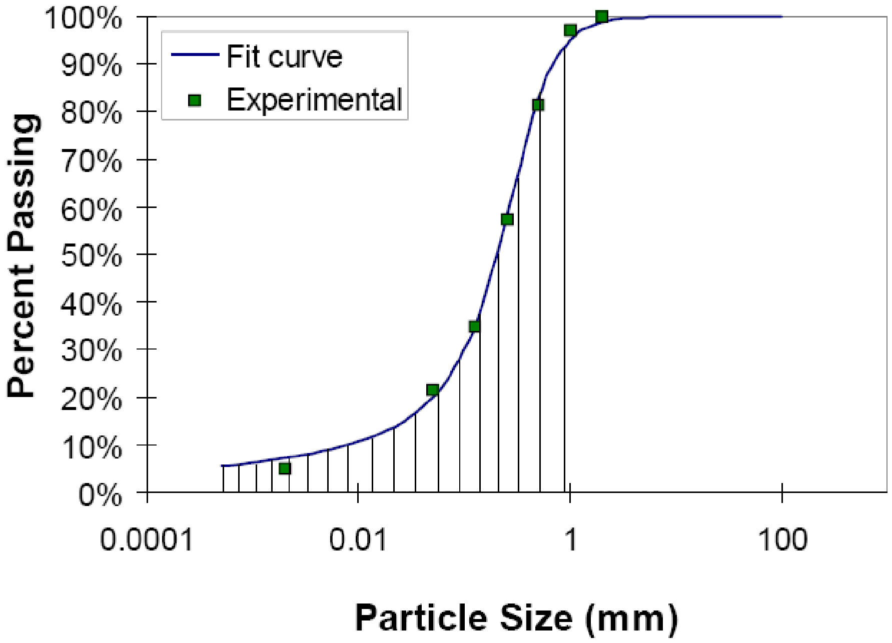

Fig 2.7 Small Divisions of Particle Size used to build Complete SWCC (Fredlund et al., 1997).

2.4 Previous Research

Puppala et al., (2006) studied the behavior of soil water characteristic curve aspects of expansive soils through the use of various additives like Fly Ash and Bottom Ash. The soil for testing was sampled from Dallas/Fort Worth International Airport in

Irving, Texas and from South Arlington, Texas; it has plasticity index values of 32% and 22%, respectively. SWCCs were obtained in the suction range of 0-1,000 kPa following drying path. The experimental results thus obtained from Pressure plate technique were then analyzed by using Fredlund and Xing (1994) model.

The experimental program undertaken by these researchers involved two phases; in the first phase, they used a Class F fly ash, a product from Mohave plant in Texas, which is termed as "Fly Ash1" or "F1", and Bottom Ash. Four different proportions were studied.

In the second phase, a unified study was conducted using Class F Fly Ash, which is termed as "Fly Ash 2" or "F 2"and Bottom Ash obtained from the Monticello plant in Texas, and Polypropylene and Nylon fibers. The SWCCS were obtained following drying path from 0 kPa to 1,000 kPa suction.

The SWCC model simulation plots show variations of water contents up to matric suctions values of 10,000 kPa. However, there modeling simulation was obtained by analyzing measured data of matric suctions up to 1,000 kPa. Hence, beyond 1,000 kPa suction the model results are extensions based on previous suction data.

Fig 2.8 and Fig 2.9 shows the SWCC of Control and Class F1 and F2 Fly Ash treated soils of DFW and Arlington soils respectively.

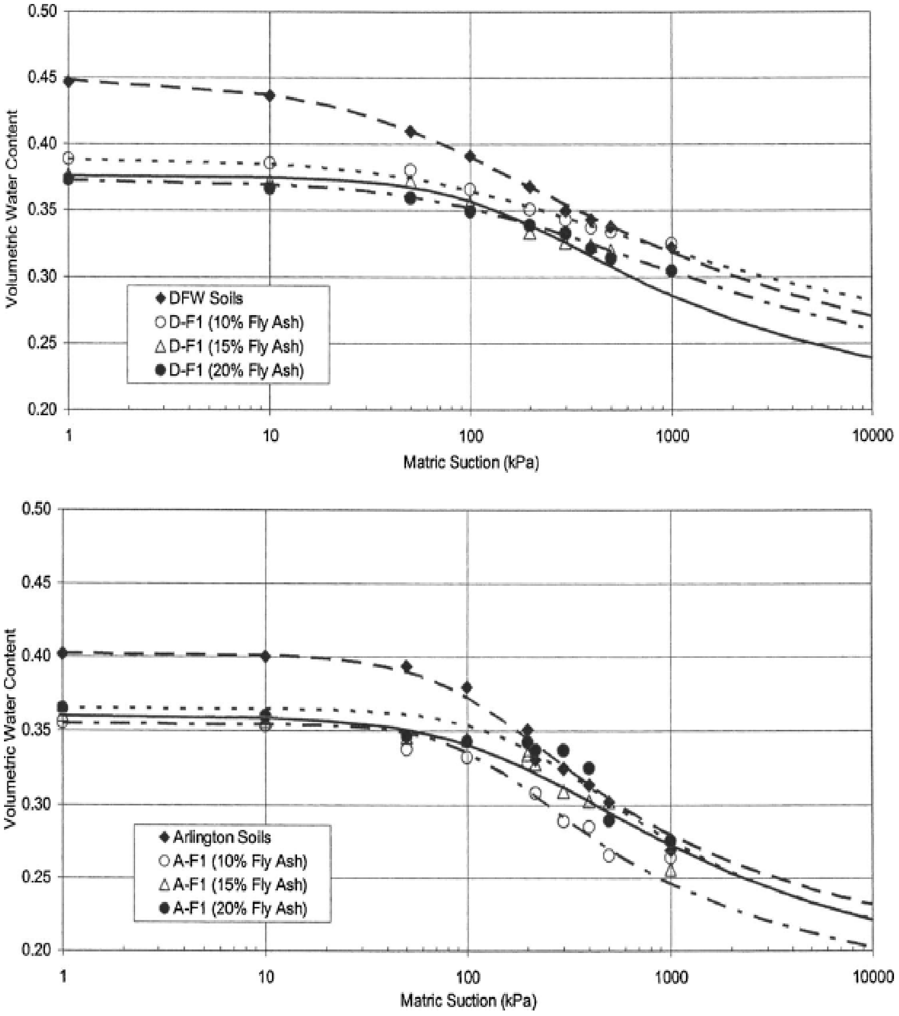

Fig 2.8 SWCCs of Control and Class F Fly Ash-Treated Soils (F1) for DFW and Arlington Soils (Puppala et al., 2006).

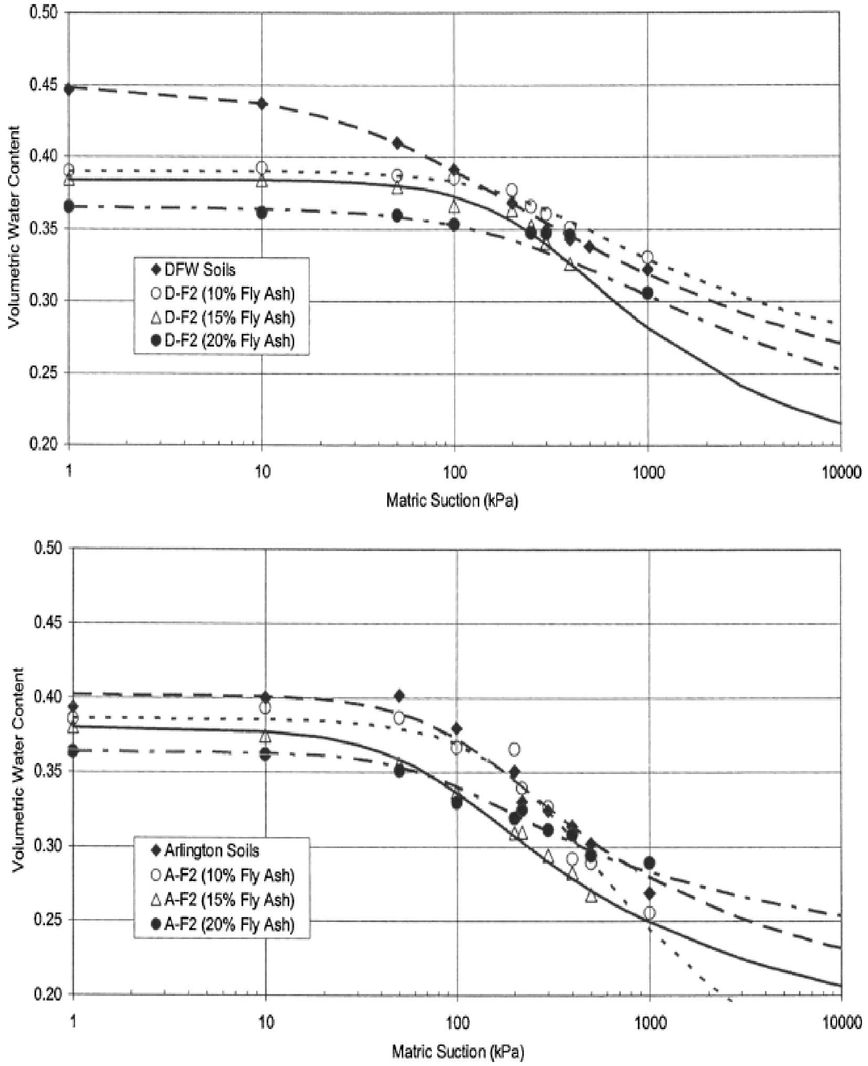

Fig 2.9 SWCCs of Control and Class F Fly Ash-Treated Soils (F2) for DFW and Arlington Soils (Puppala et al., 2006).

Results of Fly ash treated soils are summarized as follows (Puppala et al. 2006):

1) The volumetric water content of both DFW and Arlington Soils decreases as the dosage of stabilizer increases.
2) Both Class F Fly Ash treated soil (F1) and Class F Fly Ash treated soil (F2) provided similar trend since the fly ash used in the present study is fine and in

powdered form and such ash alters the particle and pore size distribution of expansive clayey soil by occupying the original voids of clayey soil and by binding finer clay particles at contact points. For this reason, the slope of SWCC of fly ash treated soils is flatter in comparison to natural expansive soils.

In the second phase they used Class F Fly Ash which is termed as "Fly Ash 2" or "F2"and Bottom ash and Polypropylene and Nylon fibers for the study. Figs 2.10-2.12 show SWCCs of control and bottom ash treated soils (B), SWCCs of control and combined stabilizers-treated soils (F1, F2, B, and Polypropylene fibers), SWCCs of control and combined stabilizer treated soils (F1, F2, B and Nylon fibers) respectively.

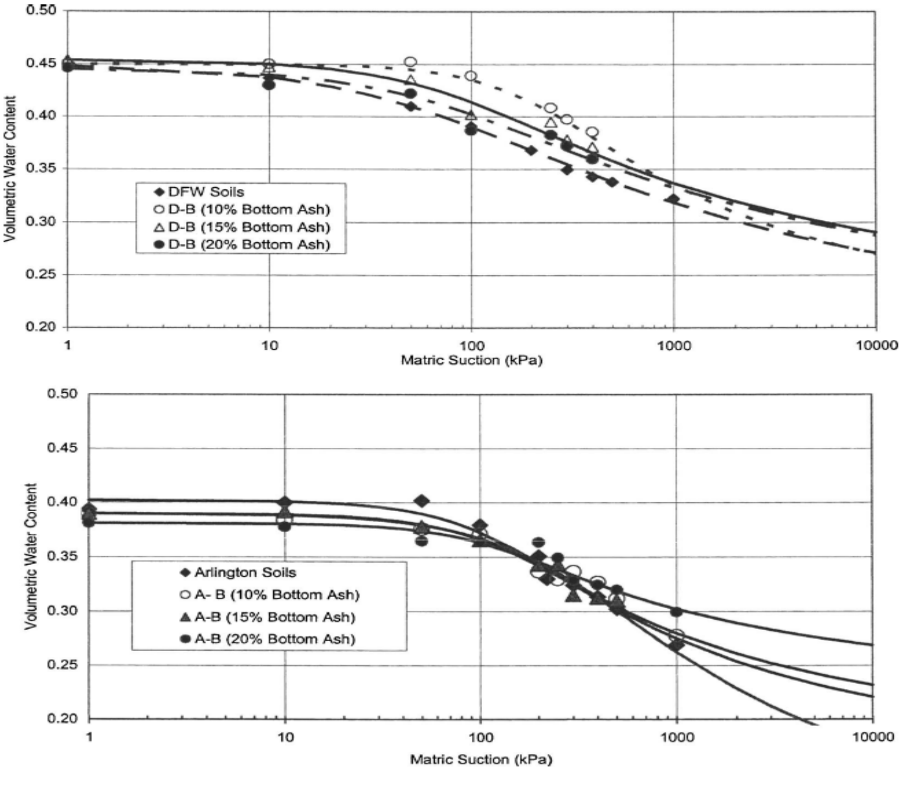

Fig 2.10 SWCCs of Control and Bottom Ash-Treated Soils (B) for DFW and Arlington Soils (Puppala et al., 2006).

