

TOTAL AND MATRIC SUCTION MEASUREMENTS WITH THE FILTER PAPER METHOD

Rifat Bulut, Ph.D.

FUGRO SOUTH, INC.

2880 Virgo Lane

Dallas, Texas 75229

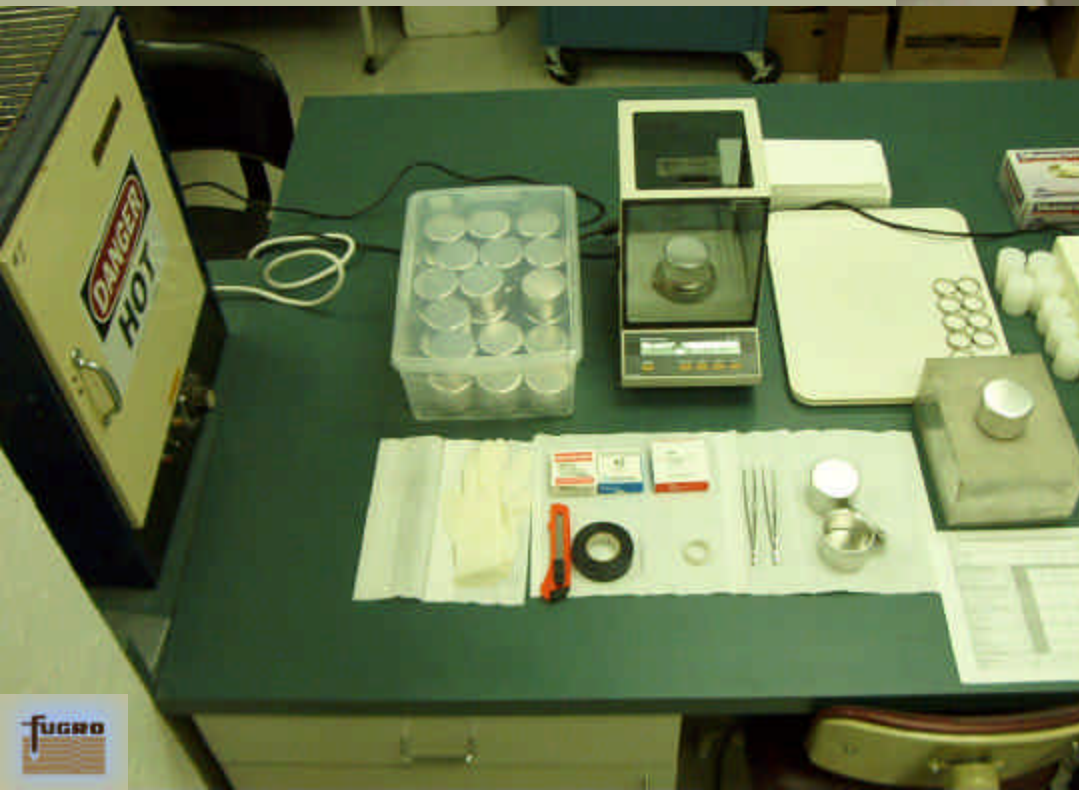
Phone : 972-484-8301

Fax : 972-620-7328



- A General View of Lab Material Needed for the Filter Paper Method

- ✓ Filter Papers
- ✓ Sensitive Balance
- ✓ Constant Temperature Container
- ✓ Oven



- ✓ Moisture Tins
- ✓ Glass Jars
- ✓ Tweezers
- ✓ Gloves
- ✓ PVC-Rings
- ✓ Electrical Tape
- ✓ Aluminum Block

