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Suction and Compressibility Characteristics of an Unsaturated Till

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This thesis is dedicated to my fiancée Katherine Sikora

For love, for now, for always

Abstract:

Most geotechnical projects involving compacted soils are typically in a state of unsaturated condition. However, compressibility characteristics of such soils are typically estimated extending the principles that are commonly used for saturated soils. The compressibility and settlement characteristics of compacted soils are influenced by several parameters such as the applied loading, water content, compaction energy and soil structure. All the above parameters are in turn influenced by matric suction, which is one of the stress state variables for interpreting the engineering behavior of unsaturated soils. The focus of the research presented in this thesis is to understand the role of matric suction on the compressibility characteristics of a typical glacial till from Indian Head till, Saskatchewan. As a part of this thesis, the current techniques available in the literature for estimating matric suction were reviewed and implemented with varying degrees of success. New and improved techniques are presented for determining the matric suction using both axis-translation and the contact filter paper techniques. Based on the experimental studies undertaken in this research program, an equation is presented for Indian Head till that relates compaction water content to matric suction.

Chapter 1: Introduction

1.1 General Information

Several regions of the Earth constitute of semi-arid or arid regions where the annual evaporation from the natural ground is greater than the annual rainfall. These regions are situated inside a window defined by longitude 10°, 40°, latitude +10°, 40°. This region covers most of northern Africa, the Middle East and the Mediterranean countries. In addition, other countries around the world outside of this zone including Australia, Brazil, Canada, China, India, South Africa and the United States have arid or semi-arid regions. Typically the soils in these regions tend to have natural ground water table at a greater depth and the soil above it, which is referred as vadose zone is in a state of unsaturated condition. In addition, most geotechnical projects involving both natural and compacted soils (i.e. slopes, pavements, soil covers and earth dams) are typically in an unsaturated state. More than 90% of geotechnical structures never reach fully saturated conditions during their design life. Due to this reason, using the principles of saturated soil mechanics for soils that are in an unsaturated state comes under direct scrutiny.

A framework for interpreting the engineering behavior of unsaturated soils in terms of two stress state variables, net normal stress, $(\sigma - u_a)$ and matric suction $(u_a - u_w)$ is available (Fredlund & Morgenstern 1977). However, there are several difficulties associated with the application of the mechanics of unsaturated soils to engineering practice due to a lack of reliable means of either determining or estimating the in-situ soil suction (van der Raadt et al. 1987). While significant advancements were made towards understanding the mechanics of unsaturated soils during the last two decades, the measurement of soil suction still remains to be fully explored (Houston et al. 1994, Leong et al. 2002).

The three key engineering properties of soils are the coefficient of permeability, the shear strength and the volume change. Significant advances were made in the research area related to the shear strength behavior and the coefficient of permeability of unsaturated soils. It has become as a standard engineering practice in recent years to predict the shear strength and the coefficient of permeability functions using the soil-water retention curve as a tool. There are several semi-empirical procedures available in the literature to achieve this objective (van Genuchten 1980, Fredlund et al. 1994, Barbour 1998, and Vanapalli et al. 1996). However, limited studies are reported in the literature about the volume change behavior, particularly towards understanding the compressibility and settlement characteristics of unsaturated soils.

1.2 Problem Statement

In compacted soils, several parameters such as the applied loading, water content, compaction energy and soil structure influence the compressibility and settlement characteristics of an unsaturated soil. All these parameters in turn are influenced by the stress state variable, matric suction. The key point to emphasize though is that the serviceability of most engineering structures is controlled by the settlement of its foundation.

The laboratory testing portion for this research constituted the determination of the compressibility characteristics of a glacial till from Indian Head, Saskatchewan both in saturated and unsaturated conditions. The focus of this research was on the influence of initial water content and compaction energy on the compressibility characteristics of the till. The initial matric suction of unsaturated Indian Head till specimens that were prepared at different initial compaction water contents, using two different energy levels, was determined using both direct and indirect methods.

The axis-translation technique (Hilf 1956), a direct laboratory method was used to determine the matric suction of test specimen. The contact filter paper technique, ASTM Standard D5298-03, was an indirect technique used to estimate the soil suction of the test specimens in this research. This method relates the filter paper water content to the soil suction of a test specimen, through the use of a pre-determined calibration curve.

The use of axis-translation was initially the only method for measuring matric suction that was contemplated in this testing program. On reviewing the literature on soil suction measurement techniques, it was discovered that the contact filter paper method was touted as being an inexpensive, quick, accurate and technically simple method that could measure a wide range of soil suction (Hamblin 1981 Chandler & Gutierrez 1986 and Huston et al. 1994). Though the ASTM Standard procedure and those of other published works were strictly followed, bacteria development on the filter papers became a serious problem during calibration.

1.3 Objectives of Present Research

The broad objective of this research was to understand the difference in the compressibility behaviour of an unsaturated compacted soil when compared to its saturated state. From this broad starting point came the following objectives listed below.

1) Development of a simple and reliable technique to estimate soil suction in the range of 20 – 500 kPa. The low suction range is of practical interest but it is the most difficult to obtain accurate estimates. This research focused on two methods to estimate soil suction namely; axis-translation and the contact filter paper method ASTM D5298-03.

2) Quantify the influence of both matric suction and soil structure on the compressibility characteristics of Indian Head till.

There are several published constitutive equations for consolidation settlement, that involve the study of the compression and flow of the two separate pore fluids of an unsaturated soil (i.e. pore-air, u_a and pore-water, u_w) which require specialized equipment and solving of higher order differential equations (Fredlund, and Morgenstern 1977 and Ho et al. 1992). There has been has limited work done on the estimation of the compressibility characteristics from a practical, practicing engineering point of view (Garga and Aboim Costa 1977).

1.4 Thesis Organization

This thesis is organized into nine separate chapters, with most chapters being written in an individual paper format with separate conclusions. Chapter 2 provides a literature review with a focus on matric suction measurement. Chapter 3 outlines the equipment designed for both the determination of the compressibility characteristics, and the estimation of matric suction. Chapter 4 details the methods and equipment used to prepare test specimens at the desired water content and density as dictated by the testing program, which is outlined in Chapter 5. Chapter 6 details the development of a series of new calibration curves for Whatman 42 filter paper. A comparison is made between the estimates of matric suctions obtained for Indian Head till specimens by both the axis-translation technique, the contact filter paper method. Chapter 7 compares the compressibility characteristics of both the saturated and unsaturated test specimens to quantify the influence of both matric suction and the soil structure. Chapter 8 reviews the methods followed to produce the different published Whatman 42 filter paper calibration curves, then compares them to the methods used in this testing program. Second, an analysis is performed on the measured matric suction results from the contact filter paper method as described in the ASTM Standard D5298-03. Thirdly, based on the results of this testing program and from published data, an equation is proposed to estimate the suction of Indian Head till tested in this research program. Lastly, the matric suction results from the filter paper method are compared with those from the axis-translation technique and to the data published for a similar till. Chapter 9 is the conclusion chapter that ties together the individual conclusion from each of the other chapters.

CHAPTER 2: THE BASIC FILTER-PAPER THEORY

2.1 Introduction

Several difficulties are associated both with the understanding and application of the mechanics of unsaturated soils due to a lack of reliable means to measure in-situ soil suction (van der Raadt et al. 1987). While significant advancements were made in the area of unsaturated soil mechanics during the last two decades, the measurement of soil suction still remains to be fully explored (Houston et al. 1994, Leong et al. 2002). In most geotechnical projects the soils are typically in a state of unsaturated condition. Due to this reason, using saturated soil mechanics for soils that are in a state of unsaturated conditions come under direct scrutiny.

Soil suction develops within the soil as the water begins to drain from soil voids and is replaced by air. The soil suction consists of three components: total, matric, and osmotic suction. Matric suction is the negative gauge pressure relative to the external gas pressure on the soil-water to which a solution identical in composition with the soil-water must be subjected in order to be in equilibrium through porous permeable wall with the soil-water. Osmotic suction is defined as the negative gauge pressure to which a pool of pure water must be subjected in order to be in equilibrium for a semi-permeable membrane with a pool containing a solution identical in composition with the soil-water. The definition of total suction is the negative gauge pressure relative to the external gas pressure on the soil water to which a pool of pure water must be subjected in order to be in the equilibrium through semi-permeable membrane with the soil-water. Mathematically, total suction is equal to the sum of matric suction plus osmotic suction

(Aitchison 1965).

Houston et al. (1994) published the following simplified definitions of the three components of soil suction. The matric suction is defined as the affinity the soil has for the water in the absence of any salt content gradients in the water. The osmotic suction contribution is due to the salt content of the pore fluid which arises from the variation in the salt content from one point to another. In the case of measuring total suction using filter-paper technique, moisture is transferred in the vapour phase and as such there is no movement of the salt content of the pore water; therefore osmotic suction is not detected. However, when measuring matric suction, the moisture transfer is in the liquid phase so the salt content of the pore water is allowed to transfer from the sample to the filter-paper. Since the salt content of the water is the same in both the filter-paper and in the pore-water, osmotic suction again is not detected. Therefore, subtracting the matric suction value from the total suction value will provide the value of osmotic suction of the sample. Since it is easier to measure matric and total suction in the laboratory; osmotic suction is normally not measured, but is inferred from the other two suction measurements.

There are two different methods to determine soil suction, one being the direct method, and the other being the indirect method (Ridley 1996). The direct method measures the soil suction directly from the specimen using apparatus referred to as the null pressure plate, or pressure membrane devices employing the axis-translation technique. The two major disadvantages with a direct measurement of matric suction are cavitation and the limited matric suction range that can be investigated. The phenomenon of cavitation occurs when the matric suction values within the system reaches a value greater than one atmosphere. In order to avoid the problem of cavitation, Hilf (1956) designed the null pressure plate apparatus which translates the negative pore-water pressure, u_w within the soil to that of the positive air pressure, u_a of the atmosphere; with that came the technique's name, axis translation. Although the problem of cavitation has now been overcome, the direct measurement of matric suction, $(u_a - u_w)$ is still limited by both safety and practicality to the range of 10 to 700 kPa (i.e., 100 psi) depending upon the air entry value of the ceramic element used in the system. Additional safety measures such as proper equipment and strong room facilities are required to measure matric suction higher than 700 kPa. Typically, the influence of changes in suction due to movement of water phase reduces at suction values greater than 1500 kPa. For this reason, matric suction measurements are restricted to 1500 kPa

Recently researchers have begun to examine methods of measuring soil suction that avoid the use of elevated air pressure. The advantage of having a system that is not based on high air pressure is that it allows the soils to be tested in environments which closely simulate in-situ conditions (Ridley 2003). The indirect method of measuring matric suction uses different characteristics of the soil sample (i.e. water content, temperature, or humidity level) and through the use of a calibration curve, relates one of these characteristics to the soil suction within the sample. In other words, the measuring device (e.g. the filter-paper) is adjusting to the samples suction, unlike in the direct suction methods (e.g. pressure plate) where the sample adjusts to the suction value of the device (Swarbrick 1995). The basic filter-paper procedure has been used mainly by soil agronomists in agricultural studies as an indirect method of measuring soil suction since the beginning of the twentieth century. Gardner (1937) has been credited with introducing filter-paper as a means of measuring soil suction for engineering purposes to North America. The filter-paper is considered to be the standard material by convention (see ASTM standard D5298-03); however, any absorbent material may be suitable for measurement of soil suction (Sibley 1990b).

The filter-paper method can be separated into two distinct methods: the first being the contact method or the direct method and the second method being the indirect or the non-contact method. It is important before proceeding with calibration, testing or using suction measurements calculated from the filter-paper method, to appreciate the differences between the two methods, as each, theoretically measures different types of suction. The contact method is used to measure matric suction while the non-contact method measures total suction. In the contact method, the filter-paper is placed in direct contact with the soil sample, by either placing the filter-paper on top of the soil sample (Bulut et al. 2001, Chandler & Gutierrez 1986, Al-Khafa & Hanks 1972), or burying them within the sample (Houston et al. 1994, Fawcett & Collis-George 1967). During the equilibrium stage, the moisture is transferred from the pores of the sample to the filter-paper until equilibrium between the two has been reached. As the moisture is transferred between the soil and the filter-paper in the liquid phase, matric suction is measured. The procedure for using the non-contact filter-paper method involves separating the filter-papers from the soil sample either, by suspending the filter-paper in the headspace over the sample (Houston et al. 1994), or using an inert spacer ring (Ridley 1994). As the filter-paper is not in direct contact with the sample, moisture transfer can only take place in the vapour phase, and therefore only total suction is measured.

There are several advantages to using the filter-paper method to measure soil suction. The method requires little technical experience or expensive equipment, and can be done in almost in any conventional geotechnical laboratory provided temperature and humidity controls are in place (Ridley 2003), Leong et al. 2002, Fredlund 1995, Houston et al. 1994, Chandler 1992, and Hamblin 1981). Since the problem of cavitation is avoided, the filter-paper system can theoretically study the full range of soil suction from completely saturated to total dry conditions. Over the years several disadvantages have prevented the filter-paper techniques from becoming a standard testing tool in geotechnical investigations. The main hurdle is the development of a proper calibration curve which relates the filter-paper's water content to the soil suction (Sibley 1990). Gardner (1937) stated that "if the tedious task of calibrating the filter-paper can be avoided, the method is a simple investigation tool to measure the entire range of soil suction".

2.2 Method to Calibrate the Filter Paper

2.2.1 Selection of the proper calibration curve

The graphical representation of the water content versus suction relationship for any porous material shown in Figure 2.1 follows two paths: the wetting curve for showing the path followed as the material goes from a state of completely dry to a complete saturated condition, and the drying curve which shows the path followed as the material goes from a state of complete saturated to completely dry state. Due to the different sizes and shapes of the pores within the porous material, the drying curve will always plot higher than the wetting curve. In other words, for any given suction value, the drying curve would show higher water content for the material than the wetting curve. If the porous material starts from a condition that is other than the completely dry or completely wet, different curves will be followed as the suction within the system is changed. These curves are called the scanning curves. The scanning curves typically follow the same shape as the two main curves of the water content vs. suction curves but follow a different path. The development of the scanning curves is called the hysteresis effect.

Originally, investigators did not distinguish the differences between calibration curves. The same calibration curve was used to calculate either total or matric suction. Recent investigations have determined that it is incorrect to assume the calibration curve will be valid for both total and matric suction due to the phenomenon of hysteresis (Bulut et al. 2000, Houston et al. 1994). Leong et al. (2002) published data showing that the filter-paper response to applied suctions is different for total and matric suction. The definition of each component of soil suction, given above, would also suggest that the curves would have different responses as they are developed through different mechanisms.

Determining which calibration curve to use (i.e. wetting or drying curves) is essential for the proper use of the filter-paper method. Studies have shown that the appropriate calibration curve to calculate soil suction is on the wetting curve, since that is the path followed by the filter-paper while measuring suction (Houston et al. 1994, Al-

Khafaf & Hanks 1972, and Fawcett & Collis-George 1967). Bulut et al. (2000) state that the wetting curve is the most appropriate to use because of the hysteresis effect. Hysteresis is present in filter-papers because of the fibrous and porous nature of the material (Ridley (1995). Deka et al. (1995) investigated calibration curves on both the drying and wetting curves and found that calculated suctions based on the drying curve, underestimate the actual suction values.

With a large variety of filter-papers commercially available, it is impossible to have a universal calibration curve for the filter-paper method. Some of the filters used in previous research include Schleicher Schuell # 589 McQueen & Miller (1968), Fisher Quantitative Coarse (9.54 A) Houston et al. (1994), and Whatman 42 Rao & Revanasiddappa (2005). Houston et al. (1994) state that calibration curves are filter-paper type dependent and are not interchangeable. Fredlund et al. (1995) published scanning electron micrographs of both the Whatman # 42 filter-papers and Schleicher Schuell # 589 filter-papers (the two most common filter-papers used in geotechnical testing). Although the micrographs show striking similarities, the published calibration curves are remarkably different. This led them to believe that the same process could be used to calibrate both types of filter-papers; however the final calibration curves would be different. Swarbrick (1990) state that characteristic curves are unique to the material being used, the ambient conditions of the laboratory, and the testing program employed.

Since the reliability of the filter-paper method depends on the accuracy of the calibration curve, obtaining an accurate calibration curve is essential. Deka et al. (1995) reported that the proper way to develop the testing program for the filter-paper method is to first determine the suction range to be investigated, and then calibrate the filter-paper for that specific range. Hence, using generalized equations for calibration curves introduces variability into the results of the soil suctions measurements and it is therefore recommended to obtain a specific calibration curve for the proposed testing environment and program.

2.2.1.1 Obtaining the proper calibration curve

The next problem, then, is to obtain a proper calibration curve. During the calibrating process, the filter-paper is subjected to known suctions values in the presence of water, either in the liquid or vapour phase, and is allowed to come to equilibrium. The water content of the filter-paper is measured at the end of a time period, thus providing suction versus water content relationship. There are three main methods that are commonly used to apply suctions to the filter-papers during calibration. These are the direct method (i.e. pressure membrane or pressure plate), total suction method (i.e. salt solutions), and using samples of known suctions. In order to obtain a full calibration curve, it is required to use a combination of these methods, as none of these three methods are able to generate the full range of suction required.

a) Direct Method

For the lower suction range (i.e. less than 1500 kPa), a combination of pressure plate and pressure membrane devices can be used to generate the calibration curve. The filter-papers are placed in direct contact with the saturated ceramic stone or membrane and the devices are used to directly apply known suction values to the filter-papers (Figure 2.2). The filter-papers are left to come to state of equilibrium condition at the applied matric suction and available water. The time period for achieving this equilibrium condition is reported to be from five to seven days (ASTM D5298-94). At the end of the equilibrium period the water content values of the filter-papers are measured and the data for a calibration curve is obtained (Figure 2.3).

b) Total suction method

The total suction method uses salt solutions to generate the required suctions. The filter-papers are suspended in the head space above the salt solution in a sealed container and allowed to come to equilibrium, for a period of seven to fourteen days. The process is based on the theory that the air space above a pool of pure, distilled water, in a sealed container, at a constant temperature will theoretically have a humidity level of 100%. As the molar concentration of the salt within the solution increases, the humidity level decreases, thereby increasing the suction level within the airspace. The calibration curve is produced by using a series of filter-papers and salt solutions that provide a range of suction values (Figure 2.4).

c) Using samples of known suctions

The final method used for calibration purposes is to use samples of known suction values to generate the required suctions. There are two ways to produce samples of known suction values. The first method is to consolidate the samples under a particular stress, using either standard oedometer or triaxial cells. When the samples have reached equilibrium with the applied stress, the load is quickly removed. Assuming one dimensional loading, no friction, and no water uptake into the sample during unloading, the suction level within the sample is assumed to be that of the applied stress (Chandler & Gutierrez 1986). The second method is to place soil samples in either a pressure plate or pressure membrane device, and directly apply known suctions to the samples. When the water content of the samples reaches equilibrium with the applied suction, the samples are ready to be used to calibrate the filter-papers.

In either case, the samples are placed in a sealed airtight container with the filter-papers and allowed to come to equilibrium (Figure 2.5). Once equilibrium is reached, the filter-papers are removed, the water content is measured, and a calibration curve is determined. Fredlund et al. (1995) state that it is possible to use samples of known suctions to develop a calibration curve for the filter-paper method. The calibration curves published by Chandler & Gutierrez (1986) were produced by consolidating samples to known suctions using conventional oedometers. McQueen & Miller (1968) calibrated their filter-papers in the suction range between 0.2 and one bar (i.e., 20 kPa to 101.3 kPa) by using samples of known suctions.

Leong et al. (2002) investigated the different methods used to calibrate filter-papers. They produced calibration curves using all three methods and found that calibration curves developed using samples of known suction values generated larger scatter than those developed by directly applying suction values to the filter-papers. The variability in the water contents of the soil samples being used as suctions source, were greater than the variability of the water content of the filter-papers. Since there is an inherent variability in the suctions source using samples of known suction values, it is not an appropriate way to accurately calibrate filter-papers.

2.2.2 Use of published calibration curves

Many calibration curves have been published for different filter-papers over the years. The proper use of these curves and when it is appropriate to use these calibration curves in a new testing program has been debated by researchers for the last three decades (Deka 1995, Leong et al. 2002). Fawcett & Collis-George (1967) state published calibration curves should only be used if the method used in their development matches the new testing program. Houston et al. (1994) state that the calibration curves developed using the contact method should only be used for matric suction calculation, and those developed using the non-contact method should only be used in total suction calculations. Leong et al. (2002) state that the calibration equations published in the ASTM standard D5298-94 is a contact filter-paper calibration curve and should only be used to determine matric suction values. Clearly there is disagreement over the use and validity of published calibration curves. Basically by obtaining a new calibration curve for a new testing program, as long as it is within the range of the rest of the published calibration curves the pitfalls of using an existing calibration curve are avoided.

2.3 Factors affecting the calibration curve

Understanding why published calibration curves are different for the same filter-papers has been investigated by several researchers. McQueen & Miller (1968) suggested that the difference between their calibration curves and the one first published by Gardner (1937) is due to the suction source used during calibration. In 1937, the technology of both the pressure plate and membrane apparatus was not available, and the use of these devices probably provided McQueen and Miller with more accurate suction sources then the sources available to Gardner. Leong et al. (2002) published calibration curves for both Whatman number 42 and Schleicher & Schuell Number 589 filter-papers that have been published over the last 40 years. They investigated several separate reasons for the differences in published calibration curves and concluded that suctions source and equilibrium time were the main reasons for the differences. He also concluded that these effects could be combined with other sources of error such as: hysteresis, bacteria growth, and filter-paper quality to further alter the calibration curve.

2.3.1 Different characteristics between different batches of filter-paper

Over time, changes in the techniques used to produce filter-papers could alter their absorbent properties, thereby requiring a new calibration curve for each new batch. To determine whether or not filter-papers were batch specific, Fawcett & Collis-George (1967) tested nine separate batches of filter-papers, bought from different research organizations, at different times. They determined that although there was significant difference in the water content of the filter-papers from each batch, there was general agreement between their standard calibration curve and the mean value of the water content values measured for the nine separate batches. They concluded that filter-papers may not be batch specific and hence the new calibration curve would not be required except where accuracy in the suction values were crucial. Hamblin (1981) calibrated two separate batches of filter-papers purchased two years apart, and determined that there was good agreement between the two calibration curves and nearly identical to the one published by Fawcett & Collis-George (1967). From this it was determined that there is no reason to recalibrate when a new batch of filter-papers was purchased, unless reasons of accuracy demands recalibration. Leong et al. (2002) published calibration curves from several published sources and compared them with their own calibration curves and are shown in Figure 2.6. They found that although the calibration curves were developed by different researchers at different times, they still remained within a narrow band implying that the quality of filter-paper was not the reason for differences between published calibration curves. They also recommended though, that with each new batch of filter-papers, a new calibration curve be developed to increase accuracy.

Sibley & Williams (1990) investigated the differences between different boxes of filter-papers purchased from the same production batch, at the same time, and from the same supplier. They found that there was no significant difference in the water content-suction curves developed. Therefore, as long as the filter-papers are from the same batch there was no need to recalibrate when using a new box of filter-papers. They suggested it would be prudent to randomly select, the filter-paper from each of the different boxes to ensure uniform results. The underlying message from the above mentioned publications is that as long as the new testing program is the same as the one used with the published calibration curve, and accuracy is not crucial, a new calibration curve is not required when filter-papers are purchased from different batches.

2.3.2 Equilibrium time

An important step in either calibrating or testing with filter-papers is the time allotted for the filter-papers to come to equilibrium with the suction source. Insufficient time will lead to higher suction values, while longer times could be sufficient to allow the filter-papers to degrade. Almost every researcher who has investigated the filter-paper method has suggested a different equilibrium time. These times have ranged from as little as 36 hours to as much as fourteen days. Leong et al. (2002) state that inadequate equilibrium time will lead to larger hysteresis effects. Deka et al. (1995) suggested a six-day equilibrium period for calibration and testing for soil suctions less than 2500 kPa. For soil suctions greater 8000 kPa, a six day equilibrium time may be insufficient for accurate measurements. Hamblin (1981) used equilibrium times from a few minutes to 36 hours depending on the saturation level and the structure of the sample. Hamblin's research was related to agricultural uses of soil suction where accuracy in suction was less crucial. Ridley et al. (2003), Houston et al. (1994), and van der Raadt et al. (1987) used a seven day equilibrium time when developing both their total suction, and matric suction calibration curves.

The different mechanisms within the filter-paper methods can also lead to different equilibrium times. Leong et al. (2002) state that it is important to properly judge equilibrium times when using the total suction method, because there are two separate equilibrium times within this method. The first equilibrium time is for the system (i.e. humidity level within the airspace above the salt solution), and the second is for the filter-paper to come to equilibrium with that particular humidity level. Of course, reducing the amount of airspace above the pool of salt solution will decrease equilibrium time for the system. They also concluded that different equilibrium times are another reason for the differences in published calibration curves. Leong et al. (2002) test data shows that at maximum required equilibrium time was fourteen days for total suction measurements using pure, distilled water. As the molar concentration of the salt within the solution increased, the equilibrium times decreased, and in most cases five days were sufficient to establish filter-paper equilibrium.

If the testing program requires a sample to be tested for both matric and total suction at the same time, to ensure complete equilibrium, the longer fourteen day equilibrium time is required. Although Rao & Revanasiddappa (2003) followed the ASTM filter-paper standard D 5928-94 for most of their testing program, they decided to increase as the equilibrium time from the recommended seven days to ten days to ensure equilibrium had been reached. Sibley et al. (1990 a&b) used two separate equilibrium times depending on the suction being measured. When measuring matric suction, a three day equilibrium time was used, and for total suction measurements a ten day equilibrium time was preferred. Swarbrick (1990) indicated that a five day equilibrium time is sufficient, though wetter samples may require longer equilibrium times. Ultimately the equilibrium time is dependent upon the suction source, contact condition, and suction level within the system. The equilibrium time for a new testing program therefore should be tested before testing or calibration begins, to ensure that the proper time is allotted for the particular filter-paper, testing program, and testing environment.

2.3.3 Bacterial growth

Bacteria growth can be a problem when dealing with the filter-paper method. Since mass of the filter-papers are measured to an accuracy of 0.0001g any amount of bacterial growth could significantly alter the water content values measured, and hence the calculated suction values. The testing environment in many cases can promote bacterial development, especially if the soil tested contains a high amount of organic content. Not all researchers agree whether or not bacteria growth is a major problem. Those researchers who believe adopt preventive measures that do not follow a standard procedure. In organic soils, the use of preventative measures (i.e. fungicides) to prevent bacterial growth could alter the soil structure and produce erroneous suction measurements (Hamblin 1981). The testing program published by Hamblin (1981) initially included preventive measures against bacterial growth but concluded that it was unnecessary because reducing the equilibrium times, does not offer enough time for bacterial development. Deka et al. (1995) also suggest that there is no need to pre-treat filter-papers to prevent bacterial growth for soils that do not contain large amounts of organic content. Leong et al. (2002) found no reports of serious problems caused by bacterial growth on the filter-papers during suction measurements in published papers and attributed it to the short seven day equilibrium time. Sibley (1990 a&b) did not pre-treat their filter-papers to prevent bacteria growth and reported no problems with bacterial growth during testing.

Fawcett and Collis-George (1967) pre-treated their filter-papers with 0.005% mercury chloride and still found some evidence of bacterial growth on filter-papers for samples at higher water contents (i.e. low suctions). They recommended the use of a higher concentration of mercury chloride as a precaution in future testing programs. Houston et al. (1994) produced calibration curves both with untreated filter-papers and with filter-papers pre-treated with 0.02% mercury chloride solution. This comparison did not indicate any measurable effect due to pre-treating. Fredlund et al. (1995) pre-treated their filter-papers with a 3% pentachlorophenol solution. McQueen & Miller (1968) determined that pre-treating their filter-papers with a 2% solution of pentachlorophenol would be sufficient to deter bacterial growth, but in their testing program decided that it was prudent to use a 3% solution in case longer equilibrium times occurred. van der Raadt et al. (1987) pre-treated their filter-papers with a fungicide to prevent bacterial growth but also reported no problems with bacterial growth. As part of a prudent testing program, some form of bacteria protection should be incorporated since their use shows no effect on the calibration curve or suction values and can prevent the loss of data and time in the event bacterial growth occurs. The formation of bacterial growth was encountered to be a problem in the present research, and mitigative measures were taken. More details are provided in later chapters.

2.3.4 Filter-papers being initially oven dried or air dried

Researchers do not agree whether or not filter-papers should be initially oven or air dried before use in calibration or suction measurements. Ridley et al. (2003), Deka et al. (1995), Chandler & Gutierrez (1986), Hamblin (1981), and Fawcett & Collis-George (1967) state that filter-papers should be initially air dried. After pre-treating to prevent bacterial growth Houston et al. (1994), van der Raadt et al. (1987), and McQueen & Miller (1968), air dried their filter-papers before use in calibration and testing. Ridley (1995) state that since filter-papers are a fibrous material that is highly prone to hysteresis, air drying them before calibrating or testing may not be sufficient. Swarbrick (1990) suggests that it is important to initially oven dry the filter-papers so that the same wetting path is followed and the hysteresis effect is avoided. To suppress the hysteresis affect, Rao et al. (2003), Fredlund et al. (1995), ASTM D 5928-94, and Sibley &

Williams (1990b) oven dried their filter-papers before calibration and testing. Due to the reduction of the hysteresis effect and to ensure the proper wetting curve is followed, it is prudent to oven dry the filter-papers before testing and calibrating.

2.4 Factors affecting the measurements of soil suction using filter-paper

2.4.1 Using stacks of filter-papers versus using a single paper

The use of several filter-papers as a stack during testing has been questioned since the method was first introduced. Crilly & Chandler (1993) state that when the number of filter-papers in the non-contact method is reduced, the equilibrium time required for total suction measurements is also reduced. The mass of filter-papers have to be weighed within accuracy of ±0.0001 g, so a small change in filter-paper mass will dramatically change the measured water content. Therefore researchers have suggested that it is imperative that a set of three filter-papers be used when measuring soil suction. This set of filter-papers consists of two sacrificial, protective filter-papers surrounding a center filter paper which is used for determining final water content (ASTM D 5928-94). Some researchers have noted that using this three filter-papers system increases equilibrium time since the water has to pass through several filter-papers and could also change the water content of the sample which in turn would change the suction value (Leong et al. 2002 & Hamblin 1981). Fredlund et al. (1995) used a three stack of filter-papers and placed them inside sample. Ridley (2003) used only one filter-paper on top and on bottom of the soil samples, but stated that when weighing filter-papers after equilibrium, the water content measurement should be discarded if soil particles can not be removed from the filter-paper. Minimizing the amount of filter-papers will reduce equilibrium time. However, sacrificial filter-paper should be used to prevent soil contamination on the filter-paper actually used for water content measurements. Equilibrium time should be tested accordingly if more than one filter-paper is used in the system.

2.4.2 Using Contact versus non contact calibration curves

Since soil suction can either be total or matric suction depending on the water content of the sample, choosing an appropriate calibration curve is essential. Fredlund et al. (1995) state that a single calibration curve can be used to measure the entire suction range as long as it is separated into two ranges, one to measure total suction and the other to measure matric suction. Ridley & Wray (1996) state that at higher suctions the meniscus of the pore water retreats into the soil sample and even with an intimate contact between the filter-paper in the soil may not guarantee that matric suction will be measured. van der Raadt et al. (1987) tested both the contact and non-contact filter paper methods under the original premise that filter-papers in direct contact with the soil will measure matric suction, and with no contact, would measure total suction. In reviewing their results they found that several contact filter paper results indicated large "spikes" in the matric suction values measured. Analyzing the results of matric suction values determined, they found these suction values closely matched the total suction values measured for the same sample measured using other suction devices; including the results of the non-contact filter paper method. They attributed this behaviour to the fact that even though the filter-papers were in direct contact with the soil sample they were not in direct contact with the soil-water within the pores of the sample. Therefore, the predominant mode of moisture transfer was in the vapour phase and total suction was measured.

Fredlund et al. (1995) showed that for suctions measured from samples compacted at water contents at or above optimum, where proper contact was ensured, there was a good agreement between the matric suction values measured by the contact filter-paper method and other reference sensors. The same sample showed little agreement between the non-contact filter-paper method and the total suction values measured by the reference sensors. For samples prepared with water contents less than optimum they reported that the suction results from the non-contact filter-paper method showed little difference when compared to the suction values measured using the contact filter-paper and the reference sensors measuring total suction. They showed that the moisture transfer mode was the dominant factor in determining the type of suction measured (i.e. total or matric suction).

Houston et al. (1994) state that two separate calibration curves should be used when calculating suctions, one for total suction, and the other for matric suction. In investigating the higher suction range (i.e. greater than 3000 kPa) the two calibration curves merge and little error would be introduced if suctions were calculated only using the total suction curve. Leong et al. (2002) also suggests that two calibration curves are required to properly measure suction with the filter-paper method, but used 1000 kPa as the boundary suction value between total and matric suction. McQueen & Miller (1968) stated that although matric suction is assumed to be measured when the filter-paper is in direct contact with the soil, at high suctions only total suction will be measured whether or not the filter-paper is in contact with the soil. They surmised that it is unlikely that the filter-papers would be in direct contact with the soil moisture and only vapour moisture transfer will occur. Clearly, it is important to know a priori the suction range being investigated and calibrate and test with the filter-paper appropriately.

2.4.3 Type of contact between the filter-paper and the sample

Since it has been shown that filter-paper not directly in contact with the pore-water will measure total suction instead of matric suction, researchers have suggested that the differences in published calibration curves could also be from uncertain contact between the filter-paper and sample (Houston et al. (1994). Proper contact between the filter-paper and either the test samples or calibration device must be ensured in order to allow the proper moisture transfer mode. Methods to ensure contact between the filter paper and the pore-water of the specimen have varied from researcher to researcher. The amount of stress applied to the filter paper is crucial because over compressing the filter-paper will alter its water uptake ability (Chandler & Gutierrez (1986).

There are four main methods to ensure contact between the soil sample and filter-paper. The first is simply placing the filter-paper on top of the sample, the second is placing it in between two halves of a compacted sample, the third is to bury the filter-paper within a compacted sample, and the fourth method is to apply an overbearing stress to the filter-papers (Figure 2.7).

McQueen & Miller (1968) ensured contact between the filter-paper in the soil sample by simply placing the filter-paper on top of the soil sample. Rao & Revanasiddappa (2003), Fleureau et al. (2002), Houston et al. (1994) and Fawcett & Collis-George (1967) ensured contact between the soil sample and the filter-paper by burying the filter-papers within the test samples. The samples were constructed by placing half the sample into the container, compacting to the proper unit weight, placing a three stack of filter-papers in the middle, and firmly placing the rest of the sample on top. Houston et al. (1994) believe that this would achieve maximum intimate contact, whereas simply placing the filter-papers on top of the sample would at best give questionable contact. Leong et al. (2002), Fredlund et al. (1995), and Hamblin (1981), ensured contact between the filter-paper and the soil sample by cutting cored samples in two, and placing a three stack of filter-papers in between the two halves, and reassembling samples for testing. This method would use the weight of the overlying soil to ensure contact with the filter-paper, and also allow the development of suction with depth profile. Rao & Revanasiddappa (2005) placed a three stack of filter papers on the bottom of the test container and used the weight of the overlying soil to ensure contact during equilibrium. Sibley (1990 a&b) used a brass ring weighing 8.3 g when calibrating with the pressure membrane. They ensured contact by placing 4 - 0.25g of lead shot on top of each filter-paper in the pressure plate devices. Deka et al. (1995) arranged the filter-papers on the tension table, covered them with a polyethylene sheet, followed by a sheet of glass when using tension table to calibrate the low suction range, (i.e. less than 65 kPa). Weights were then distributed on top of the glass giving a combined applied stress 1.5 kPa. However, a discussion on the effect of the applied stress on the calibration curve or suction measurements was not given in their paper.

Knowing how filter-papers will react under a compressive stress is an important aspect of the filter-paper method. Except for simply placing the filter-paper on top of the soil, all of the above listed methods of ensuring contact will exert some form of compression of the filter-paper. How much compression and its effect on filter-paper has not been truly investigated though Chandler, Gutierrez (1986) has stated that overestimates of suctions up to 300 kPa can result due to compression of the filter-papers.

2.4.4 Accuracy of the filter-paper method

The true test of any testing method is the accuracy and repeatability of the results measured. Many researchers have published a wide range of accuracy levels for the filter-paper method. Although the filter-paper method can test a wide range of suctions what is more important is the accuracy of the measurements (Swarbrick, 1990). Hamblin (1981) state that a preoccupation with accuracy and the errors involved with the methodology has possibly restricted the use of the filter-paper method. On examining the overall testing procedure of the filter-paper method, Chandler et al. (1992) reported an accuracy of ±25%, though in most cases accuracy of ±15% was achievable when testing samples retrieved from block sampling. They determined that it was impossible to differentiate between the errors using the filter-paper method, from those due to the variation of the suction within the soil. Tsai (1995) and Houston et al. (1994) state that confidence or accuracy in the filter-paper method is developed through replicating suction measurements of the same sample. McQueen and Miller (1968) stated that the method is at least as accurate as other methods that can measure only limited suction ranges. Rao & Revanasiddappa (2003) followed the ASTM D 5928-94 standard but since it did not have accuracy listed for the filter-paper method, their publication does not comment on the accuracy of the measured suction values.

van der Raadt et al. (1987) stated that the filter-paper method is a technique sensitive procedure and although it can measure a wide range of soil suction, the accuracy of the results can decrease if extreme care is not used when weighing the filter-papers. In order to achieve an acceptable accuracy in water content determination of the filter papers, the use of a weighing scale capable of measuring mass to a precision of 0.0001g is essential (Swarbrick, 1990). Houston et al. (1994) stated that it is impossible to measure water content of the filter-papers better than ± 0.1 % which puts a significant limitation on the use of the non-contact filter-paper for suctions less than 3000 kPa. An extremely small loss or gain in water content by the filter-paper during the testing process can dramatically alter the measured suction values. van der Raadt et al. (1987) stated that it is not possible to guarantee that matric suction will be measured using the contact filter-paper method and as such the only way to achieve accuracy with the filter-paper method is to use it only for total suction and not matric suction measurements.

The ASTM D5298-03 standard also states that "the precision of the filter paper test method is currently being evaluated" and "there is no accepted reference value for this test method therefore bias cannot be determined" making it prudent to produce a separate calibration curve depending on the testing program followed to increase accuracy of suction results. The research undertaken has therefore attempted to provide recommendations for standardization of this test method.

Figures:

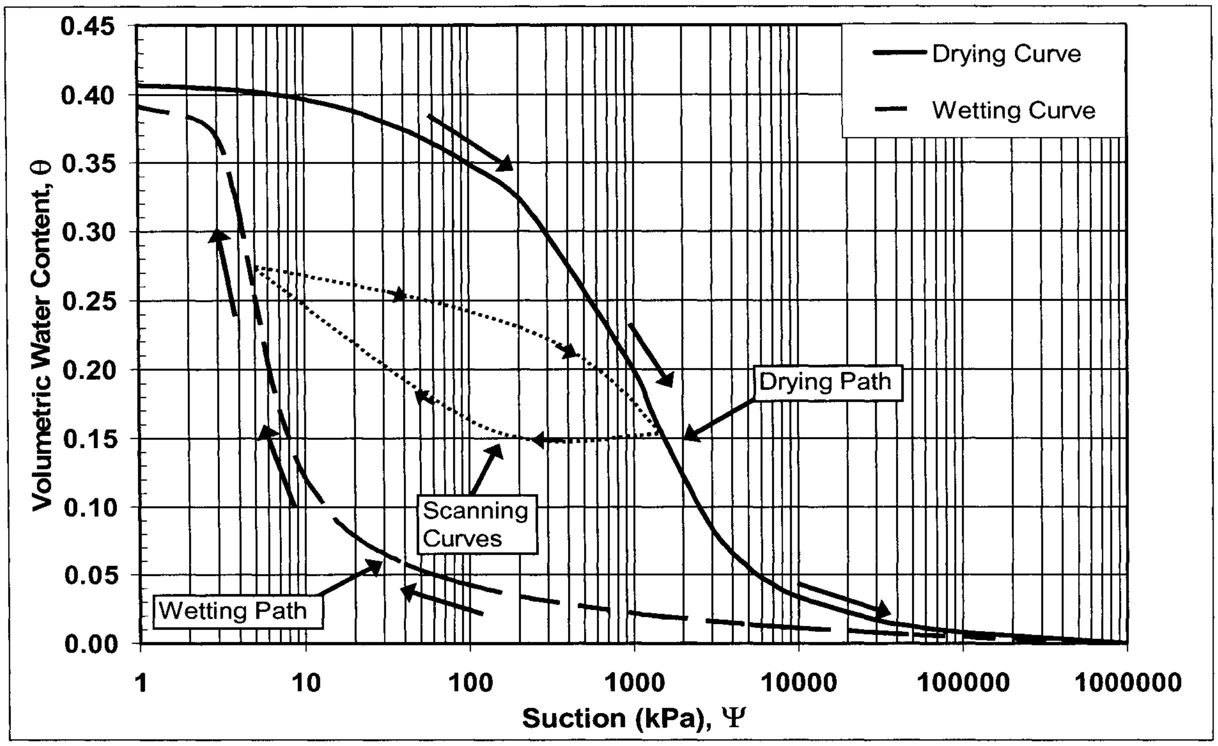


Figure 2.1: Wetting and drying curves of the soil water characteristic curve showing scanning curves.

Figure 2.2: Filter paper placed on null pressure plate for calibration.

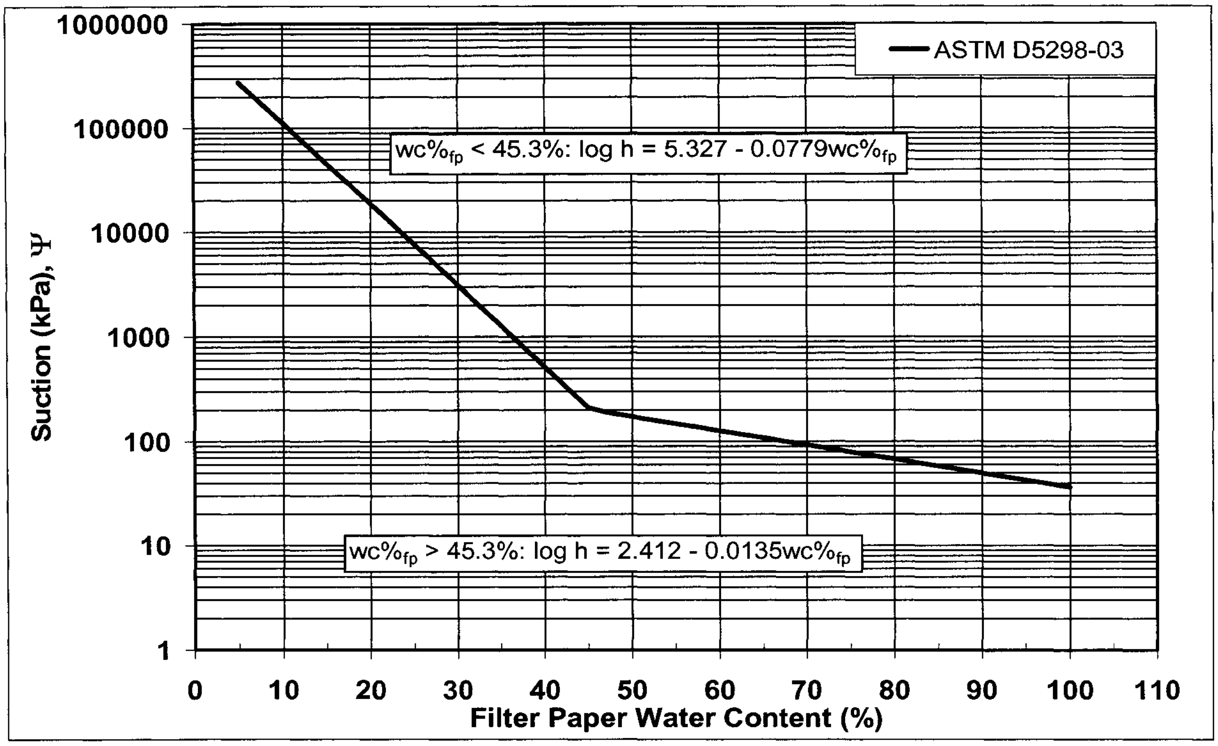


Figure 2.3: Calibration Curve for the filter paper method from ASTM D5298-94.

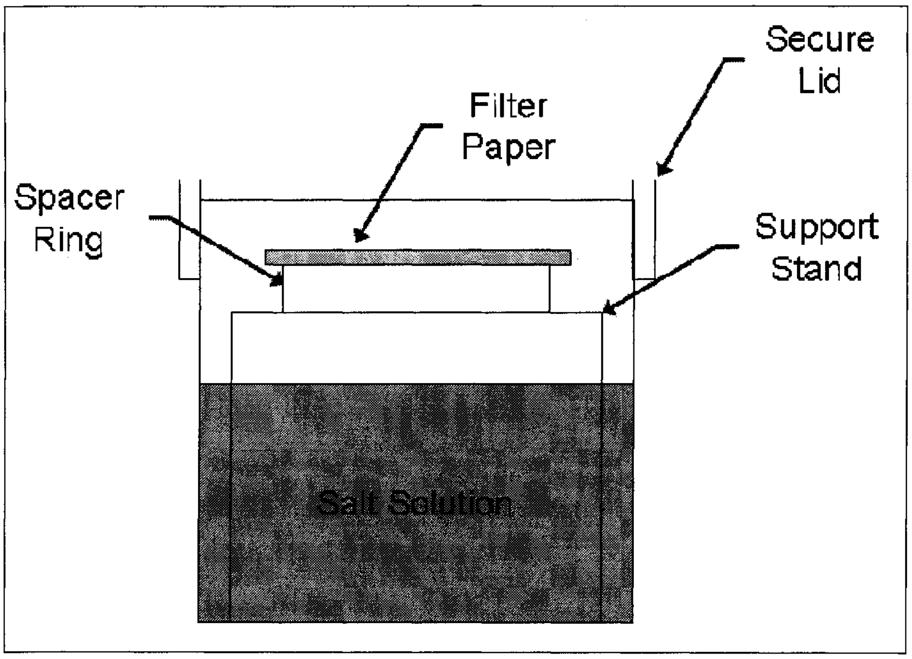


Figure 2.4: Test step up for total suction calibration of filter papers.

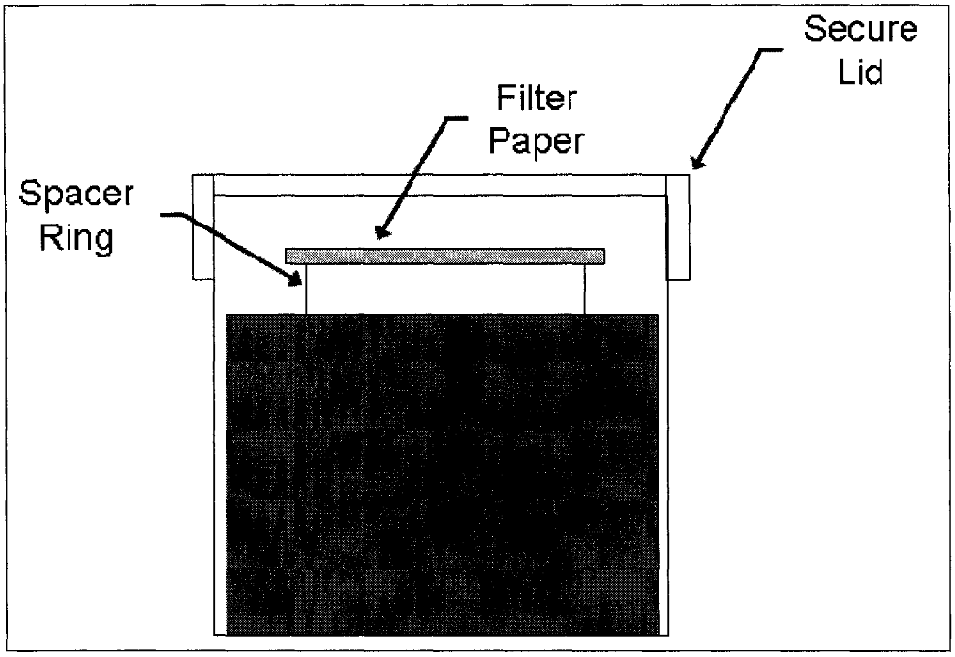


Figure 2.5: Calibration of filter paper using specimens of know suctions.

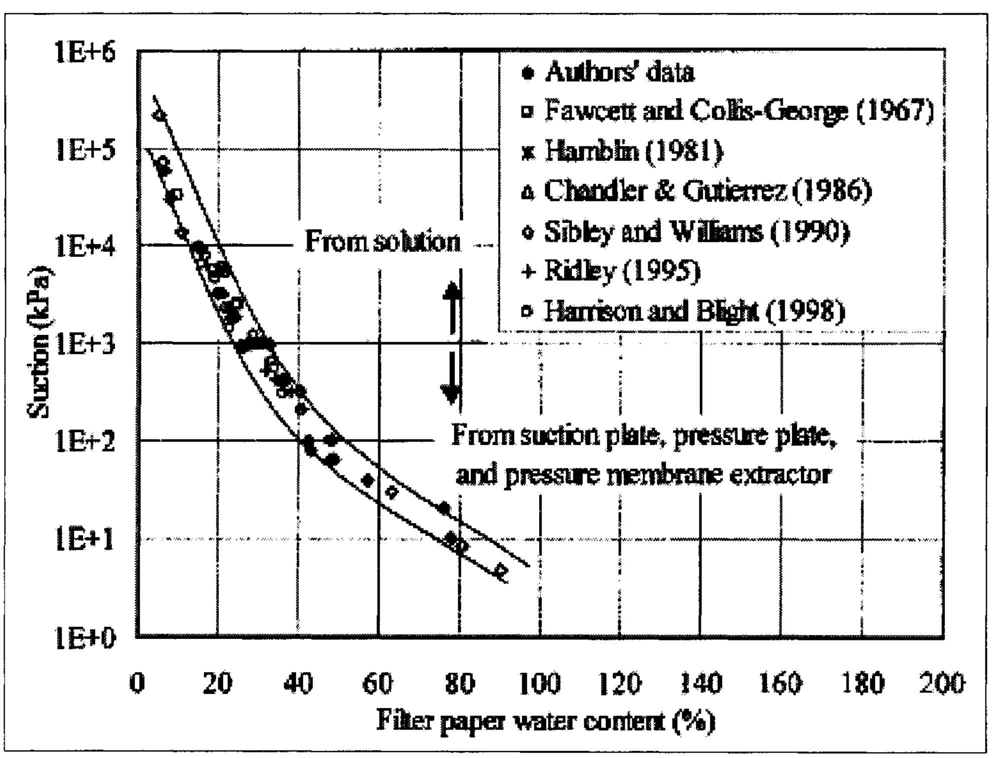


Figure 2.6: Comparison of filter paper calibration curves from Leong et a. 2002.

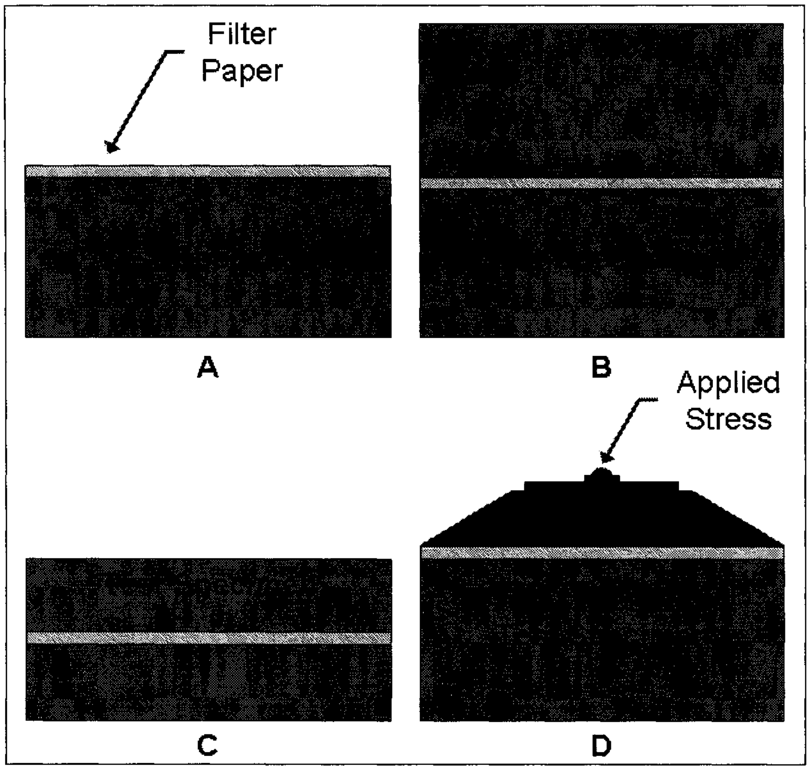


Figure 2.7: Methods to ensure contact between filter papers and pore-water. A) Filter paper placed on specimen Al-Khafaf & Hanks (1972). B) Filter paper placed between two specimen halves Fredlund et al. (1995). C) Filter paper placed in a compacted sample Houston et al. (1994). D) Applied stress to filter paper Deka et al. (1995).

Chapter 3: Equipment Details

3.1 Introduction

The laboratory testing portion of the research program constituted the determination of the effect of initial water content, matric suction and compaction energy on the compressibility characteristics of Indian Head till. The initial matric suction of unsaturated Indian Head till specimens prepared at different initial water contents using two different energy levels was determined using both direct and indirect methods. The matric suction of the unsaturated soil specimens was necessary to interpret the compressibility characteristics of the till specimens in terms of two stress state variables, namely; matric suction, $(u_a - u_w)$ and net normal stress, $(\sigma - u_a)$.

Traditional fixed-ring, Wykeham Farrance oedometer cells were modified to measure the compressibility behaviour of the soil. Due to the electrical interference present in the laboratory, dial gauges were used to measure the deformation of the test specimens and the data was recorded manually.

Two methods for measuring matric suction were used in this research project namely; axis-translation technique and the contact filter paper method (i.e. ASTM D5298-03). To determine the matric suction in unsaturated soil specimens using the axis-translation technique, a null pressure plate device was designed and used in conjunction with the available oedometer test machines and as a stand alone machine. Due to the electrical interference problem that affected the LVDTs, mentioned earlier, the matric suction of the test specimens were recorded using a 700 kPa pressure gauge and the data was recorded manually.

The following chapter provides a brief description of the equipment used in the testing program.

3.2 Oedometer Cells

Modified traditional fixed-ring, Wykeham Farrance oedometer cells were used in this research project. These cells are conventionally used to determine the consolidation characteristics of saturated soil specimens. Several design modifications were introduced to these cells such that both saturated and unsaturated soil specimens can be tested using the same equipment. These details are summarized in the following sections.

3.2.1 Original Oedometer Cells

A typical fixed-ring, Wykeham Farrance oedometer cell is shown in Figure 3.1. The cell consists of two porous stones (to facilitate two-way drainage during the process of consolidation of a saturated soil specimen), specimen ring, and loading cap. The top stone is attached to the 63 mm diameter loading cap. The specimen ring has a diameter of 63 mm and a height of 25 mm.

3.2.2 Modifications to Traditional Oedometers

Several modifications were introduced to the traditional oedometer cells in order to use the same units for testing unsaturated soil specimens. The objective of these modifications was to use the same oedometer cells for testing both saturated and unsaturated specimens. By using the similar testing apparatus, the test results would not be influenced due to the use of different types of equipment.

3.2.3 Acrylic Chambers

It is important to ensure that environmental conditions of the laboratory do not alter the water content of the unsaturated soil specimens during testing as inconsistencies will be introduced into the test results. To achieve this objective, special provisions were included through the use of an acrylic chamber to house the specimen during testing. This acrylic chamber forms a part of an integral modification of the oedometer test set up for the testing of the consolidation behavior of unsaturated soil specimens.

Figure 3.2 shows the details of the acrylic chamber used in this research program. The two openings in the top cap of the chamber facilitate in the placemen of load and dial gauges to measure the pressure and deformation acting on the soil specimens during consolidation. In order to prevent the specimen from losing moisture to the atmosphere, an inlet was added to the chamber to allow a constant stream of 100% humid air to be pumped into the chamber during testing. The humidity stream was produced by passing compressed air through the bubbling pots shown in Figure 3.3. In order to make the incoming dry air more easily accept the moisture, it was first heated, and dispersed through a porous plastic disk at base of each bubbling chamber. The air was then passed through a 100 mm high saturated sand and water column before continuing to the next bubbling chamber. Three bubbling chambers were incorporated into the system to account for the seasonal weather changes that may arise in the laboratory environment.

The effect of the 100% humid air stream on the water content of compacted specimens was tested on three compacted specimens. Two specimens were placed into chambers where the stream of 100% humid air was being pumped in, while the third specimen was placed in a chamber at the humidity level of the laboratory, approximately 50%, and left for 24 hours. The mass of the specimens in the 100% humid air stream were recorded only once an hour in order to maintain the humidity level unaltered in the chamber. The mass of the specimen without the 100% humid air stream was recorded every half-an-hour due to the dramatic drop in water content. Figure 3.4 details the water content versus time for each of the specimens. The results show a large drop in water content for the specimen left at the humidity level of the laboratory, demonstrating the need for the acrylic chambers for testing unsaturated soil specimens where maintaining initial water content of the specimen is essential.

3.2.4 Unsaturated Oedometer Cells

The oedometer cells were made from brass, and were manufactured by the University of Ottawa's in-house machine shop and are shown in Figure 3.5.

As described earlier, similar test setups were proposed for testing the compressibility behavior of saturated and unsaturated soil specimens. Due to this reason, it was planned to use similar type of stones for sandwiching the soil specimens within the oedometers. This would ensure consistency in the trends of test results of both saturated and unsaturated soil specimens. A 500 kPa high air entry disk was used in place of the conventional corundum disk in testing saturated soil specimens. Figure 3.6 shows the high air entry stones used for this testing program. Due to the brittle nature of the stones they were first machined flat to ensure that they would not break under the applied axial stress. As a final precaution the stones were sealed in a brass ring for extra rigidity. When high air entry stones are fully saturated, they allow the free passage of water between the disk and the specimen voids. However, air can not pass through the stone until the air pressure inside the chamber reaches that of the air entry value of the stone (i.e., 500 kPa); therefore, a second drainage path would have to be incorporated for the passage of pore air from the unsaturated soil specimens. The required drainage path for the pore air was achieved by drilling four, 3 mm diameter holes through the loading cap. A low-air entry brass stone was epoxied to the bottom of the loading cap which would allow the pore air to exit the specimen. A Teflon ring was inserted along the base of the loading cap to reduce side friction between the cap and specimen ring. Figure 3.7 shows the loading cap along with the other required accessories.

3.2.5 Sealing the Ceramic Disk into the Rigid Metal Rings

Preliminary tests were performed to determine an appropriate method to glue or epoxy the ceramic disks in the rigid metal rings. The epoxy could not contain any metal fillings as they would rust in the saturated testing environment, and must be viscous enough to completely fill the small 3 mm space between the ring and the ceramic disk. The epoxy chosen was manufactured by Soil Moisture Corporation and shown in Figure 3.8. It was important to ensure that no air voids formed while placing the epoxy as they would weaken the bond between the disk and the brass ring. This was accomplished by building up the epoxy in layers as shown in Figure 3.9. Each layer was allowed to cure over night under a heat lamp before the next layer was put into place. Any air voids formed in a proceeding layer were first opened and filled by the epoxy forming the next layer.

3.2.6 Loading Frame

Figure 3.10 shows the Brainard and Kilman oedometer loading machines used in the initial testing program. These oedometers have the provisions to automatically load the specimens using a bellofram system. Trial test results and data from Ho (1988) using the Indian Head till have shown that a minimum of 24 hours would be required to reach the end of the primary consolidation. During preliminary tests, it was determined that the above oedometers were unable to maintain a constant load over a 24 hour period. This problem was rectified by replacing the oedometer machines with the loading system shown in Figure 3.11. The new loading system consisted of steel loading frame, and a 25 liters plastic bucket (see Figure 3.12). Due to range of stress used in the testing program (i.e., 5 – 800 kPa), and space constraints of the laboratory, it was determined that lead shot would be the best option for application of the required dead load to simulate the required stress on the specimens. The amount of lead required to produce the required stress levels would easily fit in the 25 liters buckets used for the oedometer tests. Since lead shot was utilized instead of air pressure to apply the dead load, the lead shot would have to be manually added to each bucket as shown in Figure 3.14. The unloading process would prove to be more difficult. After considering a couple of alternatives, unloading the lead shot was accomplished by drilling four, 12.5 mm diameter holes in the bottom of each bucket, and plugging them with rubber stoppers as shown in Figure 3.13 When the load was to be reduced during the unloading portion of the test, the rubber stoppers would be removed and the lead shot would flow out of the bucket.

3.3 Single Specimen Null Pressure Plate System

Figure 3.15 and Figure 3.16 show the details of the two null pressure plate systems that were designed and developed to measure the matric suction of the unsaturated soil specimens, following the axis translation technique (Hilf, 1956). The system in Figure 3.15 was designed such that it can be accommodated into a modified oedometer which would allow the application of an axial stress and facilitate the measurement of the change in height of soil specimen along with the measurement of soil suction. The second system shown in Figure 3.16 is for measurement of matric suction only with no axial load capability. The four main components of the null pressure plate system are: the pressure chamber with a high air-entry stone, pressure gauge or transducer for measuring and recording of the matric suction measurements, and the flushing system. The details of the design of these components are summarized in the following sections.

3.3.1 Pressure Chamber

The two pressure chambers used in the null pressure plate system were designed and developed at the University of Ottawa's in-house machine shop, (see Figure 3.17 and Figure 3.18). The pressure chambers were designed to house the same specimen rings as those used in the consolidation test program thereby giving consistency between the two procedures. Each pressure chamber consists of a brass cylinder, cap, and an acrylic base. The cap of the first system was modified to allow the passage of the piston that would apply axial stress to the specimen (see Figure 3.19). The change in specimen height would be measured by either a dial gauge or LVDT. The cap of the second pressure chamber was designed without an access hole and is strictly used for the measurement of matric suction. Matric suction is measured by increasing or decreasing the applied air pressure of the chamber. Complete details of procedure for determining matric suction using the axis-translation technique are outlined in Chapter 5: Testing Program. The pressure within the chamber is measured either using a 1400 kPa pressure transducer (i.e. system with axial load capabilities) or a 700 kPa pressure gauge in the case of the second system (i.e. system used for matric suction measurements only).

3.3.2 Pressure Chamber Base

Figure 3.20 shows the details of the acrylic base of the pressure chamber. The base was made from acrylic instead of brass so that any air bubbles developing during the test would be visible to the naked eye. The spiral groove pattern in the bottom of the base is to aid in the removal of air bubbles that may develop during testing. The grooves are small enough such that when the water is pumped through them, the air bubbles are trapped within the grooves and are forced to flow out into the air-trap portion of the flushing system described in Section 3.4. Since the base was made from acrylic, "O-seal straight threaded" fittings were used for the inlet and outlet connections between the base and the flushing system. Experience has shown that regular NPT pipe fittings crack the base when tightened and allow both air and water to leak into the system.

An O-ring located in a separate circular groove on the bottom of the base was the original method of sealing the connection between the high air entry disk, and the pressure chamber base (see Figure 3.21a). During preliminary testing, it was discovered that the O-ring would compress as the air pressure within the chamber is increased, producing erroneous matric suction measurements. The new design called for a separate circular O-ring groove to be placed around the outside of the base (see Figure 3.21b). The new O-ring groove would allow the stone to sit flush with the bottom of the acrylic base and be sealed around the outside diameter of the metal ring. The five, 150 mm screws that pass through the base are bolted to the cap of the pressure chamber to securely seal the specimen inside.

3.3.3 High air Entry Disks

The axis-translation technique works by shifting the reference pressure from the negative pore water pressure of the specimen, to the applied positive air pressure within the pressure chamber (Hilf, 1956). This is achieved through use of a high air entry disk. The high air entry disk acts as a semi-impermeable membrane that allows the flow of water through its pores, but restricts the flow of the applied air flow. In other words, the high air-entry disk acts as a divider between the negative pore water pressure of the soil specimen, and the atmospheric pressure conditions (Fredlund & Rahardjo, 1993). The same 500 kPa high air entry disks that were used in the oedometers were used in the null pressure plate system for consistency. The same process described in section 3.2.5 to seal the ceramic disks into the brass rings was used to seal the high air entry discs into the stainless steel ring. Figure 3.22 shows the ceramic discs used in the null pressure plate apparatus. The disk sits flush with the bottom of the acrylic base and is sealed into place using a 3 mm diameter O-ring. In order to remove the stone from the acrylic base, eight, #2-56 diameter holes were drilled and taped at 45° increments around the outside edge of the disk. The location of the holes was such that they would not interfere with seal between stone and the pressure chamber. Since the disks were fragile, a puller device shown in Figure 3.23 was manufactured consisting of eight #2-56 diameter threaded rods 100 mm length, to safely pull the disk out of the acrylic base (see Figure 3.24).