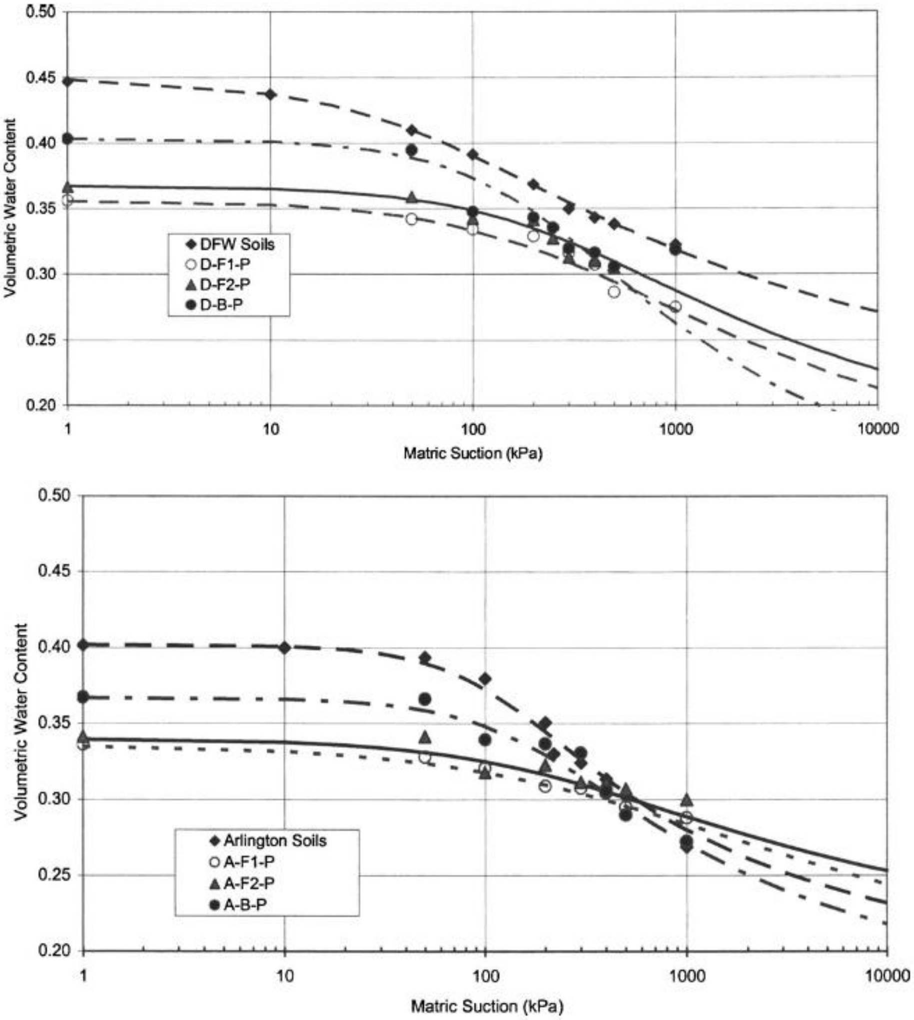

Fig 2.11 SWCCs of Control and Combined Stabilizers-Treated Soils (F1, F2, B, and Polypropylene Fibers) for DFW and Arlington Soils (Puppala et al., 2006).

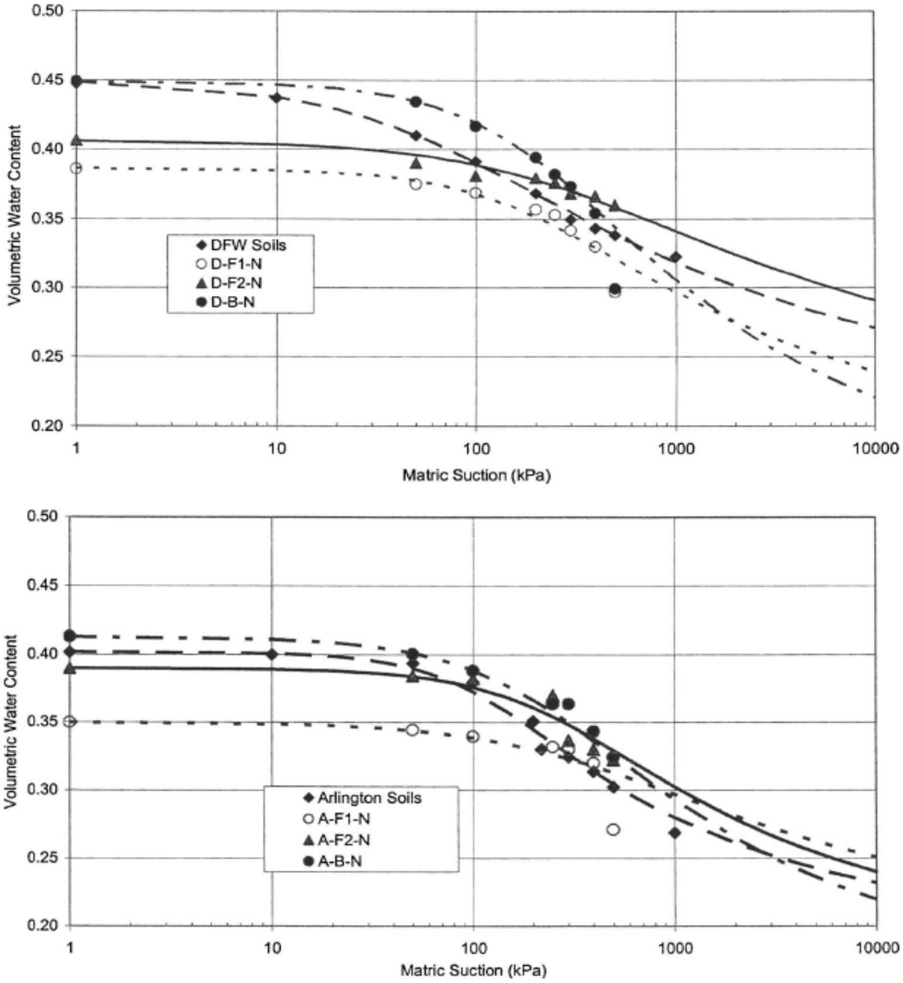

Fig 2.12 SWCCs of Control and Combined Stabilizers Treated Soils (F1, F2, B, and Nylon Fibers) for DFW and Arlington Soils (Puppala et al., 2006).

Analyses of fly ash, bottom ash and polypropylene and nylon fibers from Puppala et al. (2006) can be summarized as follows:

1) The SWCCs from fly ash and bottom ash treated soils show that there are only insignificant or small changes in the soil-water characteristics of bottom ash treated soils and control soils.

2) The small changes in the SWCC characteristics can be attributed to variations in finer particle size and their distributions of bottom ash-treated soils and control soils.
3) The particle sizes of bottom ash are coarser and such coarse stabilizer is not expected to influence the void distribution of control soils.
4) Sieve size analysis of bottom ash concluded that it contains coarser grained material, so when stabilized such coarse material is expected to slightly alter coarse size proportions of ash-treated soil, and not change the fine fraction of ash-treated soil.
5) The combined ash and fiber stabilizers decreased volumetric water contents of fly ash and fiber-treated soils in comparison to control soils.
6) The changes in volumetric water contents of bottom ash and fiber-treated soils are small which indicate the behavior of combined stabilization is controlled by the ash material stabilization. This implies that the presence of fibers in the treated soils has no significant influence on the volumetric water contents of combined stabilized or treated soils.

CHAPTER 3

FUNDAMENTALS OF PRESSURE PLATE AND FILTER PAPER TECHNIQUES

3.1 Introduction

This chapter is devoted to describing the fundamentals of Pressure plate and Filter paper techniques employed in the present work. In this study SWCCs were determined for pressures ranging from 0 to 690 kPa using Pressure plate apparatus; later on, to complete the SWCC curve for a pressure range of 690 to 1,000,000 kPa, Filter paper method is employed.

3.2 Pressure Plate Drying Test Method

The pressure plate drying test device used in the present study was to establish a relationship between volumetric water content and matric suction potentials in accordance with ASTM D 2325-68.

A ceramic pressure plate extractor manufactured by Soil Moisture Equipment Co. was used for the pressure plate studies of this investigation. A typical pressure plate extractor set up is shown in Fig 3.1. The principle on which pressure plate apparatus works and the main components are described below.

3.2.1 Principle

Pressure plate extractors work on the principle of axis translation technique. Axis translational technique refers to elevating pore air pressure u_a while maintaining constant pore water pressure, u_w (usually $u_w = 0$).

3.2.2 Apparatus Description

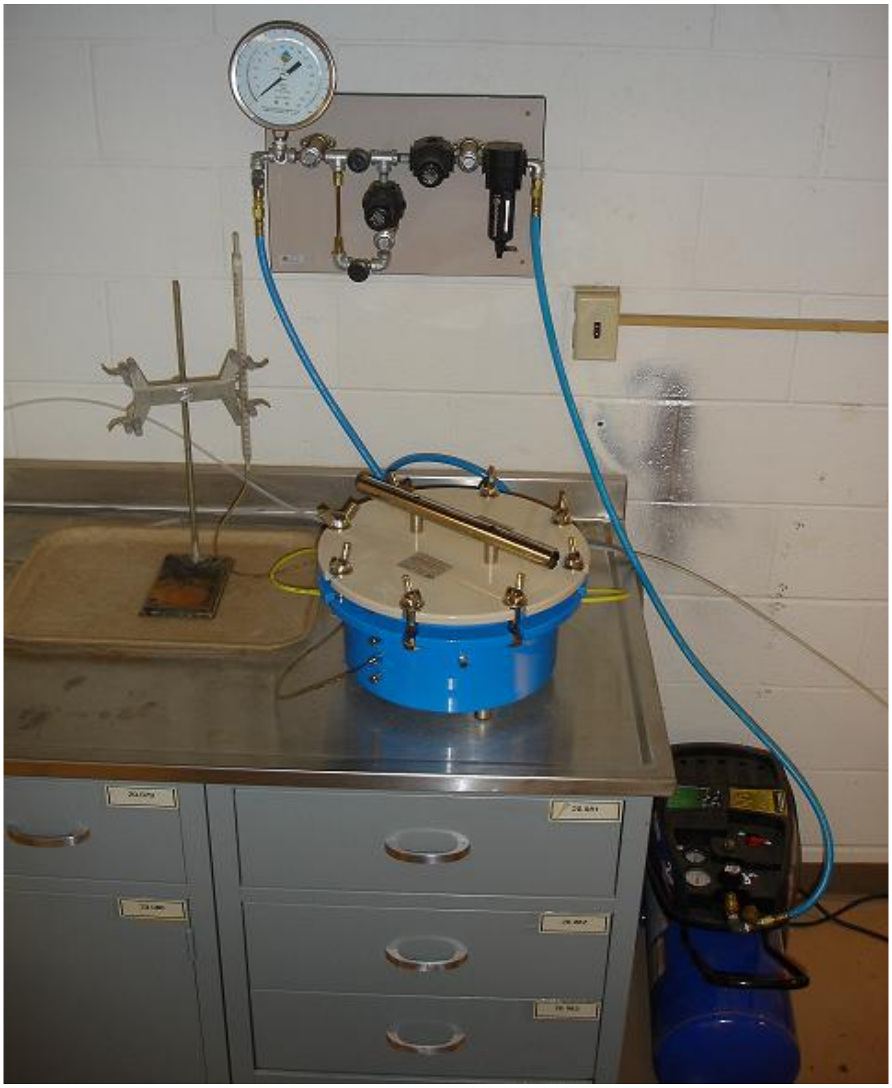

Fig 3.1 Typical Pressure Plate Extractor Setup.

Pressure Vessels:

The pressure vessel is made of steel. The general pressure vessels available in the market are 1 bar, 3 bar, 5 bar, 15 bar which can measure soil matric suction in the range of 0 to 1 bar, 0 to 3 bar, 0 to 5 bar, 0 to 15 bar, respectively. Figures 3.2 and 3.3 show the pressure vessels for 5 bar and 15 bar extractors. However, a 15 bar pressure plate extractor is used for present study. All the pressure vessels comprise a lid (pressure seal) which is assembled to the pressure vessel with clamping bolts and pressure inlet fitting and out flow tubes which is shown in fig 3.4.

Fig 3.2 5 Bar Extractor Model 1500 (Soil Moisture Corp.).

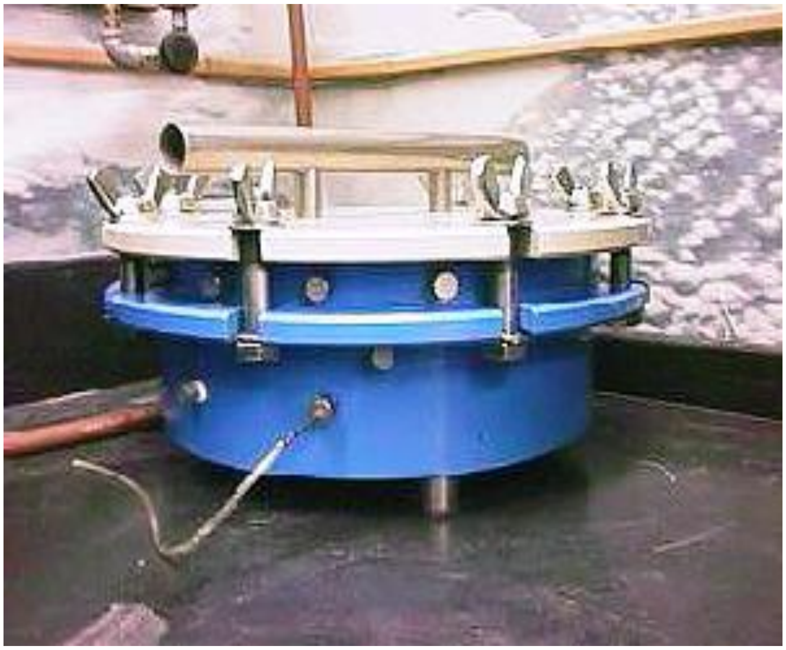

Fig 3.3 15 Bar Extractor Model 1600 (Soil Moisture Corp.).

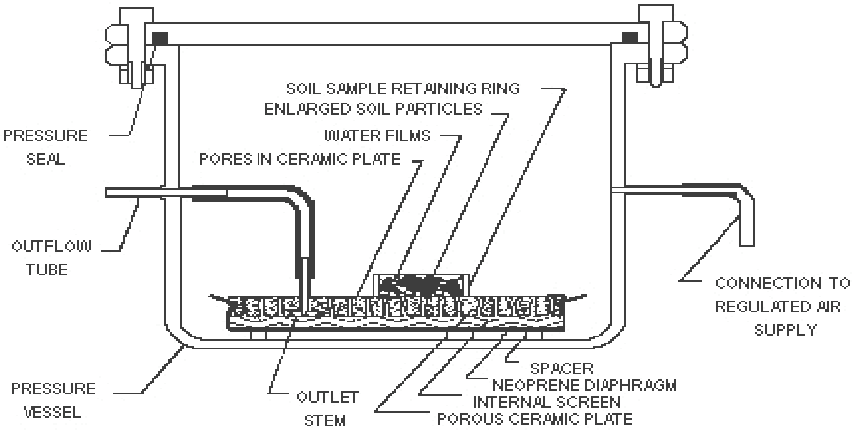

Fig 3.4 Pressure Cell.

