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An Alternative Medium for the Measurement of Soil Suction by the Filter Paper Method

Lori Ann McDowell
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Lori Ann McDowell entitled "An Alternative Medium for the Measurement of Soil Suction by the Filter Paper Method." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Eric Drumm, Major Professor

We have read this thesis and recommend its acceptance:

Baoshan Huang, John Tyler

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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An Alternative Medium for the Measurement of Soil Suction by the Filter Paper Method

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Lori Ann McDowell

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Abstract

Soil suction is the negative pressure within soil particles, which is a function of the moisture content. It plays an important role in agriculture, civil engineering, and geology. Suction is used in practice to identify expansive soils, to locate heave areas, to develop moisture requirements for arid land plants, to measure for collapse of soils around a footing, and to monitor flow movement of moisture. Soil suction varies with moisture content, and the relationship between suction and water content is known as the soil-moisture characteristic curve of a soil. There are several laboratory tests available to measure suction, but the filter paper test is an easy and inexpensive method that provides the widest range of suction values. The filter paper test is an indirect method of measuring suction, and uses the filter papers as indicators. The calibration curves developed for the filter papers are steep sloped and the accuracy of the test requires the mass to be measured to 0.0001 grams. An investigation of a new medium to provide a higher resolution and shorten the period of equilibrium was done using polymer strips found in household products. The resolution of the test was improved using the polymer strips but the time for equilibrium was not shortened. The polymer strips and filter papers were compared using similar soil samples. The polymer and the filter paper results were similar. The polymer strips improved the resolution and had repeatable data.

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Chapter 1 Introduction to Soil Suction

1.1 Soil Suction

Soil suction is the negative pressure within soil particles, which is a function of the moisture content. It plays an important role in agriculture, environmental and geotechnical engineering, and geology. Suction can be used to characterize soil behavior such as shrinking and swelling, and to "evaluate hydrologic processes…,shear strength, modulus, insitu stress, and hydraulic conductivity of unsaturated soil" (ASTM D5298-03). Measurements of soil suction can be collected in the field or the laboratory, depending on what range and type of suction is required. Alternate terms for soil suction include soil moisture stress, moisture tension, and soil water potential. Most expansive soils exhibit field suctions between about 15 and 1500 psi (100 to 10,000 kPa) (Nelson 1992).

Soil suction varies with moisture content, and the relationship between suction and water content is known as the soil-moisture characteristic curve of a soil. Different soil types, such as clays, silts, and sands, have different characteristic curves depending on soil structure, particle size, chemical composition, and texture. There are several laboratory tests available to measure suction, but the filter paper test is an easy and inexpensive method that provides a wide range of suction values. The filter paper test was developed in 1936, and because of its simplicity, it is widely used in engineering practice. Greacen et al. (1987) evaluated the filter paper test and noted that the primary limitation of the test was accuracy. But McKeen (1988) commented that the test is reliable and repeatable. The filter paper test can be used as an indicator of the two different measures of suction within the soil. When the filter paper is placed in contact

with the soil, the matric (matrix) suction is measured because the papers allow free flow of water into the paper until equilibrium is reached. To measure the total suction, the filter papers are suspended (no contact) above the sample in an air-tight jar, and the moisture in the paper comes to equilibrium with the moisture in the air above the soil. There are some limitations to measuring soil suction with filter paper, such as the 7 day period for equilibrium to reached, the small range of moisture contents that the paper can measure, and the high variability of the results. This thesis investigates the use of an alternate medium (polymers) for use in the filter paper test.

1.1.1 Pressures developed within soils

The subsurface soil is divided into the saturated and unsaturated zone by the water table. In saturated soils below the water table, the water pressure is positive, while in unsaturated soils the pore fluid is negative. The pressure can be affected by many controlling factors; including moisture variation, climate, groundwater movement, drainage (natural and manmade), water sources, vegetation, permeability, temperature, previous stress conditions, loading and unloading, and the soil profile.

Evaporation, infiltration, and transpiration affect soil suction and are often the main focus in the field investigations of suction because these factors are not constant and can not be replicated in the laboratory. Temperature is relevant with respect to the evaporation of water from the unsaturated zone. Low temperature decreases the rate of evaporation than higher temperatures. Evaporation can cause movement of water into the unsaturated zone, by capillary rise (Fetter 2001). For infiltration, the degree of saturation of the soil initially can play an important role in how the pressure of the pores are

dominated. “When ponded water is at the ground surface, the water supply is unlimited, and a wetted front is still moderately close to the water source, the soil behind the wetted front typically has a saturation greater than 50%. In this case, influence of gravity may be dominant because the soil suction is small. In very dry soil, however, suction dominates the flow, and the gravity term becomes so negligible that perhaps it is inappropriate for use in the flow equation (Walsh 1988)” (El-Ehwany 1990). Plants can cause movement of water by the roots. This can cause water to move upwards. The moisture content to where the plants can no longer pull water to the roots is known as the wilting point in soil physics and is typically 15 bars (15000 kPa).

1.1.2 Suction definition

Suction in the soil voids is brought on by different characteristics and properties: the presence of salts, changes in the relative humidity, the void and/or particle size, and the attraction of water to the soil particles (the chemical makeup of the soil particles). Soil suction defined by the Department of the Army (1983) “is a quantity that can be used to characterize the effect of moisture on volume, and it is a measure of the energy that holds the soil water in the pores or a measure of the pulling stress exerted on the pore water by the soil mass”. The two measures of suction that are of most interest in practice are the matric suction and the total suction.

Matric suction (sometimes referred to as the capillary tension) is related to the geometric configuration of the soil particles and structure, capillary tension in the pore water, and water sorption forces of the clay particles. This suction will change with the moisture content of the soil and atmospheric pressures. When soils have fairly high

moisture content, gravitational forces affect matric suction, but when the moisture content gets lower approaching the wilting coefficient the suction is higher and mainly governed by capillary forces.

Total suction is the sum of matric suction and osmotic suction. Soluble salts being present in the soil system create osmotic suction. “In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapor in equilibrium with free pure water” (Fredlund 1993). Osmotic suction is usually considered a constant in most calculations, and changes if the concentration of the salts in the system changes (Department of the Army USA 1983). Figure 1.1 shows an idealized distribution of osmotic and matric suction with respect to the soil-moisture characteristic curve (Fredlund 1992).

Several different systems of units are used for suction measurements, depending on the discipline in which the suction is to be applied. Engineers usually use measures of stress (kPa or psi). For geology and agricultural, measurements of head (cm) or mass per area (gm/cm^2) are normally used. Often for the filter paper test, suction is reported in units of Bars (stress relative to atmospheric pressure) or pf, which is the log of head in units of cm. Figure 1.2 (taken from McKeen 1988) shows the relationship between the units.

1.1.3 Causes of suction

Fine-grained soils are those in which the pressure is dominated by forces on the particle surfaces, while coarse-grained soils are controlled by gravity forces and friction

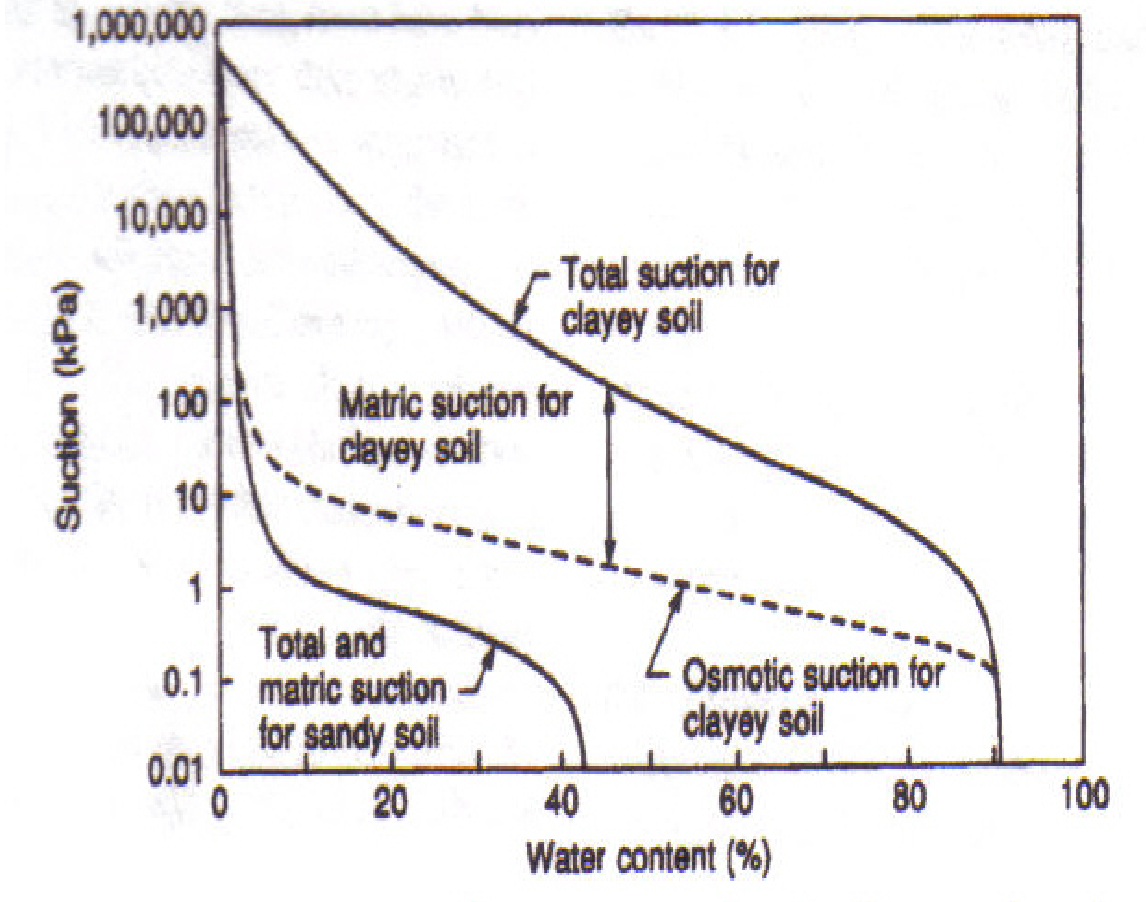


Figure 1.1 The distribution of osmotic and matric suction and the soil-moisture characteristic curve (Fredlund 1992).

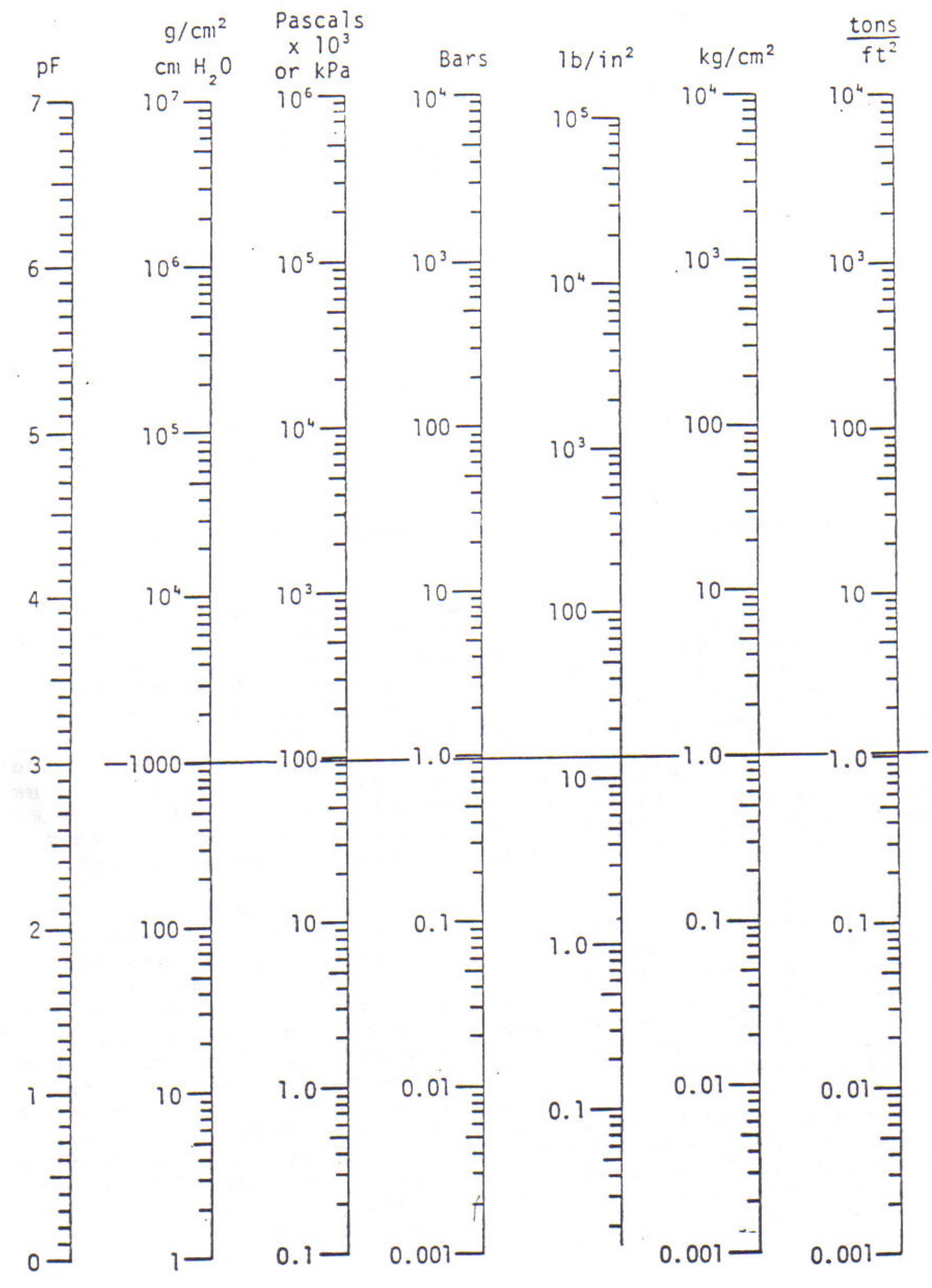


Figure 1.2 Various scales for reporting suction values (McKeen 1988).

(McKeen 1988). Both fine-grained and coarse-grained soils are affected by soil suction, but the particle size of the soil controls the magnitude of suction. Smaller particles such as those in clays generate a higher suction than that generated by larger sand particles. As a result, clays generally experience more problems with shrinking and swelling than other soils. As the moisture content of the soil changes, the suction changes. Figure 1.3 shows an ideal soil moisture characteristic curve for there different soils: sand, silt, and clay (Lu 2004).

Clay particles are normally plate-like and have a negative charge on the surface and a positive charge around the edge. Water is drawn to the electric charge. The surface charge can have different charge intensity, depending on the mineralogical character and chemistry of the particle (Murthy 2003). The water particle attraction will differ with the intensity charge of the surface. The attraction between the soil particle and water particle is also dependent on the number of layers of water particles. As the layer of water particles increases in distance from the soil particle, there is a decrease in attraction (Murthy 2003). In dry soils, salts are held closely to the soil particle, and as water is introduced the force holding the soil particles together is decreased. Sometimes this can cause a repulsion of clay particles.

1.1.4 Moisture characteristic curve

The soil moisture characteristic curve or suction-moisture curve is a relationship between suction and moisture content of the soil sample. As the moisture content of a soil decreases the suction (negative) increases. Figure 1.4 shows a typical soil moisture curve with both wetting and drying cycles (Lu 2004). A hysteresis or difference between

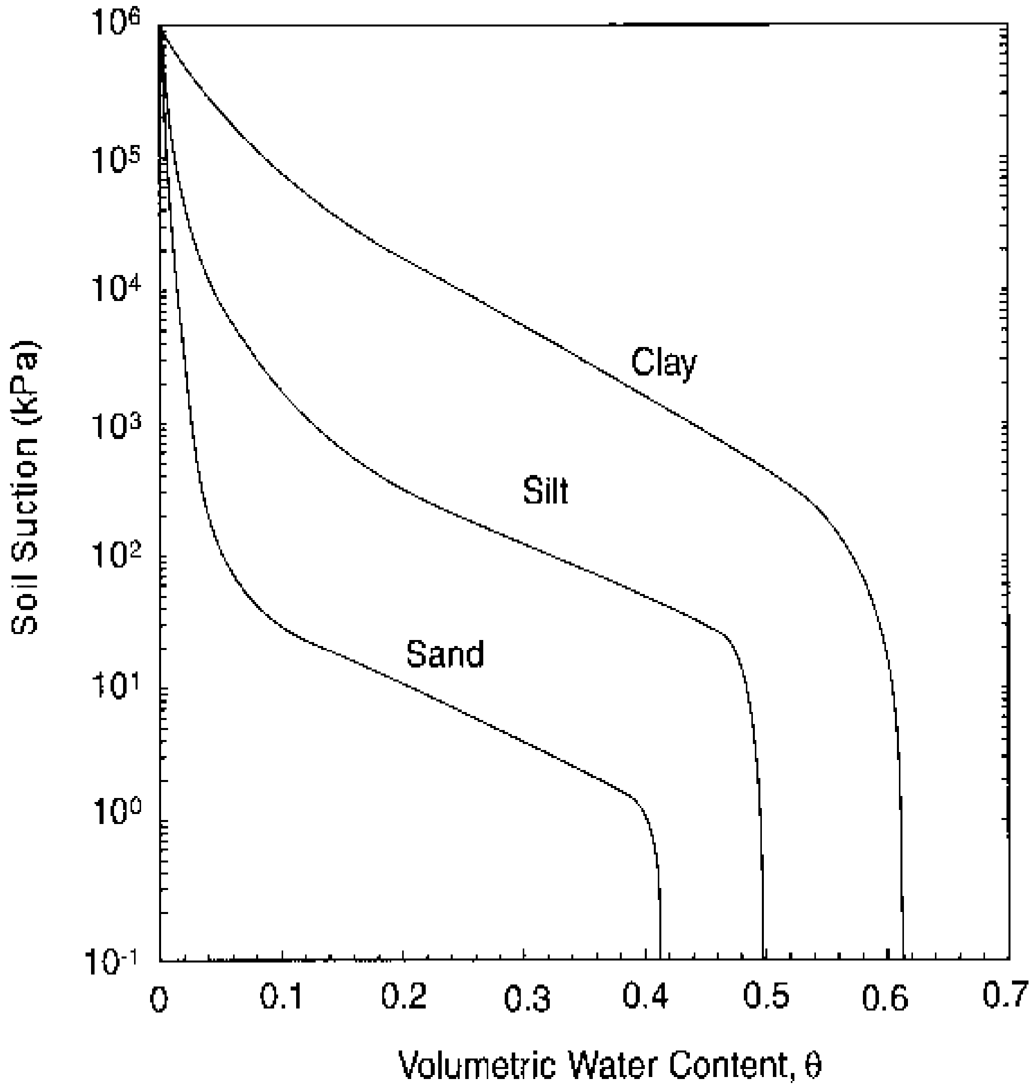


Figure 1.3 Representative soil-moisture characteristic curves for sand, silt and clays (Lu 2004).

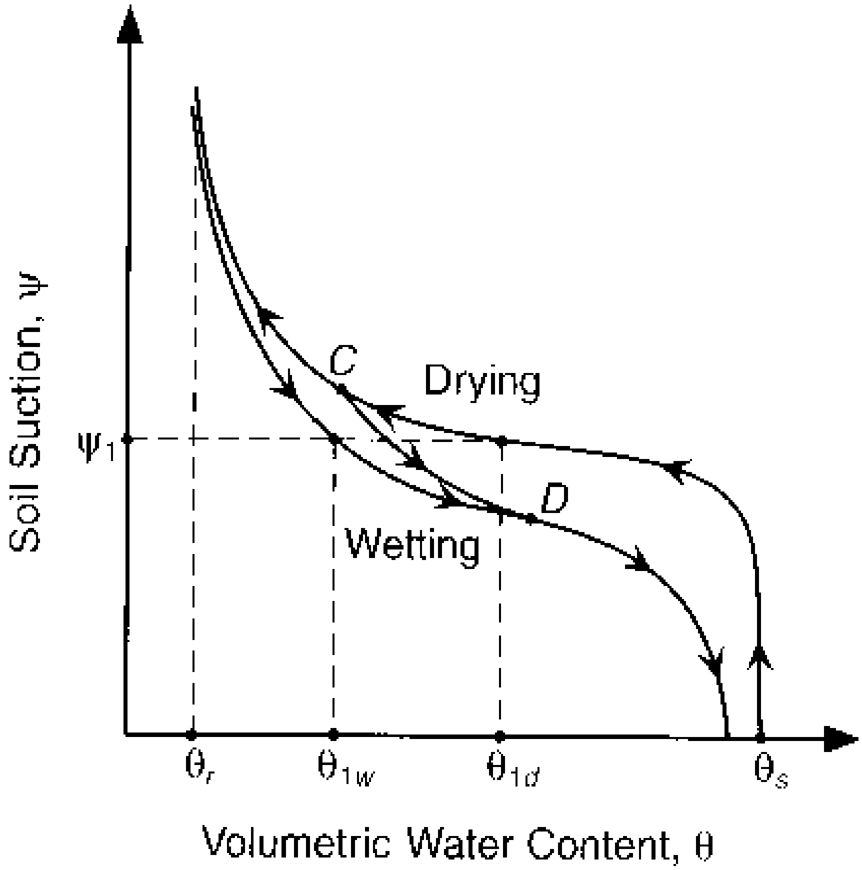


Figure 1.4 A representative soil-moisture characteristic curve with the wetting and drying cycle (Lu 2004).

the wetting and drying curves occurs because the behavior of the water is different when it is entering and leaving the pores. During the drying cycle, moisture is dominated by the narrower section of the pores, while during the wetting cycle the moisture is governed by the wider sections of the pores (Haines, 1930). The hysteresis can be used to relate moisture content to the capillary tension, and also to relate the hydraulic conductivity and tension. Before an estimation of the suction can be made, "one must know the prior moisture history of the sample" (Fetter 2001).

There are four identifiable causes for the hysteresis. The first is what most call the "Ink Bottle" effect. This is related to movement of water from one individual pore to another. The size of the opening connecting the pores controls the movement between the two. The smallest radius referred to as the "pore throat" radius controls the drainage of the individual pore. The tension increases as the meniscus draws back into the pore with decreasing radius. If the pore size increases, the radius of the meniscus will also increase, sometimes causing it to collapse because the weight of the water column can not be held up anymore. This causes the pore to drain. The largest pore radius controls the rewetting of the pore based on the same reasoning (Horton 2004). Another cause of the hysteresis is the contact angle of the water and soil particle, which is also controlled by the flow of water. If the flow is slow, there is a lower contact angle. Fast flowing is a contributing factor to the hysteresis, but usually the "draining and rewetting" happens at a slow rate, so contact angle is not important in most cases. The third cause of hysteresis is the aging effects, where air bubbles that remain trapped for a long period time eventually dissolve in the water and move toward the outer opening of the pore. The final cause of

hysteresis deals with the path of airflow to the pores. If the pathway is not a "continuous air-filled" paths, then air cannot enter the pore (Horton 2004).

1.2 Application of Soil Suction

1.2.1 Use in civil engineering

Suction values are used to relate to other properties of the soil, such as when locating active areas of a soil profile to evaluate the shrink and swell of expansive soils. Sometimes, soil index properties such as the Plastic Index and Liquid Limit can be correlated to swelling potential. Figure 1.5 is a Casagrande graph (plastic index and liquid limit) with data points showing the varying swell qualities (Thomas undated). Usually, Liquid Limits greater than 40 and a Plastic Index greater than 25 are associated with highly expansive soils (Nelson and Miller 1992). Table 1.1a from Nelson and Miller (1992) relate the degree of expansion to data from index tests including the Plasticity Index, Colloid Content, and Shrinkage Limit. Table 1.1b relates the degree of expansion to laboratory and field data: the liquid limit, percent passing the No. 200 sieve, and Standard Penetration (R). Both tables also give an estimated range for the expansion that can be expected (Nelson 1992). These can be important when associating suction with the index properties, because a range of suction values can be estimated.

The shrinking and swelling of the soil is caused by the movement of water between the soil particles. As the soil dries, water is removed from the openings and suction causes the particles to settle and compact (shrinkage). With the addition of water, the voids will be filled between the soil particles, sometimes swelling, especially when the moisture content is increased past complete saturation.

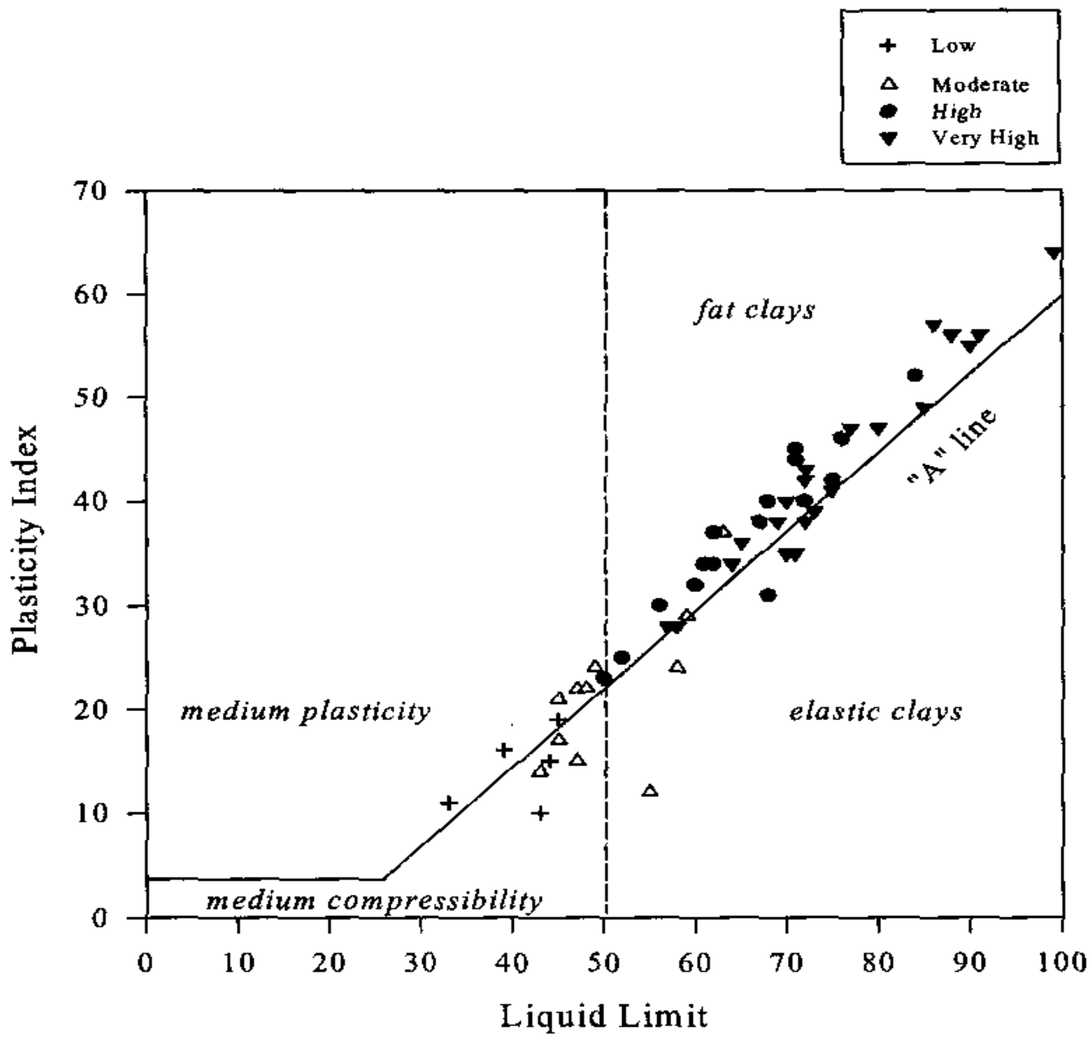


Figure 1.5 Thomas, P.J. Appendix B Swell index as related to Liquid Limit and Plasticity Index (Thomas undated).

Table 1.1a Classification of expansive soils by the data from the Index Tests (Nelson 1992).

Data from Index Tests[a]			Probable Expansion (% Total Volume Change)	Degree of Expansion
Colloid Content (% minus 0.0001 mm)	Plasticity Index	Shrinkage Limit		
>28	>35	<11	>30	Very high
20–31	25–41	7–12	20–30	High
13–23	15–28	10–16	10–20	Medium
<15	<18	>15	<10	Low

After Holtz and Gibbs (1956).
[a]Based on Vertical Loading of 1.0 psi.

Table 1.1b Expansive soil classification based on percent passing no. 200 sieve, liquid limit, and standard penetration resistance for Rocky Mountain soil (Nelson 1992).

Laboratory and Field Data			Probable Expansion (% Total Volume Change)	Degree of Expansion
Percentage Passing No. 200 Sieve	Liquid Limit (%)	Standard Penetration Resistance (Blows/ft)		
>95	>60	>30	>10	Very high
60–95	40–60	20–30	3–10	High
30–60	30–40	10–20	1–5	Medium
<30	<30	<10	<1	Low

After Chen (1965).

The shrinking and swelling of the soil can cause problems for pavements, retaining walls, light weight structures such as one and two story buildings. High plasticity clays and shale clays typically swell. The moisture content will become uneven in certain conditions, making the movement of the soil erratic and usually is the cause for most major structural damage. The movement causes the loads of the structure to be redistributed, and failure may occur due to large changes in moments and shear forces in the structure, which were not accounted for in the standard design of the structure (Department of the Army USA 1983).

The variation of soil suction versus depth can be used to locate "moisture sensitive soils" where climate and drainage are likely to have the greatest affect. The suction versus depth profile can also help find the "active zone depth" of a soil profile (McKeen 1988). This can be used in estimating slope failure and used to locate areas of high movement of water within the soil. Figure 1.6 shows an example of vertical strain (change in height over initial height, %) versus suction, expressed as log of cm of H_2O (McKeen 1988). There is an approximate linear relationship between the two.

1.2.2 Use in agriculture

Suction values are also used to find the moisture content corresponding to the wilting coefficient's. The wilting coefficient is the moisture content limit of the soil where the plants can not extract water from the soil. In agriculture 15 Bars (15 atmospheres or 15000 kPa) is often used as a rule of thumb for determining the wilting point for plants. Tensiometers are the most commonly used method of measuring suction. Suction measurements are used in the wine industry to determine when

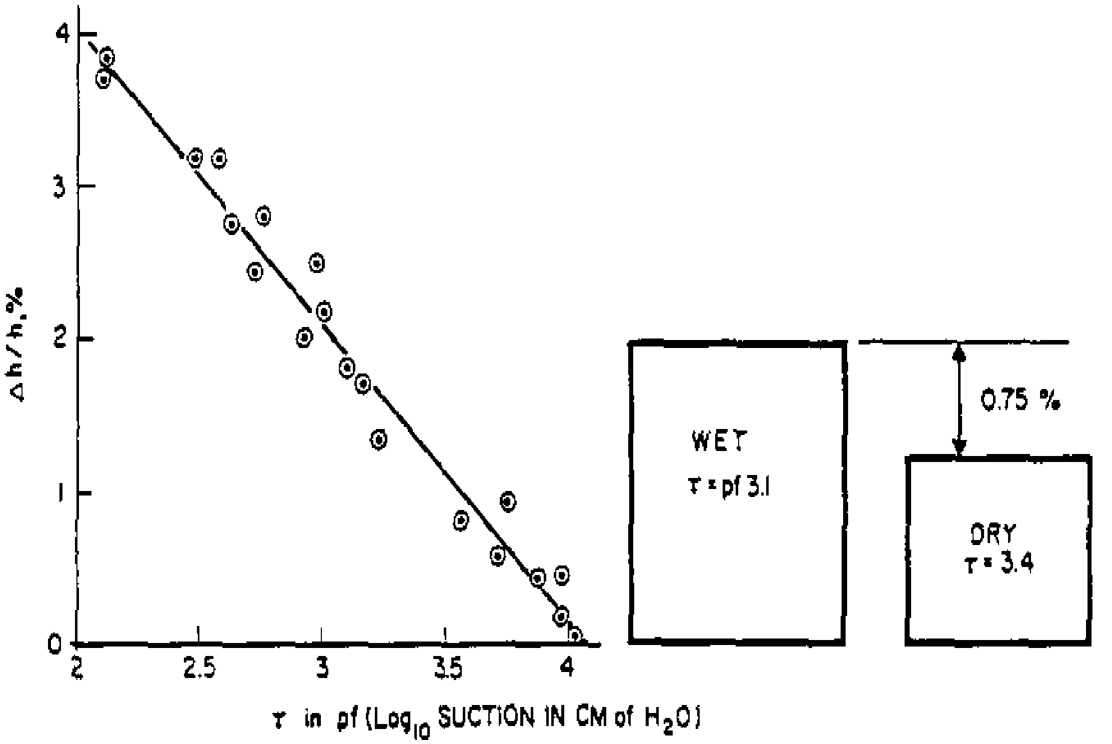


Figure 1.6 Change in height over initial height vs. suction (McKeen 1988).

irrigation of vineyard is needed. Controlling the amount of water the plants receive helps minimize the size of the grape. Smaller grapes are preferred because the concentration of juice is greater (Sharp, 2003).