THEORY OF CALIBRATION BASED ON WATER VAPOR MEASUREMENTS

$$h_t = \frac{RT}{V} \ln\left(\frac{P}{P_o}\right)$$

$$h_p = -nRTmf$$

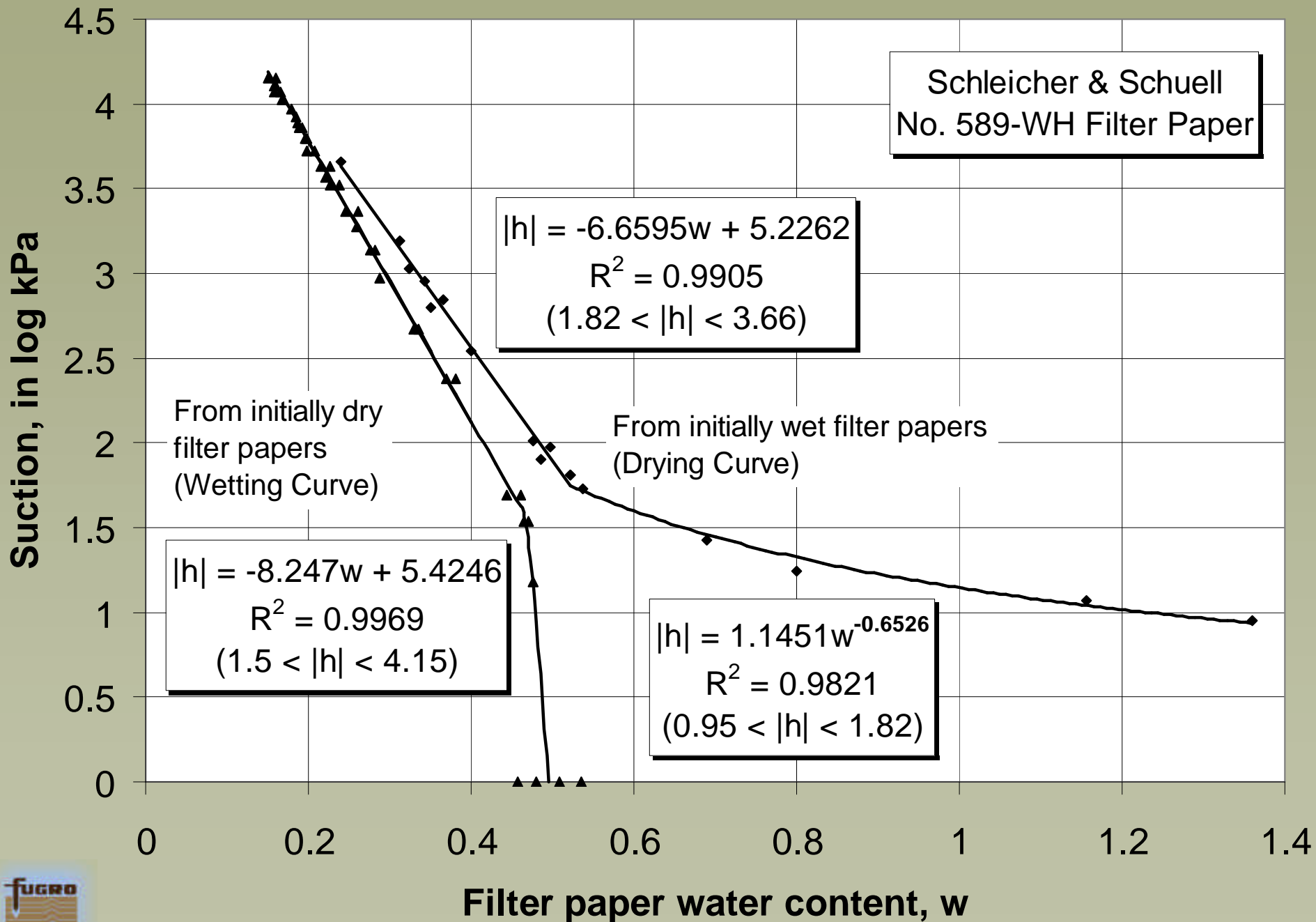


- If initially dry filter papers are used for soil suction measurements then one of the wetting filter paper calibration curves given in the next two slides can be adopted.
- A more detailed information about the calibration curves and soil suction measurements can be found in the publications:

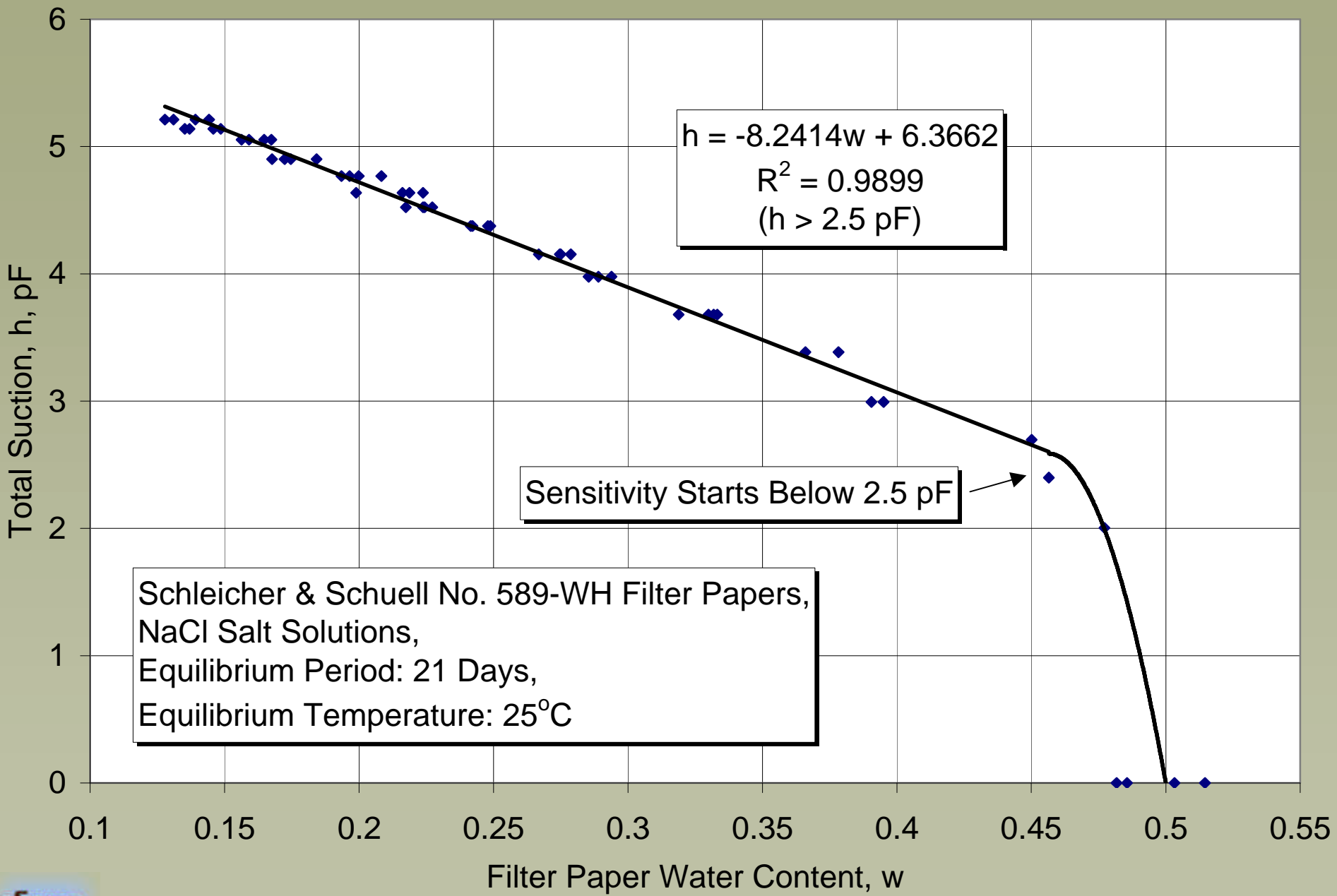
□ Bulut, R., Lytton, R. L., and Wray, W. K. (2001). “Suction Measurements by Filter Paper,” *Expansive Clay Soils and Vegetative Influence on Shallow Foundations*, ASCE Geotechnical Special Publication No. 115 (eds. C. Vipulanandan, M. B. Addison, and M. Hasen), ASCE, Reston, Virginia, pp. 243-261.