Ceramic Pressure Plate Cell:

A pressure plate cell consists of a porous ceramic plate, covered on one side by a thin neoprene diaphragm, sealed to the edges of the ceramic plate. The diameter of the ceramic plate ranges between 260 mm and 280 mm. Three types of ceramic plates are supplied with the apparatus. One can measure up to 1 bar (100 kPa) another can handle up to 3 bars (300 kPa) and the third plate can handle up to 15 bars (1500 kPa). Fig 3.5 shows a picture of the 15 bar ceramic plate. Between the plate and diaphragm, there is a screen which provides a route for the flow of water. An outlet stem is connected to an outflow tube fitting, which connects to the atmosphere outside the extractor. An internal screen provides a passage for flow of water. An outlet stem running through the ceramic plate connects this passage to the outflow tube assembly.

Fig 3.5 15 Bar Ceramic Plate.

Air Compressor:

The pressure required for the test is applied through air compressor. It is connected to the test chamber through the connecting hose. The test chamber consists of a pressure regulator which regulates the air pressure, air filter which keeps small dirt particles out of the regulators and several control valves. Figs 3.6 and 3.7 show the Pressure regulator and Air compressor used in the present study, respectively.

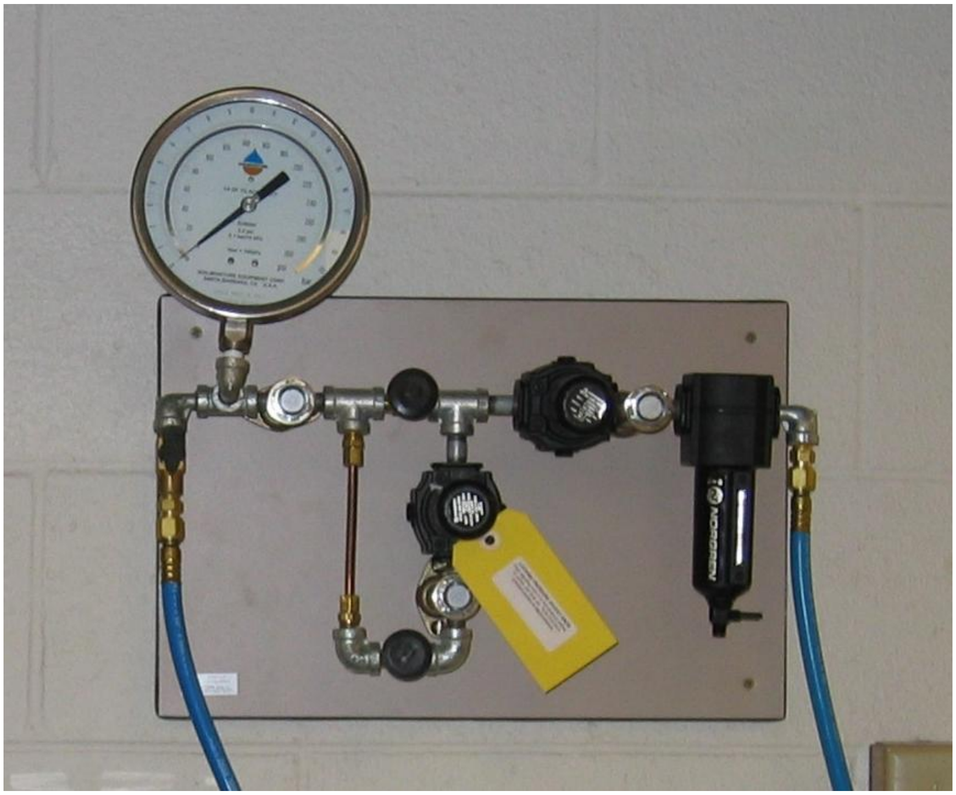

Fig 3.6 Pressure Regulator Set up.

Fig 3.7 Air Compressor.

A pressure plate cell consists of a porous ceramic plate, covered on one side by a thin neoprene diaphragm, sealed to the edges of the ceramic plate. Between the plate and diaphragm, there is a screen which provides a route for the flow of water. An outlet stem is connects this route to an outflow tube fitting, which connects to the atmosphere outside the extractor.

3.3 Test Procedure

1) Soil samples for pressure plate testing were compacted in a ring of 2.5 inch diameter and 1 inch thickness. Each soil sample was compacted to reach the target maximum dry density weight. After mixing, soil specimens were cured for fourteen days in 100% humidity control room.

Fig 3.8 Compaction of Soil Specimen.

2) The soil specimen were placed on the ceramic plate and saturated with water for 48 hours to achieve fully saturated conditions. A surcharge weight of 4000 gms is placed on soil specimens throughout the soaking period.

Fig 3.9 Saturation of Soil Specimens.

3) Then the saturated ceramic plates along with the saturated soil specimen were placed inside the pressure chamber and closed tightly using clamping bolts.

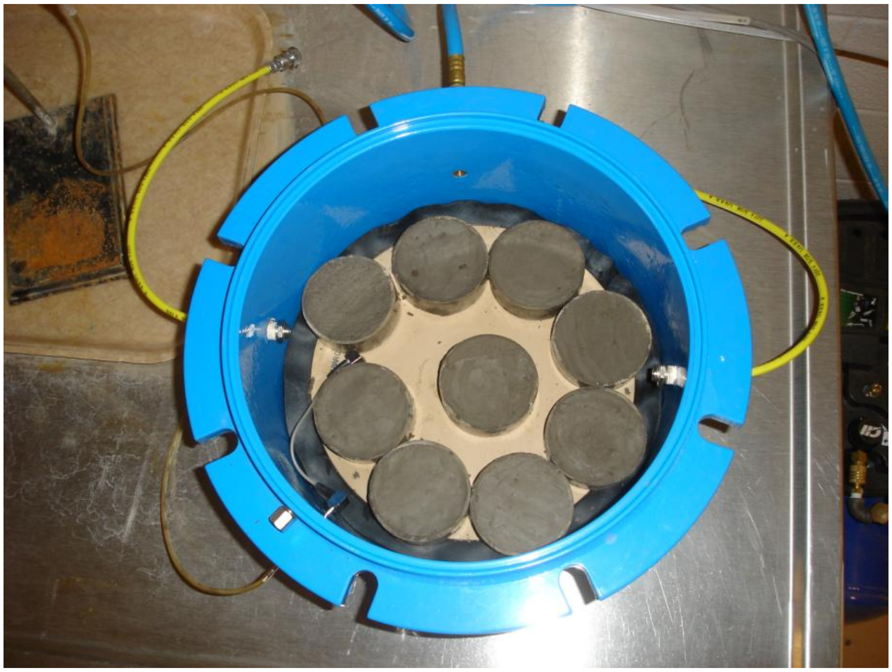

Fig 3.10 Soil Specimens in Pressure Plate Cell.

4) The air pressure was then regulated to the desired value. After a very short period of time (few minutes), water starts out flowing from the pressure chamber.

Fig 3.11 Regulation of Air Pressure.

5) Few hours later, the water outflow rate decreased significantly.

6) The specimens were removed after the outflow from the burette had ceased for 2 to 3 hours, indicating equilibrium has been reached.

7) Equilibrium was reached in 18 to 20 hours from the beginning of the test. After equilibrium was reached the pressure regulator was then turned off, the clamping bolts and lid of the pressure extractor were removed.

8) The soil specimens were immediately transferred to covered moisture cans in order to avoid changes in the water content.

9) The specimens were weighed and placed in a drying oven at a temperature of 108 degrees Celsius for 24 hours.

10) The dry specimens were removed from the oven and immediately weighed.

11) Gravimetric water contents of the soil specimens were calculated and then converted to Volumetric water content.

3.4 Filter Paper Technique

3.4.1 Introduction

The filter paper method is a soil suction measurement technique. Soil suction is one of the most important parameters describing the moisture condition of the unsaturated soils. The measurements of soil suction are crucial for applying the theories of the engineering behavior of unsaturated soils. The filter paper method is an inexpensive and relatively simple laboratory test methods, from which both total and matric suction measurements are possible.

The filter paper technique used in the present study is carried out according to ASTM D 5298 for measuring matric suction using “contact” filter paper technique, and total suction using “noncontact” filter paper technique. Fig 3.12 shows the arrangement of filter paper contact method (to measure matric suction) and non-contact method (to measure total suction).

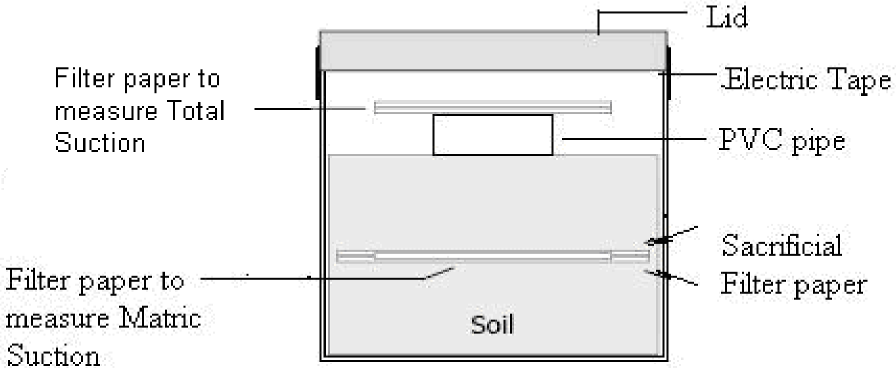

Fig 3.12 Filter Paper to measure Total Suction and Matric Suction.

3.4.2 Equipment

The following equipment is required to measure matric and total suction:

1) Schleicher & Schuell No. 589 – White Hard quantitative 5.5 cm in diameter filter papers.

2) Sensitive balance, with 0.0001 grams accuracy.

3) Oven for 110 5°C.

4) Glass jars; glass jars that are between 250 to 500 ml volume sizes are readily available in the market and can be easily adopted for suction measurements. Glass jars, especially, with 3.5 to 4 inch (8.89 to 10.16 cm) diameter can contain the 2.5 inch diameter Shelby tube samples.

5) Filter papers that are 7cm in diameter are available in the market can be used as protective filter papers.

6) Moisture can to measure filter paper water content determination.

7) A perforated sheet of steel mesh or PVC pipe of 1.5 to 2 cm height which has smaller diameter than filter paper was used to measure total suction.

8) A pair of Tweezers is used to hold the filter paper; electric tape is used to close the glass jar lid tightly. Fig 3.13 shows the equipment required to measure matric and total suction.

Fig 3.13 Equipment required to measure Matric and Total Suction.

3.5 Measurement of Total and Matric Suction

In the present thesis work, Schleicher and Schuell # 589 white hand filter papers were used to measure total suction and matric suction (ASTM D 5298). Typical size of the filter paper is circular with a 5.5 cm diameter, and weighs about 0.22 gm. A detailed procedure for measuring matric and total suction is as follows:

1) Prior to contact testing a calibration curve is obtained by measuring the relation ship between matric suction and filter paper water content. This can be accomplished by testing representative papers as one normally would test a soil specimen using a pressure plate or pressure membrane device. Similarly prior to noncontact testing papers are calibrated by determining the relationship between equilibrium water content and relative humidity using salt solution of known concentration, typically NaCl and KCl.
2) Filter paper was oven dried to consistency in mass at 105°C and then allowed to cool to room temperature in a desiccator.
3) The soil sample was placed in the jar and perforated sheet of steel mesh or PVC pipe was trimmed to fit the inner diameter of the jar and suspended one filter paper above the soil sample to measure total suction and to measure matric suction, a filter paper is sandwiched in between two sacrificial filter papers placed in between the soil specimen and the two halves of the soil specimen are brought together and sealed with electrical tape to keep the two specimens together in a good contact manner.

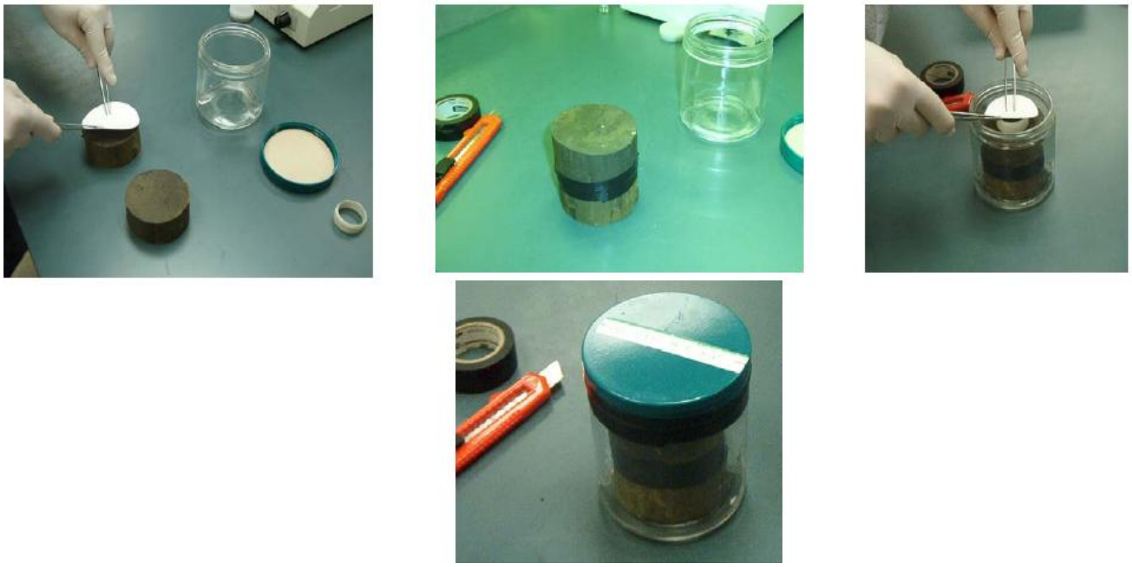

Fig 3.14 Some of the Applications of Filter Paper (Bulut et al., 2001).