3.4 Flushing System for the Null Pressure Plate System

It is essential to remove any air bubbles that form under the saturated ceramic discs in order for the axis-translation technique to properly determine the matric suction of a specimen. Although distilled, de-aired water was used in the null pressure plate system, over time; more dissolved air can come out of solution producing erroneous suction measurements. Garga & Zhang (1997) studied the rate at which de-aired water would re-oxygenate when left in a container open to the atmosphere. They showed that a 300 ml of water originally de-aired using a Mold Desecrator when left open to the atmosphere would double its oxygen content in the first 10 minutes (see Figure 3.25). It is therefore important to incorporate a flushing system to periodically remove any dissolved air that can appear within the null pressure plate system during testing.

The important features of the flushing system are: the pump and dimmer switch, the air trap with stopcock, and the glass tube to indicate the null position during testing (see Figure 3.26). An investigation into the most effective method to remove any air bubbles that form during testing was undertaken and the development of the new flushing system is summarized in the following section.

3.4.1 Pump for the Flushing System

The original pump used in the flushing system was a common automobile windshield washer pump. This style of pump was chosen because it was readily available, inexpensive, and had the appropriate force required for flushing the system. The downside of this style of pumps was that they quickly burnt out when pumping only air, a situation that occurs initially when the null pressure plate system is first saturated. The original pumps were replaced with the Grey or PQ-12 V pump shown in Figure 3.26. The new pumps are able to remain cool even while pumping air due to the fins that surround the motor. The pumps were connected to a common electrical dimmer in order to control the pumping force and eliminate any cavitation that may occur during flushing. In the event that air bubbles do form under the ceramic discs, the pump would be turned on and the air bubbles would be flushed into the air trap.

3.4.2 Air-Trap for the Flushing System

Once the air bubbles are removed from the acrylic base they flow into the air trap shown in Figure 3.26. The air-trap is attached to the pressure chamber base by 3/16", hydrophobic tygone tubing. This style of tubing was chosen to eliminate the chance that it would absorb water during testing and produce erroneous suction results. The original 50 mm high air trap is shown in Figure 3.27 which was replaced with the larger 100 mm air-trap shown in Figure 3.26. The smaller air-trap was replaced for two reasons. First, the volume of water held by the smaller air-trap was not sufficient to initially saturate the null pressure plate system. The second reason was that during flushing the elongated neck of the larger air-trap allowed more room for air bubbles to escape the water flow, rise up the neck of the air-trap and out of the system.

3.4.3 Glass Tube Indicator for the Flushing System

The applied air pressure in the pressure chamber is increased or decreased depending on the movement of water from the original null position in the glass tube as outlined in Chapter 5. During testing a decrease in water volume in the glass tube means that the water is being absorbed by the specimen meaning its matric suction is greater than the air pressure in the chamber. Flow of water into the system is stopped by increasing air pressure within the chamber. It was determined that if the 3 mm diameter glass tube was replaced with a 1 mm diameter tube, would reduced by a factor of nine the volume of water required to indicate a change in the null position greatly improving the accuracy of the technique (see Figure 3.28).

3.5 Filter Paper Technique

The contact filter paper technique was employed for this research project to determine matric suction, (Ridley et al. 2003, Houston et al. 1994, Chandler et al. 1992, Al-Khafaf 1974, Fawcett & Collis-George 1967). This technique uses commercially available filter papers in direct contact with the soil specimen to indirectly measure the matric suction. The two most common filter papers used in geotechnical research are Whatman 42 and Schleicher Schuell #589. Historically many different kinds of materials have been used in soil suction research by soil agronomist in agricultural studies, including sugar solutions Stocker (1930), and blotting paper Garmann (1934). The matric suction of the soil is determined by placing a filter paper in direct and intimate contact with the pore water of the soil specimen in a temperature and humidity control environment. When the system comes to equilibrium (i.e., the moisture transfer) between the filter paper and the soil specimen (i.e., the matric suction of the filter paper equals that of the soil specimen), the water content of the filter paper is determined. Through the use of a calibration curve that relates filter paper water content to applied air suction, that is determined separately, the matric suction of the filter paper and hence the test specimen is determined.

Since this method relies solely on the accuracy of the calibration curve the development of these curves is of importance. It has been shown by several researchers that the calibration curve is unique to the filter paper being used (Houston et al. 1994) or the type of suction being measured (i.e. matric or total suction) (Fredlund et al. 1995). Studies have also shown that the calibration curve is dependent on laboratory environment and testing program followed (Swarbrick 1990). The ASTM standard has published the calibration curve for the two most common filter papers (i.e. Whatman 42 and Schleicher Schuell # 589) based on the research of Fawcett & Collis-George (1967) and Greacen et al. (1987). The standard states that the curves present are more appropriate for the measurement of total suction which was not the particular form of soil suction being investigated in this research program. It was determined that since our testing program was slightly different from that proposed in the literature and the ASTM D5298-03 standard it would be necessary to produce a calibration curve for the University of Ottawa tests and compare it with those available in the literature. The following section details equipment used to both develop a new calibration curve and the measurement of suction using Whatman 42 filter papers.

3.5.1 Calibration Equipment for Whatman 42 Filter Paper

The Whatman 42 filter papers were calibrated using the null pressure plate system shown in Figure 3.29. The main system consists of a 300 mm diameter, 500 kPa high air-entry ceramic discs (see Figure 3.30), a 400 kPa Scientific Research pressure gauge with an accuracy reading of ¼ of 1%, and a two way regulator to control the applied air pressure. The entire system was designed so that it could be relocated to different laboratories as required.

3.5.2 Flushing System for the Null Pressure Plate System

Researchers have shown that appropriate calibration for the filter paper method is along the wetting curve as it is the path followed in the testing process (Al-Khafaf, Hanks, 1974 and Bulut et al., 2001). The concept behind the calibration is that the oven dried filter papers will imbibe water from the saturated ceramic disk under an applied air pressure in the tank over an equilibrium period of up to 14 days. The ceramic disc remains saturated as long as it remains in contact with the water present in the bag under the disc shown in Figure 3.31. Since the calibration process can takes up to 14 days per each applied matric suction level, a special provision would have to be designed to remove the dissolved air that would form in the bag under the ceramic disc due to an applied air pressure in the tank. The bag under the ceramic disc is connected to atmospheric pressure through the tub connection shown in Figure 3.32 and is attached to the syringe shown in Figure.3.33. During calibration, the water level in the syringe was monitored and when it increased by 12.5 mm, sufficient air had been developed in the bag to warrant it being removed. Flushing was accomplished by first reducing in the pressure in the tank, attaching the syringe to an aspirator and turning the water on to apply the suction force to remove the air bubbles that had formed under the ceramic disc (see Figure 3.35). The flushing of the system would have to be performed at a minimum of twice a day for suctions below 100 kPa and up to four times a day for suctions greater than 100 kPa.

3.5.3 Scrubbing System for Formaldehyde Removal

The ASTM D5298-03 recommends that 2% solution of formaldehyde be used to prevent the contamination of the filter papers due to bacterial growth if equilibrium times were longer than 14 days. The recommended 2% solution of formaldehyde was insufficient in the laboratory environment to prevent bacteria growth shown in Figure 3.34 and Figure 3.36. A 10% of formaldehyde solution was used to prevent contamination of the filter papers was used instead. With the use of 10% solution of formaldehyde, a scrubbing system would have to be incorporated in order to remove the majority of the formaldehyde from the air stream before venting it to the laboratory. The scrubbing system consisted of four - 2 liter bottles connected in series and were sealed with a rubber bung to prevent leakage. Whenever the tank was emptied to weigh the filter papers, the air in the tank would first pass through the bottles thus removing the formaldehyde from the air before it was released into the laboratory.

3.5.4 Appling Stresses to Filter Papers during Calibration

A secondary project undertaken as part this testing program was to understand the influence of applied stresses on the calibration curve generated using the null pressure plate system. Chandler & Gutierrez (1986) stated that suction could be overestimated by 200 – 300 kPa due to the compression of the filter papers but little else is mentioned in the literature about the effect of compression. Tests under some unspecified applied stresses have been used by researchers to ensure intimate contact between the filter paper and the pore water of the test specimen (Deka et al., 1995, Sibley et al., 1990). To test the compression effect, in addition to the calibration curve generated with zero applied stress, four other calibration curves were generated with applied stresses of 0.5, 1, 2, and 4 kPa applied to the filter papers. The stresses were applied by filling the specimen containers with lead shot to the desired mass (see Figure 3.37). To ensure even distribution of the applied stress, a spacer was placed between the filter paper and the specimen container. Holes were drilled into the spacer to allow the air pressure to reach the filter papers (see Figure 3.38).

The filter paper and applied loads are placed into the null pressure plate apparatus as shown in Figure 3.39. The calibration curves are generated by increasing the air pressure within the chamber and allowing the filter papers to come to equilibrium with the moisture within the ceramic stone for at least 14 days per each stress level. After the equilibrium, the filter papers are weighed and their water content is determined. The calibration curve then relates the filter paper water content to the applied suction.

3.6 Summary

This chapter has provided details of the equipment employed in determining both the compressibility behavior and the matric suction values of the Indian Head Till used in this research project. For the consolidation process fixed ring, Wykeham Farrance oedometer cells were modified to test unsaturated soils. To measure matric suction, two different methods were used namely, the axis-translation technique, and the contact filter paper method. To determine the matric suction using the first method, a null pressure plate system was specially designed to perform the axis-translation technique along with traditional oedometer machines. As a second method, the contact filter paper method was used to determine the matric suction of unsaturated soil specimens.

Figures

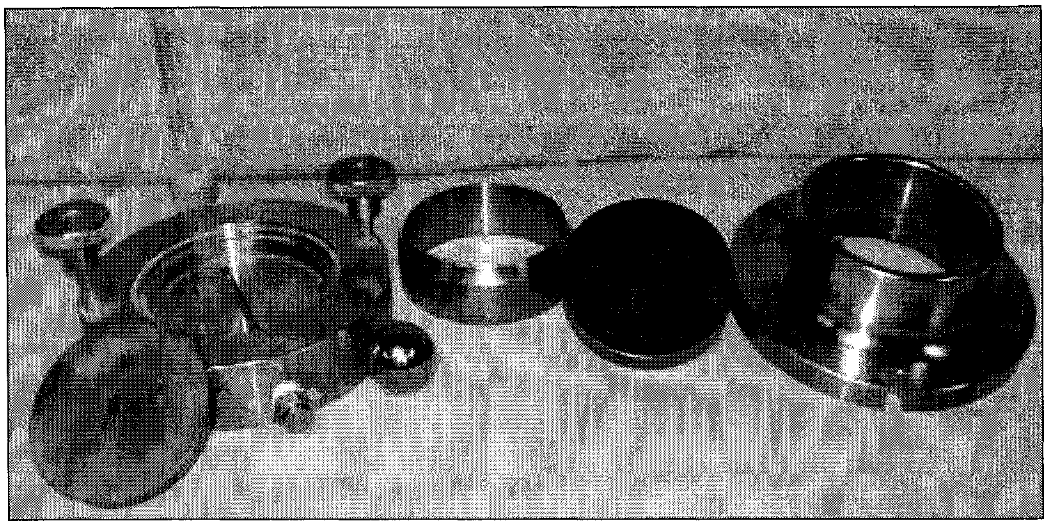


Figure 3.1: Wykeham Farrance fixed ring oedometer cell for saturated soil testing.

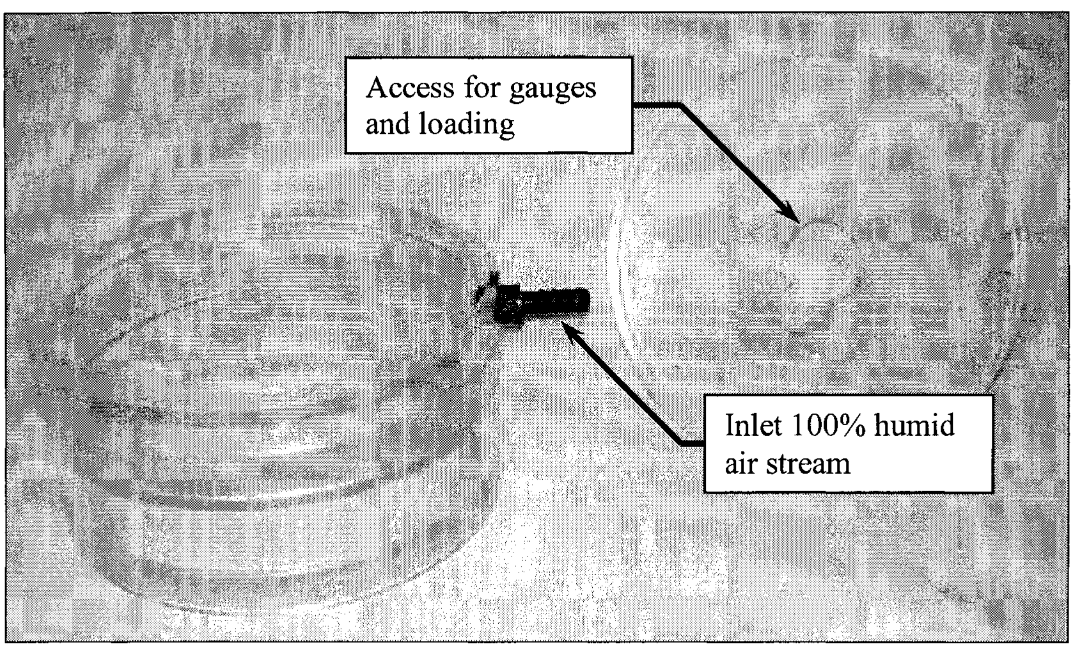


Figure 3.2: Acrylic chamber with inlet for 100% humid air stream.

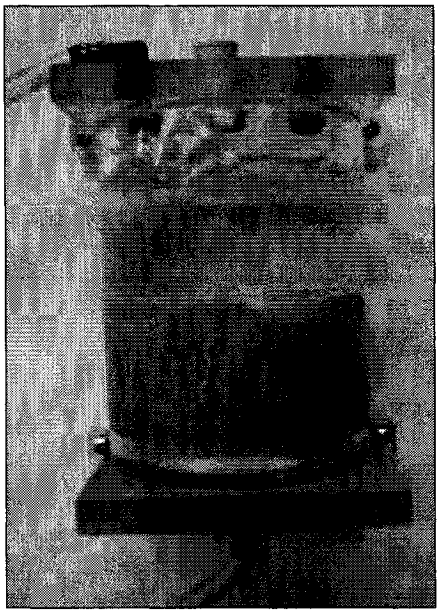


Figure 3.3: Humid air stream bubbling chamber.

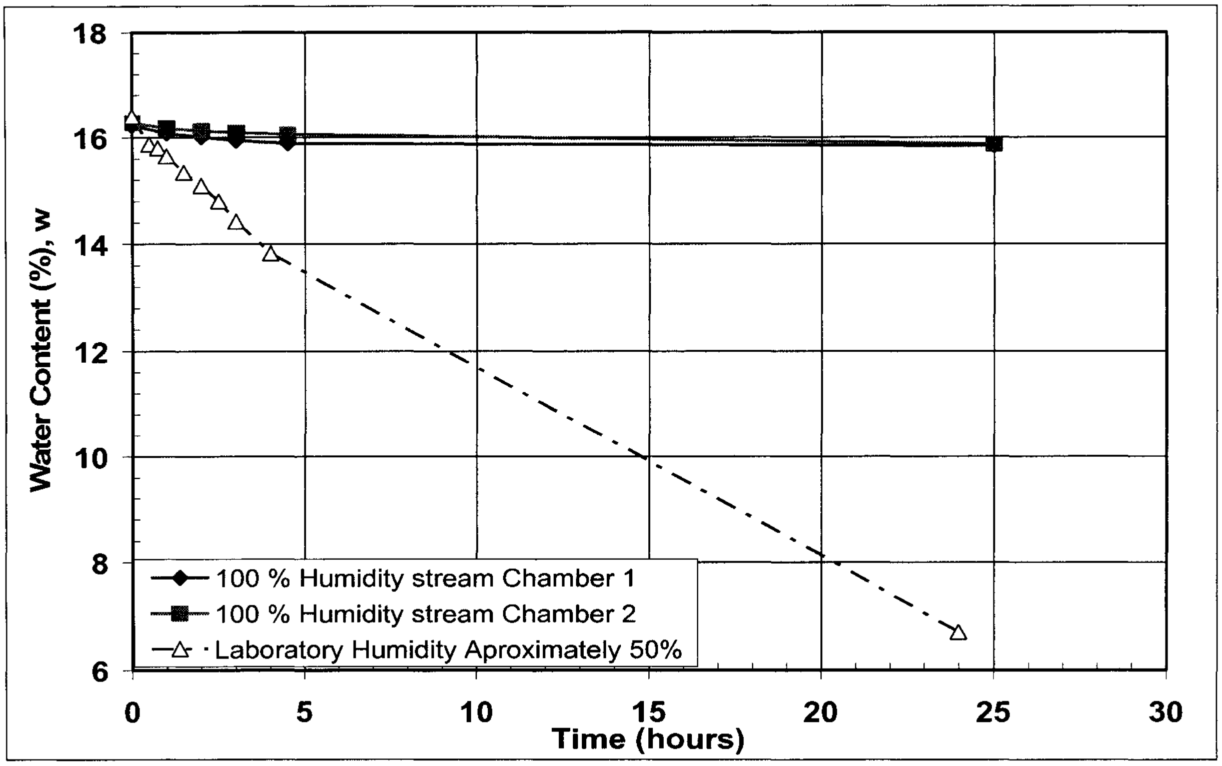


Figure 3.4: Effect of the 100% humid air stream on the water content of compacted specimens.

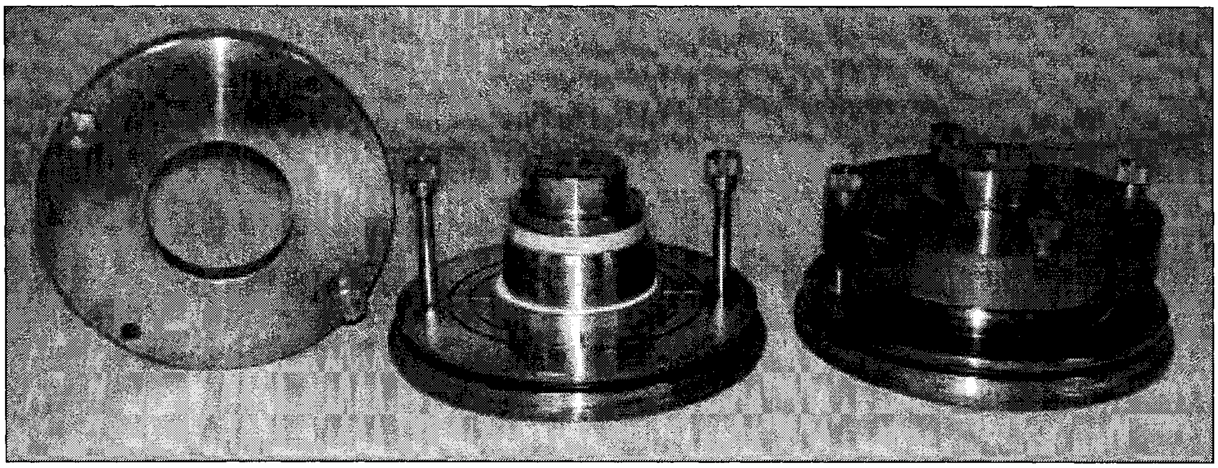


Figure 3.5: Oedometer cells for unsaturated soil testing.

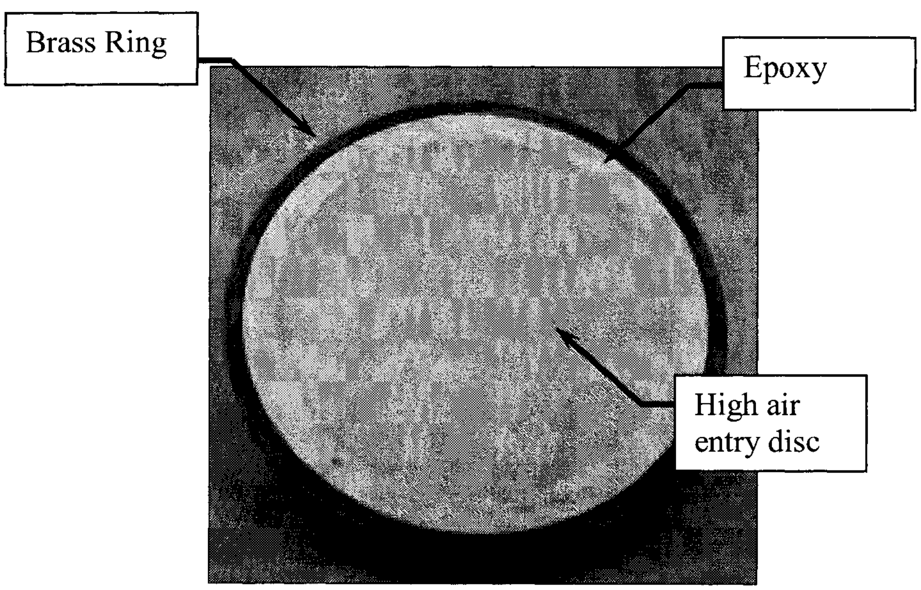


Figure 3.6: 500 kPa high air entry disc for oedometer testing of unsaturated soil specimens.

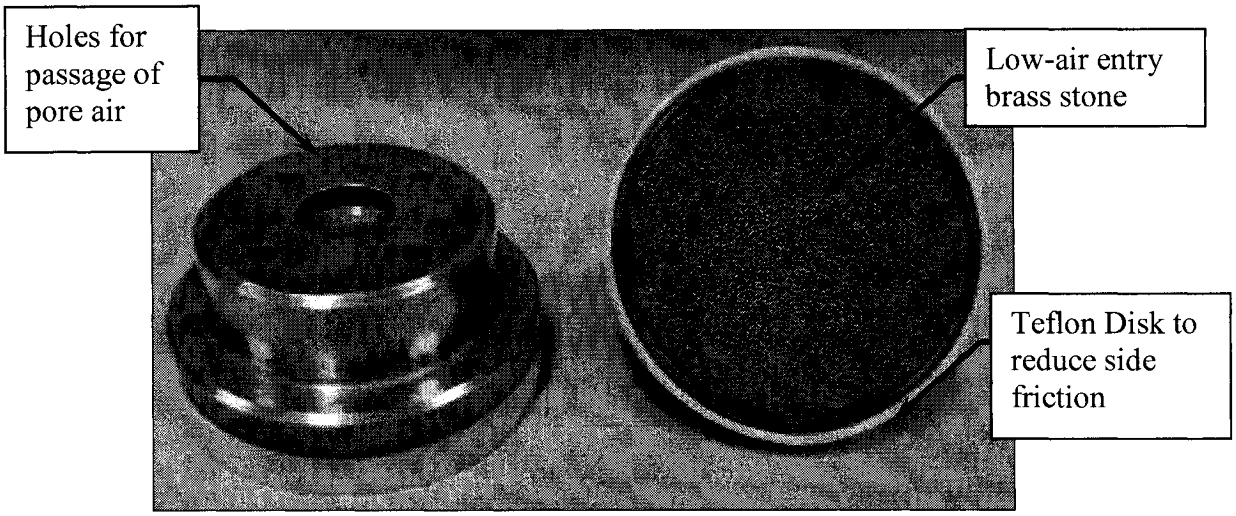


Figure 3.7: Loading cap for oedometer including low-air entry brass stone and Teflon ring.

Figure 3.8: Soil Moisture Company Epoxy Kit.

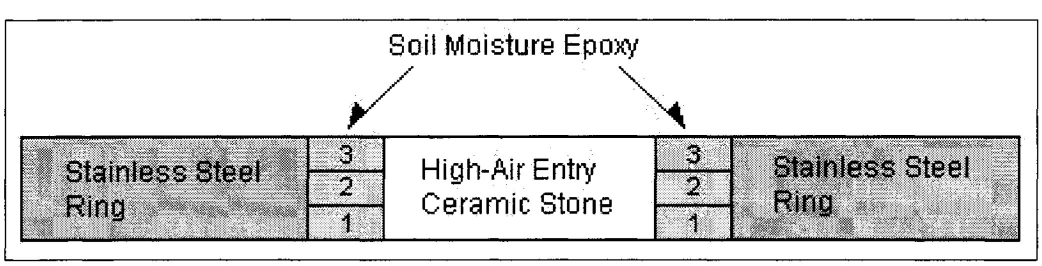


Figure 3.9: Schematic for epoxying ceramic disc into rigid frame.

Figure 3.10: Brainard and Kilman oedometer machine.

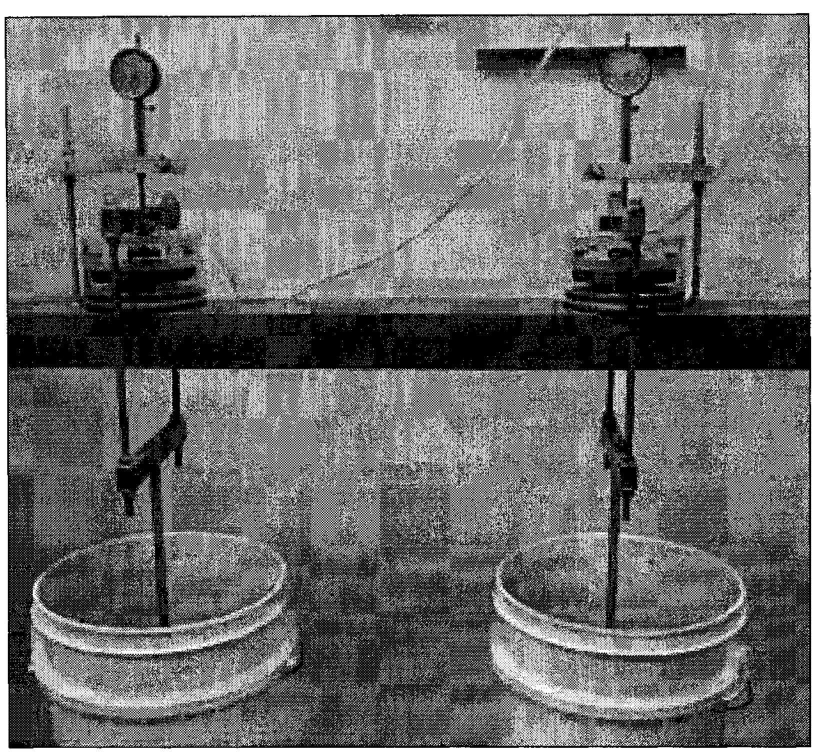


Figure 3.11: Dead load oedometer array.

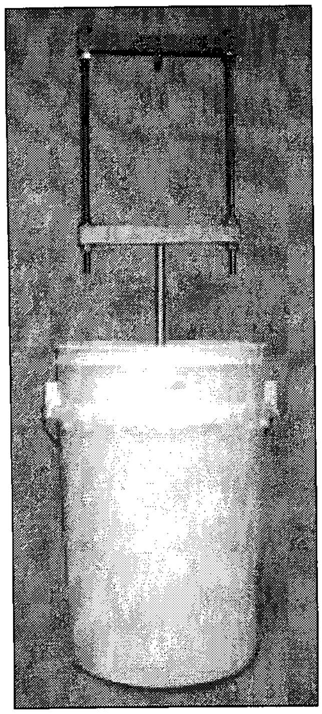


Figure 3.12: Loading frame and bucket.

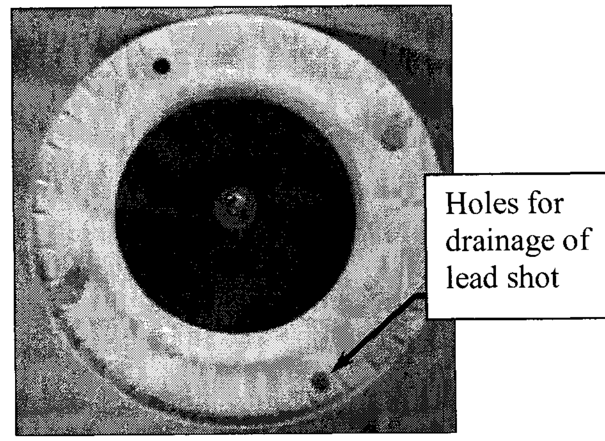


Figure 3.13: Bottom view of bucket.

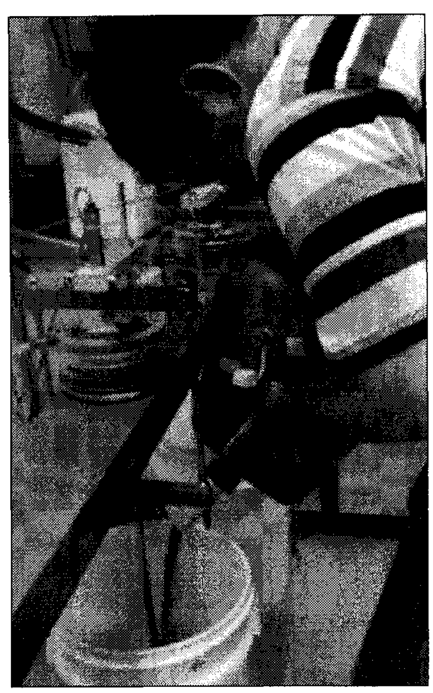


Figure 3.14: Dead load application.

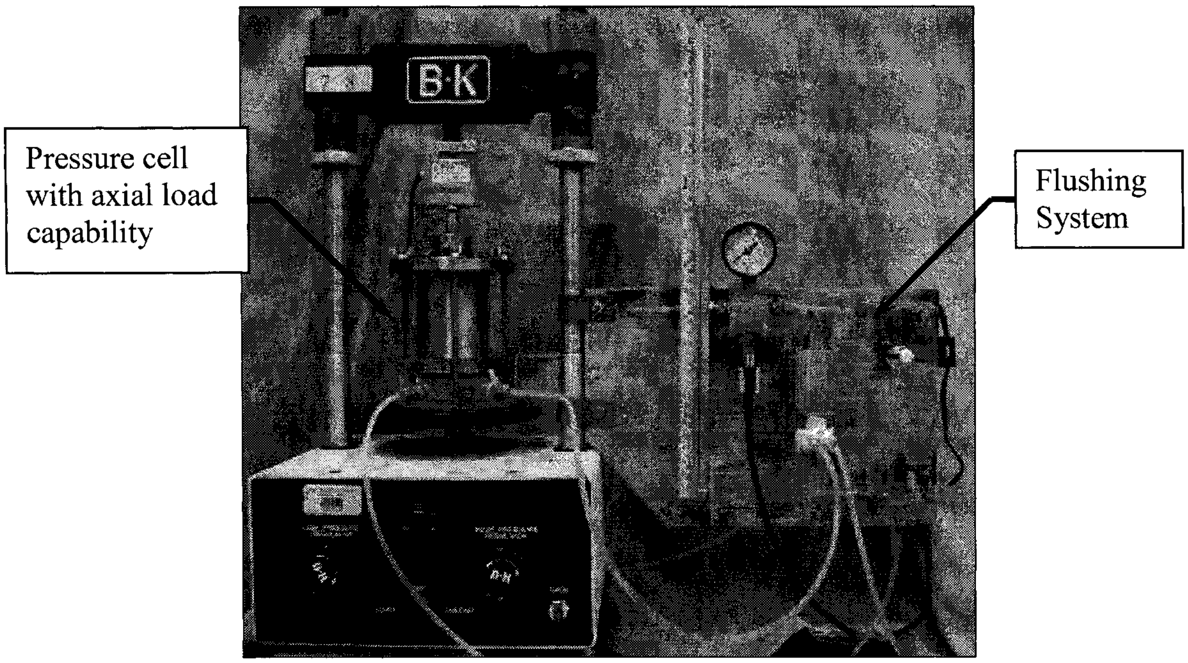


Figure 3.15: Null pressure plate system with axial loading incorporated into a Brainard and Kilman oedometer machine.

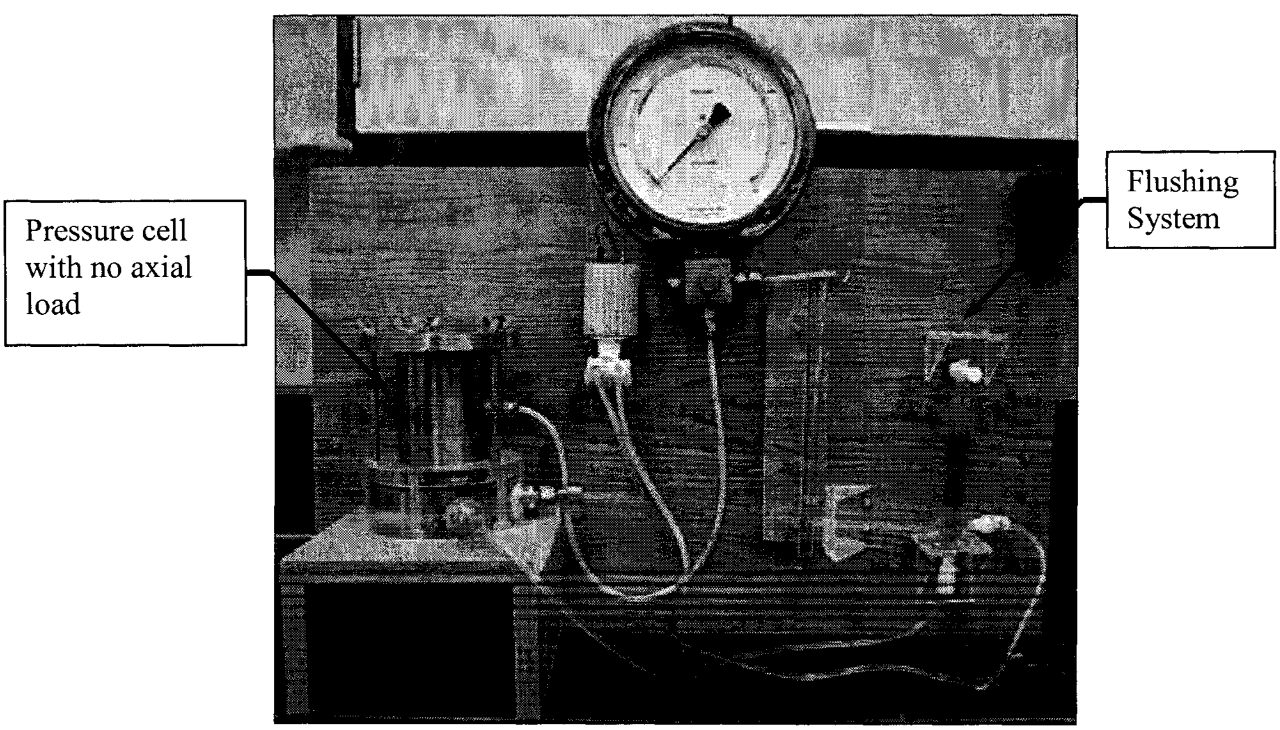
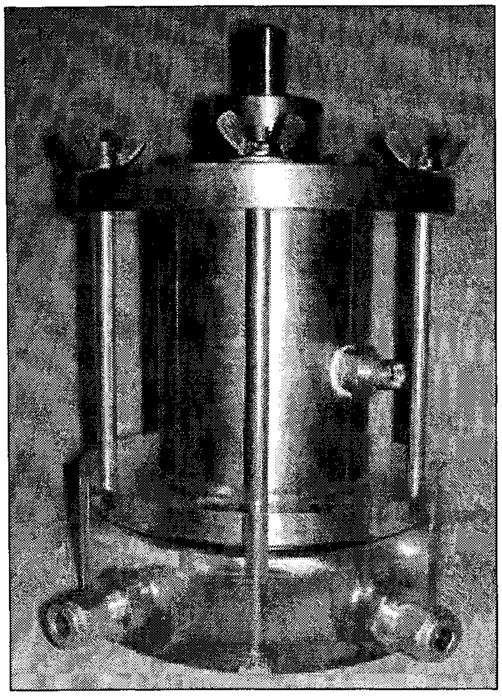


Figure 3.16: Null Pressure plate system without axial loading.



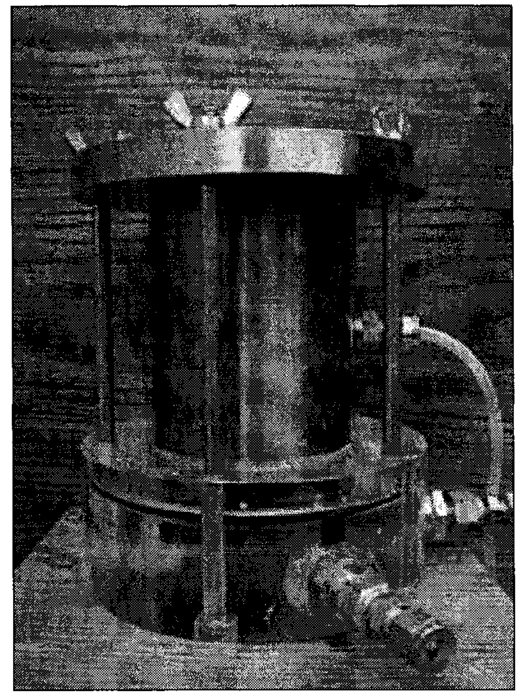


Figure 3.17: Pressure cell with axial loading capability.

Figure 3.18: Pressure cell without axial loading capability.

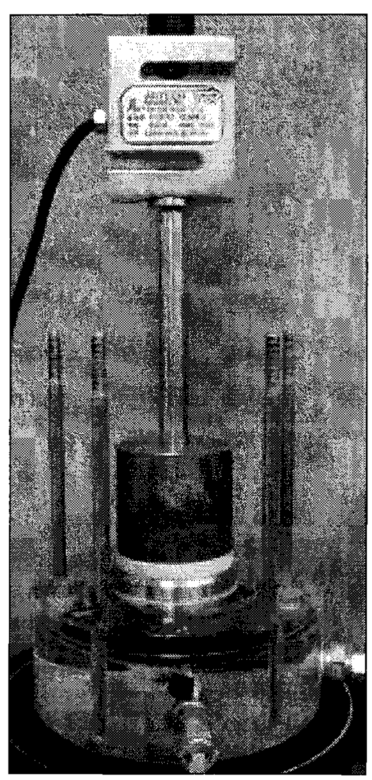


Figure 3.19: Inside the pressure chamber with axial loading capability.

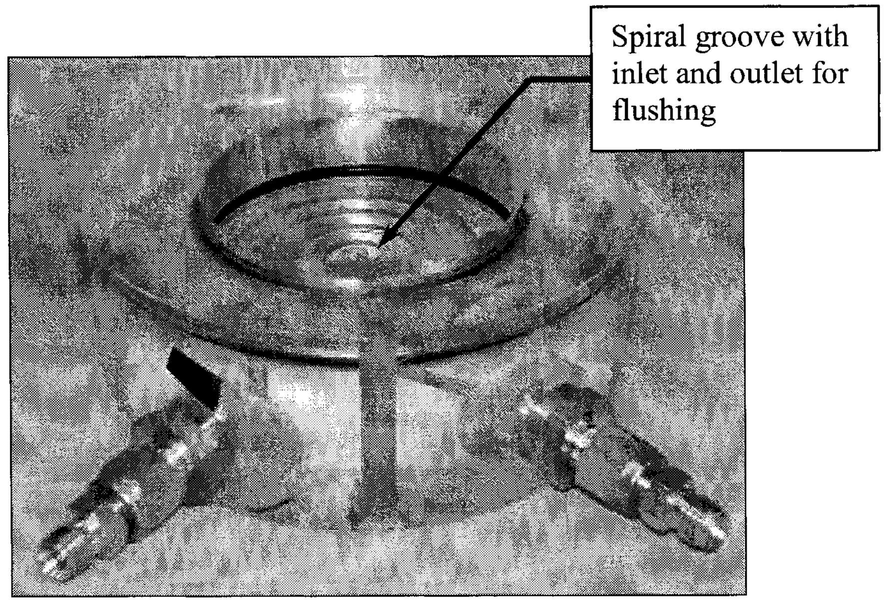


Figure 3.20: Pressure cell base with "O-ring seal straight threaded" fittings.

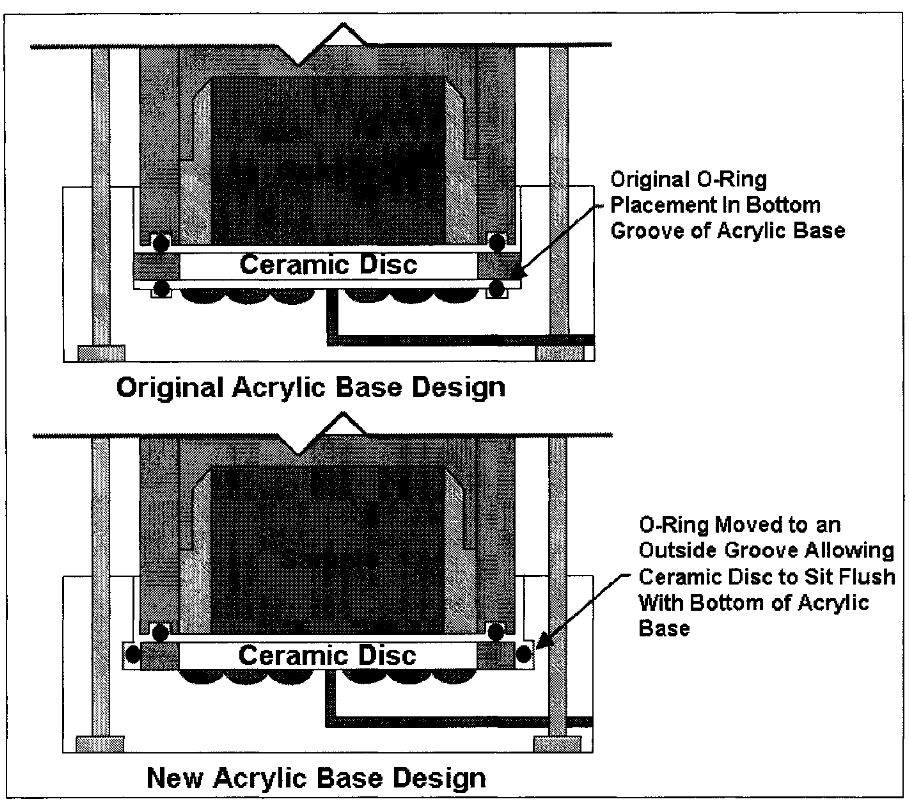


Figure 3.21: O-ring details for sealing ceramic discs in acrylic base.

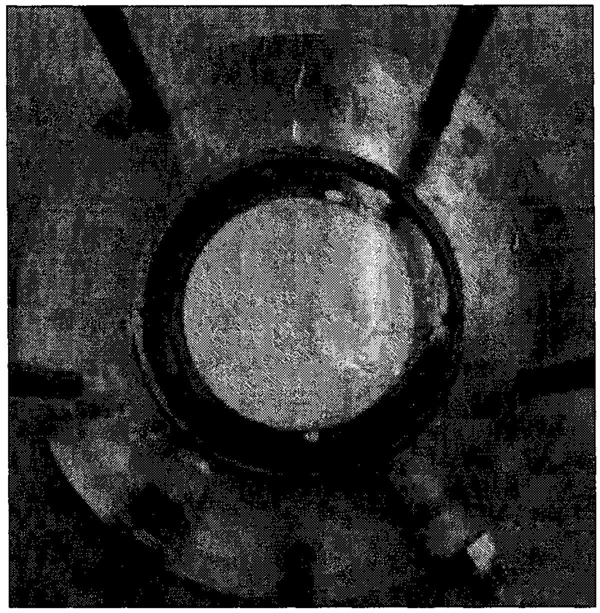


Figure 3.22: Saturated 500 kPa high air entry disk sealed in pressure cell base.

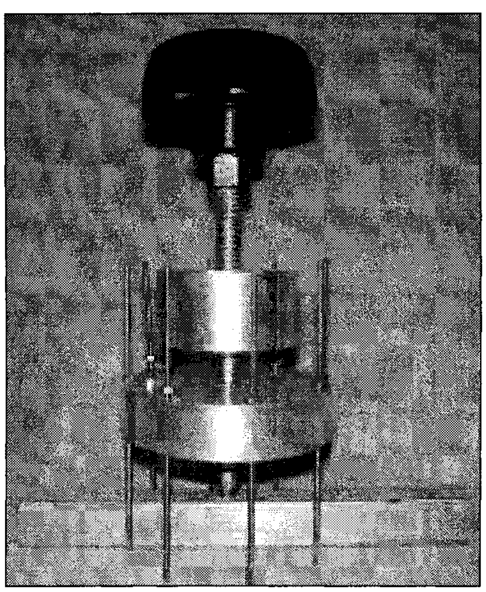


Figure 3.23: Puller device for high air entry disk.

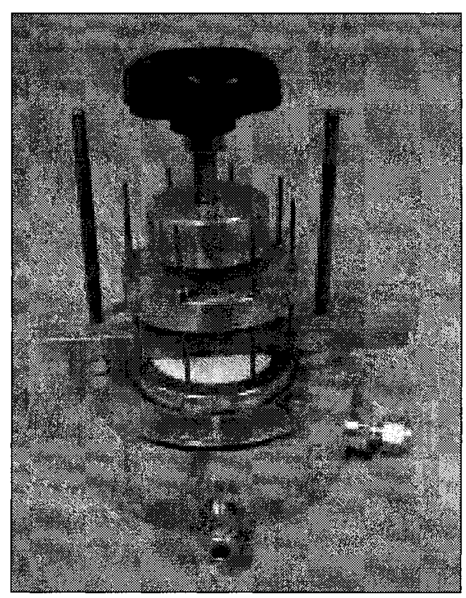


Figure 3.24: Puller device removing high air entry disk.

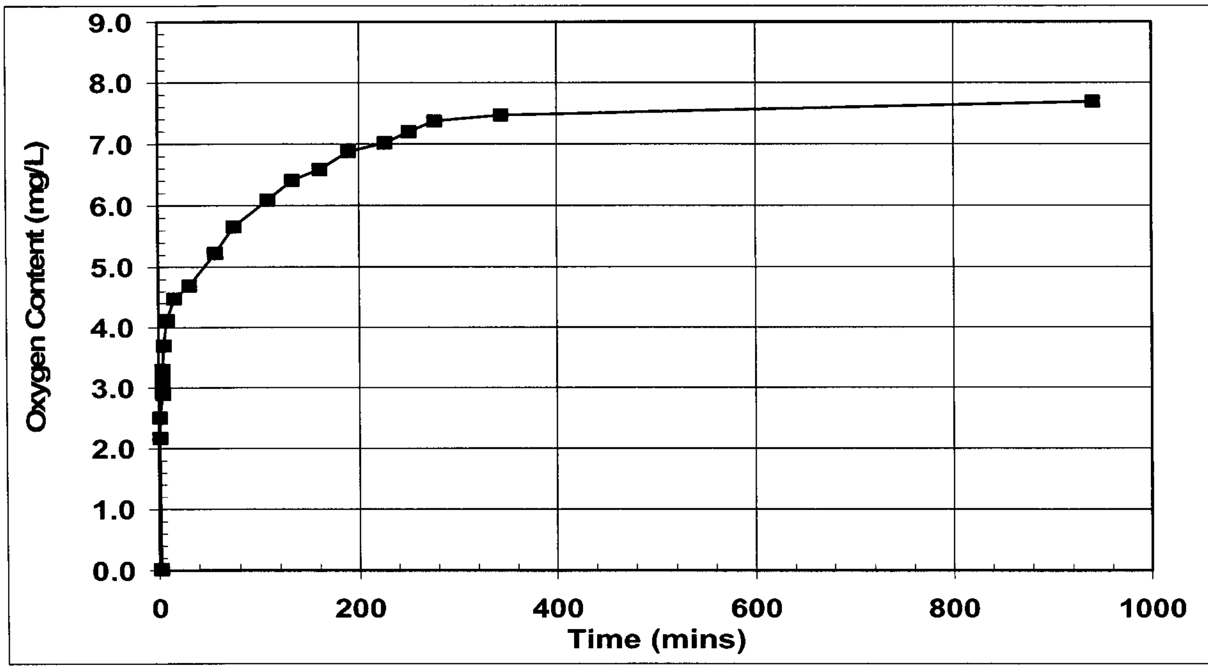


Figure 3.25: Rate of re-oxygenation of de-aired water exposed to the atmosphere from Garga & Zhang (1997).

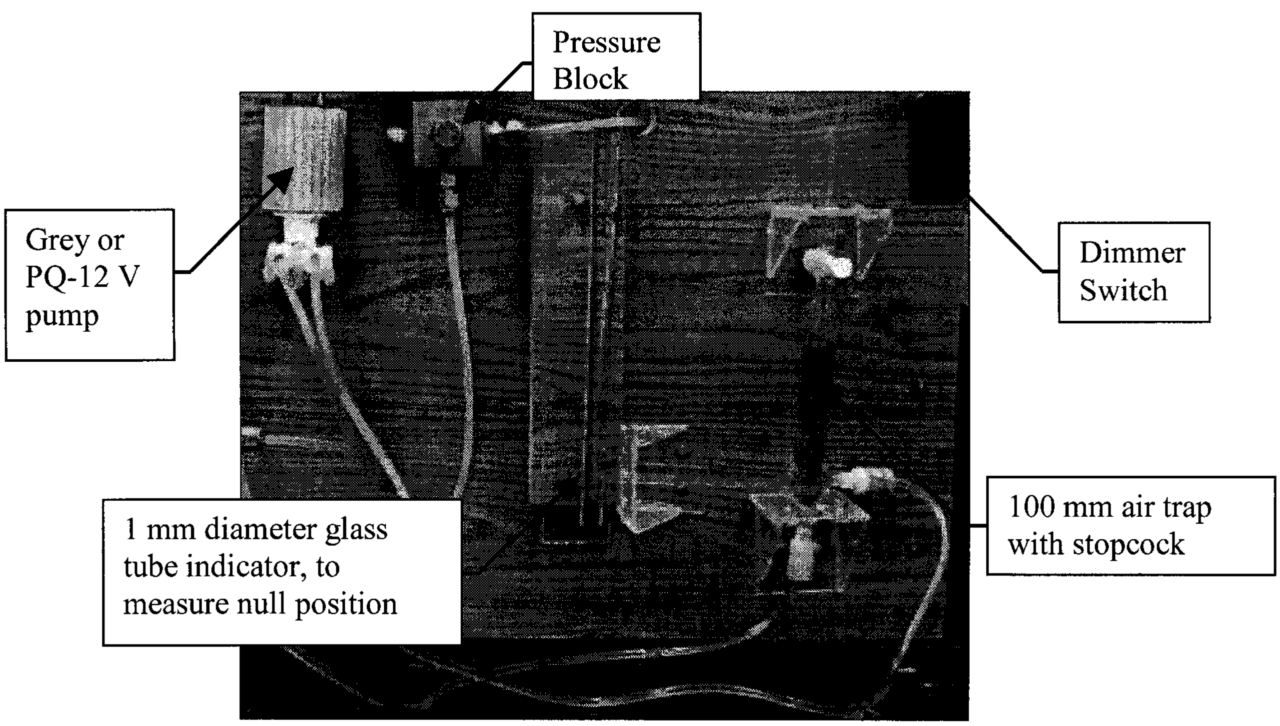


Figure 3.26: Flushing system for null pressure plate system.

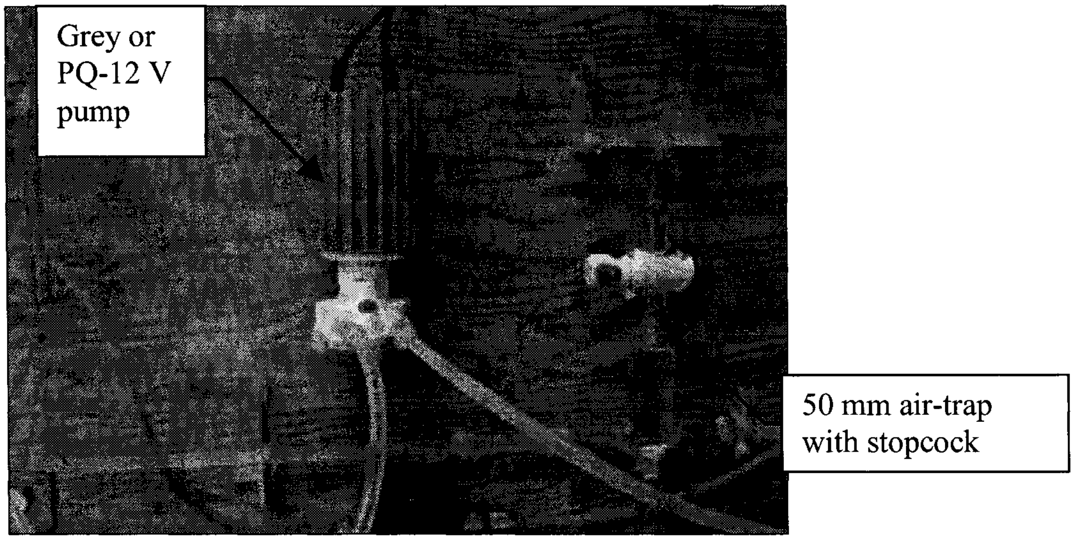


Figure 3.27: First flushing system showing 50 mm air-trap.

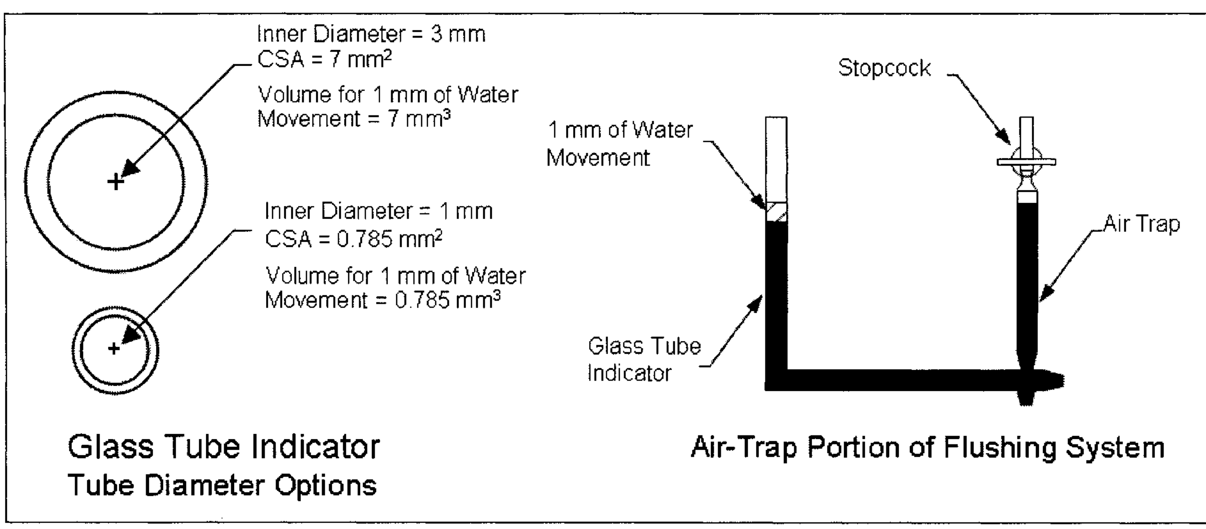


Figure 3.28: Glass tube indicator diameter changes.

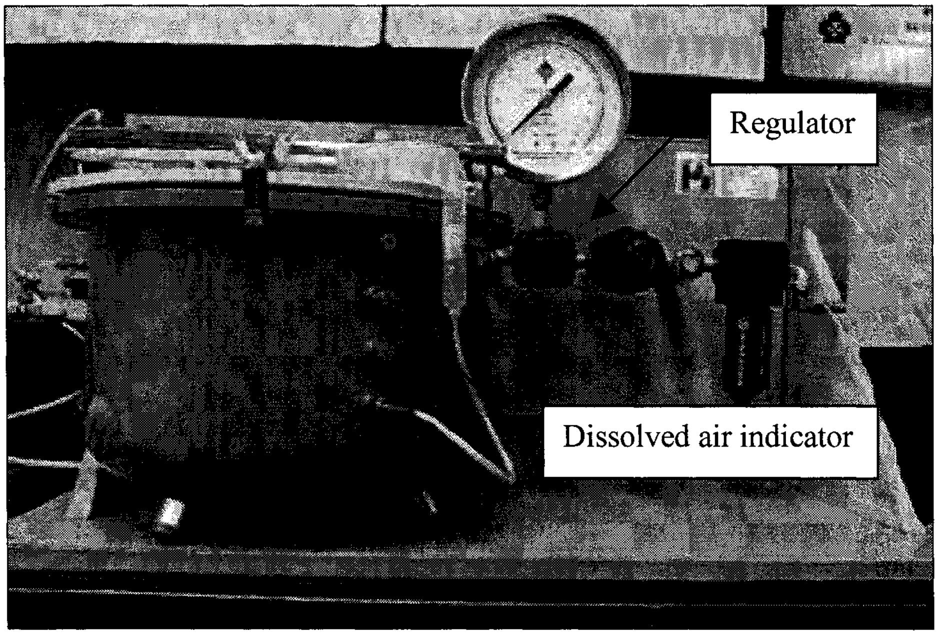


Figure 3.29: Null pressure plate for calibrating filter papers.

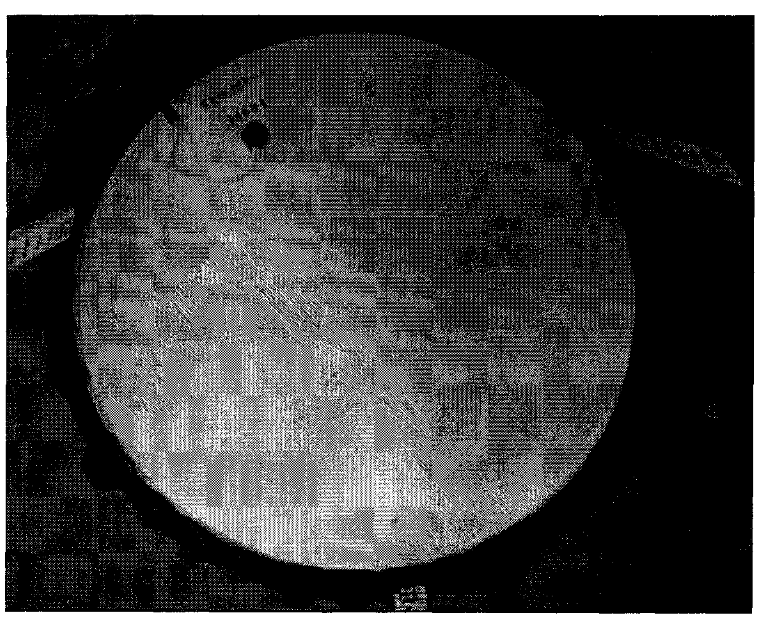


Figure 3.30: 500 kPa high air-entry ceramic disc used in null pressure plate.

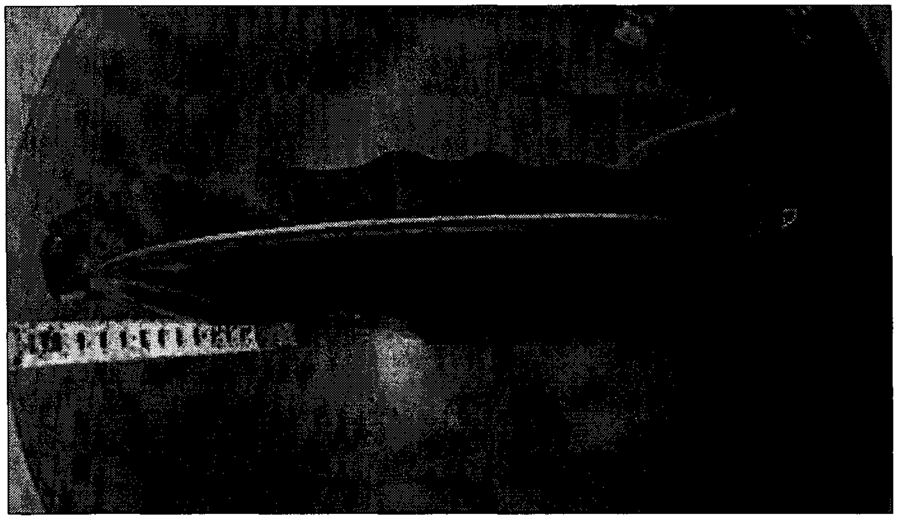


Figure 3.31: Water bag under high air-entry ceramic disc used in null pressure plate.

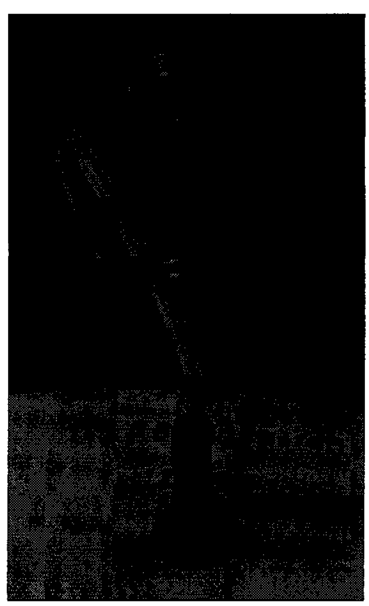


Figure 3.32: Connection between the bag under the high air-entry ceramic disc and the atmosphere.

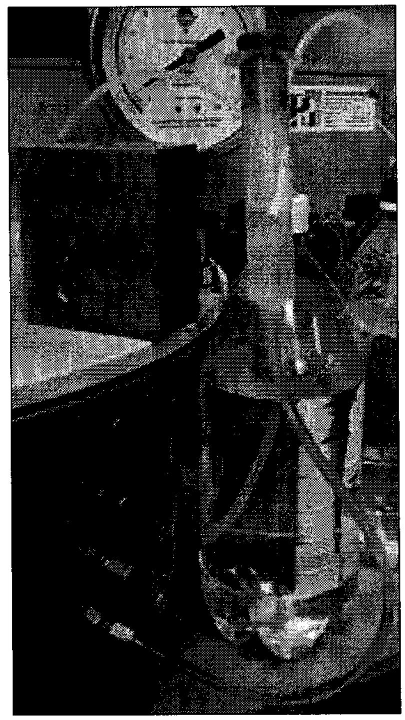


Figure.3.33: Syringe to monitor dissolved air under ceramic disc.

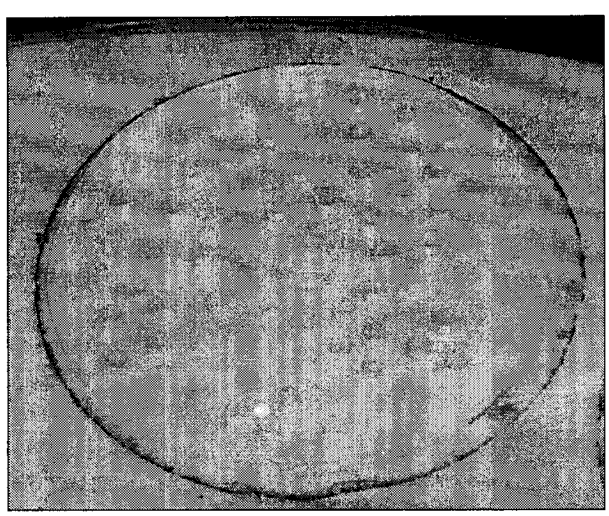


Figure 3.34: Mold growth on filter paper with 2% formaldehyde solution.

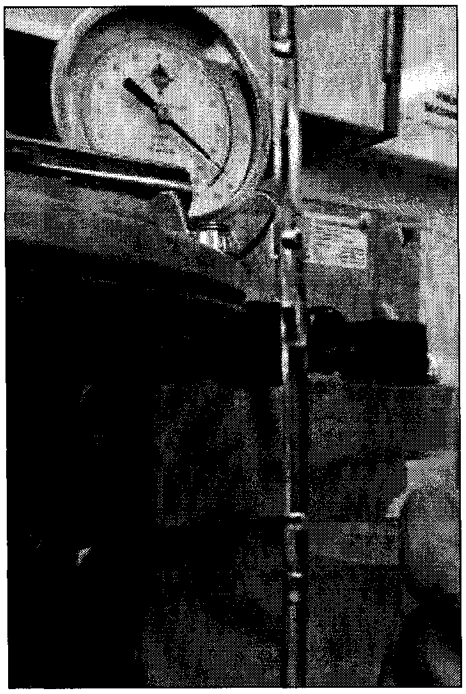


Figure 3.35: Dissolved air bubbles leaving the null pressure plate system during flushing.