□ Bulut, R., Hineidi, S. M., and Bailey, B. (2002). “Suction Measurements – Filter Paper and Chilled Mirror Psychrometer,” The Proceedings, Texas Section ASCE, Fall Meeting, Waco, Texas.

CALIBRATION CURVE [Bulut, R., Lytton, R. L., and Wray, W. K. (2001)]



CALIBRATION CURVE [Bulut, R., Hineidi, S. M., and Bailey, B. (2002)]



$$h = -8.2414w + 6.3662$$
$$R^2 = 0.9899$$
$$(h > 2.5 \text{ pF})$$

Sensitivity Starts Below 2.5 pF

Schleicher & Schuell No. 589-WH Filter Papers,
NaCl Salt Solutions,
Equilibrium Period: 21 Days,
Equilibrium Temperature: 25°C



BEFORE COMMENCING THE TESTING,
MAKE SURE THAT ALL ITEMS
RELATED TO FILTER PAPER METHOD
ARE CLEAN, MOISTURE, OIL, AND
DUST FREE!

NOTE:

- *Make sure that tweezers are used to handle filter papers*
- *Make sure that moisture tins, O-rings are handled with gloves*

- Use a container that a Shelby-tube soil sample can be fit into easily without the disturbance of the soil sample.
- Cut the soil sample into two halves for matric suction measurements.
- Make sure that the surfaces of the soil samples are smooth and flat for establishing an intimate contact between the soil sample and the filter paper for matric suction measurements.



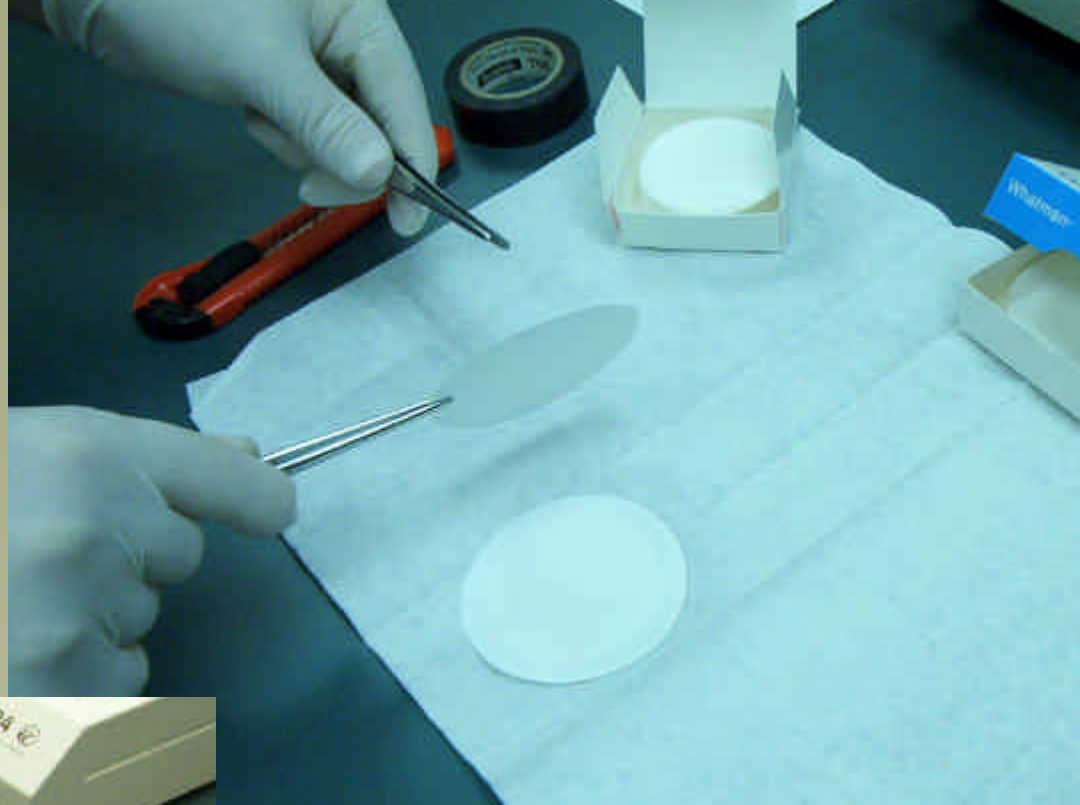
NOTE: When preparing the soil samples make sure that sample disturbance is minimal.