4) Carefully, filter paper was placed such that the paper did not touch top sides of the jar where liquid water may otherwise be absorbed.
5) The glass jar was sealed with electric tape after placing filter paper for an equilibrium period of 7 to 10 days.
6) The paper was then removed from the jar and immediately weighed to the nearest 0.0001g with the electronic balance.
7) The paper was dried in the oven and weighed again to determine the filter paper water content.
8) The water content of the filter paper was used to determine total suction and matric suction using calibration curve as shown in figure 3.15.

9) The corresponding water content of the soil is gravimetrically determined to develop one point along the soil water characteristic curve.

10) Seven different specimens were compacted at different water contents to generate additional points on the SWCC.

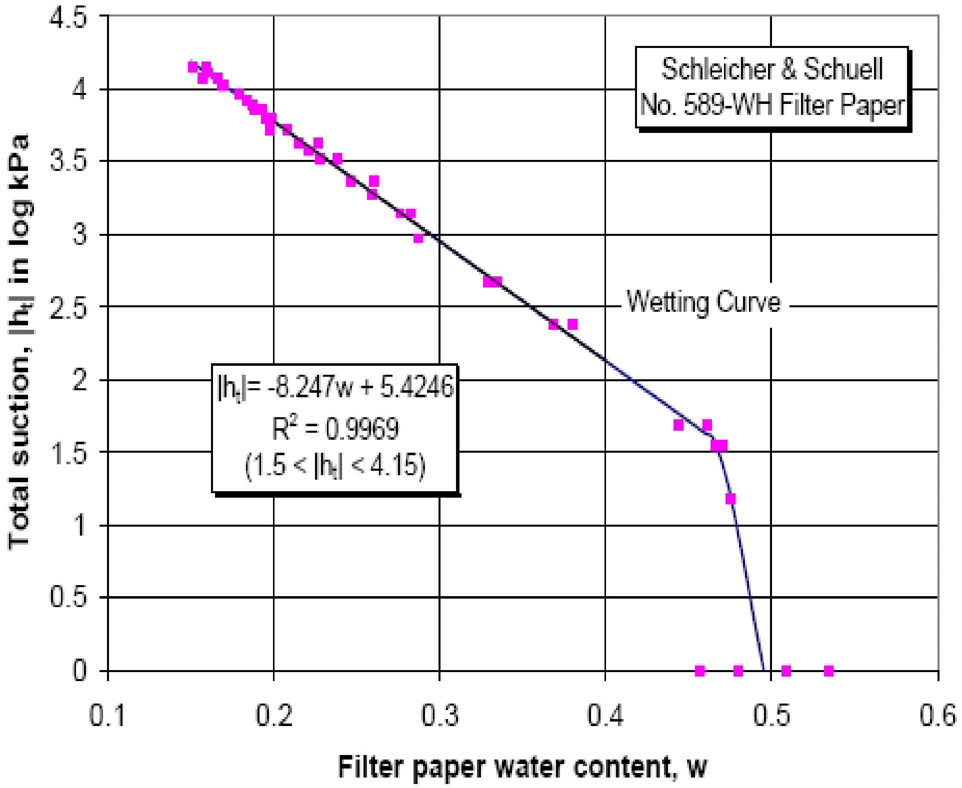

Fig 3.15 Filter Paper Calibration Curve (Bulut et al., 2001).

CHAPTER 4

EXPERIMENTAL PROGRAM AND TEST VARIABLES

4.1 Introduction

The experiment program in the present thesis work was designed to study the effect of stabilizer treatment on the soil-water characteristic curve of natural expansive soil. The natural expansive soil was stabilized with cement and lime (2%, 5%, and 10% dosages). Initially, soil-water characteristic curves were obtained following the drying path in the suction range of 0 to 690 kPa via Pressure plate technique. The other part of the curve is completed by using Filter paper method from 690 to 1,000,000 kPa suction range. This particular suction range is useful for engineers working with stabilized sub soils under covered structures such as pavements.

The following sections describe the basic properties of testing soil, types of laboratory tests performed, test equipment used and test procedure followed.

4.2 Basic Properties of Testing Soil

The natural clay used in the present study was sampled from the east side of south Cooper Estate Village in Southeast Arlington, Texas. The soil is dark brown in color, with natural water content of 4% and low sulfate content. X-ray diffraction analyses show that south Arlington soils contain clay minerals (montmorillonite and illite) and non-clay minerals, including quartz. The liquid limit of this soil is 50% and plastic limit is 19%. The plasticity index of the soil is 31%. The soil classifies as

A-7-6 and CH according to the AASHTO and USCS systems, respectively. The basic engineering properties of the testing soil are summarized in Table 4.1.

Table 4.1 Basic Engineering Properties.

Property	**Magnitude**
Passing #200 (%)	80
Specific Gravity (Gs)	2.72
Liquid Limit (LL, %)	50
Plasticity Index (PI, %)	19
Natural Moisture Content (%)	4
Standard Proctor Optimum moisture content (%)	20
Standard Proctor Maximum dry density ($_{\text{d-max}}$)	16.25
Standard Proctor Optimum moisture content (%)	20
AASHTO Classification	A-7-6

4.2.1 Atterberg Limit Test

Atterberg tests were conducted to study the plasticity nature of the natural expansive clay sampled from Arlington, Texas. This test was conducted on cohesive soil mixes as per ASTM D-4318 specifications. The liquid limit and plastic limit are the water contents at which the clayey soils exhibit both liquid and plastic nature, respectively. Liquid limit was determined by using soil passing through a 475 µm sieve. The plastic limit of each soil was determined by using soil passing through a 475 µm sieve and rolling 3mm diameter threads of soil until they began to crack. The liquid limit and plastic limit for natural expansive clay are 50% and 19%, respectively. Fig 4.1 shows the plot of liquid limit. The difference between these Liquid Limit and Plastic Limit is known as the plasticity index, which is generally used to characterize the plastic nature of soils.

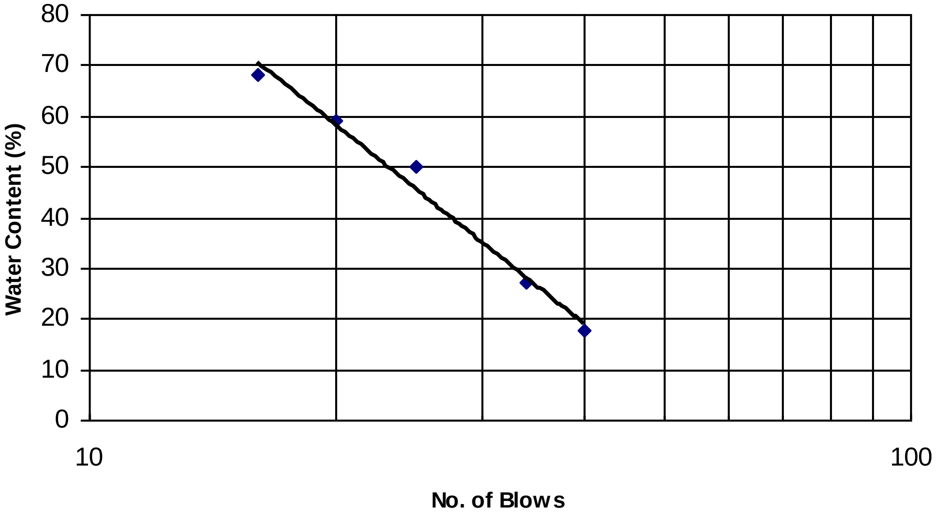

Fig 4.1 Liquid Limit Test for Control Soil.

4.2.2 Compaction Moisture Content and Dry Unit Weight Relationships

To establish the compaction moisture content and dry unit weight relationships, and to know the optimum moisture content of the control soil, soil compaction tests were conducted on control soil as well as treated soils. Standard proctor tests were conducted on the control soil as per ASTM D-3551 method. Figure 4.2 presents the compaction dry unit weight and moisture content relationships of control soil.

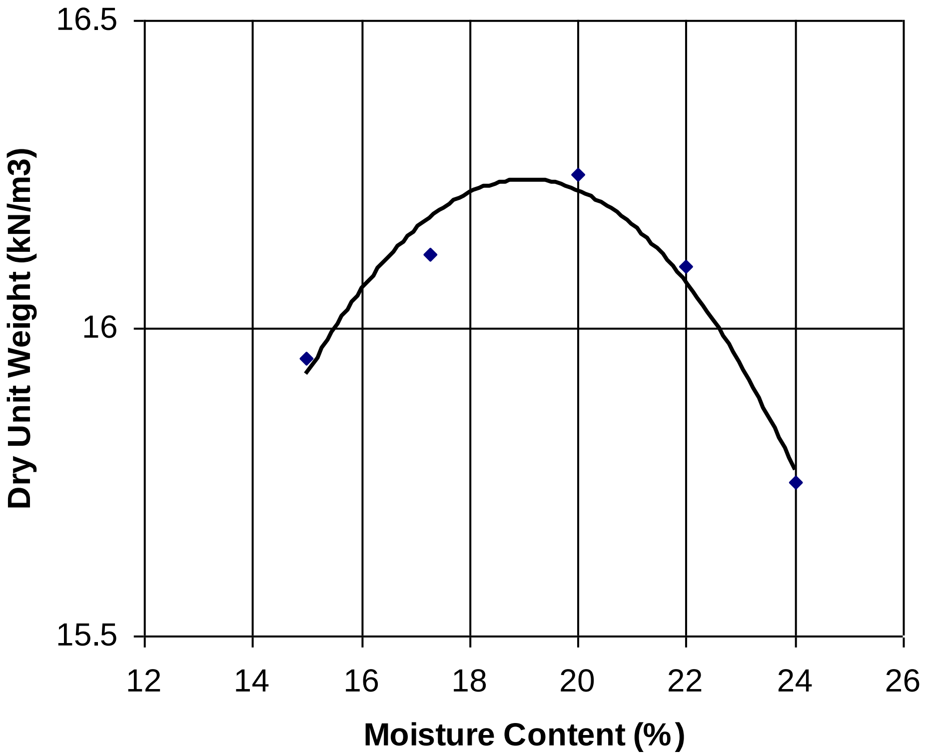

Fig 4.2 Standard Proctor Compaction Curve for Control Soil.

4.2.3 Grain Size Analysis for the Control Soil

Grain size analysis was carried out to know the particle size distribution. Fig 4.3 shows the plot between sieve size and percentage fines. The plot confirms classification of the soil as A-7-6 and CH according to the AASHTO and USCS, respectively.

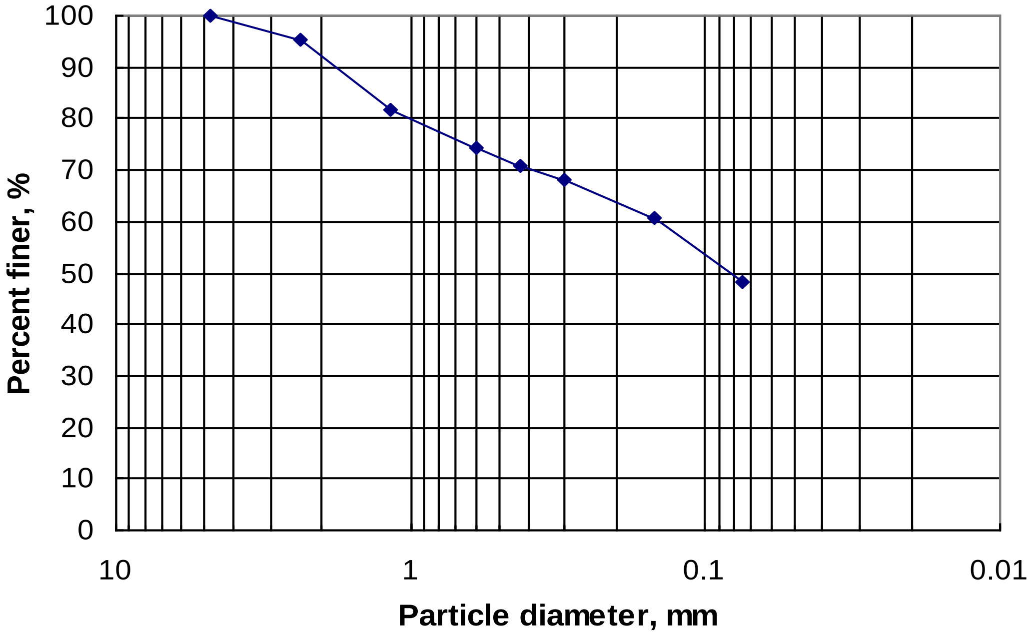

Fig 4.3 Grain Size Analysis for Control Soil.

4.3 Soil Stabilizers

Since expansive soils are unstable, there are various ways of stabilizing them to change their properties through the use of additives; most commonly used stabilizers are Lime and Cement. Three different dosages are used, Portland Type I/II cement with 0% (control soil with no treatment), 2%, 5%, 10% dosages and hydrated Lime with 0% (control soil with no treatment), 2%, 5%, 10% dosages.

Different kinds of Portland cement have been used to stabilize soils. Type I normal Portland cement and Type I air-entraining cements were used previously and gave about the same results. Presently, Type II cement has largely replaced Type I cement as greater sulfate resistance is obtained while the cost is often the same. High early strength cement (Type III) has been found to give a higher strength in some soils. Type III cement has a finer particle size and a different compound composition than do the other cement types. Type I/II Portland cement and hydrated lime are produced in local cement and lime industries in Texas, respectively. Chemical properties of type I/II cement are summarized in the following Table 4.2. The hydrated lime used in the present study has a chemical composition of mainly $Ca(OH)_2$ (71.3%) and CaO (6.1%).

Table 4.2 Chemical Components of Type I/II Cement.

Chemical Component	**Proportion (%)**
Calcium oxide (CaO)	63.8
Silicon dioxide (SiO_2)	20.1
Aluminium oxide (Al_2O_3)	4.6
Ferric oxide(Fe_2O_3)	4.2
Sulfur trioxide (SO_3	2.8
Magnesium oxide (MgO)	1.1
Loss of ignition (LOI)	N/A
Total alkalies as (Na_2O_{eq})	0.14
C_3S	N/A
C_2S	N/A
C_3A	N/A

Note: N/A = not available

Table 4.3 Chemical Components of Hydrated Lime.