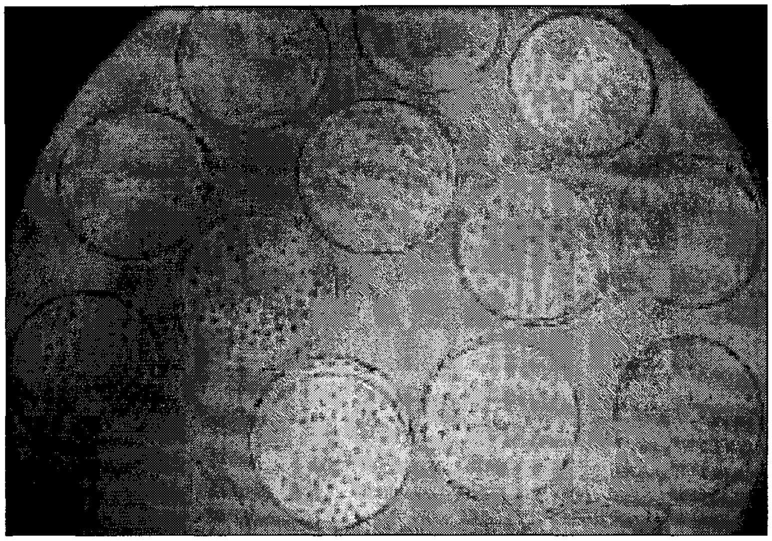


Figure 3.36: Extent of mold growth after 14 days with 2% formaldehyde solution.

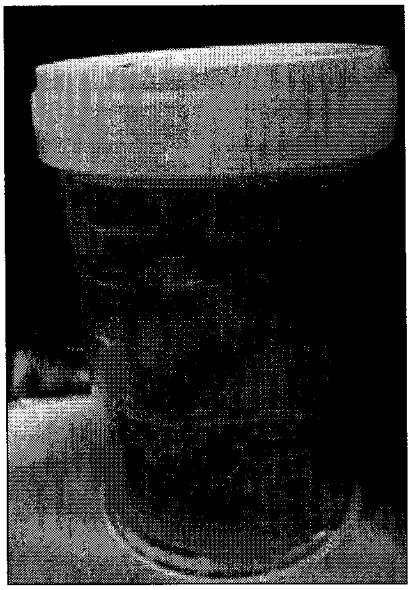


Figure 3.37: Application of stresses to filter papers during calibration.

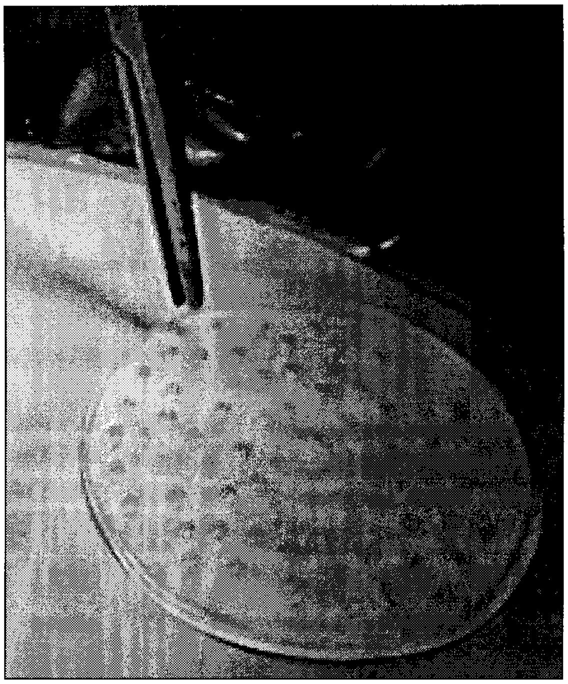


Figure 3.38: Plastic spacer to ensure evenly applied stresses to the filter papers during calibration.

Figure 3.39: Placement of filter paper and applies loads during calibration.

Chapter 4: Soil and Specimen Preparation

4.1 Introduction

The objective of the testing program employed for this research project was to determine the unsaturated compressibility properties of a glacial till from Indian Head Saskatchewan. The till arrived at the University of Ottawa laboratories directly from site in bags in a disturbed state containing bark, and large rocks (see Figure 4.1). The following describes in detail the processes followed to process this soil to one with comparable attributes (i.e. gradation and Atterberg Limits) to those of the soil used in the published works from the University of Saskatchewan (Fredlund & Rahardjo 1993).

Unlike saturated specimens, three stress states variables are required to describe the initial stress conditions of an unsaturated specimen namely: void ratio, net normal stress, and matric suction (Ho et al. 1992, Fredlund & Morgenstern 1977). Before specimens could be produced for testing, a proctor test was performed on the specimen to obtain the upper boundary of the compaction energy that could be imparted to the soil. Since the specimens were to be statically compacted, two more compaction curves were determined for the compaction energy levels to be used in this testing program (i.e. 70 and 140 kJ/m^3). These energy curves would then dictate the water content and density values for the soil. Testing specimens at the proper water content was crucial to the testing program because it dictated the soil structure of the specimens (Ridley et al. 2003, Vanapalli et al. 1999, Acar & Nyeretse 1992, Burland & Prost 1987, Barden 1974). A flocculated soil structure was used in the testing program to ensure interconnected pores within the specimens; though the water content level of the specimens was chosen such that it was never more than 4 % less than optimum. Using higher water contents levels ensured that the matric suction of the specimens would be less than the air-entry value of the axis-translation equipment (i.e. 500 kPa) used to determine the suction of the specimens. Specimens were also prepared to have an interconnected pore structure to allow the pore water to be direct contact with the filter paper for suction measurement with the contact filter paper method.

This chapter details the methods and equipment used to produce test specimens at the desired water content and density to as dictated by the testing program

4.2 Soil Type

The soil used in this research project was a glacial till obtained from Indian Head, Saskatchewan. This soil was chosen because the University of Saskatchewan has undertaken extensive research studies over the last twenty years and valuable information about the unsaturated properties of this soil are available in published literature (Fredlund et al. 1995, Ho et al. 1992, Krahn and Fredlund 1976).

Figure 4.2 shows the grain size distribution of the till from the University of Saskatchewan. Preliminary in house testing determined the Atterberg Limits and the specific gravity of the Indian Head till produced at the University of Ottawa. Table 4.1 shows the Atterberg Limits and the specific gravity *(Gs)* of the two soils in comparison to the values obtained by the University of Saskatchewan.

Table 4.1: Comparison of Atterberg Limits (University of Saskatchewan Data from Vanapalli et al. 1996)

University of Saskatchewan		University of Ottawa	
Soil Property	Value	Soil Property	Value
Plastic Limit	16.8 %	Plastic Limit	17.0 %
Liquid Limit	35.5 %	Liquid Limit	32.5 %
Plasticity Index	18.7 %	Plasticity Index	15.5 %
Specific Gravity	2.73	Specific Gravity	2.72

4.3 Soil Preparation

The first step to prepare the soil for testing was to remove all non-soil particles (i.e. grass and bark) and the larger sized pebbles and rocks. Since the soil obtained from the site was relatively dry, it was first soaked in buckets, and wet sieved through a # 10 sieve into holding buckets, as shown in Figure 4.3. All soil particles retained on the U.S. Standard # 10 sieve (i.e., 2 mm opening) were removed consistent with the test procedures followed at the University of Saskatchewan. The wet soil in suspension was then left overnight to settle out of solution. After settling out of solution the remaining free water was removed by siphoning. The remainder of the wet soil was then spread onto larger plastic sheets to be air dried for several days at room temperature in the laboratory. This process was continued until 150 kg of dried soil passing the #10 sieve was recovered.

The process of wet sieving and drying was successful at removing the unwanted material from the soil to be prepared for testing, but preliminary grain size distribution data of the new soil showed differences when compared to the grain size analysis data of the soil tested at the University of Saskatchewan. Due to this reason, the remainder of the soil had to be subjected to grinding and further processing using a mechanical grinder. The objective of the grinding was to achieve the soil grain size distribution characteristics consistent with the grain size distribution curve used by the University of Saskatchewan. Several trial grinding times were tested and it was determined that grinding a 1 kg batch of soil for two hours as was done at University of Saskatchewan. After grinding, the soil was again passed through a #200 sieve to separate the coarse material from the fine to ease the remixing process. Once the soil was separated it was mixed in the proper proportions according to Table 4.2.

Table 4.2: Particle size distribution for Indian Head till

Sieve Size	Percent Finer %
< #200	77
< # 80	85
< # 40	91
< # 10	100

4.3.1 Storage of Newly Manufactured Soil

Since 150 kg of soil would have to be mixed and stored, the ideal storage device would be one that could be used also as mixer was required. The "Wheeling Barrel of Science" was built to serve both these two functions. Brackets were bolted to the inside of the barrel to facilitate mixing (Figure 4.4). The soil mixing was accomplished by hand-rolling the barrel for 15 minutes as shown in Figure 4.5. Gradation of the newly mixed soil was tested by removing six specimens from around the outside diameter of the barrel, and four from the middle of the barrel. The fine and coarse materials were first separated by passing the specimens through # 200 sieves. The complete gradation of the soil was prepared in accordance with the ASTM D422-63. The resulting two gradation curves were then combined based on the percentage of fine and coarse material (with reference to the #200 sieve) present in each specimen. The gradation curve of the soil produced for this research project compared well with the University of Saskatchewan's gradation curve as shown Figure 4.6.

4.4 Compaction Considerations

One of the main objectives of this research project was to determine the effect of initial compaction energy on the compressibility characteristics and initial matric suction of the Indian Head till specimens. The following section details the equipment used and compaction energy curves developed to prepare the specimens for testing.

4.4.1 Specimen Compaction Equipment

The specimens were to be statically compacted at varying water contents and densities using the brass compaction equipment shown in Figure 4.7. To ensure that the specimen rings would not deform during the compaction process, the bottom of the compactor mold was designed to securely hold the specimen rings. The specimen rings were securely fastened to the compactor base by four screws to allow for easier handling. The base of the ram is made of tapered Teflon to reduce friction between ram and the walls of the mold thereby maximizing the compaction energy imparted to the soil. The Teflon base also formed a tight seal with the mold to prevent the soil particles from jamming the ram. A 25 mm circular piece of porous plastic was inserted into the Teflon base leading to an air vent to eliminate the possibility of vacuum developing inside the mold during compaction. The vent would allow any trapped air to escape out of the mold (see Figure 4.8).

The compactor was designed to accommodate different specimen heights. This was accomplished by the lowering or raising the locking device on the threaded section of the ram. As an example, lowering the locking device 14 turns will reduce the specimen height by 1.27 mm. For this research project the specimens were compacted in one layer to an initial height of 17.78 mm.

4.4.2 Static Compaction Curves

Figure 4.10 shows the standard Proctor compaction curve using ASTM Standard D698-00ae1. The optimum water content and maximum dry density of the till was 14.4% and 18.3 kN/m^3. Since the specimens were to be prepared by static compaction, it was necessary to produce a series of static compaction curves (i.e. energy curves) to determine the compaction effort imparted to the specimens.

4.4.3 Developing the Energy Curves:

Several research studies have shown that matric suction is dependent on the initial water content of the compacted specimen and not its initial density (Krahn and Fredlund 1976). In the present research, it was proposed to study the influence of both the compaction energy and water content on the settlement behavior of unsaturated soils. Hence two static compaction energies (i.e., low compaction energy of 375 kPa and high compaction energy of 750 kPa) were chosen. The low compaction energy was chosen to achieve maximum amount of settlement during consolidation. The 750 kPa compaction energy was used to test the effect of density on the development of matric suction. The high compaction effort was selected to be just less than the maximum applied stress used in the oedometer tests, described in Section 3.2.6. A comparison between the three compaction curves, standard proctor, high and low energies, is shown in Figure 4.10 and Table 4.3.

Table 4.3: Properties of specimens produced at different compaction efforts

Energy Level	Stress (kPa)	Energy (kJ/m^3)	Optimum Water Content (%)	Maximum Unit Weight (kN/m^3)
Proctor	-	600	14.2	1.87
"High Energy"	750	140	16.3	1.80
"Low Energy'	375	70	18.3	1.73

4.5 Specimen Preparation

In order to achieve consistency between the test specimens made for the different tests (i.e. compressibility, and suction measurements), the specimens were prepared using the same methods and equipment. This will allow the separate measurement of the compressibility and suction characteristics of the Indian Till without introducing inconsistencies due to different apparatuses. Once the water content for a test series was chosen, the maximum dry density is determined using the static compaction curves shown in Figure 4.10. The static compaction apparatus (i.e. drill press) shown in Figure 4.11 was used to compact all specimens produced for this testing program. In order to ensure that a proper alignment between the loading cap and the specimen ring would occur in the oedometer, the specimen height was set to 17.78 mm, 1.25 mm lower than the specimen ring height of 19.0 mm.

4.5.1 Initial Water Content of Specimens

As water content of a compacted soil approaches optimum water content the structure of the specimens changes from a flocculated to a dispersive structure. Using a range of water contents from completely flocculated (i.e. dry of optimum) to a slightly dispersive structure (i.e. 1 to 3% above optimum) enables the testing of several different specimen structures. The initial compacted water contents used in this research projects were 14 –19% for both compaction energies curves.

Since maintaining initial water content was crucial to this testing program several steps were taken to prevent the loss of water during specimen preparation. The soil was prepared in a humidity control laboratory where the humidity level was keep at or above 50%. A metal pan was used instead of plastic pan when preparing the soil and the water was added by misting the soil layers with a hand sprayer. After thoroughly mixing the soil and water, the wet soil was stored in two vacuum sealed, plastic bags. The bags of soil were then stored in a 100% humidity chamber for at least 48 hours to achieve uniform water content throughout the soil before being used to make test specimens. After 48 hours, water content checks were performed to measure the actual water content achieved.

4.5.2 Compressibility and Axis-Translation Specimens

Once the desired initial water content was chosen using the appropriate dry unit weight, depending on the compaction energy used, the proper amount of wet soil was added to the assembled compactor mold. The ram was carefully inserted into the he mold and the whole apparatus was placed into the static compactor. The applied compaction stress was monitored using a proving ring to ensure that the exact stress is applied to each specimen. The complete applied stress was maintained on each specimen for 20 seconds and then released. The ram was slowly removed, the mold was disassembled and the specimen removed from the base. The prepared specimen was then transferred to the testing apparatus.

4.5.3 Filter Paper Specimens

Originally the same process for making the compressibility specimens was to be used in making the specimens for suction measurement using the contact filter paper method. The intent was to compact four separate 100 mm specimens one at a time in the compaction mold to form one large 400 mm specimen, extract the specimen from the mold, splice it and place the filter papers as shown in Figure 4.12. The problem arose when opening the split mold, as the specimen would split in half even under extreme care (see Figure 4.13).

To solve this problem, the test specimens were made in four separate 100 mm lifts. However, instead of forming one solid specimen to be spliced later, spacers in the form of two pieces of filter paper were placed in the mold between the layers as shown in Figure 4.14. Not only did this ease the production of the test specimens, but it also reduced handling time thereby reducing the loss of water from the specimen thereby maintaining the initial water content and hence the matric suction levels. To maintain their initial compacted density, the specimens shown in Figure 4.16 were extracted from the compaction mold by applying less than half stress applied during compaction (see Figure 4.15).

The spacers were then removed; the test specimens were reassembled placing a three stack of Whatman 42 filter papers between each layer. The test specimen was then wrapped in two layers of saran wrap, placed into two vacuum sealed bags and stored in a temperature controlled cooler for an equilibrium period of at least 14 days.

4.6 Summary

This chapter has provided the details on the manner in which the specimens were prepared for both the compressibility and suction testing programs. Specimens were statically prepared based on the unit weights of the compaction curves developed specifically for the Indian Head till and this testing program. Specimens used for the axis-translation and compressibility test were compacted in the same manner to ensure consistency between the tests. Four separately compacted specimens were combined to form on single specimen when used for suction measurements using the contact filter paper method.

Figures

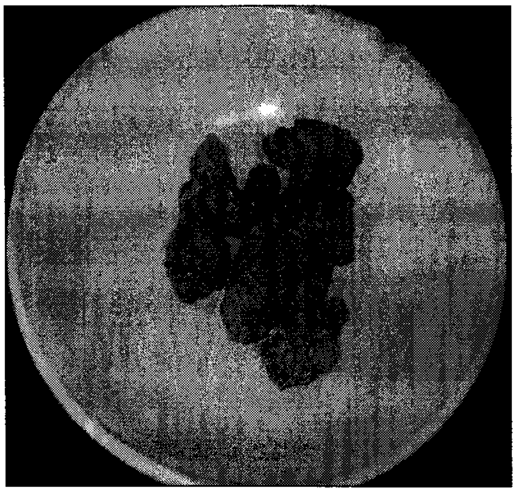


Figure 4.1: Rocks and lumps in dry Indian Head till

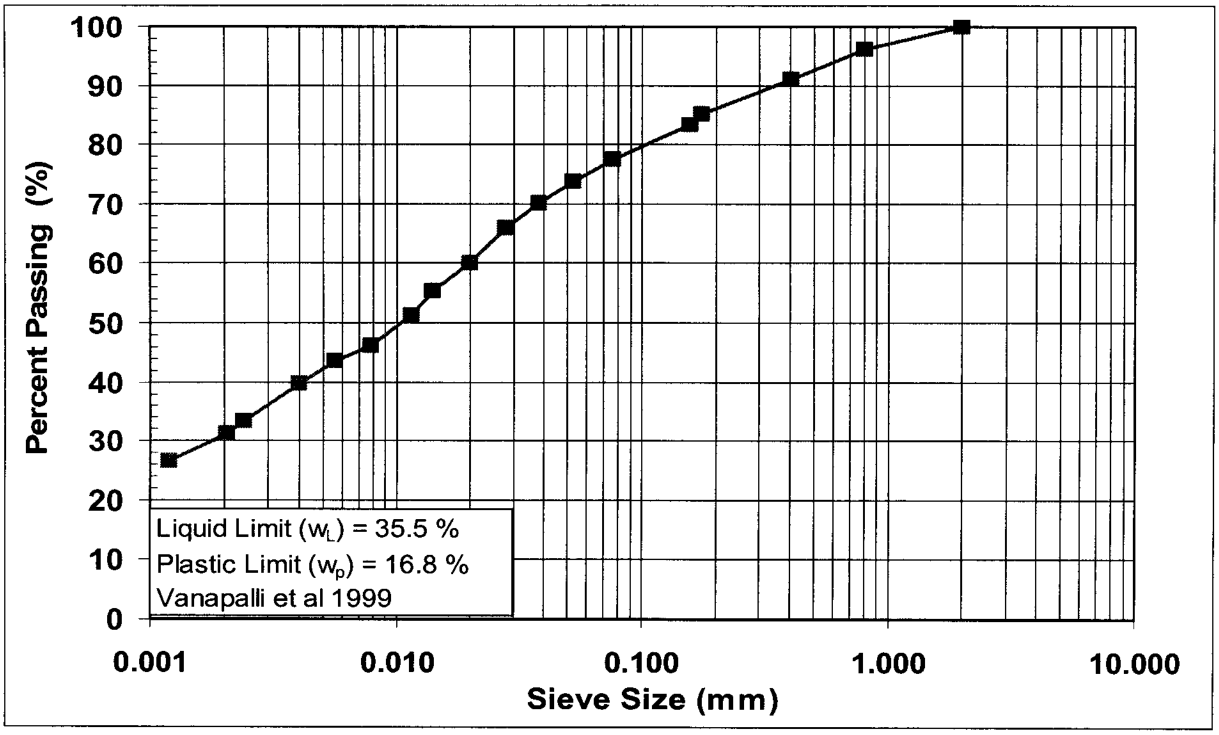


Figure 4.2: Gradation curve from the University of Saskatchewan

Figure 4.3: Wet sieving soil

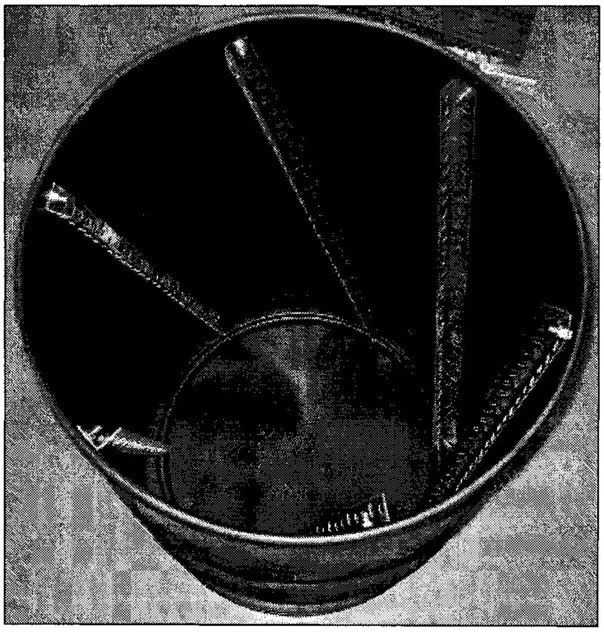


Figure 4.4: Inside the Wheel Barrel of Science showing mixing brackets

Figure 4.5: Mixing the soil in the Wheeling Barrel of Science

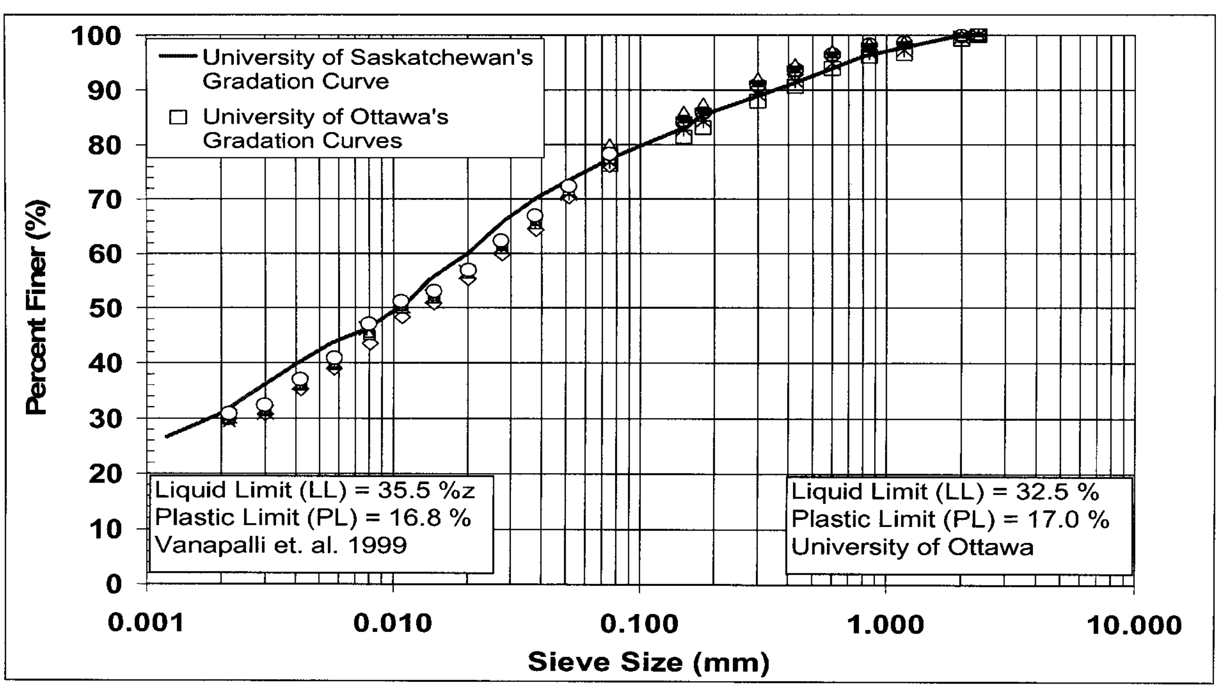


Figure 4.6: Comparison of gradation curves from University of Ottawa and Saskatchewan

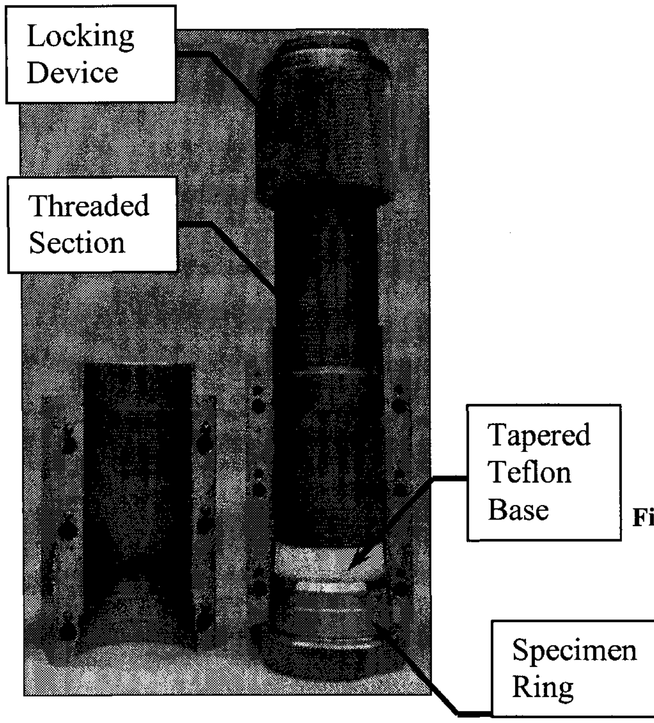


Figure 4.7: Specimen compactor mold and ram

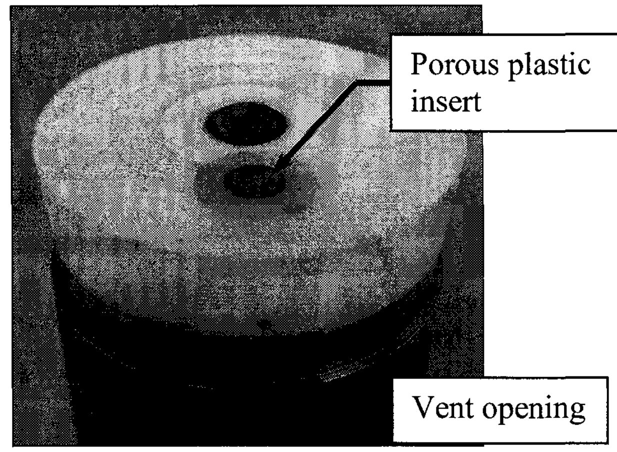


Figure 4.8: 25 mm porous plastic disk and vent opening

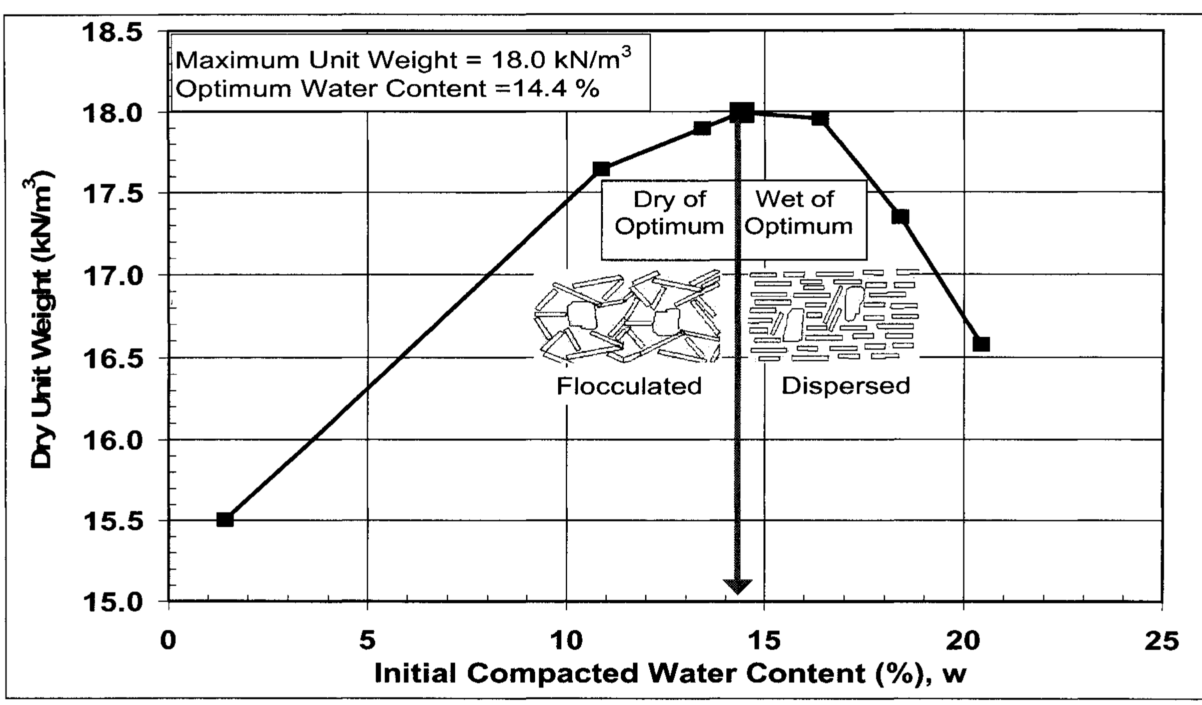


Figure 4.9: Proctor compaction curve for Indian Head till

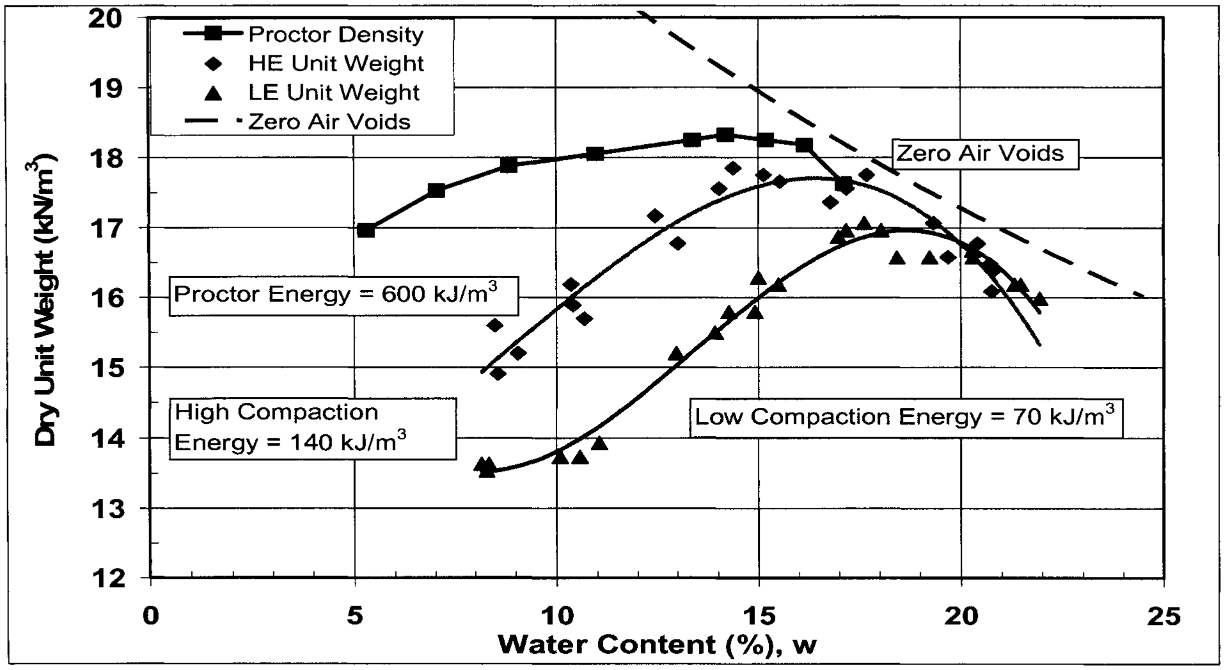


Figure 4.10: Comparison of static compaction curves

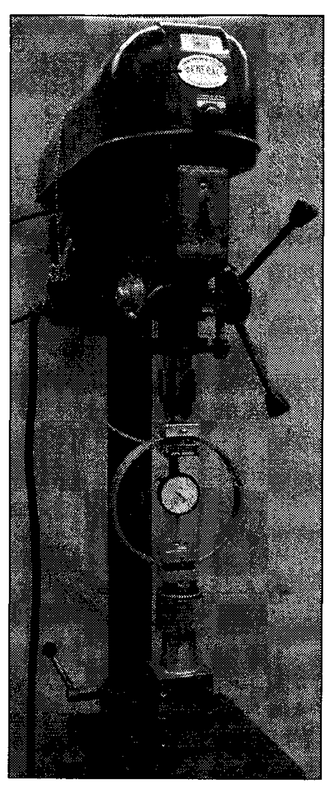


Figure 4.11: Static compactor

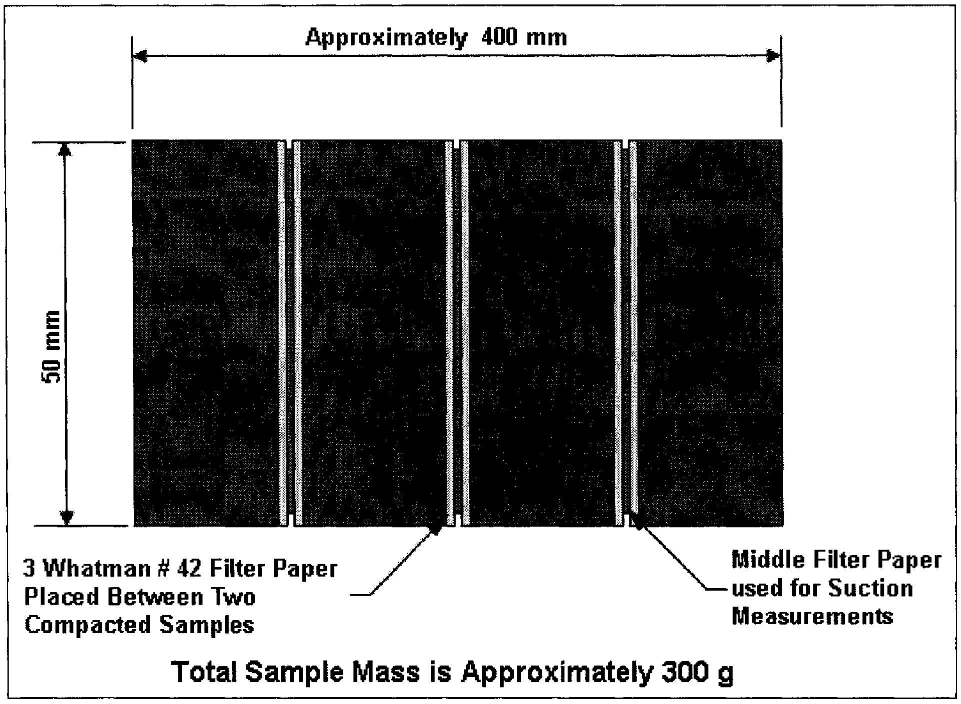


Figure 4.12: Setup for measuring matric suction using the contact filter paper method

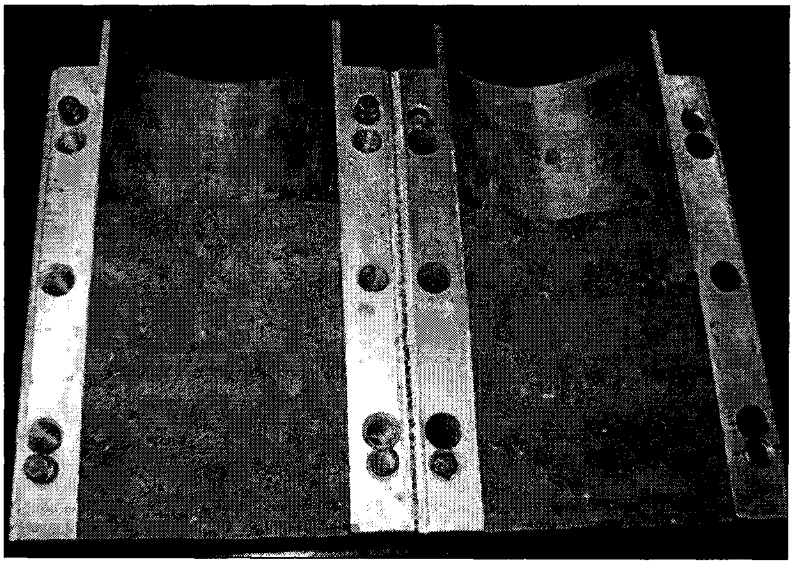


Figure 4.13: Specimen split in half when compactor mold was opened

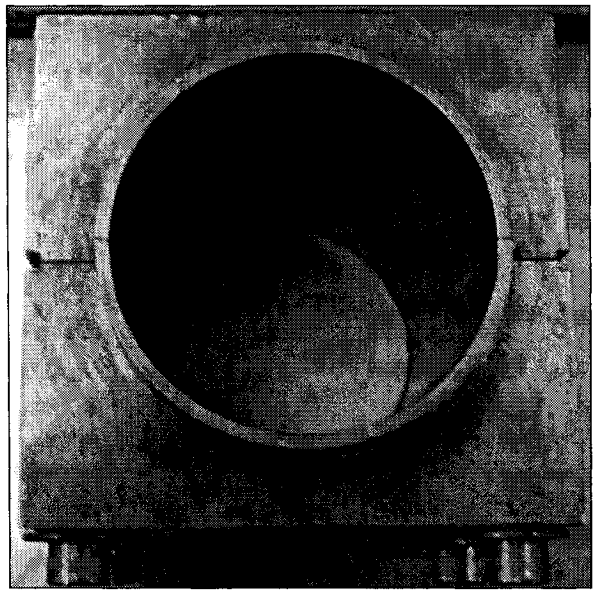


Figure 4.14: Compactor mold showing spacer used to separated the 4 test specimens

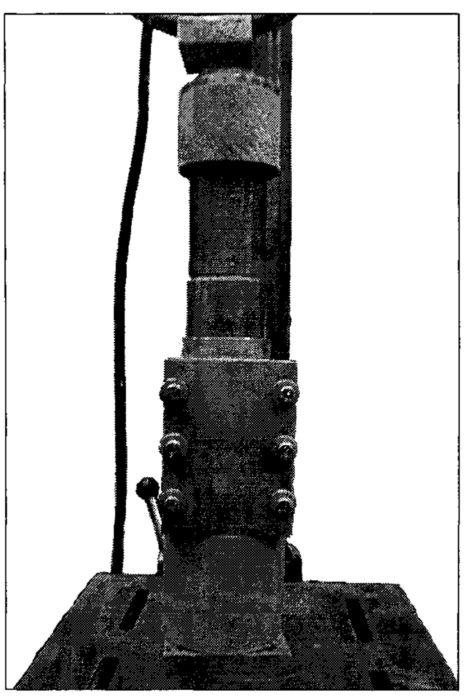


Figure 4.15: Filter paper specimen extractor

Figure 4.16: Extracted specimen with a three stack of filter inserted for testing

Chapter 5: Test Procedures

5.1 Introduction

The testing program for this research comprised of determining the compressibility characteristics and matric suction profile of an unsaturated till. Oedometer tests were performed in both inundated, ASTM Standard D4546-03, and non-inundated, ASTM Standard D2435-04, to obtain the compressibility characteristics under saturated and unsaturated conditions. Due to an electrical interference problem in the laboratory, a manual dead load system consisting of lead shot ballast was used in place of conventional load cells. Deformation was also manually recorded from dial gauge readings. The matric suction profile was determined using two methods namely; the contact filter paper method, ASTM D5298-03, (i.e. indirect method) and axis-translation technique in specially designed single specimen null pressure plate devices (direct method). Test specimens were prepared in a similar manner using the same compaction equipment to allow the separate measurement of the matric suction and compressibility characteristics.

The chapter outlines in detail the testing procedures followed for each test in the testing program.

5.2 Inundated Oedometer Test (Constant Volume Test)

The ASTM D4546-03 standard entitled, "Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils" was used for determining the swelling pressure of the unsaturated soil specimens used in this research program. The swelling pressure was determined by allowing the test specimen to imbibe water such that it attains 100%

degree of saturation under constant volume (CV) conditions. There is a tendency for the specimen to swell with an increase in the degree of saturation of the soil specimen. However, in this test procedure, the specimen is maintained at a constant volume conditions by increasing the applied stress. The uncorrected swelling pressure for the test specimen is the stress at which there is no more tendency to swell during the process of inundation. The matric suction component of the unsaturated soil specimen during inundation gradually reduces and attains a value equal to zero when the specimen is fully saturated under an applied stress. Once the swelling pressure is reached, the test specimens are loaded and unloaded following the conventional saturated oedometer test procedures.

The following sections describe the procedure followed for determining the compressibility characteristics of the Indian Head till test specimens using the constant volume test. Table 5.1 outlines the water content range, compaction energies, and the optimum dry unit weight and water contents of the specimens tested.

5.2.1 Saturating the high air entry ceramic disc used in inundated oedometer testing

1. Boil the ceramic disc for 15 minutes.
    a. Gradually allow the ceramic disc to cool to room temperature. When not in use, the ceramic disc is placed in a contained with distilled water to preserve saturation conditions.

5.2.2 Preparing inundated test specimens

1. Select the compaction energy and initial water content to be used in the test.

Table 5.1: Compaction values for oedometer test specimens.

Energy Level	Compaction Energy (kJ/m^3)	Optimun Dry Unit Weight (kN/m^3)	Optimun Water Content (%)	Water Content Range (%)
"High"	140	17.7	18.1	14-19
"Low"	70	16.8	16.1	14-19

2. Determine the dry unit weight for the test specimens using the information from step 1.

3. Determine the total mass of sample required to prepare a test specimen at a height of 17.78 mm using the information from step 2.

4. Assemble compactor mold.

   a. Measure the mass of specimen ring,

   b. Attach specimen ring to the compactor base,

   c. Assemble compactor mold ensuring that the specimen ring is held securely in the mold,

   d. Transfer the assembled compactor mold containing the specimen ring to scale and tare.

5. Evenly place the total mass of sample determined in 2 into the compactor mold in lifts.

   a. Place the sample uniformly in the mold to allow an even distribution of compaction energy,

   b. Transfer entire assemble to the drill press for static compaction after the total mass of sample has been added to the compactor mold.

6. Carefully insert the ram into compactor mold.

   a. Do not drop the ram into the compactor mold as this will cause excess compaction of the sample.

7. Using the drill press slowly apply the compaction energy previously determined in 1 to compact the sample.

   a. High compaction energy = 140 kJ/m^3,

   b. Low compaction energy = 70 kJ/m^3,

    c. Hold full compaction energy for 20 seconds and release.

8. Slowly remove the ram and disassemble the compactor mold.
9. Remove the compacted specimen from compactor base and record its initial mass.
10. Wrap specimen in Saran wrap until needed for testing.

5.2.3 Assembling Oedometer cells for inundated testing

1. Fill oedometer cells with de-aired distilled water to a height of 25 mm (see Figure 5.1).
2. Place the high air-entry disc into the oedometer so that no air bubbles are trapped under the disc.
    a. Completely cover the high air-entry disc in distilled water to ensure that the disc remains saturated during testing.
3. Measure the mass of loading cap for each oedometer.
4. Remove Saran wrap from test specimen and place it in the centre of the high air-entry disc.
    a. Ensure that there is enough water in the cell so that the water level is half way up the side of the specimen ring.
        i. Available water will allow for the inundation of the specimen required for CV Test.
5. Assemble oedometer cells.
    a. Place collar on alignment posts,
    b. Secure the collar to the alignments posts with lock nuts,
    c. Put on cover plate to acrylic chamber,
    d. Assemble loading frame and dial gauge,
    e. Record initial reading of dial gauge and begin loading sequence.

5.3 Testing procedure for the Constant Volume test

For the CV oedometer tests in this research project, loading increments of Δp/p value equal to 1 was used. Unlike conventional saturated oedometer tests the initial loading stress is not known a priori. The initial loading stress is the uncorrected swelling pressure of the specimen. The maximum applied stress chosen for this research was based on the capacity of the 227 kg (500 lb) Artech load cells used for measuring vertical load during preliminary testing.

1. Monitor the dial gauges for each specimen.
2. When the specimen begins to swell, increase the stress to the specimen in 2.5 kPa increments (i.e. 500 g of lead shot).
    a. Allow sufficient time between stress increases to ensure that the new stress level does not compress the specimen beyond the initial height of the sample.
3. Repeat Step 2 until there is no more tendency for the sample to swell.
    a. Record the final stress as the uncorrected swelling pressure.
4. After the swelling pressure has been reached use the Δp/p equal to 1 loading ratio to determine the next loading step.
    a. At this point the specimen is 100% saturated and the oedometer testing can now follow the conventional loading and unloading procedures. Table 5.3 outlines the stresses used during unloading for both inundated and non-inundated specimens.

5.4 Non-inundated Oedometer Testing (Compressibility of a Specimen in an Unsaturated State)

The following sections describe the procedure followed for determining the compressibility characteristics of the Indian Head till in an unsaturated state. The compaction energies and water contents for the used for the non-inundated specimens in the CV tests are outlined in Table 5.1.

5.4.1 Filling the acrylic chamber with 100% humid air

1. Put loading cap and low air entry brass stone into acrylic chamber so they can acclimatize to the humidity level.
2. Place humidity gauges into oedometer cells to monitor the humidity level (Figure 5.2).
3. Place the cap on acrylic chamber and cover openings leaving only a small opening for air transfer.
4. Attach tubing connected to the bubbling chambers to oedometer cells and turn on the air supply to humidity system.
    a. Monitor humidity levels in the oedometer cells. The test can begin when the humidity level reaches 99%.

5.4.2 Preparing non-inundated test specimens

Test specimens for the non-inundated oedometer testing were prepared following the same method outlined in Section 5.2.2.

5.4.3 Assembling oedometer cells for non-inundated testing

1. Measure the mass of low air-entry brass disc and loading cap for each oedometer cell.
2. Place low air-entry brass disc in the center or the oedometer cell (Figure 5.3).
    a. In non-inundated tests, distilled water will not be used in the oedometer chambers.
3. Remove saran wrap from and place test specimen on the centre of the brass disc.
4. Assemble oedometer cells (Figure 5.4).
    a. Place collar on alignment posts,
    b. Secure the collar to the alignments posts with lock nuts,
    c. Put on the cover plate to acrylic chamber,

d. Put on loading frame and dial gauge,

e. Record initial reading of dial gauge and begin loading sequence.

5.4.4 Testing procedure for the non-inundated oedometer testing

A Δp/p equal to 1 was used for the non-inundated oedometer tests for this research project. Unlike CV test discussed previously, the non-inundated oedometer tests follow the loading pattern of conventional saturated oedometer tests even though the samples are in a state of unsaturated state. Table 5.2 outlines the loading sequence followed for non-inundated oedometer testing

Table 5.2: Stresses applied to non-inundated specimens during consolidation.

Stress	Total Load (kg)	Applied Stress (kPa)
Seating Pressure	3	14.5
2	5	25
3	10	50
4	20	100
5	40	200
6	80	400
7	160	800

1. Stresses are increased by adding the appropriate mass of load shot to the bucket based on Table 5.2.

    a. For loads less than 10 kg, the stresses should be gently placed into the bottom of the bucket to reduce movement of the same during loading. Beyond this loading, there is sufficient inertial dead load in the bucket to resist any movement caused by additional placement of lead shot.

2. Unloading is done by allowing sufficient lead shot to be removed through the holes at the bottom of the bucket. Table 5.3 details the stresses used during unloading.

Table 5.3: Applied stresses for unloading portion of the non-inundated specimens.

Stress	Load Removed (kg)	Applied Stress (kPa)
0	0	800
1	80	400
2	40	200
Hanger	39	5

5.5 Filter Paper Calibration

The ASTM Standard D5298-03 entitled, "Measurement of Soil Potential (Suction) using Filter Paper was followed for the calibration of the filter papers". Changes were made to procedure listed in this standard due to the development of bacteria growth on the filter papers during calibration Figure 5.5. Preliminary test showed that mold growth would be a serious problem and would have a prominent effect on the testing procedure.

The following sections detail the procedures followed to obtain the five different calibration curves for Whatman 42 filter papers for this research.

5.5.1 Pre-treating filter papers to prevent mold growth

The ASTM Standard D5298-03 recommends the use of a 2% solution of formaldehyde to prevent bacterial growth on the filter papers during equilibrium. However, preliminary tests undertaken in this research showed that 2% strength was not sufficient to stop the growth of bacteria. Studies in the lab have shown that 10% formaldehyde was necessary in order to prevent bacterial growth.

1. The 10% formaldehyde solution was prepared by diluting a store bought solution of 38% formaldehyde with distilled water.
    a. All work with formaldehyde was performed in a fume hood.
2. Each filter paper was dipped in the 10% formaldehyde solution until

completely saturated (Figure 5.6).

   a. After saturation each filter paper was placed in a separate, numbered aluminum containers to dry.

3. Filter papers were air dried in the fume hood for 48 hours after being saturated in the formaldehyde solution. This allows most of the excess formaldehyde to be safely removed from the filter papers.

4. Filter papers were then oven dried for 24 hours at 110°C.

   a. Oven drying the filter papers will ensure that each filter paper starts from the same point on the wetting curve removing the hysteresis affect.

   b. Leave the lids of the aluminum containers slightly ajar during drying in the oven. This protects the filter paper from any foreign materials but still allows the moisture to escape (Figure 5.7).

5.5.2 Cleaning the null pressure plate device

1. The water contained in the bag under the high air-entry stone was removed and replaced with fresh distilled, de-aired water.

2. The entire null pressure plate device was cleaned with a mild anti-bacterial soap to aid in the prevention of bacteria growth.

5.5.3 Saturating the high air-entry disc used in the null pressure plate device

The high air-entry disc for the null pressure plate was saturated by passing successive heads of water through the stone. To aid in the prevention of bacteria, a 1% formaldehyde solution was added to the de-aired, distilled water used to saturate the high air-entry disc.

1. Place the high air-entry disc on the brackets and level the tank.

2. Pour distilled, de-aired water containing the formaldehyde on top of the high air-entry disc.

   a. Ensure that the head of water does not exceed the height of the membrane as it will pool under at the bottom of the tank and can allow bacterial growth to occur.

3. Place the cover on the pressure plate and securely tighten all locking screws.
4. Attach the air pressure line to the intake valve of the pressure tank.
5. Set the applied air pressure to 15 kPa.
    a. Using a low air pressure during saturation will provide a uniform flow of the water front ensuring that no entrapped air pockets will form within the pores of the high air-entry disc,
    b. Saturation should be done for 48 hours,
        i. Ensure that there is always a head of water above the high air-entry disc.

5.5.4 Applying air pressure to the null pressure plate system

Due to the continuous development of mold during calibration, compressed air in cylinders was used in place of the in-house compressed air system.

5.5.5 Measuring the mass of cold aluminum containers

The ASTM Standard D5298-03 requires that the filter papers mass be determined using a balance with an accuracy of 0.0001 g (Figure 5.8).

1. Allow the aluminum containers to reach temperature equilibrium with the laboratory before mass measurement.
2. Use tongs to transfer the aluminum containers to and from the balance. Bare hands will transfer oils to the containers (Figure 5.9).
    a. Record the cold mass of the aluminum containers,
    b. Tongs are required because of the thermal transfer during handling will alter the mass measured.

5.6 Mass measurement of the filter papers from the oven

Each aluminum containers mass containing the oven dried filter paper must be measured individually while the remainder stays in the oven at 110°C.

1. Before measuring the mass, completely close the lids of the aluminum containers then leave then in the oven for fifteen minutes to allow temperature equilibrium.
    a. Do not touch the aluminum containers with bare hands. Non-powdered latex gloves must be worn whenever the containers are handled.
2. Remove one aluminum container and place it on a metal block to cool for 30 seconds. This allows for quicker cooling and temperature equilibrium before measuring the mass of the aluminum containers.
3. Place the aluminum container with the filter paper onto the balance and record the total mass.
4. Remove the aluminum container from the balance; open it to remove the filter paper.
    a. Filter paper should be placed in an empty aluminum container to prevent contamination.
5. Close the lid and measure the mass of the empty aluminum container. Record as the hot mass of the aluminum container.
    a. Return the filter paper to its original aluminum container,
        i. Repeat Steps 2-5 for each aluminum container.

5.6.1 Lead Shot containers for applying stress to the filter papers

1. Each specimen containers should be cleaned with a mild anti-bacterial soap to help prevent the development of bacteria.
2. Holes were drilled into the cap of each of the specimen containers (Figure 5.10).
    a. The holes were to prevent pressure buildup within the specimen containers as the air pressure inside the null pressure plate increases.
3. Specimen containers were filled with lead shot following the requirements outlined in Table 5.4 and shown in Figure 5.11.

4. Spacers were used to evenly apply the stresses from the specimen containers to the filter papers.
    a. The spacers should also be cleaned with a mild anti-bacterial soap and water solution to help prevent the development of bacteria,
    b. Holes were drilled into the spacers to allow the air pressure to be distributed to the filter paper,
    c. Spacers were also used on the filter papers with zero applied stress for consistency.

5.6.2 Calibrating the filter papers for matric suction measurement

Since a calibration curve was to be developed the opportunity arose to test the effect of compression on the water retention properties of the filter papers. For this, four additional calibration curves for the Whatman 42 filter papers were obtained with different stress applied to the filter paper during their calibration. This would test the effect of compression due to applied loading on the water retention properties of the filter papers. Table 5.4 outlines the stresses applied to the filter papers during calibration.

Table 5.4: Applied Stress for filter paper calibration.

Calibration Curve	Number of Filter Papers	Appiled Load (kg)	Applied Stress (kPa)
1	3	0.000	0
2	3	0.100	0.4
3	3	0.250	1
4	3	0.500	2
5	3	1.000	4

Since only matric suction was considered for this research the Soil Moisture 500 kPa null pressure plate device was used to calibrate the filter papers. Fourteen days was the minimum equilibrium time that was used for each suction level Ridley (2003). For the lower suction levels a longer period was used to ensure equilibrium was reached.

Table 5.5 outlines the suction levels and equilibrium times used during the calibration of the Whatman 42 filter papers.

Table 5.5: Suction levels and equilibrium times for the calibration of the Whatman 42 filter papers.

Stress	Applied Stress (kPa)	Equilibrium Time (Days)
1	300	14
2	200	15
3	150	16
4	100	14
5	80	14
6	70	14
7	60	15
8	50	20
9	20	21

5.6.3 Preparing the filter papers for calibration

1. Dry the surface of the high air-entry disc to ensure that there is no free water remaining.
2. Remove the filter papers from the aluminum containers using tweezers and place them on to the saturated high air-entry disc of the null pressure plate.
    a. Tweezers are required to prevent filter paper contamination,
    b. The same placement pattern was followed each time the filter papers were returned to the tank after measuring the mass for consistency.
3. Place a spacer on top of each filter paper.
4. Place the specimen container onto the corresponding filter paper.
    a. Filter papers with the 1000 g applied load were placed nearest to the three supports of high air-entry disc to prevent any damage caused by the increased load.
5. Seal the null pressure plate ensuring each locking screw is secured.
6. Attach the air pressure line from the compressed air tanks to the intake valve of

the pressure tank of the null pressure plate device.

7. Set the regulator to the desired pressure level and release the air pressure into the tank.

5.6.4 Flushing the null pressure plate system during calibration

Although de-aired distilled water is used in the null pressure plate device dissolve air can come out of solution over the long equilibrium period and would accumulate under the high air-entry disc. As long as there is water in contact with the bottom of the high air-entry disc, it will remain saturated. If air bubbles were allowed to accumulate the disc would become de-saturated and erroneous values would be measured. A method was incorporated into the null pressure plate system to remove the air bubbles from under the stone. A syringe was attached to the outlet of the null pressure plate system and filled with water. The water level in the syringe was monitored during the equilibrium period. Air bubble formation was indicated by a rising water level.

1. When the water level in the syringe rose by 25 mm sufficient air bubbles had accumulated to warrant a flushing.
2. The air pressure in the tank was lowered.
3. An aerator was attached to the syringe and a suction force was applied to the bag under the high air-entry stone.
4. When no more bubbles were visible leaving the tank the aerator connection was removed from the syringe.
    a. When the suction on bag was released the water in the syringe would be drawn into the tank to replace the air removed. Additional water would have to added for the system for it to remain saturated,
    b. Two syringes were prepared before the aerator was removed from the monitoring syringe. One syringe contained a 2% solution of formaldehyde and the second contained only distilled water,
        i. The 2% formaldehyde solution was added to the syringe to aid in the prevention of bacteria growth,

c. Flushing of the air bubbles was done four times a day for air pressures greater than 100 kPa and twice a day for air pressures less than 100 kPa.

5.6.5 Measurement of mass of wet filter papers

The calibration of the filter papers produces a curve that relates the water content of the filter paper to the applied suction. The water content is determined by the mass of the wet filter papers at the end of each equilibrium period. Since a high concentration of formaldehyde was used to prevent bacteria growth when the air pressure was released from the tank the air was first flushed through a scrubbing system consisting of four 2 liter bottles filled with water before releasing the air to the laboratory.

1. Determine the cold mass of the aluminum containers following the procedure outlined in Section 5.5.5.
2. Release the air pressure and open the tank.
   a. 3M™ Multi-Gas/Organic Vapor Respirators 5000 Series were used when working with the formaldehyde outside of a fume hood.
3. Remove the weights from the filter papers.
4. Quickly remove the filter papers from the null pressure plate using tweezers and place them into their corresponding aluminum containers.
   a. Removal needs to done as quickly as possible to prevent the loss of moisture from the filter papers.
5. Determine the total mass of the filter paper and aluminum container following the procedure outlined in Section 5.6 except that the hot mass is not measured.
   a. The mass of the wet filter papers is found by subtracting the cold mass of the aluminum containers from Step 1 from the total mass found in Step 5.
6. Repeat steps 1 – 6 for each suction level.

5.7 Measuring Matric Suction Using the Axis-Translation Technique

Matric suction of the test specimens was measure using two methods namely axis translation and the contact filter paper method ASTM Standard D5298-03.

5.7.1 Preparing test specimens for measuring matric suction using the axis-translation technique

Test specimens prepared for the measuring matric suction using the axis-translation technique were prepared in the same manner as test specimens made for oedometer testing outlined in Section 5.2.2.

5.7.2 Sealing the high air-entry disc into the acrylic base of the single specimen null pressure plate device

Note it is important to properly place the high air-entry disc into the acrylic base. Quickly forcing the disc into the base will damage the disc or cause the disc to not properly align with the bottom of the base thereby forming an improper seal.

1. Attach tubing to both the in and outlet connections of the a acrylic base.
    a. Use sufficient length of tubing to ensure the acrylic base will remain full of water.
2. Fill the acrylic base with distilled water.
    a. Ensure that the open ends of the tubing are at higher elevation then the acrylic base so that the water is able to pool in the acrylic base.
3. Place the acrylic base into an oedometer loading machine.
4. Carefully place the high air-entry disc into the acrylic base.
5. Slowly apply the axial force to the high air-entry disc to push the disc into place.
    a. Ensure that the water is able to leave the acrylic base through the tubing. If pressure builds up under the high air-entry disc the bond between the metal disc and the ceramic stone will break and the stone would have to be replaced,
    b. The high air-entry disc is sealed into place by an O-ring along the outside

of the acrylic base.

5.7.3 Saturating the high air-entry disc used in the single specimen null pressure plate

The same technique outlined in Section 5.5.3 to saturate the high air entry disc of the multi specimen null pressure should be followed for the saturation of the high air-entry disc used for the single specimen null pressure plate device.

5.7.4 Saturating the single specimen null pressure plate system

1. De-air 1000 ml distilled water.
2. Fill a 500 ml beaker with de-air distilled water.
3. Place the tubing from the base of the stop cock into the beaker of de-air distilled water.
4. Fill the stop cock and tubing of the flushing system with de-air distilled water by turning on the pump.
   a. Ensure that the flow of water out of the flushing system is not in the beaker of de-air distilled water as the flow of water and air will re-oxygenate the water.
5. Attach the tubing from the side of the stop cock to the inlet of the acrylic base.
6. Fill the chamber underneath the high air-entry disc with de-air distilled water by again turning on the pump.
7. Quickly attach the tubing from the base of the stop cock to the acrylic base.
   a. Ensure that no air bubbles enter the line while attaching the tubing to the acrylic base.

5.7.5 Measuring matric suction using the single specimen null pressure plate and the axis-translation technique

1. Surface dry the high air-entry disc.
2. Record the initial mass of the test specimen.
3. Place the test specimen on the high air-entry disc.
4. Place the pressure chamber into the acrylic base.
5. Attach the air pressure line to the intake valve of the pressure chamber and seal the pressure chamber securely with the locking screws.
    a. Ensure that the stop cock is open while sealing the pressure chamber to allow the water to flow out from underneath the high air-entry disc.
6. Bring the water level in the glass tube indicator to the mid height of the specimen and close the stop cock.
7. Record the initial height of the water level in the glass tube indicator.

Monitor the water level in the glass tube indicator. A decrease in implies that the water level decreases meaning that the suction within the specimen is greater than the applied air pressure in the pressure chamber and the specimen is drawing water into itself. Increase the air pressure in the pressure chamber to counteract the flow of water into the specimen. Pressure increments should not be more than 5 kPa at one time. Continue to monitor the water level in the glass tube indicator and increase the air pressure in the chamber as required. The matric suction of the sample has been reached when the water level in the glass tube indicator remains constant for at least one hour.

8. Once the matric suction of the specimen has been measured, release the air pressure from within the pressure chamber and remove air pressure line from the intake valve of the pressure chamber.
9. Disassemble the single specimen null pressure plate system and remove.

10. Record the mass of the test specimen.

    a. The test is successful if the initial and final masses of the test specimen are the same, indicating that the water content of the specimen has not changed during testing.

11. Extrude the specimen from the specimen ring.

12. Divide the specimen into three parts and determine its water content.

13. Maintain a head of water on top of the high air-entry disc to keep it saturated when the single specimen null pressure plate system is not being used.

5.8 Measuring Matric Suction Using the Contact Filter Paper Method

This section outlines the preparation of the test specimens and testing environment for the estimation of soil suction using the contact filter paper method.

5.8.1 Preparing test specimens for measuring matric suction using the contact filter paper method

Test specimens used for measuring matric suction using the contact filter paper method and shown Figure 5.18 in were made in the same manner as in Section 5.2.2. The test specimens were made by combining four individual samples to get the mass specified in the ASTM Standard D5298-03. A spacer was inserted in between two successive specimens and the process was repeated until four test specimens were made producing a specimen approximately 400 mm in height. The specimens were then extruded using the drill press setup shown in Figure 5.19 to be used for suction measurement.

5.8.2 Creating a temperature and humidity controlled environment to store the test specimens during equilibrium

Two-66 liter Coleman coolers shown in Figure 5.20 were used to store the test specimen during the equilibrium period. The coolers were used so that the specimens were kept at a constant temperature and humidity (Figure 5.21).

1. 4000 ml of distilled water was placed at the bottom of the cooler to increase the humidity level of the cooler.
    a. The coolers were left for 48 hours to reach 100% humidity.
2. Humidity and temperature were monitored by three gauges throughout the test.

5.8.3 Measuring matric suction using the contact filter paper method

All filter papers used in the measurement of matric suction were pre-treated to prevent bacteria growth following the same procedure outline in Section 5.5.1 Pre-treating filter papers to prevent mold growth. A stack of three filter paper was used for measuring suction, two sacrificial filter papers and one used for suction measurement. The filter paper used for suction measurement was cut to be smaller than the two sacrificial filter papers.

1. Determine the dry mass of the filter papers used for suction measurement following the procedure outlined in Section 5.6, "Mass measurement of the filter papers from the oven".
    a. There is no need to measure the mass of sacrificial filter papers.
2. Place stack a three of filter papers between each specimen.
3. Recombine the specimens and wrap in two layers of saran wrap, place inside a vacuum sealed Ziploc bag and place inside the cooler.
4. Repeat steps 1 – 3 for each test specimen.
5. An 18 day equilibrium period was used because of the three stack of filter papers.
6. After the equilibrium period the water content of the filter papers was determined following the procedure outline in Section 5.6.5 and Section 5.6.

Through the use of the calibration curve obtained the water content of the filter papers gives the matric suction of the test specimen.