- Remove a *Schleicher & Schuell* No. 589-WH filter paper from the box using tweezers (5.5 cm in diameter)



Almost any brand of high permeability and larger diameter filter paper can be used as protective filter papers for matric suction measurements (as shown in the lower left box and in the picture, about 70 mm in diameter)

- For matrix suction measurements, insert a single Schleicher & Schuell No. 589-WH filter paper in between two larger in diameter protective filter papers as shown on the right



- Using tweezers put the sandwiched filter papers on top of the soil sample as shown on the left

- Put the other half of the soil sample on top, keeping the sandwiched filter papers in between and in intimate contact with the soil samples



- Tape the two pieces of the soil sample together

NOTE: Electrical tape works nicely for this purpose

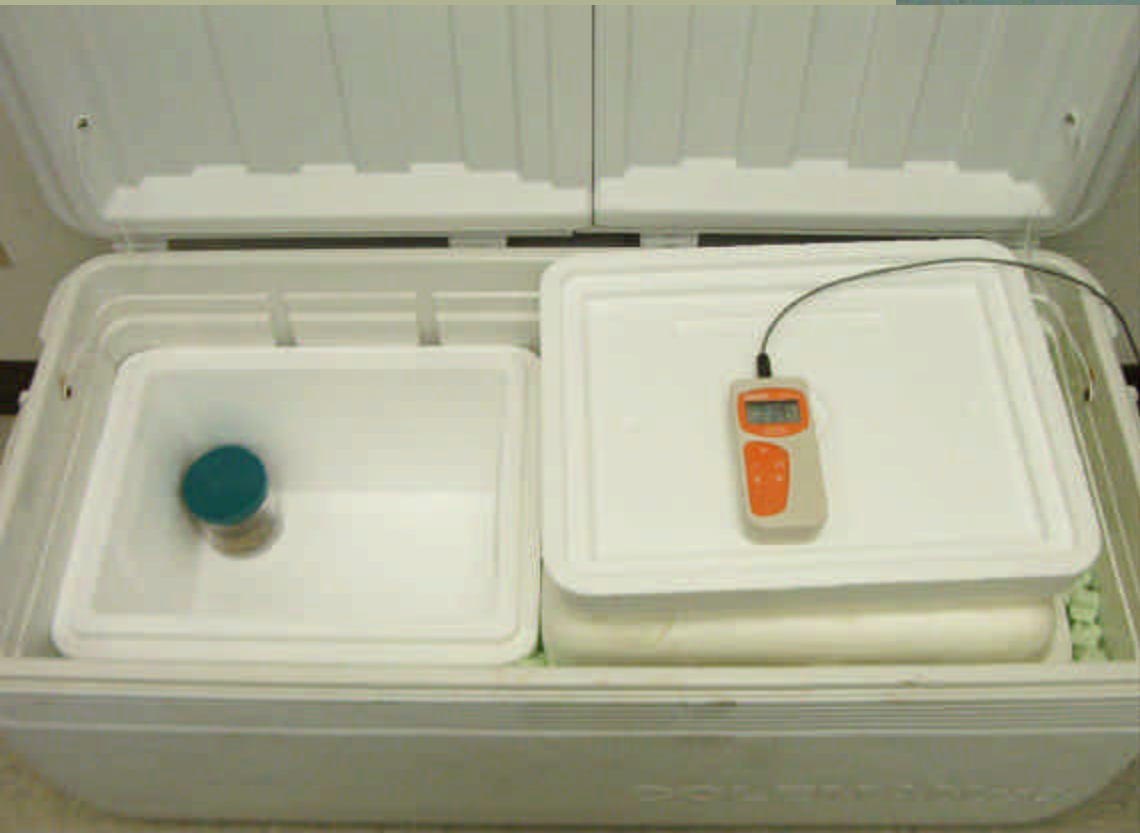
- Insert a clean PVC O-ring, with the sharp edge facing up, on top of the soil sample for total suction measurements



- Place two *Schleicher & Schuell No. 589-WH* filter papers on top of the ring as shown on the left

NOTE: Bend the edge of the top filter paper up a little so that it will be easy to remove them later!