1.3 Methods of Measuring Suction

There are several different methods for measuring suction and the range of suction values vary for each. Table 1.2 (Ridley 1993) summarizes different tests used to measure suction, the range of suction measured, whether they measure matrix or total suction, the equilibrium time, principal usage, and whether the method is direct or indirect. Measuring the pore water pressure directly can be limiting because devices typically only measure very low suctions, such as the tensiometer, or high suctions such as the pressure plate. Indirect measurements of suction are used by relating moisture to other physical properties such as humidity, adsorption or electrical resistance (Ridley 1993). For arid areas the suction values are fairly high, and most tests do not cover the necessary range. The filter paper test is useful because it can measure a large range of suctions, and is relatively simple. However, there are several aspects of the filter paper test that could be improved. The filter paper test will be discussed in detail in Chapter 2.

1.3.1 Brief review of field suction tests

The tensiometer, which measures matric suction, is used for field measurements of suction. It consists of a water filled tube with a porous bottom, usually ceramic, which is placed in the ground with a manometer (a simple water-or mercury-filled U tube, a vacuum gauge, or an electrical transducer) attached at the top. The water that comes

Table 1.2 Summary of various methods of measuring suction (Ridley 1993).

	Suction value*	Principal usage	Direct/ indirect	Range: kPa	Equilibrium time
Vacuum dessicator	Total	Lab.	Indirect	10^3–10^6	Months
Psychrometer	Total	Field	Indirect	300–7000	Months
Filter paper	Total	Field	Indirect	1000–30 000	Weeks
	Matrix	Lab.	Indirect	30–30 000	1 week
Porous block	Matrix	Field	Indirect	30–3000	Weeks
Thermal block	Matrix	Field	Indirect	0–175	Days
Suction plate	Matrix	Lab.	Direct	0–90	Hours
Tensiometer	Matrix	Field	Direct	0–90	Hours
Pressure plate	Matrix	Lab.	Direct	0–5000	Hours
Osmotic tensiometer	Matrix	Field	Direct	0–1500	Days

*As defined by Aitchison & Richards (1965).

through the pores of the ceramic tube, comes to equilibrium with the soil water. The water in the closed tube is at atmospheric pressure, so the opposing suction will pull water out of the tube. The manometer measures the change in the pressure. This test measures suction (negative pressure) from 100 kPa and below (Hillel, 1998).

Another method used to measure suction in the field is thermocouple psychrometer. It uses two junctions to measure the change in relative humidity between the ambient relative humidity and the soil relative humidity. A junction consists of two metal wires with an electrical current flowing between the wires. With the measurement of relative humidity, moisture potential can be measured. The thermocouple pshchrometer controls and monitors temperature and allows for a more accurate suction value to be measured (Martin 1993).

1.3.2 Brief review of laboratory tests

The pressure plate and suction plate are used to measure suction in the laboratory. The soil sample is placed on top of a porous ceramic plate or cellulose membrane inside a steel container. The chamber has two tubes connected to it. One provides air flow that can be used to regulate the air pressure inside the chamber, and the other tube allows moisture that is removed from the soil sample through the ceramic plate to be removed. The method brings the soil sample to equilibrium at a certain suction (air pressure) value at which point the moisture content of the soil sample is measured. After several repetitions of the test a soil-moisture characteristic curve can be created.

Some research has been done on using the grain size curve and some other index properties to estimate the soil-moisture characteristic curve. Fredlund and Xing (1994)

developed a formula for estimating soil-moisture characteristic curves from the grain size distribution curve. The formula takes certain points on the grain size curve that correspond to certain diameters which are representative to air and water flow to create the moisture curve (Fredlund 1994).

1.4 Research Objective

The filter paper test is an inexpensive, but indirect method to measure soil suction. Because it is inexpensive, it is used in engineering practice to help identify expansive soils. However, there are a number of limitations with the method, including the 7 days required for equilibrium to be reached and difficulty measuring very small changes in the filter paper mass as water is absorbed. The objective of the research was to investigate an alternative medium for measuring soil suction by the filter paper method. Specifically, polymer strips taken from readily available personal hygiene products were tested. Specific issues to be addressed are:

- Can the polymer strips be used to measure soil suction?
- Can the polymer absorb a larger quantity of water than the filter paper, rendering the measurement of water content?
- How does the sensitivity of the polymer compare with the filter paper (small change in suction is reflected by a large change in moisture)?
- What type of range of moisture content (i.e. suction) is measured with polymer strips?
- How is the reproducibility relative to the filter paper?

- Can the time for equilibrium of the moisture content be shortened? It would be desirable if the 7 day period in ASTM D5298-03 could be shortened.

Chapter 2 The Filter Paper Test for Measurement of Suction

2.1 The ASTM Standard Procedure

The filter paper test described by ASTM D5298-03 is the standard test method for measurement of soil potential (suction). It can be used to measure both matric and total suction. When running the test to measure matric suction, three filter papers are placed inside the soil sample (in contact), and the moisture content of the middle filter paper is used with a calibration curve for the given filter paper to identify the suction value. The moisture content of the soil sample is also calculated, then a comparison of the suction value and moisture content can be used to create a soil moisture characteristic curve. Contact between the filter papers and the soil is necessary to establish free flow of water. There have been problems with measurement of matric suction with the filter paper method (discussed below), where the moisture content of soil was low and a good contact was not established because there was no free flow movement of water. Though the test is useful in practice there are problems and difficulties with the test such as:

1) The procedure requires an accurate measurement to 0.0001 grams.
2) There is a temperature effect between the measurement of the mass of the can at room temperature and at hot temperatures (removed from oven). An aluminum block is used to rapidly dissipate the heat and is accounted for in the calculation.
3) The test requires that the vapor pressure to come to equilibrium within the filter paper and the soil sample. ASTM D5298-03 suggests a seven-day period, which is longer than the desirable in engineering practice.

The ASTM test for measuring total suction is simpler, because the filter paper is suspended over the top of the soil sample. This provides easier access to the filter paper and less disturbance to the soil sample. When a dry filter paper is suspended above a soil specimen vapor flow of water will occur from the soil to the filter paper until equilibrium is achieved (Fredlund 1993). It is assumed "that the filter paper water consists of capillary water filling the pores between the cellulose fibres and water is taken up by swelling of the actual fibres" (Greacen 1987). Because the soil sample is not disturbed and there is a lesser chance of losing soil, the calculation of the moisture content of the soil sample is more accurate. Since the osmotic suction on most occasions is a constant, measurements of the total suction are generally sufficient. A change in the presence of salts would have to occur before a change in osmotic suction would occur. With the reasoning that total suction is the easiest and thus more likely to be accurate to run, it was the main focus for designing this research.

2.2 Prior Research of Using Indicators to Measure Suction

Early measurements of moisture pressure were recorded in 1906 by Burton Livingston, when he was trying to describe a "relationship between desert plants and soil moisture" (Livingston 1906). Studies using seeds to measure "moisture held by soil particles" had been done, but in 1916, Charles Shull developed a routine method for using seeds as an indicator for suction (Shull 1916). The seeds shared a common genetics. The seeds were calibrated through the vapor pressure method using sulphuric acid of varying strength and compared with osmotic values. Shull's calibration method is similar to the same method used in the Filter Paper test by ASTM standards, but to

control the temperature, the sealed jars were placed in a "trough of running water." For his method of testing, the seed was buried in the soil. His one concern was that the soil (as a whole) was not coming to equilibrium, so the seeds were rotated throughout the soil sample. Samples of 60 grams of disturbed soils were used and the test run for 15 days. Also measurements were made at 5 and 10 days and showed no significant change in moisture content between the two.

In 1937 Gardner proposed a method similar to the seed method using filter papers to measure capillary tension (suction) within soils. This test method provided a full range of suction values. Previously there had been problems measuring suction values greater than 1 atmosphere (1 Bar or 100 kPa). The soil sample was divided into 3 layers with a dry filter paper between the bottom two layers and a wet filter paper between the top two layers. The filter papers used in the test were washed in 0.2 percent $HgCl_2$ and air-dried. This was done to keep decomposition and growth from occurring while the filter paper was in contact with the soil. An initial mass of the filter paper was taken before being placed in the soil. This allowed the determination of mass of soil particles that could not brushed off. The soil sample was sealed and allowed to come to equilibrium after 5 to 6 days at 25^{o}C. The moisture content of the soil and the filter papers were then measured. The moisture content of the filter papers were averaged and then compared with the calibration curve. Gardner's method is fairly similar to that used by Shull, except the filter papers allowed for a more consistent measurement. For calibration of the filter paper above the wilting coefficient (roughly 15 Bars or 1500 kPa), they were placed over sulfuric acid. Both wet and dry filter papers were calibrated with the sulfuric acid. Then an average of the wet and dry papers suspended over a certain concentration of sulfuric

acid was calculated to create the calibration curve. His data showed the wetted filter paper had a higher moisture content but was fairly consistent. For the lower suction values (higher moisture content) “a centrifuge and specially constructed tubes in the Trunion cups” were used to create the calibration curve. When looking at the calibration generated by the centrifuge (Gardner 1937), he states that the information could be incorrect due to lack in environmental control.

In the 1960’s there was an increase in the application of the filter paper test method. The test method was modified for each testing purpose. Williams and Sedgley (1965) demonstrated the ease of the test by looking at the moisture content of soils for 15-atmospheres. They looked at six different filter papers and finally decided on the Whatman No. 42 (9 mm diameter) because of its strength when wet and the pore size distribution. They also treated the filter paper with $HgCl_2$. The equilibrium time used was 7 days at 25^{o}C. The filter papers were placed within the soil sample (in contact), and before they were weighed the soil particles were brushed off. There was one main difference between their soil testing and calibration of the filter paper. When calibrating the filter papers, the papers were wetted and the water was removed, and when the papers were used in the testing procedure the papers were initially dry and then wetted. They found this to be an important error that needed attention. They suggested a concentrating on measurements at 15 atmospheres (1500 kPa) for the agricultural field. Fawcett and Collis-George (1967) used the filter paper test to measure moisture content at the 15 atmospheres pressure, which was stated before, is a rule of thumb value for the wilting point of plants. They also pretreated the filter paper with 0.005% $HgCl_2$ solution, but still

had problems with fungal and bacteria growth. They suggested that a stronger concentration of the solution may be necessary to prevent growth on the papers.

2.2.1 Development of different variations of the filter paper method and uses

After the establishment and recognition of the potential for the filter paper test, other studies for both field and laboratory were done. In 1968, the Soil and Moisture Conservation Program, Water Resources Division of the U.S. Geological Survey used the test for developing moisture requirements of arid land plants in the Western United States (McQueen 1968). Chander and Gutierrez in 1986 used the filter paper method to estimate heave at sites where plastic clay could affect the construction of buildings. They stated that the method is particularly appropriate for assessing the swelling potential of desiccated clay sites, but there are many other geotechnical problems for which this simple technique of estimating effective stresses will be of value (Chander 1986).

In 1987, Greacen, Walker, and Cook applied the filter test in the field for measuring matrix suction. A dowel with a filter paper cut and wrapped around a plastic clone attached to the bottom of the dowel was placed in a borehole and sealed off. The borehole is just slightly larger than the diameter of the dowel. When it was placed in the hole, the dowel was twisted a little to insure contact with the soil. The test results were a success, but they also noticed that condensation formed when there was a change in temperature.

A new approach to using the test by studying moisture movement from ponded water below a footing was suggested by El-Ehwany and Houston (1990). The test setup was representative of a footing. The confined soil sample had wet soil on top and dry soil

at the bottom with the water coming from the top. There was a vent at the bottom and ponded water on the top of the soil sample. The moisture measurements were relative to the bottom of the footing and areas along the side of the footer. They used the information to predict how much the soil would collapse, and then compared the predicted value with measured results in field. They observed the predicted value of collapse to be 12% greater than the measured and considered it to be a "good prediction" (El-Ehwany 1990).

Crilly, et al. (1991) developed a field test for measuring suction based on the filter paper test by placing a probe into the ground. They suggested the test is ideal for remote areas of study. The test performed "adequately". They also studied the filter paper method using different numbers of filter papers and decided that if testing is to be done using different numbers of papers that calibrations need to be developed for each set.

Mahler (1998) developed a simple field test similar to the filter paper test. He did field measurements by placing a 50mm PVC tube into the soil with a geotextile on the bottom and a cap to seal the top, and filter placed inside. He measured both total and matric suction by having papers both without contact with the soil and in contact. For the total suction measurements, the filter papers were allowed three weeks to come to equilibrium, and from 7 days and no more than three weeks for the measurement of matric suction. He found that there was no great difference in the soil-moisture characteristic curve developed from field measurements and those of the laboratory.

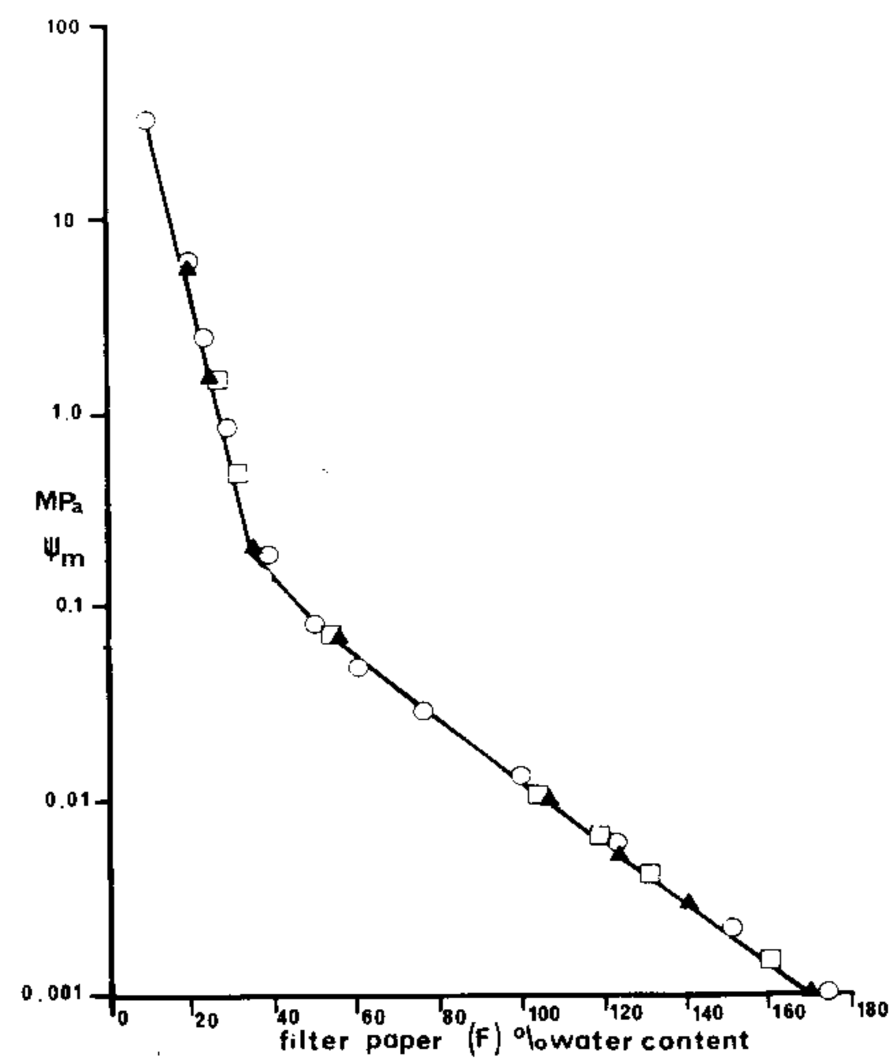
Likos and Lu (2003) used a column of soil along with the filter paper test to create a soil-moisture curve and also to monitor flow movement through the column at different depths for expansive clays. They found that the filter paper test works best during the

drying stage (lower moisture content) because flow was slow and more likely to come to equilibrium within 7 days.

2.2.2 Research studies on the precision of the filter paper test

One of the earliest studies on the performance of the filter paper test was an investigation into how temperature, temperature variation, and the contact between soil and the filter paper affect the results (Al-Khafaf 1974). They looked at papers placed within the soil sample, placed on top of the soil in "uncertain contact", and with an O-ring separating the two (soil and filter paper) in a "no contact" configuration. The setup and procedure is very similar to the current ASTM Standard test method (ASTM D5298-03). Change in temperature was found to cause erratic measurement of moisture content, and caused condensation to collect on the paper adversely affecting the results. They concluded that the moisture content was influenced by how the filter paper was in contact with the soil sample. They suggested that for best results, one filter paper should be placed beneath the soil for good contact so liquid flow and vapor flow could be established and one filter paper be placed above the soil with no contact to allow vapor flow only (Al-Khafaf 1974).

In 1981, Hamblin studied the comparison of treated and untreated Whatman's No. 42 filter paper. Two different batches of papers were tested two years apart using the same testing method. The original batch was treated with $HgCl_2$ and the second batch (2 years later) was untreated. Figure 2.1 (Hamblin 1981) is the calibration curve they developed. There was no difference found between the treated and untreated. Also shown in the figure is Fawcett and Collis-George (1967) calibration developed for



Calibration curve for Whatman® No. 42 filter papers. Original batch treated with 0.005% $HgCl_2$ (▲), new batch two years later, untreated (□), and values from Fawcett and Collis-George in 1967 (○).

Figure 2.1 Comparison of treated and untreated Whatman No. 42 filter paper (Hamblin 1981). Also included is Fawcett and Collis-George (1967) calibration.

Whatman's No. 42 filter paper, which showed no significant difference from Hamblin's calibrations. As a side study, they also looked at how long it took for equilibrium to be established when looking at the matric suction (having the filter paper in "contact" with the soil). Estimated time for equilibrium for nearly saturated soils was a few minutes, while it was suggested that nearly dry soils required approximately 36 hours. This is only accurate if there is good contact between the soil and the filter paper.

Greacen, et al. (1987) found that lower suctions, while occurring at higher water contents, result in high variability for different "batches" of filter papers and they recommended that each batch of filter papers be calibrated. They also studied the wetting of filter papers versus time at different suctions. Figure 2.2 is the figure from their paper showing that regardless of the suction values, equilibrium was achieved within 6 to 8 hours. Also they noticed when measuring suction in contact with soil there could be a problem with measuring matric suction at very high suctions (low moisture content). The increase of moisture could be dominated by vapor flow, which would mean that total suction is measured instead of matric suction. This could be a problem in field measurements of semi-arid regions where salinity is high and matric suction is the focus of measurement (Greacen, 1987). Sibley, Smyth and Williams (1990) also studied filter papers from different boxes and found that papers bought from the same production batch and purchased at the same time need only one calibration curve.

McKeen (1988) showed the accuracy of the filter paper test run simultaneously with thermocouple psychrometers. Figure 2.3 shows the values of suction calculated from each method and the "comparison indicates the two methods are equivalent and in practice they are considered equal" (McKeen 1988). They also tested the range of the

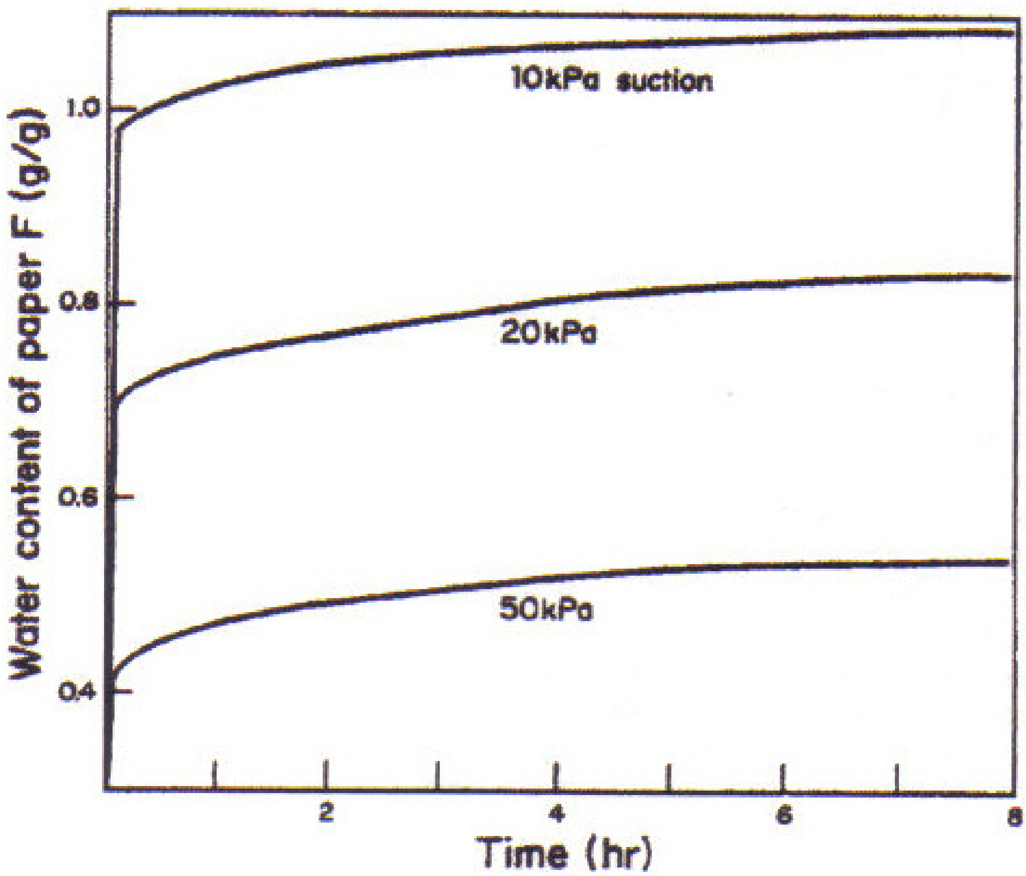


Figure 2.2 Greacen, Walker, and Cook (1987) wetting of filter papers at different suctions.

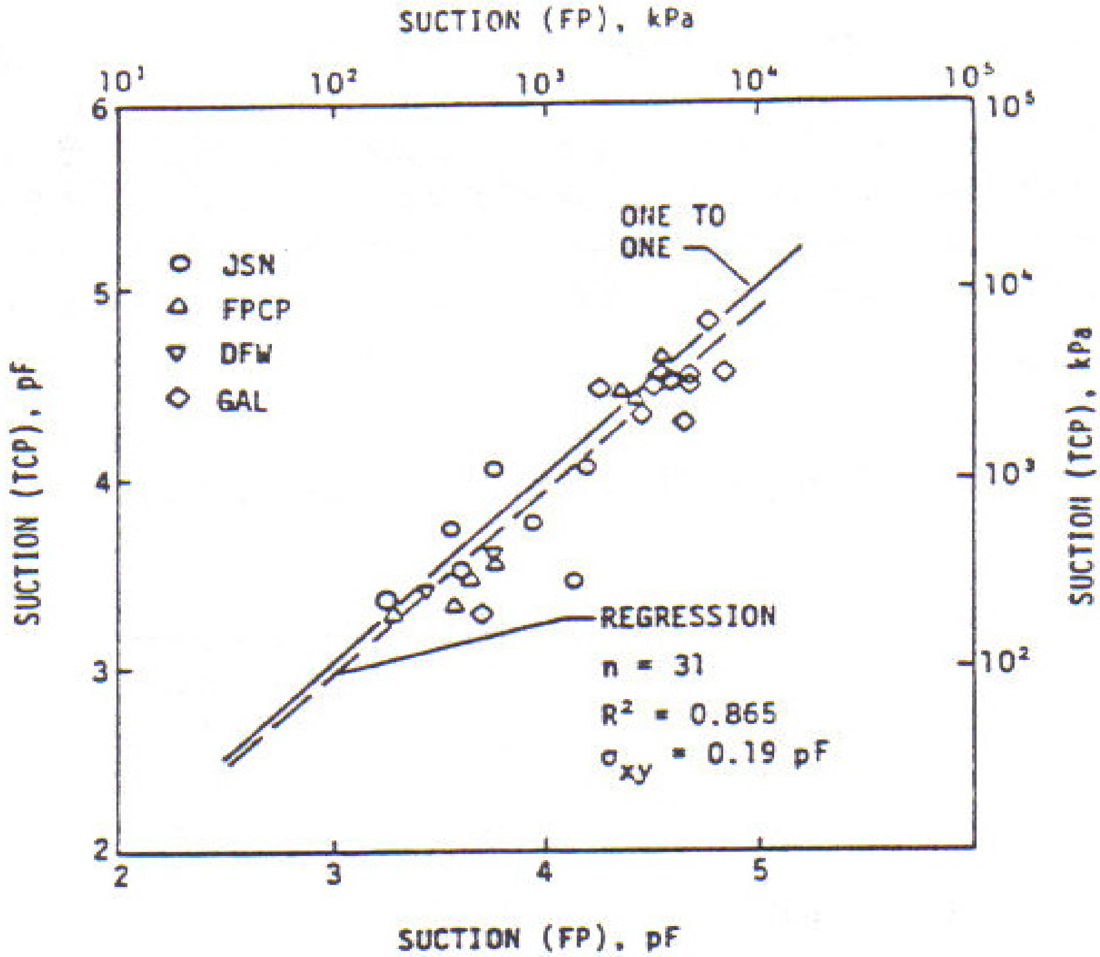


Figure 2.3 McKeen (1988) comparison graph of the filter paper method and thermocouple psychrometers.

filter paper test, and found that the best range is 2.0 pF to 6.0 pF (0.98 kPa 98,067 kPa). They considered 2 pF (0.98 kPa) to be the "wettest condition (lowest suction)", 3.5 pF (294 kPa) occurs at water contents near plastic limit, and 5 pF (9,807 kPa) to be the "driest condition (highest suction)" is likely to be encountered while measuring suction (McKeen 1988). They also developed some typical moisture characteristic curves for clays (Figure 2.4 and 2.5).

Likos and Lu (2002) also studied calibration curves developed from different batches of Whatman No. 42 filter paper. They found high variability in the calculated calibration curves. Figure 2.6 shows the calibration curves generated from each batch. It shows that for each batch of filter papers, a separate calibration curve should be developed. They also found variation in moisture content can be as high as 11% for the filter paper, which resulted in a potential error measurement of as high as 92%. The deviation of error increased as suction decreased which was shown in previous research.

2.2.3 Filter paper calibration

There are a several different methods for calibrating the filter paper, covering a range of moisture contents and means by which moisture is introduced. Some methods require the samples to be wetted and then a particular suction is applied to the sample and water is removed until equilibrium is established. Other methods utilize salt solutions, where the filter papers are initially dry and through vapor exchange moisture content increases until equilibrium is established. Table 2.1 shows different calibration methods from previous research and certain notes about the tests, including the range of suction for the calibration methods.

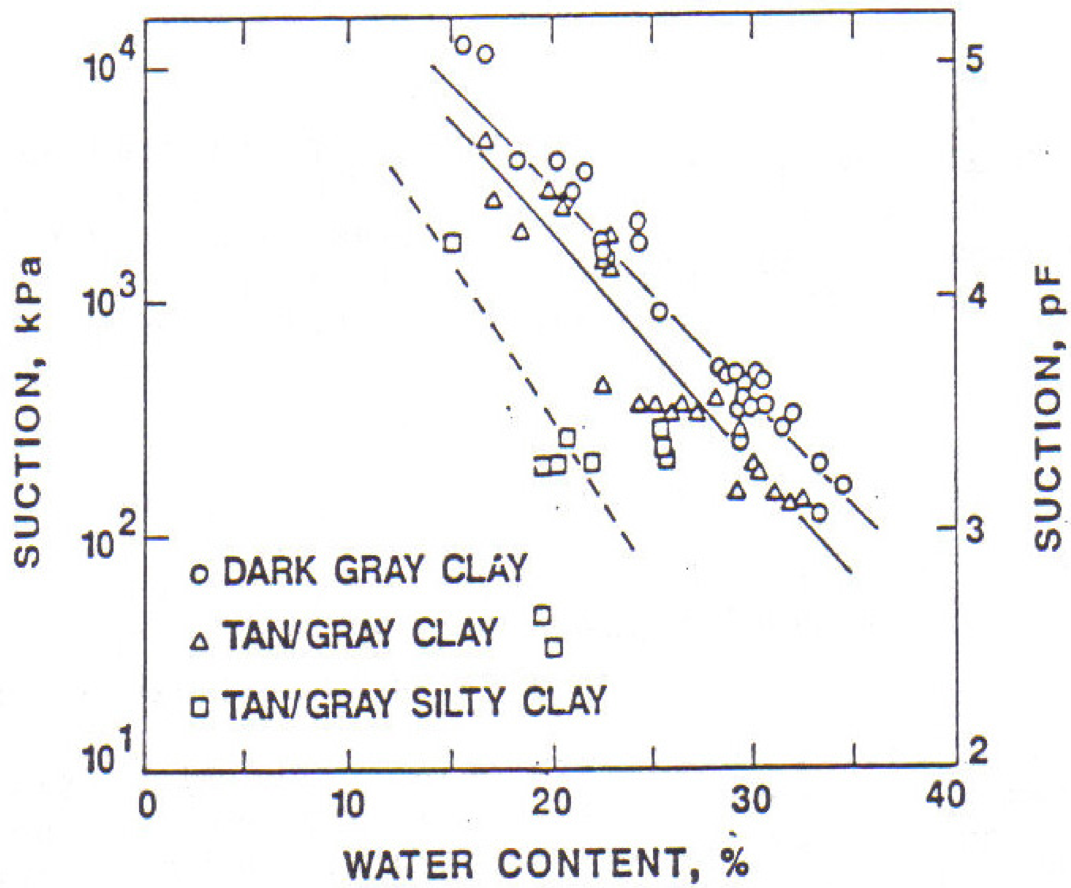


Figure 2.4 McKeen (1988) , moisture characteristic of 3 clays.

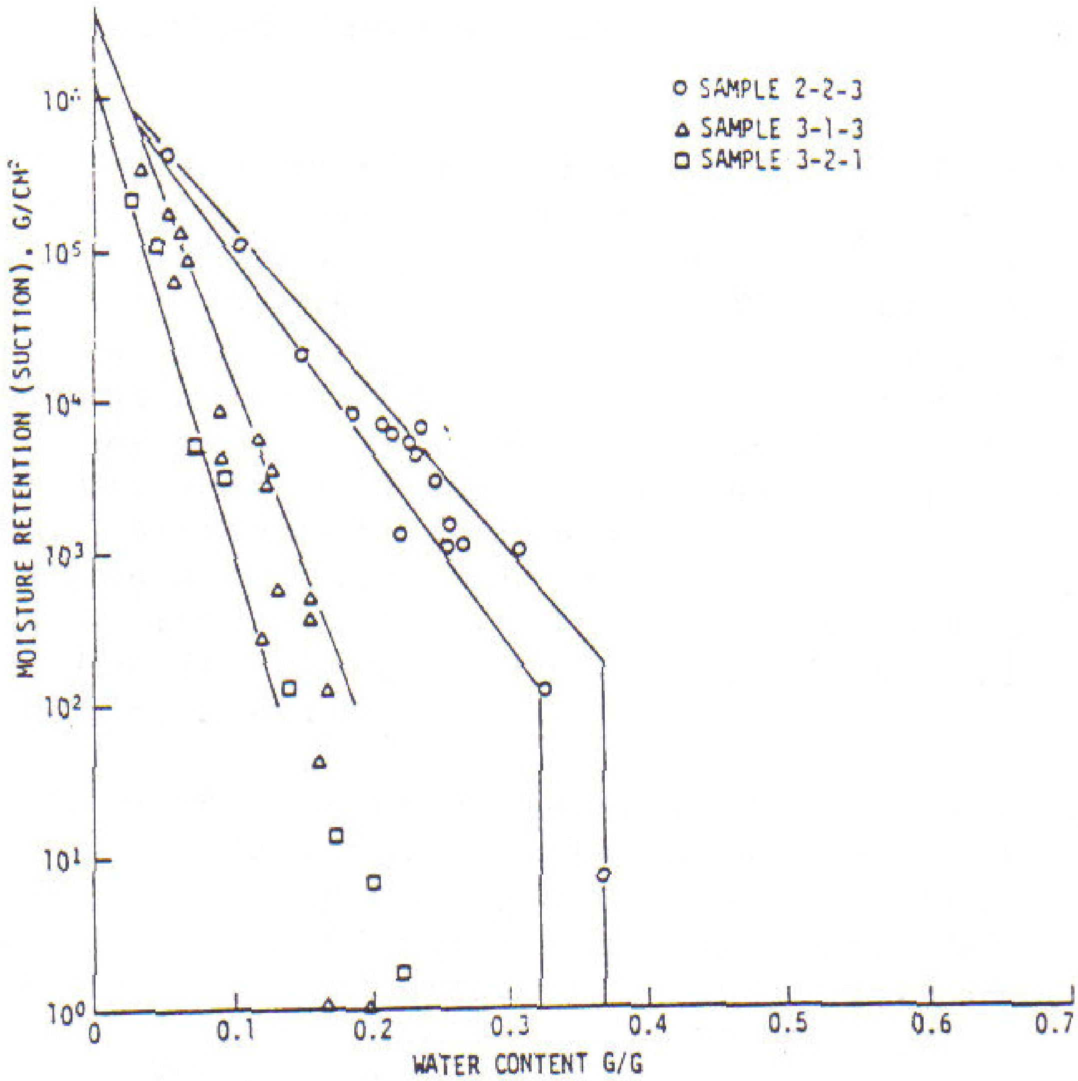


Figure 2.5 McKeen (1988) Two different Suction vs. Moisture content data from the filter paper test on clay samples.