Figures

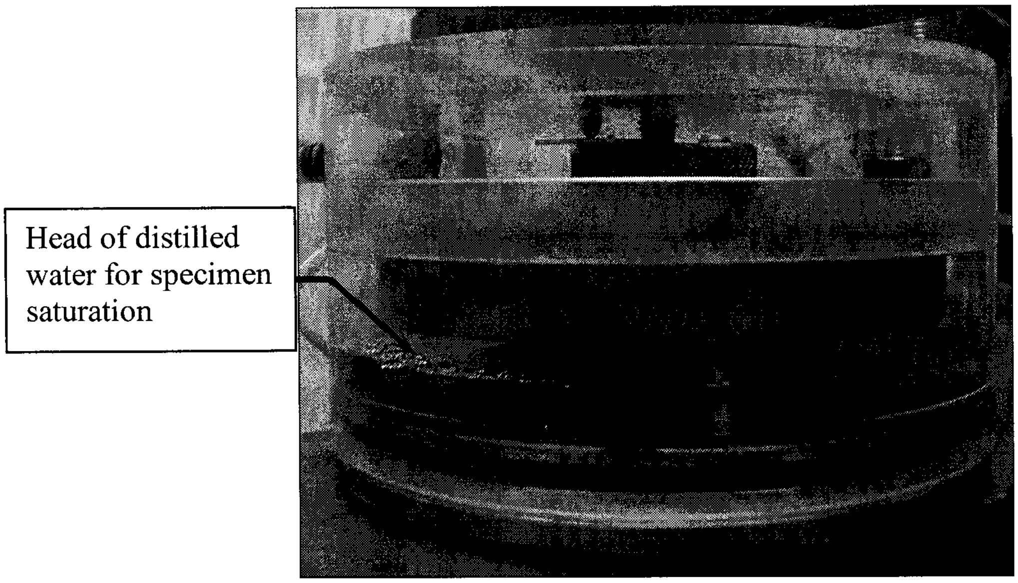


Figure 5.1: Set up for the constant volume oedometer test.

Figure 5.2: Gauge used to monitor temperature and humidity during oedometer testing.

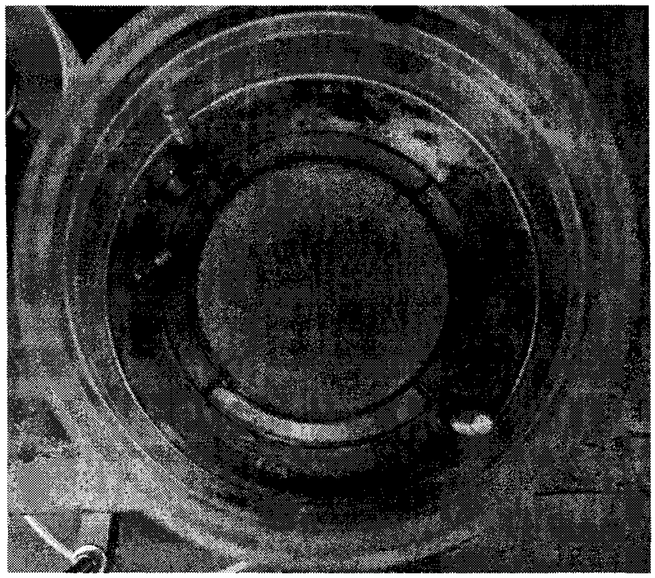


Figure 5.3: Low-air entry brass disc used in non-inundated oedometer testing.

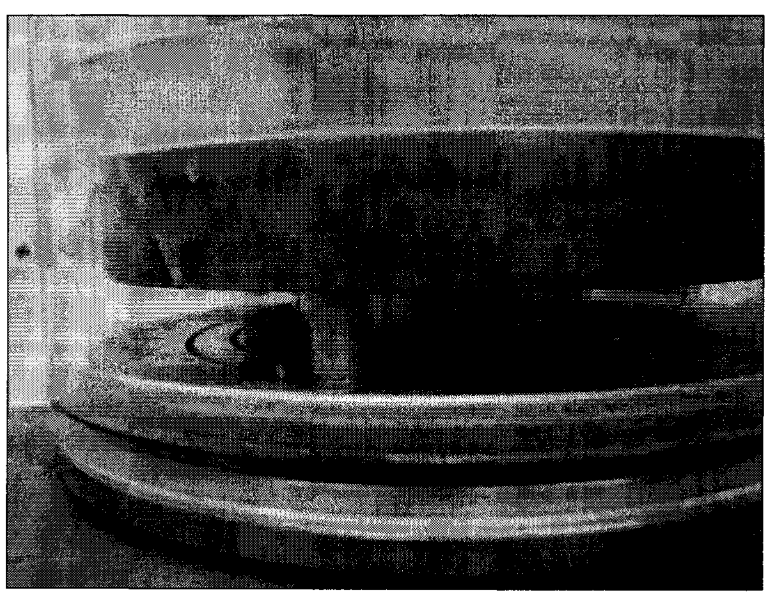


Figure 5.4: Test setup for non-inundated oedometer testing.

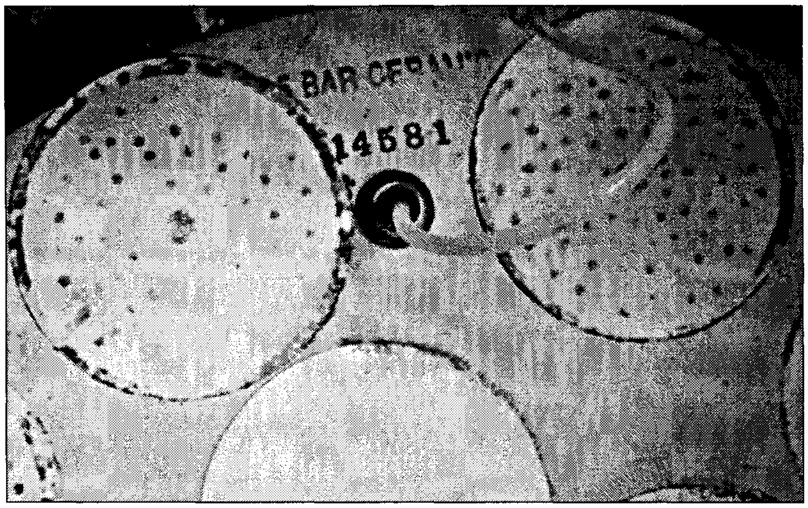


Figure 5.5: Mold on filter papers soaked in a 2% formaldehyde solution.

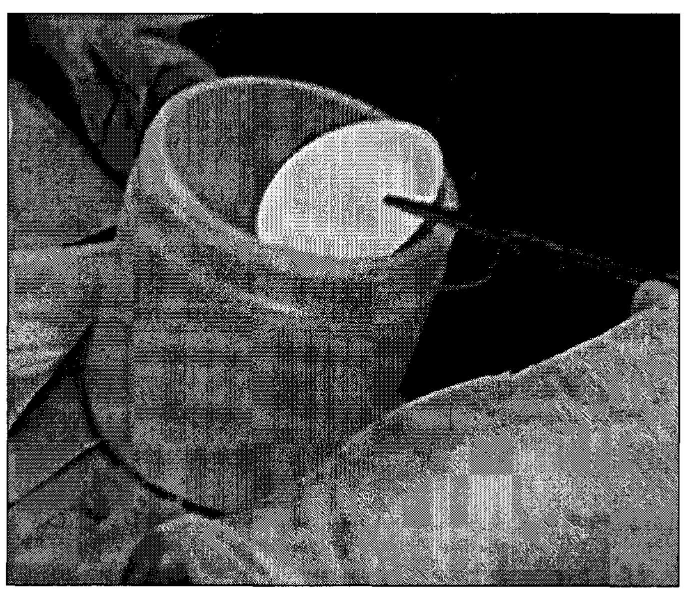


Figure 5.6: Dipping 10% formaldehyde solution to prevent bacteria growth.

Figure 5.7: Leaving aluminum containers ajar during oven drying.

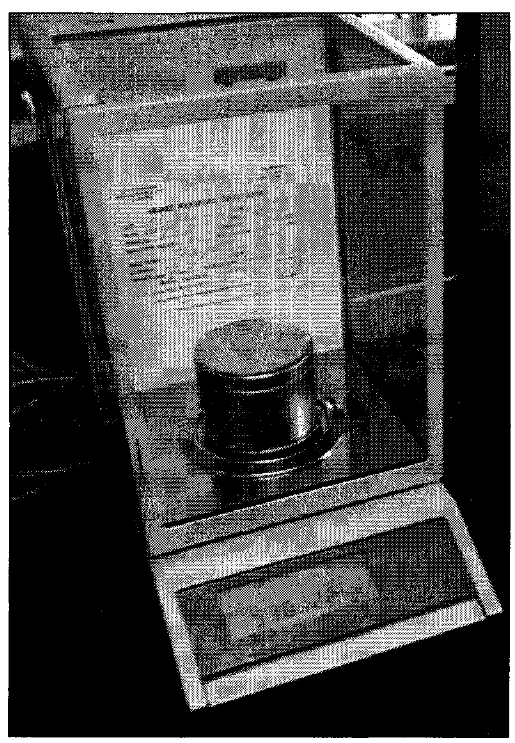


Figure 5.8: Scale with accuracy to 0.0001 g used to determine the mass of wet and dry filter papers.

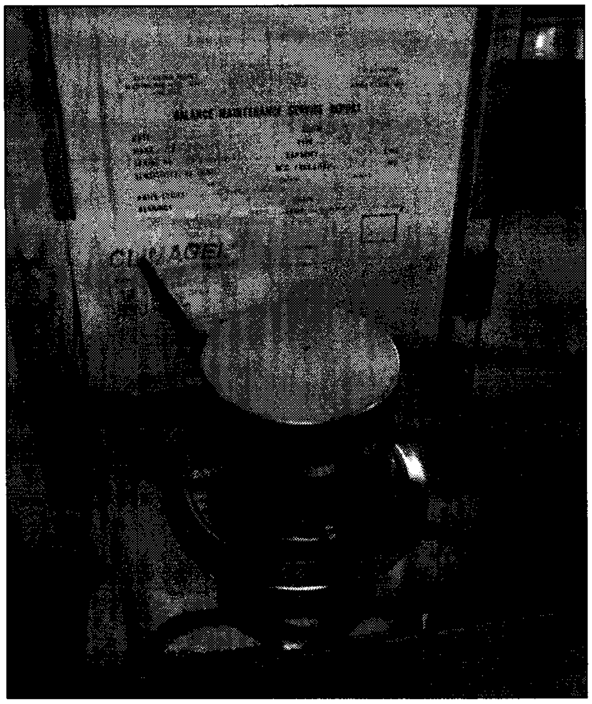


Figure 5.9: Tongs used to place and remove aluminum containers from the scale.

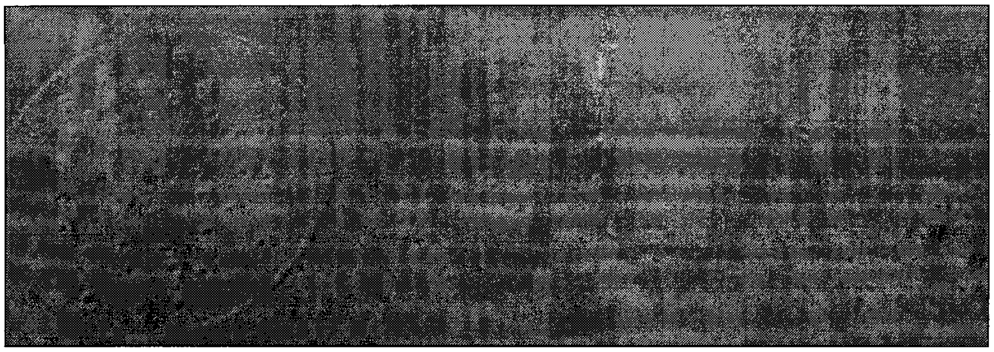


Figure 5.10: Spacers used to evenly distribute applied stress to the filter papers during calibration.

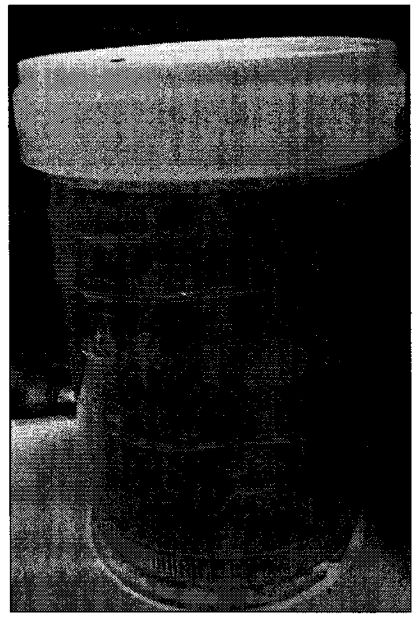


Figure 5.11: 500 g load applied to filter papers during calibration.

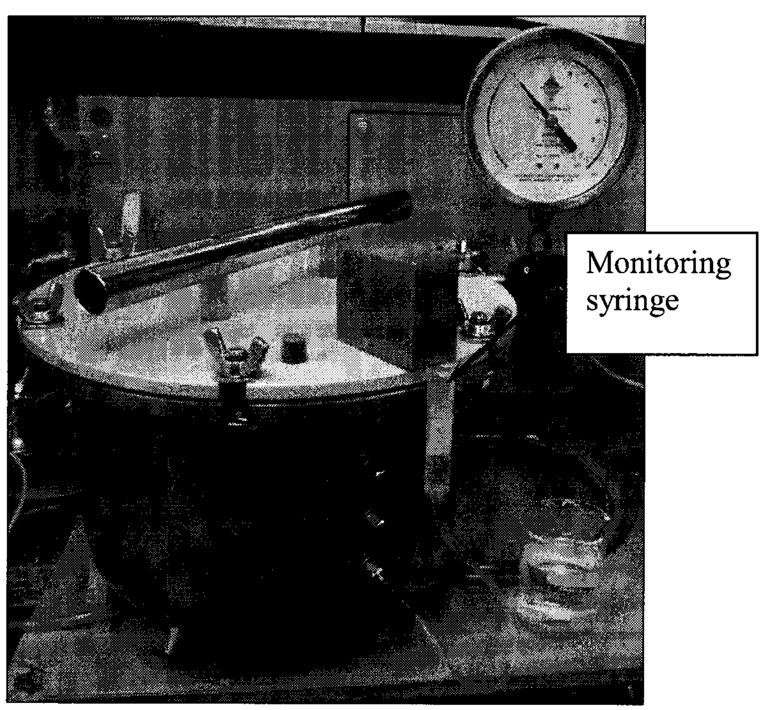


Figure 5.12: Null pressure plate device used to calibrate filter papers.

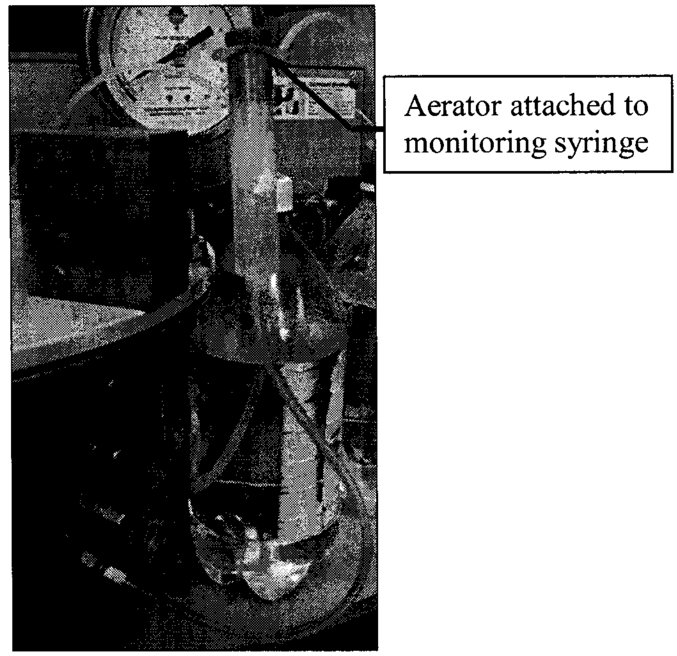


Figure 5.13: Aerator attached to monitoring syringe to remove air bubbles.

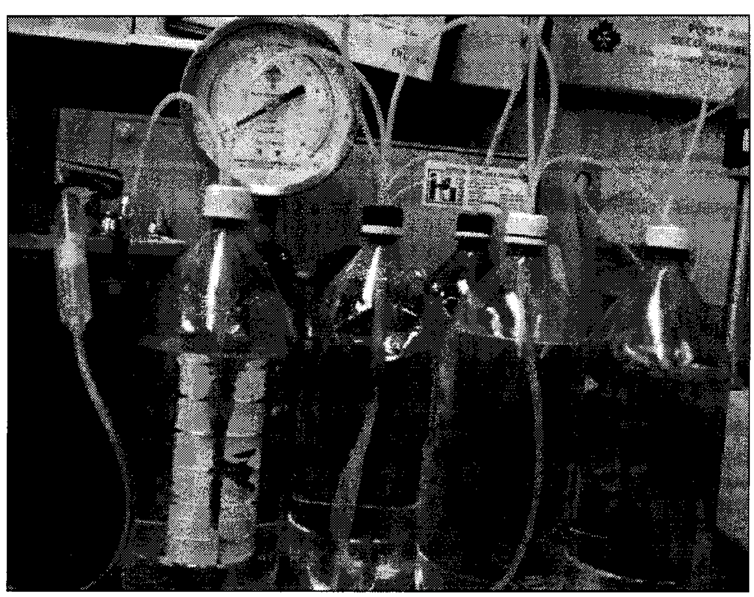


Figure 5.14: Scrubbers attached to the outlet valve of the pressure tank to remove formaldehyde from the air stream before it is released to the laboratory.

Figure 5.15: Using oedometer to slowly push high air entry disc into acrylic base.

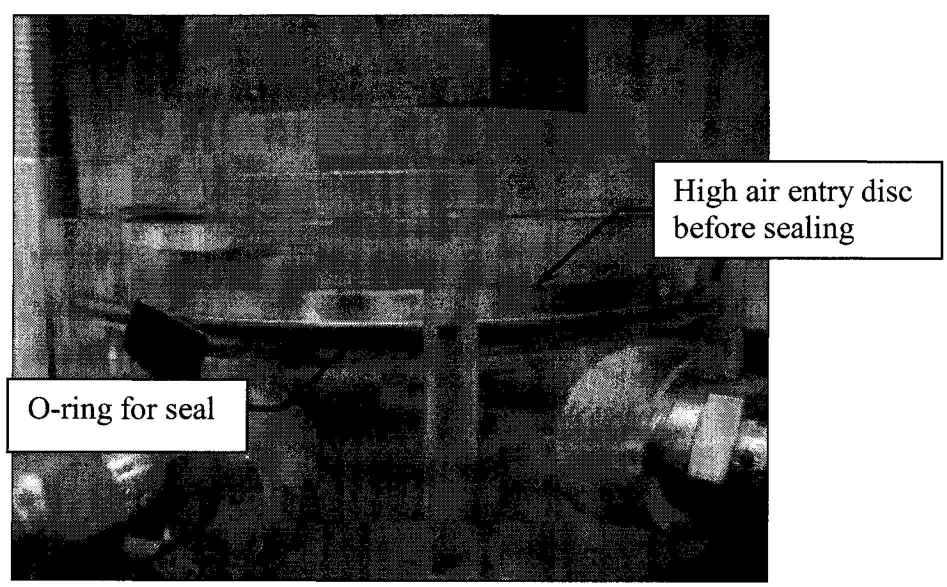


Figure 5.16: High air entry disc before being sealed into acrylic base.

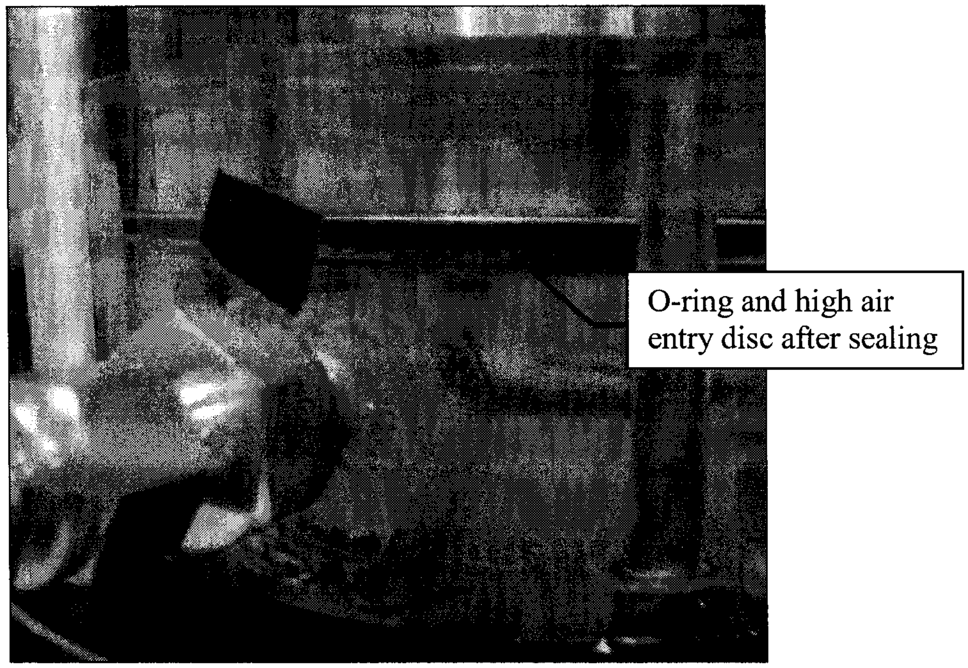


Figure 5.17: High air entry disc after being sealed into acrylic base.

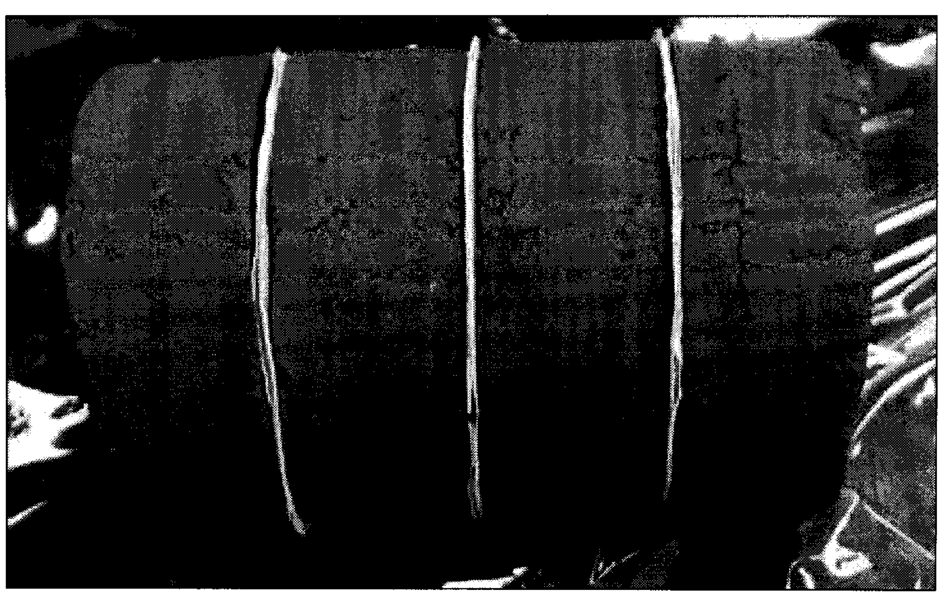


Figure 5.18: Contact filter paper specimen.

Figure 5.19: Filter paper specimen extractor.

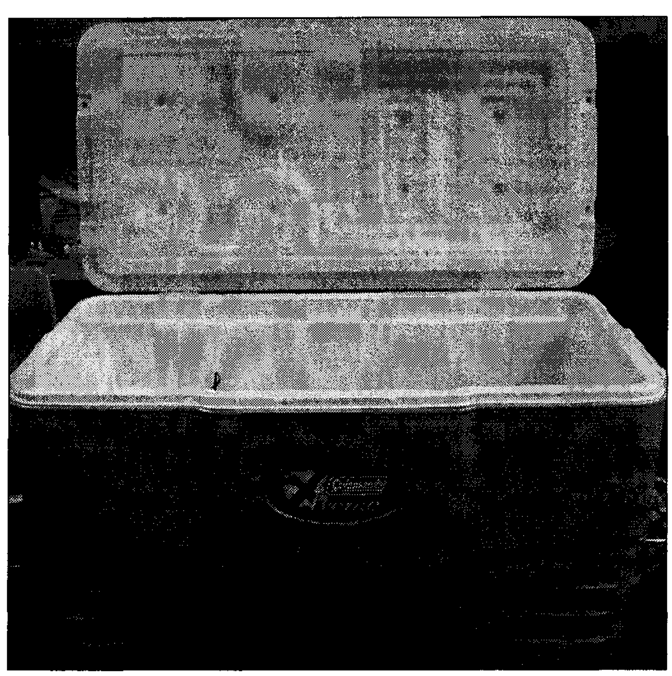


Figure 5.20: 66 liter cooler used to store contact filter paper specimens during equilibrium.

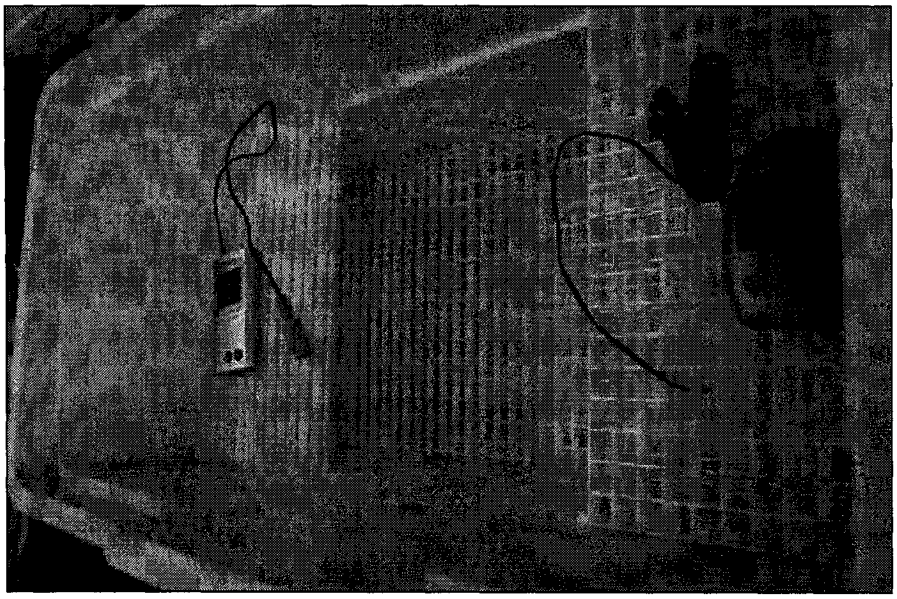


Figure 5.21: Inside view of the cooler showing shelves and humidity and temperature gauges.

CHAPTER 6: MATRIC SUCTION MEASUREMENTS

6.1 Introduction

As described in Chapter 5, a testing program was developed to determine the matric suction values of Indian Head till specimens that were statically compacted, using two different levels of energy, with initial water contents varying from 14 – 19 %. The purpose of this testing program was to determine the effect of the initial matric suction on the compressibility properties of Indian Head till under unsaturated conditions. The matric suction of the specimens was determined using both an indirect method (i.e. filter paper technique following ASTM D5298-03) and a direct method (i.e. axis-translation technique). The following sections details the development of a series of new calibration curves for Whatman 42 filter paper and the matric suctions results obtained for Indian Head till specimens determined by both methods.

6.2 The Contact Filter Paper Method

6.2.1 Calibration Equations from ASTM Standard D5298-03

The ASTM D5298-03 standard contains two calibration equations for Whatman 42 filter papers (see Eq. 6.1 and 6.2). These equations describe a bi-linear curve as shown in Figure 6.1.

$$\text{ASTM Calibration } wc_{fp} < 45.3\,\%\ h = 5.327 - 0.0779wc_{fp} \qquad \text{Eq. 6.1}$$

$$\text{ASTM Calibration } wc_{fp} > 45.3\,\%\ h = 2.412 - 0.0135wc_{fp} \qquad \text{Eq. 6.2}$$

These calibration equations were used to calculate the matric suction values of the specimens tested using the contact filter paper method.

6.2.2 Filter Paper Calibration Curves

The calibration curve is the central tool in the measurement of soil suction using the filter paper method (Gardner 1937). The calibration curve relates the water content of the filter paper to the soil suction of a test specimen. Several calibration curves have been published in the literature including (Fawcette & Collis-George 1967, Hamblin 1981, Chandler & Gutierrez, 1986, Greacen et al. 1987, Chandler et al. 1992a&b, Deka et al. 1995, Bulut et al. 2001, and Leong et al. 2002). There is debate amongst researches whether or not the same calibration curve can be used to determine both matric suction and total suction (Van Der Raadt et al. 1987, Huston et al. 1994, Leong et al. 2002). Deka et al. 1995 showed that the calibration curve should be determined based on the testing environment and program employed. The ASTM Standard states in Section 7.3 that "*The calibration curves shown are applicable to total suction*". Based on the literature review, it was decided that a new calibration curve was required that determined the matric suction of the test specimens, and would take into account environmental conditions of the laboratory.

In addition to the development of a new calibration curve for the testing program, the effect of filter paper compression on the calibration curve was also studied. During the calibration phase of the testing program, five-separate stresses 0, 0.4, 1, 2, and 4 kPa were applied to the filter papers. For each applied stress, three filter papers were used in order to determine an average filter paper water content value. Figure 6.2 illustrates the layout of, and how the stresses were applied to filter papers in the null pressure plate device during calibration. The proper use of the null pressure plate is detailed in Chapter 3. After equilibrium with the applied air pressure, the measured matric suction values were accepted or rejected in accordance with Section 9.3.1 of the ASTM Standard D5298-03 which states, "*test results should be discarded if the difference in suction between the two filter papers exceeds 0.5 log kPa*".

6.2.3 Zero Applied Stress Calibration Curve

The zero applied stress calibration curve developed for this research project is compared to the calibration curve published in the ASTM Standard and is shown in Figure 6.3. Table 6.1 is the data sheet used to calculate the matric suction values from the filter paper water contents measured using Eqs. 1 and 2. Table 6.2 compares the filter paper water contents measured for the 0 kPa calibration curve to those calculated using the ASTM calibration equations. This new calibration curve closely matches that of the ASTM standard in both the high suction range (i.e. filter paper water contents $\leq$ 45.3%) and in the low suction range (i.e. filter paper water contents $\geq$ 45.3%) providing validity to the experimental procedure. The majority of the water contents for the 0 kPa calibration curve have a percent difference of less than 5% with the largest being at a matric suction value of 20 kPa.

6.2.4 The Calibration Curve with an Applied Stress of 0.4 kPa

The calibration curve obtained with an applied stress of 0.4 kPa is shown in Figure 6.4 and is compared with the ASTM Standard calibration curve. Table 6.3 is the data sheet used to calculate the matric suction values from the filter paper water contents measured for each suction level using Eqs. 1 and 2. Of the applied stresses less than 1 kPa, the 0.4 kPa calibration curve shows the most variation from the ASTM Standard as shown in Table 6.4. The maximum percent difference is still less than 15% with an average error of 7.9%. The filter paper water contents measured for the matric suction of 70 kPa were rejected as they did not comply with Section 9.3.1 of the ASTM Standard. The entire calibration curve with an applied stress of 0.4 kPa was not abandoned as only the water contents for the 70 kPa matric suction had to be discarded.

6.2.5 The Calibration Curve with an Applied Stress of 1 kPa

Figure 6.5 shows the calibration curve obtained with an applied stress of 1 kPa in comparison to the that of the ASTM Standard. The matric suction values calculated from the filter paper water contents measured are tabulated in Table 6.5. A comparison of the percent differences in the measured water content values to those calculated from Eq. 1 and 2 are shown in Table 6.6. The 1 kPa applied stress calibration curve closely matches that of ASTM standard in both the high and low suction ranges as was observed in the 0 kPa curve. The error for the majority of the measured water contents was less than 5% with and average error of 4.8%. The maximum error of 15% was observed for the 20 kPa matric suction.

The applied stress of 1 kPa is recommended as the proper stress to apply to the filter paper during equilibrium as it does not significantly affect the calibration curve, and would ensure intimate contact between the pore-water of the test specimens and the filter paper during equilibrium.

6.2.6 The Calibration Curve with an Applied Stress of 2 kPa

The shift in the calibration curve away from the ASTM Standard becomes more evident at the applied stress level of 2 kPa. Figure 6.6 compares the ASTM Standard calibration curve to the one obtained with an applied stress of 2 kPa. The calculated matric suction values are outlined in Table 6.7.

There is a significant increase in the percent difference between the water content values measured for this new calibration curve to those calculated from the ASTM Standard equations (see Table 6.8 for more details). The maximum error was greater than 23% for water contents measured for the 60 kPa matric suction. However, the average error was equal to a

12.3% which is almost three times that of the error obtained for the calibration curve with an applied stress of 1 kPa.

6.2.7 The Calibration Curve with an Applied Stress of 4 kPa

The largest percent error between the measured and calculated filter paper water content values was obtained for calibration curve with an applied stress of 4 kPa (see Figure 6.7 and Table 6.9). The matric suction values calculated using the water content values are tabulated in Table 6.10. The average error for this calibration curve was 24.2% which is more than five times greater than the average error obtained for the calibration curve with an applied stress of 1 kPa and twice that of the 2 kPa curve. The increase in applied stress has again been shown to significantly alter the calibration curve obtained for Whatman 42 filter paper. With all the filter papers selected for calibration being from the same batch and box, being calibrated at the same time, in the same null pressure plate device, for the same equilibrium time, this increase in percent difference in the measured water content can only be attributed to the increased applied stress.

6.3 Measuring Matric Suction Using the Contact Filter Paper Method

Twelve sets of specimens were prepared as described in Chapter 4. The specimens comprised of six different water contents and initial densities based on the two compaction energy curves. An eighteen day equilibrium period was used to ensure that the water transfer between the sample and the filter paper was complete. This section provides the results of the matric suction measurements using the contact filter paper method.

6.3.1 Matric Suction Results from the Contact Filter paper method

The matric suction values were measured based on the ASTM Standard and are detailed in Figure 6.9 for specimens prepared using the high compaction energy curve, and Figure 6.10 for specimens prepared using low compaction energy. Table 6.11 summarizes the matric suction values measured using the contact filter paper method. Table 6.12 is the data sheet used to calculate the matric suction values from the filter paper water contents measured.

Vanapalli et al. 1999 measured the matric suction values following the axis-translation technique for specimens prepared from a till sample with similar characteristics to the soil used in this research project. The matric suction results measured using filter paper for the specimens prepared for this research show similar trend lines to those published by Vanapalli et al. 1999 (see Figure 6.14).

6.4 Measuring Matric Suction with the Axis-translation Technique

The axis-translation technique allows for the direct measurement of matric suction of a test specimen. A single specimen null pressure plate device is shown in Figure 6.11 was used to measure the matric suction values of the test specimens prepared for this research project. Test specimens were prepared in the same manner as those in used in the oedometer tests for consistency. Table 6.13 details the initial water contents of the test specimens and the matric suction results measured using the axis-translation technique. The matric suction values measured for this research are shown in Figure 6.12 for specimens prepared using the high compaction energy curve, and Figure 6.13 for specimens prepared using low compaction energy.

From the data published in Vanapalli et al. 1999 and shown in Figure 6.14, Eqn 6.3 was obtained which relates the soil water content to the matric suction value for the Indian Head till specimens. A comparison was made between of the results of the published matric suction values to those obtained in this research project using axis-translation and are detailed in Figure 6.15. The results show similar trends between the sets of measured matric suction values.

$$h = -51.169(wc\%_{soil}) + 999.26 \qquad \text{Eq. 6.3}$$

A rigorous analysis of the test procedures and the matric suction results outlined in this chapter in comparison to the results of published procedures and data is undertaken in the Chapter 8.

6.5 Summary

Results outlined in this chapter have shown that when a stress is applied to filter papers during calibration, there is a significant affect on the calibration curve obtained when compared to that of the ASTM Standard. A summary of the effect of the applied stress on the calibration curve for Whatman filter paper is shown in Figure 6.8. The error between the ASTM Standard calibration curve and those obtained from this research significantly increases as the applied stress increases as outlined in Table 6.14. With all the filter papers selected for calibration being from the same batch and box, calibrated at the same time and equilibrium period, in the same null pressure plate device, this increase in percent difference in the measured water content can only be attributed to an increase in the applied stress.

In other Geotechnical test such as consolidation or direct shear tests, a seating load is applied to the test specimen to ensure proper alignment of the equipment before the tests begins.

The same can be said for the contact filter paper method. Sufficient contact must be ensured between the filter paper and the pore-water of the test specimen if the moisture transfer is take place in the liquid phase (Houston et al. 1994). However, too large of a contact stress will alter the water retention properties of the filter paper, thereby producing erroneous suction results (Chandler & Gutierrez 1986). The magnitude of this contact stress for the filter paper method has been the focus of this chapter. In examining the affect of the contact stress on matric suction calibration curves obtained for Whatman 42 filter paper, results show that an applied contact stress of up to 1 kPa will provide the contact necessary without significantly altering the calibration curve. Therefore, it is recommended that the stress applied to the filter papers be less than 1 kPa during the measurement of matric suction using the contact filter paper method.

Table 6.1: Filter Paper Water Contents for the University of Ottawa Calibration Curve with Zero kPa Applied Stress Including Suction Results following the ASTM D5298-03 Standard.

			ASTM Calculations				
Filter Paper Water Content (%)	Average Filter Paper wc (%)	Change in Filter Paper wc (%)	Calibration Equation	log (Matric Suction) (kPa)	Discard / Kept	Matric Suction (kPa)	Median Matric Suction (kPa)
37.12	37.64	2.09	Equation 1	2.44	Value Kept	272	238
37.92		0.00	Equation 1	2.37	Value Kept	236	
37.87		0.12	Equation 1	2.38	Value Kept	238	
38.61	37.31	1.90	Equation 1	2.32	Value Kept	209	209
33.95		13.74	Equation 1	2.68	Value Kept	481	
39.36		0.00	Equation 1	2.26	Value Kept	182	
39.91	37.91	0.00	Equation 1	2.22	Value Kept	165	186
34.57		13.39	Equation 1	2.63	Value Kept	431	
39.26		1.63	Equation 1	2.27	Value Kept	186	
42.52	40.18	0.00	Equation 1	2.02	Value Kept	104	133
36.89		13.22	Equation 1	2.45	Value Kept	284	
41.13		3.25	Equation 1	2.12	Value Kept	133	
46.79	44.88	0.00	Equation 2	1.78	Value Kept	60	62
41.79		10.70	Equation 1	2.07	Value Kept	118	
46.07		1.55	Equation 2	1.79	Value Kept	62	
47.00	43.68	0.00	Equation 2	1.78	Value Kept	60	86
40.46		13.93	Equation 1	2.18	Value Kept	150	
43.58		7.29	Equation 1	1.93	Value Kept	86	
48.54	46.86	0.05	Equation 2	1.76	Value Kept	57	57
43.49		10.43	Equation 1	1.94	Value Kept	87	
48.56		0.00	Equation 2	1.76	Value Kept	57	
51.93	49.30	0.00	Equation 2	1.71	Value Kept	51	54
45.77		11.85	Equation 2	1.79	Value Kept	62	
50.19		3.35	Equation 2	1.73	Value Kept	54	
75.69	72.33	0.00	Equation 2	1.39	Value Kept	25	26
67.71		10.54	Equation 2	1.50	Value Kept	31	
73.59		2.77	Equation 2	1.42	Value Kept	26	

Table 6.2: Comparison of the filter paper water contents from the ASTM calibration equations to the average measured water content for the 0 kPa calibration curve

Matric Suction (kPa)	ASTM Filter Paper Water Content (%)	University of Ottawa 0 kPa Filter Paper Water Content (%)	Percent Difference (%)
300	36.58	37.64	2.89
200	38.84	37.80	2.68
150	40.45	37.91	6.27
100	42.71	40.18	5.92
80	43.95	43.27	1.55
70	44.69	44.27	0.93
60	46.95	46.86	0.18
50	52.82	49.30	6.67
20	82.29	72.33	12.11

Table 6.3: Filter Paper Water Contents for the University of Ottawa Calibration Curve with 0.4 kPa Applied Stress Including Suction Results following the ASTM D5298-03 Standard.

			ASTM				
Filter Paper Water Content (%)	Average Filter Paper wc (%)	Change in Filter Paper wc (%)	Calibration Equation	log (Matric Suction) (kPa)	Discard / Kept	Matric Suction (kPa)	Median Matric Suction (kPa)
33.38	33.90	3.09	Equation 1	2.73	Value Kept	533	488
34.44		0.00	Equation 1	2.64	Value Kept	440	
33.87		1.66	Equation 1	2.69	Value Kept	488	
34.97	34.83	11.97	Equation 1	2.60	Value Kept	401	359
33.95		13.74	Equation 1	2.68	Value Kept	481	
35.59		10.40	Equation 1	2.55	Value Kept	359	
35.62	37.06	9.80	Equation 1	2.55	Value Kept	357	328
39.49		0.00	Equation 1	2.25	Value Kept	178	
36.08		8.63	Equation 1	2.52	Value Kept	328	
38.65	37.16	0.00	Equation 1	2.32	Value Kept	207	244
35.10		9.18	Equation 1	2.59	Value Kept	391	
37.75		2.34	Equation 1	2.39	Value Kept	244	
43.87	44.57	8.28	Equation 1	1.91	Value Kept	81	81
47.83		0.00	Equation 2	1.77	Value Kept	58	
42.01		12.17	Equation 1	2.05	Value Kept	113	
43.03	#N/A	41.43	Equation 1	1.97	Value Discarded	#N/A	#N/A
73.47		0.00	Equation 2	1.42	Value Discarded	#N/A	
42.50		42.16	Equation 1	2.02	Value Discarded	#N/A	
48.07	48.56	8.11	Equation 2	1.76	Value Kept	58	58
52.31		0.00	Equation 2	1.71	Value Kept	51	
45.29		13.41	Equation 1	1.80	Value Kept	63	
49.98	50.40	6.54	Equation 2	1.74	Value Kept	55	55
53.47		0.00	Equation 2	1.69	Value Kept	49	
47.75		10.71	Equation 2	1.77	Value Kept	59	
69.51	70.30	3.56	Equation 2	1.47	Value Kept	30	30
72.07		0.00	Equation 2	1.44	Value Kept	27	
69.31		3.83	Equation 2	1.48	Value Kept	30	

Table 6.4: Comparison of the filter paper water contents from the ASTM calibration equations to the average measured water content for the 0.4 kPa calibration curve

Matric Suction (kPa)	ASTM Filter Paper Water Content (%)	University of Ottawa 0.4 kPa Filter Paper Water Content (%)	Percent Difference (%)
300	36.58	33.90	7.33
200	38.84	34.83	10.31
150	40.45	37.06	8.38
100	42.71	37.16	12.98
80	43.95	44.57	1.41
70	44.69	#N/A	#N/A
60	46.95	48.56	3.42
50	52.82	50.40	4.58
20	82.29	70.30	14.57

Table 6.5: Filter Paper Water Contents for the University of Ottawa Calibration Curve with 1 kPa Applied Stress Including Suction Results following the ASTM D5298-03 Standard.

			ASTM				
Filter Paper Water Content (%)	Average Filter Paper wc (%)	Change in Filter Paper wc (%)	Calibration Equation	log (Matric Suction) (kPa)	Discard / Kept	Matric Suction (kPa)	Median Matric Suction (kPa)
37.79	36.64	0.00	Equation 1	2.38	Value Kept	242	262
34.79		7.95	Equation 1	2.62	Value Kept	414	
37.34		1.19	Equation 1	2.42	Value Kept	262	
41.10	37.70	0.00	Equation 1	2.13	Value Discarded	#N/A	253
34.46		16.15	Equation 1	2.64	Value Discarded	#N/A	
37.54		8.67	Equation 1	2.40	Value Kept	253	
41.43	38.39	0.00	Equation 1	2.10	Value Kept	126	273
36.65		11.55	Equation 1	2.47	Value Kept	297	
37.10		10.46	Equation 1	2.44	Value Kept	273	
44.52	41.43	0.00	Equation 1	1.86	Value Kept	72	144
39.11		12.15	Equation 1	2.28	Value Kept	191	
40.68		8.63	Equation 1	2.16	Value Kept	144	
47.37	45.05	0.00	Equation 2	1.77	Value Kept	59	78
44.08		6.94	Equation 1	1.89	Value Kept	78	
43.72		7.70	Equation 1	1.92	Value Kept	83	
50.26	46.68	0.00	Equation 2	1.73	Value Kept	54	63
44.31		11.84	Equation 1	1.88	Value Kept	75	
45.46		9.55	Equation 2	1.80	Value Kept	63	
55.53	51.30	0.00	Equation 2	1.66	Value Kept	46	54
48.07		13.43	Equation 2	1.76	Value Kept	58	
50.29		9.44	Equation 2	1.73	Value Kept	54	
55.24	53.25	0.00	Equation 2	1.67	Value Kept	46	49
51.14		7.43	Equation 2	1.72	Value Kept	53	
53.38		3.37	Equation 2	1.69	Value Kept	49	
68.06	69.86	3.83	Equation 2	1.49	Value Kept	31	29
70.74		0.05	Equation 2	1.46	Value Kept	29	
70.77		0.00	Equation 2	1.46	Value Kept	29	

Table 6.6: Comparison of the filter paper water contents from the ASTM calibration equations to the average measured water content for the 1 kPa calibration curve

Matric Suction (kPa)	ASTM Filter Paper Water Content (%)	University of Ottawa 1 kPa Filter Paper Water Content (%)	Percent Difference (%)
300	36.58	36.64	0.17
200	38.84	37.70	2.93
150	40.45	38.39	5.08
100	42.71	41.43	2.99
80	43.95	45.05	2.51
70	44.69	46.68	4.45
60	46.95	51.30	9.26
50	52.82	53.25	0.82
20	82.29	69.86	15.11

Table 6.7: Filter Paper Water Contents for the University of Ottawa Calibration Curve with 2 kPa Applied Stress Including Suction Results following the ASTM D5298-03 Standard.

			ASTM				
Filter Paper Water Content (%)	Average Filter Paper wc (%)	Change in Filter Paper wc (%)	Calibration Equation	log (Matric Suction) (kPa)	Discard / Kept	Matric Suction (kPa)	Median Matric Suction (kPa)
39.79	40.95	5.95	Equation 1	2.23	Value Kept	169	142
42.31		0.00	Equation 1	2.03	Value Kept	107	
40.75		3.69	Equation 1	2.15	Value Kept	142	
44.10	44.71	6.69	Equation 1	1.89	Value Kept	78	78
47.26		0.00	Equation 2	1.77	Value Kept	59	
42.76		9.52	Equation 1	2.00	Value Kept	99	
43.68	41.74	0.00	Equation 1	1.92	Value Kept	84	87
43.48		0.46	Equation 1	1.94	Value Kept	87	
38.06		12.86	Equation 1	2.36	Value Kept	230	
49.19	47.98	0.00	Equation 2	1.75	Value Kept	56	57
48.35		1.72	Equation 2	1.76	Value Kept	57	
46.40		5.67	Equation 2	1.79	Value Kept	61	
50.12	48.58	0.15	Equation 2	1.74	Value Kept	54	54
50.19		0.00	Equation 2	1.73	Value Kept	54	
45.45		9.45	Equation 2	1.80	Value Kept	63	
52.95	51.91	0.00	Equation 2	1.70	Value Kept	50	50
52.55		0.76	Equation 2	1.70	Value Kept	50	
50.24		5.12	Equation 2	1.73	Value Kept	54	
61.23	57.91	0.00	Equation 2	1.59	Value Kept	38	44
57.18		6.61	Equation 2	1.64	Value Kept	44	
55.32		9.65	Equation 2	1.67	Value Kept	46	
56.18	57.59	7.49	Equation 2	1.65	Value Kept	45	45
60.73		0.00	Equation 2	1.59	Value Kept	39	
55.85		8.03	Equation 2	1.66	Value Kept	46	
78.27	74.73	0.00	Equation 2	1.36	Value Kept	23	25
70.70		9.68	Equation 2	1.46	Value Kept	29	
75.22		3.91	Equation 2	1.40	Value Kept	25	

Table 6.8: Comparison of the filter paper water contents from the ASTM calibration equations to the average measured water content for the 2 kPa calibration curve

Matric Suction (kPa)	ASTM Filter Paper Water Content (%)	University of Ottawa 2 kPa Filter Paper Water Content (%)	Percent Difference (%)
300	36.58	40.95	11.95
200	38.84	44.71	15.10
150	40.45	41.74	3.19
100	42.71	47.98	12.34
80	43.95	48.58	10.54
70	44.69	51.91	16.17
60	46.95	57.91	23.35
50	52.82	57.59	9.02
20	82.29	74.73	9.19

Table 6.9: Comparison of the filter paper water contents from the ASTM calibration equations to the average measured water content for the 4 kPa calibration curve

Matric Suction (kPa)	ASTM Filter Paper Water Content (%)	University of Ottawa 4 kPa Filter Paper Water Content (%)	Percent Difference (%)
300	36.58	58.46	59.81
200	38.84	45.66	17.55
150	40.45	47.50	17.42
100	42.71	49.40	15.66
80	43.95	51.57	17.34
70	44.69	58.98	31.99
60	46.95	63.73	35.73
50	52.82	63.11	19.49
20	82.29	84.93	3.20

Table 6.10: Filter Paper Water Contents for the University of Ottawa Calibration Curve with 4 kPa Applied Stress Including Suction Results following the ASTM D5298-03 Standard.

			ASTM				
Filter Paper Water Content (%)	Average Filter Paper wc (%)	Change in Filter Paper wc (%)	Calibration Equation	log (Matric Suction) (kPa)	Discard / Kept	Matric Suction (kPa)	Median Matric Suction (kPa)
53.23	58.46	17.30	Equation 2	1.69	Value Kept	49	43
64.36		0.00	Equation 2	1.54	Value Kept	35	
57.79		10.21	Equation 2	1.63	Value Kept	43	
45.33	45.66	8.91	Equation 2	1.80	Value Kept	63	63
41.87		15.86	Equation 1	2.07	Value Kept	116	
49.77		0.00	Equation 2	1.74	Value Kept	55	
48.95	47.50	4.58	Equation 2	1.75	Value Kept	56	56
42.22		17.70	Equation 1	2.04	Value Kept	109	
51.31		0.00	Equation 2	1.72	Value Kept	52	
49.74	49.40	6.69	Equation 2	1.74	Value Kept	55	55
45.14		15.32	Equation 1	1.81	Value Kept	65	
53.31		0.00	Equation 2	1.69	Value Kept	49	
55.04	51.57	0.00	Equation 2	1.67	Value Kept	47	55
49.77		9.57	Equation 2	1.74	Value Kept	55	
49.91		9.33	Equation 2	1.74	Value Kept	55	
58.43	58.98	4.30	Equation 2	1.62	Value Kept	42	42
57.47		5.87	Equation 2	1.64	Value Kept	43	
61.05		0.00	Equation 2	1.59	Value Kept	39	
62.80	63.73	7.85	Equation 2	1.56	Value Kept	37	37
60.24		11.61	Equation 2	1.60	Value Kept	40	
68.14		0.00	Equation 2	1.49	Value Kept	31	
61.08	63.11	8.94	Equation 2	1.59	Value Kept	39	39
61.19		8.77	Equation 2	1.59	Value Kept	39	
67.07		0.00	Equation 2	1.51	Value Kept	32	
83.88	84.93	3.93	Equation 2	1.28	Value Kept	19	19
83.58		4.28	Equation 2	1.28	Value Kept	19	
87.31		0.00	Equation 2	1.23	Value Kept	17	

Table 6.11: Summary of the matric suction value measured using the contact filter paper method

Low Compaction Energy		High Compaction Energy	
Soil Water Content %	Matric Suction kPa	Soil Water Content %	Matric Suction kPa
14.3	275	14.3	256
15.2	237	15.3	231
16.4	162	16.5	105
17.3	86	17.3	82
18.3	39	18.1	48
19.2	41	19.2	33

Table 6.12: Matric Suction Measurements Using ASTM D5298-03 Calibration Equations Compared to Vanapalli et al. 1999.

							ASTM Suction						
Compaction Energy	Soil Water Content (%)	Soil Water Content (%)	Filter Paper wc (%)	Average Filter Paper wc (%)	Change in Filter Paper wc (%)	Mold on Filter Paper Y / N	Calibration Equation	Log (Matric Suction) (kPa)	Discard / Kept	Matric Suction (kPa)	Change in Matric Suction (%)	Median Matric Suction (kPa)	Vanapalli 1999 Matric Suction (kPa)
Low Energy	14.3		37.1		0.8	No	Equation 1	2.44	Value Kept	275	-6		
	14.3	14.3	37.4	37.0	0.0	No	Equation 1	2.41	Value Kept	260	0	275	269
	14.3		36.7		1.9	No	Equation 1	2.47	Value Kept	295	-13		
	15.2		37.4		3.7	No	Equation 1	2.42	Value Kept	261	0		
	15.2	15.2	38.8	38.0	0.0	No	Equation 1	2.31	Value Kept	202	23	237	222
	15.2		37.9		2.3	No	Equation 1	2.37	Value Kept	237	9		
	16.4		39.7		1.9	No	Equation 1	2.24	Value Kept	172	0		
	16.4	16.4	40.4	40.2	0.3	No	Equation 1	2.18	Value Kept	152	11	162	161
	16.4		40.5		0.0	Yes	Equation 1	2.17	Value Discarded	#n/a	#N/A		
	17.3		43.5		8.0	No	Equation 1	1.93	Value Kept	86	15		
	17.3	17.3	47.3	44.5	0.0	No	Equation 2	1.77	Value Kept	59	16	86	112
	17.3		42.7		9.9	No	Equation 1	2.00	Value Kept	101	0		
	18.3		61.4		0.0	No	Equation 2	1.58	Value Kept	38	0		
	18.3	18.3	59.8	60.6	2.7	No	Equation 2	1.61	Value Kept	40	-5	39	62
	18.3		60.6		1.3	No	Equation 2	1.59	Value Kept	39	-3		
	19.2		55.2		14.8	No	Equation 2	1.67	Value Kept	46	-35		
	19.2	19.2	59.0	59.6	8.9	No	Equation 2	1.62	Value Kept	41	-20	41	15
	19.2		64.7		0.0	No	Equation 2	1.54	Value Kept	35	0		
High Energy	14.3		37.6		0.0	No	Equation 1	2.39	Value Kept	248	0		
	14.3	14.3	36.8	37.3	2.2	No	Equation 1	2.46	Value Kept	287	-16	256	266
	14.3		37.5		0.5	No	Equation 1	2.41	Value Kept	256	-3		
	15.3		38.2		0.0	No	Equation 1	2.35	Value Kept	226	3		
	15.3	15.3	38.0	38.1	0.3	No	Equation 1	2.36	Value Kept	231	1	231	215
	15.3		38.0		0.4	No	Equation 1	2.37	Value Kept	232	0		
	16.5		44.7		0.0	Yes	Equation 1	1.84	Value Discarded	#n/a	#N/A		
	16.5	16.5	43.7	43.6	2.3	Yes	Equation 1	1.92	Value Discarded	#n/a	#N/A	105	157
	16.5		42.5		5.0	No	Equation 1	2.02	Value Kept	105	0		
	17.3		42.3		4.8	No	Equation 1	2.03	Value Kept	107	0		
	17.3	17.3	44.5	43.5	0.0	No	Equation 1	1.86	Value Kept	73	32	82	113
	17.3		43.8		1.5	No	Equation 1	1.91	Value Kept	82	23		
	18.1		53.8		1.6	No	Equation 2	1.69	Value Kept	48	-3		
	18.1	18.1	53.2	53.9	2.7	No	Equation 2	1.69	Value Kept	49	-5	48	71
	18.1		54.7		0.0	No	Equation 2	1.67	Value Kept	47	0		
	19.2		61.7		9.4	No	Equation 2	1.58	Value Kept	38	-3		
	19.2	19.2	66.6	65.5	2.2	No	Equation 2	1.51	Value Kept	33	-5	33	19
	19.2		68.1		0.0	No	Equation 2	1.49	Value Kept	31	0		

Table 6.13: Matric suction results obtained using the axis-translation technique for Indian Head till

Soil Water Content (%)	High Energy Matric Suction (kPa)	Low Energy Matric Suction (kPa)	Vanapalli et al. 1999 Matric Suction (kPa)
19.3	35	35	10
18.0	55	60	79
17.5	80	95	105
16.1	120	130	175
15.0	205	210	230

Table 6.14: Summary of the percent difference for each of the calibration curves.

Matric Suction (kPa)	ASTM Filter Paper Water Content (%)	0 kPa Curve Difference (%)	0.4 kPa Curve Difference (%)	1 kPa Curve Difference (%)	2 kPa Curve Difference (%)	4 kPa Curve Difference (%)
300	36.58	2.89	7.33	0.17	11.95	59.81
200	38.84	3.95	10.31	2.93	15.10	17.55
150	40.45	6.27	8.38	5.08	3.19	17.42
100	42.71	5.92	12.98	2.99	12.34	15.66
80	43.95	2.12	1.41	2.51	10.54	17.34
70	44.69	2.26	#N/A	4.45	16.17	31.99
60	46.95	0.18	3.42	9.26	23.35	35.73
50	52.82	6.67	4.58	0.82	9.02	19.49
20	82.29	12.11	14.57	15.11	9.19	3.20
	Average Error (%)	**4.71**	**7.87**	**4.81**	**12.32**	**24.24**

Figures

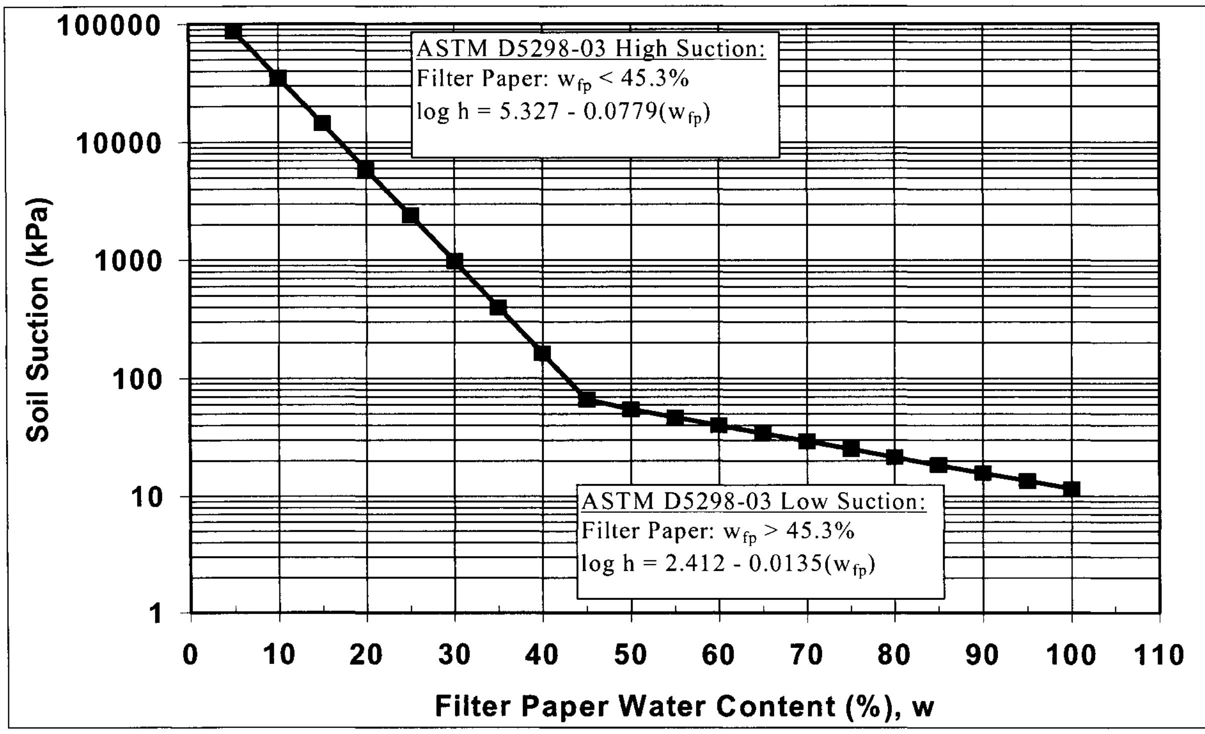


Figure 6.1: Calibration equations for Whatman 42 filter paper from ASTM D5298-03.

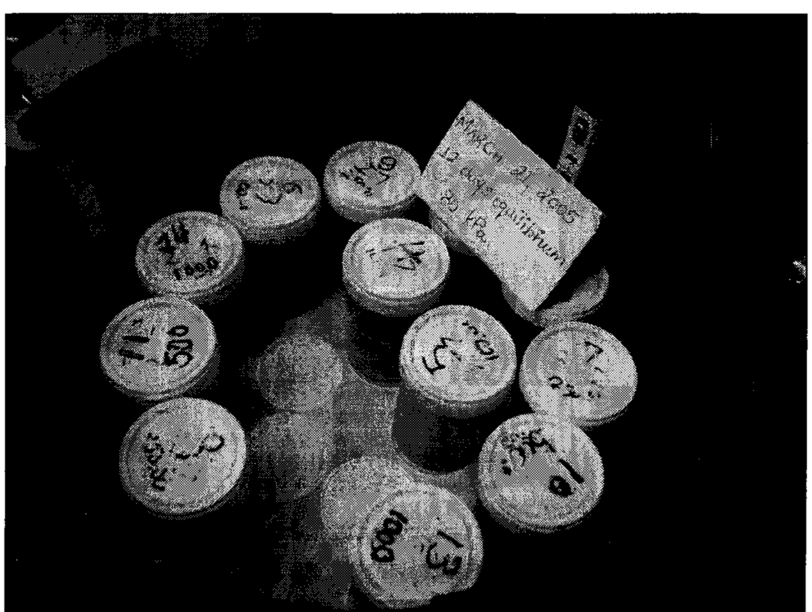


Figure 6.2: Placement of filter papers in null pressure plate during calibration with surcharge load on filter papers.

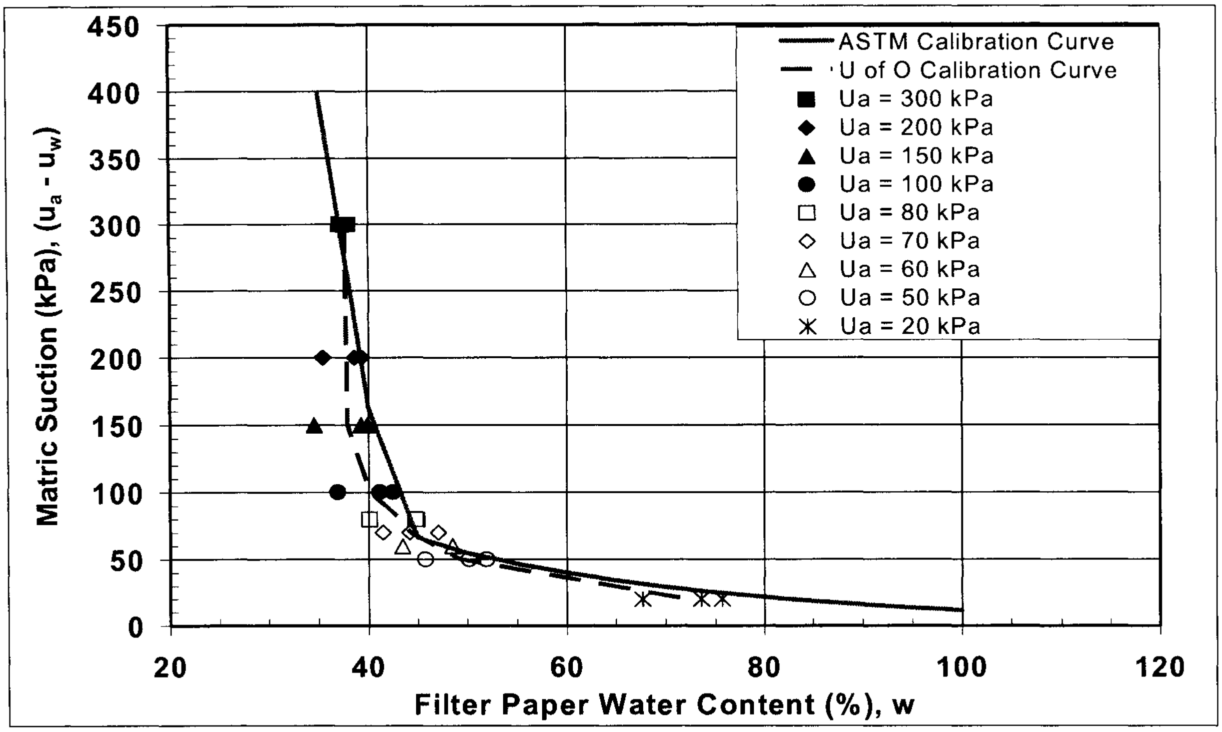


Figure 6.3: Comparison of ASTM D 5298 – 03 to University of Ottawa's 0 kPa stress calibration curve.