- Put the lid on and tape it tight to prevent any moisture exchange between the air inside and the air outside of the jar
- Label the jar as necessary



- Insert the glass jar into a well-insulated container for suction equilibrium

NOTE: Temperature control is critically important

- ✓ Soil suction measurement set up, as described in the previous slides, will be kept in a temperature-controlled environment for at least one week
- ✓ Temperature fluctuations should be kept as low as possible, preferably below $\pm 1^{\circ}\text{C}$
- ✓ Refer to the publications that were cited before for detailed information about the equilibration periods and temperature control

**AT THE END OF AT LEAST
ONE WEEK OF
EQUILIBRIUM PERIOD:**

- Before opening the lid of the temperature-controlled container, take the dry, cold weight of the moisture tins



- Record all the weights with their corresponding tin numbers

NOTE: Use a balance at least to the nearest 0.0001 g. accuracy

- Remove a glass jar from the temperature-controlled container
- Time is critical at this stage and thus it is suggested that two people share the work
- The time that the filter papers are exposed to the lab environment should be minimal, preferably less than a few seconds



Note that while one person is opening the glass jar the other person is ready to pick up the filter papers

- Open the glass jar and quickly carry the filter paper to the moisture tin using tweezers, in less than a few seconds



- Immediately close the lid of the moisture tin with the wet filter paper inside

- After closing the lid of the moisture tin, immediately weigh the tin with the wet filter paper inside



- Record the weight as cold tare plus wet filter paper mass

Note that this is a total suction measurement

- Continue with the matric suction measurement by removing the tape that was holding the soil samples together



- Remove the filter paper that was sandwiched between the two protective filter papers
- Immediately carry the filter paper to the moisture tin

- Immediately close the lid of the moisture tin and weigh the tin with the wet filter paper inside



- Record the weight as cold tare plus wet filter paper mass

Note that this is a matric suction measurement

- After opening all the glass jars and recording the weight of the moisture tins with the wet filter papers inside, carry them to a hot oven with the lids half open
- Leave them in the oven for at least 10 hours



- Before taking them out from the oven, close their lids for equilibrium and leave them in the oven for about 5 minutes

- Remove a hot tin from the oven and put on a large aluminum block

NOTE: The aluminum block will expedite the process of the cooling



- Leave the tin on the block for about 20 seconds
- Weigh the hot tin with the dry filter paper inside
- Record the weight as hot tare plus dry filter paper mass

- Finally, take the dry filter paper out of the tin

- Weigh the empty hot tin



- Record the weight as hot tare mass

- Repeat the above process for other tins in the oven

- Calculate the moisture content of each filter paper for both total and matric suction measurements. A calculation work sheet as given in the next slide can be used
- Obtain the suction value from an appropriate calibration curve that was provided above

MEASUREMENT OF SOIL SUCTION USING FILTER PAPER

BORING NO.: _____

DATE TESTED: _____

DATE SAMPLED: _____

TESTED BY: _____

SAMPLE NO.: _____

Depth							
Moisture Tin No.							
Top Filter Paper/Bottom Filter Paper (circle)		<u>Top/Bot.</u>	<u>Top/Bot.</u>	<u>Top/Bot.</u>	<u>Top/Bot.</u>	<u>Top/Bot.</u>	<u>Top/Bot.</u>
Cold Tare Mass, g	Tc						
Mass of Wet Filter Paper + Cold Tare Mass, g	M1						
Mass of Dry Filter Paper + Hot Tare Mass, g	M2						
Hot Tare Mass, g	Th						
Mass of Dry Filter Paper, g (M2-Th)	Mf						
Mass of Water in Filter Paper, g (M1-M2-Tc+Th)	Mw						
Water Content of Filter Paper, g (Mw / Mf)	Wf						
Suction, cm of water	h						
Suction, pF or log kPa	h						



***A GOOD LABORATORY PROTOCOL IS
ESSENTIAL IN THE FILTER PAPER
SOIL SUCTION MEASUREMENTS***

-- Rifat Bulut, Ph.D.

SOIL SUCTION MEASUREMENTS BY FILTER PAPER

Rifat Bulut, M.ASCE, Robert L. Lytton, F.ASCE, and Warren K. Wray, F.ASCE

Geotechnical Special Publication Number 115

Expansive Clay Soils and Vegetative Influence on Shallow Foundations

Proceedings of Geo-Institute Shallow Foundation and Soil Properties
Committee Sessions at the ASCE 2001 Civil Engineering Conference

Sponsored by

The Geo-Institute of the American Society of Civil Engineers

October 10-13, 2001
Houston, Texas

Edited by

C. Vipulanandan
Marshall B. Addison
Michael Hasen

Soil Suction Measurements by Filter Paper

Rifat Bulut¹, M.ASCE, Robert L. Lytton², F.ASCE, and Warren K. Wray³, F.ASCE

Abstract

This paper reports on an evaluation of wetting and drying filter paper suction calibration and soil total and matric suction measurement techniques of filter paper method. Calibration of the method was investigated by constructing two calibration curves; one by using the process of wetting the filter papers through vapor flow and the other by using the method of drying the filter papers through fluid flow. The wetting curve was constructed using sodium chloride (NaCl) salt solutions and Schleicher & Schuell No. 589-WH filter papers. It was found that the change in the wetting suction curve is very sensitive to minor changes in filter paper water content below about 1.5 log kPa (2.5 pF) suction. The drying curve was established by employing both pressure plate and pressure membrane devices and the same filter papers. In developing the filter paper calibration curves, the capabilities, pitfalls, and limitations of the method are also discussed.