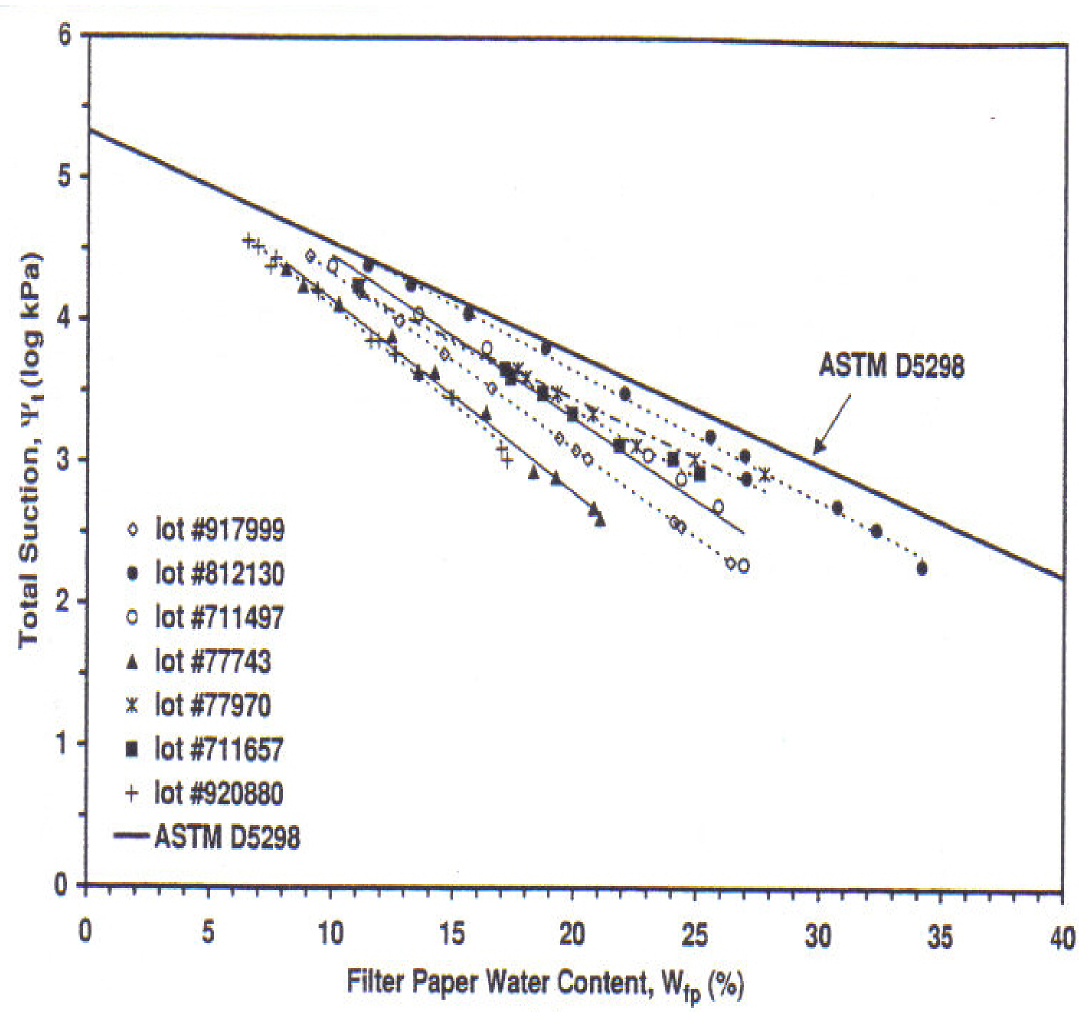


Figure 2.6 Likos and Lu (2003) calibration curves for different batches of Whatman No. 42.

Table 2.1 Filter paper calibration methods used in previous research.

Author	Calibration test
Fawcett and Collis-George (1967)	Pressure Membrane, Pressure Plate, and Vacuum desiccator
Al-Khafaf and Hanks (1974)	Salt Solutions, Thermocouple Psychrometer, Pressure Plates, and Soil Columns
Hamblin (1981)	Up to - 70 kPa - Direct Suction Plate Up to - 0.7 MPa - Direct Pressure Plate Up to - 1.5 MPa - Pressure Membrane Up to - 5.5 MPa - Saturated Vapor Pressure
Chander and Gutierrez (1986)	Standard Concentration of H_2SO_4 and Oedometer Test
Sibley and Williams (1990)	Pressure Plate and Pressure Membrane (3 days), and a Vacuum Desiccator (10 days)
El-Ehwany and Houston (1990)	3 Salt Solutions and Distilled Water
Harrison and Blight (1998)	NaCl and Pressure Plate (7 and 10 days)
Bulut, Lytton, and Wray (2001)	NaCl for wetting cycle, and both pressure plate and pressure membrane for drying cycle
Likos and Lu (2003)	Sodium Chloride and Potassium Chloride - Range of 4.5 – 2.75 log kPa

A commonly overlooked problem in the calibration testing is whether the filter paper is being wetted or dried. The filter paper will undergo hysteresis when wetting and drying. Not much investigation has been conducted on the difference, but it has been noted and mentioned in many research papers. Fawcett and Collis-George (1967) were the first to note that their calibration methods were on the drying side of the hysteresis. Al-Khafaf and Hanks (1979) noted that the filter papers should always be wetted up (initially dry) to avoid problems with the hysteresis. In 1986, Chander and Gutierrez tested the rate of wetting and drying for total suction of the filter paper over a period of time. Figure 2.7 (Chander 1986) shows the rate of change for both (wetting and drying), and demonstrates that the rate of change is much greater in the drying cycle, suggesting that the filter paper has a hysteresis. They also found that the variation in moisture content was larger for lower suctions (higher moisture content) than higher suctions (lower moisture content). Figure 2.8 is their generated calibrations curve from using H_2SO_4 concentrations and the oedometer tests compared with previous research calibration curves (Chander 1986). The bars represent the range of the calculated moisture content and the numbers beside the bar are the number of data points.

The hysteresis of the filter papers is a concern in testing suction of soils and calibration. With the ASTM standard, the filter paper is initially dry when placed in contact with the soil (matric suction) and moisture is introduced through flow. When the filter paper is suspended over the soil sample (total suction), it is initially dry and the moisture increase is through vapor transfer. So the calibrations should follow the same wetting cycle of the filter paper as in the calibration and in the suction test.

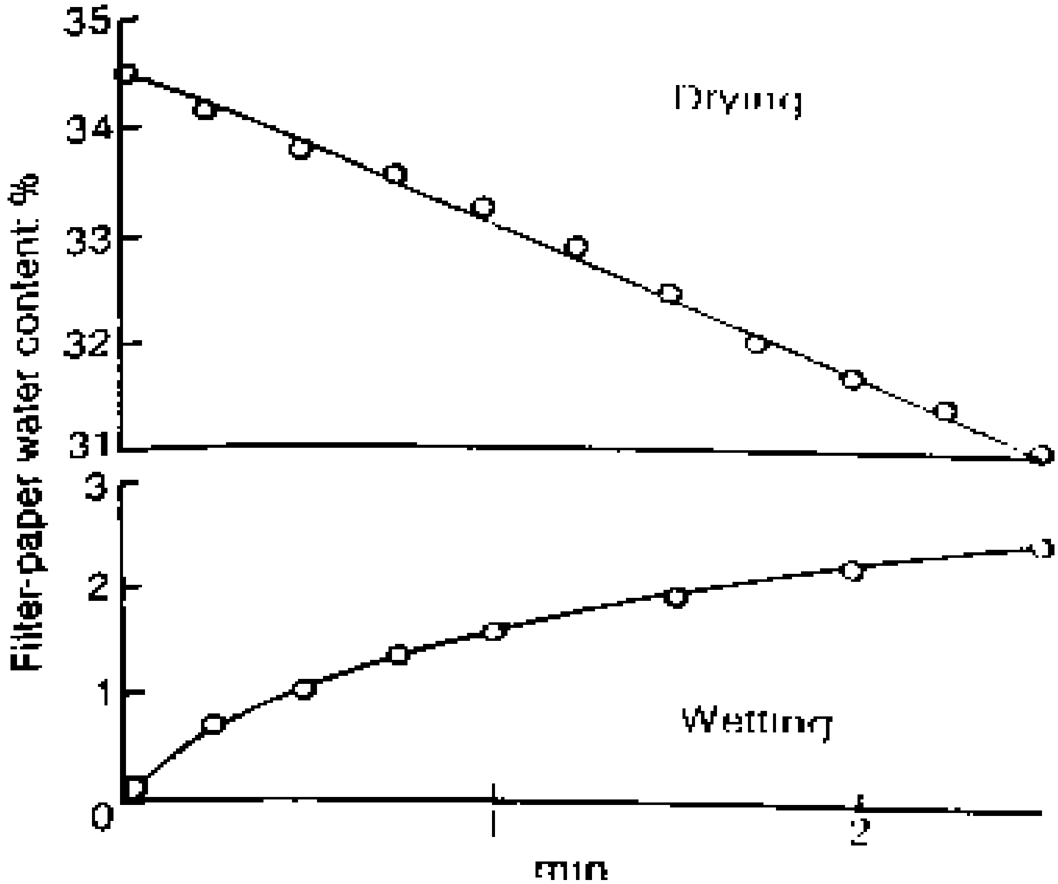


Figure 2.7 Chander and Gutierrez (1986) results from the drying and wetting of the filter paper.

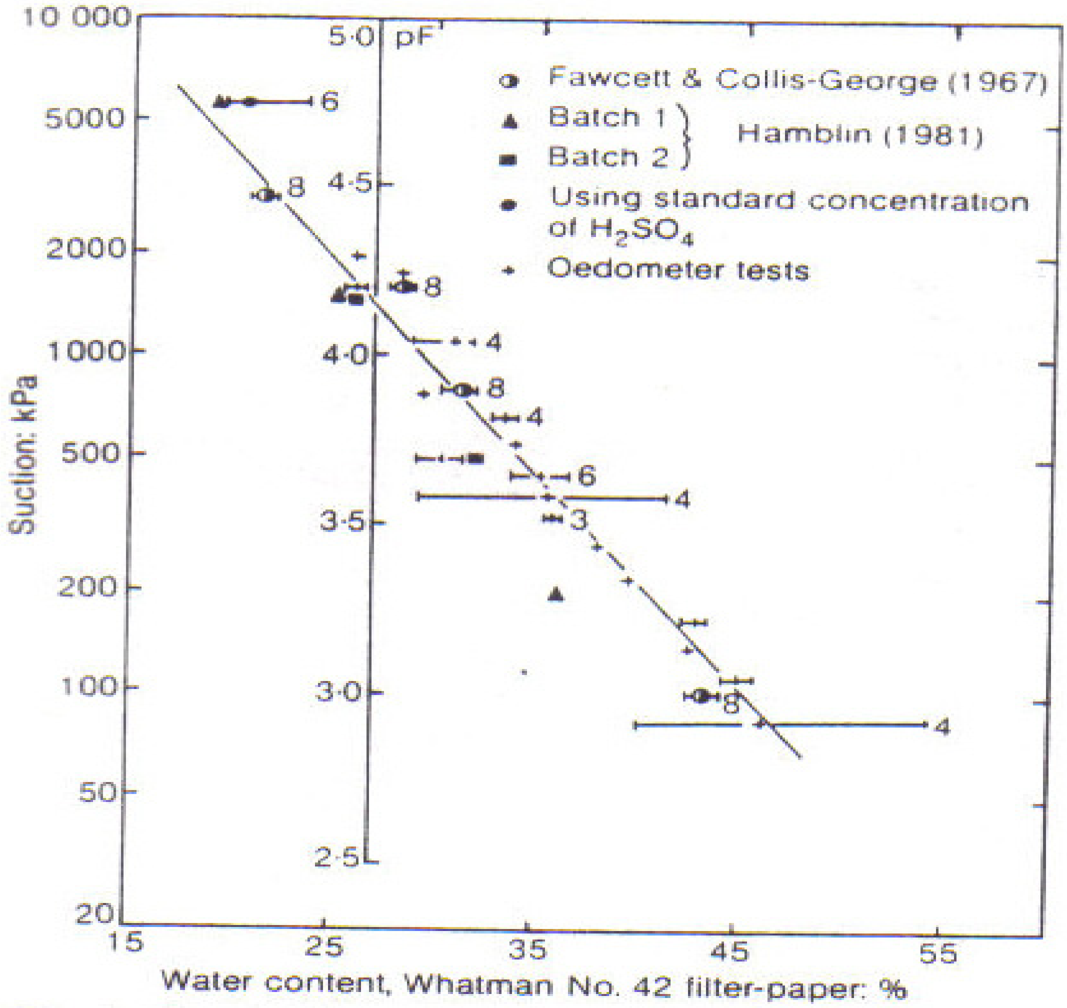


Figure 2.8 Chander and Gutierrez (1986) calibration comparison of their calibrations and previous research.

Table 2.2 summarizes some of the equations for the calibration curves generated from previous research. Many of the very first calibration expressions have been used in subsequent research testing and for comparison against other calibrations. An example is Lee and Wray's (1992) study of soil suction instruments, where McKeen's 1985 calibration curve was used for their research. Some companies and government associations have developed their own calibrations for certain filter papers for their soil testing. The USGS and NMERI have developed a calibration, as shown by McKeen (1988), Figure 2.9. The USGS has developed calibrations for various filter papers.

In the research done by Houston, et al. (1994), the difference between calibrations for total and matric suction was investigated. They noted the difference between total and matric suction at higher values was very small and the calibration methods used to create the calibration curve varied in their measurement of total and matric suction. Such as with salt solutions, the measurement of suction was total, and with tensiometers and pressure plates, matric suction is measured. They also stated that the moisture content of the filter papers could only be determined no closer than plus or minus 0.1%. In 1995 Ridely wrote a discussion on the paper by Houston, et al. (1994), where he showed the difference in matric and total suction calibrations (Figure 2.10). Figure 2.10 also shows the difference between 7 and 14 days and the difference between wet and drying cycle of the filter paper.

In 1998, Harrison and Blight created calibrations curves using Sodium Chloride (NaCl) and a pressure plate. Figure 2.11a and 2.11b show the calibration curves they developed for both the Whatman No. 42 and Schleicher and Schuell 589 filter papers. They calibrated the filter papers by looking at both the wetting (dry-to-moist) and drying

Table 2. 2 Previous research calibration equations for certain filter papers and the range, where Ψ = suction and mc = moisture content.

Author	Calibration equation	mc (%) or suction range	units	Filter paper
Fawcett and Collis George (1967)	$\log_{10} \Psi = 4.777 - 0.0600mc$	mc < 43	kPa	Whatman No. 42
	$\log_{10} \Psi = 2.271 - 0.0230mc$	mc > 43		
McQueen and Miller (1968)	$\log_{10} \Psi = 3.2380 - 0.0723mc$	mc < 54	Bars	Schleicher and Schuell No. 589
	$\mathrm{Log}_{10} \Psi = (9.8966-10) - 0.01025mc$	mc > 54		
Al-Khafaf and Hanks (1974)	$\log_{10} \Psi = 5.117 - 0.0337mc$	mc < 83	kPa	Schleicher and Schuell No. 589
	$\log_{10} \Psi = 1.983 - 0.0090mc$	mc > 83		
Hamblin (1981)	$\mathrm{Ln}\ \Psi = -2.397 - 3.683\ln(mc)$	For less than -3.0 MPa	MPa	Whatman No. 42
McKeen (1985)	$\Psi = 5.90 - 6.2407mc$	From 6 - 2 pF	pF	Schleicher and Schuell No. 589
	$\Psi = 2.25 - 0.6853mc$	From 2 - 1.5 pF		
Chandler and Gutierrez (1986)	$\Psi = 5.85 - 0.0622mc$	From 2.9 - 4.8 pF (mc > 47%)	pF	Whatman No. 42
Greacen, Walker, and Cook (1987)	$\log_{10} \Psi = 5.058 - 0.0688mc$	mc < 54	kPa	Schleicher and Schuell No. 589
	$\log_{10} \Psi = 1.882 - 0.0102mc$	mc > 54		
	$\log_{10} \Psi = 5.327 - 0.0780mc$	mc < 45.3	kPa	Whatman No. 42
	$\log_{10} \Psi = 2.413 - 0.0135mc$	mc > 45.3		
Miller and Nelson (1992)	$\log_{10} \Psi = 4.883 - 0.0599mc$	mc < 43	kPa	Thomas Scientific 4705-F10
Houston, Houston, Wagner (1994)	$\log_{10} mc = 3.63 - 0.483\Psi$	higher suction range		Whatman No. 42
Likos and Lu (2003)	□ = -0.138mc + 5.48	higher suction range	log kPa	Whatman No. 42

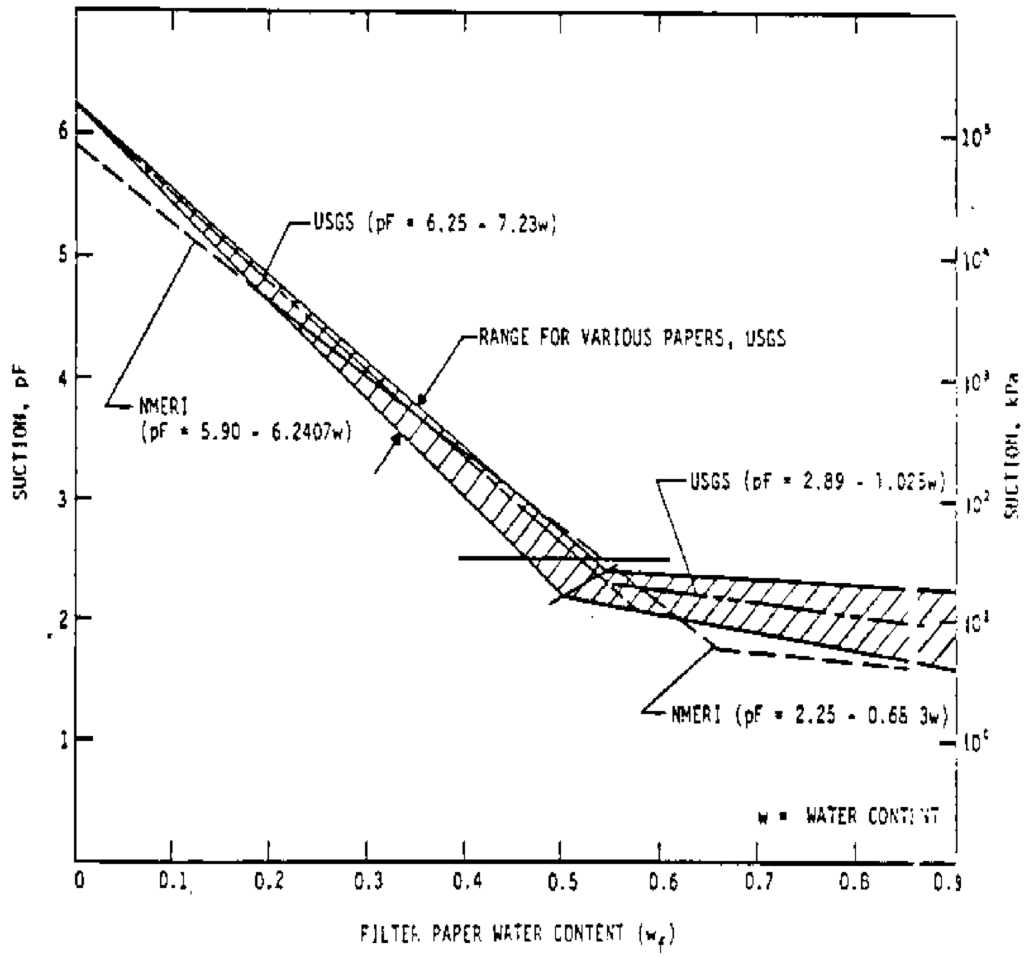


Figure 2.9 Calibrations for the USGS and NMERI, and a range for various filter papers for the USGS, (McKeen 1988).

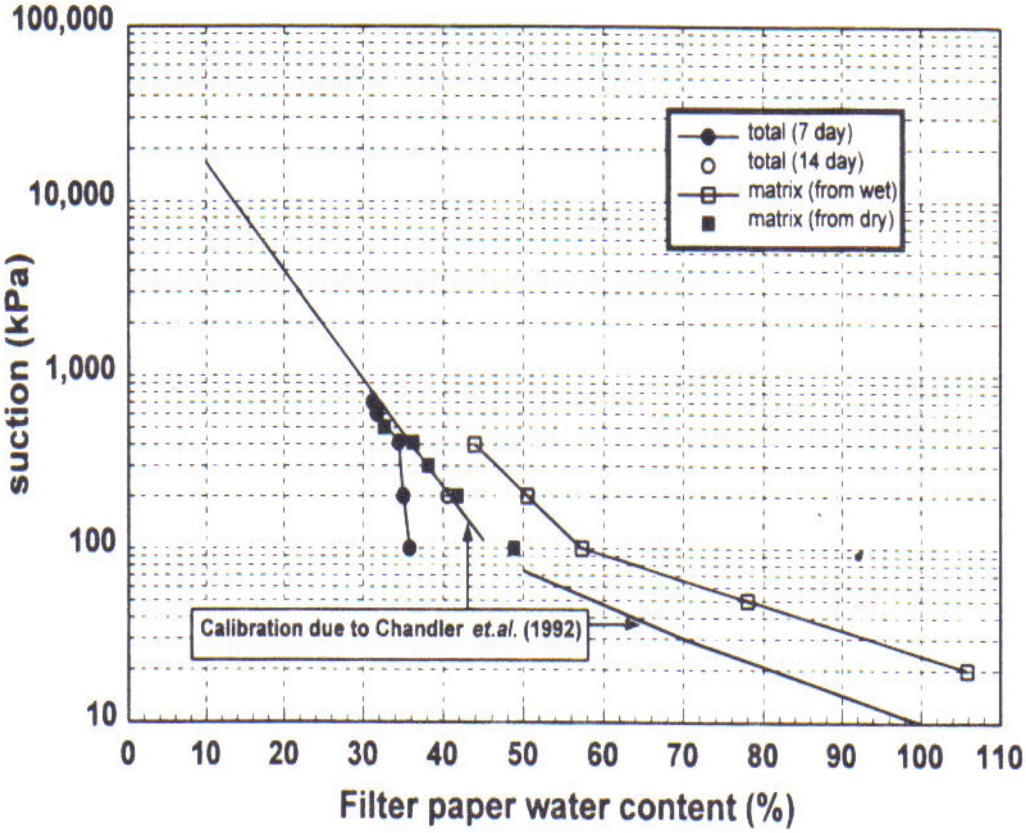


Figure 2.10 The difference between matric and total suction calibration of Houston, et al. (1994) (Ridley 1955).

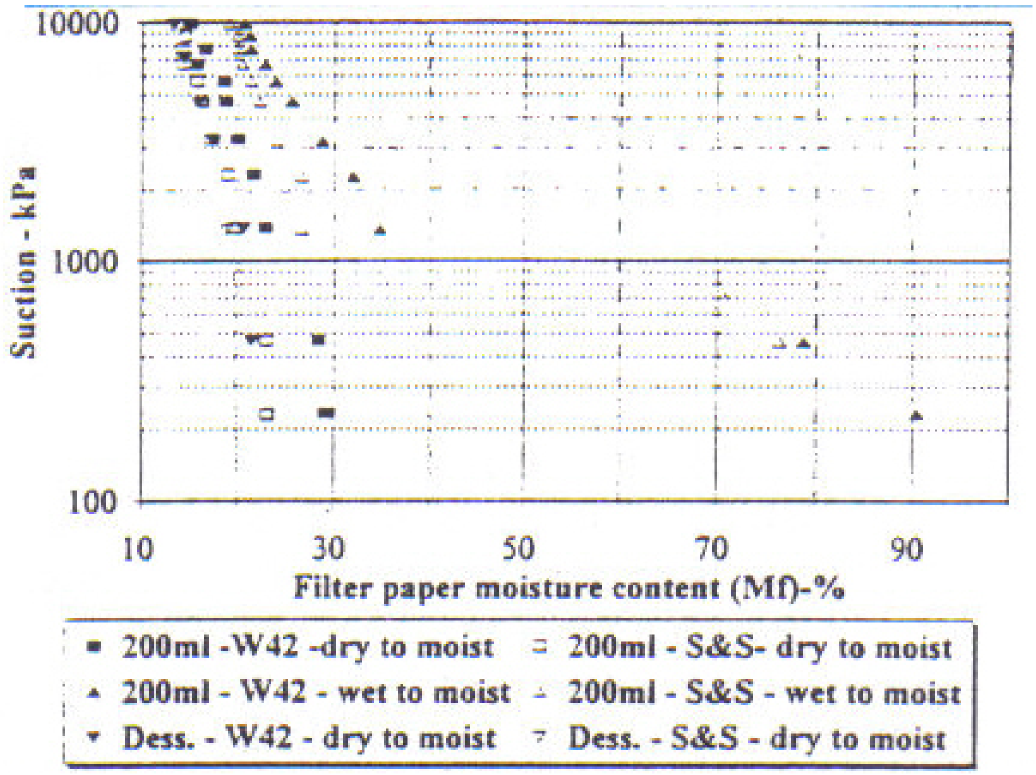


Figure 2.11 Harrison (1998) calibration curves for Whatman No. 42 and Schleicher and Schuell No. 589 filter paper of the drying and wetting cycle (a) by salt solutions.

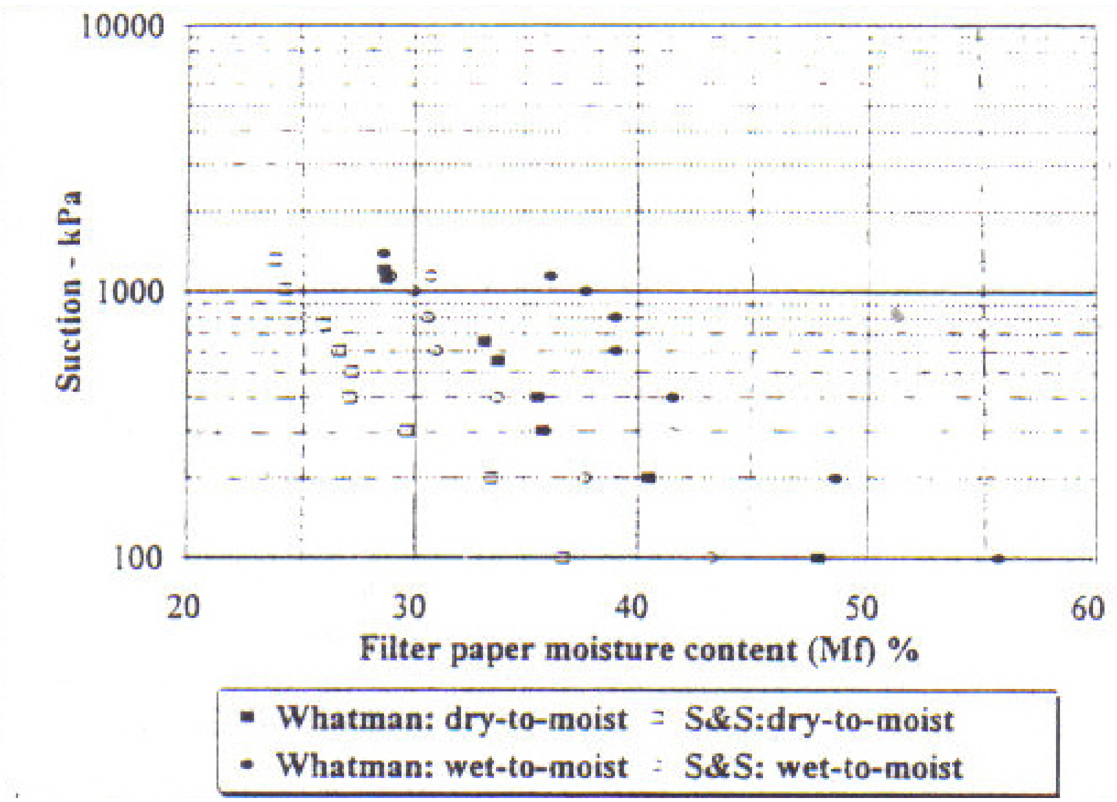


Figure 2.11 continued (b) by pressure plate method.

(wet-to-moist) cycle of the suction characteristic curve. The Whatman No. 42 filter paper showed a higher moisture content than Schleicher and Schuell 589. The relationship between moisture content and suction for the wetting cycle than the drying cycle show a steeper slope for the drying cycle than the wetting cycle. They also noted that the calibration data collected from the salt solution are dependant on the distance of the filter paper from the salt solution rather than the size of the container used. Overall they found that the measurement of suction from the filter paper method was different than the other instruments (C52 chamber and PST probe thermocouple psychrometers) used.

Leong, et al. in 2002 studied the difference between total and matric suction for the filter paper test. They also calculated calibrations for the Whatman No. 42 and Schleicher and Schuell 589 filter paper. They studied the difference between the total and matric suction calibration curves. Figure 2.12a and 2.12b shows the calibration curves. Figures 2.12a and 2.12b suggest that as suction values decrease the difference between total and matric suction increases. It was suggested that as moisture is introduced during matric suction, that flow through the filter paper is brought on by capillary action. Also salts in the water are allowed free flow into the filter papers and the salts that enter in the filter paper could be drawing in water.

2.2.4 Equilibrium time for filter paper calibrations and testing

The time required for the filter paper to come to equilibrium with the soil suction value has been of interest in several studies. McQueen and Miller (1968) used 7 days for their testing, which is the interval suggested by the ASTM standard (D5298-03). Hamblin (1981) checked the equilibrium time for matric suction and said that the

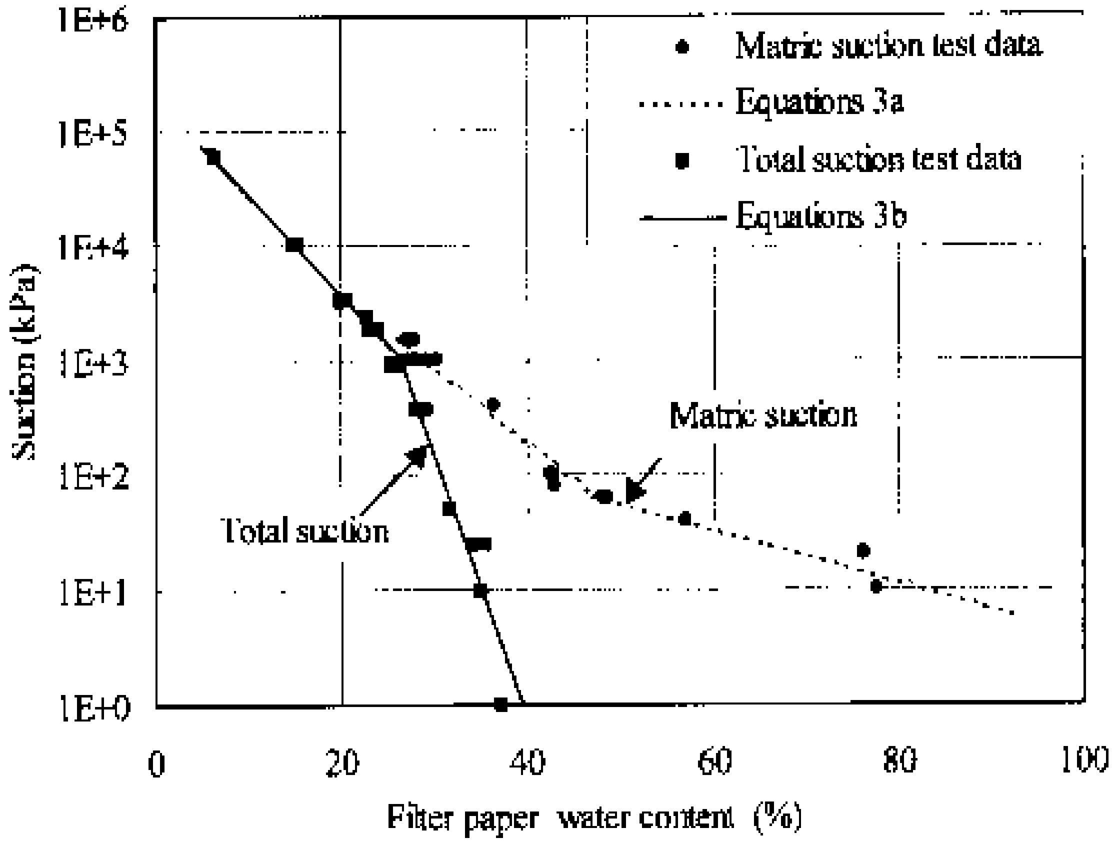


Figure 2.12 Leong, et al. (2002) calibration curve of total and matric suction (a) for Whatman No. 42.