Chemical Component	**Proportion (%)**
Calcium hydroxide $Ca(OH)_2$	71.3
Calcium oxide (CaO)	6.1

Type I/II Cement and Hydrated Lime were selected as stabilizers because of the enhanced soil properties, market availability, simplicity of use in field applications, and low cost (Bugge and Bartelsmeyer, 1961; Sherwood, 1995). Moreover, most of the North Texas soils contain large amount of sulphates and are prone to exhibit sulfate heaving when calcium-rich stabilizers are used for stabilization (Kota et al., 1996; Perrin, 1992). Type I/II Cement and Hydrated Lime were most commonly used as stabilizers to mitigate sulphate heaving for these expansive soils.

4.3.1 Cement and Lime Stabilization Mechanisms

Stabilization of soils using lime and cement has been in practice for a quite long time. When lime and cement are added to reactive soil, two main reaction types occur:

Short term reaction which include cation exchange, flocculation, agglomeration and carbonation, and

Long term reaction includes pozzolanic reaction.

The hydration of cement and lime releases calcium ions, which in turn replaces original cations (most commonly sodium ions) in clay particles. This process is called as cation exchange process. The free calcium of lime and cement exchanges with the adsorbed cations of the clay mineral, which results in reduction in size of the diffused water layer surrounding the clay particles. This reduction in the diffused water layer allows the clay particles to come closer to one another, causing flocculation, agglomeration of the clay particles. Flocculation also causes decrease in soil plasticity characteristics .Overall the flocculation and agglomeration of lime stabilization results in a soil that is more readily workable, mixable.

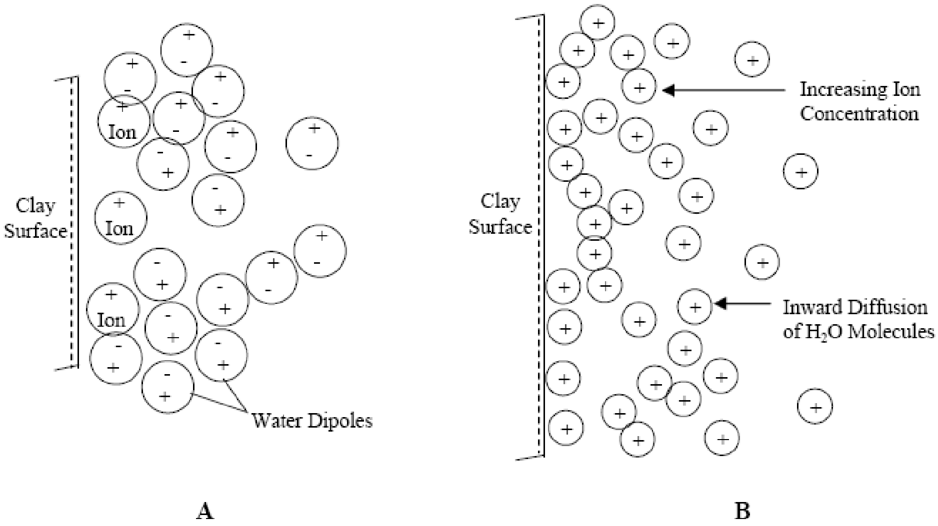

Fig 4.4 Formation of Diffused Water Layer around Clay Particle (Little, 1987).

Practically all fine grained soils display cation exchange and flocculation–agglomeration reactions when treated with lime in the presence of water. The reactions occur quite rapidly when lime is added to soil depending on the availability of various types of cations in the pore fluid, cation replacement can take place. In general the cations are arranged in the order of their replacing power according to Lyotropic series

$Li^+ < Na^+ < H^+ < K^+ < NH^{4+} < Mg^{2+} < Ca^{2+} < Al^{3+,}$ in general higher valency cations replace those of lower valency, and any cation will tend to replace the left of it.

When lime carbonation reaction occur in soil-lime mixture, lime reacts with carbondioxide to form calcium carbonate which is undesirable reaction instead of forming cementations CAHs and CSHs.

The reactions between lime, water, soil silica, and alumina that form various cementing type materials are referred to as pozzolanic reactions. The cementing products are calcium-silicate-hydrates and calcium-aluminate-hydrates. The basic pozzolanic reaction is given by:

$$Ca(OH)_2 \rightarrow Ca^{++} + 2(OH)^-$$

$$Ca^{++} + OH^- + SiO_2 \text{ (soluble clay silica)} \rightarrow \text{calcium-silicate-hydrate (CSH)}$$

$$Ca^{++} + OH^- + Al_2O_3 \text{ (soluble clay alumina)} \rightarrow \text{calcium-aluminate-hydrate (CAH)}$$

Possible sources of silica and alumina in typical fine-grained soils include clay minerals, quartz, feldspars, micas, and other similar silicate or alumino-silicate minerals, either crystalline or amorphous in nature.

Strength gain in soils using cement stabilization occurs through the same type of pozolanic reactions found using lime stabilization. Both lime and cement contain calcium required for the pozolanic reactions to occur. Similar to lime stabilization, carbonation can also occur when using cement stabilization when cement is exposed to air, the cement will react with carbondioxide from the atmosphere to produce a relatively insoluble calcium carbonate.

4.4 Soil Specimen Preparation

The testing soil samples were compacted at optimum moisture content. It was essential to determine and choose the optimum compaction-moisture state since it closely resembles initial in-situ soil conditions of stabilized subsoils. Soil samples were compacted into a custom-made ring of 2.5 inch diameter and 1 inch thickness). Lime and cement treated soils, with four dosage levels 0% (control soil with no treatment), 2%, 5%, and 10%, respectively, were studied. A total of 9 soil samples for each stabilizer dosage are tested. After the soil is thoroughly mixed, soil specimens were cured for fourteen days in a 100% humidity controlled curing room. After curing for 14 days, soil specimens are soaked in water for 48 hours to achieve maximum possible saturation and then subjected to pressure plate drying testing.

4.4.1 Pressure Plate Testing

A pressure plate extractor was used for a soil matric suction range of 0 kPa to 690 kPa. The pressure extractor can accommodate up to 9 soil samples which were in contact with the ceramic plate. Once the extractor was closed tightly with clamping bolts, an air pressure was applied to a desired value. After some time, water starts flowing from the outlet tube into the outer glass burette. Attainment of equilibrium was judged when outflow of water ceased. The samples were then removed and gravimetric water content was measured. One soil specimen corresponded to a single point on the soil-water characteristic curve.

4.4.2 Filter Paper Method

In order to complete the SWCC curve at highest values of matric suction (i.e., after the last point achieved via pressure plate testing), filter paper method was used. Filter paper can measure higher suctions up to 1,000,000 kPa. The filter paper method was briefly described in chapter 3.

The following chapter includes the analysis of all test results, including the Multiple Regression Analysis of the SWCC experimental data.

CHAPTER 5

ANALYSIS OF TEST RESULTS

5.1 Introduction

In this research, a total of 63 specimens were compacted to determine matric suction using pressure plate and 98 specimens are compacted to determine both matric suction and total suction using filter paper technique. The experimental procedure of pressure plate and filter paper techniques are described in the previous chapter.

This chapter presents the analysis of all test results obtained from pressure plate and filter paper and the analysis of Fredlund and Xing‟s model applied to the obtained SWCC data. The chapter also deals with a Multiple Regression Analysis to develop correlations between basic soil and stabilizer properties, such as water content, dry density, liquid limit, plastic limit, and stabilizer dosage and type, and the model constants obtained from Fredlund and Xing‟s SWCC model equation.

5.2 Soil Specimens for Testing

Nine specimens were compacted into a ring of 2.5 in diameter and 1 in thickness at optimum moisture content. Four dosages levels of cement and lime are studied (i.e. 0%, 2%, 5%, and 10%). For 0% treatment, i.e. control soil with no treatment, a total of 9 specimens are prepared; each soil specimen corresponds to a single point generated on the SWCC. Similarly, 56 specimens are compacted for the remaining three different dosages (i.e,. 2%, 5% and 10%), 9 specimens for each dosage using both cement and lime treatments. Table 5.1 shows proportions of stabilizers added to cement and lime treated soils.

Table 5.1 Proportions of Stabilizers added to Arlington Soils.

Stabilizer	**Proportion (% per dry weight of soil)**
Cement	0, 2, 5, 10
Lime	0, 2, 5, 10

In order to complete the SWCC curve beyond the last point obtained from the pressure plate technique, 98 soil specimens were compacted, each of 2.5 inch diameter and 1 inch height, using cement and lime treatments in order to measure total and matric suctions.

A total of nine (9) different points are generated on the SWCC using pressure plate technique, whereas seven (7) different points are generated using filter paper, for each percentage of stabilizer dosage (0%, 2%, 5%, and 10%).

5.3 Specimen Notation

A simple notation was adopted in order to facilitate the reading of all variables corresponding to a given specimen and its compaction and treatment conditions. For instance, a soil specimen identified as A-C-2 indicates that it is made of Arlington soil, treated with Cement at 2% dosage per dry weight of soil. Likewise, a soil specimen identified as A-L-5 indicates that it is made of Arlington soil, treated with Lime at 5% dosage per dry weight of soil.

5.4 Results and Analysis

In this thesis the SWCCs are plotted with matric suction on the x-axis (log scale) against volumetric water content on the y-axis for different stabilizer dosages. The soil-water characteristic curves for control soil (untreated) and cement treated soils are shown in Fig 5.1. The soil-water characteristic curves for control soil (untreated) and lime treated soils are shown in Fig 5.2.

Prior to SWCC testing on control and treated soils, the feasibility of the pressure plate device for yielding reasonably repeatable results was assessed. A few SWCC tests were first conducted on identically prepared specimens with similar moisture content and dry unit weight conditions at same matric suction values. The results were statically analyzed. Volumetric water content results yielded low standard deviations. SWCC results for control soil shown in Figs 5.1 and 5.2 correspond to average values from three tests.

Solid lines in Figs 5.1 and 5.2 represent the best-fit curves using Fredlund and Xing‟s (1994) equation. The points represent actual experimental data. As it is observed from these figures, chemical stabilization has a paramount effect on the shape and position of the SWCCs of treated soil. Best-fit SWCC model parameters are summarized in Table 5.2.

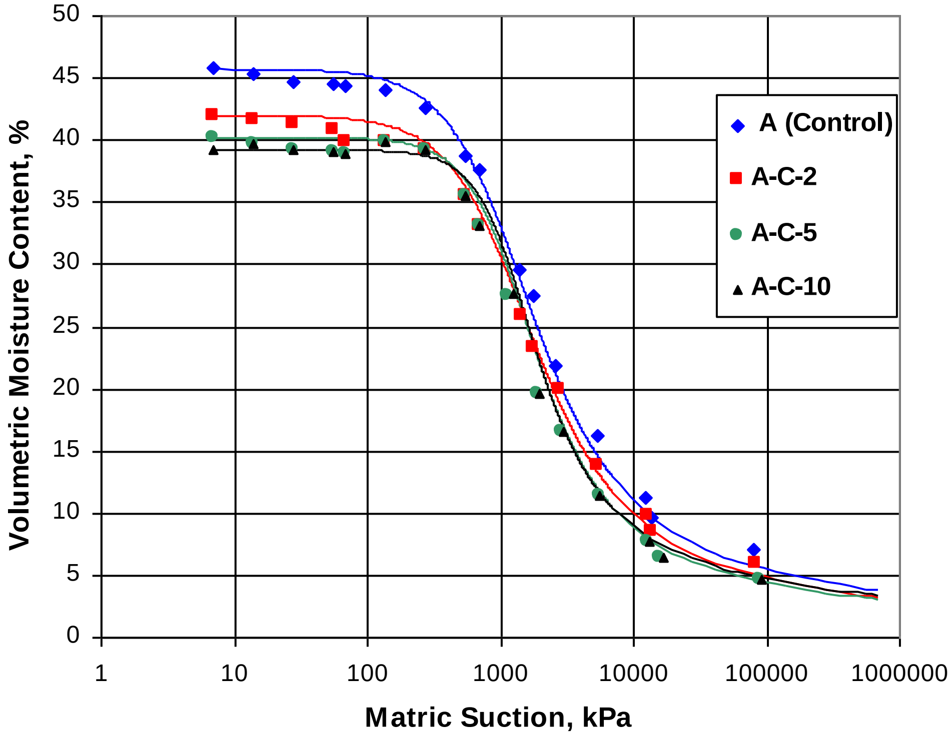

Fig 5.1 SWCCs for Control and Cement Treated Soils.
Note: A-C-2 = Arlington soil with 2% Cement.

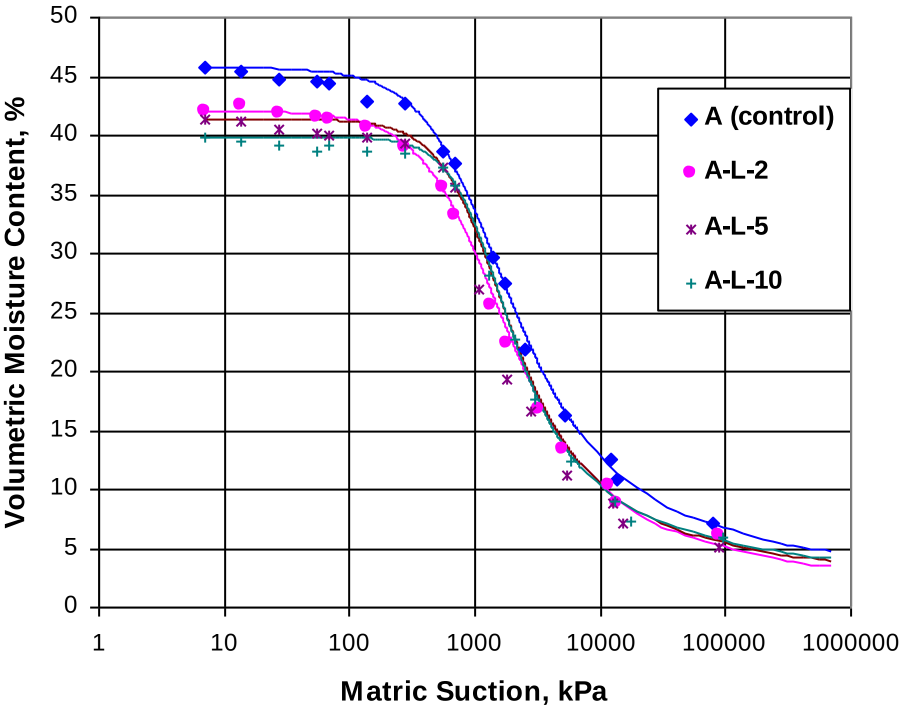

Fig 5.2 SWCCs for Control and Lime Treated Soils.
Note: A-L-2 = Arlington soil with 2% Lime.