Introduction

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

¹Graduate Student, Department of Civil Engineering, Texas A&M University, College Station, Texas 77843-3136; phone 979-458-4147; r-bulut@tamu.edu.

²A.P. and Florence Wiley Professor of Civil Engineering, Texas A&M University, College Station, Texas 77843-3136; phone 979-845-8211; r-lytton@tamu.edu.

³Provost and Senior Vice President for Academic and Student Affairs, Michigan Technological University, Houghton, Michigan 49931-1295; wkwray@mtu.edu.

suction measurements are possible. With a reliable soil suction measurement technique, the initial and final soil suction profiles can be obtained from samples taken at convenient depth intervals. The change in suction with seasonal moisture movement is valuable information for many engineering applications.

This paper evaluates calibration techniques for filter paper wetting and drying processes, and soil total and matric suction measurements with filter paper method by construction of two calibration curves. The wetting curve was constructed using NaCl salt solutions and Schleicher & Schuell No. 589-WH filter papers. Salt solutions and filter papers were brought to equilibrium through vapor flow (filter paper wetting process) at isothermal conditions. Equilibrium time and temperature were two weeks and 25°C, respectively. The temperature was maintained at 25°C within $\pm 0.1^\circ\text{C}$ fluctuations. The drying curve was established using both pressure plate and pressure membrane devices and the same filter papers. The pressure plate apparatus can measure matric suction values up to 150 kPa. However, with the pressure membrane device matric suction values can be extended up to 10,000 kPa. The equilibration periods were selected as 3, 5, and 7 days depending on the testing set up, which will be described below.

A Brief Historical Background

There are many soil suction measurement techniques and instruments in the fields of soil science and engineering. Most of these instruments have limitations with regard to range of measurement, equilibration times, and cost. Therefore, there is a need for a method which can cover the practical suction range, be adopted as a basis for routine testing, and is inexpensive. One of those soil suction measurement techniques is the filter paper method, which was evolved in Europe in the 1920s and came to the United States in 1937 with Gardner (1937). Since then, the filter paper method has been used and investigated by numerous researchers (Fawcett and Collis-George 1967; McQueen and Miller 1968; Al-Khafaf and Hanks 1974; McKeen 1980; Hamblin 1981; Chandler and Guierrez 1986; Houston et al. 1994; Swarbrick 1995), who have tackled different aspects of the filter paper method. Different types of materials were used, such as filter papers and suction measuring devices, and different experimental techniques to calibrate the filter paper and to measure suction of the soil sample. Therefore, it is very difficult to compare these methods on a one-to-one basis.

All the calibration curves established from Gardner (1937) to Swarbrick (1995) appear to have been constructed as a single curve by using different filter papers, a combination of different soil suction measuring devices, and different calibrating testing procedures. However, Houston et al. (1994) developed two different calibration curves; one for total suction and one for matric suction measurements using Fisher quantitative coarse filter papers. For the total suction calibration curve, saturated salt solutions and for the matric suction calibration curve tensiometers and pressure membranes were employed. Houston et al. (1994) reported that the total and matric suction calibration curves were not compatible. This simply implies that two different calibration curves, one for matric and one for total suction, need to be used in soil suction measurements. However, in this paper

the fact is presented that the two curves reflect an expected hysteresis between wetting and drying effects and that the appropriate curve for both matric and total suction is the wetting curve since this matches the process that the filter paper undergoes in the measurement process.

Soil Suction Concept

In general, porous materials have a fundamental ability to attract and retain water. The existence of this fundamental property in soils is described in engineering terms as suction, negative stress in the pore water. In engineering practice, soil suction is composed of two components: matric and osmotic suction (Fredlund and Rahardjo 1993). The sum of matric and osmotic suction is called total suction. Matric suction comes from the capillarity, texture, and surface adsorptive forces of the soil. Osmotic suction arises from the dissolved salts contained in the soil water. This relationship can be formed in an equation as follows:

$$h_t = h_m + h_p \quad (1)$$

where h_t = total suction (kPa), h_m = matric suction (kPa), and h_p = osmotic suction (kPa).

Total suction can be calculated using Kelvin's equation, which is derived from the ideal gas law using the principles of thermodynamics and is given as:

$$h_t = \frac{RT}{V} \ln\left(\frac{P}{P_o}\right) \quad (2)$$

where h_t = total suction, R = universal gas constant, T = absolute temperature, V = molecular volume of water, P/P_o = relative humidity, P = partial pressure of pore water vapor, and P_o = saturation pressure of water vapor over a flat surface of pure water at the same temperature.