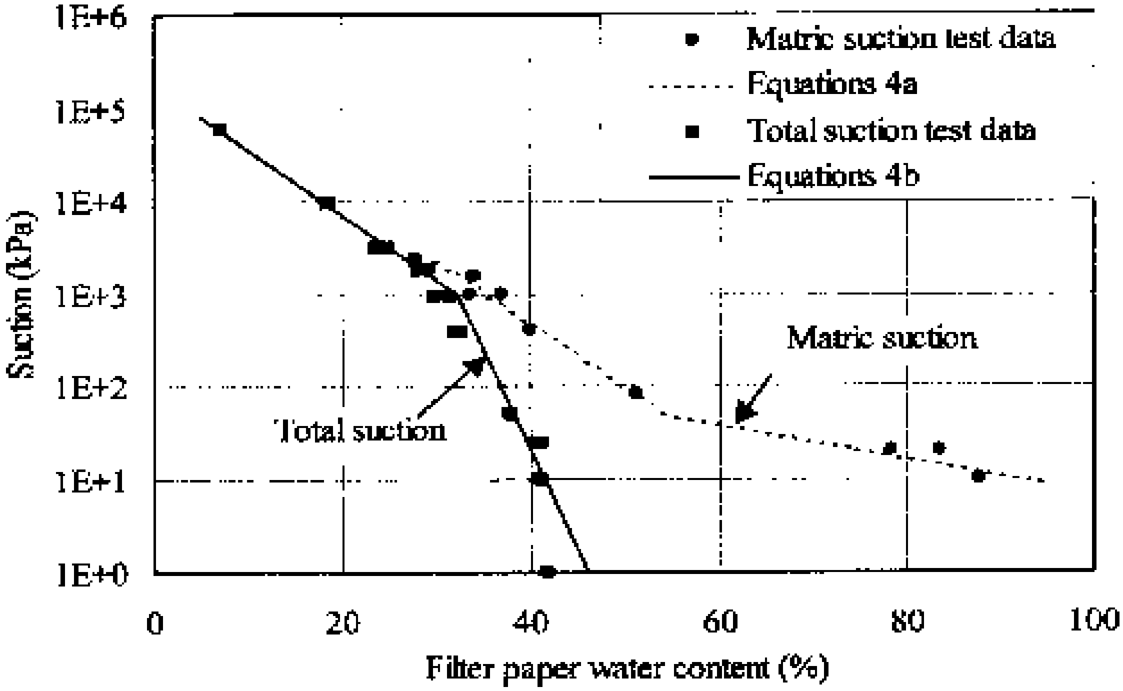


Figure 2.12b continued (b) for Schleicher and Schuell No. 589.

estimated time for equilibrium for nearly saturated soils is a few minutes, while nearly dry soils are approximately 36 hours. Chander and Gutierrez (1986) stated that "usually 7 days are allowed, but at least 5 days are required" for testing. The time for equilibrium to be reached will be investigated in this study.

In 1995 Swarbrick investigated several different aspects of the filter paper test: 1) range and accuracy, 2) hysteresis, 3) calibration and 4) equilibration. They noted that measurements of mass of the filter paper needs to be at least to 0.0001 grams to minimize error in calculating moisture content. But his most focused topic was equilibration for filter papers. He noted the difference in soil suction error versus time. Figure 2.13 shows this with measurements for dry, intermediate, and wet samples. He suggested that soil suction error becomes small after about 7 to 8 days.

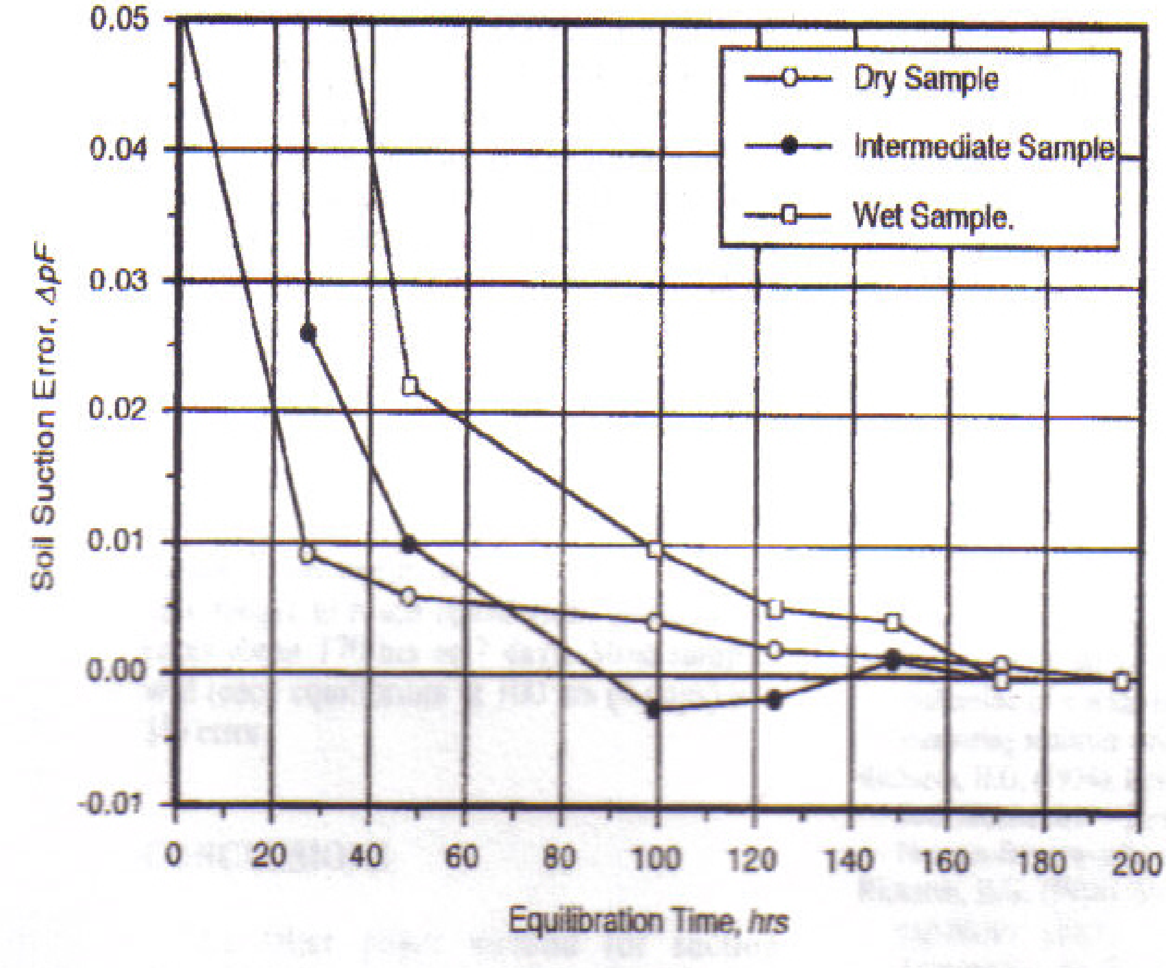


Figure 2.13 Swarbrick (1995) comparison of dry, intermediate, and wet samples for soil suction error versus time.

Chapter 3 Specifics of Procedure, Calibration, and Testing

3.1 Deviation from the ASTM Standard D5298-03

The ASTM Standard D5298-03 provides an outline and certain conditions that must be met during the measurement of soil suction by the filter paper test. The research described here generally follows the procedure in the ASTM standard D5298-03, with the following exceptions:

- The jars were not sealed with tape.
- No solution for fungal and bacterial prevention was used.
- The cooling period on the aluminum block (discussed later) for the measurement of dry mass was changed from 30 seconds to 25 seconds because of the time required for the manual balance to stabilize.

A detailed description of the testing procedure can be found in Appendix A.

The test setup required the sample to be enclosed within a sealed container, so that the filter paper or polymer strip can come to moisture equilibrium with the sample. The test should be performed at a constant temperature, but the tests in this research were not run in a strictly controlled temperature environment. Standard room air conditioning was used to maintain a fairly consist temperature. However, the samples were stored in polystyrene coolers and the temperature was recorded when readings were taken. The ASTM standard suggested the lids of the sample jars be sealed with tape, but it was not done because of the potential for disturbance to the jars.

The ASTM standard also suggests that the filter paper be dipped into a solution for prevention of fungal and bacterial growth, but this was not done for this research.

Previous research suggest that this is usually a problem for tests that are going to run past seven days. Hamblin (1981) investigated pretreated and untreated filter paper, and found that there was no different in their measurements.

The test is somewhat user dependent, due to the requirement to accurately measure small changes in the filter paper mass. A routine has to be established when measuring the mass of each filter paper, and the timing of the reading needs to be fairly consistent, especially when doing the drying reading. For this research, the consistency of the mass readings was a main priority. The same person took the readings each time.

Metal containers were used for oven drying the filter paper and polymer strips. When calculating the moisture content of the filter paper, a change in mass due to the rapid cooling of the metal container has to be considered. It was noticed that the mass of the metal containers fluctuated with the change in temperature. In 1986 Chander and Gutierrez compared weighing times (Figure 2.7) and recommended that no more than 30 seconds to pass for weighing. The ASTM standard also suggests the metal container be placed on an aluminum block for 30 seconds to disperse the heat from the container faster producing more accurate mass measurements. The scale used in the testing a Mettler H80 was a manual scale. So the containers were only placed on the metal block for 25 seconds, because it took some time before the scale leveled out. The difference between the hot and cold mass of the can is taken into consideration when calculating.

The calculations for the water content determination of the filter papers are shown in Table 3.1. Table 3.1 summarizes the calculation of moisture content in the filter paper, taking into consideration the temperature variation in the hot metal container. Note that temperature effects the equation by requiring the tare can to be weighed

Table 3.1 Calculations done to find moisture content of filter paper.

Variable	Definition
$w_f = 100^* (M_w/M_f)$	Moisture content of the filter paper.
$M_w = M_2 - T_h$	Mass of water
$M_f = M_1 - M_2 + T_h - T_c$	Mass of filter paper
M_1	Mass of tare and wet filter paper
M_2	Mass of tare (hot) and dry filter paper
T_c	Mass of tare (cold) at room temperature
T_h	Mass of tare (hot), when taken out of the oven

twice. Also the mass of the hot tare will fluctuate more because moisture is being drawn into the can. The use of plastic bags to calculate the dry mass was also investigated, as suggested by ASTM D5298-03, but it was found not to be an improvement over the metal cans.

3.2 Calibration of Filter Paper with Salt Solutions

Before soil testing can be done, a relationship between vapor pressure and the moisture content of the filter paper needs to be established. Calibration of the filter papers for certain suction ranges can be produced by different methods. The ASTM standard suggests using salt solutions to create a given vapor pressure for the larger suction range (100 to 10,000 kPa) and suggests using the pressure membrane (100 to 1500 kPa) and ceramic plate (10 to 100 kPa) for lower suction ranges. For this research,

salt solutions were used for calibration because there was more interest in the higher suction values and because salt solution calibrations correspond to the wetting cycle.

In the beginning of the investigation, the pressure plate method was investigated for comparison against the salt solutions for the calibration. But the results did not compare well. The filter papers used in the pressure plate were wetted and then the pressure was applied, pulling the moisture out until equilibrium established. It was seen from the first attempt that the moisture contents were high and were representative of the drying cycle of the moisture curve. In the calibration with the salt solutions, the filter papers are initially dried and then placed in the container with the solution. The moisture content of the filter paper is increased through vapor exchange creating the wetting cycle of the moisture curve. Because of the difference in the moisture characteristic curve during drying and wetting, the results did not compare well. The results are provided in Appendix B.

The various filter papers and polymers used in this research have different properties, so calibration curves must be developed for each. The calibrations produced in this research were done by suspending the filter paper over a salt solution that has a known vapor pressure value, and the moisture content for the filter papers is calculated, generally following the procedure discussed by ASTM D5298-03. For this research, potassium chloride was the primary salt used for calibration. The solutions with small amounts of salt added to the distilled water have very small suction values and the higher the concentration of the salt solution the greater the corresponding suction. In addition, a limited number of calibration tests were run using a purchased solution from Wescor, Inc. of Sodium Chloride (NaCl) solutions with water potential of –250 kPa, -725 kPa, and

–2500 kPa to validate the results. A problem arose in comparing the results from the two salt solutions because the purchased solutions of NaCl provided published suction values given at 25°C. In the ASTM method, a table with salts (potassium chloride and sodium chloride) in grams per liter is given with the suction value at 20°C. The calibration and soil testing for this research were performed at 25°C, so a temperature correction for the calculation of the vapor pressure from the salt solutions were needed.

Relative humidity plays an important role in calculating suction. Relative humidity can be used to calculate the suction with some other known variables. But measuring the relative humidity of the salt solution to the accuracy needed for calculations would require very expensive and sensitive equipment, because the smaller suction values are so close to having a relative humidity of 1. In 1945, R. A. Robinson wrote an article on vapor pressures of salt solutions (Potassium Chloride and Sodium Chloride) and this was used to calculate the suction values. The article contains a table (see Appendix A, Table A-1) with molality versus relative humidity at 25 °C. So with this the suction could be calculated. Appendix A contains the details of the temperature correction equations and information used in the calculation.

The calibrations with the salt solutions were setup very similar to that used for the measurement of soil suction. Figures 3.1 and 3.2 show the filter paper and polymer strip calibration setup, respectively, with a schematic (a) and picture (b). Two inch diameter PVC pipe, 1 inch in height, was glued to the bottom of the jar to establish stability, so the filter paper will not move. 110 ml of the salt solution was used which is representative of the size of the soil samples tested. The space between the filter paper and the solution

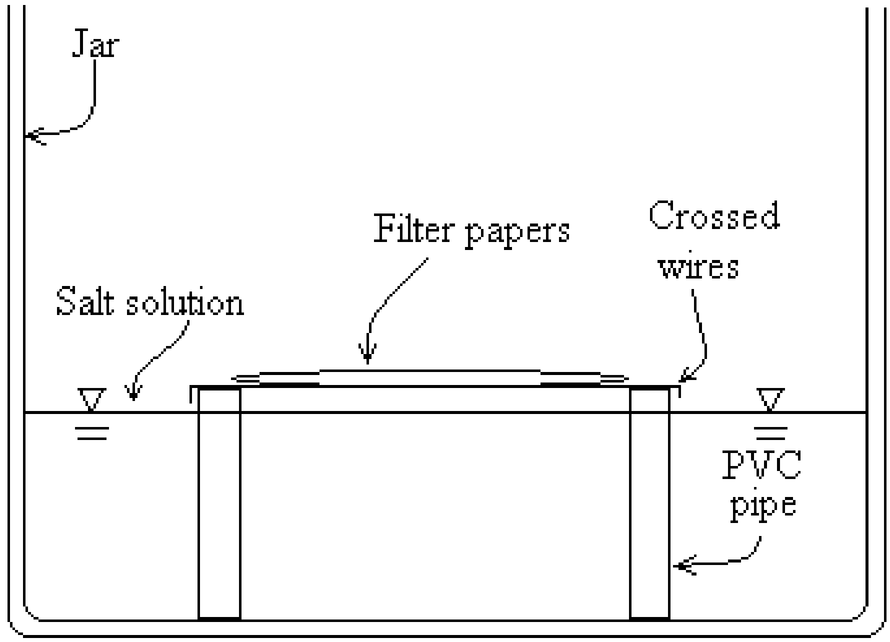


Figure 3.1 Calibration setup of filter paper (a) schematic (elevation).

Figure 3.1 continued (b) picture (elevation).

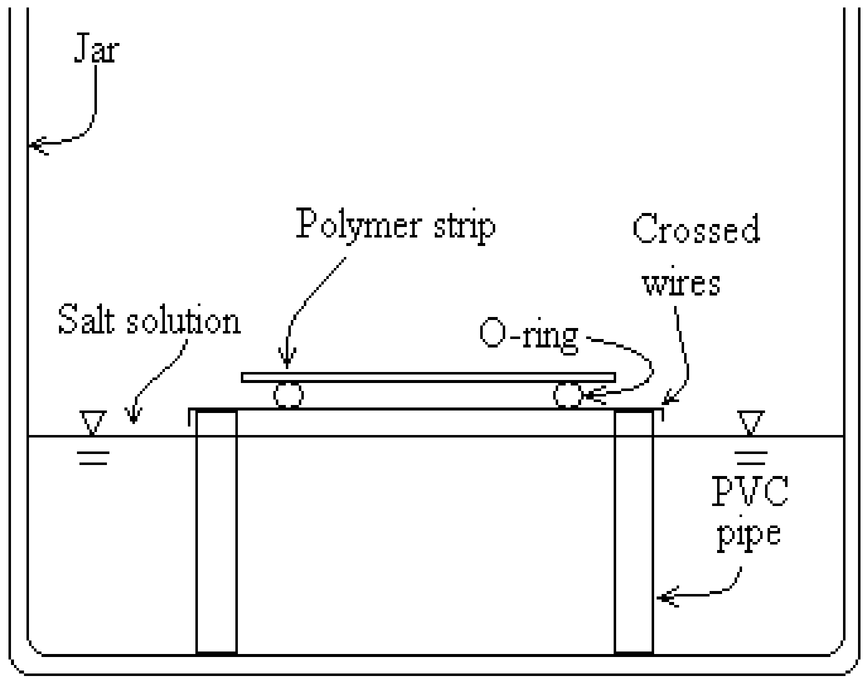


Figure 3.2 Calibration setup of polymer (O-ring added) (a) schematic (elevation).

Figure 3.2 continued (b) picture (elevation).

needs to be similar to the space between the soil and filter paper. The calibration test was run for seven days. In a few cases, data was collected daily to investigate the time required for equilibrium to take place. This was done both for the polymer strips and filter papers, and will be discussed later.

To support the filter paper over the solution, a wire mesh was placed on top of the PVC pipe at first, but it tended to retain water in the mesh openings. Therefore, 22 gage electrical wires were glued across the top of the PVC with epoxy. It was established that 3 –4 wires were needed to prevent any tipping of the filter papers into the solution. The wires were crossed across the center of the PVC, and evenly spaced, Figure 3.3. The epoxy was placed at the very top, because the papers were getting wet when the epoxy extended into the solution due to capillary rise. When the polymer strips were calibrated, an o-ring was added on top of the wires, Figure 3.4. This was done to raise the material slightly to avoid the tendency for the corners to fall into the solution. Increase in the distance above the solution should not make a difference between the measure of moisture content for the calibration test and the soil test.

3.3 Materials

3.3.1 Filter papers

The filter papers required by the ASTM D-5298 94 are to be ash-free, quantitative, Type II filter paper, with a diameter of 5.5 cm. Whatman No. 42, Fisherbrand 9-790A, and Schleicher and Schuell No. 589 White Ribbon are recommended papers. These papers are the primary filter papers used in previous research dealing with the filter paper test. One aspect of this research was to investigate

Figure 3.3 Calibration setup - top view of wires crossed for the filter paper calibration.

Figure 3.4 Calibration setup - top view of wires crossed with O-ring for the polymer strip calibration.

the difference between qualitative paper and quantitative paper and to compare the calibration curve from the literature with calibrations generated from this research. The difference between qualitative and quantitative filter papers depends on the use of the filter paper data. Quantitative filter papers are used to accurately measure the retained materials, while qualitative filter papers are used more for detecting the presence of retained materials.

Three different filter papers were chosen for the research. All of the filter papers used in the testing were 5.5 cm in diameter. The Fisherbrand Q8 filter paper was chosen because it follows the ASTM standard D5298-03 description of filter papers that are to be used for the test. The filter paper is ash-free, quantitative, and Type II. The VWR 454 was also chosen because it also follows the guidelines for selecting filter papers that were set by the ASTM standard. Mainly the VWR 454 was chosen for comparison with the VWR 415, which is used in engineering practice (Hunsdar 2001). The company, CTL|Thompson, Inc., uses the VWR 415 regularly when performing the filter paper test method to measure suction. The VWR 415, however, does not fall within the required specification set by the ASTM standard because the filter paper is qualitative. The same company manufactures the two VWR filter papers, so the difference between qualitative and quantitative could be established.

3.3.2 Polymers

Because of variations within the same type of filter paper, and differences between papers, the investigation of a new materials to use as a replacement for the filter paper has been of previous interest. Sibley and Williams (1990) investigated new

materials for the filter paper test. Their main interest was to improve test sensitivity and extend the range of moisture content for the filter paper method. They investigated Millipore MF filtration membrane, with mean pore sizes of 0.025 and 0.050 μm and a cellulose seamless dialysis tubing. The results were compared with Whatman No. 42 filter paper. When choosing an alternative material there were certain desirable attributes they suggested:

- Robustness in any state of saturation
- Uniformity (in porosity, pore size distribution and compressibility)
- Stability
- Sensitivity ("a small change in suction should produce a large change in moisture content") (Sibley and Williams 1990).

A comparison of the data from Sibley and Williams (1990) can be seen in Figure 3.5. Each material had a different range in which it worked best. For the range 5-6 pF (9,807 kPa to 98,067 kPa), the unwashed dialysis tubing was found to be the best product to use. From 4 –5 pF (981 kPa to 9,807 kPa), the washed dialysis tubing appeared to be the best. Both sizes of the Millipore filtration membrane were best for the mid-range 2.5 – 4 pF (29.4 kPa to 981 kPa). For below 2.5 pF, the Whatman No. 42 filter paper did the best. They concluded that "if only one material is to be used over the entire suction range, then Whatman No. 42 filter paper is the most appropriate" (Sibley and Williams 1990).

Certain polymers are very sensitive to moisture and can be highly absorptive, such as those used in diapers and feminine hygiene products. In this study, the application of a common household polymer as a replacement for the filter paper

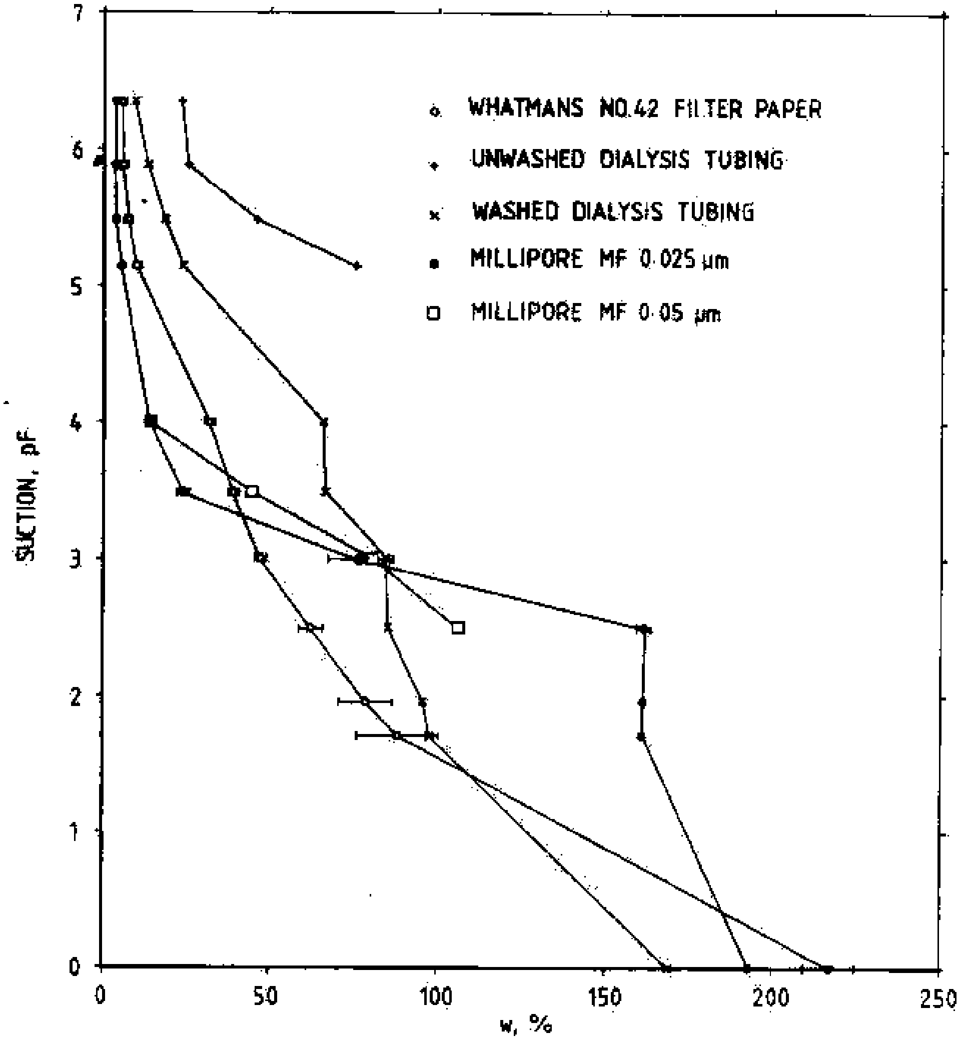


Figure 3.5 Comparison of data for different materials used the filter paper test (Sibley and Williams 1990).

was investigated for soil suction measurements. Potential advantages of a polymer are

1) more sensitivity to the suction values
2) establishment of a larger range of moisture contents for the same suction range
3) test duration shortened

One of the problems anticipated with the polymer is that the material is not mass produced in a form ready for soil suction measurements.

The polymer used in this test was taken from STAYFREE® Ultra Thin Overnight with Wings Pads. It was difficult to find a product with a single layer of polymer, because in many products the polymer is mixed with a cotton-like batting. The original product can be seen in Figure 3.6. The polymer layer can be seen when held up to a light, this can be seen in Figure 3.7. The edges were trimmed off and the top layer that consisted of cotton-like material was removed (Figure 3.8 and 3.9). Figure 3.10 shows how the polymer layer looked when the top layer is removed. Some of the cotton material stuck to the polymer layer (Figure 3.11), so it had to be removed carefully with tweezers (Figure 3.11) or the polymer layer could be removed along with the cotton. Figure 3.12 shows the polymer layer without the cotton layer. Next the polymer layer was carefully removed (Figure 3.13), because there was glue holding the material to the outer layer and the material would tear if a slow and steady hand was not used. The final product from the removal of the polymer layer can be seen in Figure 3.14. The polymer layer removed from the product was consistent in shape and size for each layer removal. It was noticed when removing the polymer that the thickness was not always consistent, because some of the polymer was glued to the outer wrapping. These areas of the

Figure 3.6 STAYFREE® Ultra Thin Overnight with Wings Pads, the original product before removal process of the polymer layer.

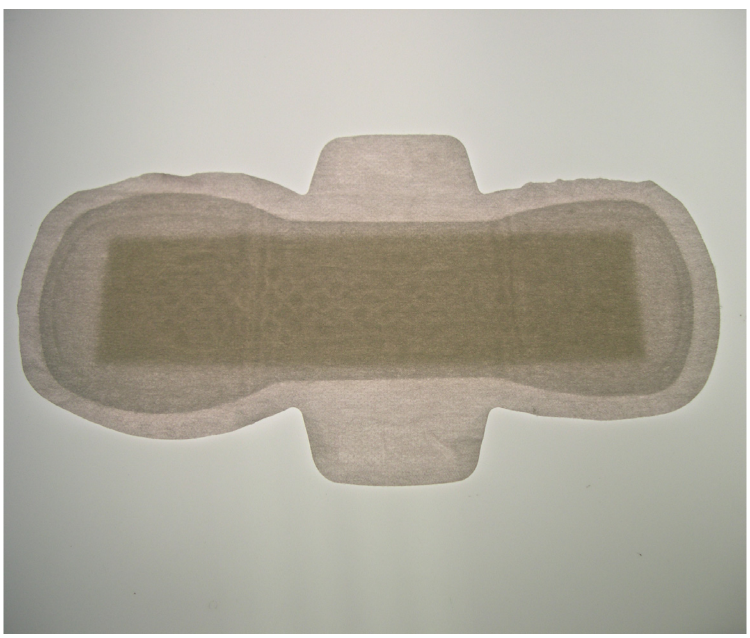


Figure 3.7 The polymer layer in the STAYFREE® product shown when placed in front of a light.

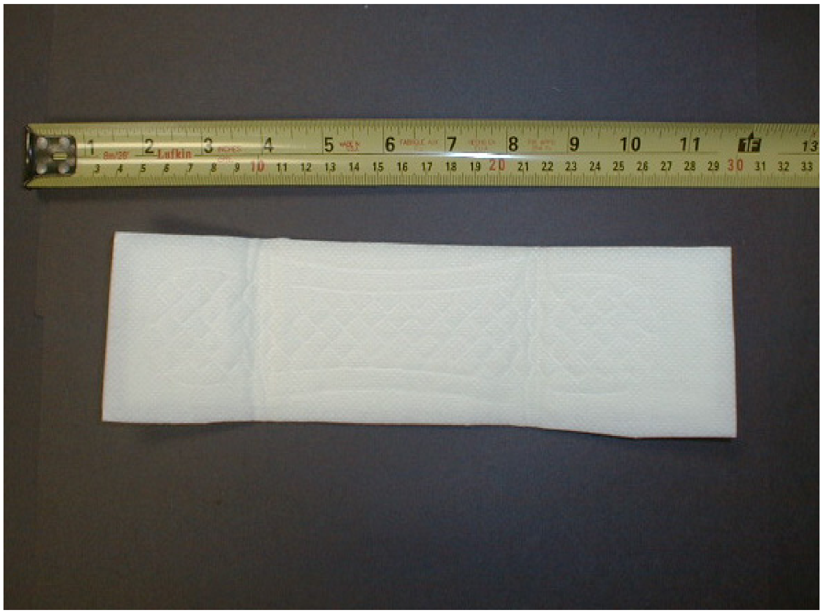


Figure 3.8 Trimmed edges of the STAYFREE® product.

Figure 3.9 Top cotton layer pulled back from the polymer layer.

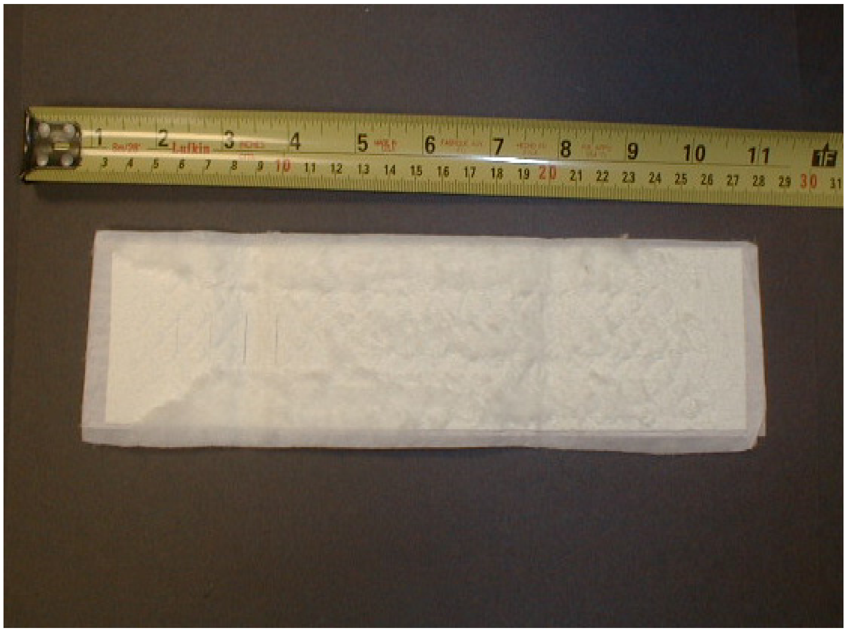


Figure 3.10 Picture of polymer layer with the cotton layer removed, and some cotton still stuck to the polymer layer.