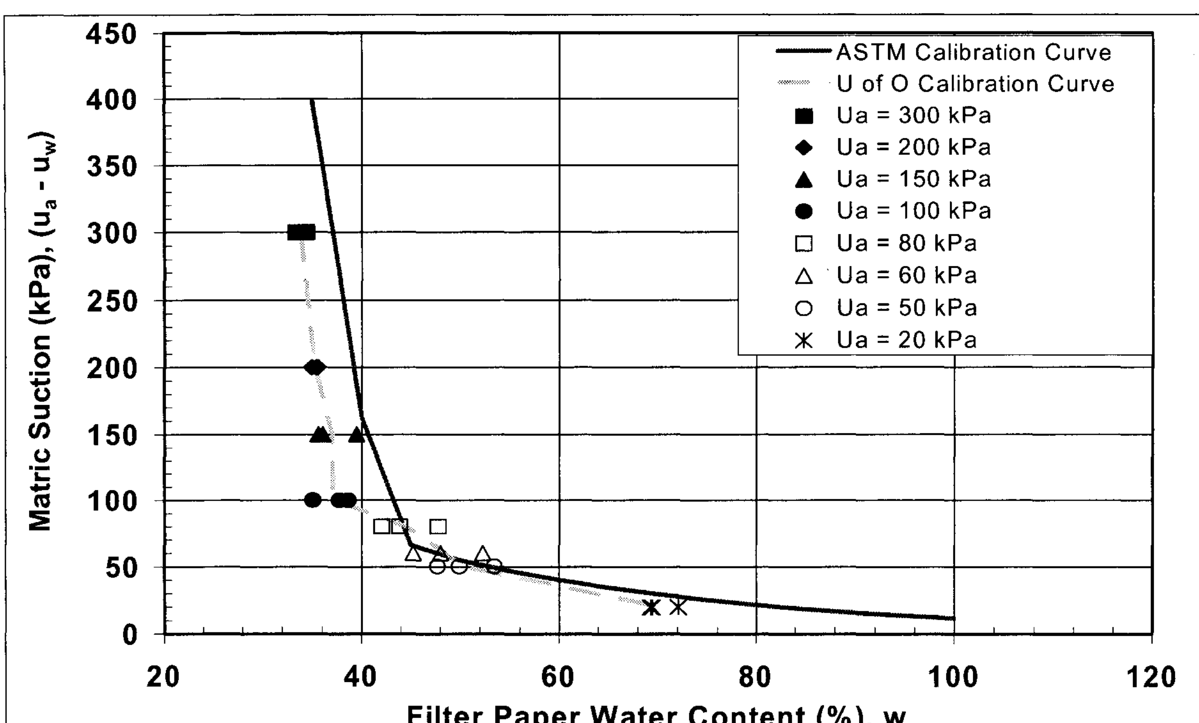


Figure 6.4: Comparison of ASTM D 5298 – 03 to University of Ottawa's 0.4 kPa stress calibration curve.

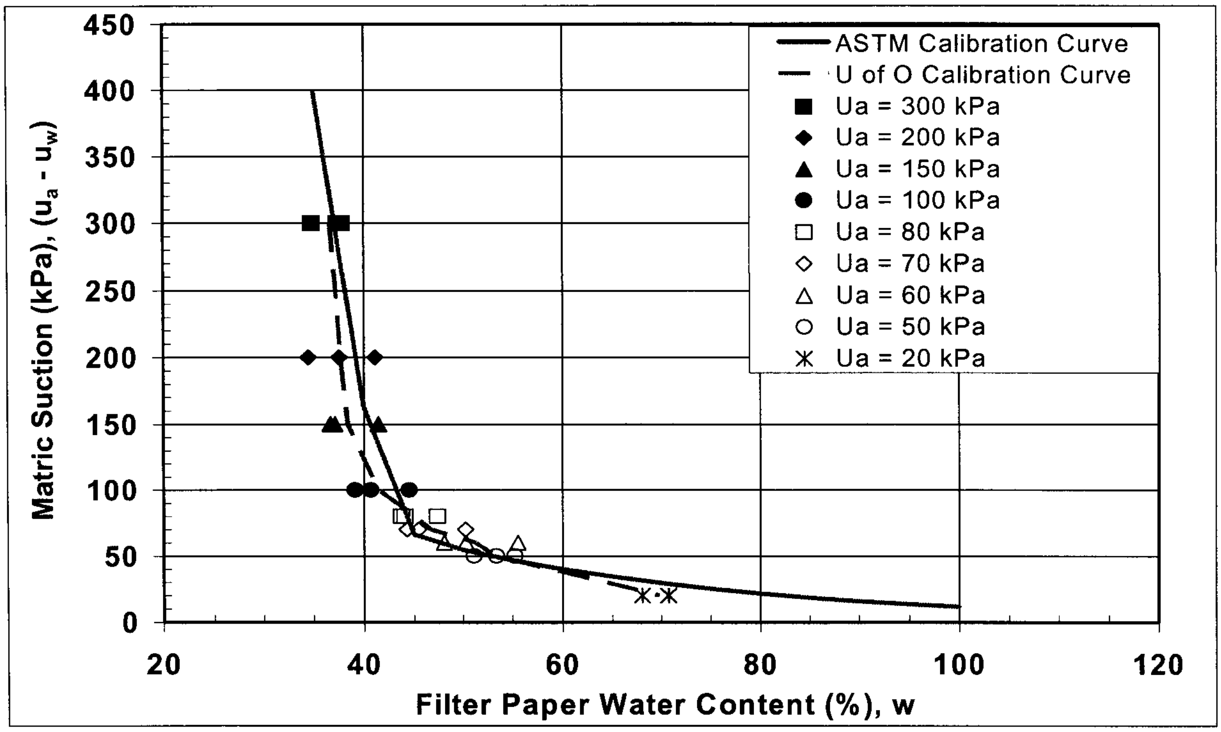


Figure 6.5: Comparison of ASTM D 5298 – 03 to University of Ottawa's 1 kPa stress calibration curve.

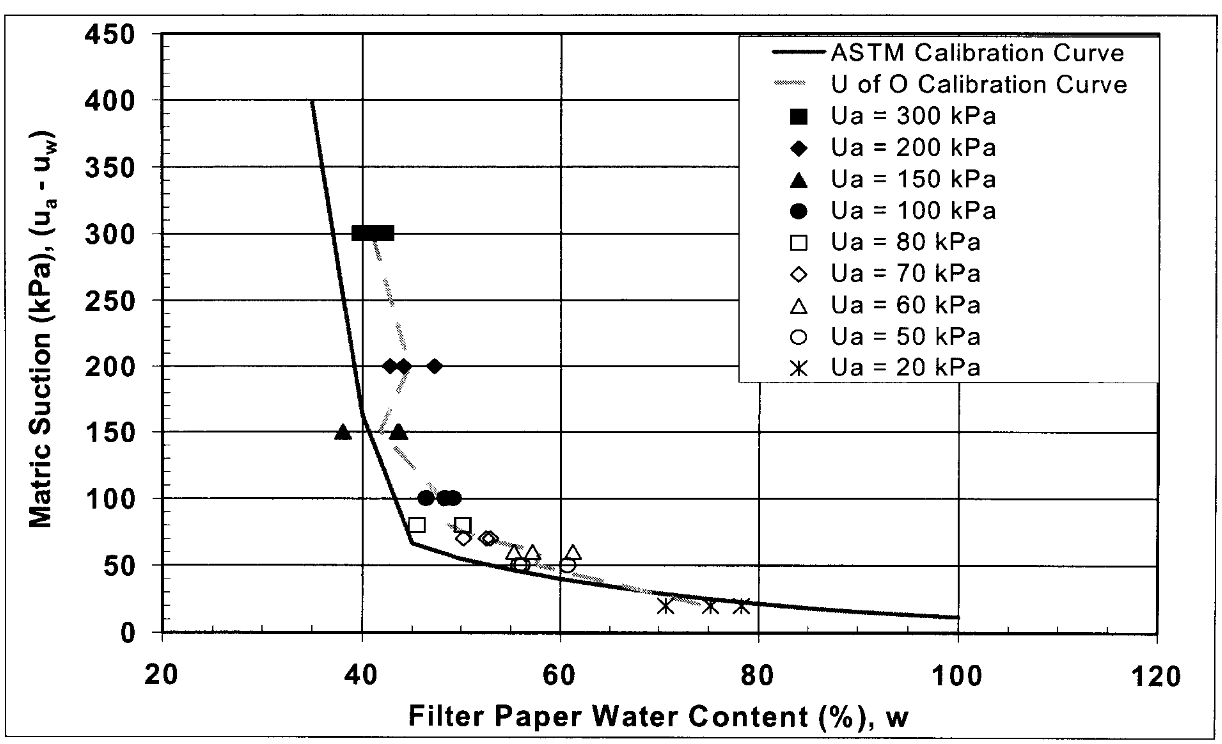


Figure 6.6: Comparison of ASTM D 5298 – 03 to University of Ottawa's 2 kPa stress calibration curve.

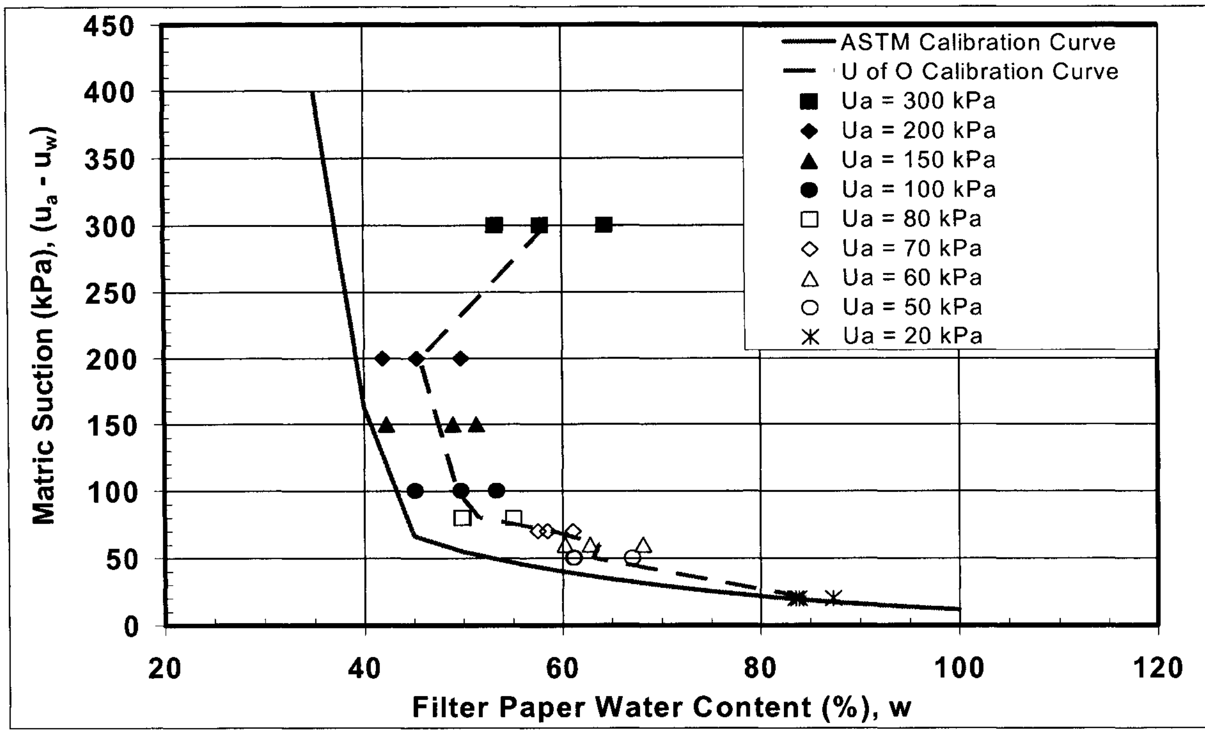


Figure 6.7: Comparison of ASTM D 5298 – 03 to University of Ottawa's 4 kPa stress calibration curve.

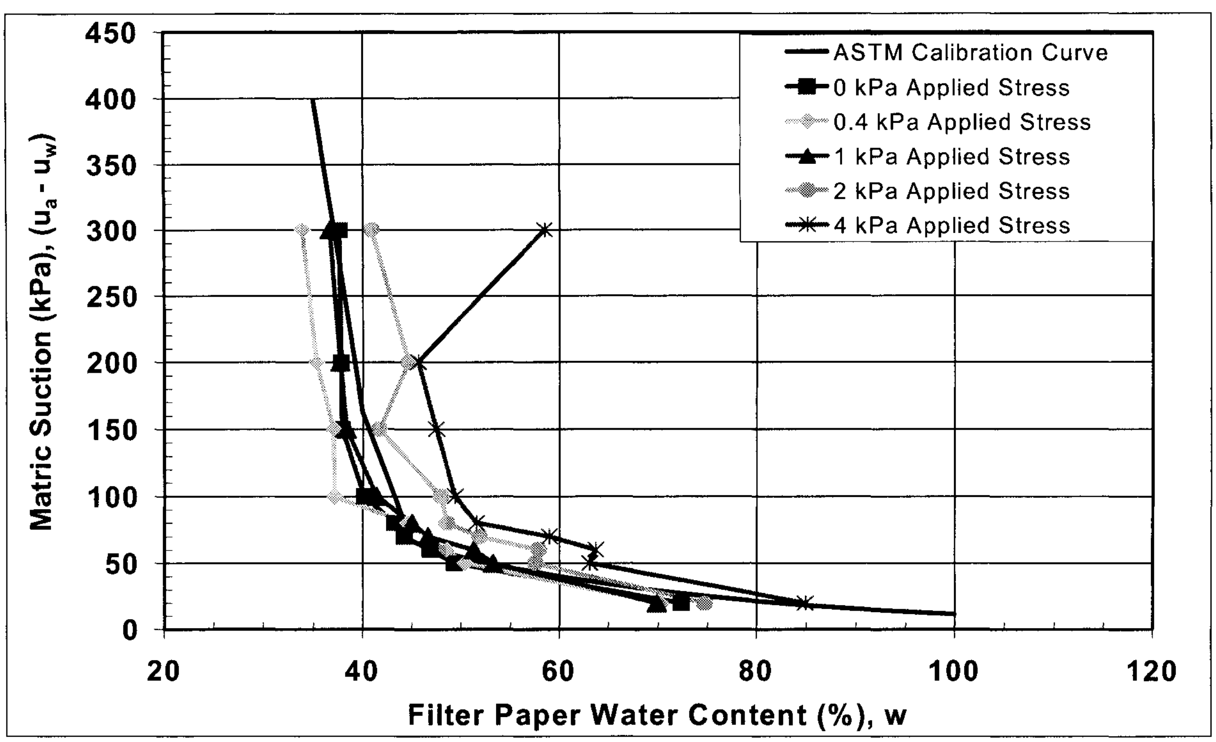


Figure 6.8: Effect of compression on the calibration curves of Whatman 42 filter papers. Each point represents the median of three filter paper measurements.

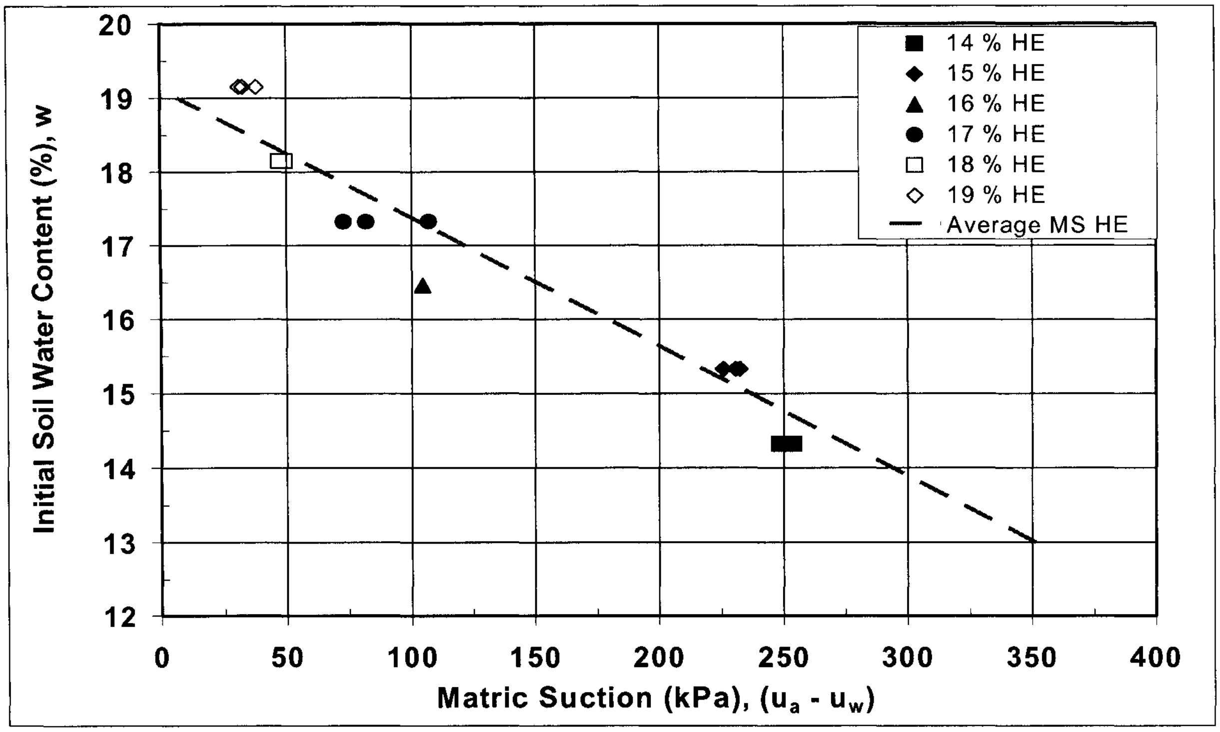


Figure 6.9: High compaction energy matric suction values measured using filter paper.

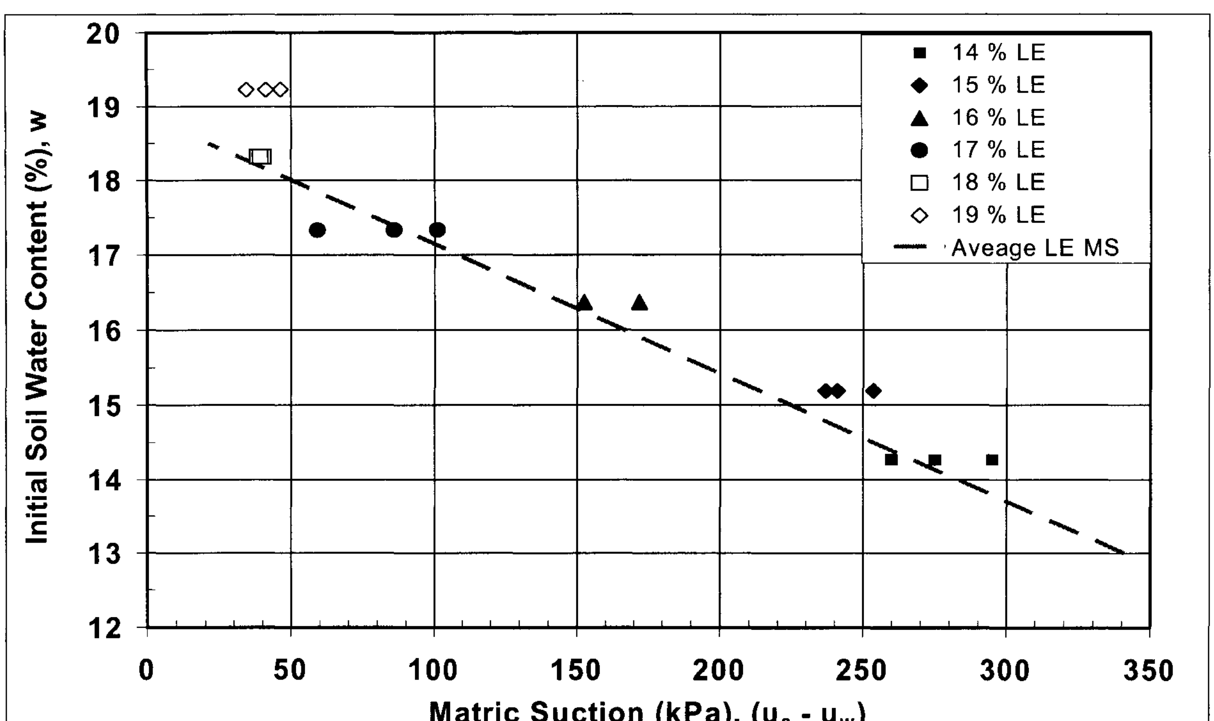


Figure 6.10: Low compaction energy matric suction values measured using filter paper.

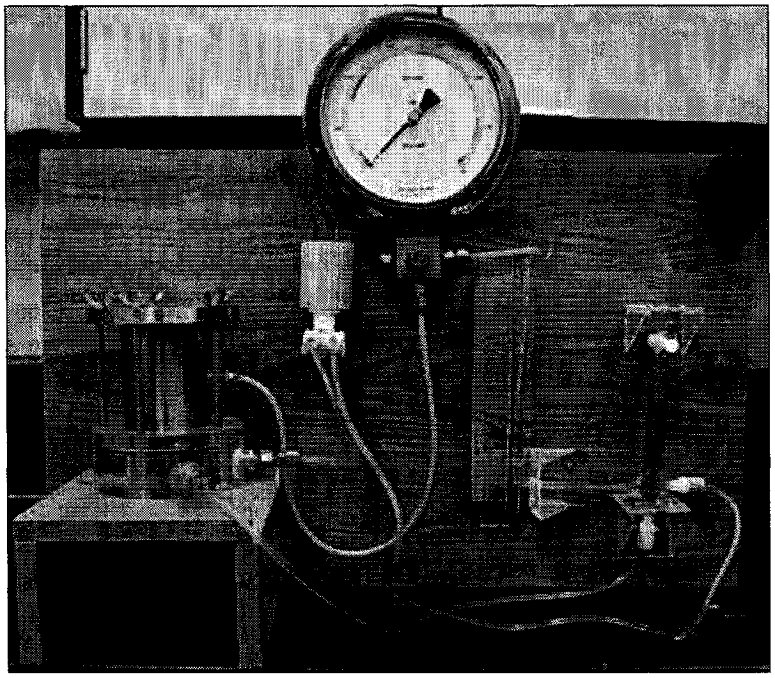


Figure 6.11: Single specimen null pressure plate device used to measure matric suction using the axis-translation technique.

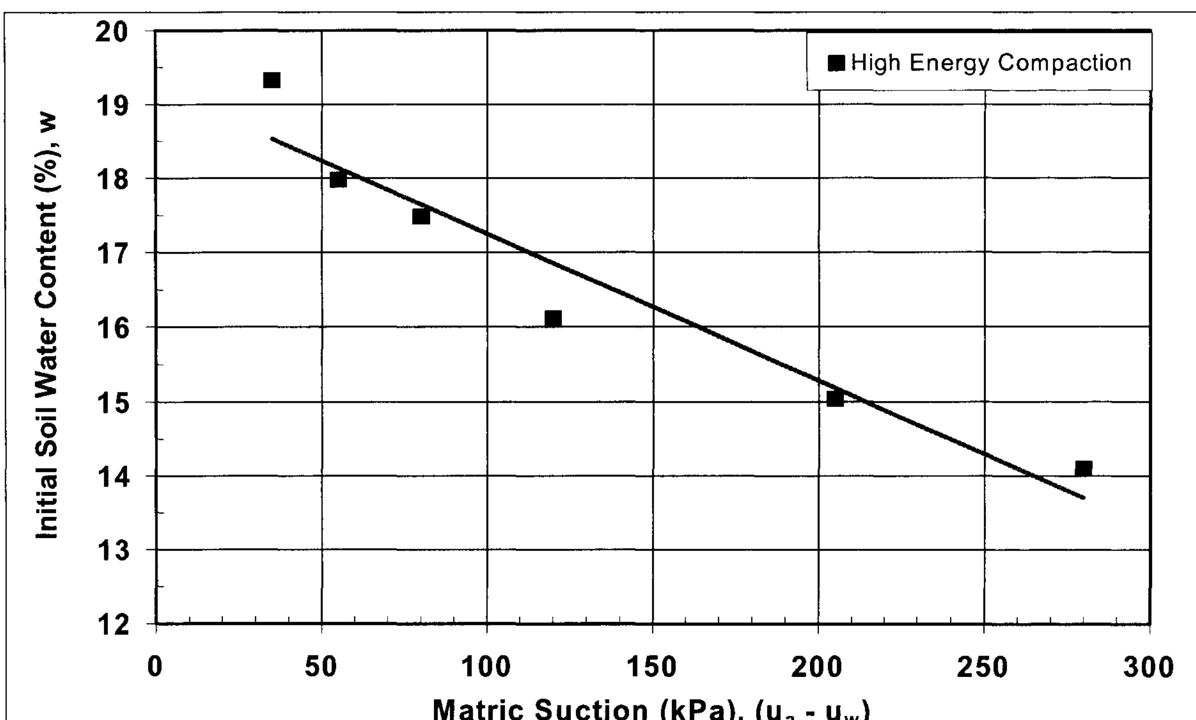


Figure 6.12: Axis-translation matric suction values for high compaction energy.

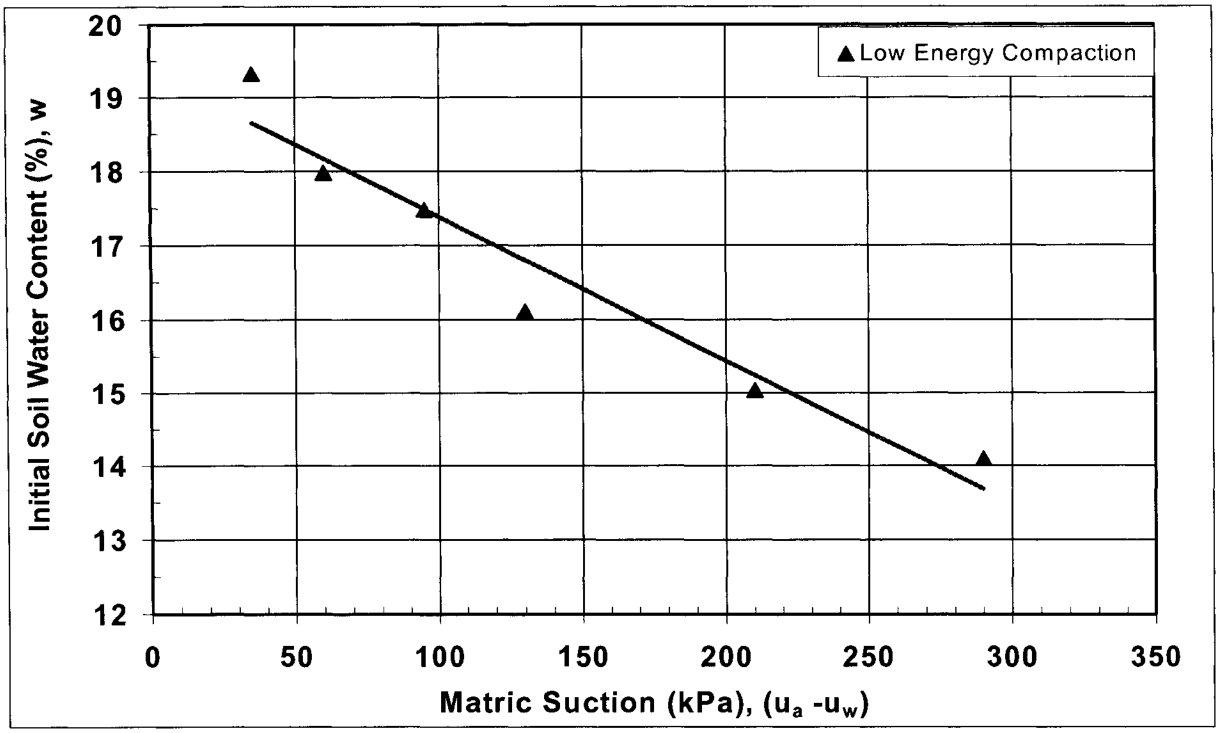


Figure 6.13: Axis-translation matric suction values for low compaction energy.

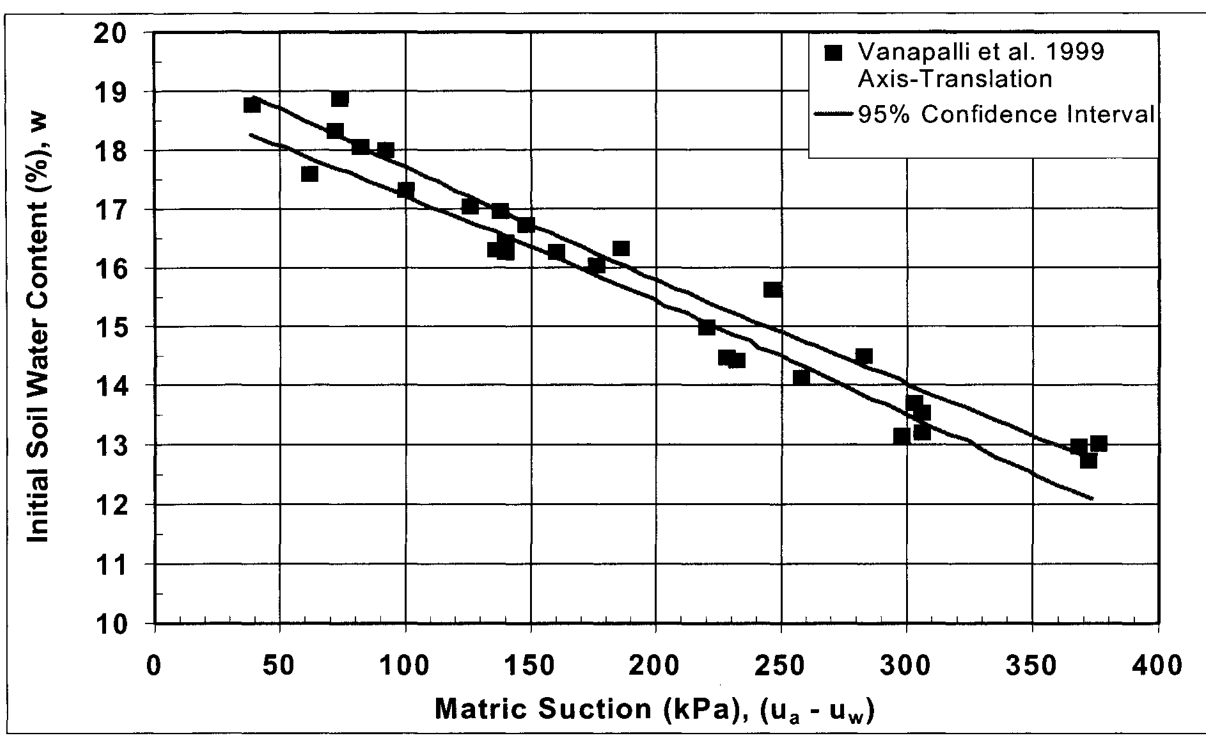


Figure 6.14: Axis-translation matric suction values from Vanapalli et al. with a 95% confidence interval.

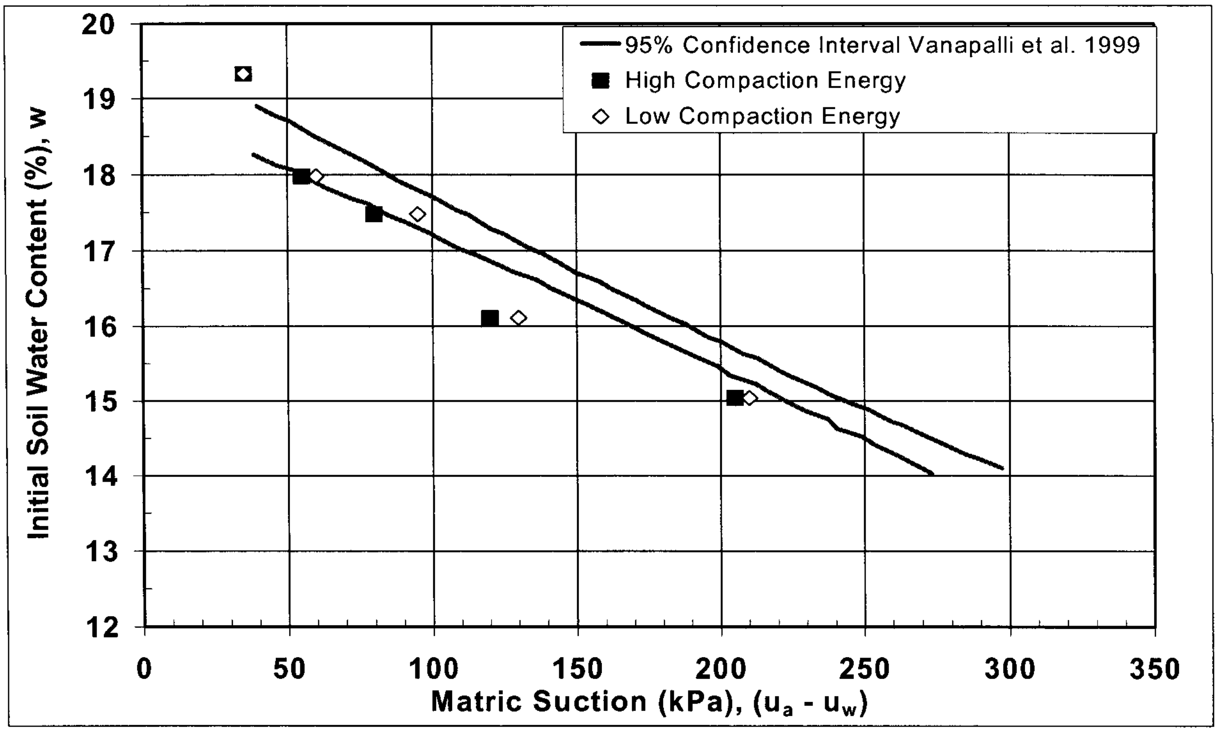


Figure 6.15: Axis-translation matric suction values for high and low compaction energies compared to the 95% confidence interval of Vanapalli et al. 1999.

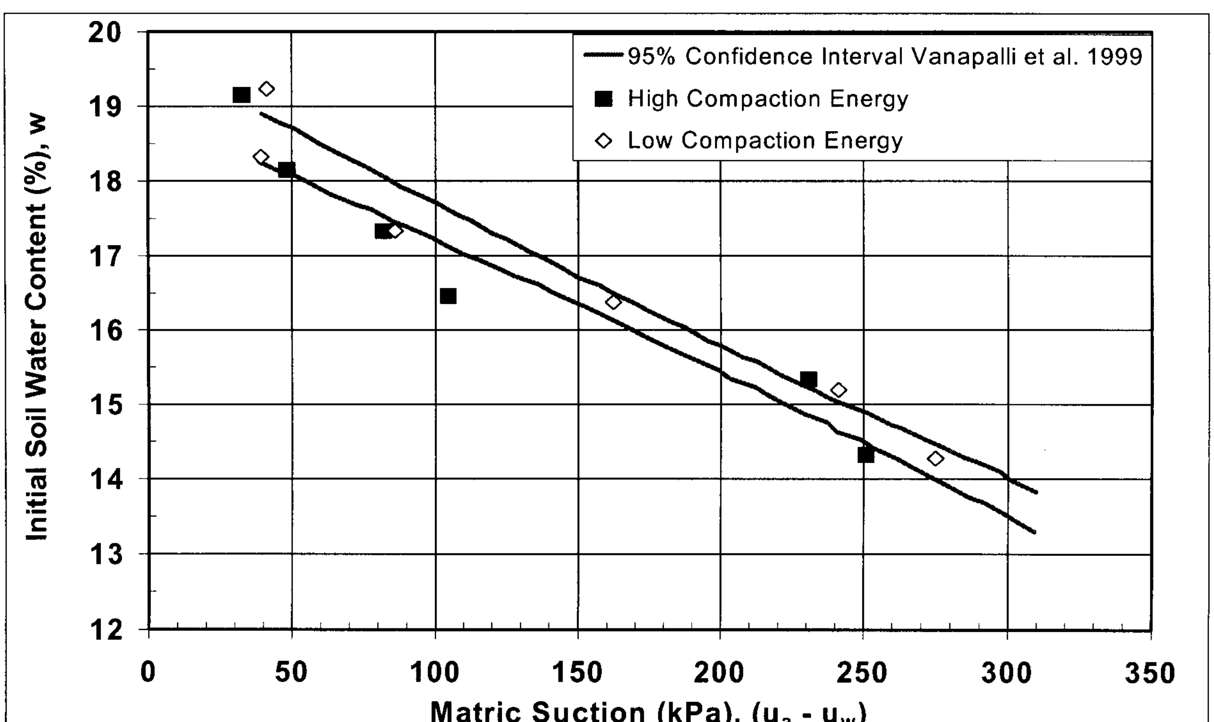


Figure 6.16: Filter paper median matric suction values for high and low compaction energies compared to the 95% confidence interval of Vanapalli et al. 1999.

Chapter 7: Analysis of Compressibility Test Results

7.1 Introduction

The principles of saturated soil mechanics are conventionally used in the settlement analysis of compacted soils that are typically in a state of unsaturated condition. This approach leads to erroneous estimates in the settlement analysis as the influence of matric suction is conventionally not considered. One of the key objectives of this research program was to extend the conventional oedometer testing technique towards understanding the influence of various parameters that influence the settlement of compacted soils. Experimental investigations were undertaken to study the compressibility characteristics of Indian Head till specimens both under saturated and unsaturated conditions. In particular, the influence of matric suction on the deformation behaviour of an unsaturated, compacted glacial till was studied.

It is well known that fine-grained soils exhibits a flocculated (i.e. open structure) if the initial water content used for compaction is on the dry side of the optimum conditions. Also, the soil structure exhibits a dispersed (i.e. orientated) structure if the initial water content used for compaction is on the wet side of the optimum conditions (Lambe 1958, Barden & Sides 1965 and 1971, Benson & Daniel 1990, Elsbury et al. 1990). The soil structure, which is typically defined as the arrangement of soil particles within a soil matrix is influenced both by the initial compaction water content and the energy used for compaction. Studies by Vanapalli et al. (1999) on Indian Head till demonstrate that there is a strong relationship between the soil structure and the matric suction of fine-grained soils. For this reason, in this research, the compressibility characteristics of the compacted test specimens were determined under an applied stress range of 15 – 800 kPa, with varying water contents (i.e. 14 – 19%), using two compaction energies, namely; 70 and 140 kJ/m^3 to understand the effect of soil structure along with the initial matric suction on the same soil.

This chapter provides a comparison between the compressibility characteristics of both saturated and unsaturated soil test specimens, to quantify the influence of both matric suction and the soil structure on several conventional soil parameters.

7.2 Testing Program

The following section outlines the two separated oedometer testing programs used for this research. The first series of tests was performed to determine the conventional saturated compressibility characteristics. The second series was conducted to determine the compressibility characteristics of unsaturated till using modified conventional oedometer test equipment.

7.2.1 Oedometer Tests on Saturated Soil Specimens

The ASTM Standard D4546-03 Method C (i.e. constant volume conditions) entitled, "Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils" was used for assessing the swelling pressure for the inundated specimens. By following this technique, a fully saturated specimen is obtained by a gradual increase in the degree of saturation through inundation. This process will eliminate the initial matric suction component of unsaturated test specimens. Upon complete inundation of the test specimen, the conventional oedometer testing procedures were followed to determine the deformation characteristics of the saturated soil specimens through one dimensional oedometer tests.

7.2.2 Oedometer Tests on Unsaturated Soil Specimens

In order to compare the saturated and unsaturated compressibility test results, it was crucial to maintain the initial compaction water content of the specimens tested under unsaturated conditions in the oedometer tests. As described in Chapter 3: Equipment Details, specially designed acrylic chambers were used to house the unsaturated soil specimens during testing. To maintain the initial compaction water content of the unsaturated test specimens, a 100% humid air stream was pumped into the acrylic chamber during testing. The unsaturated soil test specimens were placed inside the acrylic chambers once the humidity level inside the chambers reached 100%. The soil specimens were then loaded and unloaded following conventional oedometer test procedures.

7.3 Compressibility Characteristics of Saturated Soil Specimens

The change in volume of a saturated test specimen during loading depends on the applied stress range, initial water content and density (i.e. initial void ratio, *e*). The coefficient of volume compressibility m_v which is the change in volume of test specimen due to an increase in applied stress is calculated following Eqn. 1.

$$m_v = \left(\frac{1}{1+e_o}\right)\left(\frac{e_o - e_1}{\sigma'_1 - \sigma'_o}\right) \qquad \text{Eqn.1}$$

The rate of consolidation due to an increase in applied stress is calculated by determining the coefficient of consolidation, C_v using Eqn. 2. This equation shows that the higher the coefficient of permeability, k of the soil, the higher the rate of settlement.

$$C_v = \frac{k}{m_v \gamma_w} \qquad \text{Eqn. 2}$$

The coefficient of saturated permeability of a soil specimen compacted dry of optimum conditions is typically two to three orders greater than the coefficient of permeability of specimens initially compacted with a water content that is wet of optimum conditions (Lambe and Whitman 1971, Haug et al. 1992 and Benson & Daniel 1990). Elsbury et al. (1990) investigation's on the failure of compacted clay liners demonstrate that large soil clods are formed when a fine-grained soil is compacted with water content on the dry side of optimum. In other words, initial compaction under dry of optimum conditions will impart an open structure to the fine-grained soil and hence will have a higher coefficient of permeability under saturated conditions.

Along with all the above parameters, matric suction has a significant influence on the compressibility characteristics of compacted soils that are in a state of unsaturated condition. The study presented in this chapter throws some light on how various variables influence the compressibility characteristics under two different conditions; namely inundated and non-inundated conditions.

7.3.1 Relationships between the *e* vs. applied stress, σ'_v

The conventional void ratio, e vs. applied stress, σ'_v analysis was preformed on both saturated and unsaturated test specimens prepared using both low and high compaction energies. The author is aware that σ'_v is not a term that is characteristic or representative of an unsaturated soil specimen for the present tests. However, this term is used for consistency in comparative studies between inundated and non-inundated test results. This term is chosen because most of the unsaturated soil specimens were either attaining fully saturated conditions or close to saturated conditions under the applied stresses.

A series of *e vs.* σ'_v relationships were determined for each of the six initial compacted water contents used in this research. For brevity only the *e vs.* σ'_v relationships for w = 14% and 17% are located in this chapter. The remaining *e vs.* σ'_v relationships are located in Appendix A and show similar trends to the ones discussed in this chapter. Each of these plots shows the *e vs.* σ'_v relationships for both the saturated and unsaturated test specimens taking account of the influence of several parameters such as initial compaction water content, matric suction, and compaction energy, to compare and understand the compressibility characteristics. The specimens for both saturated (i.e. solid line) and unsaturated tests (i.e. dashed line) were prepared such that they had identical initial conditions (i.e. void ratio, degree of saturation, matric suction and soil structure).

7.3.2 Compressibility for specimens initial compacted with low initial water contents

Figure 7.1 and Figure 7.2 show the *e vs.* σ'_v relationship for specimens prepared with an initial water content of 14% for both the high and low compaction energies respectively. The test specimens that are in a state of unsaturated condition initially offer a higher resistance to the applied stress as denoted by the relatively small decrease in void ratio compared to the specimens that are in a state of saturated condition. This resistance can be attributed to the matric suction in the test specimens. Alternatively, this behavior can be explained in terms of degree of saturation which is shown in Figure 7.3 as the relationship between the degree of saturation, S and void ratio, e for the same test specimens. Table 7.1 summarizes the variations in several volume-mass relationships along with other properties derived from the test results undertaken in this study. The initial degree of saturation, S for unsaturated soil specimen prepared using low compaction energy and initial water content, w of 14%, is 53%.

The degree of saturation in the specimen gradually increases due to a reduction in void ratio upon an increase in the applied stress. An increase in the degree of saturation, S is associated with a decrease in the matric suction, which causes an increase in compression of the test specimen. The test specimens with an initially low degree of saturation will have a higher matric suction value than those with a high degree of saturation (see Table 7.1). The matric suction of an unsaturated test specimen offers resistance to deformation in spite of an increase in the applied stress.

The initial void ratio for the specimens prepared using low and high compaction energies was 0.732 and 0.545 respectively (see Figure 7.1 and Figure 7.2). The reduction in void ratio, e for unsaturated test specimens for both low (i.e. 0.7) and high (i.e. 0.525) compaction energies for the stress range up to 200 kPa is small. However, for the same stress range (i.e. 200 kPa) there is a significant drop in void ratio, e compared to the initial conditions for both the low (i.e. 0.6) and high (0.5) compaction energies for saturated specimens. This difference in deformation can be attributed to the influence of the matric suction component of the unsaturated test specimens.

As the degree of saturation, S of the unsaturated soil specimen increases due to an increase in the applied stress, its behavior begins to resemble that of the initially saturated test specimens. The e *vs.* σ'_v relationship for both the saturated and unsaturated test specimens shows similar slopes for the virgin compression part of the curve (see Figure 7.2). At this point the degree of saturation of the initially unsaturated soil specimen is approaching that of saturated specimens as shown in Figure 7.3.

7.3.3 Compressibility for specimens initial compacted with high initial water contents

The matric suction influence on the compressibility characteristics of the unsaturated soil specimens is significantly reduced for specimens prepared with initial water contents greater than 17%. The e *vs.* σ'_v relationships for specimens prepared with an initial water content of 17%, using low and high compaction energies are shown in Figure 7.4 and Figure 7.5 respectively. Though there may be some influence due to matric suction for specimens prepared using low compaction energy, its influence is negligible for specimens prepared using the high compaction energy as the initial degree of saturation is relatively high. Referring to Figure 7.6, the degree of saturation of the unsaturated specimens quickly approaches 100% meaning that the matric suction value is tending to zero, if not zero, and therefore cannot offer the same resistance as before due to an increase in the applied stress.

7.3.4 Initial matric suction and the preconsolidation pressure, σ'_{pc}

Figure 7.8 shows the preconsolidation pressure, σ'_{pc} *vs.* initial compaction water content, w relationship, for test specimens compacted using both low and high compaction energies. In the low initial compaction water content range (i.e. $w < 16\%$) the non-inundated test specimens possess a higher preconsolidation pressure than inundated test specimens irrespective of the compaction energy. This increase in preconsolidation pressure, σ'_{pc} for the inundated test specimens, can be attributed to the presence of the initial matric suction of the non-inundated test specimens. As with the change in initial void ratio, e discussed earlier, there is little difference in the preconsolidation pressure, σ'_{pc} between low and high compaction energies in the high initial compaction water content range (i.e. $w > 18\%$).

As shown in Figure 7.9 there is an increase in the preconsolidation pressure, σ'_{pc} for test specimens with a high initial matric suction value. This effect is more pronounced in the specimens prepared using the high compaction energy.

7.3.5 Initial matric suction and the compression index C_c

Figure 7.10 illustrates the compression index, C_c *vs.* initial compaction water content, w relationship for both inundated and non-inundated test specimens initially compacted using both low and high compaction energies. For non-inundated specimens prepared using the low initial compaction energy, and initial water content (i.e. $w < 16\%$) the effect of structure is clearly evident. For these specimens, as mentioned earlier, an open structure is obtained due to the low initial compaction energy and would have less resistance upon saturation and have a relatively higher compression index, C_c than their inundated counterparts. In terms of matric suction, the low compaction energy test specimens tend to have an increased compression index, C_c which is consistent with the previous findings as these specimens would tend to deform more upon saturation then the specimens prepared using the high compaction energy (see Figure 7.11). Figure 7.12 offers a complete picture of the compression index, C_c and matric suction, $(u_a - u_w)$ results determined for this research project.

Regardless of the initial water content Figure 7.10 shows that, the difference in the value of the compression index, C_c between the inundated and non-inundated test specimens, prepared using the high compaction energy reduces to a value approximately equal to 0.2. For these specimens the effect of structure is less pronounce than those prepared using low compaction energy.

7.4 Compressibility Test Results

In this section the effects of matric suction and soil structure on the coefficient volume compressibility m_v and coefficient of consolidation, C_v are discussed.

7.4.1 Comparison of the coefficient of volume compressibility m_v for inundated specimens prepared using low compaction energy

The relationships of the coefficient of volume compressibility m_v *vs.* applied effective stress, σ'_v for inundated specimens prepared using low compaction energy and for all initial compaction water contents, are shown in Figure 7.13. In the applied stress range, which is lower than 140 kPa, the effect of soil structure is clearly evident.

Specimens prepared using the low compaction energy and low initial water content, will have a higher void ratio and would compress more under relatively lower applied stresses, hence would have a higher coefficient of volume change, m_v as shown in Table 7.2.

Once the applied stress is higher than 300 kPa, the effect of soil structure is significantly reduced due to the applied loading. Figure 7.14 shows the upper and lower limits of the coefficient of volume compressibility, m_v obtained for using specimens prepared using low compaction energy and all six initial water contents. The test results show that for a stress range lower than 300 kPa there is a wide variation in the m_v depending on the initial water content of the test specimen. However, for the higher stress range, the band narrows with little variation regardless of initial compaction water content, m_v approximately equals 0.15 MPa^{-1}.

There is an increase in the coefficient of volume compressibility, m_v of the test specimens with an initial compaction water content of 19% (i.e. 1% wetter than optimum). For compaction water contents greater than the optimum, when initially preparing the specimen, the static compaction energy is no longer being completely transferred to the soil skeleton of the specimen. A part of this energy is transmitted to the pore-water of the test specimen. Similar observations were reported by Vanapalli et al. (1999) testing on the same soil. As the initial compaction energy is no longer entirely being transferred to the soil skeleton, the initial void ratio increases for initial water contents greater than optimum. These test specimens therefore show greater compressibility upon consolidation.

7.4.2 Comparison of the coefficient of volume compressibility m_v for inundated specimens prepared using high compaction energy.

To investigate the effect of soil structure on the compressibility characteristics in greater detail, a second series of oedometer tests were undertaken on test specimens prepared using compaction energy equal to 140 kJ/m^3 (i.e. double that of the low compaction energy used for the first series of oedometer tests). As detailed in Table 7.3, the use of a high compaction energy produced specimens with lower initial void ratios and hence higher initial unit weights when compared to the specimens compacted using the lower compaction energy. The coefficient of volume compressibility, m_v vs. applied effective stress, σ'_v relationships, for inundated specimens prepared using high compaction energy, and all initial water contents, are outlined in Figure 7.17.

Though evident, the effect of soil structure is less significant for specimens prepared using the high compaction energy. For this series of test specimens the effect of initial compaction energy has a greater impact on the compressibility than the resulting structure after compaction. Figure 7.18 shows the upper and lower bands for the coefficient of volume compressibility, m_v for the high compaction energy specimens. Though in the low applied stress range (i.e. < 100 kPa) there is a slight variation in the coefficient of volume compressibility, after which a value of m_v equal to 0.1 MPa^{-1} can be used no matter the initial water content or applied stress range.

7.4.3 Comparison of the coefficient of efficient volume compressibility m_v for non-inundated specimens prepared using low compaction energy.

The relationships of coefficient of volume compressibility, m_v, *vs.* applied effective stress, σ'_v for non-inundated specimens prepared using low compaction energy, and for all initial water contents is shown Figure 7.15. Although, like in the saturated specimens, soil structure has an effect on the compressibility characteristics it is less evident on the unsaturated soil specimens prepared using low compaction energy. Unlike the saturated soil specimens, the deformation in the low stress range (i.e. less than 150 kPa) is small. In this case matric suction is the dominate factor in the compressibility. In the low stress range (i.e. < 150 kPa) and initial water contents less than the optimum conditions (i.e. w < 18%); there is a marked reduction in the coefficient of volume compressibility, m_v, in comparison to inundated test specimens. This increased resistance to the applied stress is due to the contribution of matric suction component of the non-inundated specimens. As the applied stress increases though, the degree of saturation of the test specimens increase and there is a reduction in the matric suction value. This is shown in the sharp increase in the coefficient of volume compressibility, m_v, in the stress range greater than 200 kPa.

It is important to note the narrow band of m_v with average effective stress shown in Figure 7.16. For these tests, m_v can be considered to be equal to 0.2 MPa^{-1} regardless of the initial water content and applied stress.

7.4.4 Comparison of the coefficient of volume compressibility m_v for non-inundated specimens prepared using high compaction energy.

The effect of compaction energy is the dominating factor in terms of the compressibility characteristics on unsaturated soil specimens prepared with the high compaction energy. This is clearly demonstrated in Figure 7.19. Although there is some variation in the low applied stress range, the m_v values consistently remain in a narrow band as shown in Figure 7.20. This behavior can be attributed to the high initial density stemming from the high initial compaction during preparation of the test specimens. With the high initial compaction effort applied to the test specimens despite the different initial water contents, the m_v for these test specimens is approximately equal to 0.1 MPa^{-1}.

7.4.5 Comparison of the coefficient of consolidation, C_v for inundated specimens

The coefficient of consolidation, C_v vs. applied effective stress, σ'_v relationships obtained for inundated specimens prepared using low and high compaction energies are detailed in Figure 7.24 and Figure 7.26 respectively. They show that the compaction energy and therefore, soil structure has insignificant effect on the coefficient of consolidation, as a narrow band for C_v was obtained for inundated test specimens regardless of the initial compaction energy. In either case, for a fully saturated specimen, no matter what initial compaction water content or energy used to prepare the specimen, C_v equals approximately 2.0×10^{-8} m^2/sec.

7.4.6 Comparison of the coefficient of consolidation, C_v for non-inundated specimens

Unlike the inundated test specimens where there was one unique value for C_v, the varying soil structure and low initial degree saturation of the non-inundated specimens control the rate of compression of these specimens. In the low applied stress range (i.e. < 200 kPa) for specimens compacted on the dry side of optimum (i.e. w < 18% and w < 16% for low and high initial compaction energy respectively), due to the presence of the initial matric suction there is a relatively low m_v (see Figure 7.15), lending to an increased coefficient of consolidation, C_v as shown in Figure 7.25 and Figure 7.27. In the higher applied stress range (i.e. > 300) the specimens are rapidly approaching close to fully saturation conditions and the initial matric suction is tending to a zero value thereby increasing coefficient of volume compressibility, m_v and reducing the coefficient of consolidation, C_v.

7.5 Summary

Several parameters which include initial compaction water content, compaction energy, and the degree of saturation influence the compressibility characteristics of unsaturated soil specimens. In fact, it is the interplay of all these parameters that affects the deformation of the soil due to an applied stress. The matric suction in an unsaturated soil offers an increased resistance to deformation. This behaviour can also be explained in terms of degree of saturation. The influence of all the compressibility parameters of an unsaturated soil can be understood in terms of the stress state variable matric suction, $(u_a - u_w)$.

The influence of matric suction on the compressibility characteristics of the unsaturated specimens is significantly reduced for specimens prepared with initial water contents greater that 17% as their degree of saturation, S is relatively high. Also during loading, the matric suction reduces as the applied stress increases and its effect on the compressibility significantly reduces in the high stress range. The effect of initial compaction energy on the compressibility characteristics is mainly observed when the energy used for compaction is relatively large. In this research, doubling the initial compaction effort resulted in a decrease in the coefficient of volume change, m_v. The effect of soil structure is clearly evident in specimens prepared using low compaction energy and low initial water contents. These specimens have a higher void ratio and would compress more even under relatively lower applied stresses. The effect of soil structure on the compressibility characteristics diminishes in the high stress range. It is important to develop more understanding with respect to the compressibility and settlement behavior in terms of the stress state variable matric suction, especially under low stresses.

Table 7.1: Initial and final specimen characteristics low compaction energy. Optimum values are indicated with boldface.

Compaction Energy	Test Type	Initial Water Content, w (%)	Initial Void Ratio, e	Dry Unit Weight, γ (kN/m^3)	Degree of Saturation, S (%)	Matric Suction, $(u_a - u_w)$ (kPa)	Preconsolidation Pressure, σ'_{pc} (kPa)	Compressibility Index, C_c	Recompressibility Index, C_r
Low 70 kJ/m^3	Inundated	14	0.732	15.40	52.7	290	97	0.266	0.021
		15	0.669	15.99	61.3	210	90	0.264	0.031
		16	0.629	16.38	70.0	130	182	0.255	0.025
		17	0.591	16.78	78.9	95	200	0.218	0.018
		18	**0.572**	**16.97**	**85.6**	**60**	**177**	**0.165**	**0.012**
		19	0.581	16.87	89.8	35	180	0.211	0.023

Compaction Energy	Test Type	Initial Water Content, w (%)	Initial Void Ratio, e	Dry Unit Weight, γ (kN/m^3)	Degree of Saturation, S (%)	Matric Suction, $(u_a - u_w)$ (kPa)	Preconsolidation Pressure, σ'_{pc} (kPa)	Compressibility Index, C_c	Recompressibility Index, C_r
Low 70 kJ/m^3	Non-inundated	14	0.732	15.40	52.7	290	263	0.513	0.004
		15	0.669	15.99	61.3	210	225	0.433	0.005
		16	0.629	16.38	70.0	130	232	0.296	0.011
		17	0.591	16.78	78.9	95	190	0.242	0.019
		18	**0.572**	**16.97**	**85.6**	**60**	**177**	**0.212**	**0.021**
		19	0.581	16.87	89.8	35	163	0.191	0.022

Table 7.2: Comparison of the coefficient of volume change for the low stress range of less than 140 kPa.

Initial Water Content (%)	Average Applied Stress (kPa)	Coefficient of Volume Change (MPa^{-1})
14	108	0.577
15	105	0.507
16	137	0.236
17	134	0.195
OMC 18	**90**	**0.155**
19	80	0.273

Table 7.3: Initial and final specimen characteristics high compaction energy. Optimum values are indicated with boldface.

Compaction Energy	Test Type	Initial Water Content, w (%)	Initial Void Ratio, e	Dry Unit Weight, g (kN/m^3)	Degree of Saturation, S (%)	Matric Suction, $(u_a - u_w)$ (kPa)	Preconsolidation Pressure, σ'_{pc} (kPa)	Compressibility Index, C_c	Recompressibility Index, C_r
High 140 kJ/m^3	Inundated	14	0.545	17.27	70.4	280	223	0.198	0.034
		15	0.520	17.56	78.7	205	315	0.193	0.020
		16	**0.511**	**17.66**	**86.4**	**120**	**262**	**0.168**	**0.025**
		17	0.520	17.56	89.9	80	445	0.200	0.027
		18	0.537	17.36	92.1	55	195	0.161	0.032
		19	0.545	17.27	94.7	35	190	0.176	0.030

Compaction Energy	Test Type	Initial Water Content, w (%)	Initial Void Ratio, e	Dry Unit Weight, g (kN/m^3)	Degree of Saturation, S (%)	Matric Suction, $(u_a - u_w)$ (kPa)	Preconsolidation Pressure, σ'_{pc} (kPa)	Compressibility Index, C_c	Recompressibility Index, C_r
High 140 kJ/m^3	Non-inundated	14	0.545	17.27	70.4	280	425	0.274	0.004
		15	0.520	17.56	78.7	205	380	0.218	0.006
		16	**0.511**	**17.66**	**86.4**	**120**	**360**	**0.237**	**0.013**
		17	0.520	17.56	89.9	80	400	0.198	0.015
		18	0.537	17.36	92.1	55	215	0.169	0.022
		19	0.545	17.27	94.7	35	172	0.176	0.028

Figures

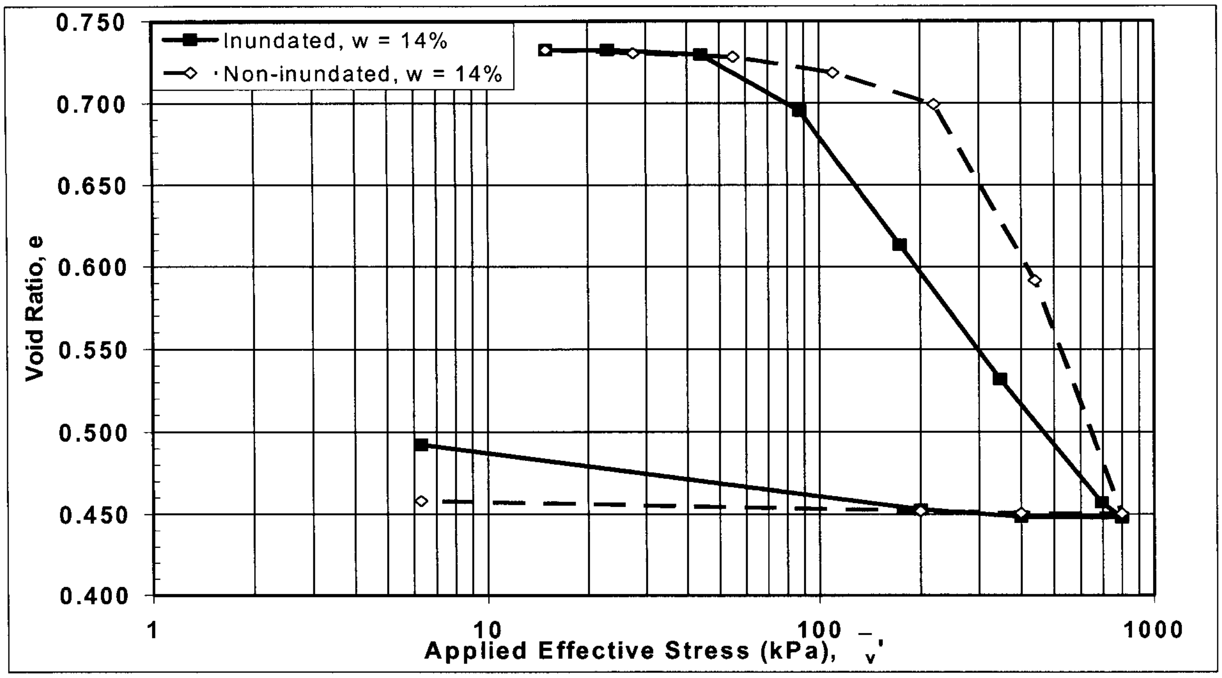


Figure 7.1: Comparison of e-logσ_v' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 14%.

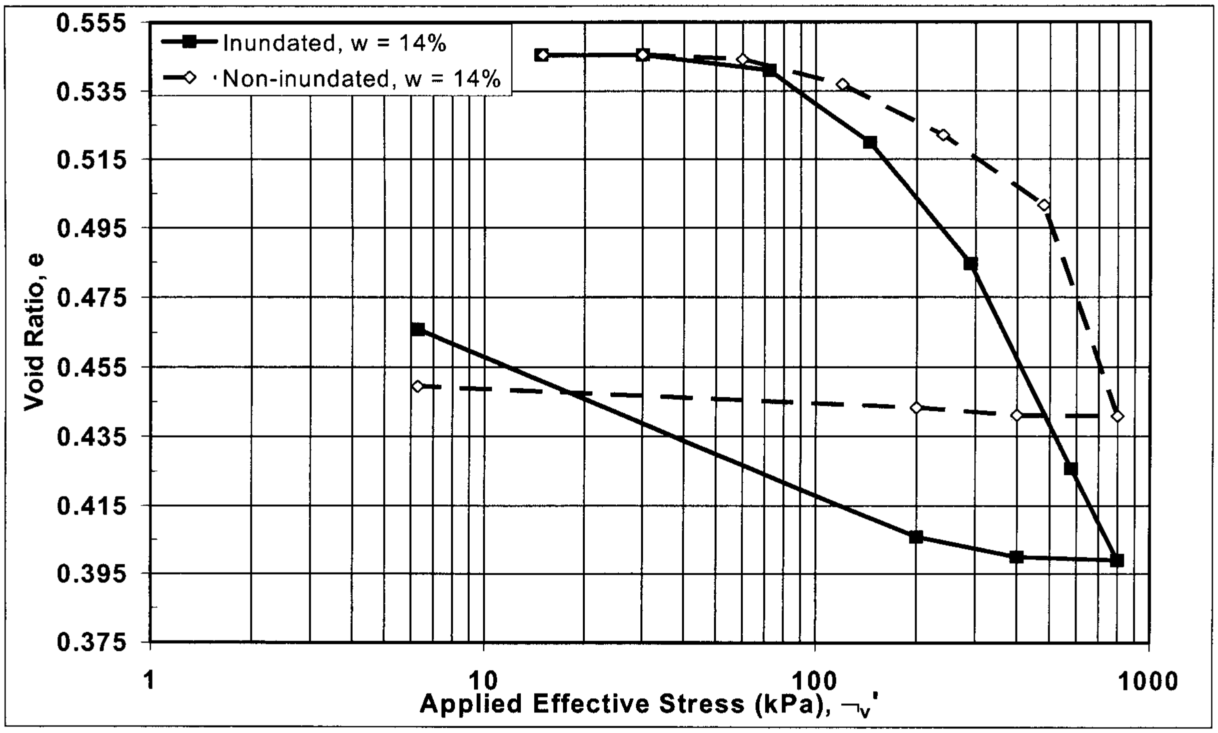


Figure 7.2: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content= 14%.