If Eq. (2) is evaluated at a reference temperature of 25°C, the following total suction and relative humidity relationship can be obtained:

$$h_t = 137182 \times \ln(P/P_o) \quad (3)$$

Figure 1 shows a plot of Eq. (3) at 25°C temperature. From Fig. 1, it can be seen that there is nearly a linear relationship between total suction (h_t) and relative humidity (P/P_o) over a very small relative humidity range. It can be said, in general, that in a closed system under isothermal conditions the relative humidity may be associated with the water content of the system such as 100 percent relative humidity refers to a fully saturated condition. Therefore, the suction value of a soil sample can be inferred from the relative humidity and suction relationship if the relative humidity is evaluated in some way. In a closed system, if the water is pure enough, the partial pressure of the water vapor at equilibrium is equal to the saturated vapor pressure at

temperature, T . However, the partial pressure of the water vapor over a partly saturated soil will be less than the saturation vapor pressure of pure water due to the soil matrix structure and the free ions and salts contained in the soil water (Fredlund and Rahardjo 1993).

In engineering practice, soil suction has usually been calculated in pF units (Schofield 1935) (i.e., suction in $pF = \log_{10}(|\text{suction in cm of water}|)$). However, soil suction is also currently being represented in $\log kPa$ unit system (Fredlund and Rahardjo 1993) (i.e., suction in $\log kPa = \log_{10}(|\text{suction in kPa}|)$). The relationship between these two systems of units is approximately $\text{suction in } \log kPa = \text{suction in } pF - 1$.

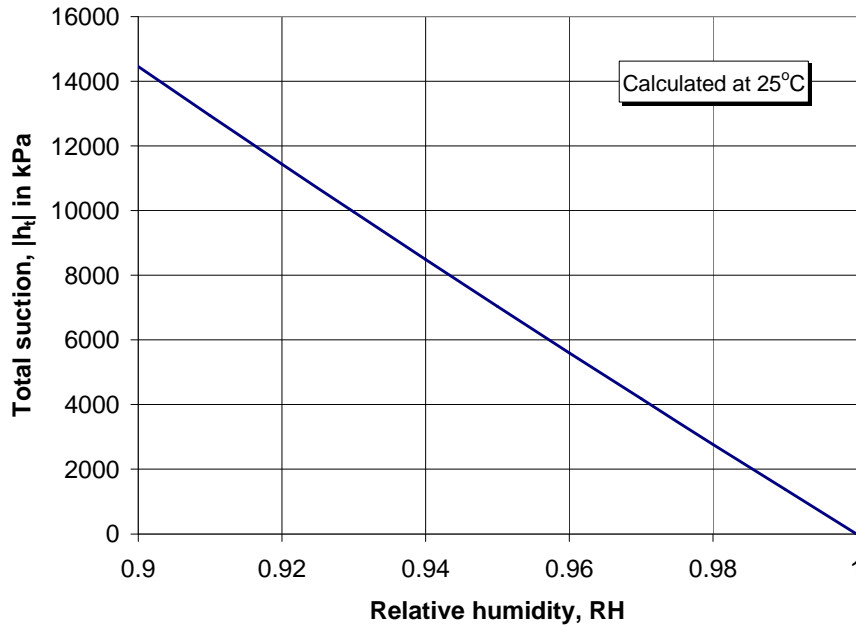


Figure 1. Total Suction versus Relative Humidity.

If total suction in kPa from Fig. 1 is converted to $\log kPa$ units, Fig. 2 is obtained. The difference between Fig. 1 and Fig. 2 is only the suction unit. The suction unit in Fig. 1 is kPa whereas it is $\log kPa$ in Fig. 2. From Fig. 2 it can clearly be seen that when relative humidity approaches 100 percent, the total suction becomes very sensitive. The sensitivity in the suction is due to the common logarithm used to convert suction from kPa to the $\log kPa$ unit.

Matric suction can be calculated from pressure plate and pressure membrane devices as the difference between the applied air pressure and water pressure across a porous plate. Matric suction can be formed in a relationship as follows:

$$h_m = -(u_a - u_w) \tag{4}$$

where h_m = matric suction, u_a = applied air pressure, and u_w = free water pressure at atmospheric condition.

The osmotic suction of electrolyte solutions, that are usually employed in the calibration of filter papers and psychrometers, can be calculated using the relationship between osmotic coefficients and osmotic suction. Osmotic coefficients are readily available in the literature for many different salt solutions. Table 1 gives the osmotic coefficients for several salt solutions. Osmotic coefficients can also be obtained from the following relationship (Lang 1967):

$$f = -\frac{r_w}{vmw} \ln\left(\frac{P}{P_o}\right) \quad (5)$$

where f = osmotic coefficient, v = number of ions from one molecule of salt (i.e., $v = 2$ for NaCl, KCl, NH_4Cl and $v = 3$ for Na_2SO_4 , CaCl_2 , $\text{Na}_2\text{S}_2\text{O}_3$, etc.), m = molality, w = molecular mass of water, and r_w = density of water.