Figure 3.11 Removal of attached cotton-like material to the polymer layer with tweezers.

Figure 3.12 Polymer layer with the cotton material removed.

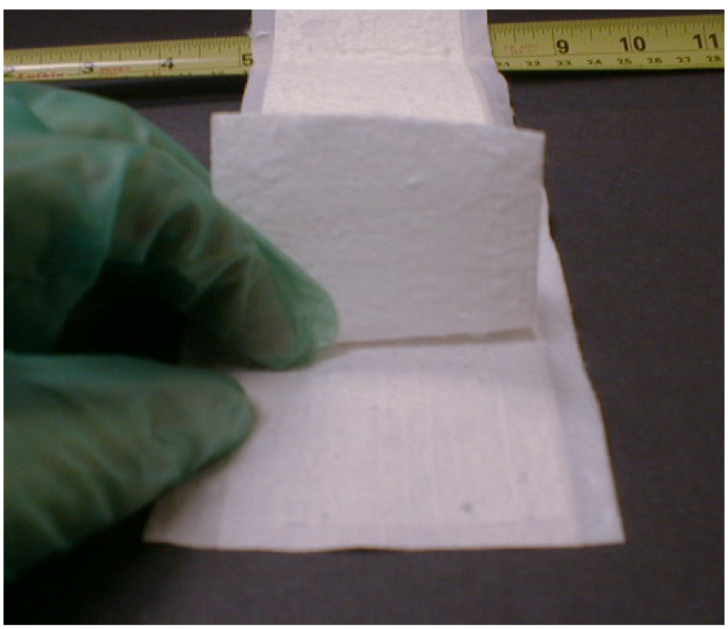


Figure 3.13 Removal of polymer layer from the outer plastic layer.

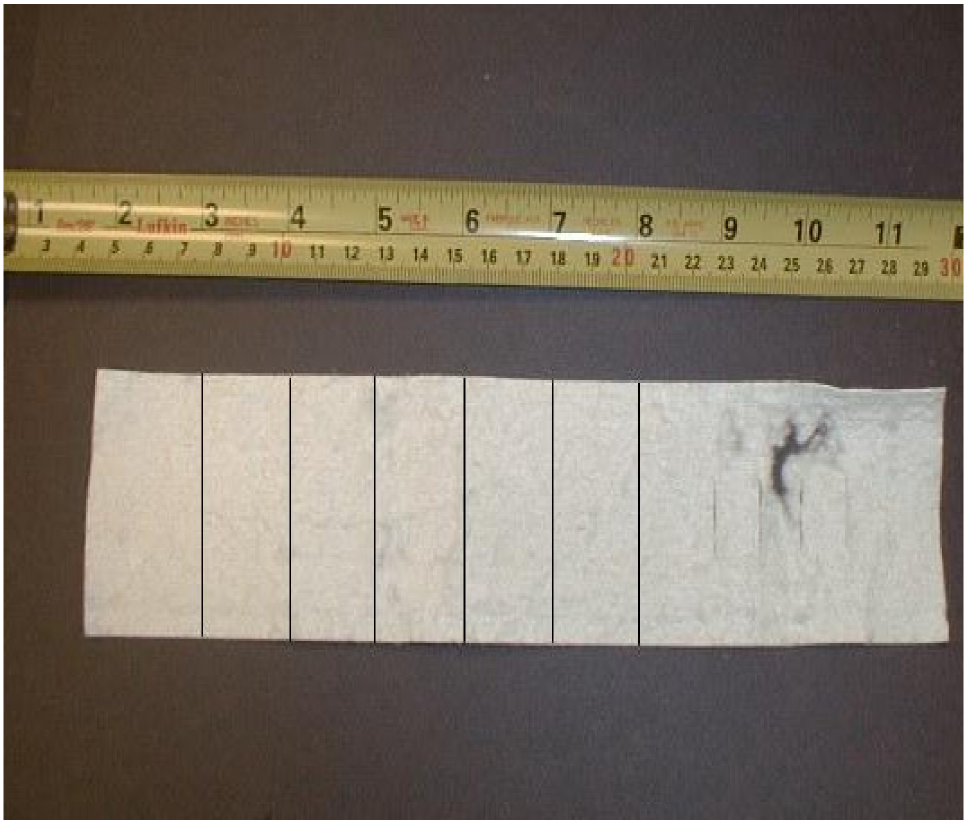


Figure 3.14 Final product of the removal process. It is showing the location of the 2.54 cm (1 inch) by 6.03 cm (2.375 inch) strips prior to removal.

polymer were not used in the testing. The polymer layers were cut into strips of 2.54 cm by 6.03 cm (1 inch by 2 $^{3}/_{8}$ inch) (Figure 3.15). Also to be consistent with the ASTM standard, the polymer was oven dried and placed in a desiccant jar prior to testing.

3.4 Soils Used in the Research

The soils for this research consist of soils from Overton and Blount County Tennessee, and pre-consolidated samples of Bentonite and Kaolin clay. The Overton and Blount County samples were collected from an instrumented pavement site (Rainwater 2004). These samples were taken from beneath the asphalt about 1.54 m (5 ft). from the surface. Also Kaolin clay and Bentonite were chosen because they represent a low swell and a high swell clay, respectively. The Kaolin and Bentonite were consolidated to 69.9 kPa. Kaolin clay is known to be a low swell material. Bentonite is highly absorptive and high swell . The liquid limit for the Bentonite clay has range of 100 to 900. Where the Kaolin clay has an estimated liquid limit of 47.

The behavior of soil samples can vary depending on sample disturbance. The samples used in these tests are from Shelby tubes taken from the field and laboratory consolidated slurry samples. The Shelby tube samples are considered to be undisturbed. With the cutting and preparations of the samples there is disturbance to the sample, but it should be small in error.

Figures 3.16 and 3.17 show the soil sample setup and jar. The soil samples from Blount and Overton County had a diameter of 2.7 inches (the size of the Shelby tube) and the Kaolin and Bentonite samples were cut to roughly the same diameter. All the soil

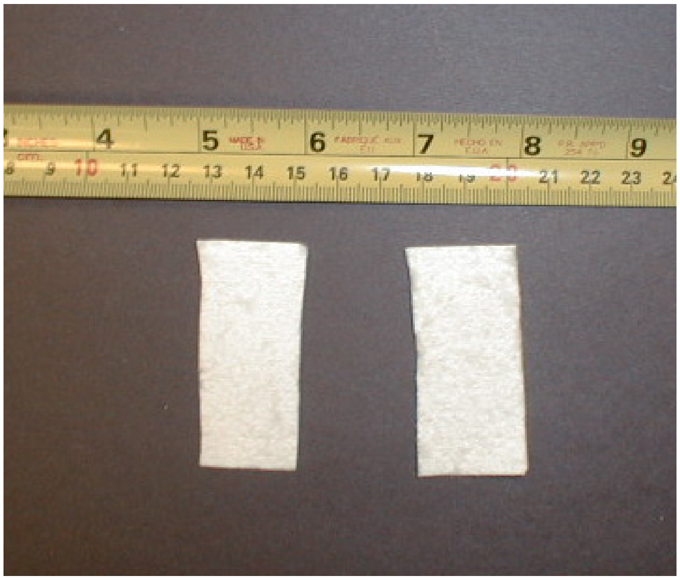


Figure 3.15 Picture of polymer strips used in testing.

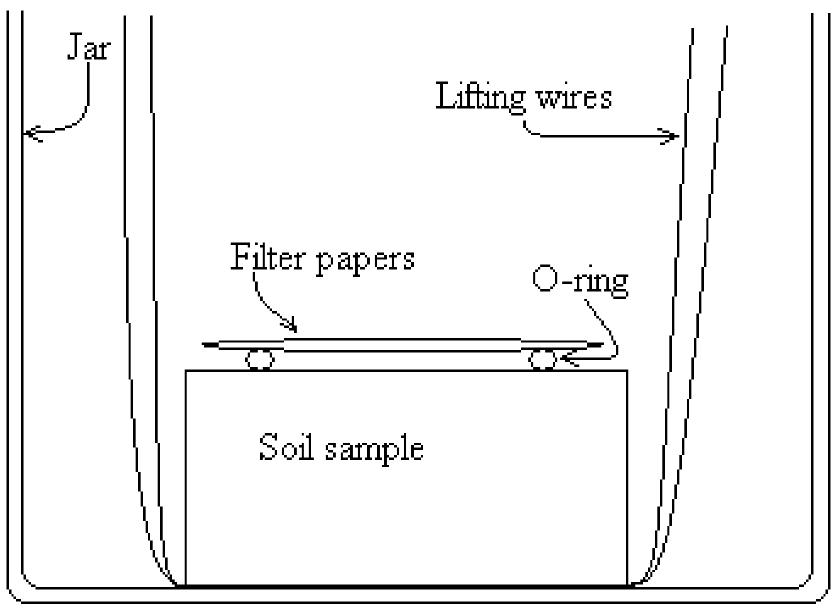


Figure 3.16 Kaolin soil test setup with the filter paper (a) schematic (elevation).

Figure 3.16 continued (b) picture (elevation).

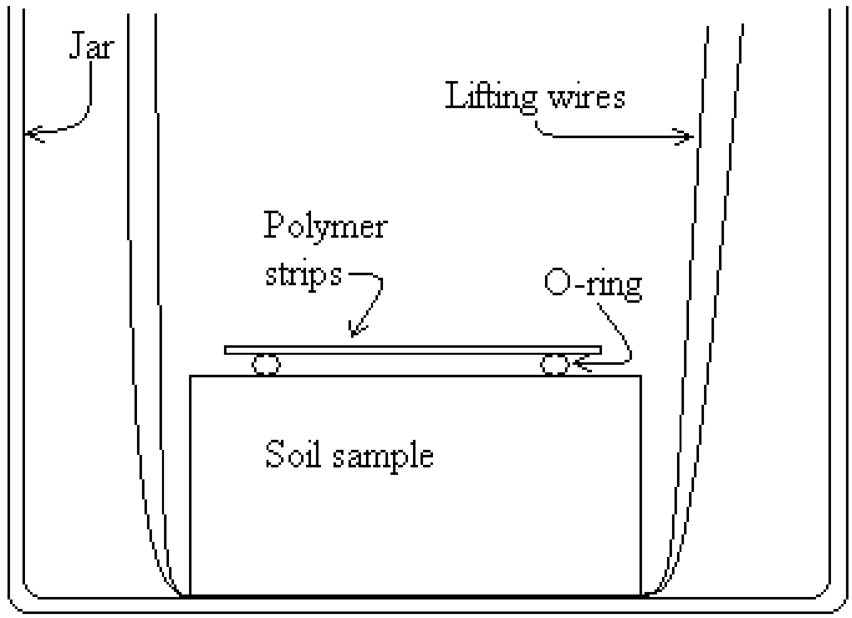


Figure 3.17 Kaolin soil test setup with the polymer strip (a) schematic (elevation).

Figure 3.17 continued (b) picture (elevation).

samples were cut to 1 inch in height. An O-ring was placed underneath and on top of the soil sample, to avoid sample contact with the jar and to facilitate equilibrium. Then two filter papers were placed on the top O-ring. Electrical wires were wrapped underneath the sample, to facilitate removal of the sample from the jar and to minimize disturbance for weighing.

The initial moisture content of the Blount and Overton soil samples was taken from shavings of the samples. The surface of the sample was scratched up, so a smooth impermeable surface did not hinder the exchange of moisture. The soil sample was weighed for an initial mass. Assuming a specific gravity of 2.65, and calculating the density with the measurement of volume of the soil, the moisture content could be changed by an estimation of 3 – 5% at a time by adding a known mass of water to the sample. During each period of moisture change, the filter papers and polymers were placed on the soil sample for seven days and the moisture content of the papers was measured. Also the mass of the soil sample was measured before and after each test to calculate the moisture content of the soil samples.

When the Kaolin and Bentonite soils were cut into samples, the initial mass was measured. There were 8 samples from the Bentonite and 6 from the Kaolin. Two samples of each from the Kaolin and Bentonite were tested at the initial moisture content with the Fisherbrand Q8 filter paper and the polymer strips. The remaining samples were allowed to air dry and then tested, so a large range of moisture content could be established.

Chapter 4 Results from Calibration and Testing

4.1 Calibrations

The suction value corresponds to a measured water content is determined from the salt solution calibration testing. The calibration for the VWR 415, VWR 454 and Fisherbrand Q8 included investigation of the difference between the measurement of the top and bottom papers, the difference between repetitions, the difference between 6 and 7 days equilibrium time, and the difference between quantitative and qualitative filter papers. The calibration of the polymer strips was done in a similar manner and the effect of one polymer strip versus two polymer strips was investigated. Also, an investigation was conducted on the rate of moisture equilibrium for the polymer strips and the Fisherbrand Q8 filter paper.

4.1.1 Filter papers

For the filter paper calibrations, multiple repetitions were obtained to get an accurate trendline and estimate the variability. The first filter paper calibrated was VWR 415, which is not one of the quantitative papers recommended by ASTM D5298-03, but is a qualitative paper that has been used in engineering practice. (Hunsdar, 2001) The ASTM standard for the filter paper test uses the average of the water content measurements from a pair of stacked papers to establish a calibration curve. Figure 4.1 shows the calibration curve and the average linear trendline calculated the VWR 415 after the 7-day equilibrium period. There were a total of six repetitions used to calculate the calibration curve. The variation of the top and bottom filter paper moisture content was also

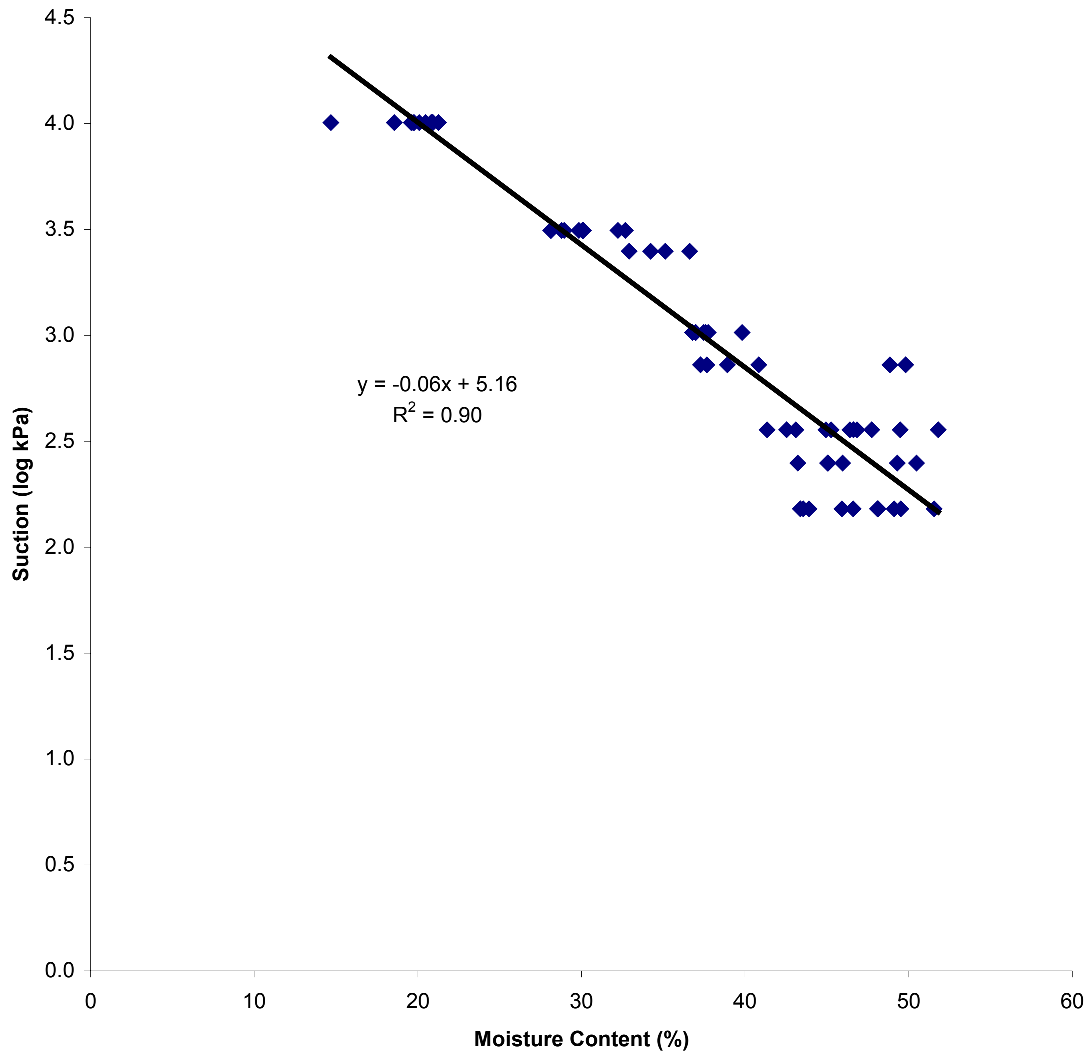


Figure 4.1 VWR 415 7-day calibration results with all data and trendline.

investigated. Figure 4.2 shows the VWR 415 7-day calibration with the data from the top and bottom papers distinguished and shows the range of the calculated data for each suction value. There is not a large difference between the results as presented in Figure 4.1 and 4.2, except that R^2 was higher for the top and bottom separately than for all the data put together. Figure 4.3 shows the trend line for each of the different repetitions, where the mean values are the mean of the top and bottom filter paper. It can be seen from all three figures that for lower suctions (higher moisture content) the variations are somewhat greater.

Figure 4.4 compares the calibration curves for the VWR 415 (qualitative) and VWR 454 (quantitative) filter papers. The VWR 454 paper, which is recommended by ASTM D5298-03, displays a smaller moisture content range over the same range of suction values than that for the VWR 415 paper, and the data has a smaller R^2. The results suggest the apparent reasoning for using VWR 415 in practice, because the slope of the calibration curve for the VWR 415 is less than that for the VWR 454. Thus, the suction value for a given moisture content measurement can be determined with greater resolution with the VWR 415 paper.

A comparison of how the moisture content and corresponding calibration curves varied from 6 to 7 days is shown in Figure 4.5. The mean value and range of all data for each calibration test is shown. There seems to be a significant difference between the 6 and 7 day results, suggesting that it would cause a fairly large error in the calculated suction value if the moisture content were measured at different times. It is recommended that all tests to be run for the same amount of days. The ASTM D5298-03 standard recommends 7 day readings.

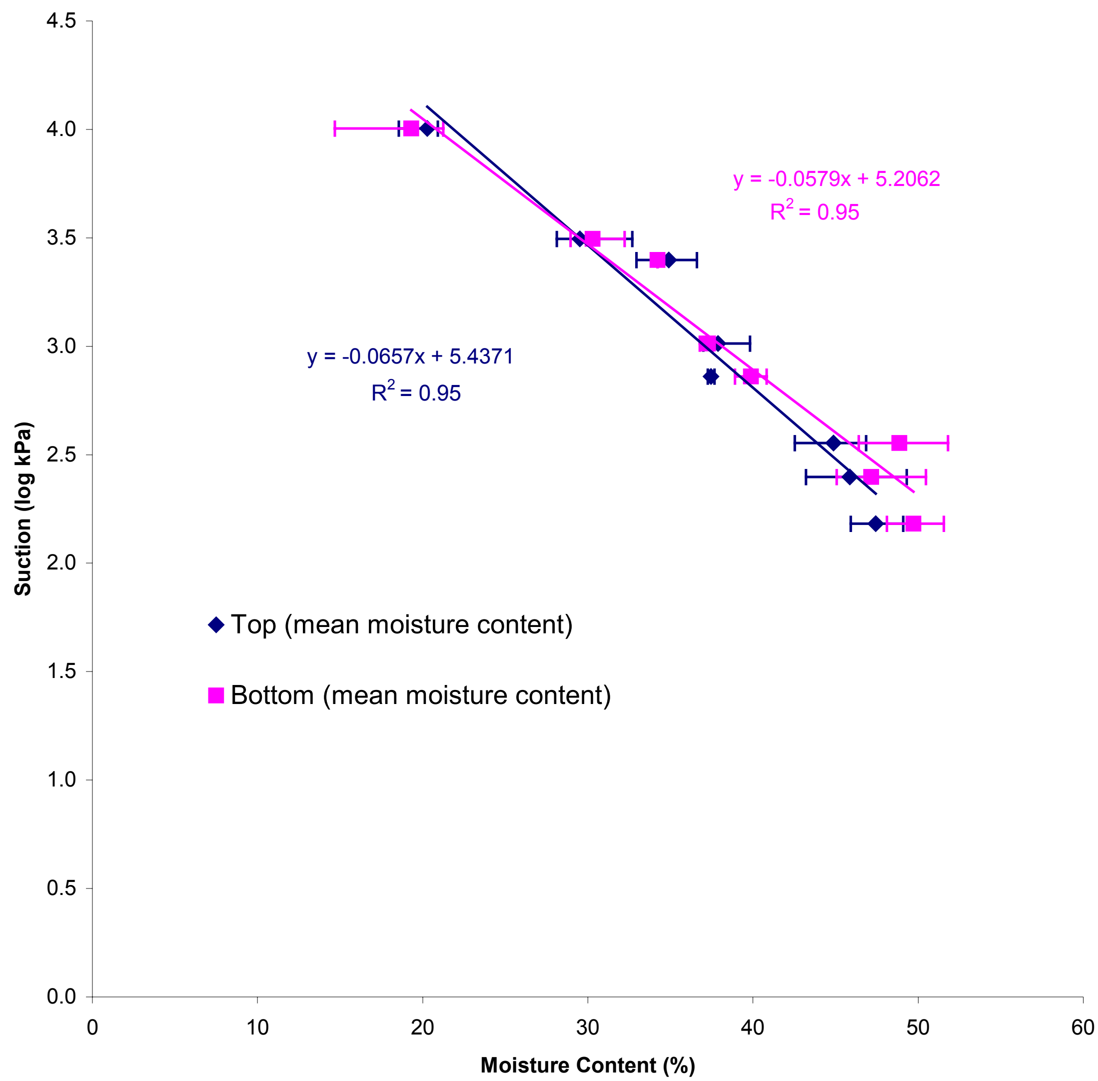


Figure 4.2 VWR 415 7-day calibration results with the top and bottom filter paper data distinguished, and the mean value and range (lowest and highest data point) of measurements for each suction value.

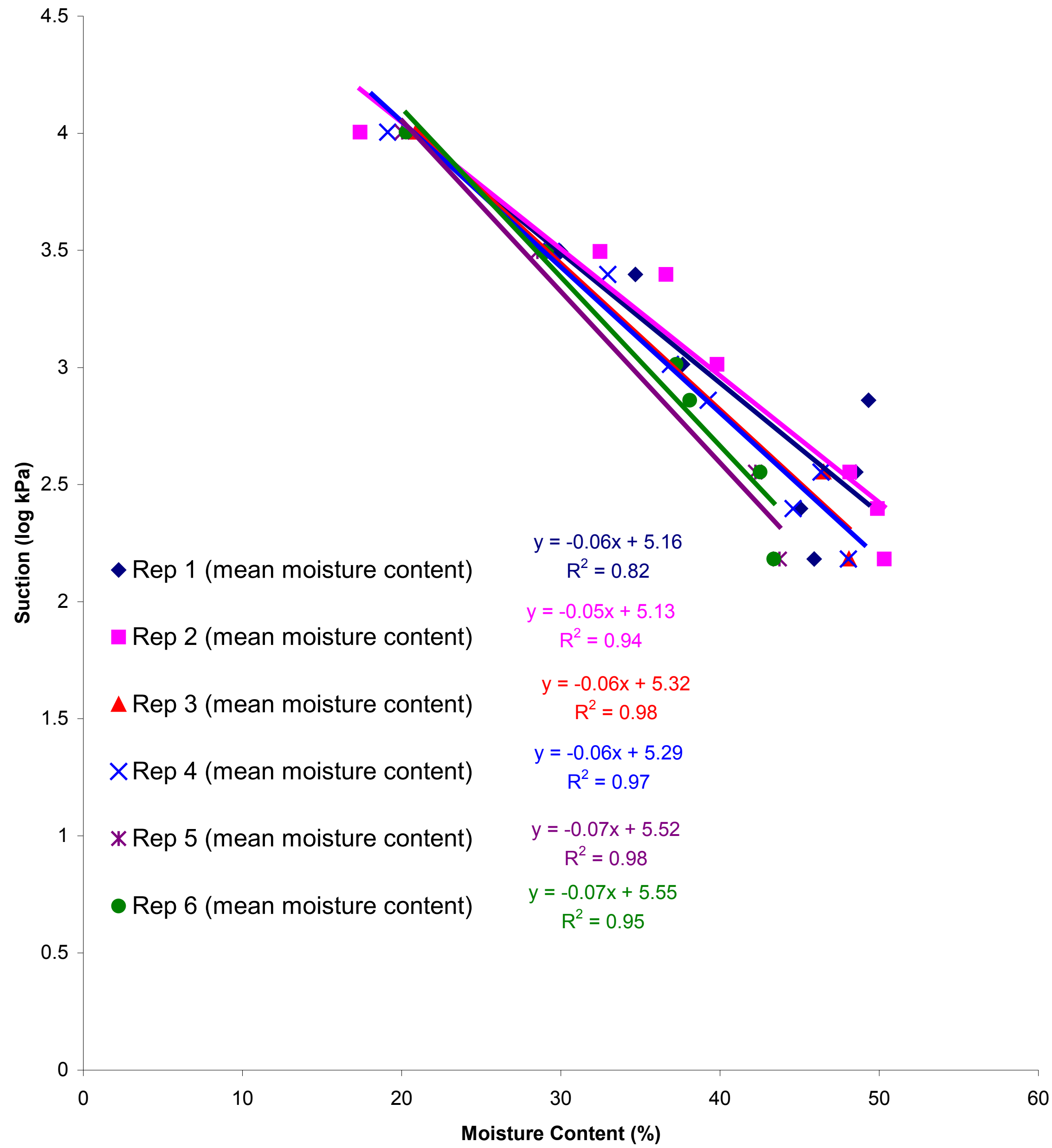


Figure 4.3 VWR 415 7-day calibration results with the results for six different repetitions distinguished.

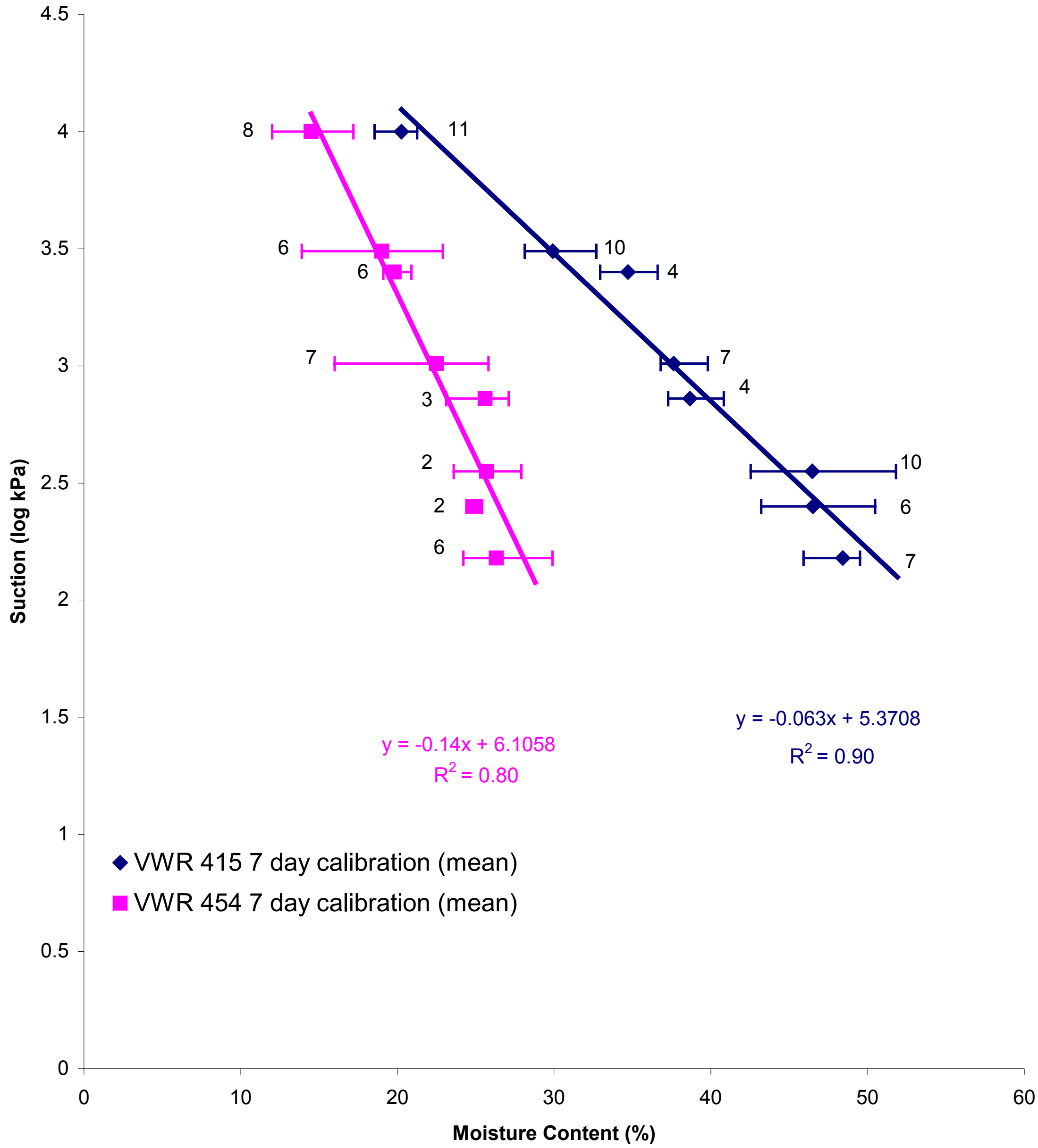


Figure 4.4 Comparison of VWR 415 and VWR 454 filter paper average of all repetitions, with mean and range of moisture content. The bars show the lowest and highest calculated values. Numbers indicate the number of data points for each suction value.

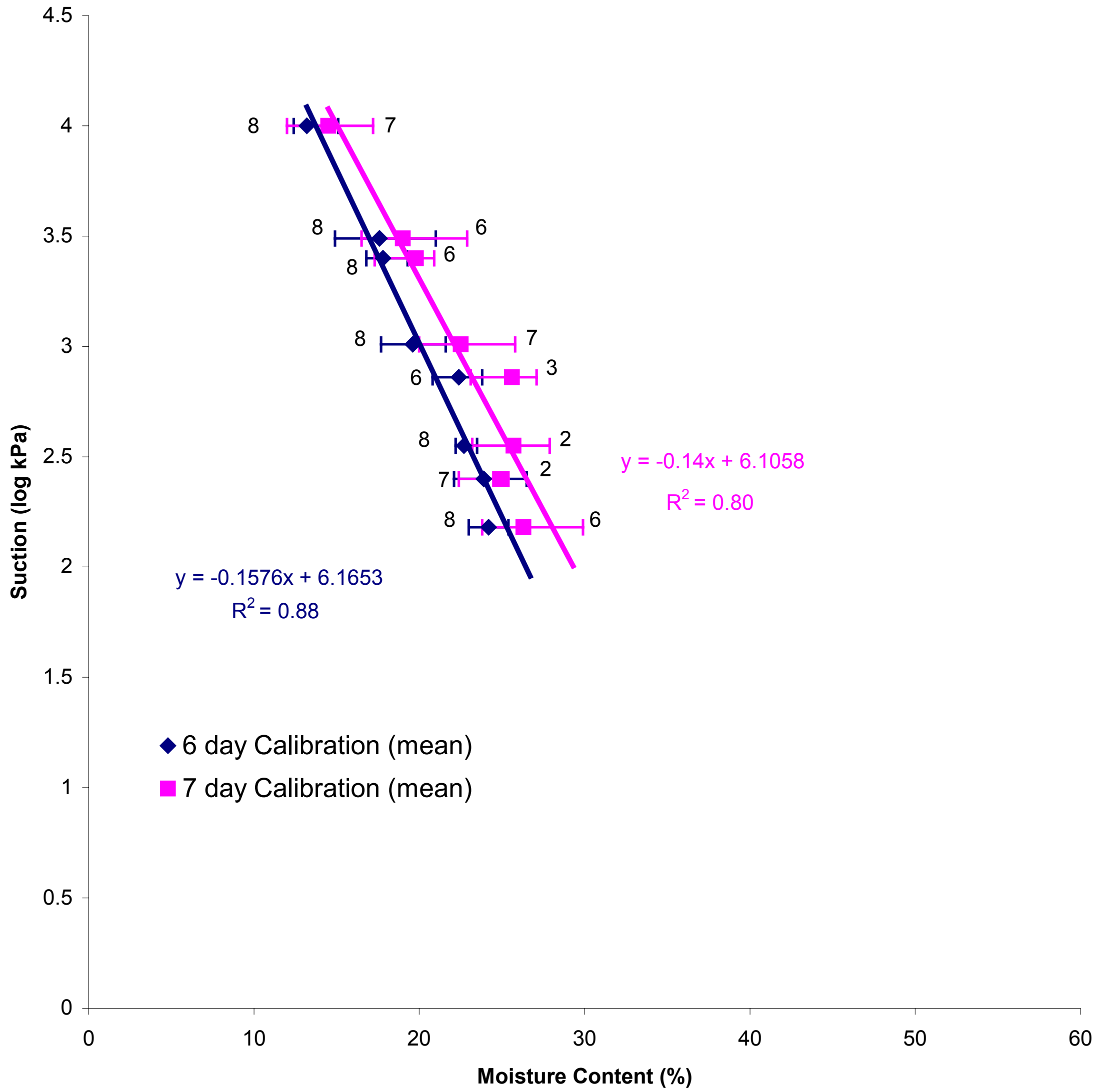


Figure 4.5 Comparison of VWR 454 calibrations for 6 and 7 days. Mean values and range of moisture is shown with the bars indicating the lowest and highest calculated values. The numbers indicate the number of data points for each suction value.