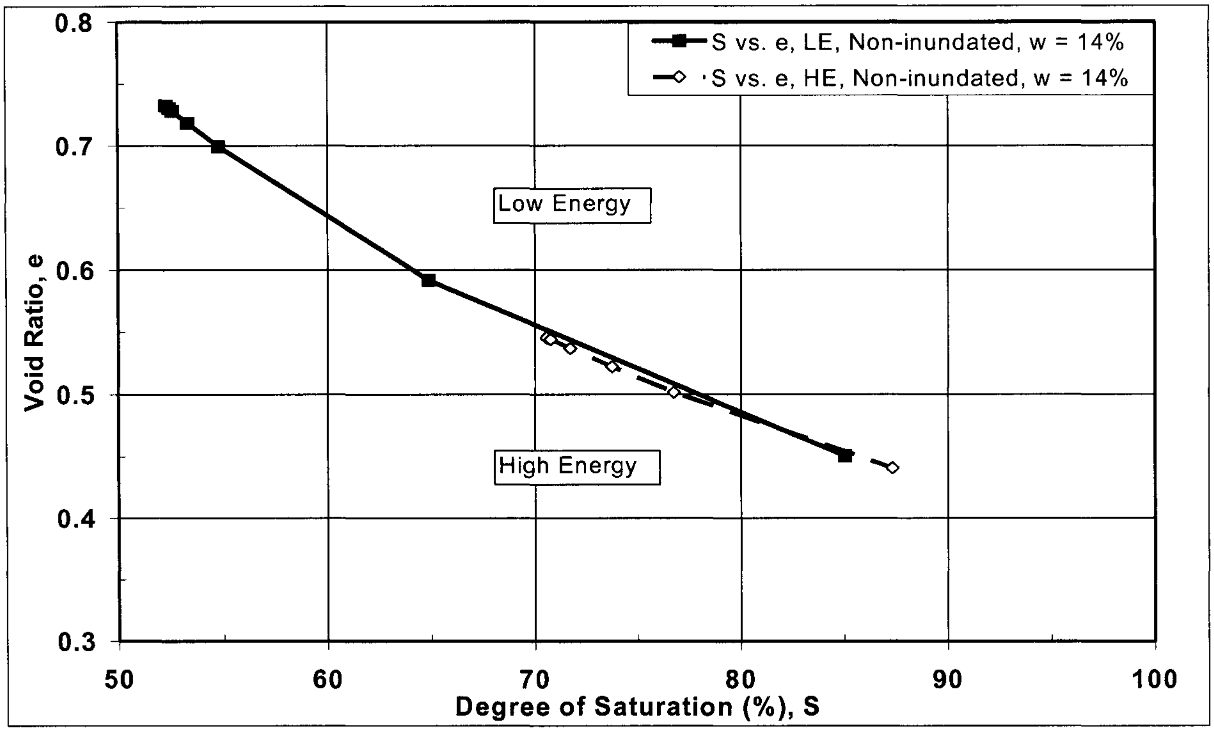


Figure 7.3: Degree of saturation vs. void ratio for non-inundated test specimens prepared using low and high compaction energies and an initial water content of 14%.

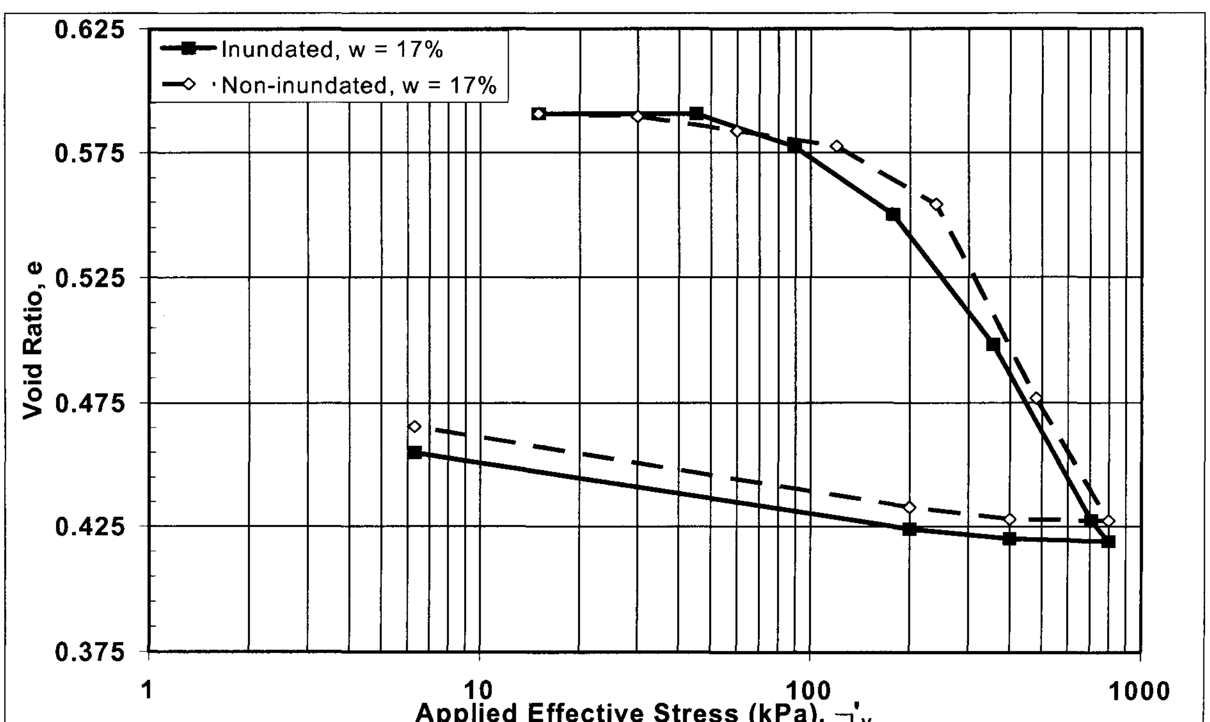


Figure 7.4: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 17%.

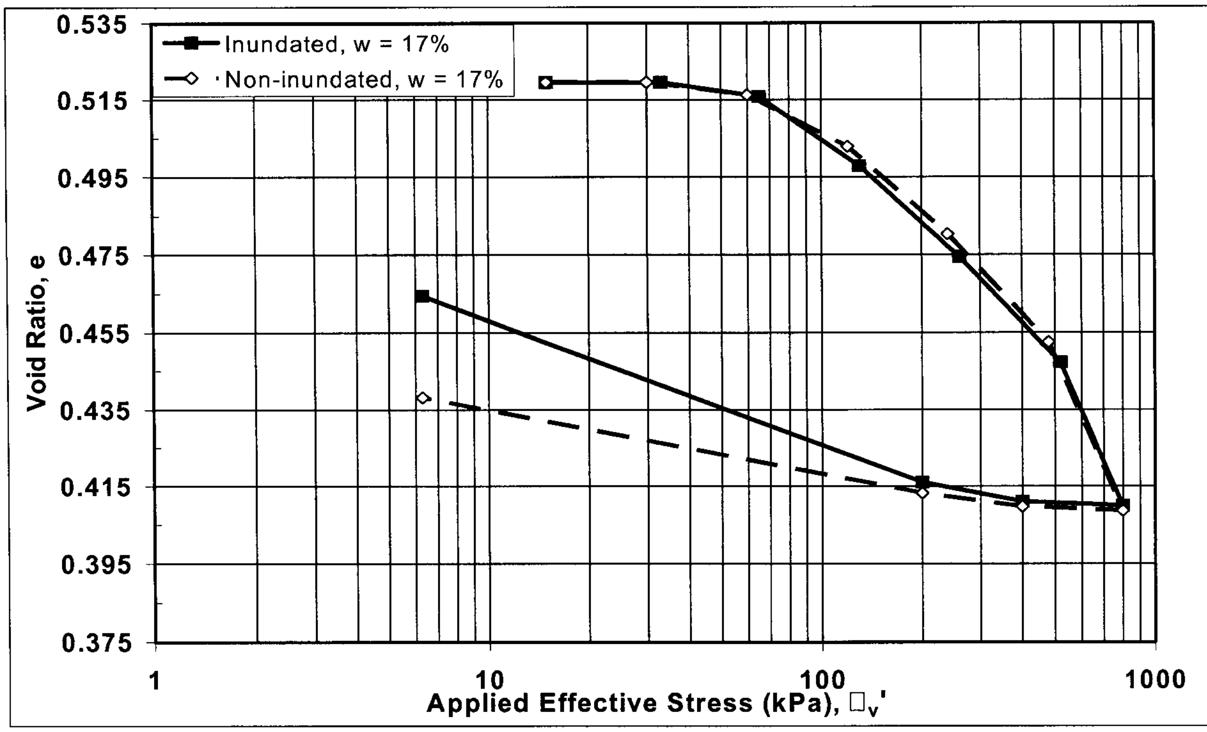


Figure 7.5: Comparison of e- logσ$_v$' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content = 17 %.

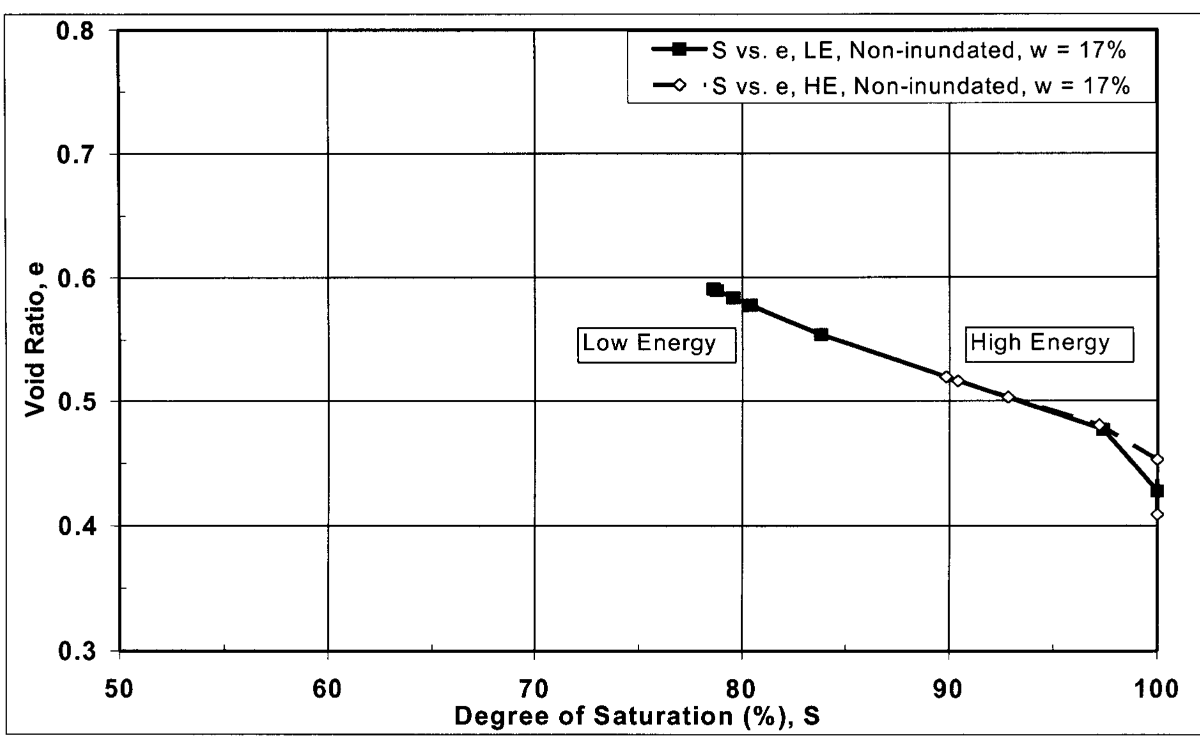


Figure 7.6: Degree of saturation vs. void ratio for non-inundated test specimens prepared using low and high compaction energies and an initial water content of 17%.

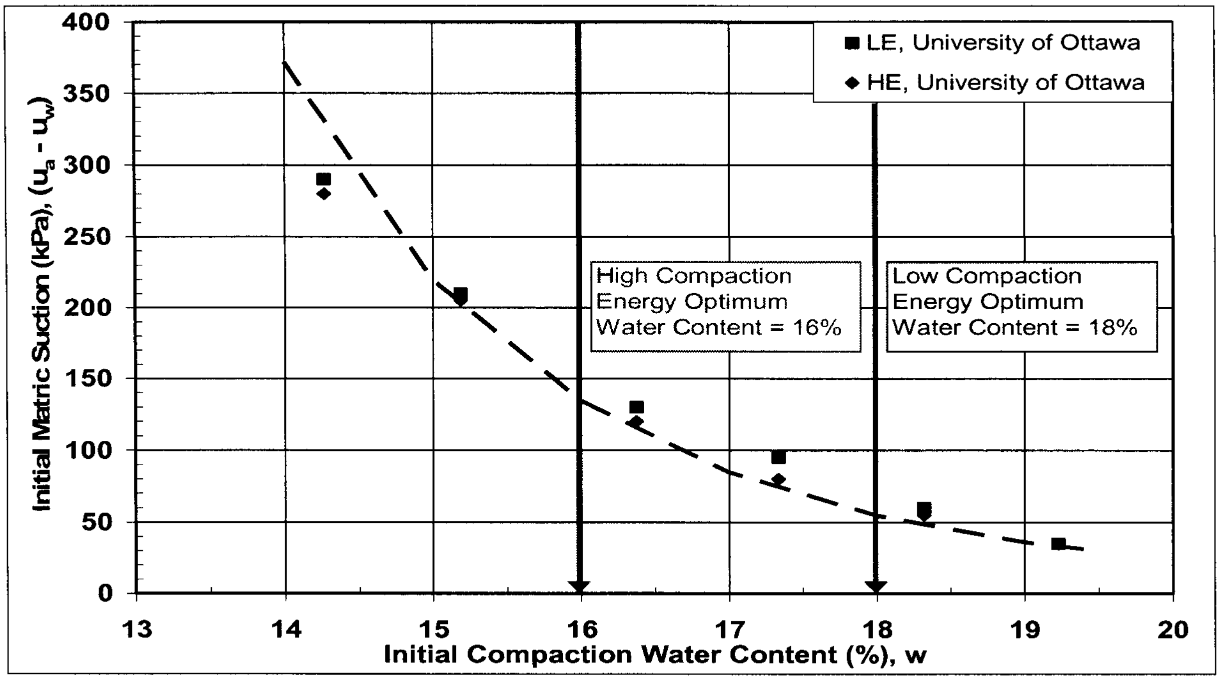


Figure 7.7: Initial compacted water content vs. initial matric suction prepared with low and high compaction energies. Matric suction values were estimated using axis-translation.

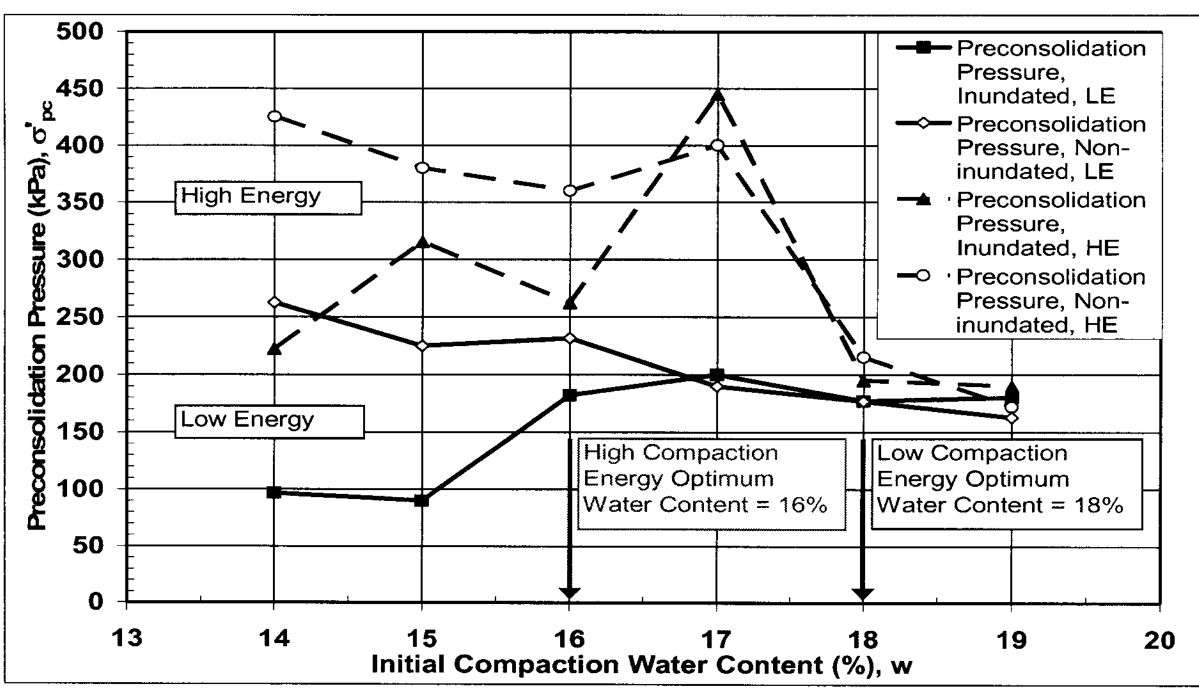


Figure 7.8: Preconsolidation pressure vs. initial compaction water content for inundated and non-inundated test specimens prepared using low and high compaction energies.

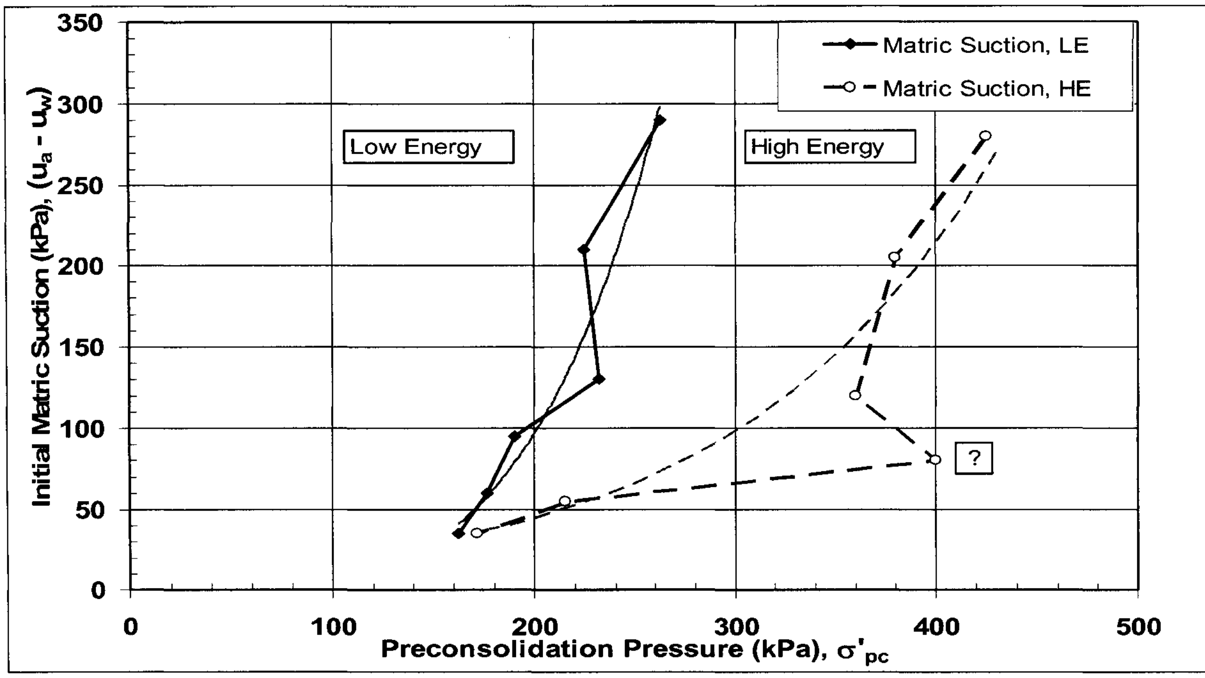


Figure 7.9: Preconsolidation pressure vs. initial matric suction for non-inundated specimens prepared using both low and high compaction energies.

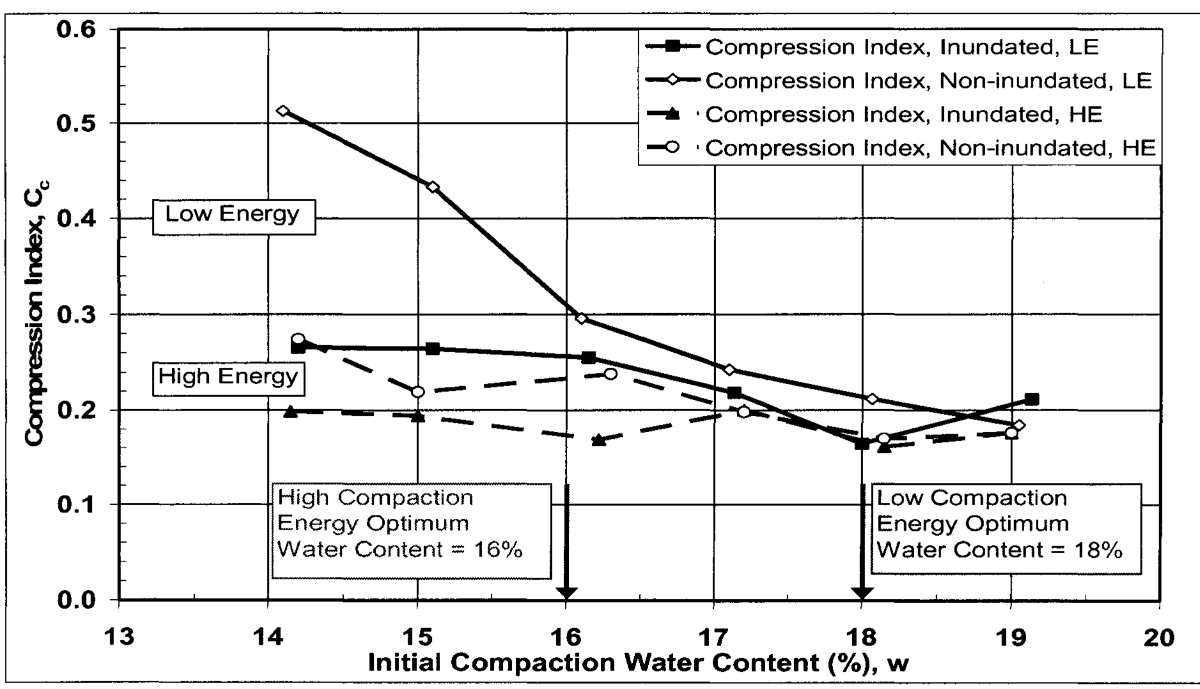


Figure 7.10: Compression index vs. initial soil water content for specimens prepared using both low and high compaction energies.

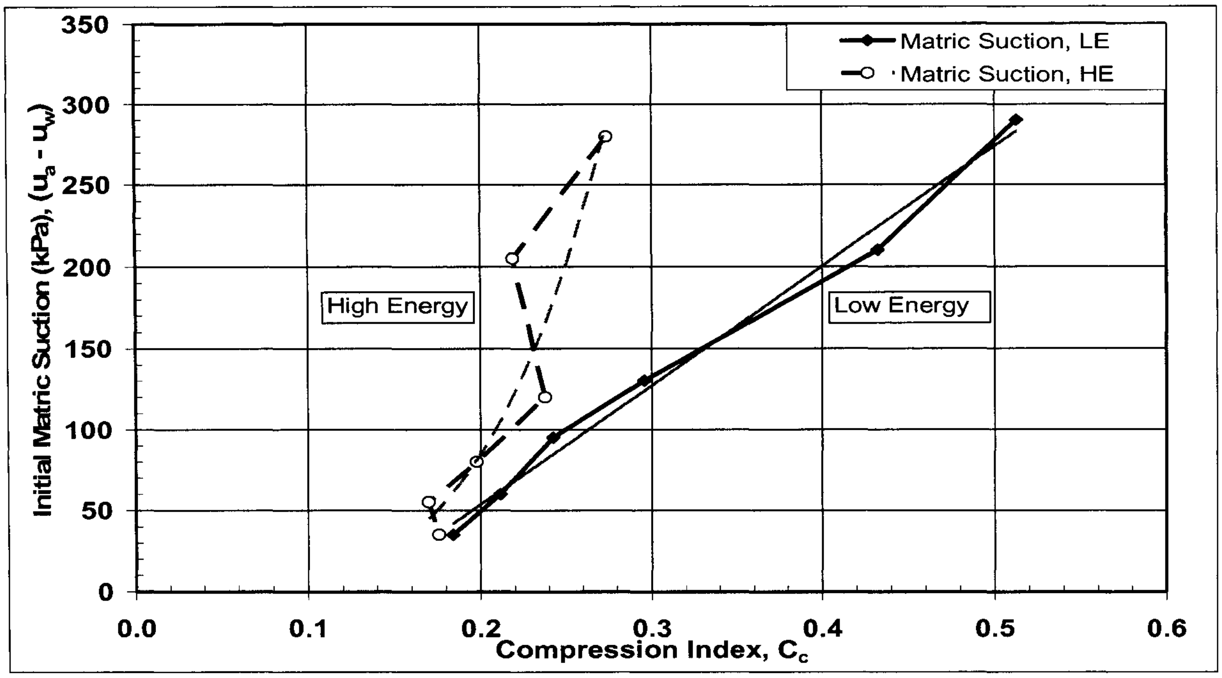


Figure 7.11: Compression index vs. initial matric suction for non-inundated specimens prepared using high and low compaction energies.

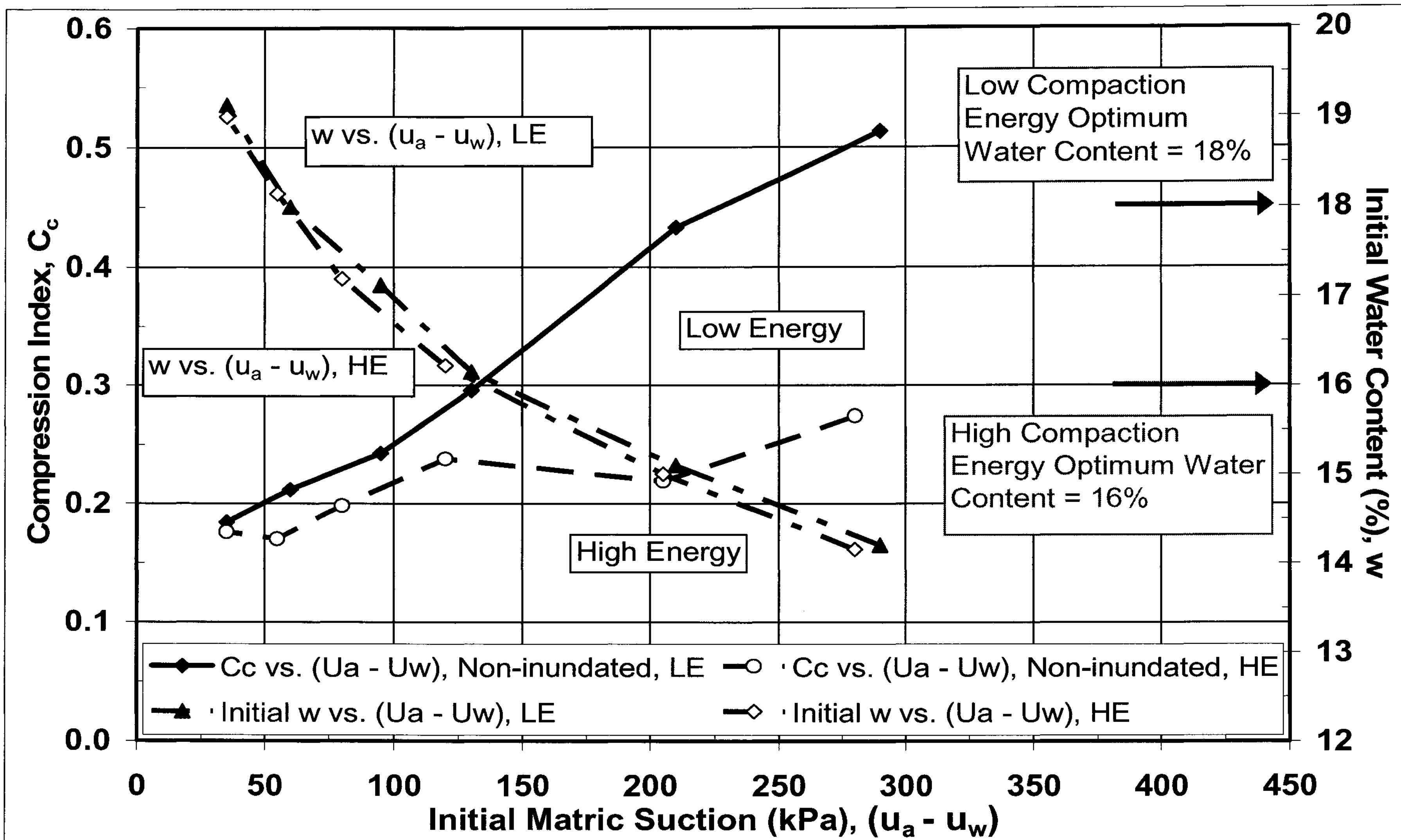


Figure 7.12: Comparison of the compression index vs. initial matric suction (axis-translation (A-T) University of Ottawa data) and initial water content vs. initial matric suction for specimens prepared using both high and low compaction energies.

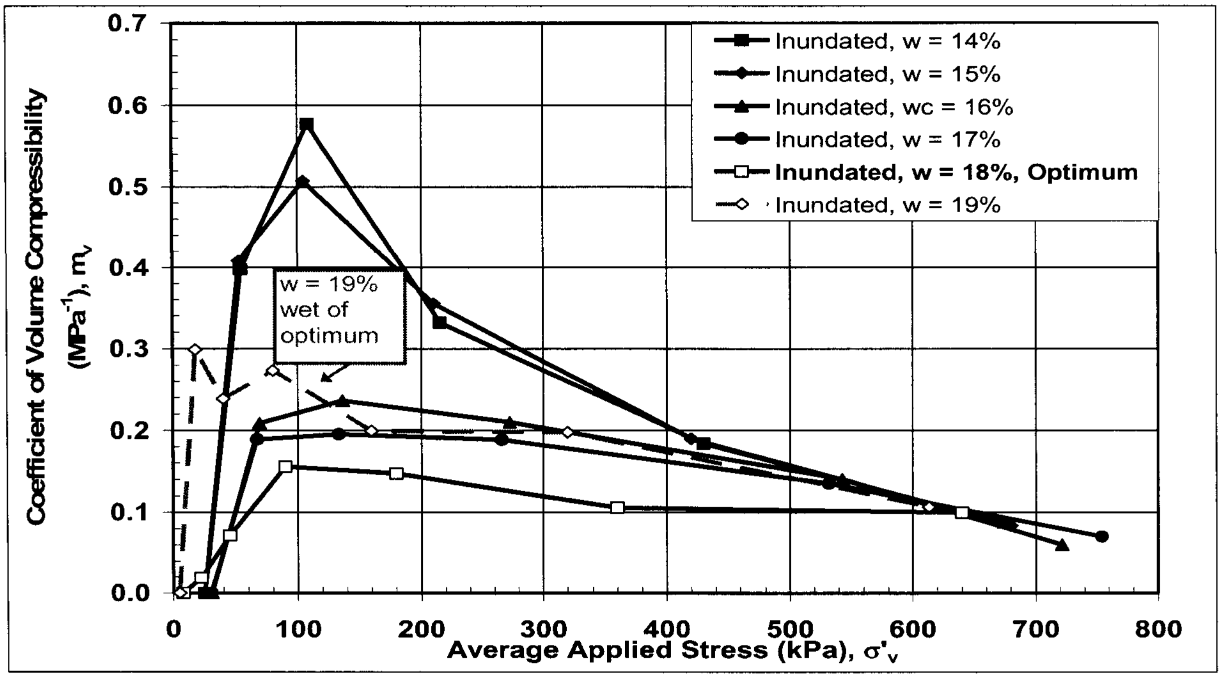


Figure 7.13: Coefficient of volume compressibility vs. average applied stress for inundated test specimens prepared using low compaction energy.

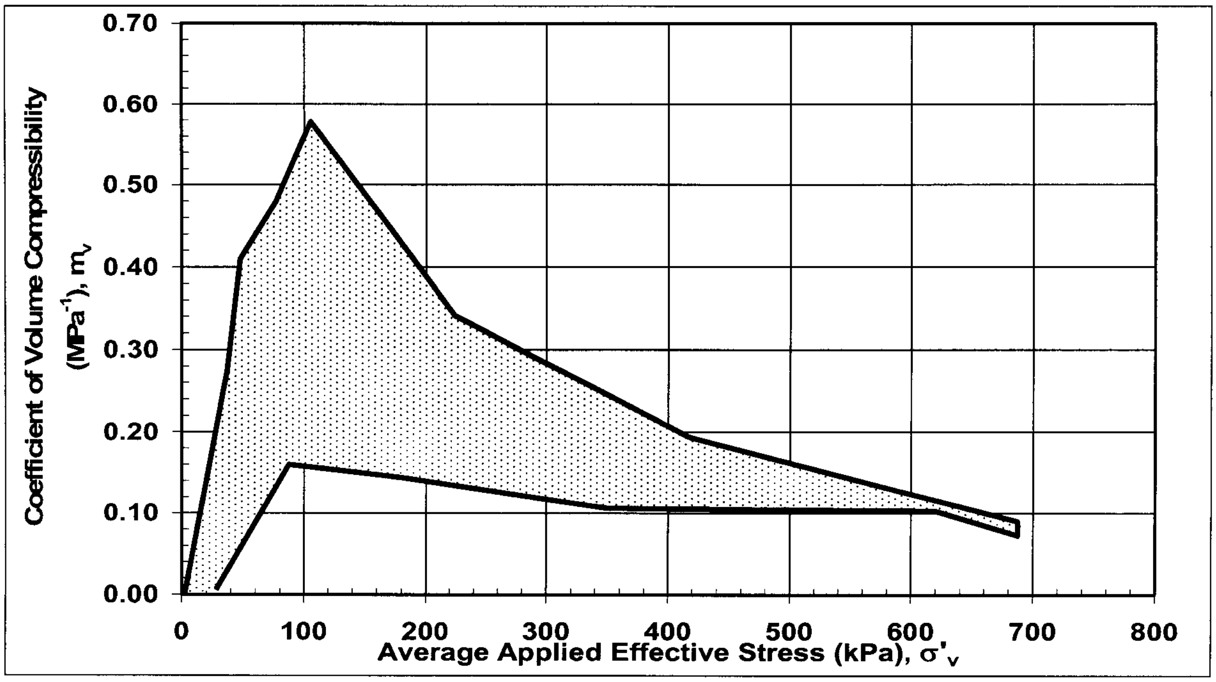


Figure 7.14: Upper and lower bands for coefficient of volume compressibility vs. average applied stress for inundated test specimens prepared using low compaction energy.

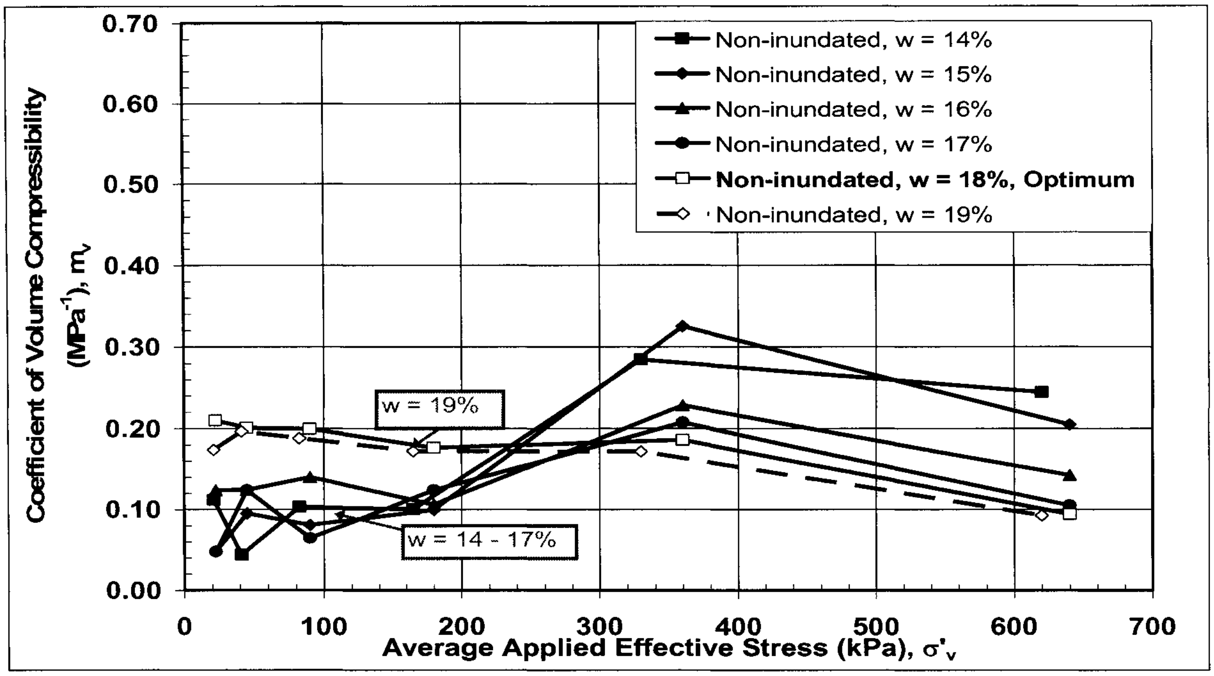


Figure 7.15: Coefficient of volume compressibility vs. average applied stress for non-inundated test specimens prepared using low compaction energy. Optimum water content is 18%.

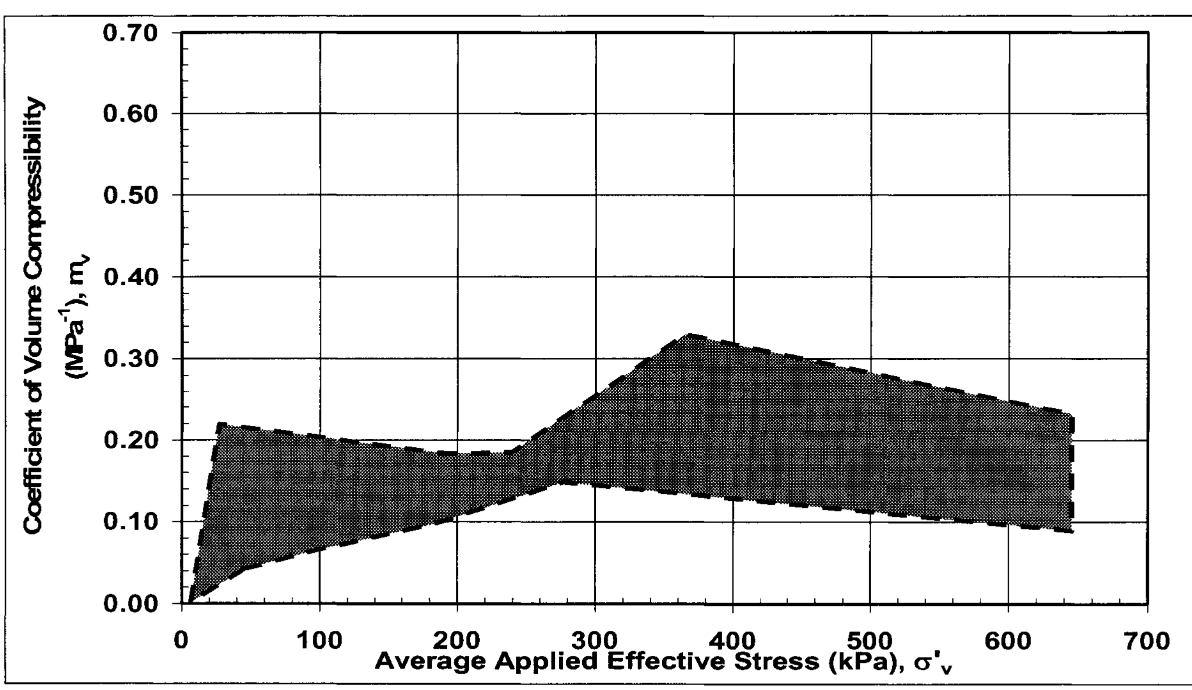


Figure 7.16: Upper and lower bands for coefficient of volume compressibility vs. average applied stress for non-inundated test specimens prepared using low compaction energy.

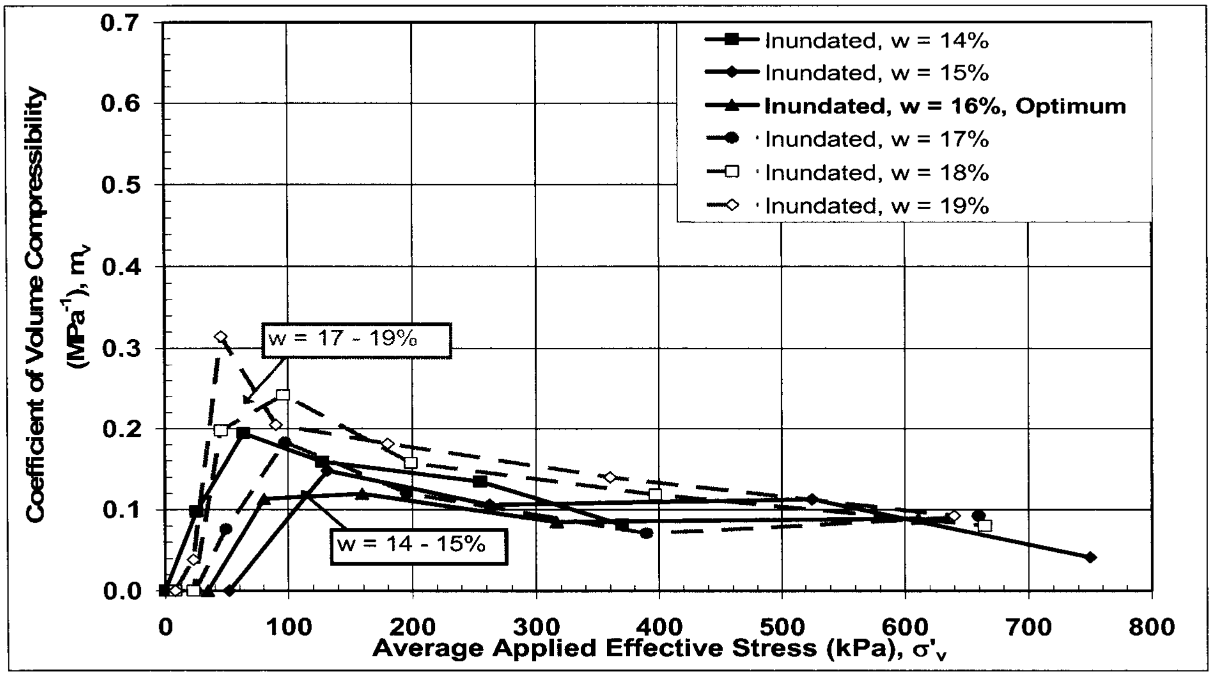


Figure 7.17: Coefficient of volume compressibility vs. average applied stress for inundated test specimens prepared using high compaction energy.

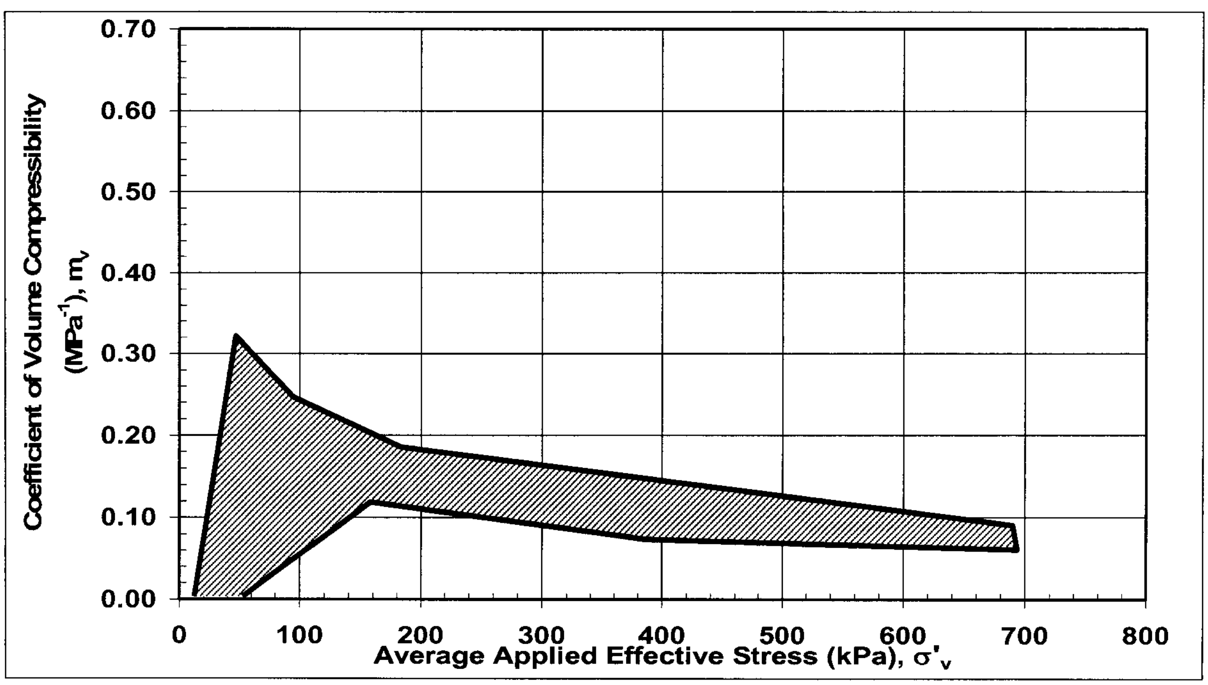


Figure 7.18: Upper and lower bands for coefficient of volume compressibility vs. average applied stress for non-inundated test specimens prepared using low compaction energy.

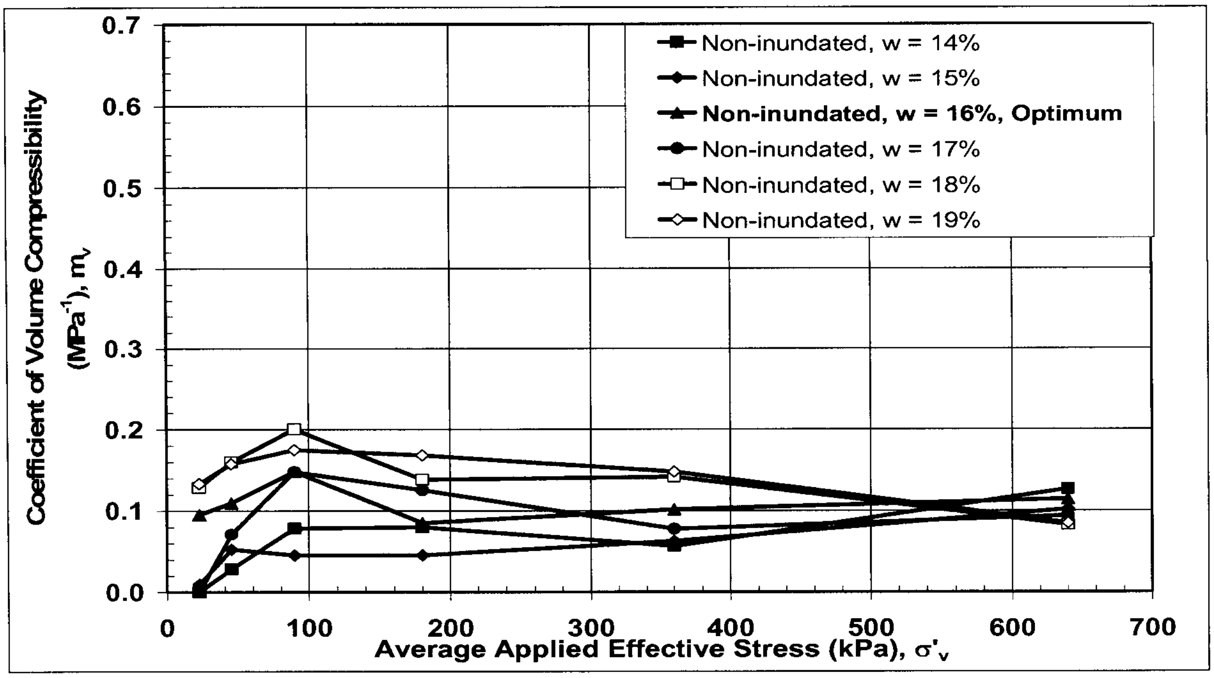


Figure 7.19: Coefficient of volume compressibility vs. average applied stress for non-inundated test specimens prepared using high compaction energy. Optimum water content is 16%.

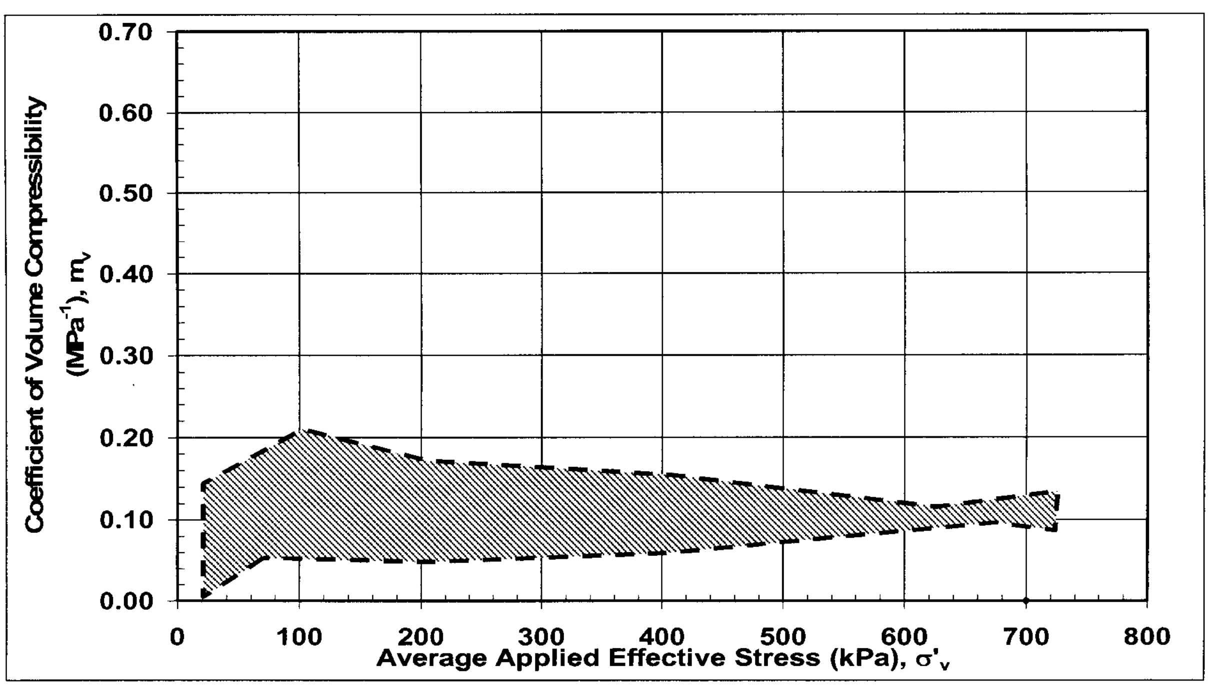


Figure 7.20: Upper and lower bands for coefficient of volume compressibility vs. average applied stress for non-inundated test specimens prepared using high compaction energy.

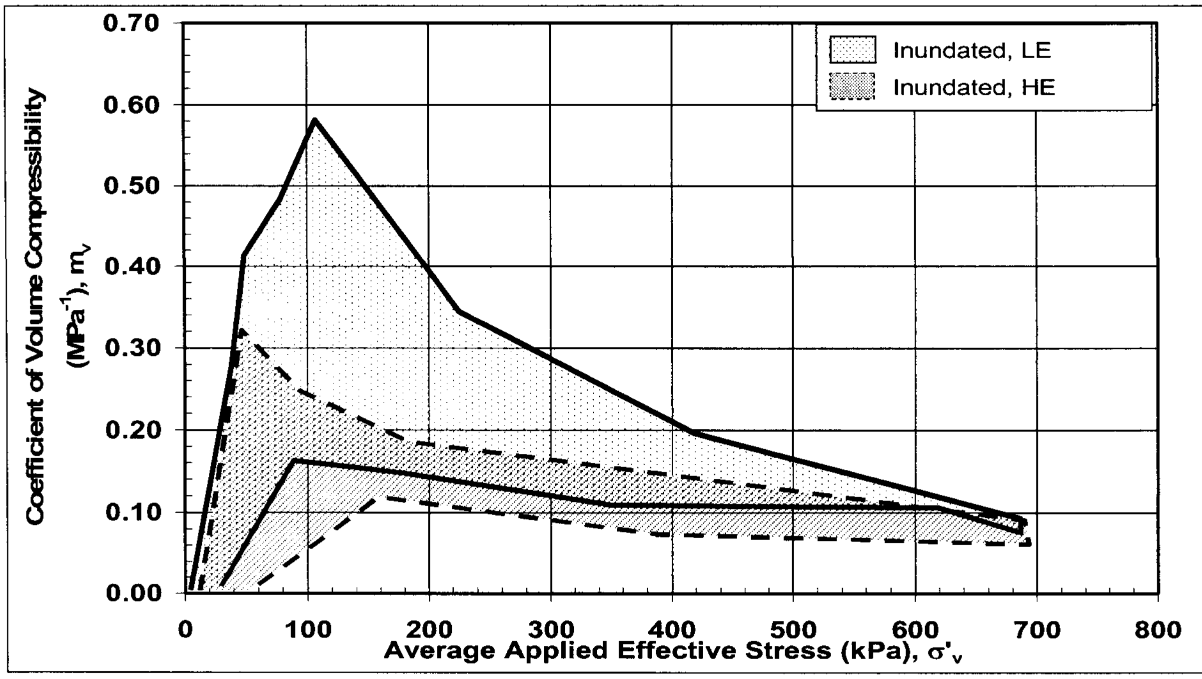


Figure 7.21: Comparison of the upper and lower bands for the coefficient of volume compressibility vs. average applied stress for inundated test specimens prepared using high and low compaction energies.

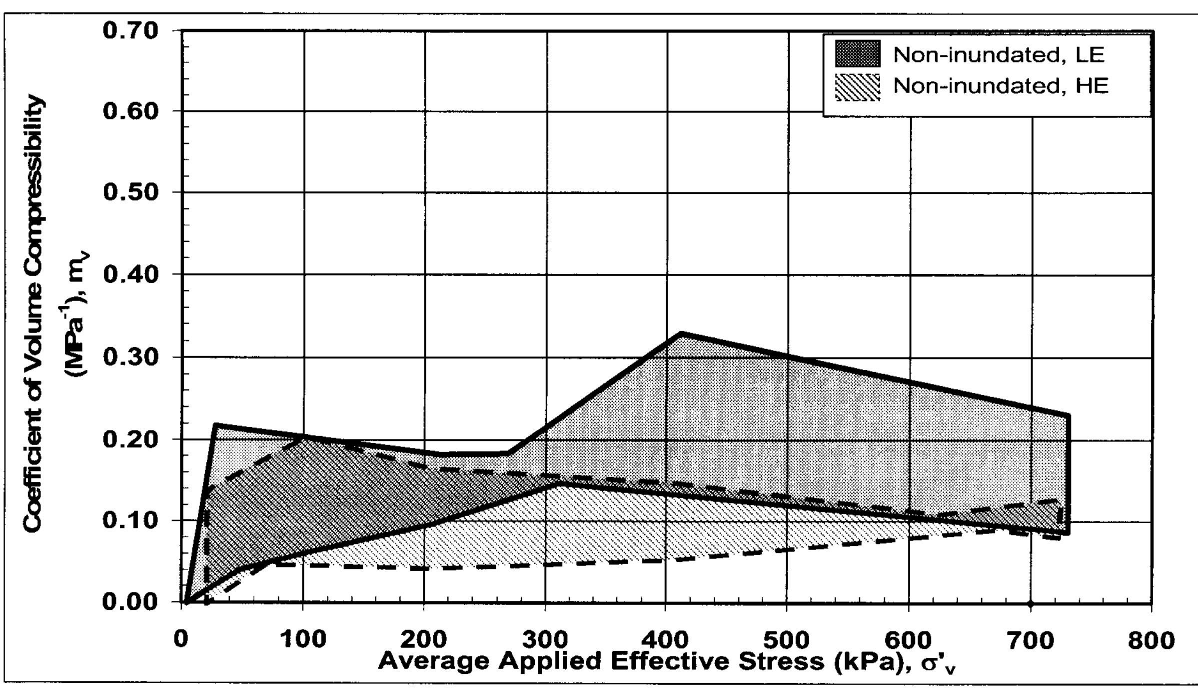


Figure 7.22: Comparison of the upper and lower bands for the coefficient of volume compressibility vs. average applied stress for non-inundated test specimens prepared using high and low compaction energies.

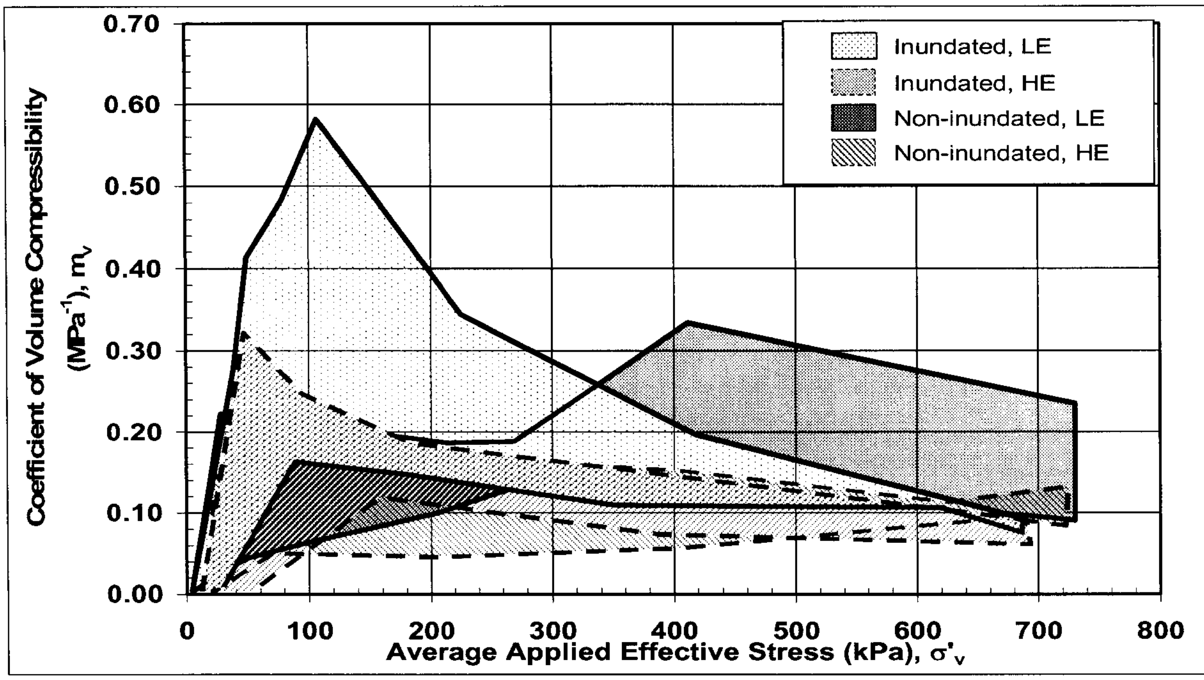


Figure 7.23: Comparison of the upper and lower bands for the coefficient of volume compressibility vs. average applied stress for inundated and non-inundated test specimens prepared using high and low compaction energies.

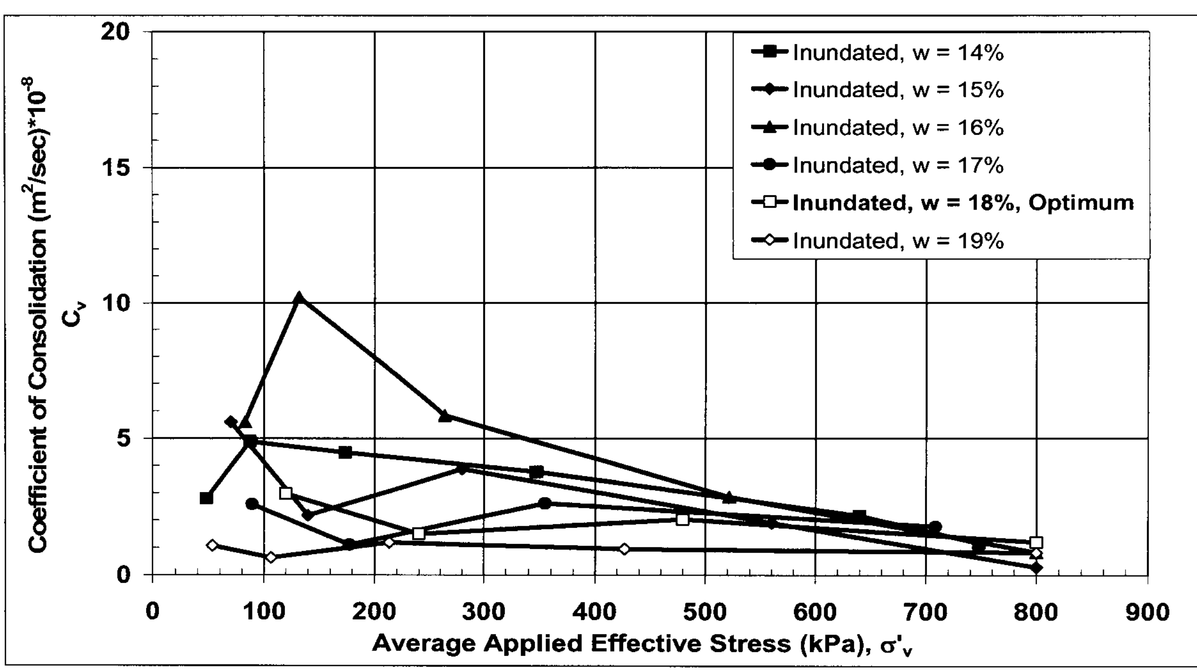


Figure 7.24: Comparison of average coefficient of consolidation vs. average applied effective stress for inundated specimens prepared using low compaction energy.

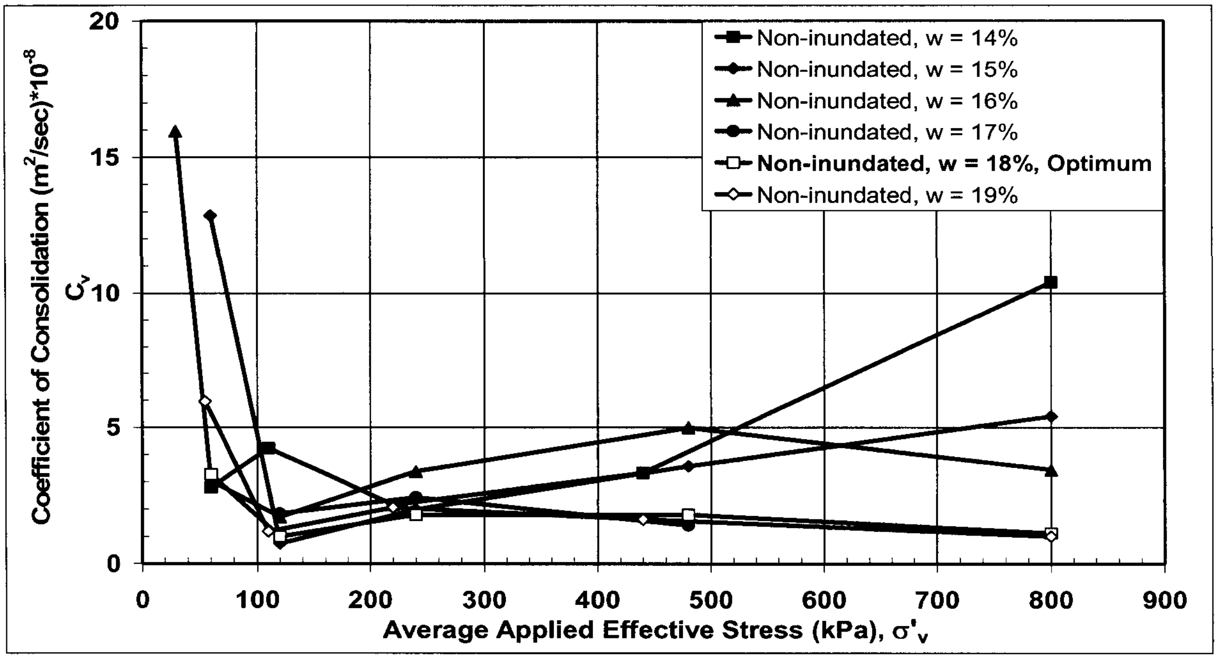


Figure 7.25: Comparison of average coefficient of consolidation vs. average applied effective stress for non-inundated specimens prepared using low compaction energy.