Table 5.2 Fredlund and Xing‟s Model Constants for Treated Soils.

Soil Sample	a	n	m
A	910	1.50	1.07
A-C-2	955	1.65	1.10
A-C-5	1050	2.00	1.00
A-C-10	1100	2.34	0.90
A-L-2	925	1.50	1.10
A-L-5	1010	1.85	1.00
A-L-10	1070	2.20	0.85

Note: A = Arlington soil; C = Cement; L = Lime; A-C-2% = Arlington soil with 2% Cement; a, n and m = Fredlund and Xing‟s model constants.

Results shown in Figs 5.1 and 5.2 and Table 5.1 can be analyzed as follows:

In both cases, Cement and Lime treated soils, the volumetric water content decreases as the percentage dosage of cement and lime increases. Volumetric water content in the case of cement treated soils, for the same amount of dosage, is slightly more than that of lime treated soils. This can be attributed to the fact that the cement used in the present study is finer than the lime, therefore considerably reducing the pore size distribution of the control soil by occupying the original voids and inducing stronger bonds with clay particles at contact points. No significant change in the initial values of volumetric water content are observed for lime treated soils, which can also be attributed to the coarser nature of the lime.

The air-entry parameter is related to the soil air-entry value, which is the matric suction for which air starts to enter the largest pores in the soil. The parameter „a‟ does not affect the overall shape of the SWCC curve, but as the „a‟ value increases the curve shifts towards higher suction ranges. The air-entry value for soils with higher percentage of fines is typically larger than those with no fines. Hence, with an increase in the percentage of dosage for cement treated soils the air-entry value correspondingly increases.

Air-entry values of lime treated soils are relatively lower when compared with those yielded by cement treated soils, for the same amount of dosage. This also can be attributed to the coarser nature of the lime.

The SWCC model parameter „n‟ is related to the pore-size distribution; the larger the values of „n‟, the more uniform the pore sizes in the soil. It is observed that the „n‟ values in this study ranged from 1.45 to 2.34, and increases as the percentage of dosage increases for both treatment methods. Such behavior indicates that the treated soils exhibit a more uniform pore-size distribution than control (natural) expansive soil.

The SWCC model parameter „m‟ is related to the asymmetry of the SWCC. Low values of „m‟ indicate moderate slopes of the SWCC (when „m‟ is less than 0.5), whereas higher values of „m‟ indicate steeper slopes (when „m‟ is more than 1.2). The „m‟ values for cement and lime treated soils varied from 0.85 to 1.10. Chemical treatment do not have a significant effect on the SWCC slope.

5.4.1 Multiple Regression Analysis

In the present study the uniqueness of the obtained SWCC data was examined using the model constants of the Fredlund and Xing‟s (1994) equation via a statistical Multiple Regression Analysis.

The model parameters determined in the previous section were correlated with basic soil properties, such as optimum moisture content (w), liquid limit (w_L), plastic limit (w_P), maximum dry density ($\gamma_{d\text{-}max}$), and stabilizer dosage and type applying the multiple regression analysis.

Correlations between Fredlund and Xing‟s (1994) equation parameters (a, n, and m) with soil and stabilizer properties can be determined via multiple regression equations as follows:

$$\ln a = {}_{0(a)} \quad {}_{1(a)}X_{1(a)} \quad {}_{2(a)}X_{2(a)} \quad ..... \quad {}_{k(a)}X_{k(a)} \tag{5.1}$$

$$\ln n = {}_{0(n)} \quad {}_{1(n)}X_{1(n)} \quad {}_{2(n)}X_{2(n)} \quad ..... \quad {}_{k(n)}X_{k(n)} \tag{5.2}$$

$$m = {}_{0(m)} \quad {}_{1(m)}X_{1(m)} \quad {}_{2(m)}X_{2(m)} \quad ..... \quad {}_{k(m)}X_{k(m)} \tag{5.3}$$

where, ${}_{0(a)}, {}_{1(a)}, {}_{2(a)}\text{'''} \cdot\cdot, {}_{k(a)}, {}_{0(n)}, {}_{1(n)}\text{'''} \cdot\cdot, {}_{k(n)}$ and ${}_{0(m)}, {}_{1(m)}, {}_{2(m)}\text{'''} \cdot\cdot, {}_{k(m)}$ = regression coefficients determined from the multiple regression analysis, and k = number of soil stabilizer variables used in the analysis.

Soil and stabilizer coefficients were selected systematically in the present regression analysis and the correlations were developed according to the coefficients of correlations (*r* values). Correlation coefficients are defined as:

$$r_{xy} = \frac{\sum_{i=1}^{n} (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2 \sum_{i=1}^{n} (x_i - \bar{x})^2}} \tag{5.4}$$

where x represents soil and stabilizer parameters, y represents model parameters, and $\bar{x}$ and $\bar{y}$ represent the mean of stabilizer parameters and the mean of model parameters, respectively.

A strong relationship between model constants and independent variables is portrayed by a high value of *r* (0.90 or above).

Table 5.3 summarizes the coefficient of correlation *r* between experimental data in Figs 5.1 and 5.2 and Fredlund and Xing‟s model constants.

Table 5.3 Soil Water Characteristic Parameters for Cement and Lime Treated Soils.

Soil Sample	a	n	m	r
A	910	1.55	1.07	0.99
A-C-2	955	1.65	1.10	0.99
A-C-5	1050	2.00	1.00	0.98
A-C-10	1100	2.34	0.90	0.98
A-L-2	900	1.50	1.10	0.98
A-L-5	1010	1.85	1.00	0.99
A-L-10	1070	2.20	0.85	0.98

Note: a, n, and m = model constants from Fredlund and Xing model; r = coefficient of correlation from experimental data and Fredlund and Xing‟s model.

5.4.2 Regression Analysis Results

As mentioned previously, the model constants obtained using the Fredlund and Xing‟s (1994) equation were correlated via multiple regression analysis with basic soil properties such as optimum moisture content, dry density, liquid limit, plastic limit and other different stabilizer properties to determine the uniqueness of the data.

Initially, the correlations are developed with three independent parameters, which yields an average correlation coefficient of $r = 0.71$. Correlation coefficients for four, five, and six independent parameters correlations were 0.74, 0.81, and 0.89, respectively. Table 5.4 presents all the independent variables used in the correlations for cement and lime treated soils.

Table 5.4 Independent Variables for Cement and Lime Treated Soils.

Soil Sample	w (%)	$\gamma_{d\text{-max}}$ (kN/m^3)	w_L	w_P	D	S
A	20.00	16.28	50	19	0	0
A-C-2	18.75	16.49	49	21	2	1
A-C-5	16.20	16.54	47	22	5	1
A-C-10	15.45	16.98	46	24	10	1
A-L-2	19.12	16.36	48	18	2	2
A-L-5	17.54	16.42	46	22	5	2
A-L-10	16.52	16.78	44	23	10	2

Note: A-C-2 = 2% Cement added to Arlington soil; w = optimum moisture content; w_L = liquid limit; w_P = plastic limit; $\gamma_{d\text{-max}}$ = optimum dry unit weight; D = stabilizer proportion (% per dry weight of soil); S = stabilizer type.

Table 5.5 summarizes the values of the correlation coefficients r for four, five, and six independent parameters correlations. Results indicate that correlation coefficient *r* increases with the number of soil and stabilizer parameters considered in the multiple regression analysis.

Table 5.5 Correlation Coefficients (r) of Soil and Stabilizer Parameters with Model Parameters (a, n, and m) of Lime and Cement Treated Soils.

Number of parameters	Parameters	ln(a)	ln(n)	m	Average *r*
3	w, w_L, w_P	0.73	0.69	0.72	0.71
4	$w, w_L, w_{P, D}$	0.76	0.73	0.74	0.74
5	$w, w_L, w_{P, D,}$ $\gamma_{d\text{-max}}$	0.83	0.79	0.80	0.81
6	$w, w_L, w_{P, D,}$ $\gamma_{d\text{-max},}$ S	0.92	0.87	0.88	0.89

Note: w = optimum moisture content; $\gamma_{d\text{-max}}$ = dry density; w_L = liquid limit; w_P = plastic limit; D = stabilizer proportion; and S = stabilizer type.

5.4.3 Model Evaluations

The predicted values of volumetric water content obtained from Fredlund and Xing‟s (1994) model are to be compared with the experimental volumetric water contents from pressure plate and filter paper tests. Figs 5.3 and 5.4 show the comparisons between predicted and measured volumetric water contents for cement treated and lime treated soils. It can be observed that the difference between predicted and measured values of volumetric water contents are within _ 15%, which can be considered a reasonably acceptable difference.

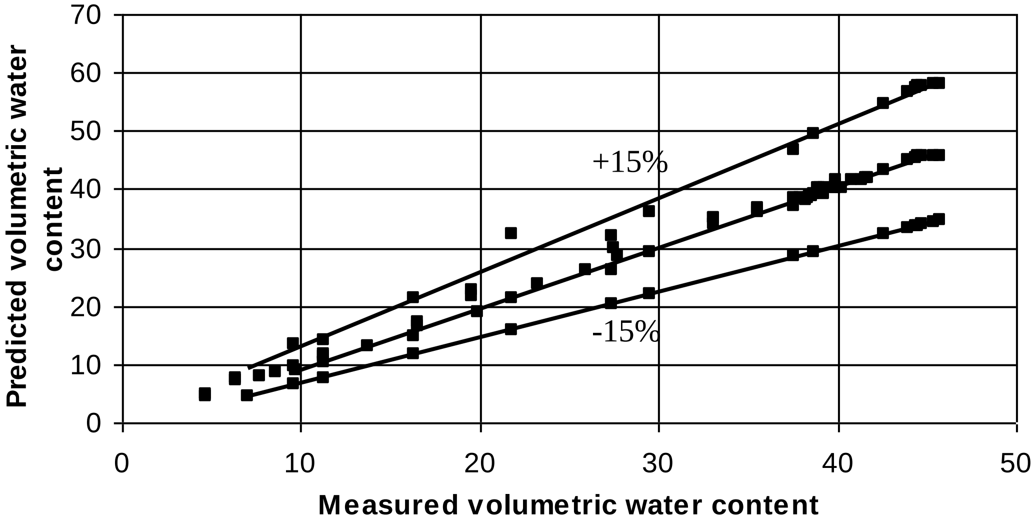

Fig 5.3 Comparison between Predicted and Measured Volumetric Water Contents for Cement Treated Soils.

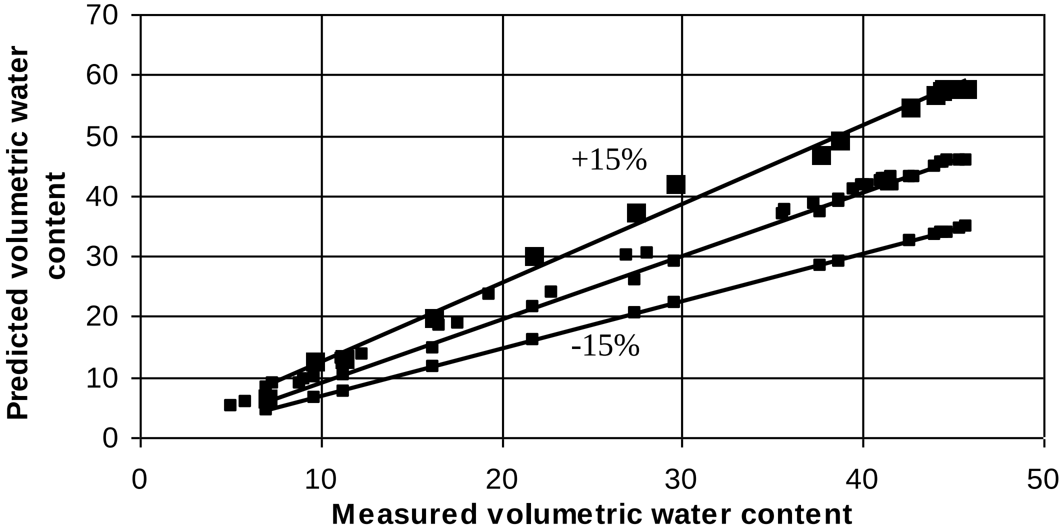

Fig 5.4 Comparison between Predicted and Measured Volumetric Water Contents for Lime Treated Soils.

5.4.4 Determination of Air Entry Parameters

The air-entry parameters, i.e. air-entry suction and air-entry volumetric water content, and residual parameters, i.e. residual suction and residual water content, can be determined graphically following the desorption curve as shown in Fig 5.5. Tables 5.6 and 5.7 summarize the SWCC air-entry and residual parameters of cement and lime treated soils, respectively. The variation of these SWCC parameters with cement and lime dosages are shown in Figs 5.6-5.8. Behavioral trends in these figures further substantiate the observations drawn from previous SWCC Figs 5.1 and 5.2. In general, as the percentage dosage of treatment increases, the air-entry suction increases and the residual suction decreases.