The third filter paper calibrated was the Fisherbrand Q8, which is a qualitative paper also recommended by the ASTM D5298-03 standard for filter papers. It produced a calibration curve that was very similar to that for the VWR 454, with a smaller moisture content range than the VWR 415. Figure 4.6 shows the calibration data and trendline distinguished for each 7 day repetition. The Fisherbrand Q8 calibration data yielded a more consistent slope, and a relatively consistent variation of the moisture content at the high and low suction values. Figure 4.7 shows the mean value and range for each suction value and compares the results of the Fisherbrand Q8 with the VWR 415 and VWR 454 papers. The two filter papers, VWR 415 and Fisherbrand Q8, that meet ASTM D5298-03 standard have very similar calibration curves, while the VWR 415 shows a much wider moisture range and provides more resolution when used to determine the suction from a measured water content. The VWR 415 had the highest R^2 of the three filter papers, and the highest moisture content range. The VWR 415 is a qualitative filter paper, while the VWR 454 and Fisherbrand Q8 filter paper are a quantitative filter paper.

A comparison of the generated regression lines for the filter papers used in this research was compared with previous research (Miller 1992, Greacen 1987, Al-Khafaf 1974 and Fawcett 1967) calibration curves for quantitative filter papers. Figure 4.8 compares the calibration of the filter papers. The previous research calibration curves follow more closely to the generated qualitative VWR 415 filter paper than the calibrations curves generated from the quantitative filter papers from this research. The calibration curves taken from previous research (Greacen 1987 and Al-Khafaf 1974) for the Schleicher and Schuell No. 589 filter paper show very different calibration curves.

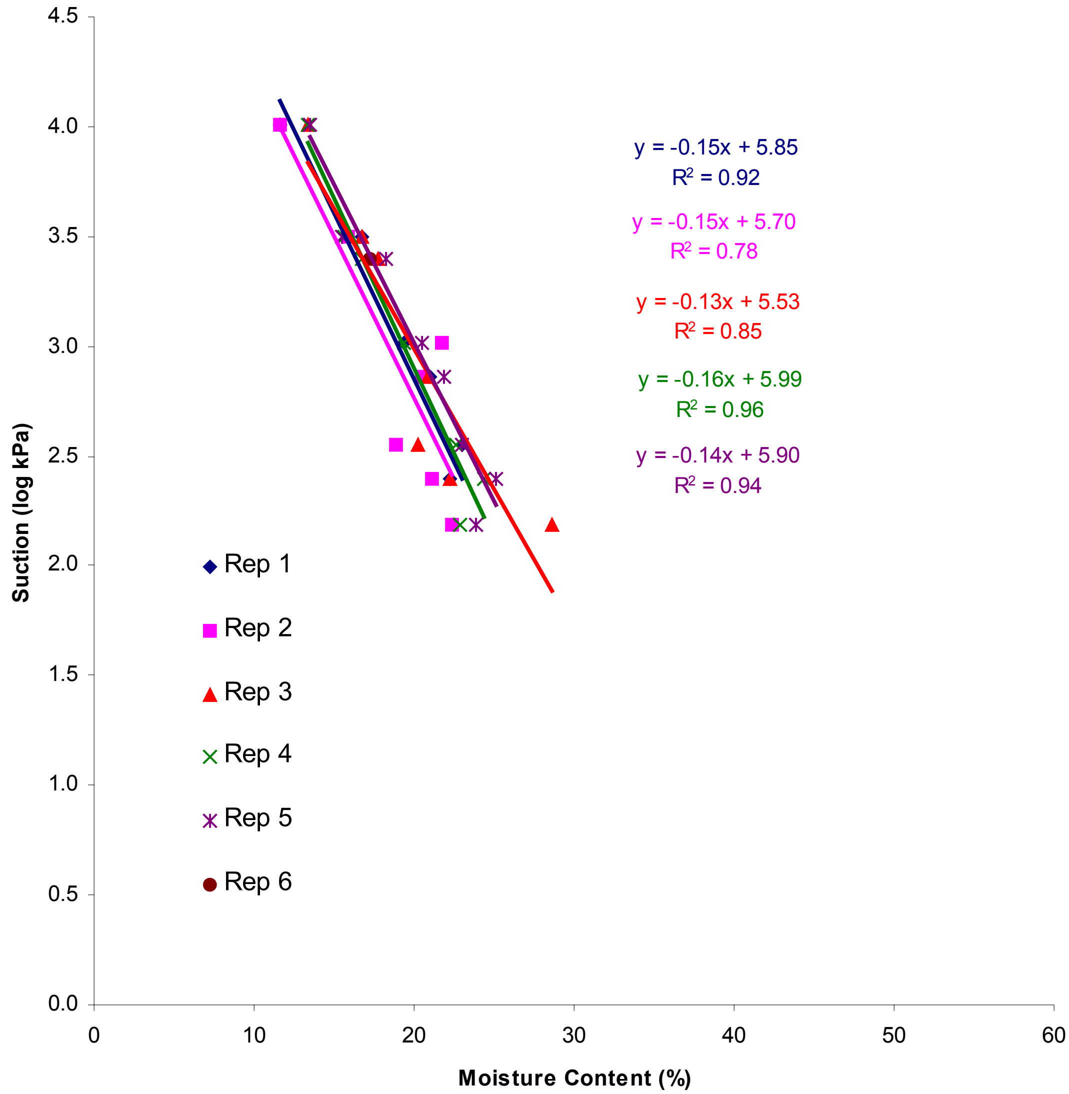


Figure 4.6 The Fisherbrand Q8 7-day calibration results, distinguished by repetition.

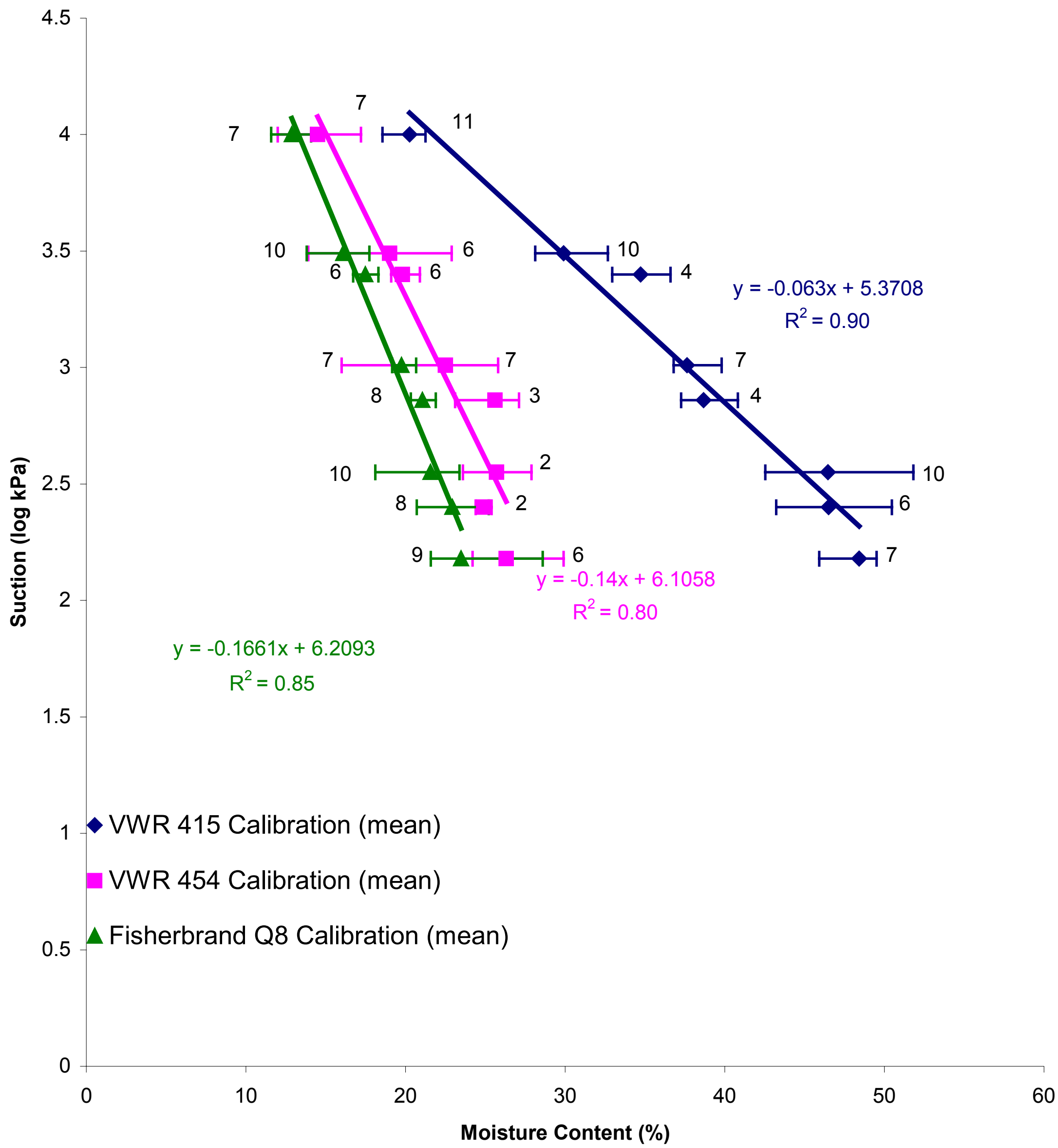


Figure 4.7 Comparison of 7-day calibration test data for three different filter papers. Mean values and range of moisture is shown with the bars indicating the lowest and highest calculated values. The numbers indicate the number of data points for each suction value.

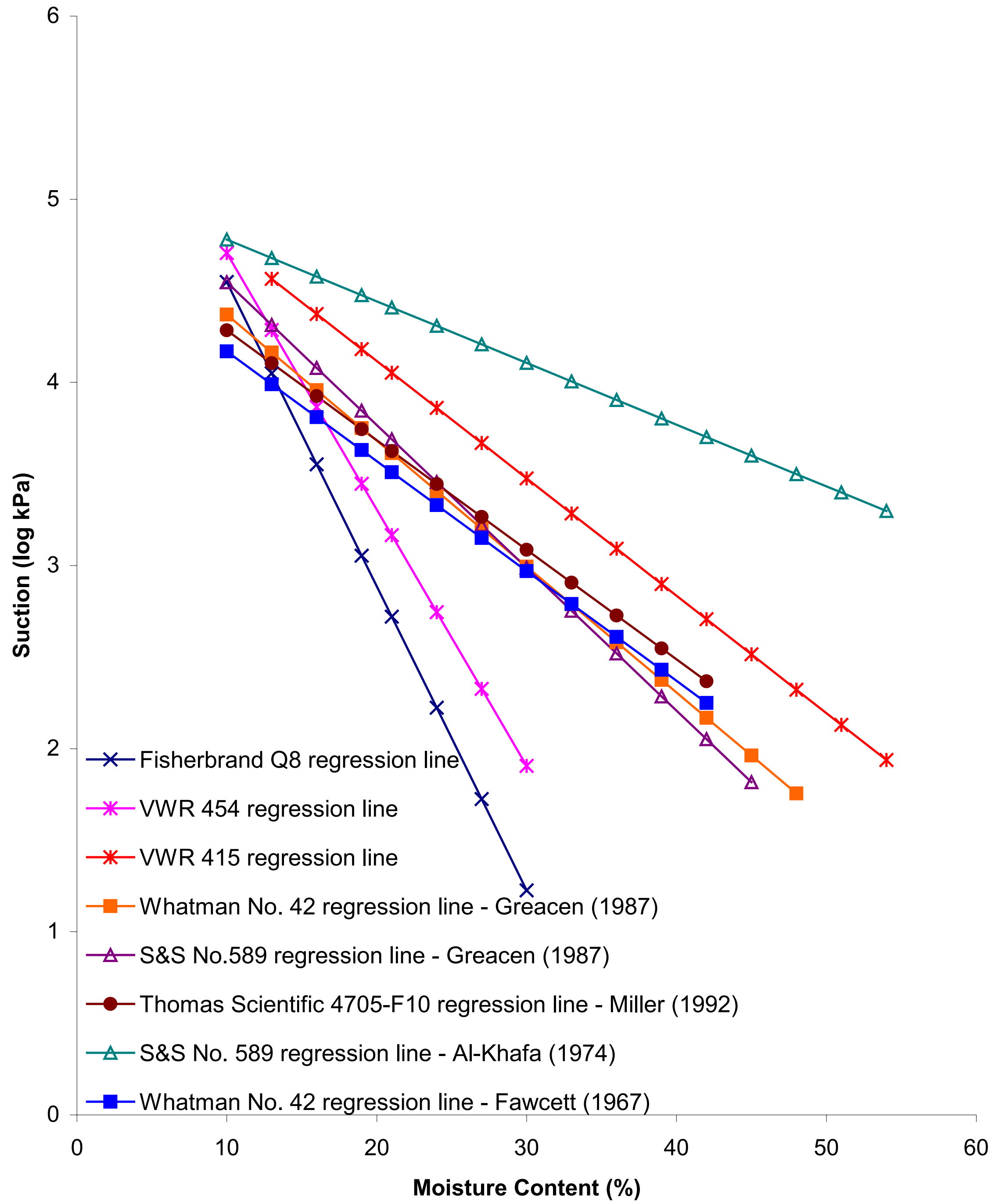


Figure 4.8 Comparison of the filter papers from this research with previous research. S&S is Schleicher Schuell filter paper.

4.1.2 Polymer strips

Figure 4.9 shows the calibration data from all repetitions for both the top and bottom polymer strips for 7-day equilibrium period. The range of water contents for the calibration is (50-200%) is very different from that for the filter papers (20-50%). As with the filter paper, the moisture content varied more for lower suction (higher moisture content), than for the higher suction (lower moisture content). This is consistent with previous research (Greacen 1987 and Chander 1986), which has shown that for lower suctions (higher moisture content) the moisture content variation is greater than at higher suction. As discussed subsequently, this may be related to the time required for equilibrium of the moisture content to be reached. The polymer strips show promising results in having a higher adsorption rate and much wider moisture content range.

In the early testing of the polymer strips, it was noticed that the measurements at lower suctions (higher moisture content) had a greater difference between the top and bottom polymer strips. Originally the polymers were cut without a template, and the smaller polymer strips were placed on the top. After using a template, the difference in the top and bottom measurements was reduced significantly.

Figure 4.10 compares the mean value and range of all the data (top and bottom) at each measured suction value for three the filter papers and the polymer strips. The calculated R^2 for each media is shown, with the polymer strips yielding the largest value at 0.94, while also having the broadest variation of data. The polymer strips clearly yield a larger range of moisture content than any of the papers. The lower slope of the suction water content curve provides improved resolution in the determination of soil suction.

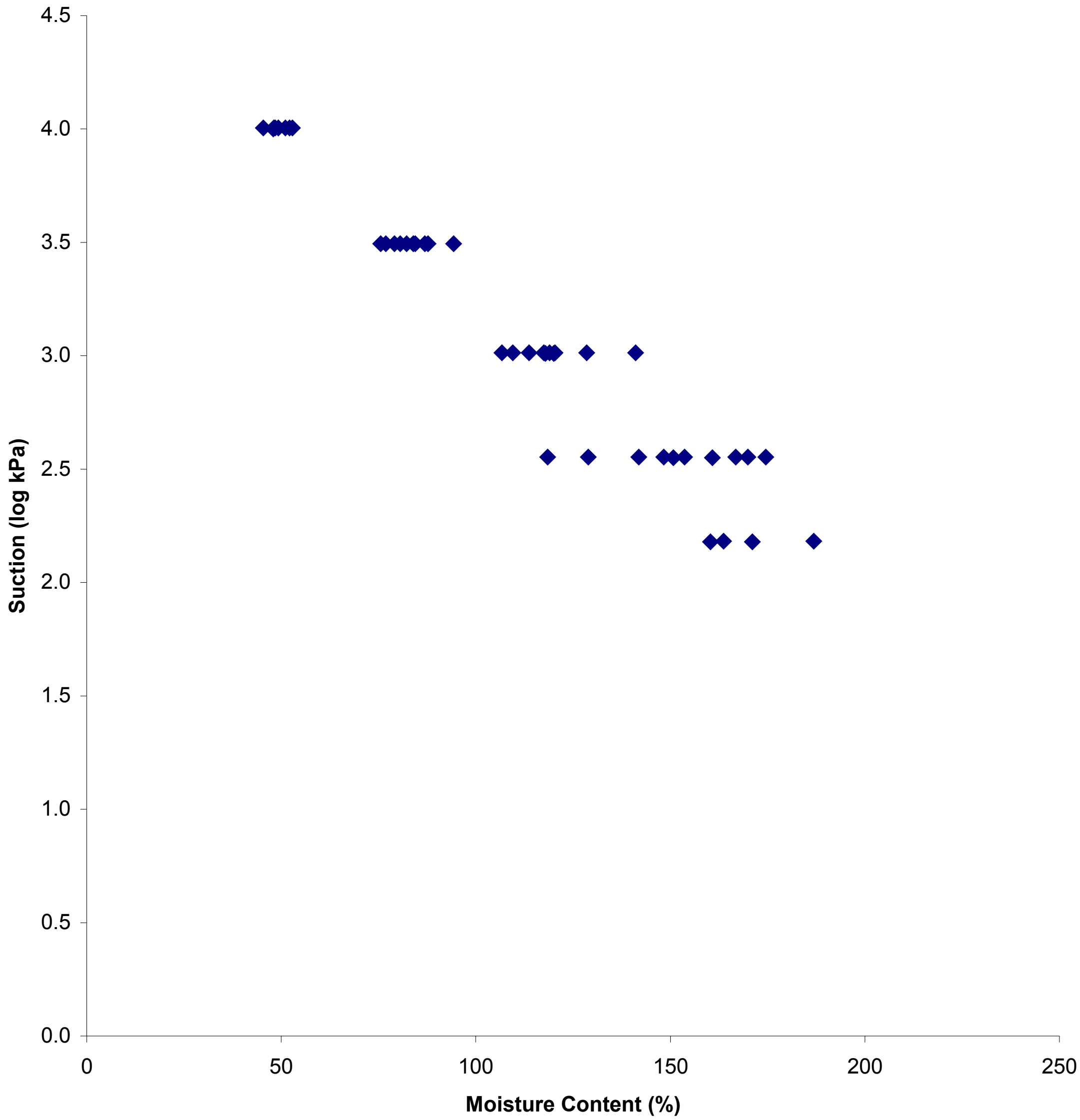


Figure 4.9 Polymer strip 7- day calibration of all data from the top and bottom strips.

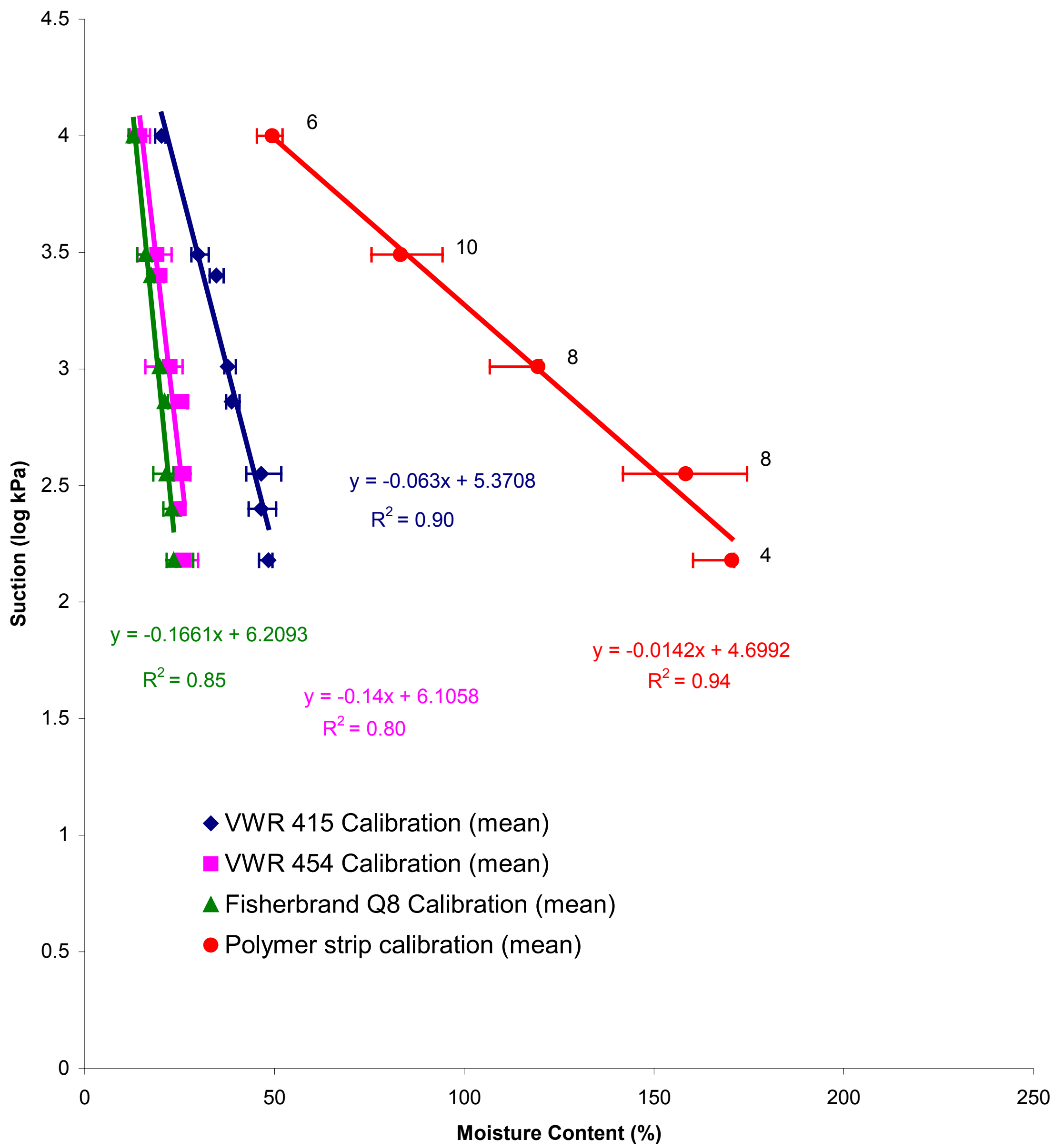


Figure 4.10 Comparison of the filter papers and the polymer strips calibrations. Mean values and range of moisture is shown with the bars indicating the lowest and highest calculated values. The numbers indicate the number of data points for each suction value. The number of data points for the filter papers can be seen in Figure 4.7.

4.2 Variation in Moisture Content with Time for Reaching Equilibrium

The ASTM D5298-03 standard of 7 days to reach an equilibrium moisture content is a limitation of the filter paper test. Earlier research, Chander and Gutierrez (1986) and Greacen, et. al. (1987), showed that moisture increases with time as the test is coming to equilibrium. The test results from this research showed the same increase. In the interest of trying to shorten the period of equilibrium when polymer strips were used, the first calibration tests with the polymer strips were run from 3 to 7 days. Figure 4.11 shows the measured moisture content calculated as a function of time, with the data for the top and bottom polymer strips distinguished. For the lower moisture content (higher suctions), the moisture content reached equilibrium quickly, while at higher water contents (lower suction) the samples take longer to reach equilibrium and the difference in moisture content between the top and bottom strips is greater. A second calibration of moisture content versus time was done with a single polymer strip. For this test, each suction value had three repetitions. Figure 4.12 shows the results from the single strip polymer tests. The dip in moisture content on the third day is assumed to be caused by a drastic (about 10^{o}C) change in temperature in the laboratory. This change in moisture due to temperature fluctuation is consistent with earlier research by Al-Khafaf and Hanks (1974), suggesting that change in temperature can cause erratic measurement of suction. Figure 4.13 combines the calibration versus time data for one and two polymer strips. There is no noticeable difference between the two except at the highest moisture content (lowest suction value).

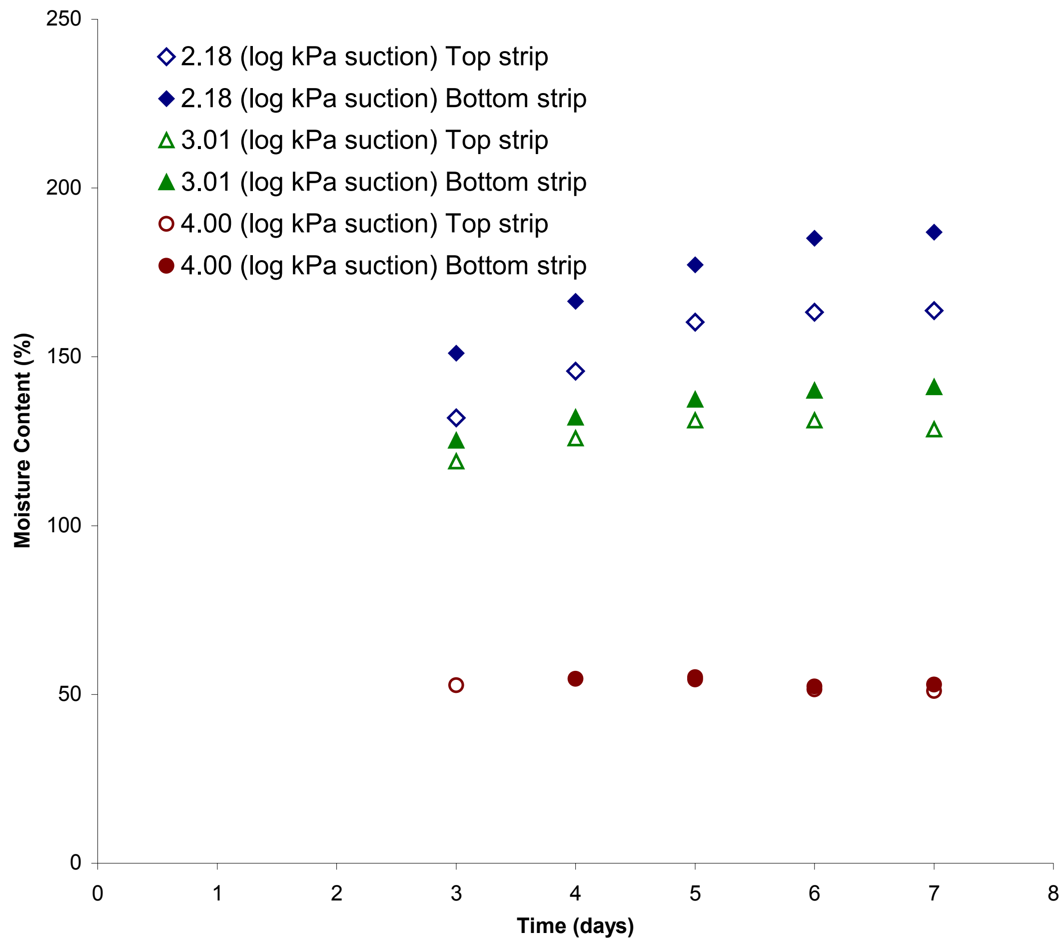


Figure 4.11 Moisture content versus time (days) for polymer strips calibration.

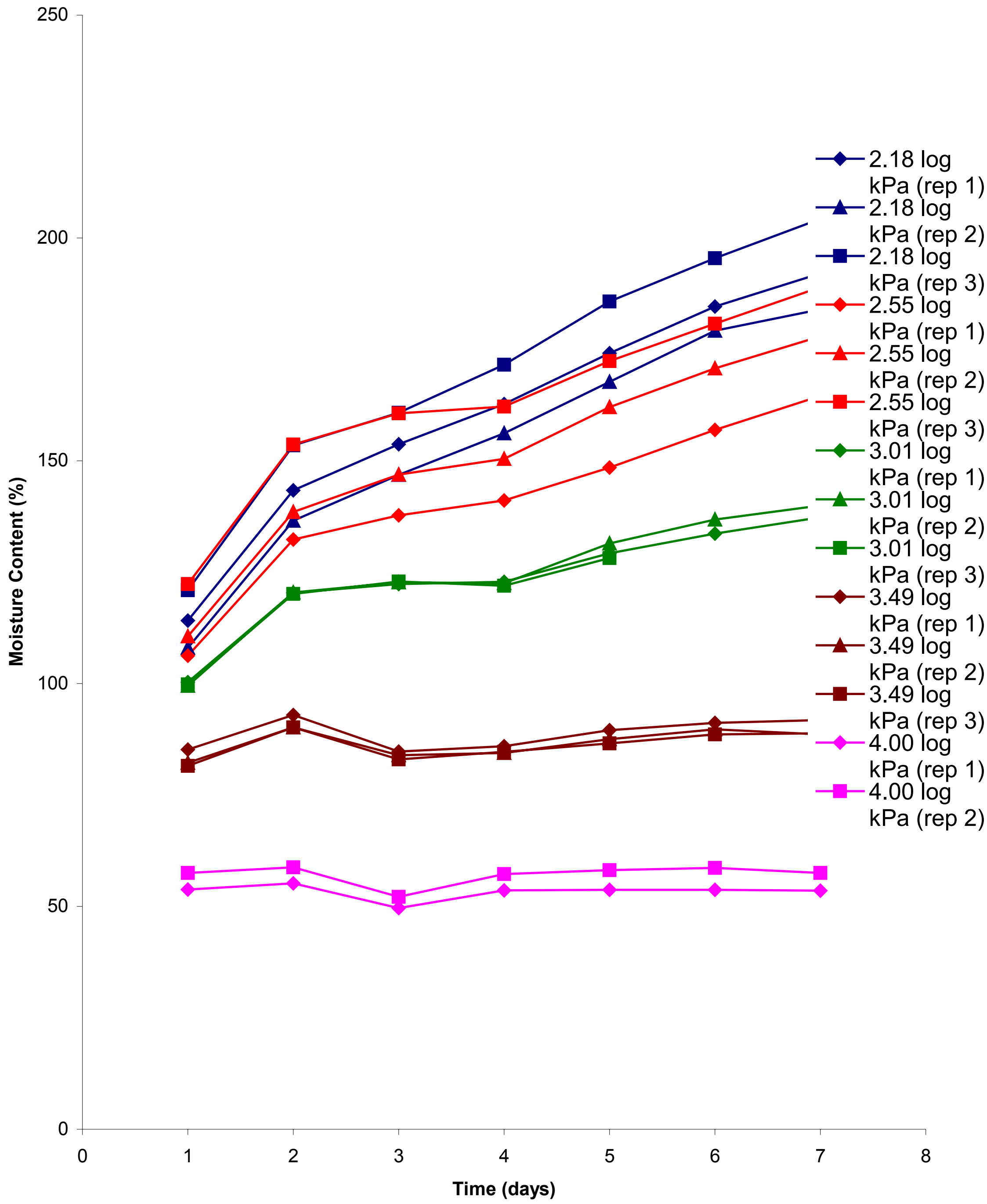


Figure 4.12 Moisture content versus time for single polymer strip (3 repetitions for each suction tested).