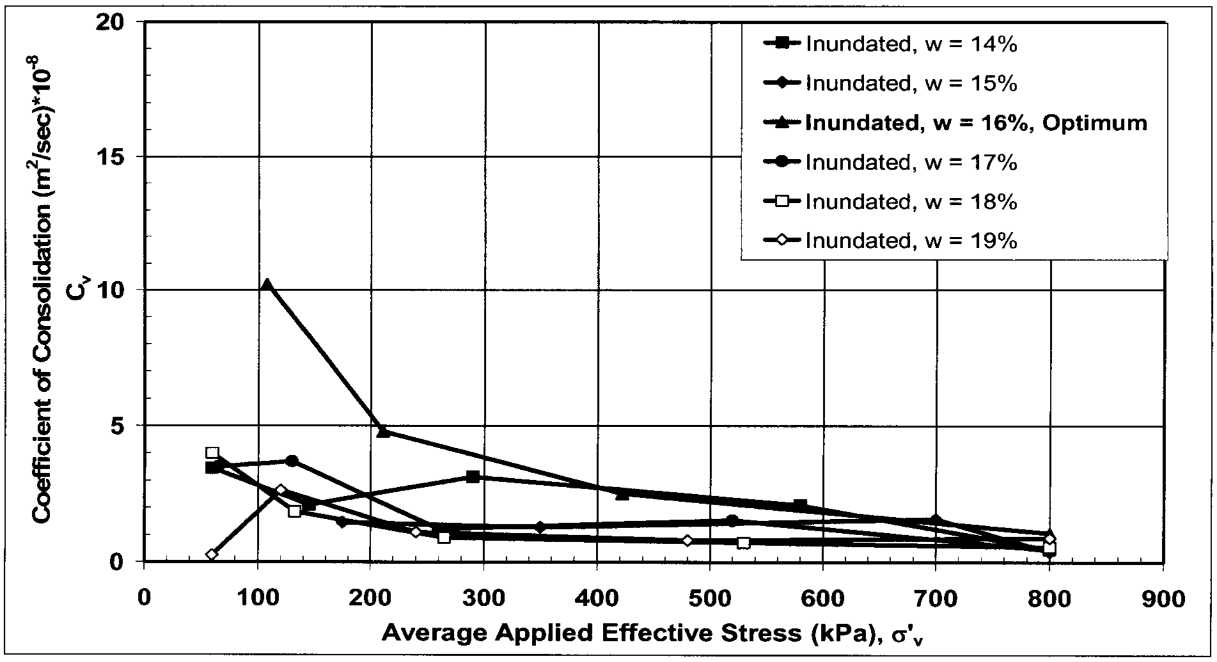


Figure 7.26: Comparison of average coefficient of consolidation vs. average applied effective stress for inundated specimens prepared using high compaction energy.

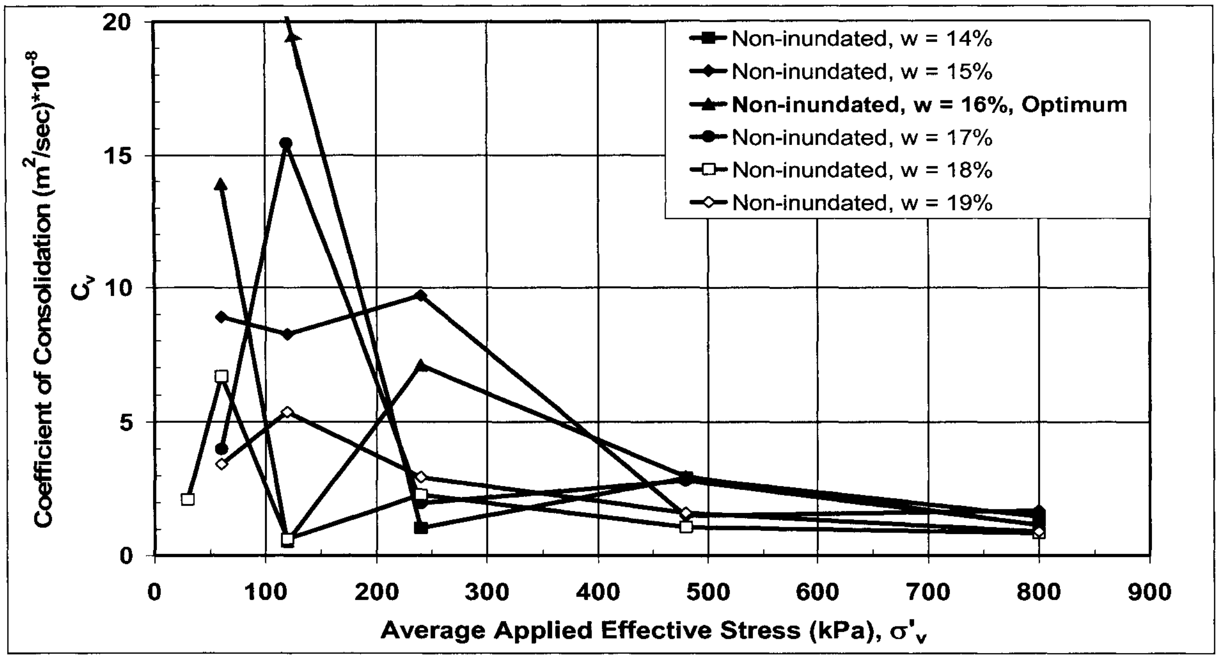


Figure 7.27: Comparison of average coefficient of consolidation vs. average applied effective stress for non-inundated specimens prepared using high compaction energy.

Chapter 8: Analysis of Suction Test Results

8.1 Introduction

Several calibration curves were independently developed using Whatman 42 filter paper and published in the literature (Fawcette & Collis-George 1967, Sibley & Williams, Chandler et al. 1992a&b and ASTM D5298-03). A calibration curve is defined as the relationship between the filter paper water content and the soil suction. After determining the filter paper water content, the soil suction value is estimated using the independently developed calibration curve as a tool. In recent years, it has become a conventional engineering practice to estimate the soil suction values using one of these calibration curves.

More recently, the ASTM Standard D5298-94 filter paper method has been used by several investigators for estimating soil suction values (Rao and Revanasiddappa 2002 & 2005, Ridley et al. 2003). This technique does not recommend the use of an independent filter paper calibration curve. However, several investigators have recommended the development of an independent calibration curve that takes into account the testing environment and laboratory conditions (Houston et al. 1994, Deka et al. Bulut et al. 2001)

In order to analyze the results of the testing program used in this research and compare them to other published works, it is important to understand the key differences between the methods used by the several investigators and the limitations of the published filter paper calibration curves. For this reason, in this chapter, a review of the methods followed to produce the different published calibration curves is first presented and then comparisons are provided between the different methods used in this testing program. Second, an analysis is performed on the measured matric suction results from the contact filter paper method as described in the ASTM Standard D5298-03. Thirdly, based on the results of this testing program and from published data, an equation is proposed to estimate the suction of Indian Head till tested in this research program. Lastly, the matric suction results from the filter paper method are compared with the axis-translation technique results and to the data published for a similar till.

8.2 Published calibration methods

In this section the methods followed to develop and test the previously published Whatman 42 filter paper calibration curves are reviewed including the restrictions and limitations of each of the calibration equations. A comparison is then made between these methods, the ASTM Standard D5298-03 and the procedure followed for this research.

8.2.1 Fawcette & Collis-George (1967)

Gardner (1937) has been credited with the development of the filter paper technique. The calibration curve developed on Whatman 42 filter paper by Fawcette & Collis-George (1967) using this originally proposed technique, has been used by several investigators. Fawcette & Collis-George (1967) provided standard deviations between the measured suction data. However, no calibration equation has been proposed from this work. In this rigorous study, Fawcette & Collis-George (1967) examined the difference in the water-retention properties between nine different batches of Whatman 42 filter papers. The results published in this work show that in spite of variations in the measured water content between different batches, there were little differences in the measured mean suction values or the calibration curve. Many other investigators have developed calibration curves for filter papers and provided comparisons with Fawcette & Collis-George calibration curve (Hamblin 1981, Chandler & Gutierrez 1986 and Deka 1995).

The method used by Fawcette & Collis-George (1967) to produce the wetting calibration curve shown in Figure 8.1 is as follows. Filter papers were initially treated with a 0.005% solution of $HgCl_2$ to prevent bacterial growth and oven dried before using them in the development of calibration curves. The filter papers were calibrated using three different apparatus: pressure plate, pressure membrane and vacuum desiccators depending on the suction level applied. The calibration curve obtained was then used to estimate the suction of specimens of a clay soil from the Narrabri district of New South Wales. The in-situ soil was brought to the laboratory, air dried, ground and passed through a 2 mm sieve. The soil was then wetted in separate batches using different quantities of water applied with a hand sprayer so that test specimens could be prepared to achieve different suction levels. Test specimens were prepared by half filling 750 mm diameter containers, placing a stack of three filter papers on top of the soil. The remainder space was filled by firmly packing more lose soil into the container. The specimens were sealed and stored in a lagged box for a period of 6 to 7 days. The mass of the filter papers were then determined after attaining equilibrium conditions in an air tight bottles with an accuracy of 0.001 gm. Evidence of bacterial growth was observed on the filter papers with higher water contents in spite of using fungicide to prevent such growth. For this reason, a higher concentration of fungicide was recommended through this study. The suction range investigated by Fawcette & Collis-George (1967) was 0.1 -

900 bars (0.01 - 90 MPa).

8.2.2 Hamblin (1981)

Hamblin (1981) investigated several agricultural soils whose suction values were in the range of 100 to 3000 kPa. The focus of the study was to extend the filter paper technique to facilitate quick measurement of a large volume of soil and to obtain a more accurate picture of seasonal variation of field conditions of agricultural soils. The wetting calibration curve shown in Figure 8.2 was developed using three different machines following the procedures presented in Fawcette & Collis-George (1967). The calibration curve was obtained through the use of a direct suction plate for suction values lower than 7 kPa, a direct pressure plate to a suction of 70 kPa, a pressure membrane device to 1500 kPa, and up to 5.5 MPa with saturated vapour pressure at 20°C. The equilibrium period of 36 hours was deemed to be insufficient for bacteria development so the initially air dried filter papers were not pre-treated with any fungicide. The format of the calibration equation for Whatman filter paper published in Hamblin (1981) is unique, as it uses a single equation to describe the entire suction range. In general, the suction range is described by two separate equations depending on the filter paper water content (i.e. one equation for high suction range, and another for the low suction range).

Hamblin (1981) also investigated the batch effect by developing separate calibration curves for two different batches of Whatman 42 filter papers. The study shows that these calibrations were nearly identical and closely match with the previously published results. For this reason, it was concluded that recalibration of new batches of Whatman 42 filter papers was not necessary unless a higher degree of accuracy is required. The soil suction values of borehole samples of undisturbed and ploughed specimens were determined using the developed calibration equation. Test specimens were prepared by placing a single filter paper between two halves of the borehole samples. It was assumed that the mass of the top half of the specimen would ensure contact between the filter paper and pore-water of the test specimen. The test specimens were placed in separate tins and put into an insulated storage container during the equilibrium period.

8.2.3 Chandler & Gutierrez (1986)

The measurement of soil desiccation was the focus of Chandler and Gutierrez (1986) and Chandler et al. (1992a&b) work. The soil suction was proposed to be used as an indicator of soil desiccation and hence a quick and efficient method was required to measure the soil suction of large quantities of soil. Chandler & Gutierrez (1986) developed a calibration curve only for the suction range of 80 – 6000 kPa. The calibration curve was not used for suction values from 0 to 80 kPa as significant variances were observed in the measured water content of the filter papers in this low suction range. In their later work, Chandler et al. (1992a&b) refined and produced a calibration curve for the lower suction range. A new break point based on the water content of the filter paper was 47%. This water content was used to distinguish the high and low suction ranges as shown in Figure 8.3. A filter paper water content of 15% was the lowest that could be used to accurately measure soil suction. Chandler & Gutierrez (1986) showed that their calibration curve more closely matched Fawcette & Collis-George (1967) in comparison to Hamblin (1981). This was attributed to the fact that Hamblin (1981) performed few tests in the suction range investigated by Chandler & Gutierrez (1986). Chandler et al. (1992a) stated that with repeat suction measurements it was possible to achieve an accuracy of ±25%, though with practice a better accuracy of ±15% was possible.

The wetting calibration curve shown in Figure 8.3 was developed by Chandler & Gutierrez (1986), and Chandler et al. (1992a) using specimens of known suction values. The specimens were consolidated in oedometers to a stress level corresponding to the required suction value. The vertical stress was then released, and a single filter paper was placed at each end of the test specimen that remained in the confining ring. Both ends of the test specimen were then covered with Perspex discs, waxed and stored at 21°C for five days. The soil suction of London clay test specimens was determined using the new calibration curve. Test specimens were made from 108 and 38 mm borehole samples. Single filter papers were inserted into specimens, which were then wrapped in cling film, waxed and stored at 20°C for 5 days.

8.2.4 Deka et al. (1995)

Early research into the use and accuracy of the filter paper method was undertaken by Deka et al. (1995). Different aspects of the filter paper method were examined and attempted to refine the techniques published by previous researchers. Results from the research of Deka et al. (1995) showed that not only were the calibration curves material dependant, but they were also batch specific. This would mean that each new batch of filter paper would have to be re-calibrated before being used to estimate soil suction. The result of batch specific calibration curves was in contrast to the previous research findings of Fawcette & Collis-George (1967), Hamblin (1981) and Chandler & Gutierrez

(1986). To aid in the use the of filter paper method, Deka et al. (1995) proposed a calibration equation based on all the available published works using the Whatman 42 filter paper, and is shown as Equation 3 in Figure 8.5. Deka et al. (1995) showed that accuracy in suction estimates would increase if generalized equations were replaced with independently developed calibration curves obtained specifically for the each new batch of filter paper and for the suction range to be investigated by the testing program.

The calibration curve obtained by Deka et al. (1995) was obtained using different devices depending on the suction level and followed the wetting path. A tension table was used for suctions between 1 – 65 kPa under an applied stress of 1.5 kPa, and a thermocouple psychrometer was used for suctions between 0.25 to 100 MPa. Test specimens were produced by half filling a 64 mm x 50 mm plastic jar with loose soil and placing a single filter paper on top. The remaining space in the container was filled with loose soil. The jars were sealed and placed in an insulated box for a six day equilibrium period. To ensure no moisture loss from the filter paper during weighing, the mass of the wet filter papers was determined inside a humidity controlled box to an accuracy of ±1 mg.

8.2.5 Leong et al. (2002)

A more recent review of the filter paper technique was published by Leong et al. (2002). This paper examined the associated reasons why researchers obtained different calibration equations for the same filter paper. The differences in calibration curves were mainly attributed to the different suction sources and equilibrium times used by the researchers. Leong et al. (2002) examined the different types of soil suction (i.e. matric and total suction) and discovered that the same calibration curve could not be used for both types of suction. Similar observations were reported and highlighted by Houston et al. (1994); however, it was for a different type of filter paper. Figure 8.6 details the separate calibration equations for matric and total suction obtained by Leong et al. (2002) which shows a boundary line between the two types of soil suction of 1000 kPa.

Leong et al. (2002) tested the calibration methods used by previous researches and found that calibrating filter paper using samples of known suctions gave the least accurate results. They obtained the matric suction curves using the null pressure plate device and the total suction calibration curves using different salt concentrations (see Figure 8.6). To verify the calibration curves, suction values were induced in test specimens in a null pressure plate device. A single filter paper was placed in the bottom of a 500 ml container and the test specimens were placed on top. A second filter paper was suspended over test specimen on an inert disc to measure total suction. The containers were sealed and stored in an insulated box for 14 days. After equilibrium the filter paper water content was determined from the wet mass determined on a 4 digit scale (change to testing procedure of pervious researchers after the adoption of the ASTM D5298-94 Standard). The percent difference between the induced suction of the test specimens and that measured using the contact method (i.e. matric suction) was ±18%.

8.2.6 ASTM Standard D5298-03 "Standard Test Method for Measurement of Soil Potential Using Filter Paper

The ASTM Standard for the measurement of soil potential using filter paper was first approved in 1992 and this approval was extended again in 1994 after a review. This standard was discontinued in 2002, reinstated in 2003 and re-published in 2004 edition. The reasons behind the reinstatement are not fully known. However, it is of interest to note some statements in these standards. The 1994 Annual book of ASTM Standards, and again in the 2003 edition, under Section 11 Precision and Bias states *"11.1: Data are being evaluated to determine the precision of this test method. In addition, Subcommittee D18.04 is seeking pertinent data from users of the test method". "11.2 There is no accepted reference value for this test method; therefore, bias cannot be determined".* On accuracy of the measured suction values in Section 9.31 the ASTM Standard states "*Test results should be discarded if the difference in suction between the two filter papers exceeds 0.5 log kPa*". The calibration curves and equations shown in Figure 8.4 it is important to note are considered "*applicable to total suction*" in Section 7.3 of the ASTM Standard. Although in Note 4 it does state that: "*filter papers can be calibrated by ceramic plate using ASTM Test Method D2325*", though no separate matric suction calibration is provided. The ASTM D5298-03 Standard provides example specimen setups for measuring matric and total suction and shown in Figure 8.9.

8.3 University of Ottawa (2005)

The use of axis-translation was initially the only method for measuring matric suction that was contemplated in this testing program. Due to delays in the in-house manufacturing and breaking of the ceramic discs in the null pressure plate device, an alternate method was used to facilitate the measuring of matric suction. Research into the different methods commercially available to measure matric suction was undertaken. On reviewing the literature on soil suction measurement techniques, it was discovered that the contact filter paper method was touted as being an inexpensive, quick, accurate and technically simple method that could measure a wide range of soil suction (Hamblin 1981 Chandler & Gutierrez 1986 and Huston et al. 1994). It was soon discovered that to embark on using the contact filter paper method would disprove each of these descriptors.

It is recognized that the acquisition cost of the filter papers is inexpensive compared to the purchase of tensiometers or psychrometers, but that does not include the cost of providing the environmental controls required to accurately measure soil suction with the filter paper method. Although several research studies have used the filter paper method as an in-situ test, strict temperature and humidity controls are required in laboratory to produce results that have acceptable levels of accuracy. The accuracy of the filter method is still under debate and the ASTM Standard does not provide any indication of the accuracy rating for its calibration equations or method. This clearly demonstrates that more research is needed in this area.

The filter paper technique appears simple at first, as it is simply allows the filter paper to come to equilibrium with the pore-water of the test specimens; however, the intricacies of the method introduce several difficulties. Researchers still debate the type of suction that is measured, the use of a generalized calibration equations, whether or not bacteria will develop, equilibrium times, methods of calibration and contact stress, to name a few of the variables (Houston et al. 1994, Deka et al. 1995, Fredlund et al. 1995, and Bulut et al. 2001 Leong et al. 2002). It would therefore appear that there are only two aspects on which consensus has been reached in terms of the filter paper technique. The first is that published calibration curves are material specific (i.e. a Whatman 42 calibration curve can only be used with Whatman 42 filter paper). The second point of consensus is that published calibration curves can be used in new research without re-calibrating unless increased accuracy is required.

It therefore became evident that there was a need to establish a new procedure that would not only incorporate the separate findings from all the published works but include the solutions to problems found by attempting to use the filter paper method at the University of Ottawa. The complete step by step procedure is outlined in Chapter 5 therefore only portions will be highlighted in this section that indicates changes to published works.

The foremost problem with the filter paper method encountered at the University of Ottawa was the development of bacteria during the calibration of the filter papers. The testing program involved the measurement of only matric suction in the range of 10 – 500 kPa, which is more challenging and at the same time of more interest to the practicing engineers. Therefore, the entire calibration curve could be obtained using only the null pressure plate device. The latest development from recent studies demonstrated the equilibrium period used for calibration should be the same as planned for testing (Leong et al. (2002), Bulut et al. 2001). Therefore, a calibration program consisting of nine suction levels between 20 – 300 kPa was developed. This implied that if a fourteen day equilibrium period was planned for testing, then the same amount of time would be required at each suction level during calibration. If a single set of filter papers was to be used during calibration to ensure consistency, they would be exposed to the moist environmental conditions in the null pressure plate, ideal for bacteria growth, for at least

126 days, or more than 4 months. The equilibrium time the filter papers were to be exposed was far greater than the fourteen days most researchers used when calibrating a single filter paper following the total suction method; in retrospect bacteria development was inevitable.

The wetting matric suction calibration curve shown in Figure 8.7 was obtained by calibrating initially oven dried filter papers pre-treated with a 10% formaldehyde solution (i.e. five times stronger than that recommended by the ASTM Standard). An equilibrium period of at least 14 days at each suction level was used to be consistent with the planned suction measurement. The calibration curve closely matches that of the one in the ASTM Standard in the suction range up to 300 kPa. Test specimens were made in 4 separate lifts and a stack of three of filter paper was inserted between each lift. The specimen were then wrapped in two layers of cling film placed into two, vacuum sealed Ziploc bags and stored in an insulated cooler for eighteen days. The extra time was given to allow for the system to come to equilibrium with the soil water (i.e. the two sacrificial filter papers protecting the filter paper used for water content measurement) and then the filter paper used to measure matric suction (Hamblin 1981, Leong et al. 2002).

8.4 Comparing Measured Suction Values

It is important before using any of the published calibration equations to know any implied restrictions; or when to apply a particular equation so that erroneous suction results are not obtained. Table 8.1 outlines the published calibration equations for Whatman 42 filter paper and their restrictions discussed earlier. In the following sections these equations will used to demonstrate the range of matric suction values that are obtained for the Indian Head till test specimens prepared for this research. The matric suction values obtained from the ASTM Standard calibration equations will be used as a basis for comparison

8.4.1 Matric suction values from the ASTM Standard calibration equations

Based on the filter paper water contents measured, the matric suction values for the Indian Head till test specimens prepared from both the low and high compaction energies (i.e. 70 and 140 kJ/m^3 respectively) were predicted using the ASTM calibration equations and are detailed in Table 8.2. The median of the three separate matric suction measurements are summarized in Table 8.3.

Using the same filter paper water contents, the matric suction values were then evaluated based on the published calibration equations and are tabulated in Table 8.4. The average percent difference between the matric suction values calculated with the ASTM Standard to those calculated with published calibration equations are detailed in Table 8.5 and in Figure 8.10.

These results show that the equations from Leong et al. (2002) and Fawcett & Collis-George (1967) produce matric suction values that more closely match those estimated using the ASTM Standard values. This can be attributed to the similarities in the calibration procedures used by Leong et al. (2002) and Fawcett & Collis-George (1967) to those followed for this research. Similar to the calibration procedure of the current testing program, Leong et al. (2002) obtained a separate calibration curve for matric suction, and calibrated their filter paper in the low suction range (i.e. 10 – 1000 kPa) with the null pressure plate device.

An unexpected result was obtained when the matric suction values were compared to those calculated from the calibration equation of Crilley & Chandler (1993). Due to the variation in water content throughout the specimen used for calibration of the filter papers calibration curves obtained using specimens of known suction values were supposed to be the least accurate (Leong et al. (2002). In this analysis, the results obtained from the calibration equations from Crilley & Chandler (1993) demonstrate matric suction results with an average percent difference of 27%, which is 10% higher in comparison to Fawcett & Collis-George (1967) curve who calibrated with known suction sources.

The calibration equation by Hamblin (1981) consistently gave matric suction results with the greatest percent difference from those calculated from the ASTM Standard. Hamblin (1981) used a single calibration equation to cover the entire suction range and used a short equilibrium time (i.e. maximum of 36 hours) in the calibration process. These variations in calibration procedures will account for the larger percent difference from the ASTM Standard values measured not only from the data in this research but also from other researches as well.

The varying matric suction results calculated from the various published calibration equations demonstrate the importance of selecting an appropriate calibration equation for the desired testing program.

8.5 University of Ottawa's Matric Suction Calibration Equations

The two calibration equations (Eqn. 1 and Eqn. 2) were developed based on the results from the calibration of the Whatman 42 filter papers performed at the University of Ottawa (Figure 8.7). These equations describe two-bilinear lines that can be used in the determination of the matric suction of tests specimens for filter papers in the water content range of 37 – 80%. A breakpoint of a filter paper water content of 38% was used to distinguish between high and low matric suction.

$$37 \leq wc_{fp} \leq 38\,\% : \log h = 151.13 - 94.343 * \log(wc_{fp}) \qquad \text{Eq. 1}$$

$$wc_{fp} > 38\,\% : \log h = 6.712 - 2.933 \log(wc_{fp}) \qquad \text{Eq. 2}$$

8.5.1 Comparing University of Ottawa Matric Suction Calibration to the ASTM Standard

A series of comparisons were made to test the calibration equations developed from this testing program. The matric suction obtained using the measured filter paper water contents and Eq. 1 and 2 were compared to the matric suction values calculated using the ASTM Standards. The percent difference between the calculated values are outlined in Table 8.6 and Figure 8.10 and show similar trends to those measured for the Fawcett & Collis-George (1967), Chandler and Gutierrez (1986), and Leong et al. (2002). The median matric suction value for the test specimens prepared with a soil water content of 14% using the low compaction energy (i.e. 70 kJ/m^3) was not recorded as the average filter paper water content of 37.4% was less than the minimum requirement of 37.5% to use the University of Ottawa calibration equation. The average percent difference between the values obtained using the University of Ottawa calibration equation to those of the ASTM Standard equations was 20% for specimens prepared with the low compaction energy (i.e. 70 kJ/m^3) and 23% for specimens prepared using the high compaction energy (i.e. 140 kJ/m^3).

8.5.2 Filter paper sensitivity

The limited suction range investigated in this testing program is the main reason for the higher percent difference between the estimated matric suction values of the University of Ottawa and the ASTM Standard mentioned earlier. The focus of the testing program was to develop methods to determine matric suction values in the low suction range, the region of most importance to engineers and yet, the most difficult to measure (Chandler and Gutierrez 1986, and Huston et al.1994). At the transition point between the low and high suction ranges the calibration curve is sensitive to slight changes in filter paper water content. Referring to the ASTM Standard curve shown in Figure 8.11, the water content range of 40 – 50% represents approximately a ±5% of the filter paper water content breakpoint of 45.3%. A 45% filter paper water content represents a soil suction of approximately 70 kPa. An increase of only 5% in water content (i.e. w_{fp} = 50%) provides a 30% decrease in soil suction (i.e. 55 kPa). Reducing the filter paper water content by 5% (i.e. w_{fp} = 40%) provides a 300% increase in the soil suction (i.e. 170 kPa).

Sibley & Williams (1990) investigated the sensitivity range of several different filter materials and showed that an increase in accuracy of measured results was obtained when the calibration curve was constructed using a series of filter materials instead of the conventional single filter material. As an example, one of the materials used in the study were the 0.025 μm millipore filtration membranes. These have shown a 11% increase in calibration accuracy compared to the Whatman 42 filter paper in the low suction range of

30 – 100 kPa (i.e. w_{fp} = 40 – 50%). An additional finding was that if only one filter material was to be used to calibrate the entire suction range then the Whatman 42 filter paper provided the most consistent results. It is the sensitivity of the filter material that causes such significant variation in soil suction with slight changes in water content of the filter paper.

8.6 Application of a standardized equation for estimating the matric suction of Indian Head Till

The matric suction data obtained from the present research and that of Vanapalli et al. (1999) are shown in Figure 8.12. Using this data, a standardized equation (Eqn. 3) that would relate soil water content of the Indian Head till to its matric suction irrespective of the compaction energy was obtained.

$$\log h = 11.32 - 7.634 * \log(w_{soil}) \qquad \text{Eqn. 3}$$

The 95% confidence interval for Eqn. 3 is shown in Figure 8.13 including the suction data originally shown in Figure 8.13. A comparison of the matric suction results calculated using Eqn. 1 to the measured values is outlined in Table 8.7 for specimens prepared using low compaction energy and Table 8.8 for those prepared using the high compaction energy. The matric suction results calculated using Eqn. 1 closely match those measured using the axis-translation method.

8.7 Accuracy of the ASTM Standard D5298-03 method

The accuracy of the measurement of soil suction with the filter paper method has yet to be specified by the ASTM Standard; it does recommend disregarding measurements when a difference between two suction measurements is greater than 0.5

log(kPa) as stated earlier. In reviewing the ASTM procedure and the matric suction values estimated based on its calibration equations, the 0.5 log(kPa) accuracy rating allows for large variation of soil suctions to be acceptable for a single test specimen.

To demonstrate what the 0.5 log(kPa) accuracy rating suggested by the ASTM Standard means in terms of actual suction values, the calibration curve originally shown in Figure 8.4 is re-plotted in Figure 8.14. This new figure shows the ASTM Standard calibration curve in addition to the error lines associated with an accuracy rating of 0.5 log(kPa). As an example, assume two soil suction values, *(A & B)* were obtained from the same test specimen. If the first suction value, *(A)* was 1.74 log(kPa) (i.e. 55 kPa), using the 0.5log(kPa) accuracy rating, the second suction value, *(B)* could be either as low as 1.24 log(kPa) (i.e. 17.4 kPa) or as high as 2.24 log(kPa) (i.e. 174 kPa) and both the estimates of soil suction *(A & B)* would still be "acceptable" values. This would imply that for the 0.5log(kPa) accuracy rating given by the ASTM Standard, a 316% percent difference between the two suction values would be acceptable. Clearly this is unacceptable for use in practice.

Consequently, an improved method was used in the estimation procedures for this research. Instead of using only a two-suction comparison as outlined in the ASTM Standard, three suction values were obtained on the same test specimen. To demonstrate the effect, if three suction values were obtained for the same specimen as detailed in the previous example, then the accuracy between the suction values would be as follows. If the first suction value, *(A)* was again 1.74 log(kPa) the second suction value *(B')* could be, as before, 1.24 or 2.24 log(kPa). Assume it would be 2.24 log(kPa). If the third suction value, *(C')* was the lower limit of 1.24 log(kPa) it would be acceptable if compared to first suction *(A)*, but not if compared to the second *(B')* (i.e. 2.24 – 1.24 = 1 log(kPa) > 0.5 log(kPa). If at least three suction values are obtained from same specimen the error band between the measurements reduces. If suction *(A)* is 1.74 log(kPa), then at worst suctions *(B')* and *(C')* could only be 2.00 log(kPa) (i.e. 100 kPa) and 1.50 log(kPa) (i.e. 32 kPa) respectively, and still comply with the ASTM 0.5 log(kPa) accuracy rating. This would give a percent difference of about 75%; a significant drop from the 316% from the first example by simply increasing the number of suction values obtained from a single test specimen from two to three.

Clearly increasing the number of suction values obtained from a test specimen would increase the reliability of the results. Increasing the number of suction values would translate to the use of increasing number of filter papers placed into a test specimen. Care must be taken such that the increased number filter papers do not extract too much water from the test specimens and change specimen's suction level (Hamblin 1981 Fredlund & Rahardjo 1993).

8.8 Matric Suction and Compaction Energy

Table 8.7 and Figure 8.15 detail the matric suction values for Indian Head till measured using contact filter paper method and axis-translation for the two compaction energies used in this research. The results show that the compaction energy, hence soil structure, influences the development of the matric suction of test specimen consistent with findings of Rao & Revanasiddappa (2005). Test specimen prepared using the low compaction energy (i.e. 70 kJ/m^3) consistently show higher matric suction values than those of the prepared using the higher compaction energy (i.e. 140 kJ/m^3). To understanding why two specimens, prepared using the same soil, but compacted at different energies would have different matric suction values, the different components that affect the development of matric suction (i.e. water content, void ratio, and density) must be investigated.

The matric suction is influenced by several variables such as water content and compaction energy, void ratio, degree of saturation, and soil structure. The initial conditions of the test specimens prepared for this testing program are outlined in Table 8.9 for specimens prepared using low compaction, and Table 8.10 of those prepared using the high compaction energy. The optimum values for the low and high compaction energies specimens are found for water content values of 18% and 16% respectively.

Each of the independent variables (i.e. water content and compaction energy) will play either a dominant or secondary role in the development of matric suction of a test specimen depending on were the soil lies on the compaction plot. The two compaction energies for Indian Head till used in this research are plotted together in Figure 8.15 along with the matric suction results obtained using the axis-translation technique. As discussed in Chapter 4, during compaction the soil structure of a specimen changes from being an open structure (i.e. flocculated) when dry of the optimum state, to a dispersed structure when wet of optimum state. The effect of the change in soil structure is more pronounced in specimens prepared using the low compaction energy as the soil structure obtained after compaction is more open (i.e. flocculated) then those prepared using the high compaction energy.

The compaction energy imparted to the soil specimen is a dominate factor when comparing the varying matric suctions of test specimen for water contents on the dry side of optimum. Specimens prepared using the low compaction energy undergo significant structural changes with the increase in water content but the saturation level remains low and hence there is a larger suction. By doubling the initial compaction energy but keeping the initial water content range the same there is a decrease in the initial void ratio and hence and increase in the initial saturation thereby decreasing the suction level.

8.9 Summary

Particular attention and care is needed in the selection of a calibration curve for the estimation of soil suction using the filter paper method. It is important that the calibration curve has the suction range that is intended to be investigated. An increase in accuracy can be achieved by recalibrating filter papers for the planned testing program and environment. It is also pertinent to note that the ASTM Standard curve is a total suction curve, and care should therefore be exercised in comparing suctions measured using the contact filter paper method to the ASTM standard curve. Sibley & Williams (1990) investigated the sensitivity of different filter material and showed that depending on the suction range, the sensitivity of the filter material alters the accuracy of the measured matric suction. Significant errors in the measurement of soil suction can be obtained if the methods used to produce the calibration curve do not match the planned testing program. Increasing the number of filter papers used in the contact filter paper method will reduce the allowable percent difference and increase the accuracy of the estimated soil suction values. Preliminary tests should be undertaken to ensure that planned number of filter papers does not significantly alter the initial water content and hence the suction of a test. The results of this study have shown that if proper precautions and care (i.e. 10% formaldehyde to prevent bacterial growth, contact stress less than 1 kPa to ensure contact, and increased equilibrium time) are taken the contact filter paper method is as reliable as the axis-translation technique in the measurement of matric suction.

A standardized matric suction equation was developed to relate matric suction to the initial water content of a test specimen. The suction values calculated based on this equation closely match the values measured using the axis translation technique.

It has been shown that the compaction energy significantly influences the soil suction in the soil specimens. The increase in compaction energy will decrease the void ratio and thereby decrease the matric suction of a specimen prepared with the same water contents.

Table 8.1: Listing of published calibration equations including the University of Ottawa (2005).

Equation	Authors	Suction Range (pF)	Suction Range (kPa)	Suction Range High/Low	Suction Type Matric/Total	Filter Paper wc Range (%)	Suction Equation
1	Fawcett & Collis-George (1967)	3 - 7	100 - 1e6	High	N/A	< 45.3 ASTM	$h_{pF} = 6.601 - 0.0839wc\%_{fp}$
2		1 - 3	1 - 100	Low	N/A	> 45.3 ASTM	$h_{pF} = 3.642 - 0.0151wc\%_{fp}$
3	Hamblin (1981)	N/A	1 - 3000	Both	N/A	N/A	$Ln\ h = 2.397 - 3.683Ln(wc\%_{fp})$
4	Chandler & Gutierrez 1986	2.9 - 4.8	80 - 6000	High	N/A	N/A	$h_{pF} = 5.850-0.0622wc\%_{fp}$
5	Chandler et al. 1992a	N/A	80 - 6000	High	N/A	? 47%	$log\ h = 4.84 - 0.0622wc\%_{fp}$
6		N/A	N/A	Low	N/A	> 47%	$log\ h = 6.05 - 2.48log(wc\%_{fp})$
7	Chandler et al. 1992b	N/A	? 80	High	N/A	? 47%	$log\ h = 4.84 - 0.0622wc\%_{fp}$
8		N/A	? 80	Low	N/A	? 47%	$log\ h = 6.05 - 2.48log(wc\%_{fp})$
9	Crilly & Chandler 1993	N/A	N/A	High	N/A	15 ? wc%fp ? 47%	$log\ h = 4.84 - 0.0622wc\%_{fp}$
10		N/A	N/A	Low	N/A	> 47%	$log\ h = 6.05 - 2.48log(wc\%_{fp})$
11	Deka et al. 1995	N/A	> 47.9	High	N/A	< 55.6	$log\ h = 5.297 - 6.507(wc\%_{fp})$
12		N/A	< 47.9	Low	N/A	> 55.6	$log\ h = 2.380 - 1.259(wc\%_{fp})$
13	Deka et al. 1995	N/A	> 48.9	High	N/A	< 51.3	$log\ h = 5.320 - 7.083(wc\%_{fp})$
14		N/A	< 48.9	Low	N/A	> 51.3	$log\ h = 2.338 - 1.266(wc\%_{fp})$
15	Deka et al. 1995 Fawcett & Collis-George 1967 Chandler & Gutierrez 1986 Greacen et al. 1987	N/A	> 51.6	High	N/A	< 51.2	$log\ h = 5.144 - 6.699(wc\%_{fp})$
16	Deka et al. 1995 Fawcett & Collis-George 1967 Chandler & Gutierrez 1986 Greacen et al. 1987	N/A	< 51.6	Low	N/A	> 51.2	$log\ h = 2.383 - 1.309(wc\%_{fp})$
17	Leong et al. 2002	N/A	< 1000	High	Matric	< 47	$log\ h = 4.945 - 0.0673wc\%_{fp}$
18		N/A	< 1000	Low	Matric	? 47	$log\ h = 2.909 - 0.0229wc\%_{fp}$
19	Leong et al. 2002	N/A	> 1000	High	Total	< 26	$log\ h = 5.31 - 0.0879wc\%_{fp}$
20		N/A	> 1000	Low	Total	? 26	$log\ h = 8.779 - 0.222wc\%_{fp}$
21	ASTM D5298-03	N/A	N/A	High	N/A	< 45.3	$log\ h = 5.327 - 0.0779wc\%fp$
22		N/A	N/A	Low	N/A	> 45.3	$log\ h = 2.412 - 0.0135wc\%fp$
23	University of Ottawa	N/A	300	High	Matric	? 38 %	$log\ h = 151.13 - 94.343log(wc_{fp})$
24		N/A	20 - 300	Low	Matric	> 38 %	$log\ h = 6.7116 - 2.932log(wc_{fp})$

Table 8.2: Matric suctions values calculated using the ASTM Standard calibration equations.

Low Compaction Energy					High Compaction Energy				
Soil Water Content (%)	Filter Paper wc (%)	Log (Matric Suction) (kPa)	Matric Suction (kPa)	Median Matric Suction (kPa)	Soil Water Content (%)	Filter Paper wc (%)	Log (Matric Suction) (kPa)	Matric Suction (kPa)	Median Matric Suction (kPa)
14.27	37.07	2.44	275	275	14.32	37.65	2.39	248	251
	37.38	2.41	260			37.51	2.40	254	
	36.68	2.47	295			37.58	2.40	251	
15.19	37.52	2.40	254	241	15.33	38.17	2.35	226	231
	37.80	2.38	241			38.05	2.36	231	
	37.90	2.37	237			38.01	2.37	232	
16.37	39.69	2.24	172	162	16.46	44.70	1.84	#n/a	105
	40.36	2.18	152			43.69	1.92	#n/a	
	40.47	2.17	#n/a			42.46	2.02	105	
17.33	43.55	1.93	86	86	17.33	42.33	2.03	107	82
	47.33	1.77	59.3			44.46	1.86	73.0	
	42.65	2.00	101.0			43.81	1.91	82.0	
18.32	61.39	1.58	38.3	39.3	18.15	53.85	1.69	48.4	48.4
	59.76	1.61	40.3			53.21	1.69	49.4	
	60.59	1.59	39.3			54.70	1.67	47.2	
19.23	55.15	1.67	46.5	41.3	19.15	61.67	1.58	38.0	32.6
	58.97	1.62	41.3			66.60	1.51	32.6	
	64.73	1.54	34.5			68.10	1.49	31.1	

Table 8.3: Median matric suction values from measured filter paper water contents using the ASTM Standard calibrations equations.

Low Compaction Energy		High Compaction Energy	
Soil Water Content (%)	Median Matric Suction (kPa)	Soil Water Content (%)	Median Matric Suction (kPa)
14.27	275	14.32	251
15.19	241	15.33	231
16.37	162	16.46	105
17.33	86	17.33	82
18.32	39.3	18.15	48.4
19.23	41.3	19.15	32.6

Table 8.4: Matric suction values calculated using the measured filter paper water contents and published calibration equations.

	Median Matric Suction (kPa)						Compaction Energy
Soil Water Content (%)	14	15	16	17	18	19	
Fawcett & Collis-George (1967)	310	269	164	89	53	56	Low
	281	256	109	84	67	43	High
Hamblin (1981)	425	395	311	235	70	77	Low
	404	386	232	230	107	49	High
Chandler (1986 - 1992)	342	308	214	135	43	46	Low
	318	297	133	130	57	34	High
Deka et al. (1995)	458	409	276	169	39	41	Low
	423	394	165	162	48	32	High
Leong et al. (2002)	282	252	169	103	33	36	Low
	261	242	101	99	47	24	High

Table 8.5: Average percent difference between matric suction values calculated with the ASTM Standard calibration equations to those calculated with published calibration equations.

	Average Percent Difference (%)						Average Error
Soil Water Content (%)	14	15	16	17	18	19	(%)
Fawcett & Collis-George (1967)	12.2	11.3	11.3	2.8	36.1	33.2	17.8
Hamblin (1981)	57.8	65.7	106.8	176.5	99.5	68.5	95.8
Chandler (1986 - 1992)	25.6	28.4	29.3	58.1	13.2	6.9	26.9
Deka et al. (1995)	67.6	70.1	63.9	96.6	1.3	0.7	50.0
Leong et al. (2002)	3.2	4.7	3.8	20.5	8.7	19.0	10.0

Table 8.6: Comparison of the matric suction values calculated using the ASTM Standard to those calculated with the new University of Ottawa calibration equations.

	Low Compaction Energy			High Compaction Energy		
	University of Ottawa	ASTM D5298-03		University of Ottawa	ASTM D5298-03	
Soil Water Content (%)	Median Matric Suction (kPa)	Median Matric Suction (kPa)	Percent Difference (%)	Median Matric Suction (kPa)	Median Matric Suction (kPa)	Percent Difference (%)
14	N/A	275	#N/A	350	251	39.5
15	202	241	16.4	120	231	48.1
16	100	162	38.1	80	105	23.9
17	80	86	6.6	79	82	3.8
18	30	39	22.3	43	48	11.0
19	33	41	20.1	23	33	29.1

Table 8.7: Listing of the measured matric suction values from the various methods and equations for specimens compacted using low compaction energy.

	Low Compaction Energy				
	Contact Filter Paper Method		Stanadard Equation	Axis-Translation	Axis-Translation
Soil Water Content (%)	University of Ottawa Matric Suction (kPa)	ASTM Matric Suction (kPa)	University of Ottawa Matric Suction (kPa)	University of Ottawa Matric Suction (kPa)	Vanapalli 1999 Matric Suction (kPa)
14.3	#N/A	275	322	290	269
15.2	202	241	200	210	222
16.4	100	162	113	130	161
17.3	80.3	86	73	95	112
18.3	30.5	39	48	60	62
19.2	33.0	41	33	35	15

Table 8.8: Listing of the measured matric suction values from the various methods and equations for specimens compacted using low compaction energy.

	High Compaction Energy				
	Contact Filter Paper Method		Stanadard Equation	Axis-Translation	Axis-Translation
Soil Water Content (%)	University of Ottawa Matric Suction (kPa)	ASTM Matric Suction (kPa)	University of Ottawa Matric Suction (kPa)	University of Ottawa Matric Suction (kPa)	Vanapalli 1999 Matric Suction (kPa)
14.3	350	251	313	280	269
15.3	119	231	186	205	222
16.5	80	105	108	120	161
17.3	79	82	73	80	112
18.1	43	48	51	55	62
19.2	23	33	34	35	15

Table 8.9: Initial conditions of specimens prepared using low compaction energy. Optimum values are indicated with by boldface.

Compaction Energy	Test Type	Initial Water Content, w (%)	Initial Void Ratio, e	Dry Unit Weight, γ (kN/m^3)
Low 70 kJ/m^3	Inundated	14	0.732	15.40
		15	0.669	15.99
		16	0.629	16.38
		17	0.591	16.78
		18	**0.572**	**16.97**
		19	0.581	16.87

Table 8.10: Initial conditions of specimens prepared using high compaction energy. Optimum values are indicated with by boldface.

Compaction Energy	Test Type	Initial Water Content, w (%)	Initial Void Ratio, e	Dry Unit Weight, γ (kN/m^3)
High 140 kJ/m^3	Inundated	14	0.545	17.27
		15	0.520	17.56
		16	**0.511**	**17.66**
		17	0.520	17.56
		18	0.537	17.36
		19	0.545	17.27

Figures:

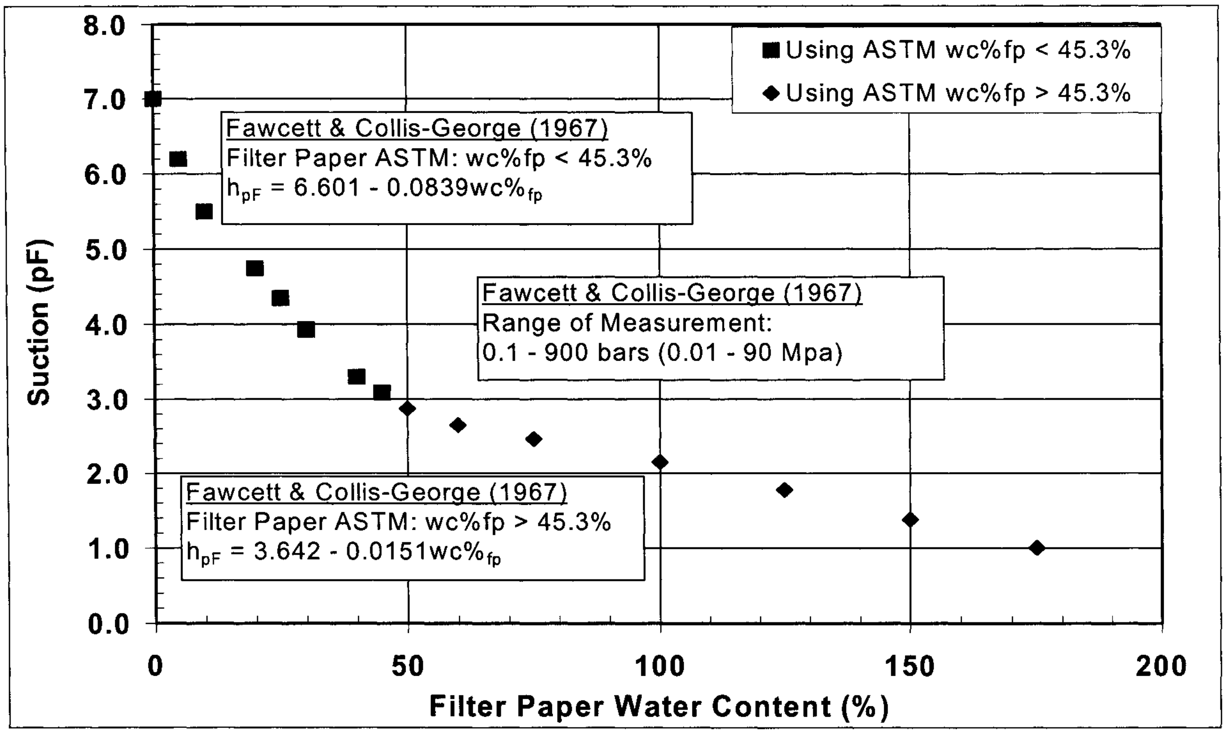


Figure 8.1: Calibration curve for Whatman 42 filter paper from Fawcett & Collis-George (1967).

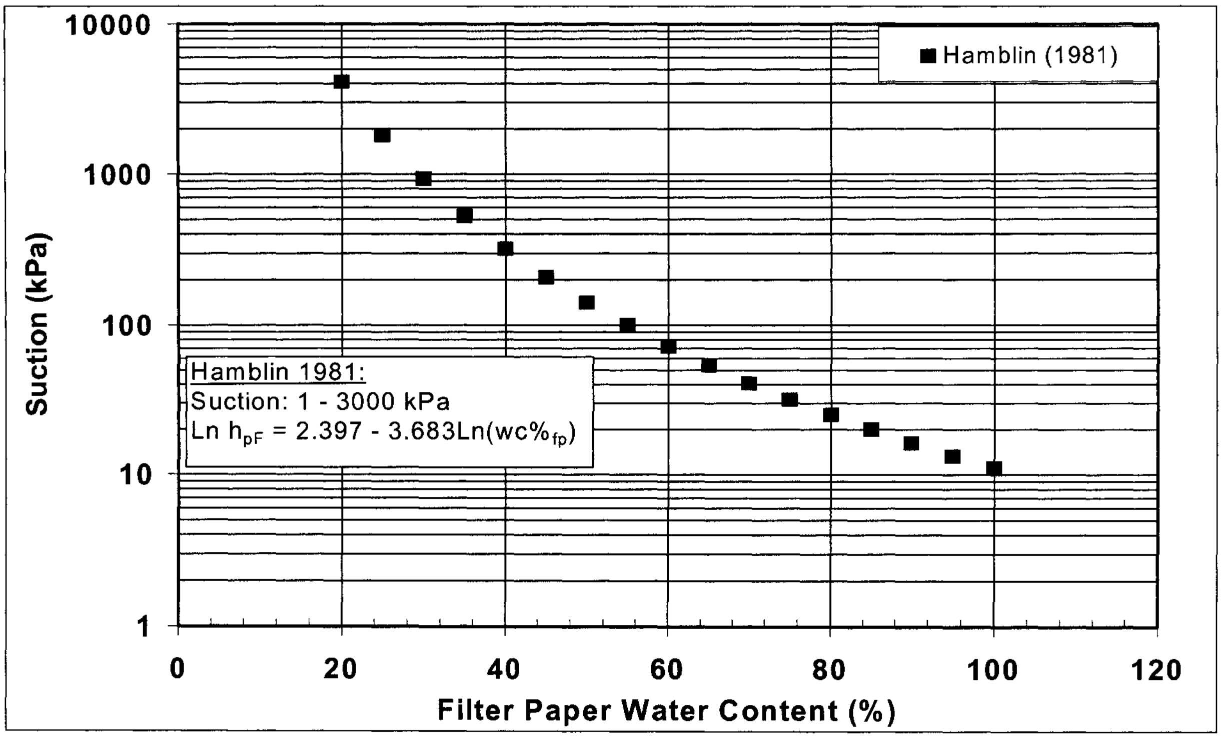


Figure 8.2: Calibration curve for Whatman 42 filter paper from Hamblin (1981).

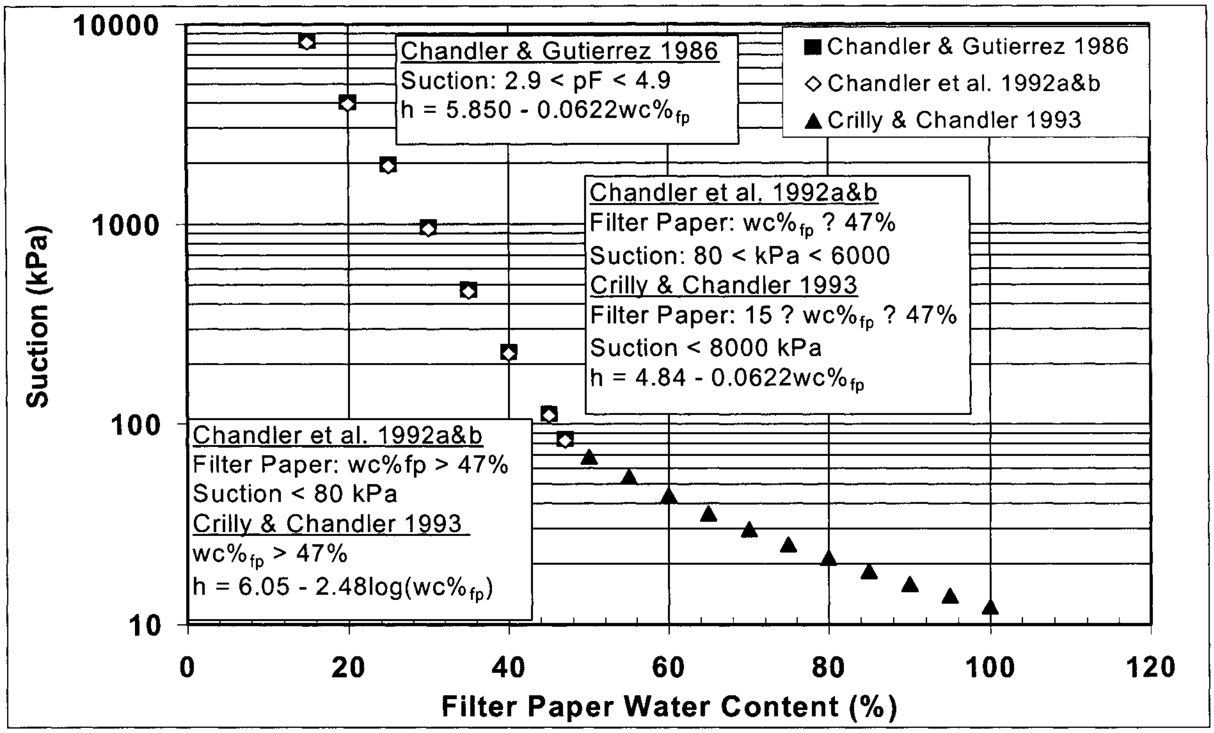


Figure 8.3: Calibration curves for Whatman 42 filter paper from Chandler & Gutierrez 1986 Chandler et al. 1992a&b and Crilly & Chandler 1993.

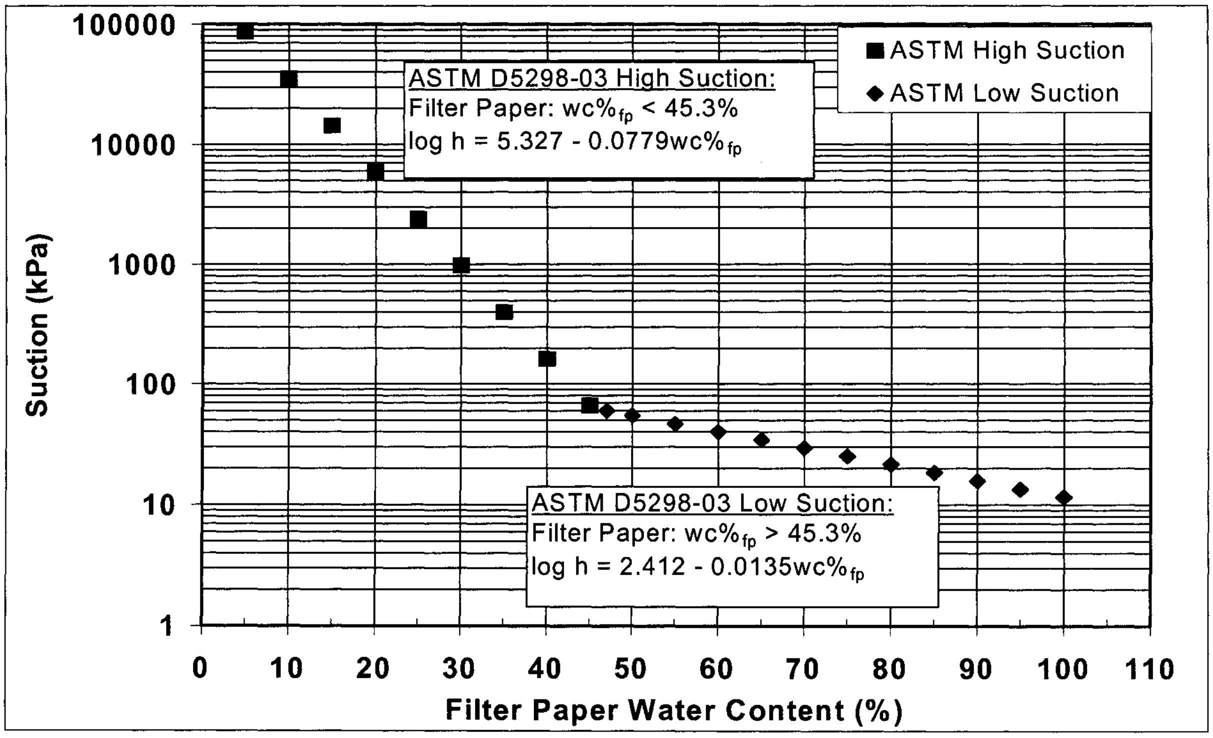


Figure 8.4: Calibration curve for Whatman 42 filter paper from ASTM D5298-03 for suction measurement using the filter paper method.

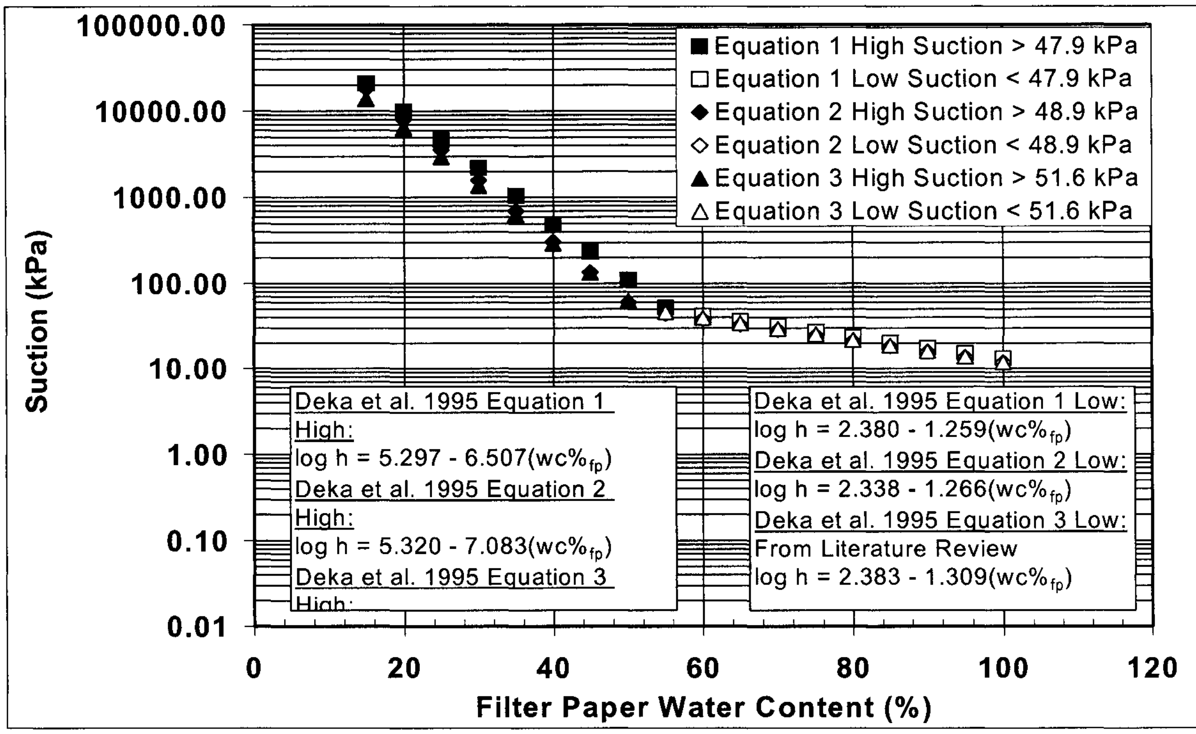


Figure 8.5: Calibration curve for Whatman 42 filter paper from Deka et al. 1995.

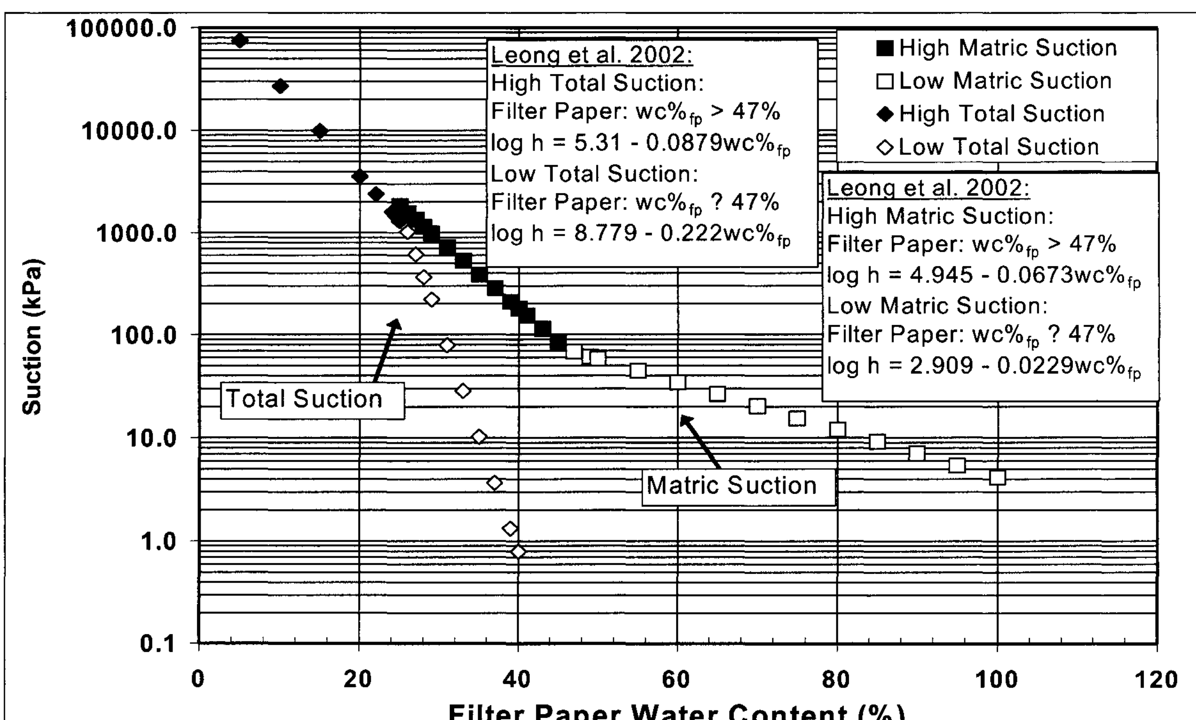


Figure 8.6: Calibration curves for Whatman 42 filter paper from Leong et al. (2002).

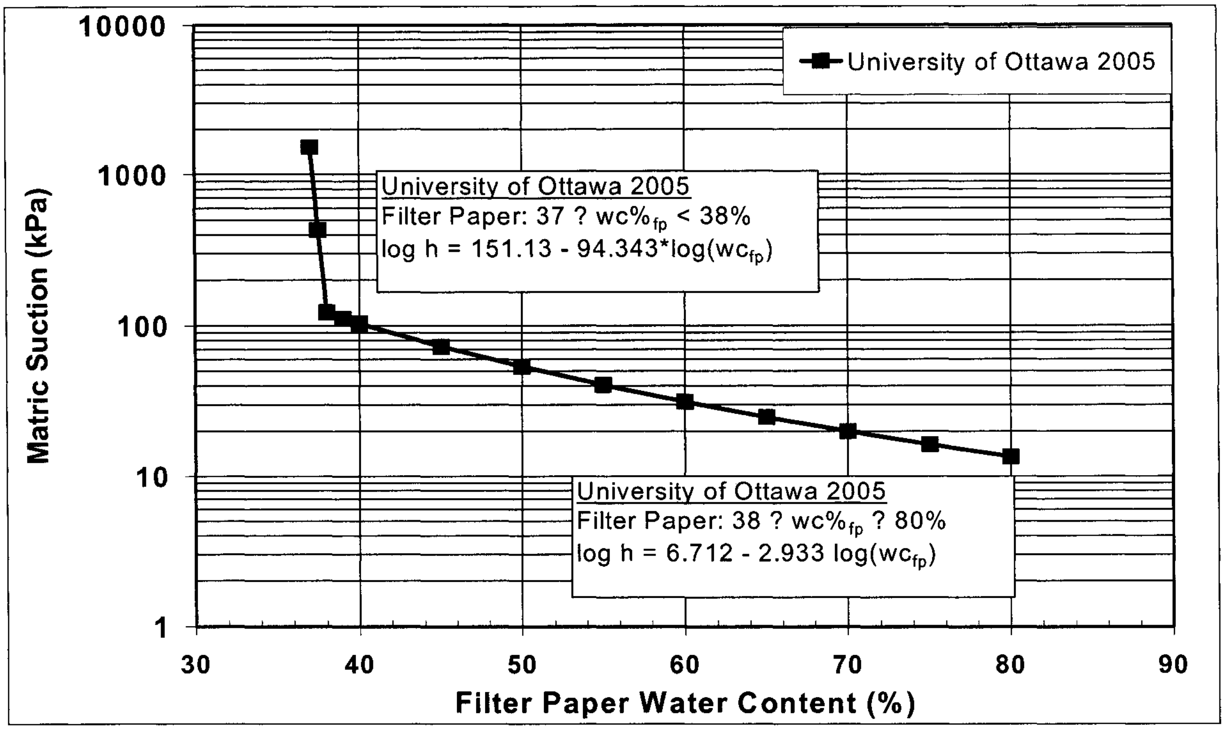


Figure 8.7: Calibration curve for Whatman 42 filter paper from the University of Ottawa 2005 for matric suction measurement using the filter paper method.