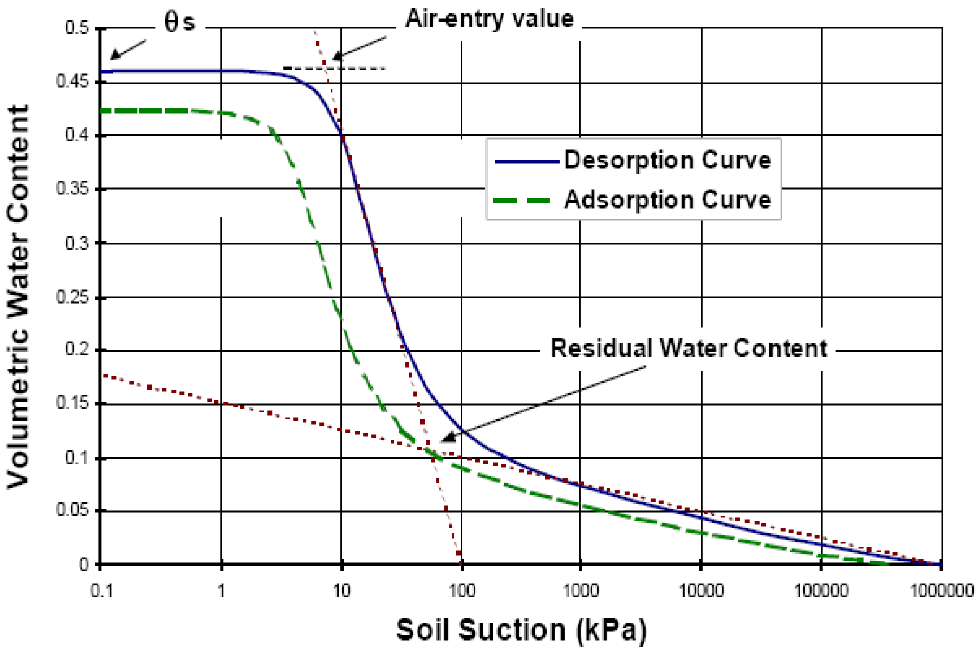

Fig 5.5 Graphical Representation of Air Entry Parameters and Residual Parameters (Fredlund and Xing, 1994).

Table 5.6 SWCC Parameters of Cement Treated Soils.

Cement (%)	Air-entry parameters		Residual parameters	
	Θ_a (%)	Ψ_a (kPa)	Θ_r (%)	Ψ_r (kPa)
0	45.0	910	15	1900
2	43.9	955	11	1850
5	42.9	1050	10	1700
10	41.7	1100	9	1600

Table 5.7 SWCC Parameters of Lime Treated Soils.

Lime (%)	Air-entry parameters		Residual parameters	
	Θ_a (%)	Ψ_a (kPa)	Θ_r (%)	Ψ_r (kPa)
0	45	910	15	1900
2	41.7	925	9.5	1800
5	40.3	1010	8.5	1600
10	38.6	1070	8.0	1500

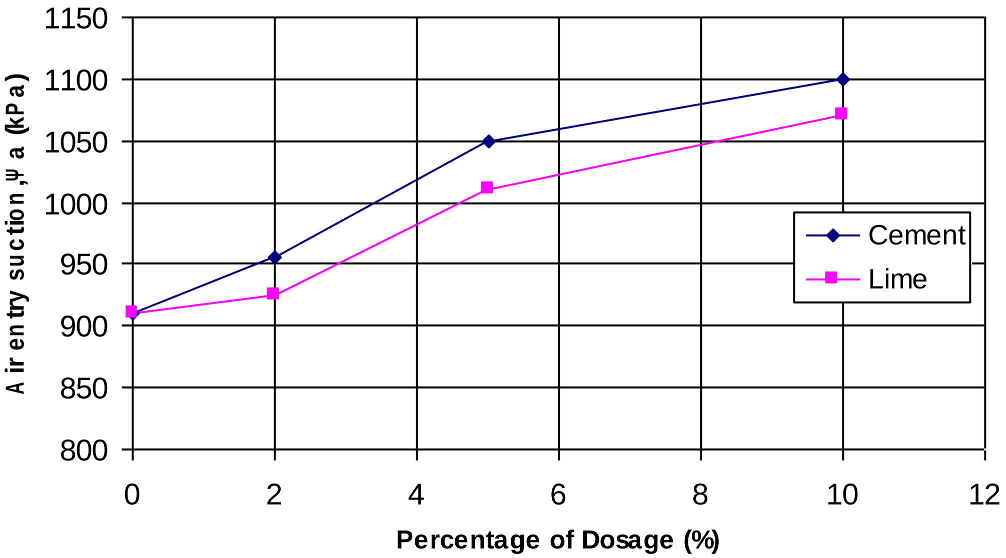

Fig 5.6 Variation of Air Entry Suction with Cement and Lime Dosage.

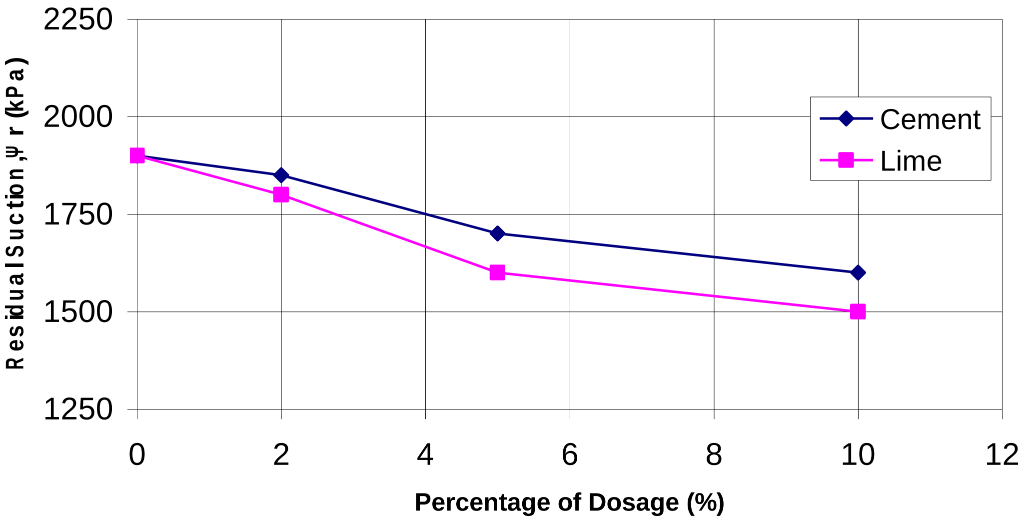

Fig 5.7 Variation of Residual Suction with Cement and Lime Dosage.

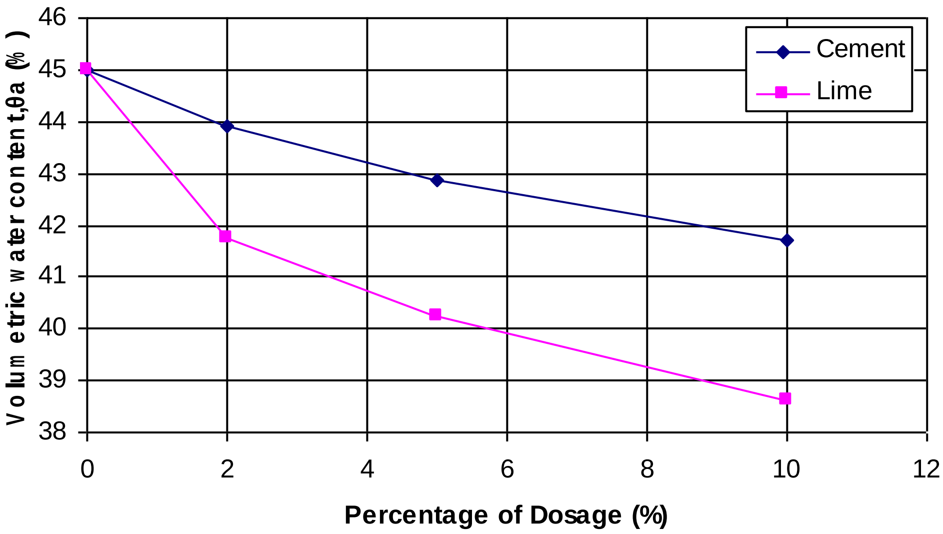

Fig 5.8 Variation of Air-Entry Water Content with Cement and Lime Dosage.

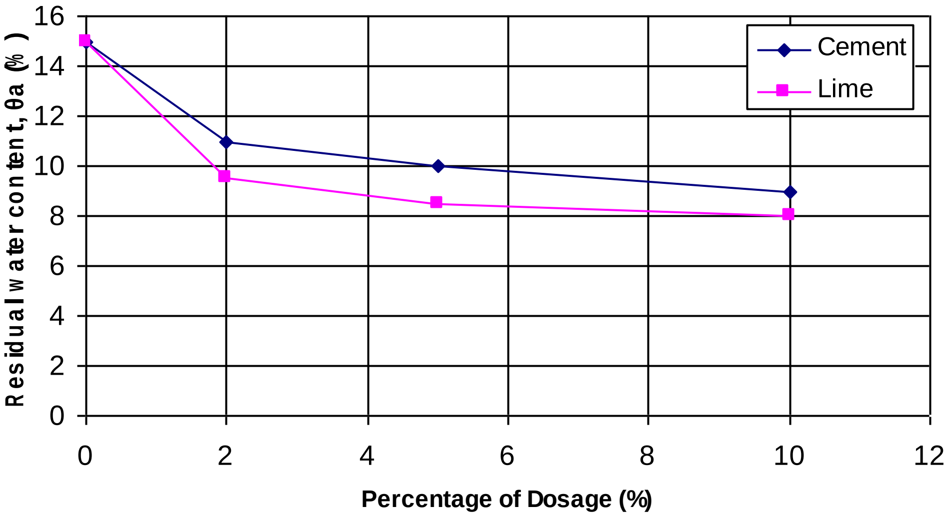

Fig 5.9 Variation of Residual Water Content with Cement and Lime Dosage.

5.4.5 Comparison with Previously Reported Treatments (Puppala et al., 2006)

The results obtained from cement and lime treated soils are compared with those of Fly ash treated soils previously reported by Puppala et al., (2006). The comparisons included in this section are primarily aimed at gaining some initial insight into how the SWCC response of treated soils might change with different chemical stabilization methods.

However, further testing is needed to arrive to any specific, conclusive observations since the control soils investigated by Puppala et al., (2006) are slightly different in nature.

In order to compare the SWCCs of cement treated and lime treated soils with ash treated soils, Fredlund and Xing‟s (1994) model trends for cement and lime treated soils in the present study, for various dosages, are plotted together with Fredlund and Xing‟s (1994) model trends for fly ash and bottom ash treated soils considered in the investigation recently undertaken by Puppala et al., (2006). The plots are shown in the following figures 5.10 through 5.16.

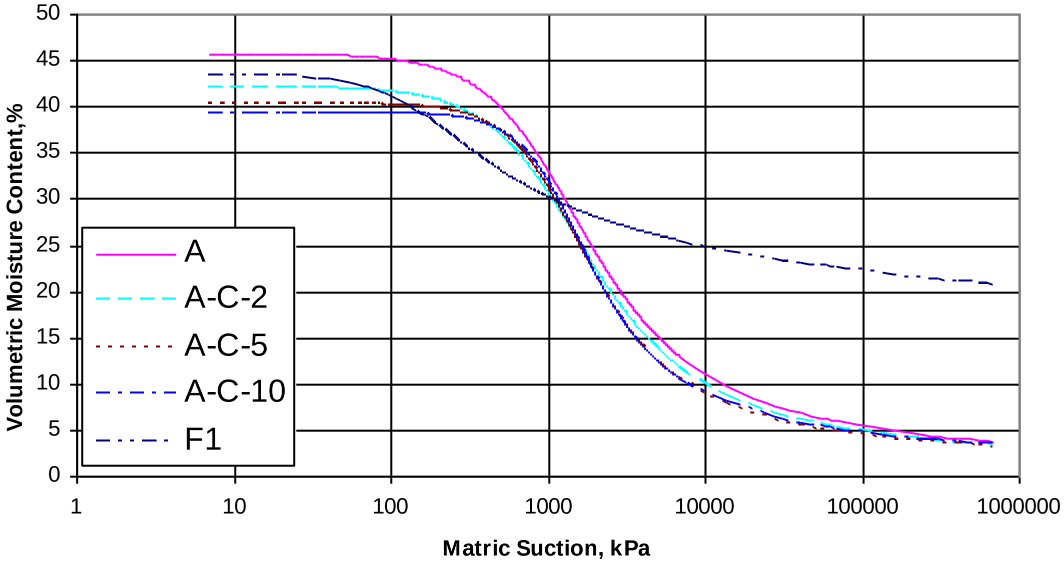

Fig 5.10 Comparison with Cement and Fly Ash Treatments from Mohave Plant (Puppala et al., 2006). Note: A = Arlington soil; A-C-2 = 2% Cement added to Arlington soil; F1 = Fly ash from Mohave plant.

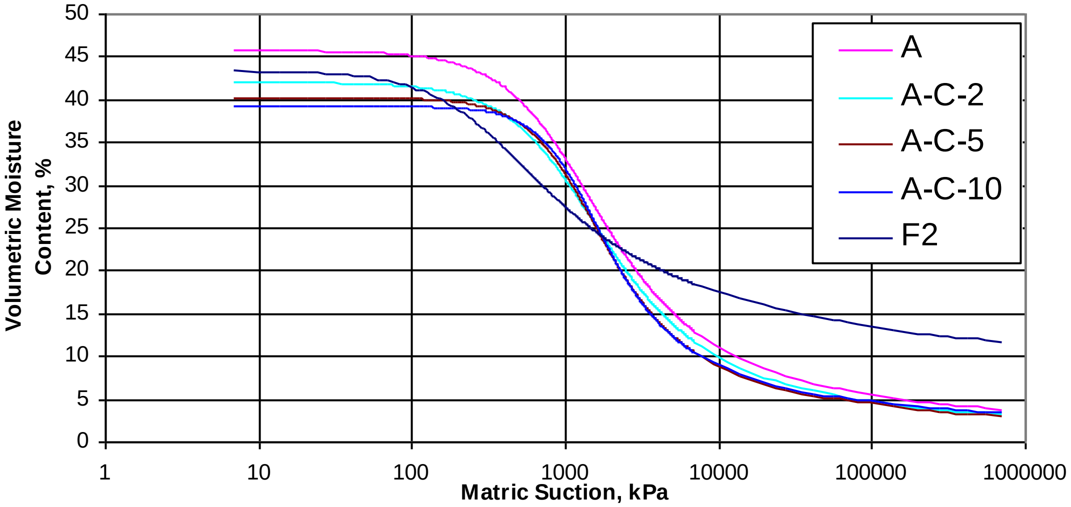

Fig 5.11 Comparison with Cement and Fly Ash Treatments from Monticello Plant (Puppala et al., 2006). Note: A = Arlington soil; A-C-2 = 2 % Cement added to Arlington soil; F2 = Fly ash from Monticello plant.