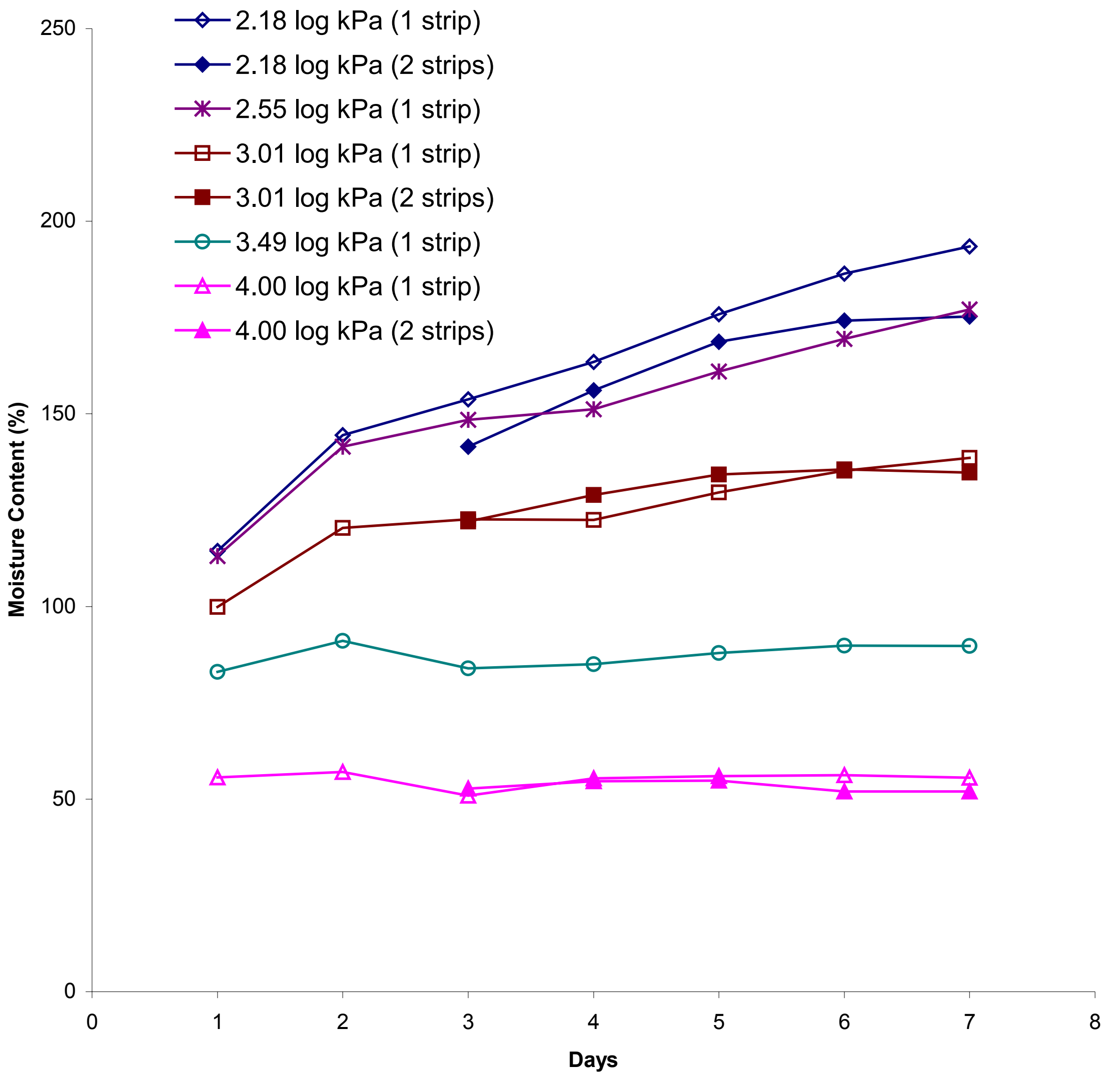


Figure 4.13 Moisture content versus time, comparison of results for single polymer strip and 2 polymer strips. For the single polymer strip, the data shown is for one repetition. For the 2 strips the mean from 3 repetitions is shown, except for 4.00 log kPa, where the mean is derived from 2 repetitions.

The Fisherbrand Q8 filter paper was also tested to measure the increase of moisture content over time. Three repetitions were run for each suction value. Figure 4.14 shows the variation of the mean moisture content data for each suction value. The time variation in moisture content is very small except for the lowest suction (2.18 log kPa), where the moisture content starts well below the readings for the 2.55 and 3.01 log kPa. Not until day 7 does the moisture content of the filter paper reach as high as 2.55 log kPa. Also in the figure there is a random fluctuation in moisture content on day 2 for all the suction values tested. These results suggest that the Fisherbrand Q8 paper reaches an equilibrium moisture content relatively quickly, except at the higher moisture contents. The rate at which equilibrium is reached is significantly faster than that for the polymer strips.

4.3 Repetition and Variation of the Calibration Data

Variation of the calibration data was investigated for the filter papers and the polymer strips at a 95% confidence level. Some of the data that was considered to be in error was also added into the calculations for figuring the 95% confidence level, so a more real range of moisture content could be established. Figure 4.15 shows the 95% confidence level for the VWR 415. The number by each data set for the tested suction values is the number of data points used to calculate the confidence level. The smaller numbers of repetitions gave a large range of the moisture content. Figure 4.16 shows the 95% confidence level of moisture content versus suction for the VWR 454 filter paper. The VWR 454 filter paper had a smaller number of data points for some suction values, and the moisture range for the smaller data set was larger. Overall, the variation in the

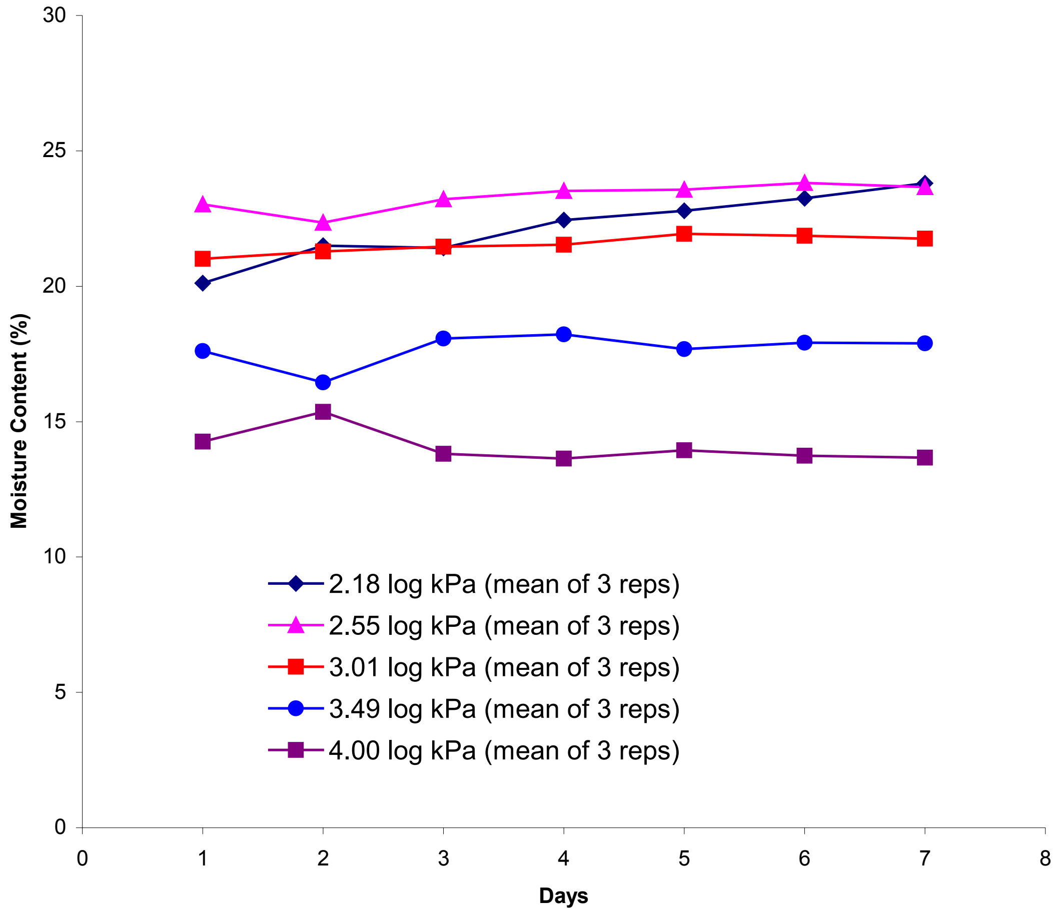


Figure 4.14 Moisture content versus time for Fisherbrand Q8 filter paper.

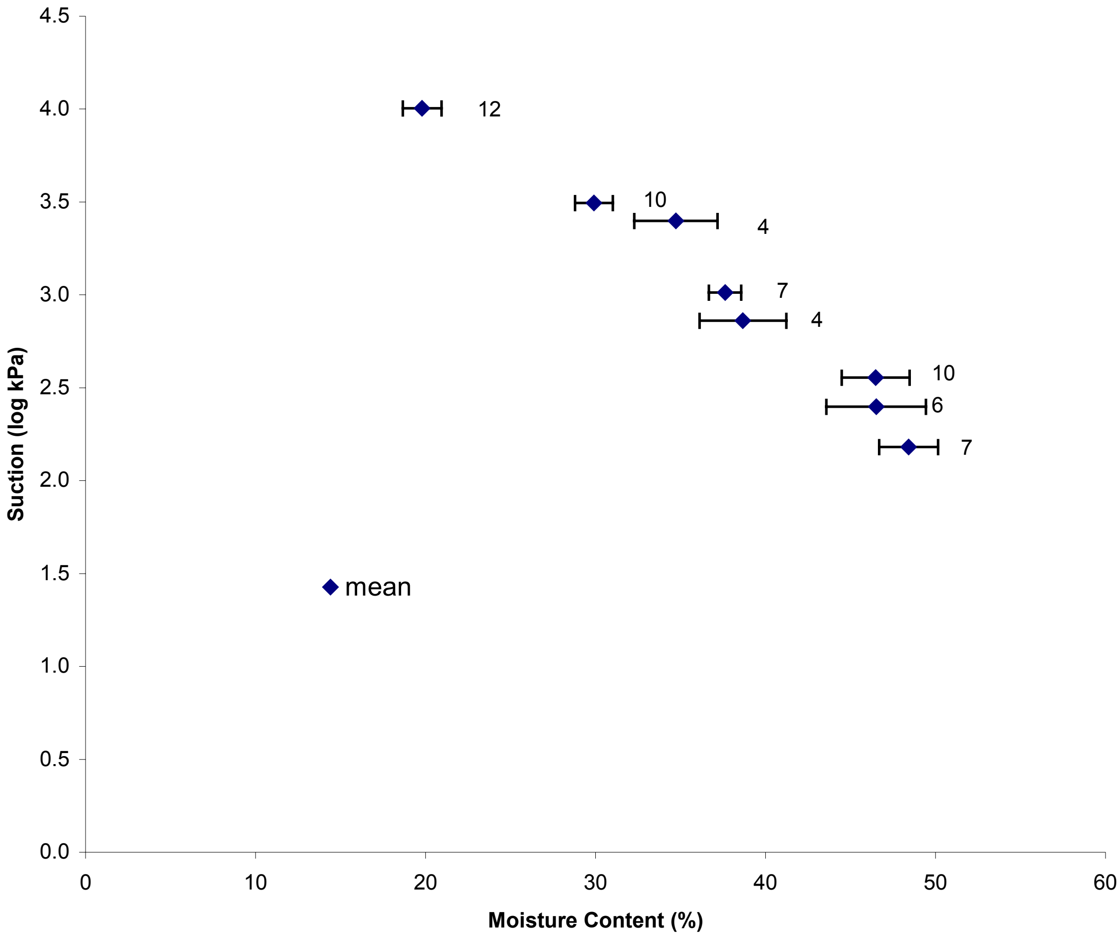


Figure 4.15 Calibration curve for VWR 415 filter paper with 95% confidence levels. Numbers near each mean data point indicate number of samples.

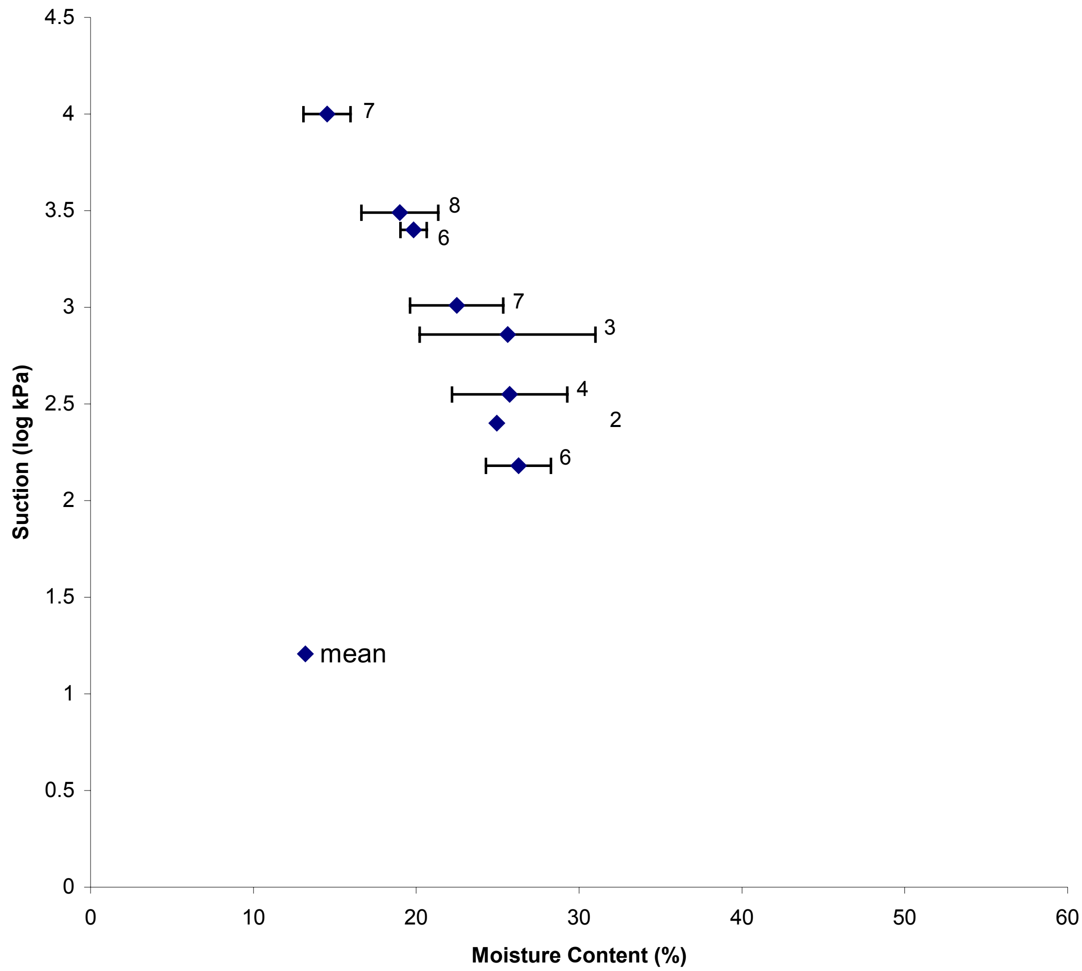


Figure 4.16 Calibration curve for VWR 454 filter paper with 95% confidence levels. Numbers near each mean data point indicate number of samples.

moisture range was not as consistent as the VWR 415. The 95% confidence range is shown in Figure 4.17 for the Fisherbrand Q8. The figure shows that the moisture range representing the 95% confidence level is fairly consistent for all the suction values and smaller than the VWR 454. Similarly, Figure 4.18 shows the calculation of the 95% confidence level for calibrations with two polymer strips. The moisture range is larger for the smaller suction, and decreases as the suction increases.

When looking at Figures 4.15 to 4.17 for the filter papers and comparing with Figure 4.18 for the polymer strips, it can be seen that the filter papers have a smaller 95% confidence moisture content range. The 95% confidence range for the filter papers seems to extend about 5%, while the 95% confidence levels for the polymer strips vary from about 10% to 40 %. Although this might suggest that the filter paper may be a more suitable material for the measurement of suction, the slope of the calibration curve also affects the determination of suction.

Figure 4.19 shows a schematic of a portion of the calibration curve for the Fisherbrand Q8 filter paper and the polymer strip. When plotting the trendline thru the mean data values and the 95% confidence range of each data point, the moisture range can be extended to the trendline, and the resolution of the suction measurement can be established. The resolution can be considered to be the inverse of the change in suction measurement ($\Delta\Psi$). Because the slope of the calibration curve for the polymer strip is lower than that for the Fisherbrand Q8 filter paper, the use of the polymer provides a higher resolution (lower $\Delta\Psi$) for the suction measurement. Figure 4.20 shows the measured $\Delta\Psi$ for each mean data point for the polymer strips and for the Fisherbrand Q8

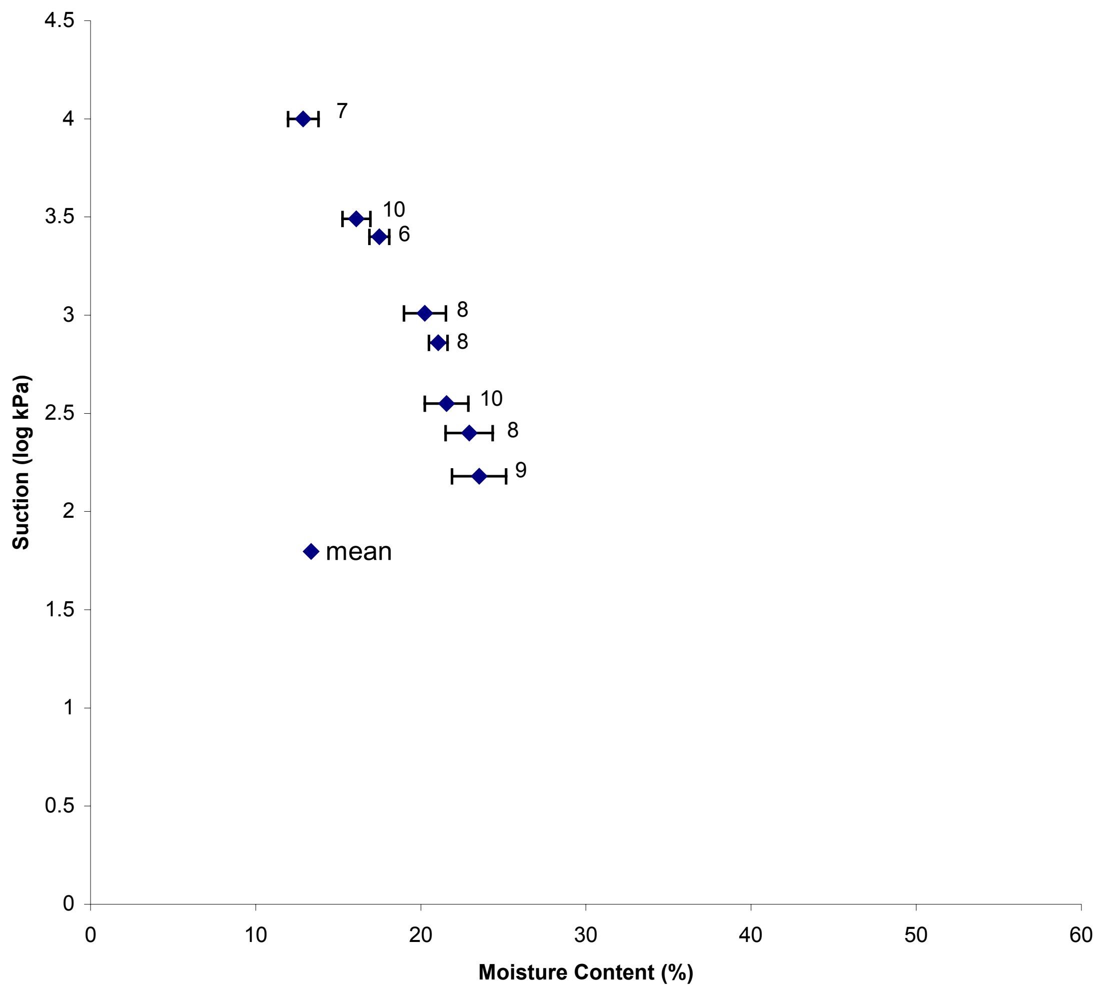


Figure 4.17 Calibration curve for Fisherbrand Q8 filter paper with 95% confidence level. Numbers near each mean data point indicate number of samples.

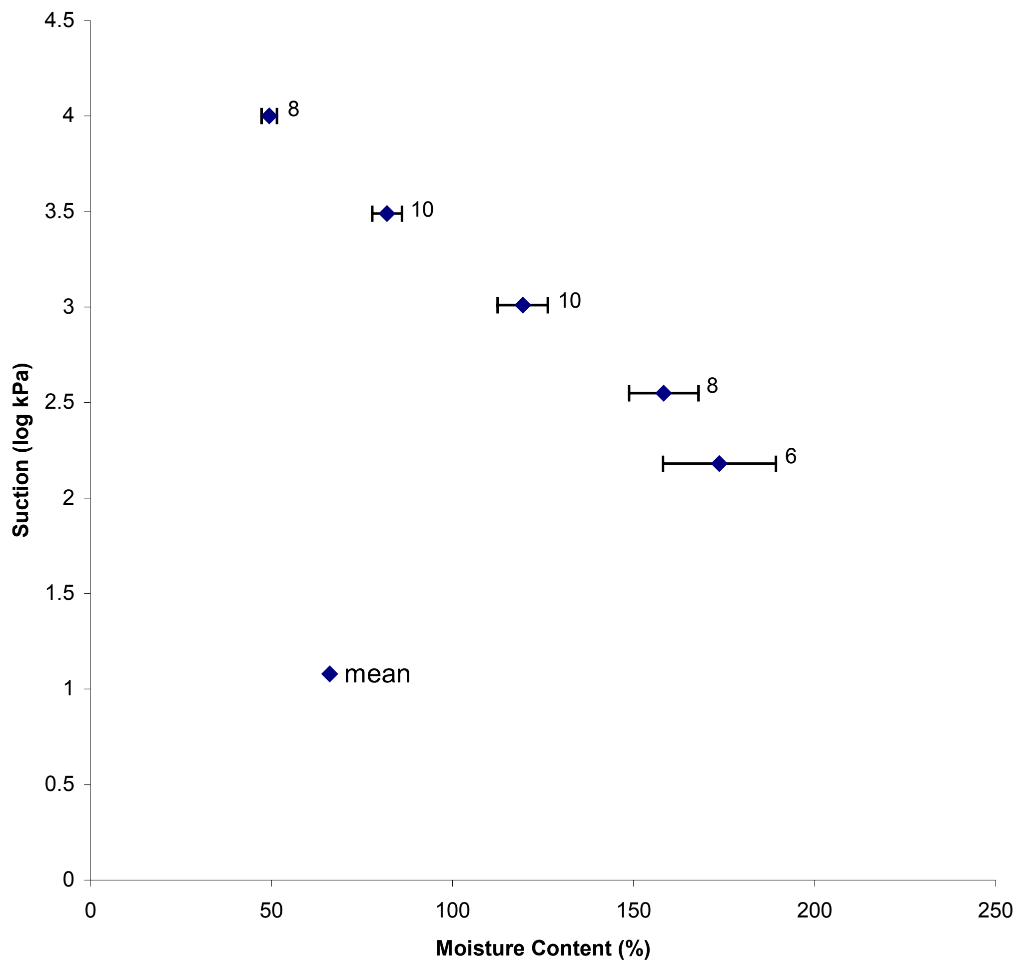


Figure 4.18 Calculation of 95% confidence interval from the calibrations with two polymer strips. The bars represent the 95% confidence range of the water content, and the numbers beside the bars indicate the number of data points.

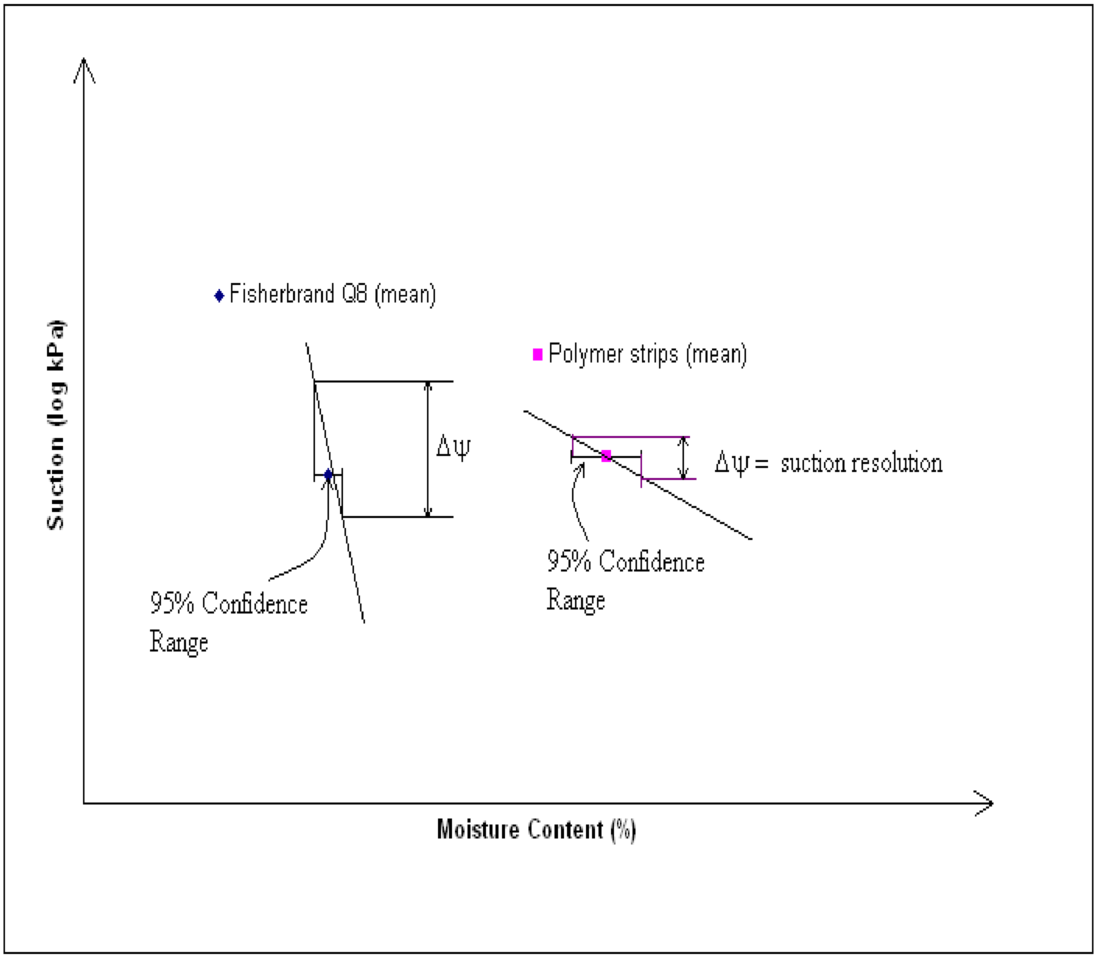


Figure 4.19 Schematic depicting the resolution of the suction measurement for two media with different slopes of the calibration curve. The bars indicate the moisture content range for the 95% confidence level, and the vertical arrows indicate the resolution or range with which the soil suction can be predicted.

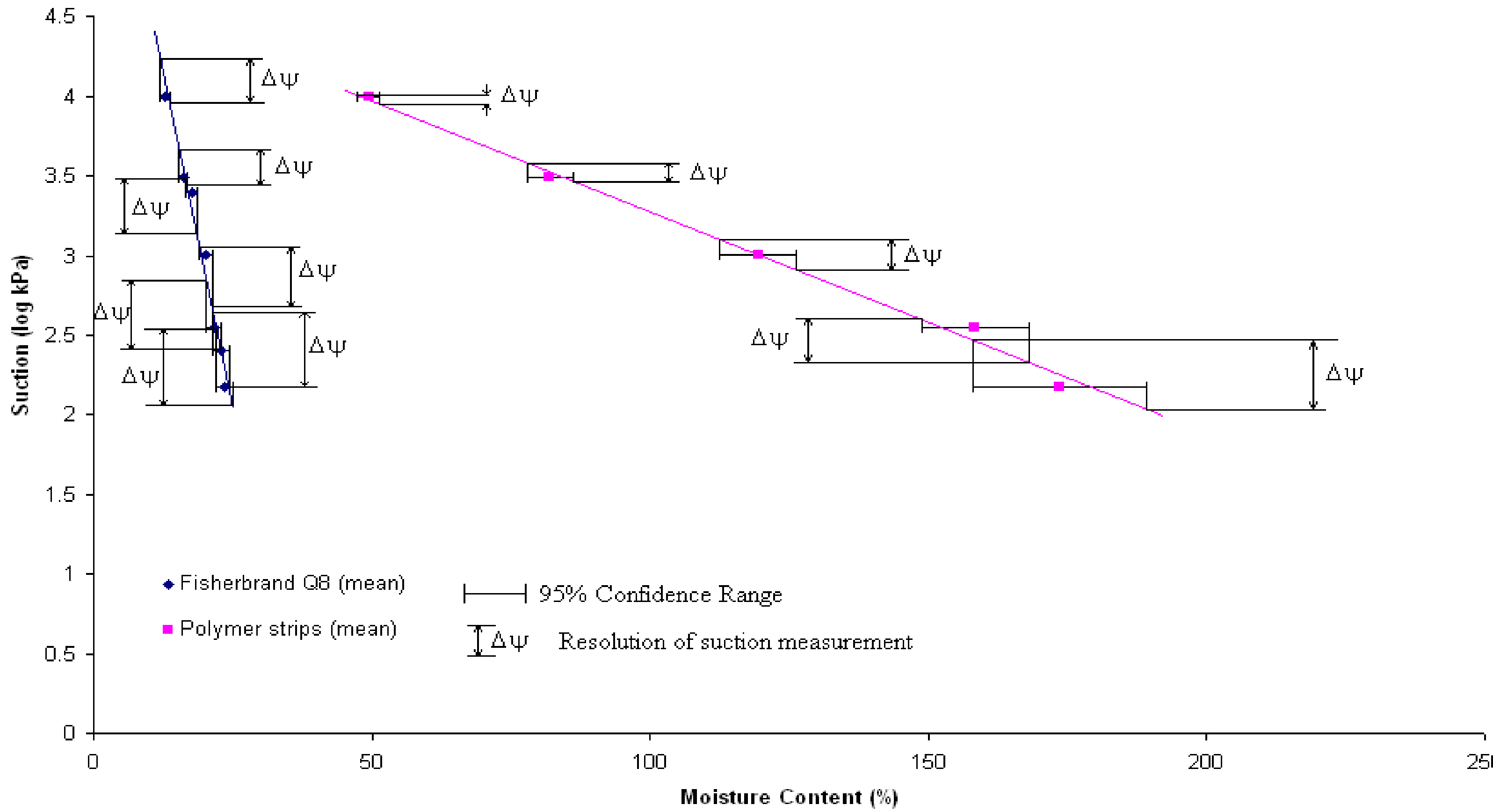


Figure 4.20 Resolution of suction range from the 95% confidence level for the calibrations of the polymer strips and the Fisherbrand Q8 filter paper.

filter paper. The polymer strips had a higher resolution (smaller $\Delta\Psi$) than the Fisherbrand Q8 paper at each data point. Figure 4.21 graphically shows the suction resolution (plotted as $\Delta\Psi$) as defined in Figure 4.20 versus the corresponding suction. It is observed that as $\Delta\Psi$ decreases as the suction increases (moisture content decreases) for both the filter paper and the polymer. This reflects the previous discussion of larger error at higher moisture contents. Figure 4.21 also suggests that $\Delta\Psi$ for the polymer is less than that for the filter paper over the entire suction range and may be a preferable to the filter paper.

4.4 Soil Tests Results

The characteristic curve of water content-suction response was determined for the Blount and Overton County soil samples can be seen in Figure 4.22. Results are shown from measurement with Fisherbrand Q8 filter paper, VWR 415 filter paper, VWR 454 filter paper and polymer strips. For a similar suction value, the Blount County sample had lower moisture content than the Overton County sample. The Blount County sample number 1 was tested with both the Fisherbrand Q8 filter paper and the polymer strips, with the two different media producing similar results. Figure 4.22 also shows results from Blount County samples #2, #3 and #4 measured with the Fisherbrand Q8, VWR 454 and VWR 415, which all produced similar results but have a different water content range than sample #1. The suction measurements in Figure 4.22 cover only a very small range of soil moisture content which does not clearly define the moisture characteristic curve.