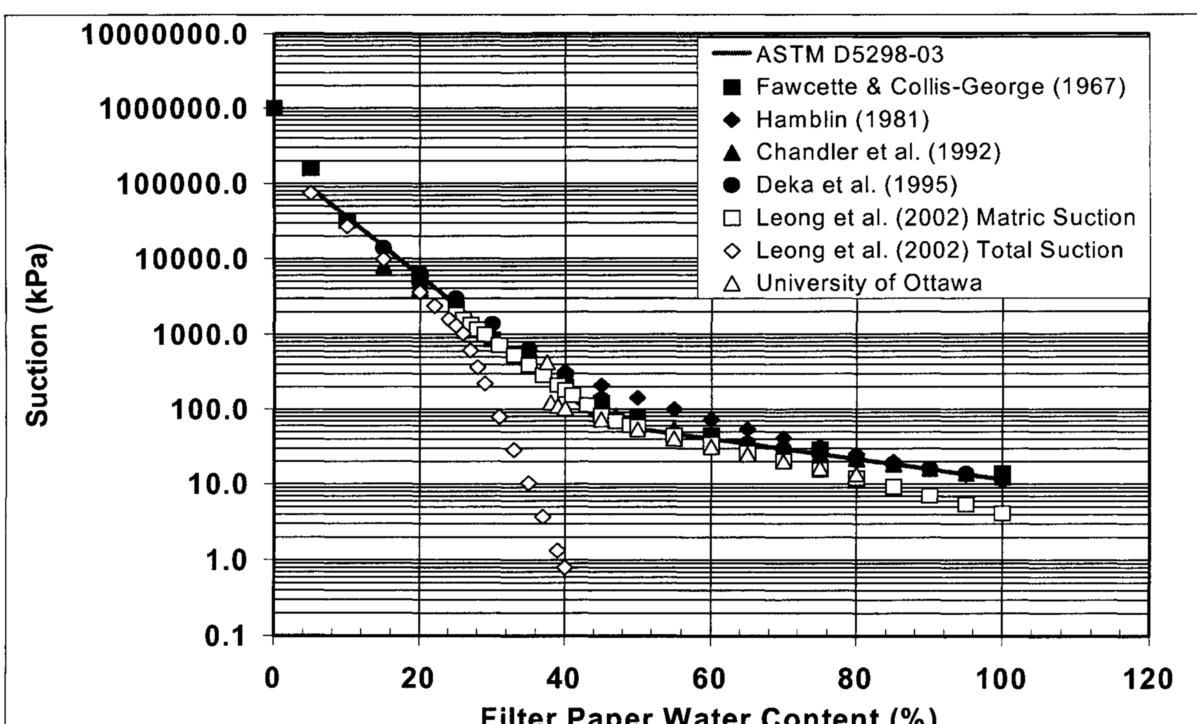


Figure 8.8: Calibration curves for Whatman 42 filter paper from published data including the new curve from the University of Ottawa in comparision to ASTM D5298-03.

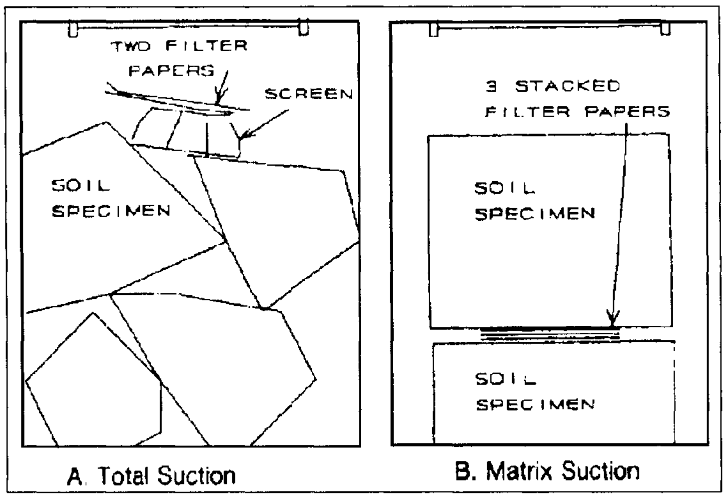


Figure 8.9: Recommended specimen setup from ASTM D5298-03 for measuring matric and total suction.

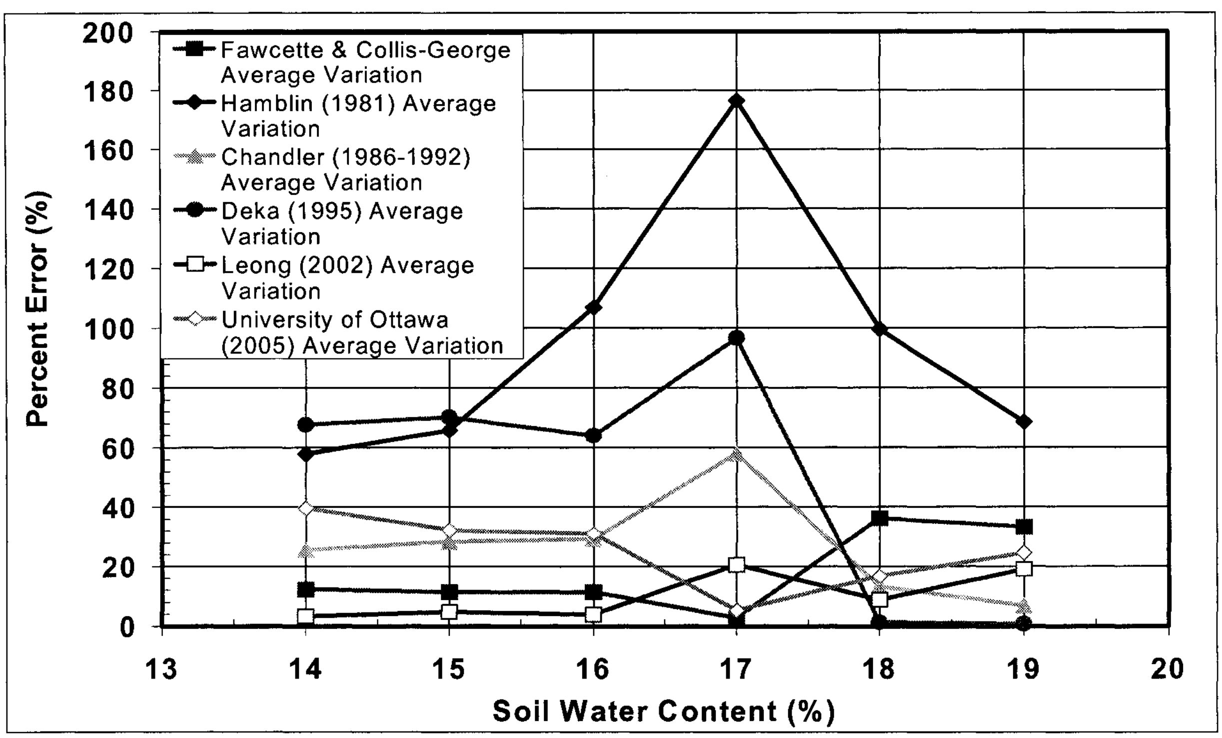


Figure 8.10: Percent variation between the ASTM Calibration equation to those published in the literature.

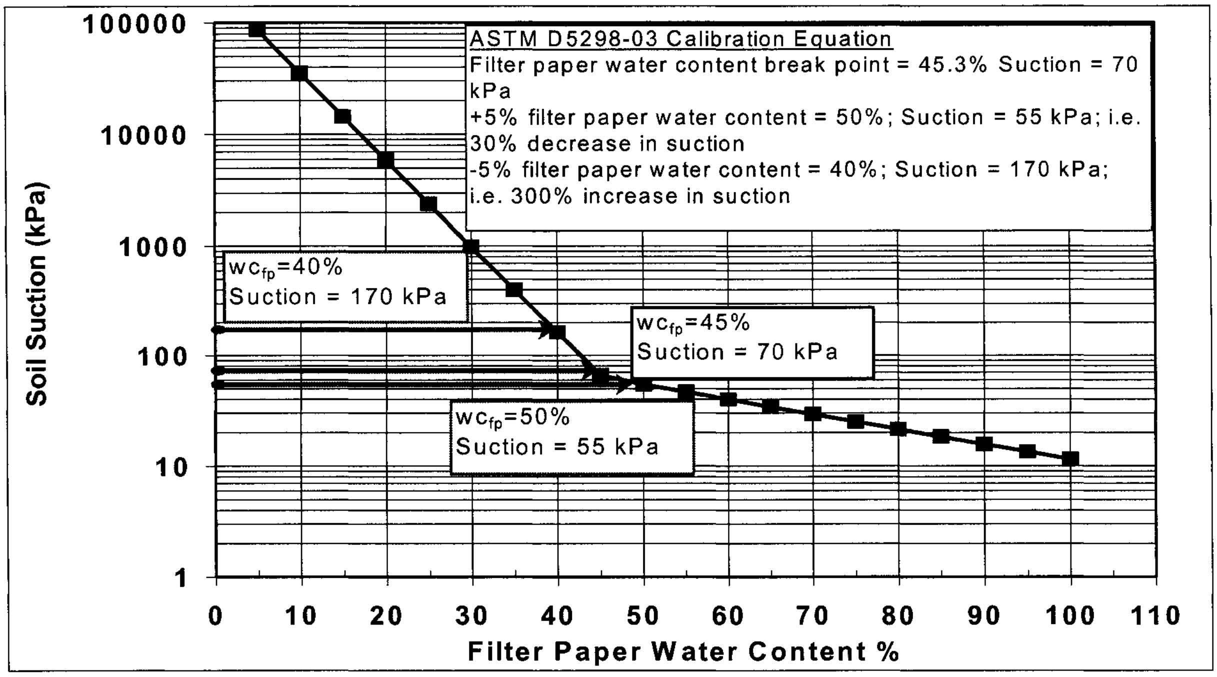


Figure 8.11: ASTM Standard calibration curve showing sensitivity of the equations ±5% of the filter paper water content breakpoint of 45.3%.

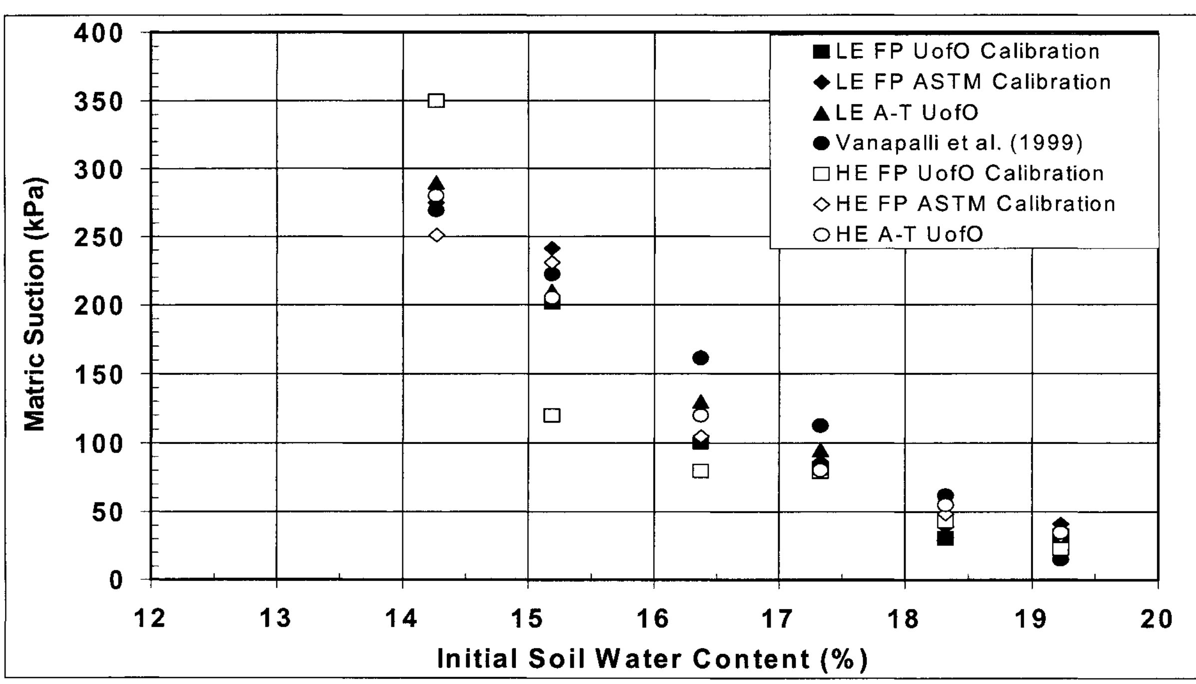


Figure 8.12: Graph of matric suction values for Indian Head till measured using contact filter paper method and axis-translation and varying compaction energies.

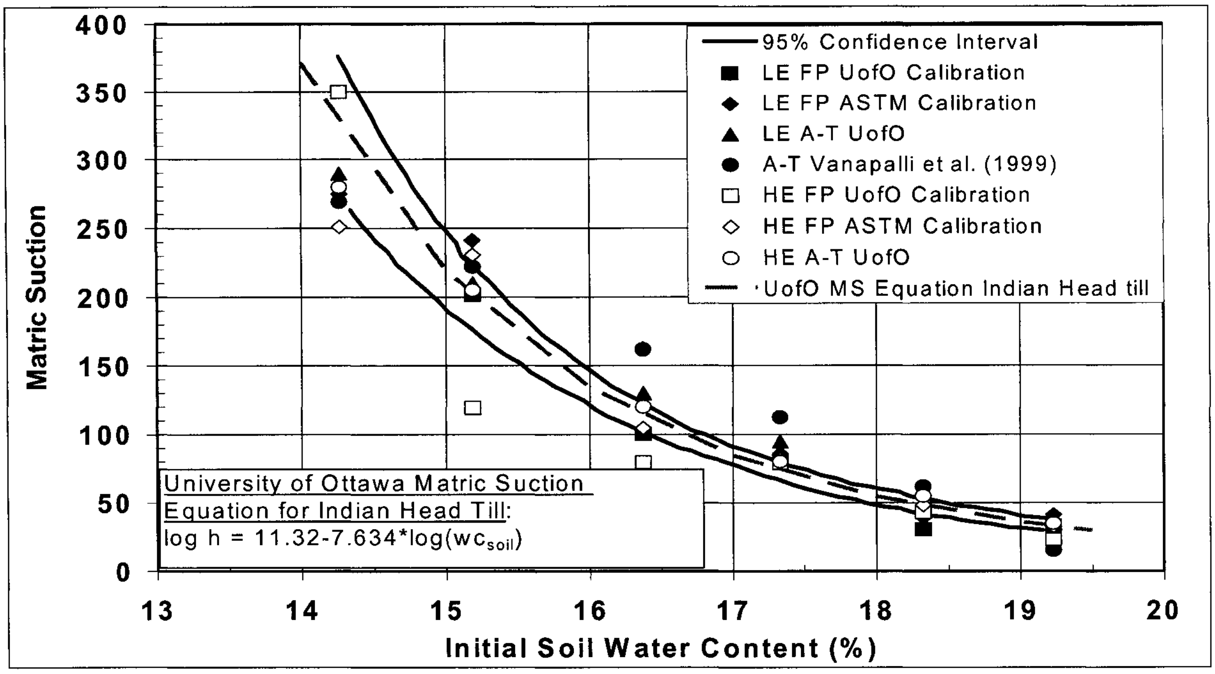


Figure 8.13: Standardized equation to relate matric suction the to soil water content for Indian Head till with 95 % confidence interval.

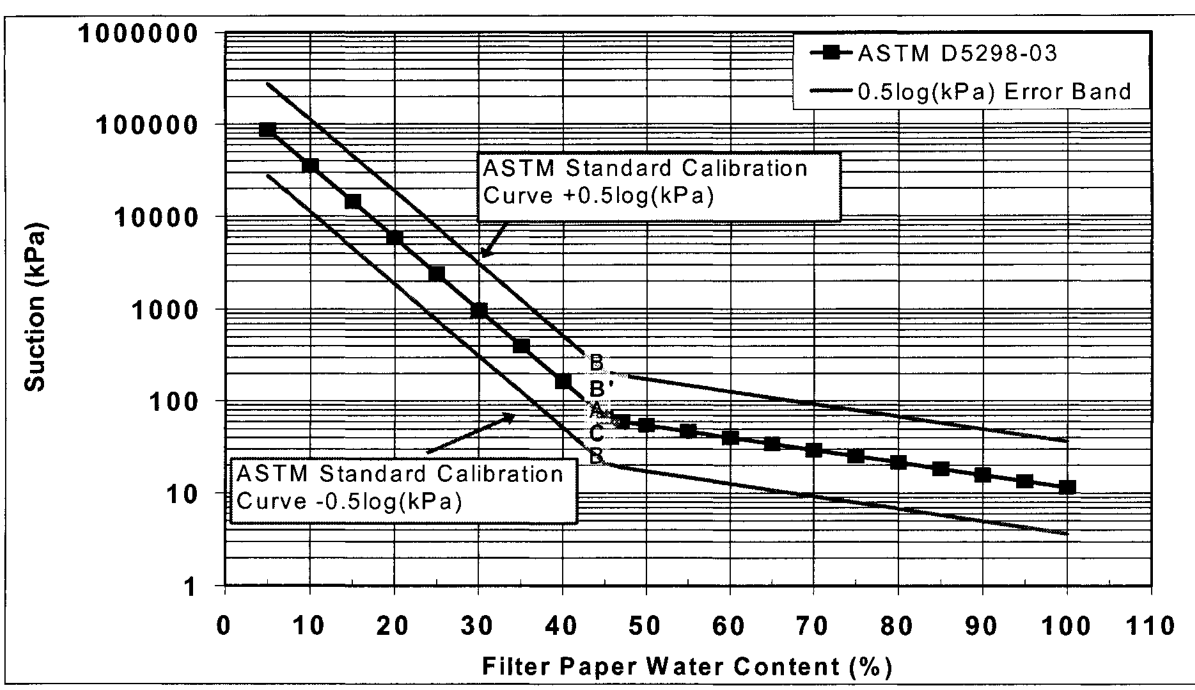


Figure 8.14: ASTM Standard calibration curve showing the 0.5log(kPa) error bands

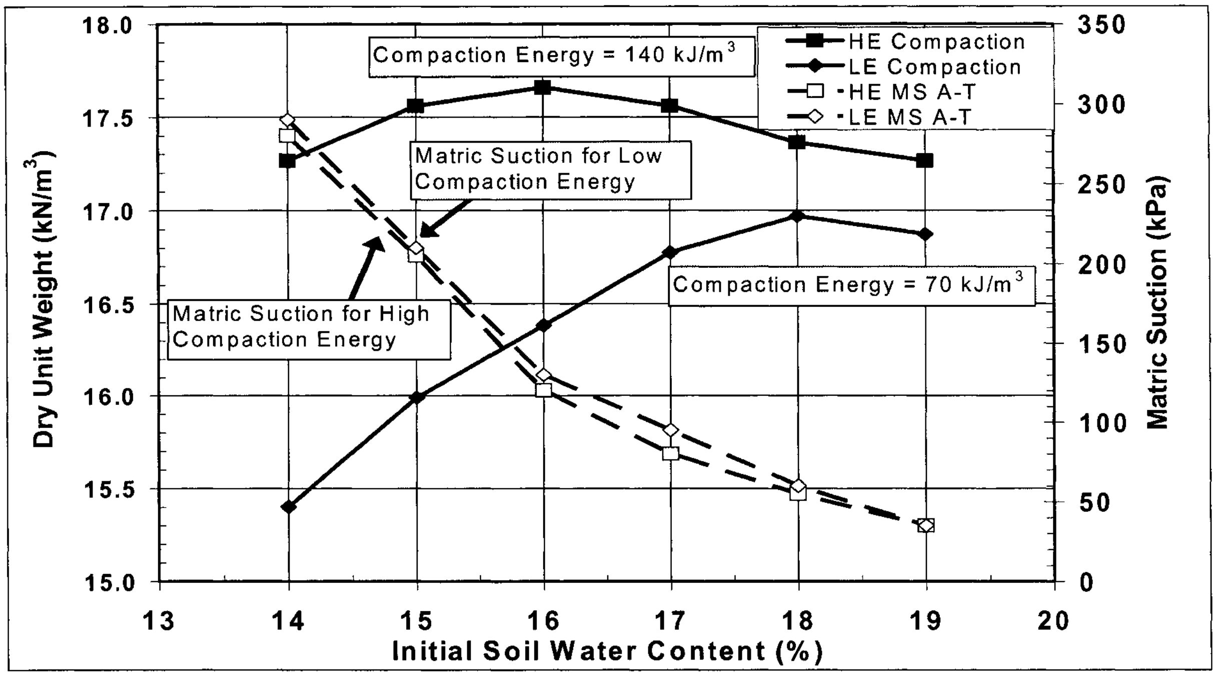


Figure 8.15: High (HE) and low (LE) compaction energy curves for Indian Head till and the matric suction values obtained from this research using axis-translation (A-T).

Chapter 9: Summary and Conclusions

9.1 Introduction

In compacted soils, several parameters such as the applied loading, water content, compaction energy and soil structure influence the compressibility and settlement characteristics of an unsaturated soil. The key point to emphasize though is that the serviceability of most engineering structures is controlled by the settlement of its foundation.

The broad objective of this research was to understand the difference in the compressibility behaviour of an unsaturated compacted soil when compared to its saturated state. From this broad starting point came two finite goals. The first was the development of a simple and reliable technique to estimate soil suction in the range of 20 – 500 kPa and the second was to quantify the influence of both matric suction and soil structure on the compressibility characteristics of Indian Head till

9.2 Soil prepared for this research

The soil used in this research project was a glacial till obtained from Indian Head, Saskatchewan. This soil was chosen because the University of Saskatchewan has undertaken extensive research studies over the last twenty years and valuable information about the properties of this soil under unsaturated conditions are available in published literature (Krahn and Fredlund 1976, Ho et al. 1992, Fredlund et al. 1995, Vanapalli et al. 1999). Using this soil allowed for the comparison of both the compressibility characteristics soil suction values from this research to that of the published works.

9.3 Methods in the Estimation of Soil Suction

Two different techniques were used to estimate the soil suction in this research namely; axis-translation (i.e. direct method) and the contact filter paper method (i.e. indirect method).

9.3.1 Axis-translation technique

There were two key improvements to the axis-translation technique that were brought forth from this research. The first was in the area of the removal of diffused air. A Greylor PQ 12 V pump was incorporated into the new design of the single specimen null pressure plate device used to determine matric suction using the axis-translation technique. The pump allowed for the quick and efficient removal of any diffused air bubbles that can form under the high air-entry disc during testing. An electrical dimmer was used to control the pumping force so that no damage was done to the high air-entry disc, and in the prevention of water cavitation during pumping. The second improvement was in the area of accuracy. The diameter of the glass tube indicator that monitors the null position of the system was reduced, from 3 mm to 1 mm. The smaller diameter tube would reduce by a factor of nine, the volume of water required to indicate a change in the null position which would greatly improve the accuracy of the technique.

9.3.2 Contact filter paper method

Different procedures were explored for the estimation of matric suction using the conventional contact filter paper technique during this research program. Three fundamental changes to this conventional technique have been used in this research. First, if the calibration equilibrium time is to match the equilibrium time planned for the estimation of matric suction, then an increase in the concentration of formaldehyde from the recommended 2% to 10% is required to prevent the development of bacteria. With the increased concentration in formaldehyde though, special precautions are required so that formaldehyde is removed from the air being released from the null pressure plate device into the laboratory at the end of the equilibrium period. Second, when using the contact filter paper method, it is important to ensure that there is direct contact between the filter paper and the pore-water of the test specimen so that moisture flow takes place primarily in the liquid phase. It has been shown in this research that by applying a large normal stress significantly affects the calibration curve. It is therefore recommended that a contact stress of no more than 1 kPa be used for the contact filter paper method. Lastly it is recommend that the equilibrium time used for moisture transfer be increased from the recommended 7 days to 18 days, if a stack of three filter papers is used in the estimation of matric suction. The extra time would allow for the system to come to equilibrium with the soil water (i.e. the two sacrificial filter papers protecting the filter paper used for water content measurement) and then the filter paper used to measure matric suction.

9.4 Compressibility Characteristics

Several parameters which include initial compaction water content, compaction energy, and saturation influence the compressibility characteristics of unsaturated soil specimens. In fact, it is the interplay of all these parameters that describes the actual deformation of the soil due to an applied stress (Elsbury 1990). The matric suction of an unsaturated test specimen offers resistance to deformation in spite of an increase in the applied stress for unsaturated specimens. This behavior can also be explained in terms of degree of saturation. However, the influence of all the parameters combined can be understood in terms of the stress state variable matric suction, $(u_a - u_w)$.

The matric suction influence on the compressibility characteristics of the unsaturated specimens is significantly reduced for specimens prepared with initial water contents greater that 17% as their degree of saturation, *(S)* is relatively high. Also during loading, the matric suction reduces as the applied stress increases and its effect on the compressibility is lost in the high stress range. The effect of initial compaction energy on the compressibility characteristics is mainly observed when the energy used for compaction is relatively large. In this research by doubling the initial compaction effort showed a significant drop in the deformation characteristics. Higher compaction energies result in the preparation of soil specimens with relatively larger initial unit weights which offer more resistance to deformation. The effect of soil structure is clearly evident in specimens prepared using low compaction energy and low initial water contents. These specimens generally have a higher void ratio and would compress more even under relatively lower applied stresses. As with matric suction, the effect of soil structure on the compressibility characteristics is no longer seen in the high stress range.

9.5 Suggestions and Recommendations for Further Study

A thorough investigation into the compressibility characteristics and the estimation of suction of the Indian Head till was preformed through this research project. However, due to limitation of time and the need to restrict the scope of this thesis, there are aspects arising from work that need further research and/or experimental verification. Some of these aspects are outlined below.

9.5.1 Compressibility studies

Further study into the time rate of settlement of soils in an unsaturated state is important in the development of a better understanding of compressibility characteristics of unsaturated soils. It is essential though, to restrict any further research to practical engineering techniques similar to the focus of this research. A single soil was studied in this research so that the results of the new testing equipment developed could be verified with published data of a similar till. With the development of an unsaturated laboratory at the University of Ottawa, and the establishment of testing procedures complete, is now possible to expand the soil database and develop a more general compressibility framework for unsaturated soils.

9.5.2 Techniques for the estimation of soil suction

Determination of matric suction reliably using simple technique is of primary concern and needs full investigation for the advancement of the principles of unsaturated soil mechanics into engineering practice. Therefore further research into the different components (i.e. matric and total suction) and their direct determination or estimation techniques is required. For the filter paper techniques, further study into the differences between two separate calibration curves is required in the measurement of total and matric suction is also required

The axis-translation technique is currently a long and cumbersome test. Further study in the automation of this testing procedure is urgently required. By reducing the time for soil suction estimates using the axis-translation technique, would make the technique more practical and would allow for a more efficient development of soil suction profiles.

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Appendix A:

Compression Results

Appendix A:

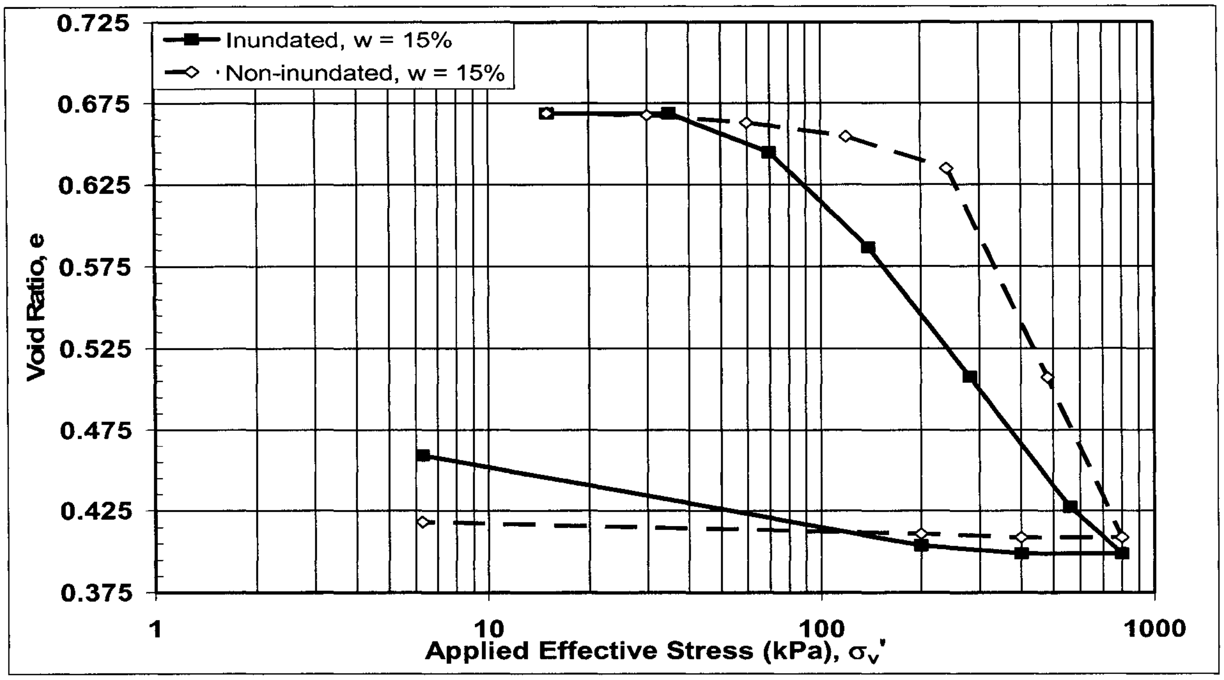

Figure A.1: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 15%.

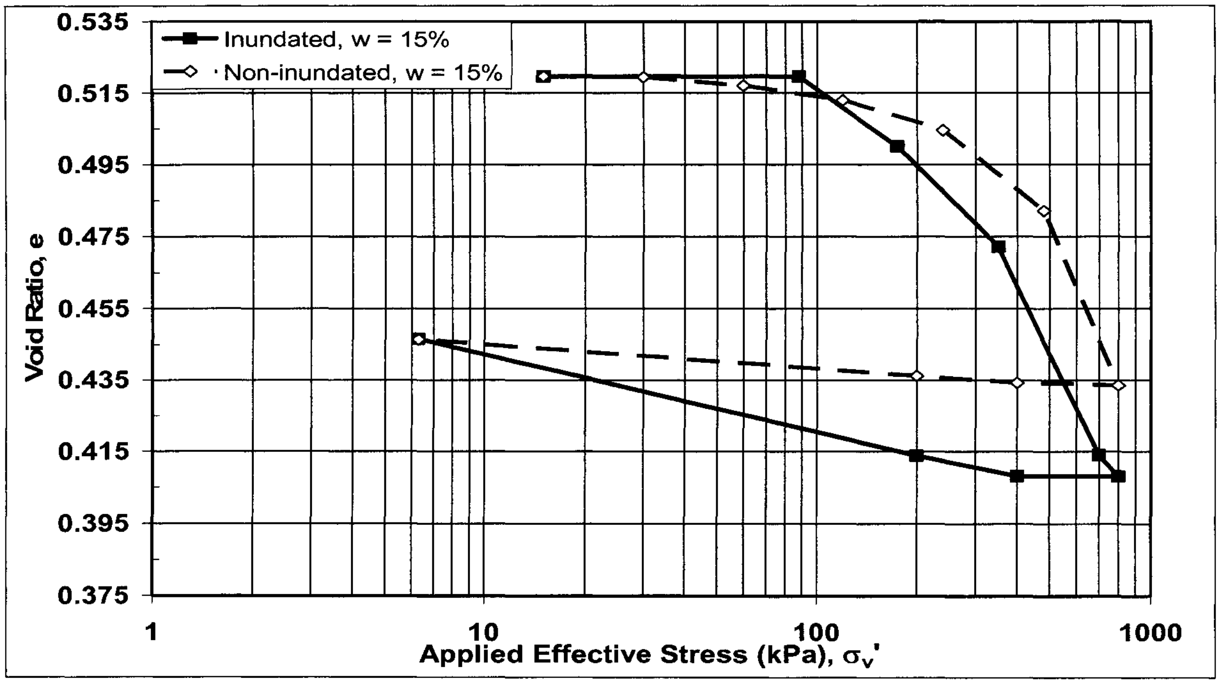

Figure A.2: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content = 15%.

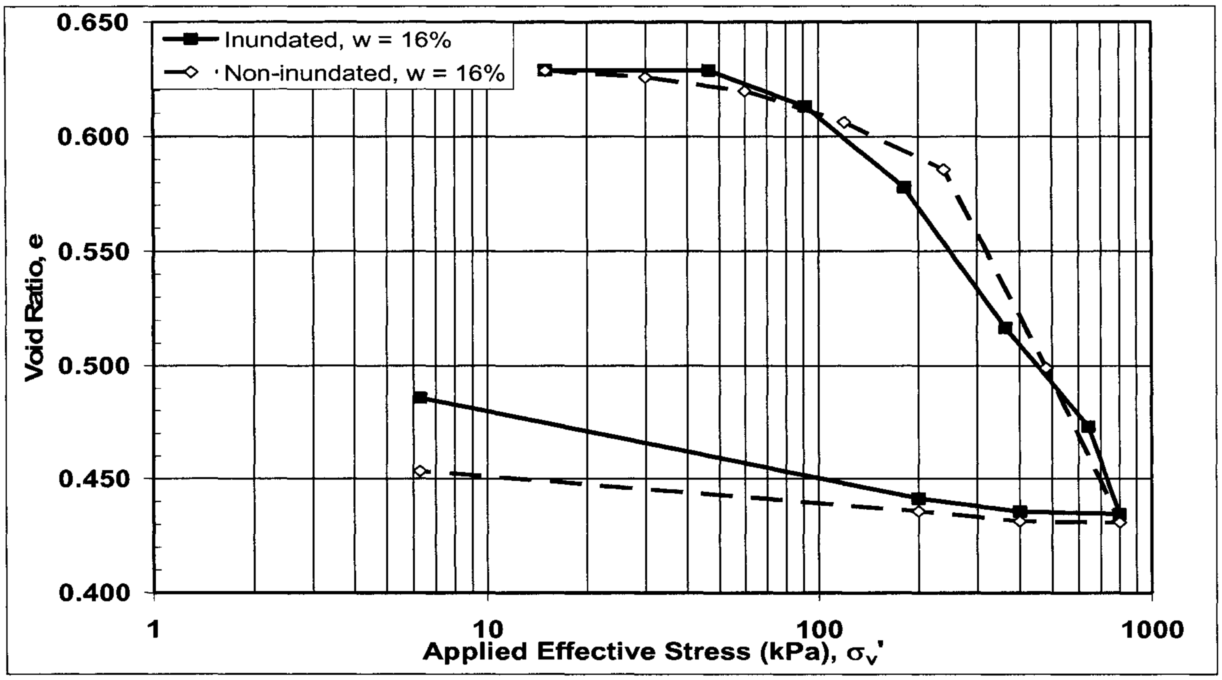

Figure A.3: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 16%.

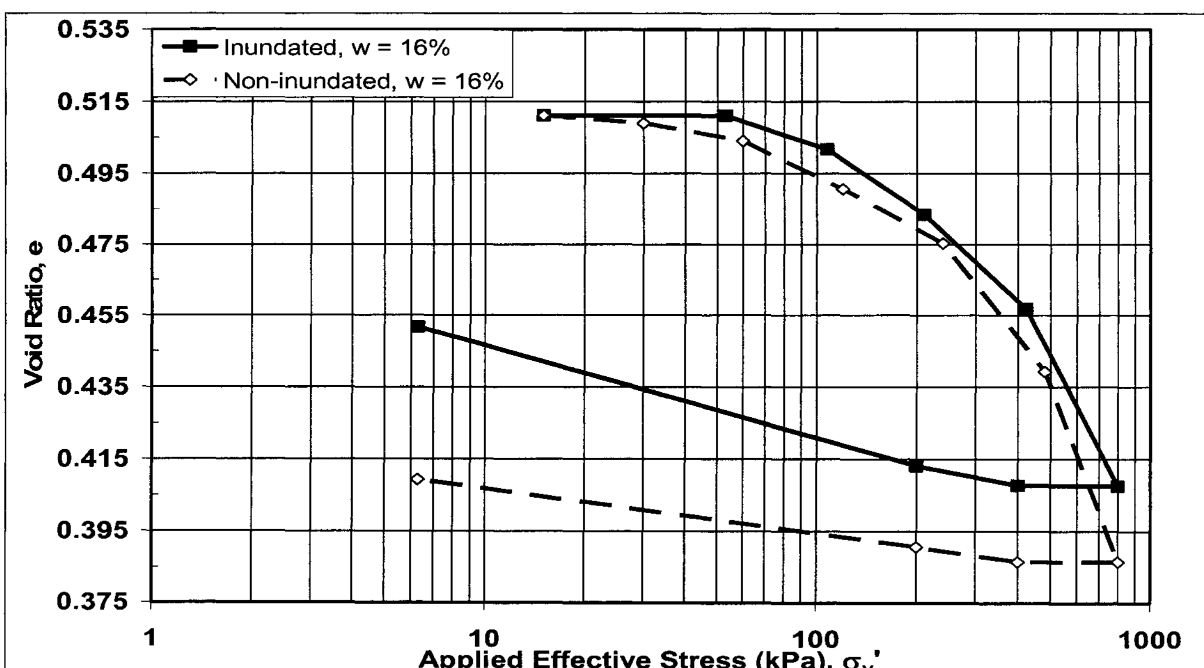

Figure A.4: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content = 16 %.

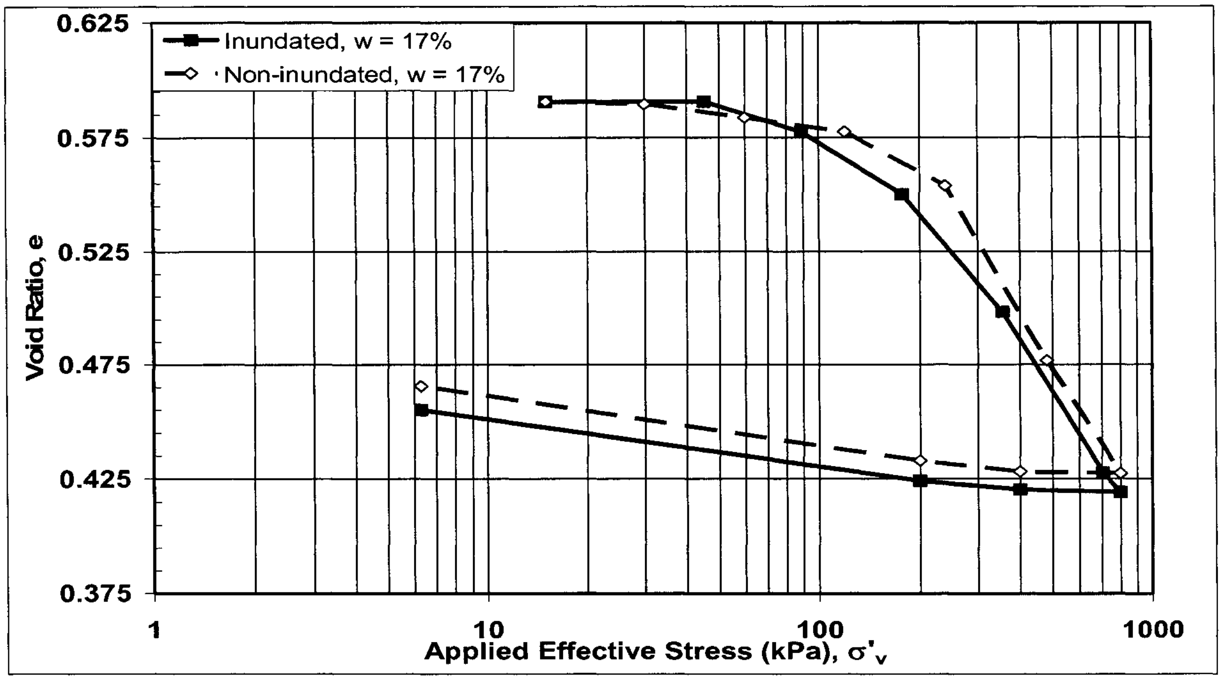

Figure A.5: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 17%.

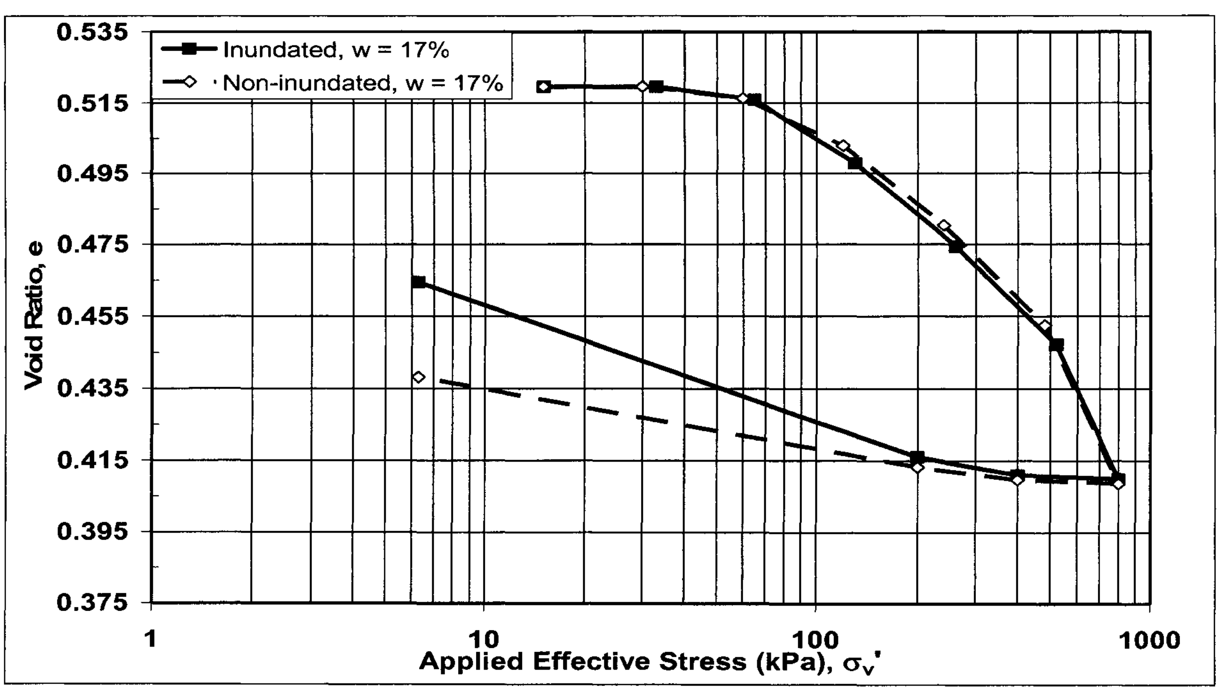

Figure A.6: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content = 17 %.

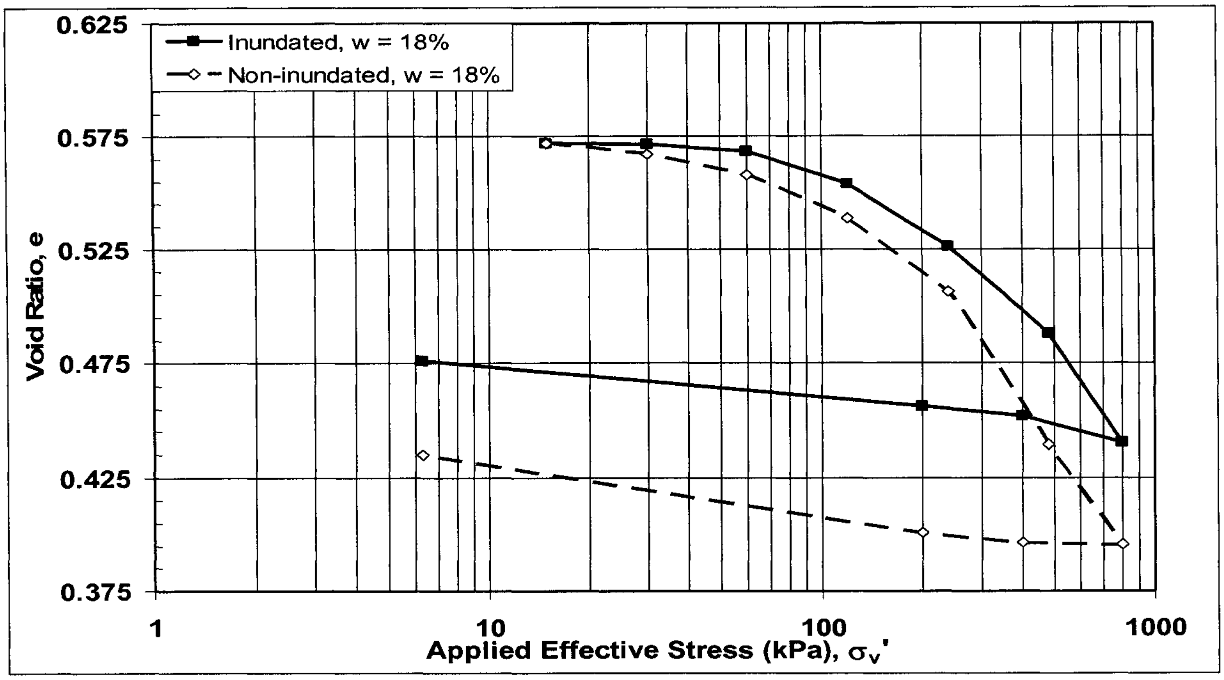

Figure A.7: Comparison of e- logσ$_v$' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 18%.

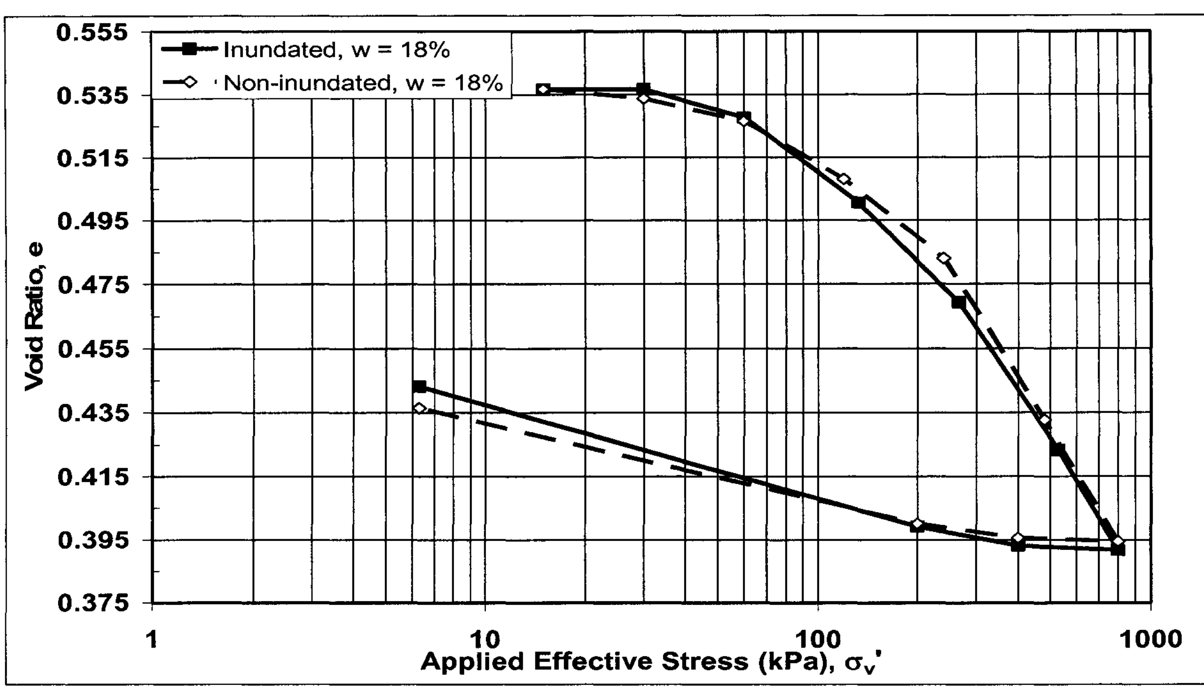

Figure A.8: Comparison of e- logσ$_v$' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content = 18%.

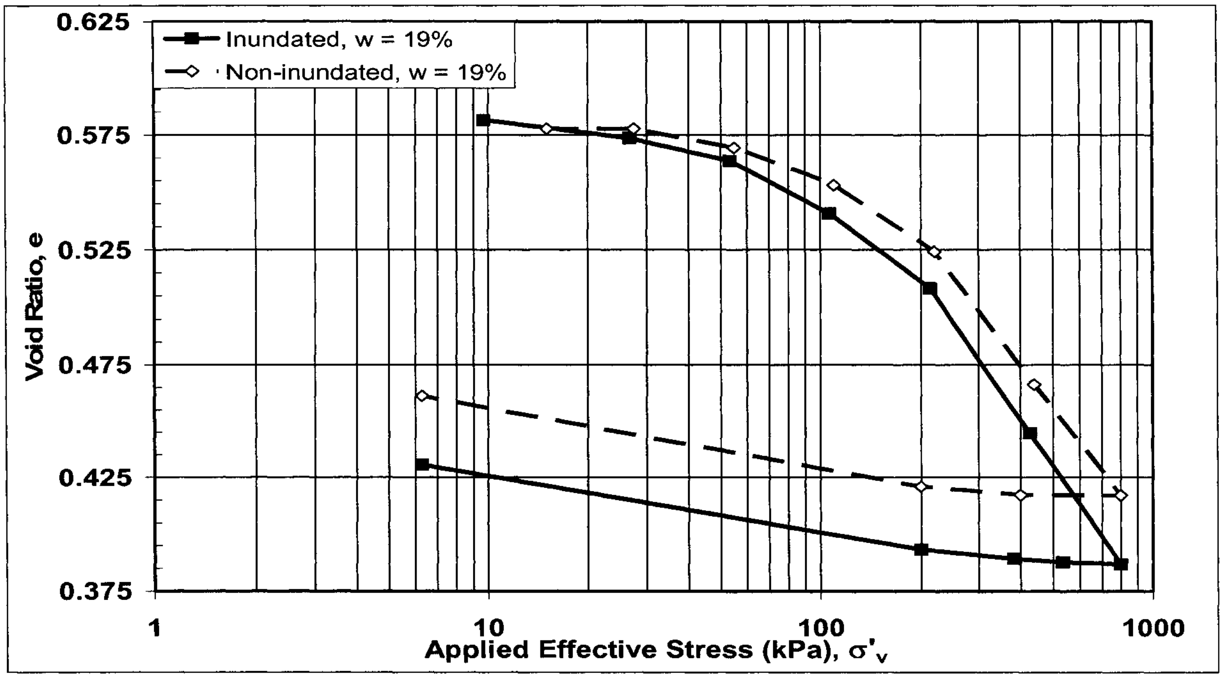

Figure A.9: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using low compaction energy for water content = 19%.

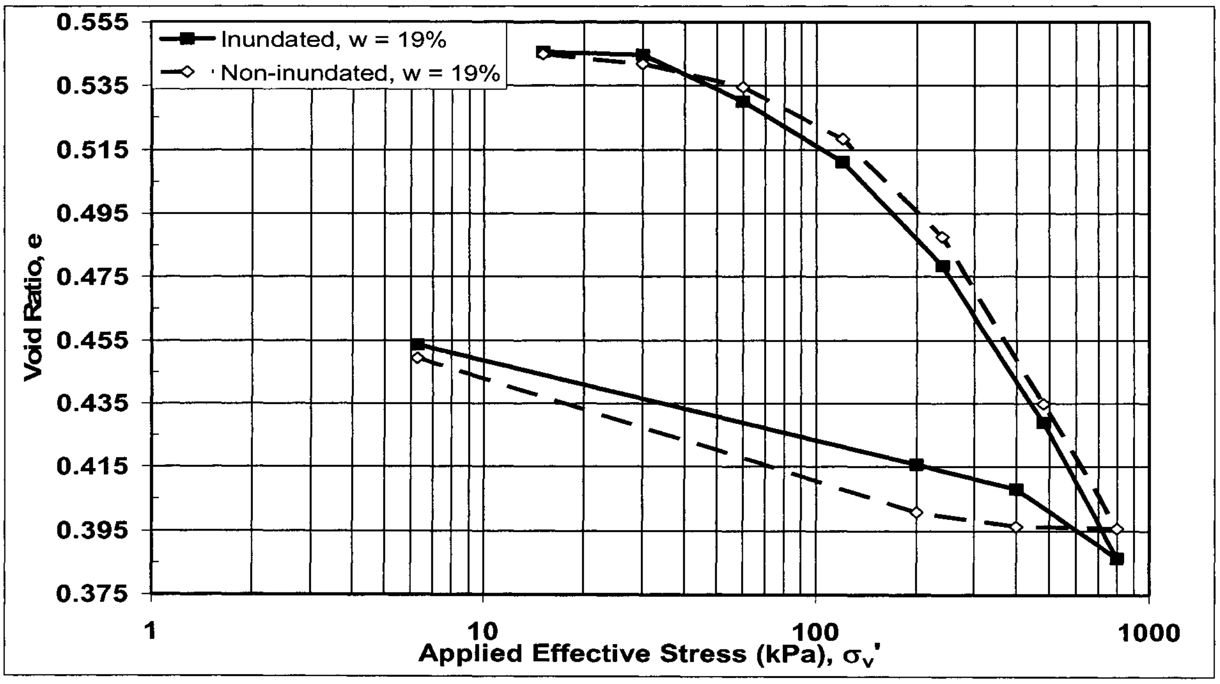

Figure A.10: Comparison of e- logσ_v' graphs inundated & non-inundated test specimens prepared using high compaction energy for water content = 19%.

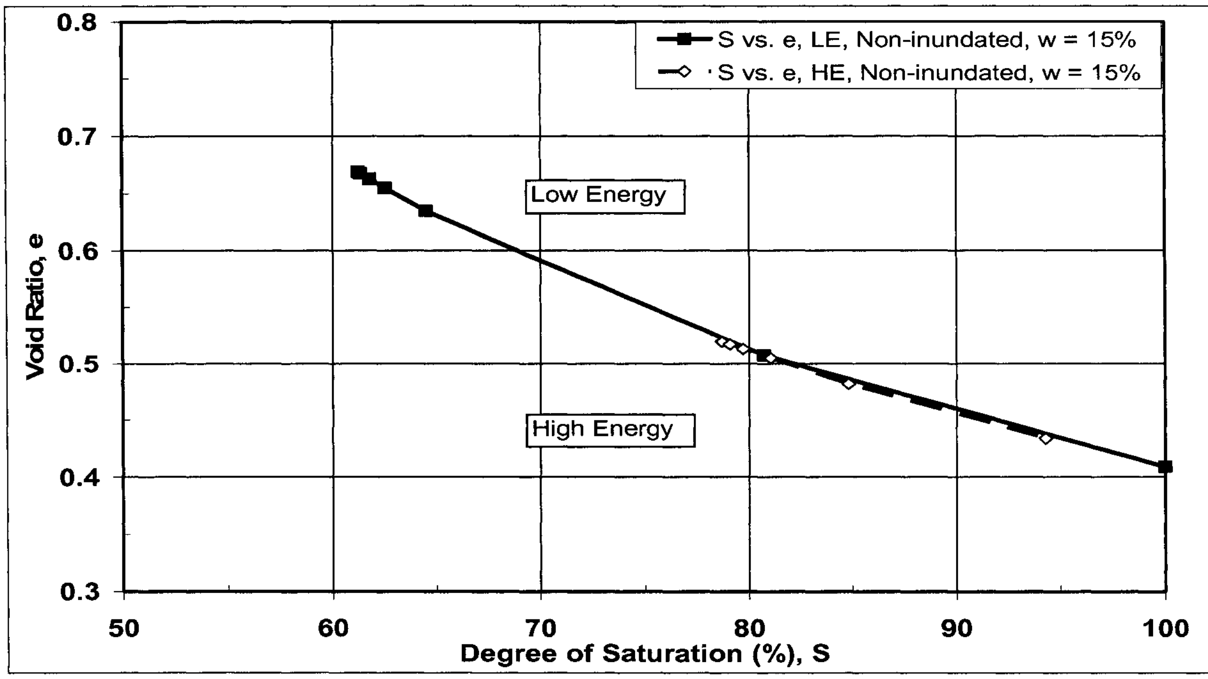

Figure A.11: Degree of saturation vs. void ratio for non-inundated test specimens prepared using low and high compaction energies and an initial water content of 15%.

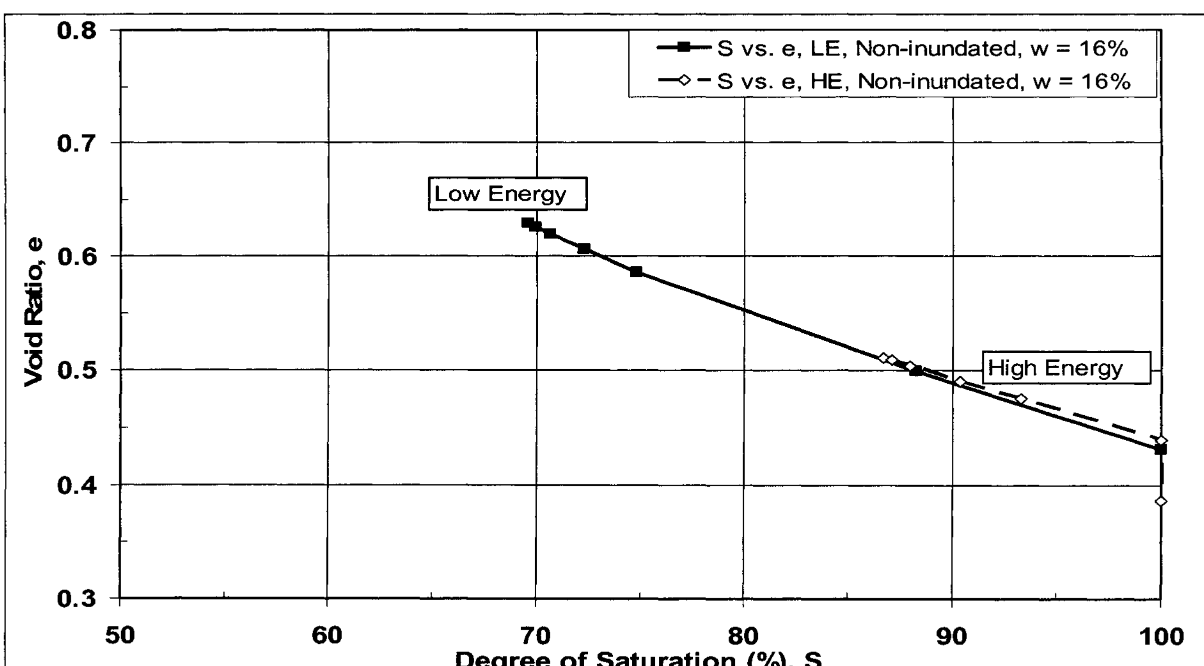

Figure A.12: Degree of saturation vs. void ratio for non-inundated test specimens prepared using low and high compaction energies and an initial water content of 16%.

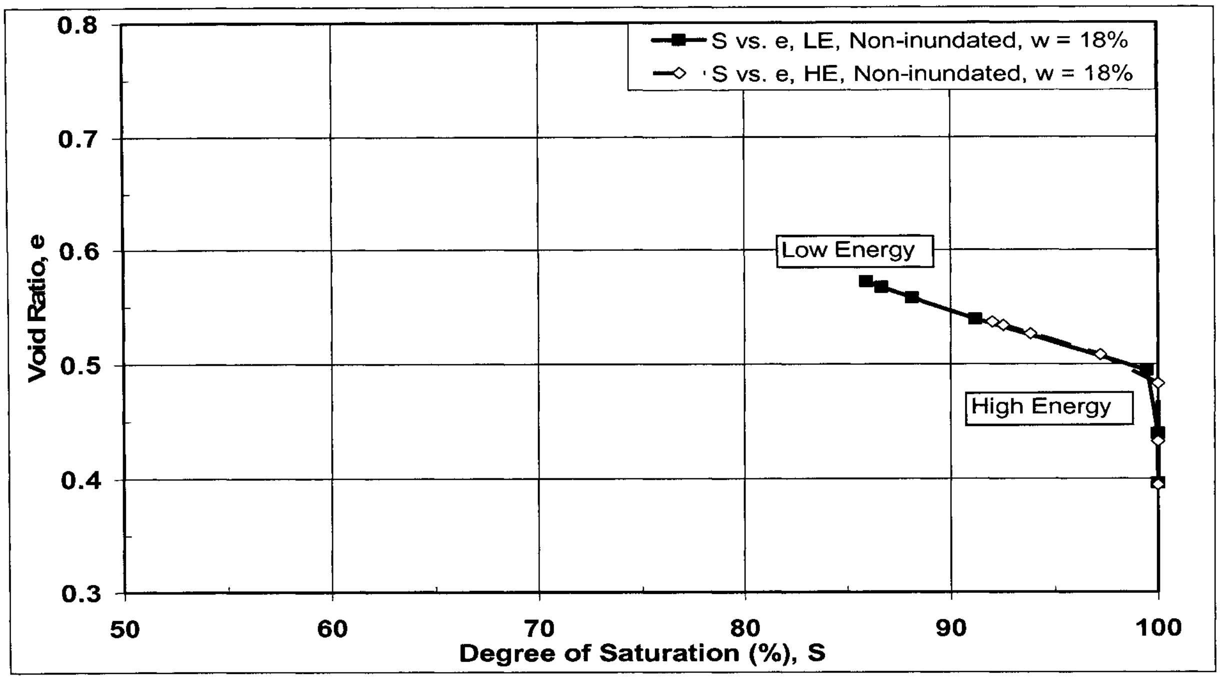

Figure A.13: Degree of saturation vs. void ratio for non-inundated test specimens prepared using low and high compaction energies and an initial water content of 18%.

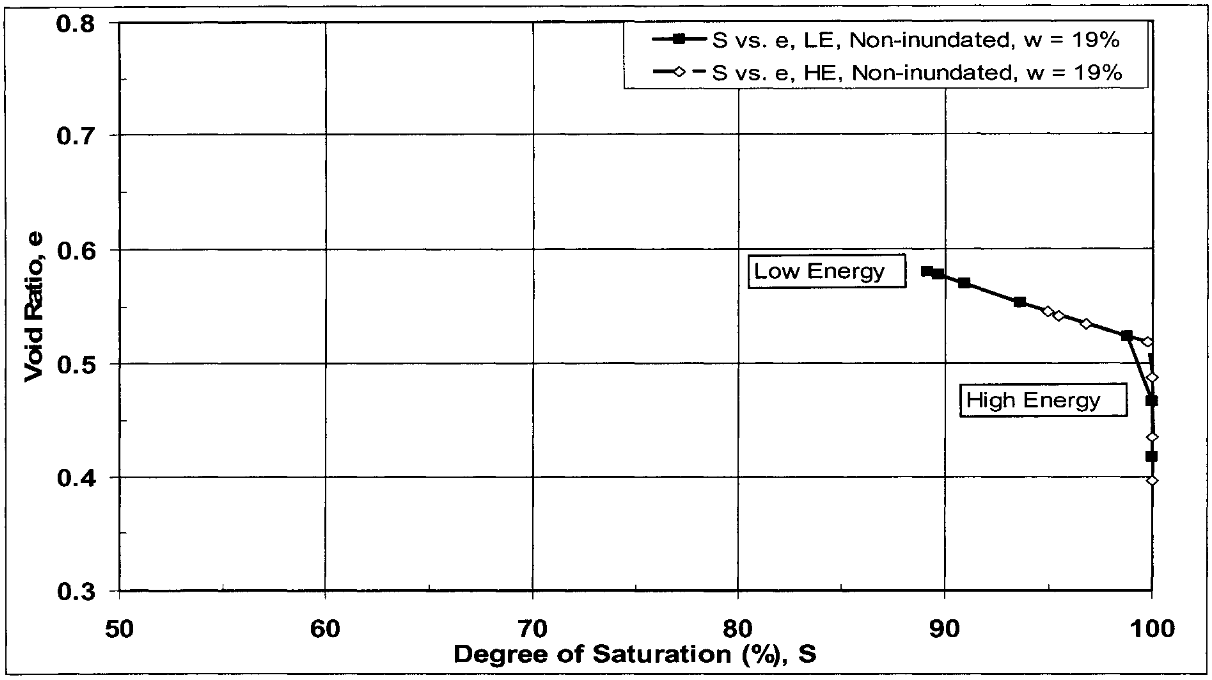

Figure A.14: Degree of saturation vs. void ratio for non-inundated test specimens prepared using low and high compaction energies and an initial water content of 19%.