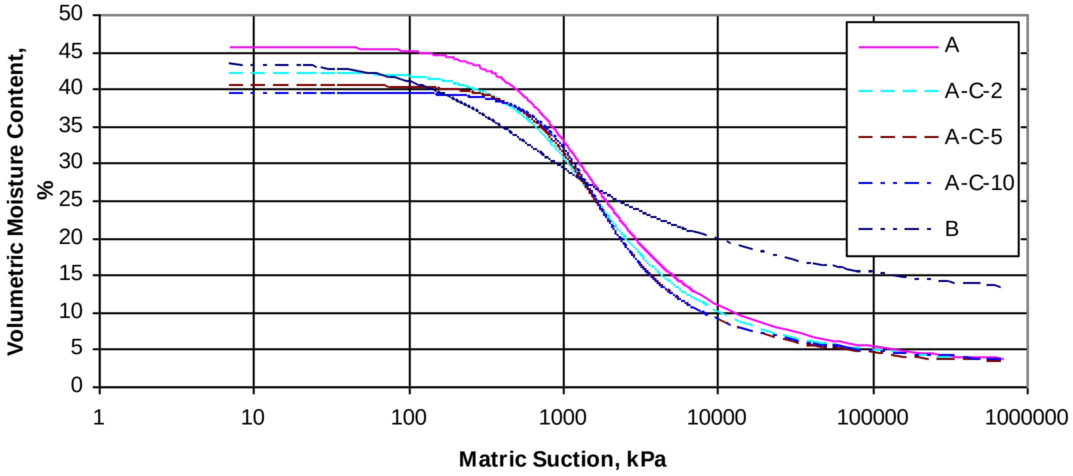

Fig 5.12 Comparison with Cement and Bottom Ash Treatments from Monticello Plant (Puppala et al., 2006). Note: A= Arlington soil; A-C-2 = 2% Cement added to Arlington Soil; B = Bottom Ash from Monticello Plant.

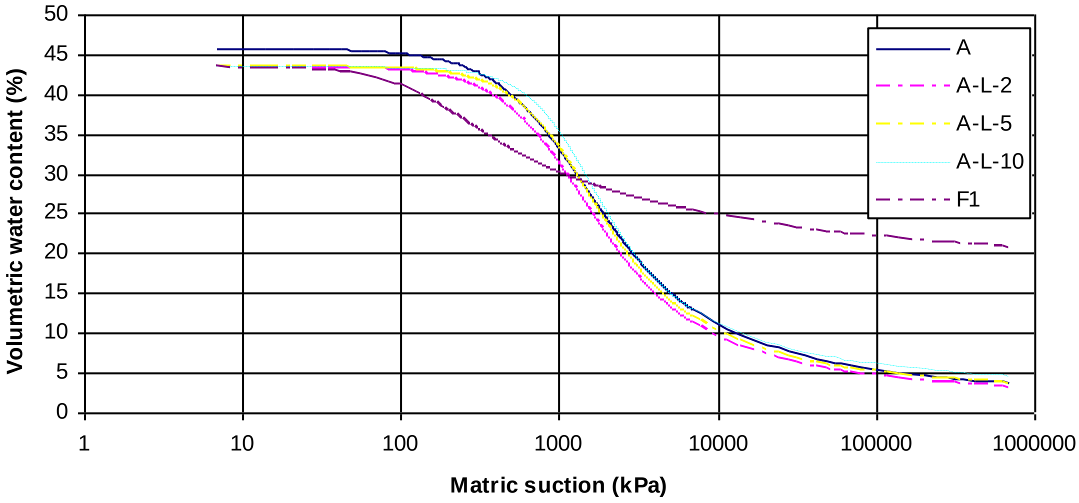

Fig 5.13 Comparison with Lime and Fly Ash Treatments from Mohave Plant (Puppala et al., 2006). Note: A = Arlington soil; A-L-2 = 2% Lime added to Arlington Soil; F1 = Fly Ash from Mohave Plant.

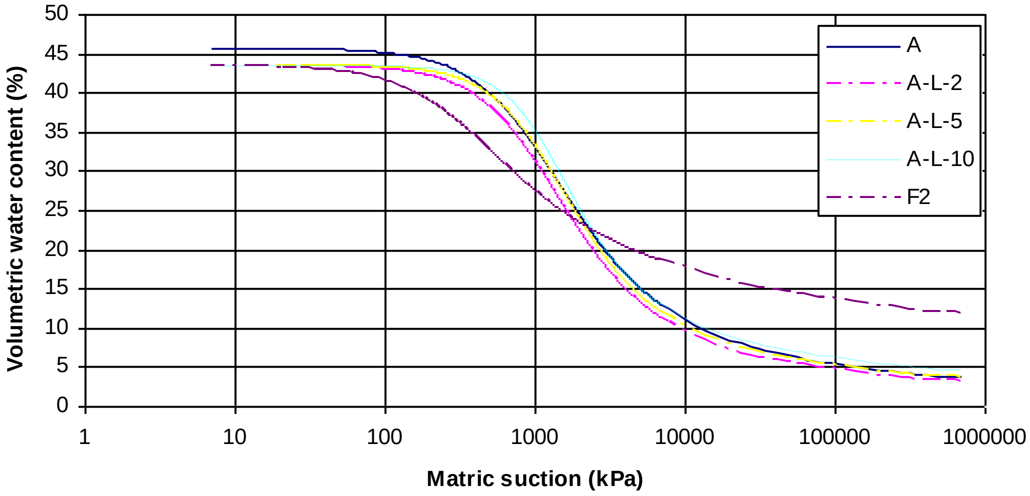

Fig 5.14 Comparison with Lime and Fly Ash Treatments from Monticello Plant (Puppala et al., 2006). Note: A = Arlington soil; A-L-2 = 2% Lime added to Arlington Soil; F2 = Fly Ash from Monticello Plant.

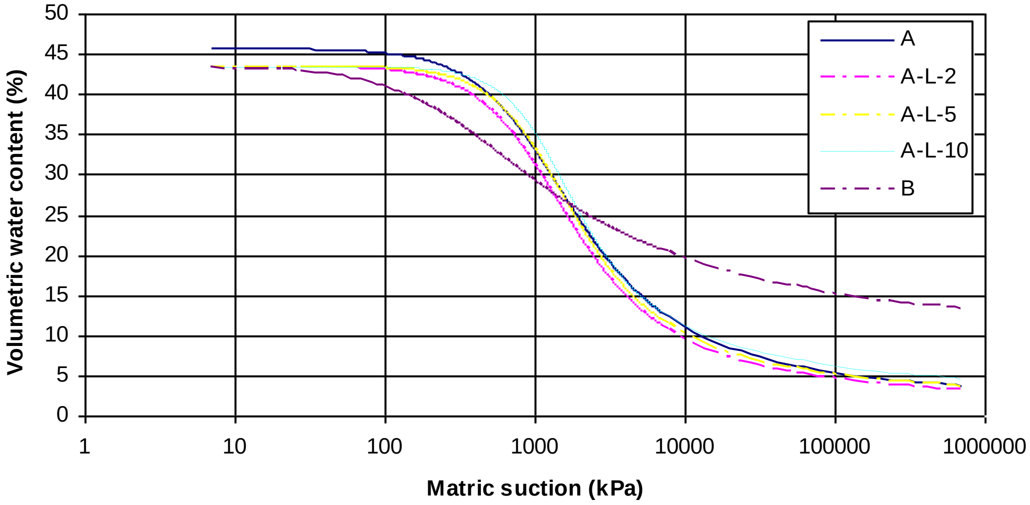

Fig 5.15 Comparison with Lime and Bottom Ash Treatments from Monticello Plant (Puppala et al., 2006). Note: A = Arlington soil; A-L-2 = 2% Lime added to Arlington Soil; B = Bottom Ash from Monticello Plant.

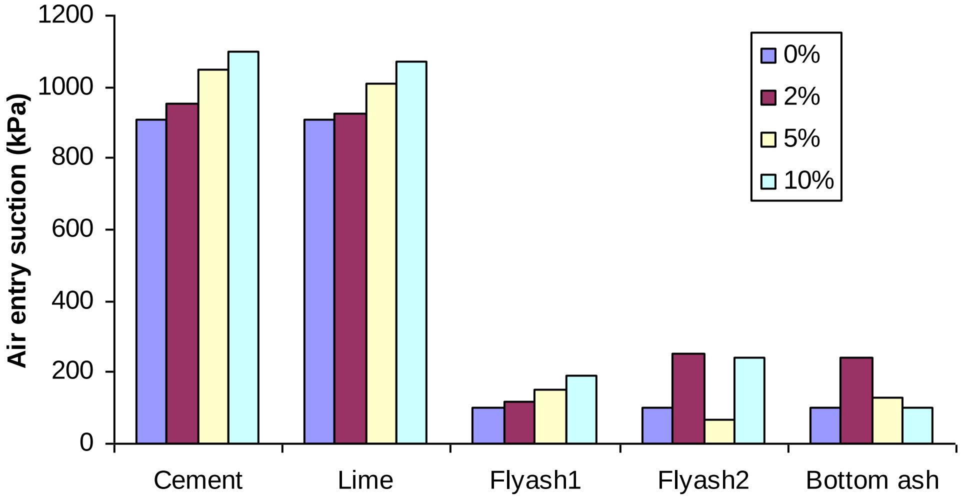

Fig 5.16 Variation of Air-Entry Suction Values for Cement, Lime, Fly Ash 1, Fly Ash 2 and Bottom Ash Treatments.

The following observations can be annotated from the SWCC behavioral trends shown in figures 5.10 through 5.16. above:

(1) The volumetric water content of the fly ash treated Arlington soils and cement and lime treated Arlington soils are almost all the same and decreases with increase in percentage of dosage.

(2) The air-entry value (a) of fly ash treated soils and cement, lime treated soils increases with increase in percentage of dosage and the SWCC shifts towards the right side as the air-entry value increases.

(3) The pore size distribution (n) of fly ash treated soils and cement and lime treated soils increases with increase in percentage of dosages indicating treated soils exhibit more uniform pore sizes.

(4) The value of the „m“ parameter for fly ash treated soils is lower than cement and lime treated soils. This is because Puppala et.al employed pressure plate technique to analyze the SWCC and they extrapolated the data after 1000 kPa. Lower value of m indicates moderate slopes where as higher value indicates steeper slope.

The following chapter summarizes the concluding remarks from this research work and some recommendations for future work.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The soil-water characteristic curves of expansive soil from south Arlington, Texas were measured under both natural and treated conditions using pressure plate (suction range of 0-690 kPa) and filter paper (suction range 690-1,000,000 kPa) techniques. The measured results were then analyzed using Fredlund and Xing‟s (1994) SWCC model equation. In addition, correlations were developed between basic soil and stabilizer properties, such as optimum moisture content, dry density, liquid limit, plastic limit, and stabilizer dosage and type, and Fredlund and Xing‟s model constants via multiple regression analysis.

The following summarizes the main concluding remarks from the present research work:

(1) In general, chemical treatment of high-plasticity expansive clay was observed to have a significant influence on the SWCC response of treated soils.

(2) The initial volumetric water content of both cement and lime treated soils, after 48-hour water-soaking, tend to decrease with an increase in stabilizer dosage. This can be attributed to the bonding effects of cement and lime based treatments, which considerably reduce the pore size by binding finer clay particles at contact points.

(3) The air-entry value for cement treated soils are slightly higher than that for lime treated soils, which also can be attributed to the greater bonding effects of cement over lime treatment.

(4) Best-fit model parameters were successfully devised for cement and lime treated soils based on Fredlund and Xing"s (1994) SWCC model, with coefficient of determination (R2) averaging 0.98.

(5) SWCC model constant „n" is an approximate indicator of the pore size distribution. Their values appear to confirm that treated soils exhibit more uniform pore size distributions than untreated soil.

(6) A multiple regression analyses using six (6) soil and stabilizer parameters proved to be reasonably feasible for the range and types of experimental variables used in the present study.

(7) Comparisons with fly and bottom ash treated soils, previously reported by Puppala et al. (2006), show a significant difference between SWCC response of cement or lime treated soils and ash treated soils. These comparisons were primarily aimed at gaining some initial insight into how the SWCC response of treated soils might change with different chemical stabilization methods. Further testing, however, is needed to arrive to any specific, conclusive observations since the control clays investigated by Puppala et al., (2006) were slightly different in nature.

6.2 Recommendations for Future Work

Additional investigations to be undertaken in order to further substantiate the results obtained in the present research work include: (1) Further SWCC testing on additional treatment methods and types of expansive soils; (2) Investigations on the feasibility of other regression models proposed in the literature; (3) Investigations on potential effects of curing period and compaction effort on SWCC response of treated soils; (4) Digital image-based analyses and X-ray diffraction (XRD) or scanning-electron-microscopic (SEM) studies to better explain SWCC behavioral trends of treated soils; and (5) Studies on potential seasonal effects on the SWCC response of treated soils (i.e, wet-dry and freeze-thaw cycles).

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Thudi Harshavardhan Reddy received his Bachelors degree in Civil Engineering from Osmania University, Hyderabad in June 2004. After graduation with B.E degree, he decided to pursue graduate studies majoring in geotechnical engineering at University of Texas at Arlington in 2004. During his studies he had the opportunity to work as a graduate research assistant under supervision of Dr. Anand J. Puppala. He received his Master of Science degree in Civil Engineering from The University of Texas at Arlington in August 2006.