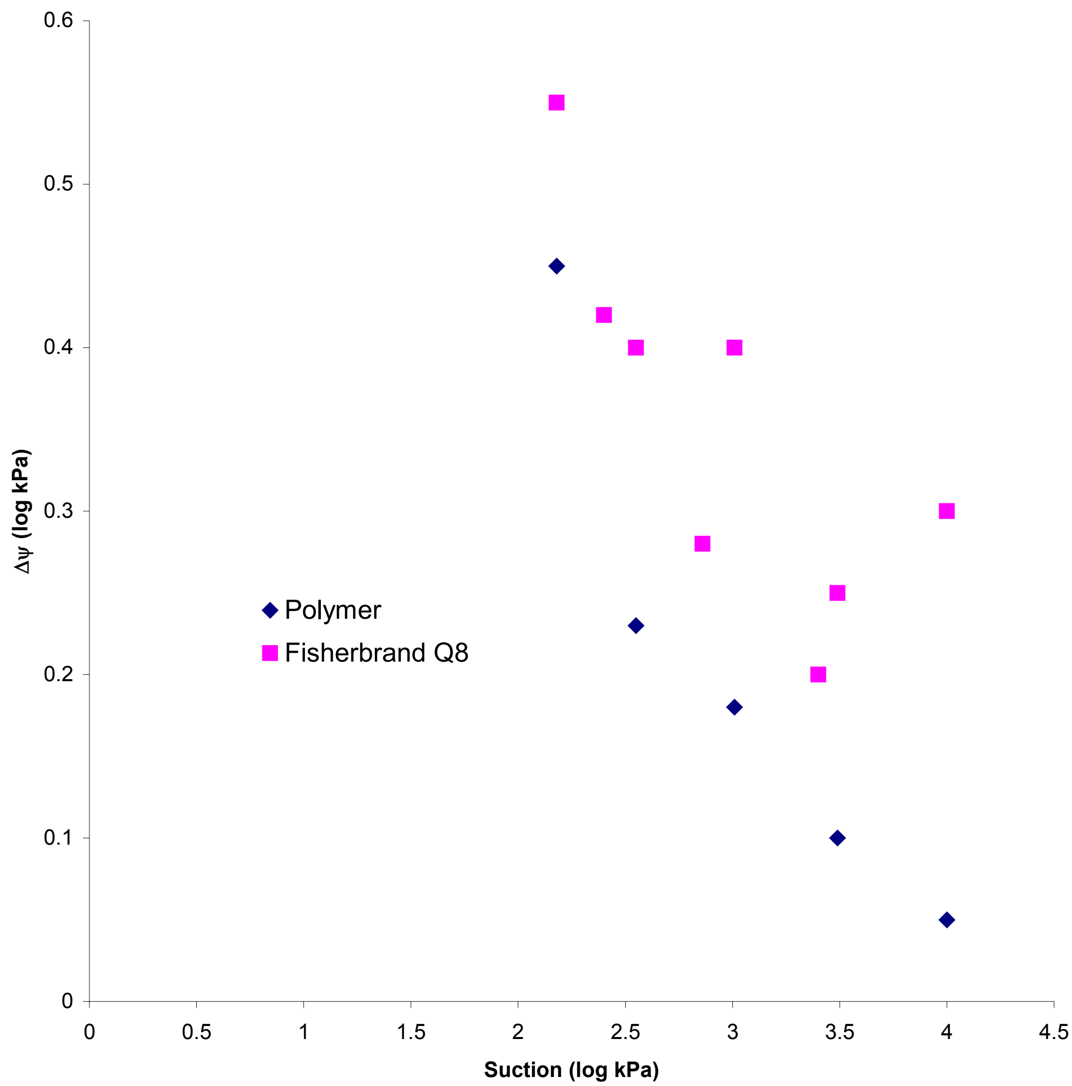


Figure 4.21 Δψ of each specific suction for Fisherbrand Q8 filter paper and polymer strips.

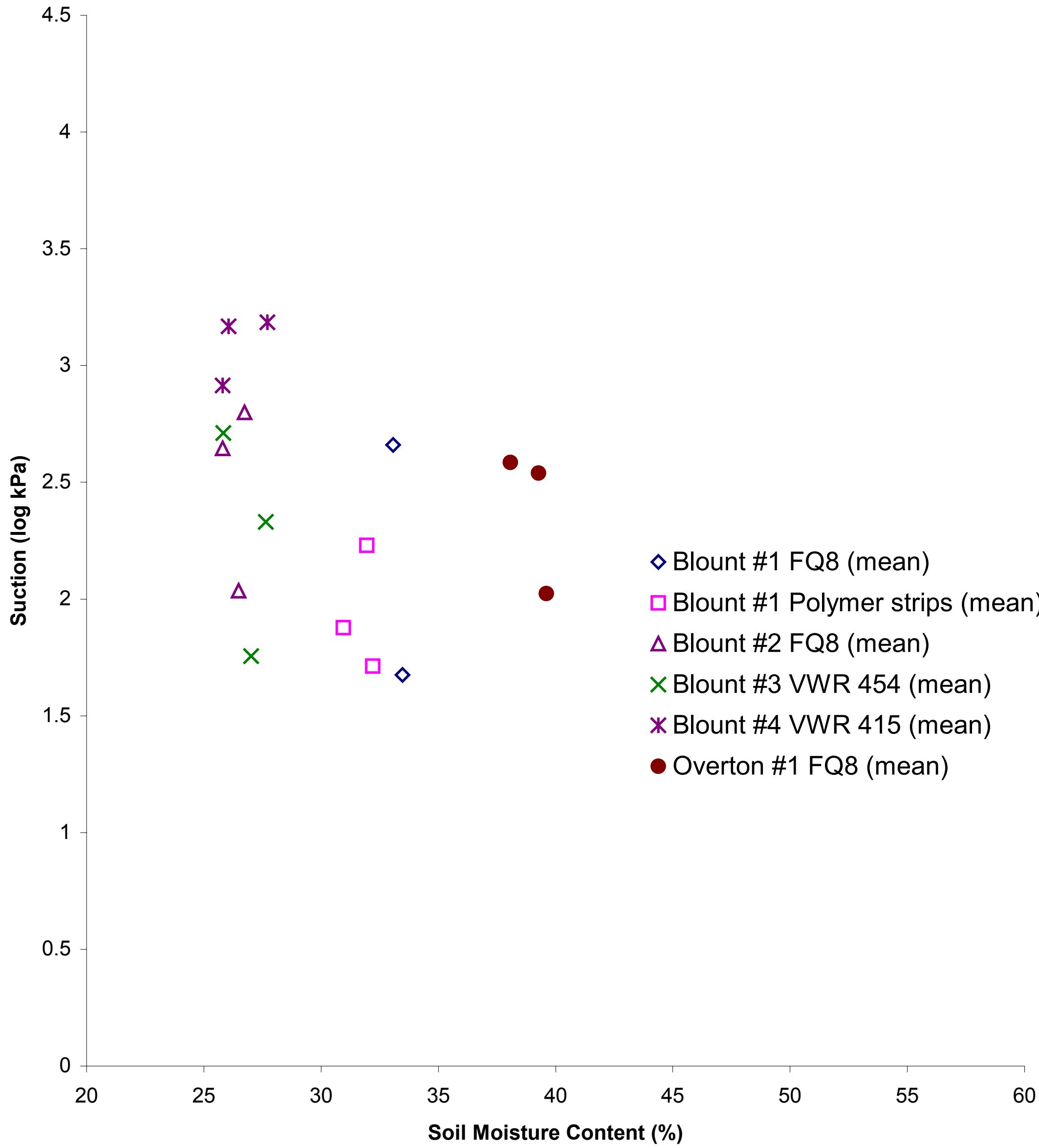


Figure 4.22 Blount and Overton County moisture characteristic curves. FQ8 is the Fisherbrand Q8 filter paper.

Figure 4.23 shows the moisture characteristic curves developed for the Bentonite and Kaolin samples, which is more well developed due to the larger range of soil moisture tested. The soil samples were tested with Fisherbrand Q8 filter paper, two polymer strips and a single polymer strip. The reasoning for using a single and double polymer strips was to investigate the difference in measuring the suction. As shown in Figure 4.23, there was not much difference in single and double polymer strips. A definite difference is observed between the moisture characteristic curves for the Bentonite and Kaolin clay, with the Bentonite sample displaying a larger range of moisture contents than the Kaolin. The measurements for the Kaolin clay samples showed smaller variation than did the Bentonite. The variation in the Bentonite seems to get larger with the increase of moisture content. Each material was fairly consistent in the moisture curve each created. The polymers and the ASTM standard suggested filter paper, Fisherbrand Q8, produced essentially the same moisture characteristic curves for the Kaolin and Bentonite.

4.5 Problems Encountered

As in any study or series of laboratory tests, several problems were encountered. A few noteworthy problems are as follows:

- There was a tiny loss of soil during the removal of the soil sample from the jar which affected the measurement of the soil mass.

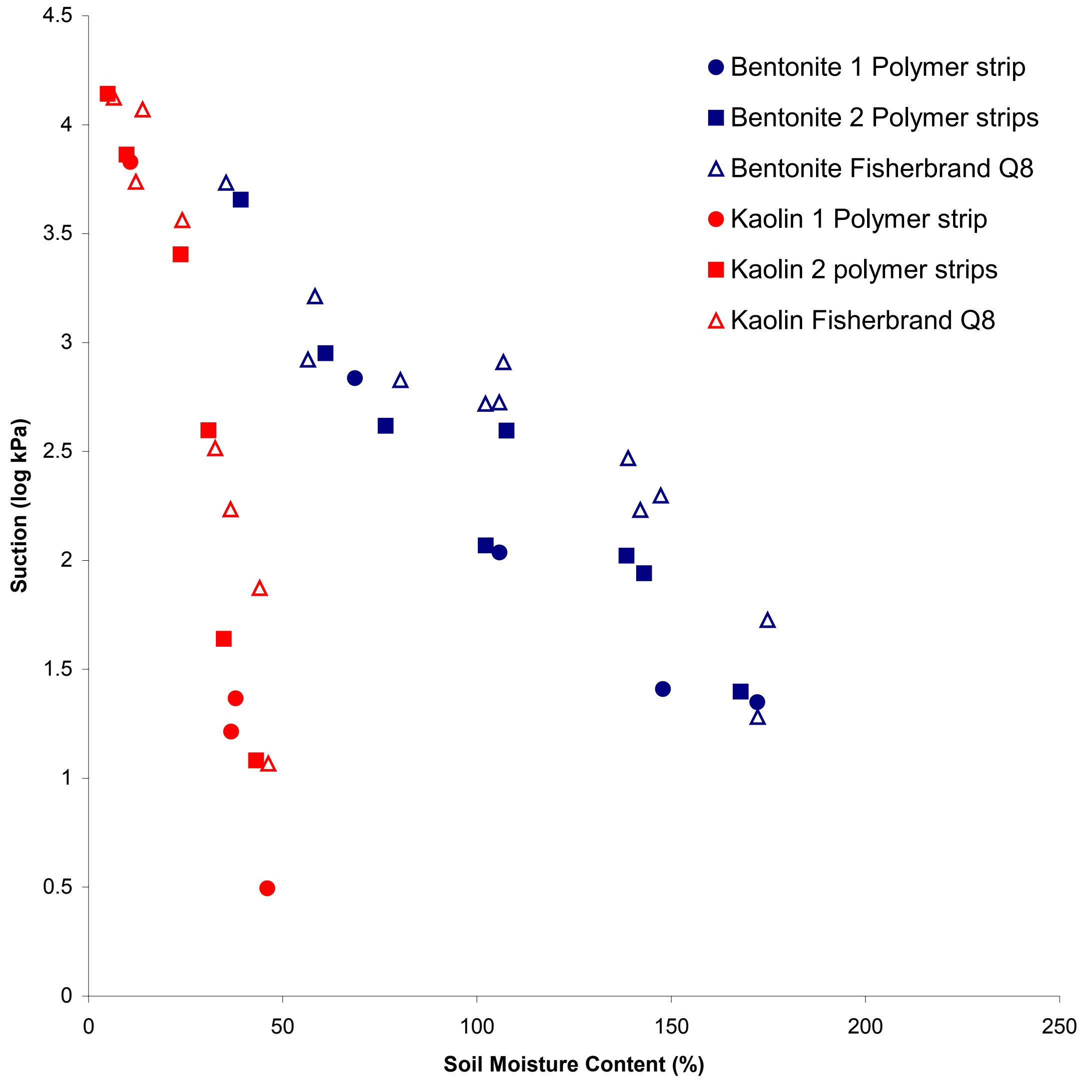


Figure 4.23 Bentonite and Kaolin clay characteristic curves.

- When measuring the mass of the filter paper at hot temperatures it was difficult to get a consistent measurement of mass, because of the sudden drop in temperature.
- The calibrations could be off due to variations in the preparation of the salt solutions (for the lower suction values the amount of salts that are added to the distilled water to create the calibration solution is very small) , and due to deviations from the specified temperature of 25^0 C.
- The volume calculation of the soil samples could be in error because the samples may have had voids (rocks & cuts, and loss of materials).

Chapter 5 Conclusions

The filter paper test can be used to indirectly measure a large range of soil suction values. There have been several studies on the accuracy of the test, but the use of the test in practice is still limited. However, because the test is more simple than many direct measurements of suction, the test has been proven to be economically attractive, and has found applications such as:

- Developing moisture requirements of arid land plants
- Identification of expansive soils and estimation of heave
- Measuring collapse of soil around a footing and comparing with predicted values
- Monitoring the moisture flow movement and creating soil moisture characteristic curve

The filter paper test has proved itself as a good indicator of soil suction. However, the small range of moisture content measured with typical filter paper media require that the mass of the paper be measured to 0.0001 grams. Polymer strips were investigated, and found to have a greater range of the moisture content which is thought to provide greater resolution in the prediction of suction. The quantitative filter papers recommended by ASTM have roughly a moisture content range of about 15%, while the qualitative filter paper (VWR 415) had almost double the moisture content range of about 30%. The polymer strips displayed a range of moisture content of about 100%. The polymer strips performed just as well as the filter papers and have repeatable values. The primary limitation is the lack of mass production of the material in a form suitable for

suction measurements. The polymer strips had to be removed from the " as-manufactured" product.

The 95% confidence levels for the filter papers and the polymer strips, were determined, and this confidence level corresponded to a 5% range of moisture for the filter paper, but the polymer strips had a moisture range of between 10% to 40% depending on the moisture content. However, due to the lower slope of calibration curve for the polymer strips, the polymer strips provided a higher resolution (inverse of error in suction measurements $\Delta\psi$) than the Fisherbrand Q8 filter paper even though the 95% confidence moisture content range is larger. The suction error ($\Delta\psi$) was shown to decrease with increasing suction reflecting increased errors at high moisture content. For all values of suctions, the polymer was shown to have a smaller $\Delta\psi$ than the Fisherbrand Q8 filter paper.

When trying to shorten the testing period, the polymer did not prove to reach equilibrium faster than the required ASTM Standard D5298-03 7-day period, and the Fisherbrand Q8 filter paper seemed to come to equilibrium quicker than the 7 day standard. The polymer strips performed just as well as the filter papers when used in actual soil suction testing. The calculated suction values are fairly similar to each other. The variations in the plotted moisture characteristic curves were evident with both the filter papers and the polymers strips. The polymer strips show promise in replacing the filter papers as an indicator in measuring soil suction, but a source of the polymer strips in a form ready for suction testing needs to be identified.

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Appendices

Appendix A

Calibration Test Setup and Procedure:

List of Materials used for testing:

- mixed salt solutions
- glass jars
- aluminum can
- PVC pipe, 2 inch diameter and 1 inch tall
- epoxy
- medium flexible, coated wire
- alcohol
- gloves
- cooler
- balance
- tweezers
- oven
- towels
- thongs
- metal block
- timer

The calibrations were setup as shown in Figure 3.1 and 3.2. The jars are the same size and have easy screw off lids. Wire is glued across the top of the PVC and then an O-ring glued on top of the wires (Figure 3.3 and 3.4), then glued to the bottom of the jar. 110 mL of the salt solution in poured into the jar. Very carefully with a piece of lint free towel whip the top the pvc and the wires until dry. Next the filter paper or the polymer can be placed on top with tweezers and the top is screwed on.

When the material comes to equilibrium, it is then weighed. An aluminum can is wiped down with alcohol to make sure no dirt or oil is on the can. With gloves, determine the cold tare mass of the can. While holding the can in one hand, and opening the jar, place the material in the can and immediately put the lid on and weigh (M_1). Put the can in an oven at 110^{o}C (+ or - 5 ^{o}C) for a least 2 hours. Also place the lid of the can on for 15 minutes "to allow temperature equilibration."(ASTM D 5298) With tongs take the can from the oven and place on the metal block for 25 seconds to help dissipate the

heat. The can is then place on the balance and weighed (M_2). The material is removed from the can quickly and then the can is weighed once more to get a hot tare mass (T_h).

Moisture content is calculated as follows:

Mass of the filter paper (M_f) = $M_2 - T_h$

Mass of water in filter paper (M_w) = $M_1 – M_2 + T_h - T_c$

Water Content of filter paper (w_f) = 100 * (M_w/M_f)

Calculation of Salt Solution Vapor Pressure:

The salt solution used in the calibration process was Potassium Chloride. The ASTM had suction values calculated for 20^{o}C, and the calibrations were run at 25 ^{o}C. Vapor pressure changes with temperature. So calculation of the new suction value was needed. The vapor pressure of the different salt solutions was calculated from the relative humidity values provided by Robinson (1945). Figure A-1 is from Robinson (1945) with the values of relative humidity (a_w). First the molality, m, and relative humidity needed to be graphed out and a trendline needed to be found. Figure A-2 shows the plot of molality vs. relative humidity and the equation for the generated trendline. Next the molality of the salt solutions is equal to the moles of the salt divided by the mass of the water. The calculations for each of the solutions can be found in Table A-1. Using the equation generated earlier, the relative humidity can be calculated. Then using the following equation, the suction (h) can be calculated:

$$h = (RT/v)*\ln R_h$$

The suction value calculated by this formula is in kPa. R is the ideal gas constant, 8.31432 Joules/mole·K. T is equal to the absolute temperature in degrees Kelvin (K). v is volume of 1000 moles of liquid water, 0.018m^3. Finally, R_h is the relative humidity fraction. (ASTM D 5298) Table A-2 is a comparison of the calculated suction values at 25 ^{o}C and the ASTM given values for the # of grams per 1000 mL. Figure A-3 shows the difference between the results at 20 ^{o}C and 25 ^{o}C.

APPENDIX II.

WATER ACTIVITIES, OSMOTIC COEFFICIENTS, ACTIVITY COEFFICIENTS, AND RELATIVE MOLAL VAPOUR PRESSURE LOWERINGS OF SODIUM AND POTASSIUM CHLORIDE SOLUTIONS AT 25°.

	Sodium Chloride				Potassium Chloride			
m	a_w	φ	$1 + \log \gamma$	$\frac{p^\circ - p}{M p^\circ}$	a_w	φ	$1 + \log \gamma$	$\frac{p^\circ - p}{M p^\circ}$
0.1	0.996646	0.9324	0.8912	0.03354	0.996668	0.9266	0.8864	0.03332
0.2	.993360	.9245	.8661	.03329	.993443	.9130	.8562	.03279
0.3	.99009	.9215	.8511	.03303	.99025	.9063	.8373	.03250
0.4	.98682	.9203	.8406	.03295	.98709	.9017	.8233	.03228
0.5	.98355	.9209	.8332	.03290	.98394	.8989	.8124	.03212
0.6	.98025	.9230	.8278	.03292	.98078	.8976	.8038	.03203
0.7	.97692	.9257	.8240	.03296	.97763	.8970	.7967	.03196
0.8	.97359	.9288	.8211	.03301	.97448	.8970	.7907	.03190
0.9	.97023	.9320	.8190	.03308	.97133	.8971	.7854	.03186
1.0	.96686	.9355	.8175	.03314	.96818	.8974	.7809	.03182
1.2	.9601	.9428	.8158	.03325	.9619	.8986	.7733	.03175
1.4	.9532	.9513	.8159	.03343	.9556	.9010	.7676	.03171
1.6	.9461	.9616	.8178	.03369	.9492	.9042	.7634	.03175
1.8	.9389	.9723	.8208	.03394	.9428	.9081	.7603	.03178
2.0	.9316	.9833	.8245	.03420	.9364	.9124	.7580	.03180
2.2	.9242	.9948	.8291	.03445	.9299	.9168	.7564	.03186
2.4	.9166	1.0068	.8344	.03475	.9234	.9214	.7554	.03192
2.6	.9089	1.0192	.8402	.03504	.9169	.9264	.7549	.03198
2.8	.9011	1.0321	.8466	.03532	.9103	.9315	.7548	.03204
3.0	.8932	1.0453	.8535	.03560	.9037	.9367	.7550	.03210
3.2	.8851	1.0587	.8608	.03591	.8971	.9421	.7557	.03216
3.4	.8769	1.0725	.8684	.03621	.8904	.9477	.7567	.03223
3.6	.8686	1.0867	.8766	.03650	.8837	.9531	.7578	.03230
3.8	.8600	1.1013	.8852	.03684	.8770	.9588	.7593	.03237
4.0	.8515	1.1158	.8939	.03713	.8702	.9647	.7610	.03245
4.2	.8428	1.1306	.9029	.03743	.8634	.9707	.7629	.03252
4.4	.8339	1.1456	.9122	.03775	.8566	.9766	.7649	.03259
4.6	.8250	1.1608	.9218	.03804	.8498	.9824	.7670	.03266
4.8	.8160	1.1761	.9315	.03833	.8429	.9883	.7693	.03273
5.0	.8068	1.1916	.9415	.03864				
5.2	.7976	1.2072	.9517	.03892				
5.4	.7883	1.2229	.9620	.03920				
5.6	.7788	1.2389	.9726	.03950				
5.8	.7693	1.2548	.9833	.03977				
6.0	.7598	1.2706	.9940	.04003				

Vapour pressures in columns 2, 5, 6, and 9 are tabulated relative to p° = 23.756 mm. for pure water at 25°.

Figure A-1 R. A. Robinson (1945) table of calculation of relative humidity for different molality, for Potassium Chloride and Sodium Chloride at 25 degrees C.

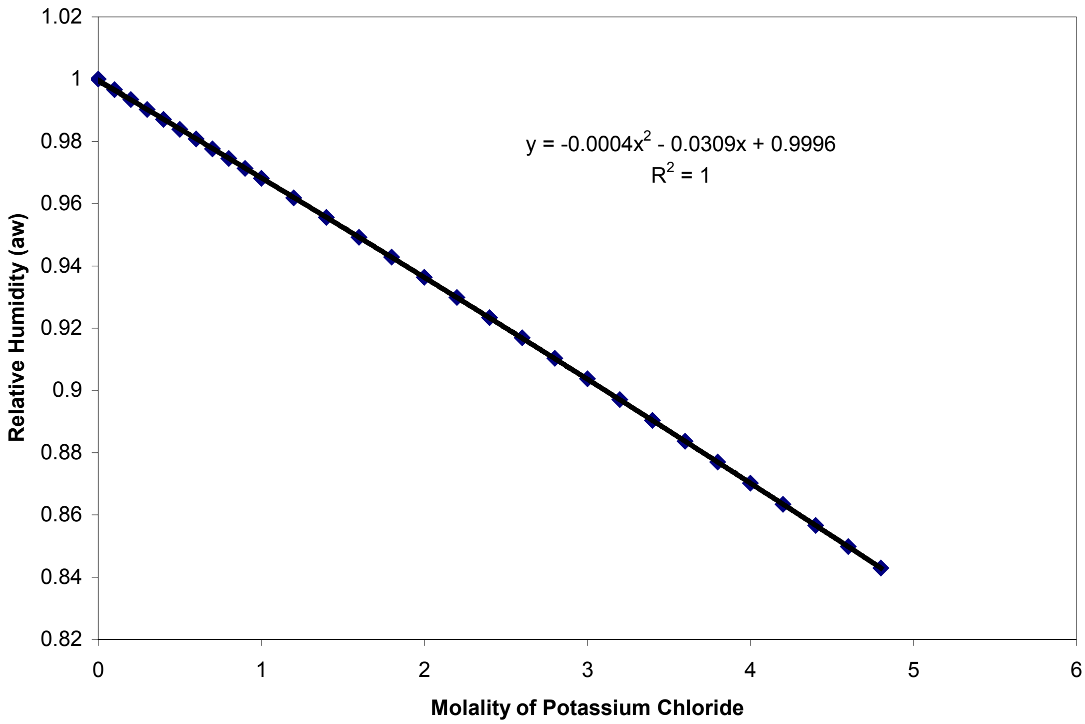

Figure A-2 Relationship of Relative Humidity and KCl molality at 25 degrees Celcius from Robinson (1945) data.

Table A-1 Calculation of Potassium Chloride Vapor Pressure from the Relative Humidity, and equation from Robinson (1945) data.

# grams	Mole (KCl)(mole)	Mass H_20(kg)	C(KCl)	aw (from equation)	Suction (kPa)
1.7	0.022803182	0.99708	0.02287	0.998893109	-151.98442
5.3	0.071092272	0.99708	0.0713	0.997394782	-357.984425
17	0.228031817	0.99708	0.2287	0.99251226	-1031.41989
52.7	0.706898633	0.99708	0.708969	0.977491809	-3124.12487
165	2.21324999	0.99708	2.219732	0.92903941	-10100.8018

Table A-2 Comparison of Calculated Suction values at 25 degrees Celcius and ASTM given suction values at 20 degrees Celcius for the same solutions.

Calculated (Robinson) @ 25 C			ASTM D 5298 Table 1 @ 20C		
grams /1 L	Suction (kPa)	Log kPa	grams /1 L	Suction (kPa)	Log kPa
1.7	151.984	2.18	1.7	98	1.99
5.3	357.984	2.55	5.3	310	2.49
17	1031.42	3.01	17	980	2.99
52.7	3124.12	3.49	52.7	3099	3.49
165	10100.8	4.00	165	9800	3.99

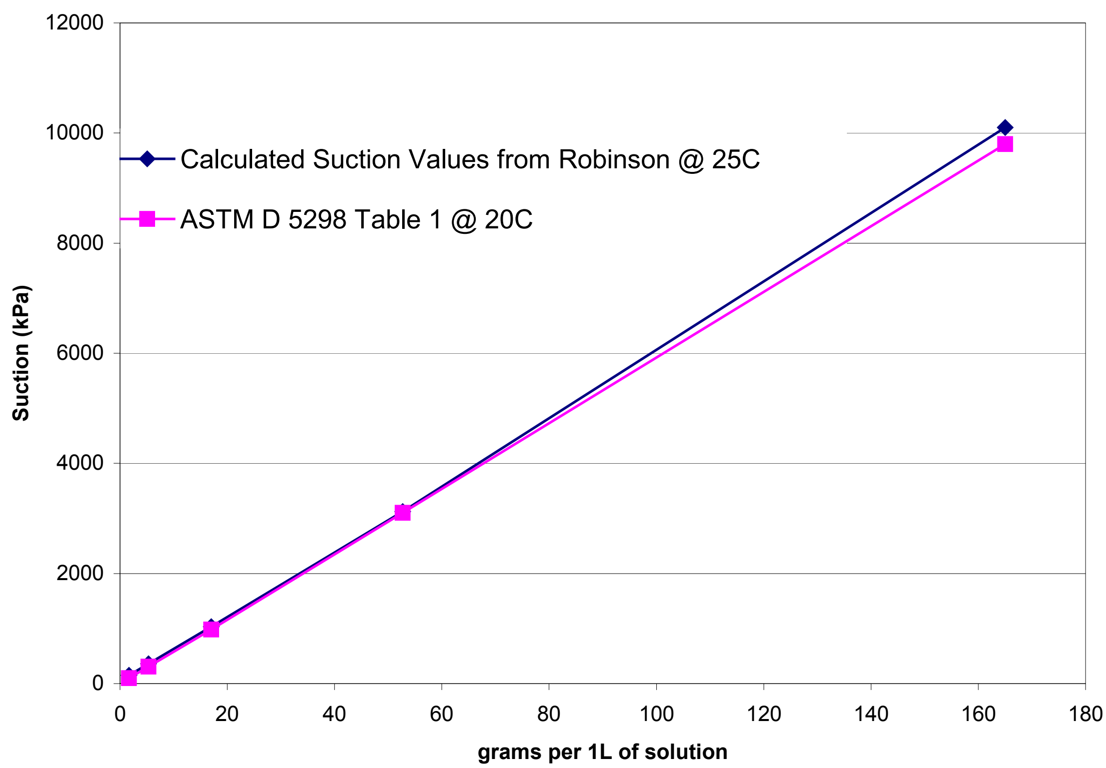

Figure A-3 Comparison of calculated values and ASTM given values.

Appendix B

Pressure Plate

The pressure plate was used to create a calibration graph for comparison against the salt solutions. It was seen in the first run that there was a large difference and it was decided to discontinue with the testing. Figure B-1 is the resulting calibration graph from the pressure plate. The filter paper used for the pressure plate was the VWR 454. It can clearly be seen that there is a fairly large difference between the two calibrations.

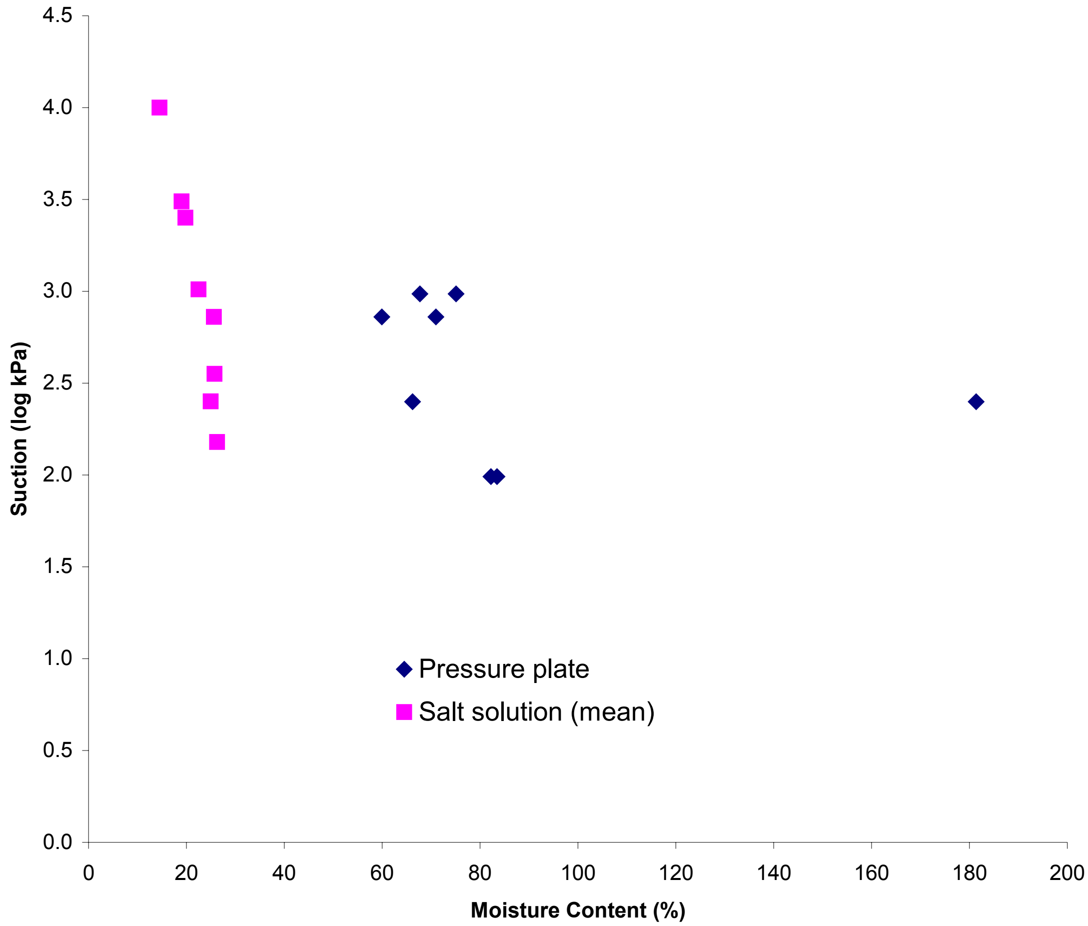

Figure B-1 Pressure plate and salt solution calibration comparison.

Vita

Lori Ann McDowell was born on December 12, 1978 in Claiborne County, TN. She went to Claiborne Co. High School and graduated in 1997. Then went to Walter State Co. College for a year. Then in 1998 transferred to the University of Tennessee, Knoxville and graduated with a Bachelor of Science in Civil Engineering in the spring of 2001. She furthered her education by graduating with of Masters of Science in Civil Engineering with a specialty in Geotechnical Engineering at the University of Tennessee, Knoxville in the fall of 2004.