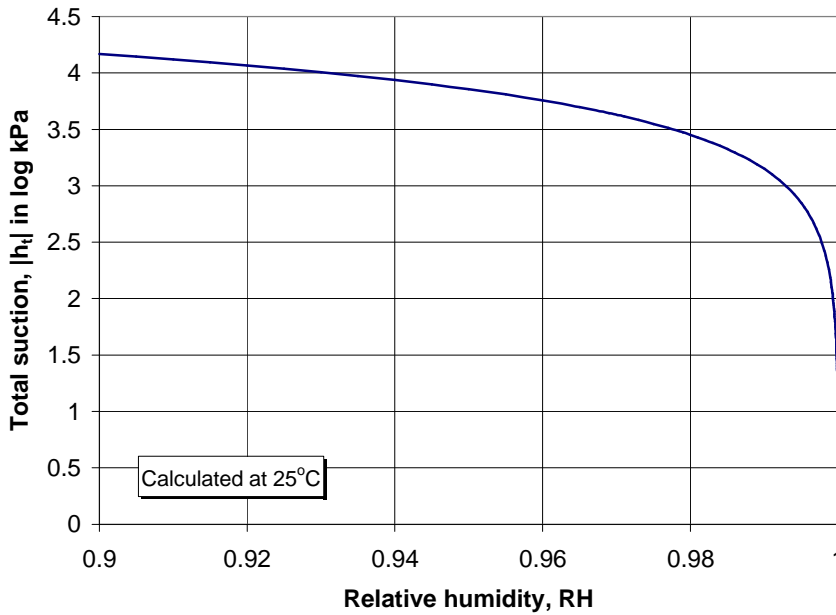


Figure 2. Total Suction and Relative Humidity Relationship.

The relative humidity term (P/P_o) in Eq. (5) is also known as the activity of water (a_w) in physical chemistry of electrolyte solutions. The combination of Eq. (2) and Eq. (5) gives a useful relationship that can be adopted to calculate osmotic suctions for different salt solutions:

$$h_p = -vRTmf \quad (6)$$

Table 2 gives osmotic suctions for several salt solutions using osmotic coefficients from Table 1 and Eq. (6).

Table 1. Osmotic Coefficients of Several Salt Solutions.

Osmotic Coefficients at 25°C							
Molality (m)	NaCl ^a	KCl ^a	NH ₄ Cl ^a	Na ₂ SO ₄ ^b	CaCl ₂ ^c	Na ₂ S ₂ O ₃ ^b	MgCl ₂ ^c
0.001	0.9880	0.9880	0.9880	0.9608	0.9623	0.9613	0.9627
0.002	0.9840	0.9840	0.9840	0.9466	0.9493	0.9475	0.9501
0.005	0.9760	0.9760	0.9760	0.9212	0.9274	0.9231	0.9292
0.010	0.9680	0.9670	0.9670	0.8965	0.9076	0.8999	0.9106
0.020	0.9590	0.9570	0.9570	0.8672	0.8866	0.8729	0.8916
0.050	0.9440	0.9400	0.9410	0.8229	0.8619	0.8333	0.8708
0.100	0.9330	0.9270	0.9270	0.7869	0.8516	0.8025	0.8648
0.200	0.9240	0.9130	0.9130	0.7494	0.8568	0.7719	0.8760
0.300	0.9210	0.9060	0.9060	0.7262	0.8721	0.7540	0.8963
0.400	0.9200	0.9020	0.9020	0.7088	0.8915	0.7415	0.9206
0.500	0.9210	0.9000	0.9000	0.6945	0.9134	0.7320	0.9475
0.600	0.9230	0.8990	0.8980	0.6824	0.9370	0.7247	0.9765
0.700	0.9260	0.8980	0.8970	0.6720	0.9621	0.7192	1.0073
0.800	0.9290	0.8980	0.8970	0.6629	0.9884	0.7151	1.0398
0.900	0.9320	0.8980	0.8970	0.6550	1.0159	0.7123	1.0738
1.000	0.9360	0.8980	0.8970	0.6481	1.0444	0.7107	1.1092
1.200	0.9440	0.9000	0.8980	...	...	...	...
1.400	0.9530	0.9020	0.9000	...	...	...	...
1.500	...	...	...	0.6273	1.2004	0.7166	1.3047
1.600	0.9620	0.9050	0.9020	...	...	...	...
1.800	0.9730	0.9080	0.9050	...	...	...	...
2.000	0.9840	0.9120	0.9080	0.6257	1.3754	0.7410	1.5250
2.500	1.0130	0.9230	0.9170	0.6401	1.5660	0.7793	1.7629

References:

^aHamer and Wu, 1972^bGoldberg, 1981^cGoldberg and Nuttall, 1978

The Filter Paper Method

The filter paper method has long been used in soil science and engineering practice and it has recently been accepted as an adaptable test method for soil suction measurements because of its advantages over other suction measurement devices. Basically, the filter paper comes to equilibrium with the soil either through vapor (total suction measurement) or liquid (matric suction measurement) flow. At equilibrium, the suction value of the filter paper and the soil will be equal. After equilibrium is established between the filter paper and the soil, the water content of the filter paper disc is measured. Then, by using a filter paper water content versus suction calibration curve, the corresponding suction value is found from the curve.

This is the basic approach suggested by ASTM Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper (ASTM D 5298). In other words, ASTM D 5298 employs a single calibration curve that has been used to infer both total and matric suction measurements. The ASTM D 5298 calibration

curve is a combination of both wetting and drying curves. However, this paper demonstrates that the “wetting” and “drying” suction calibration curves do not match, an observation that was also made by Houston et al. (1994).

Table 2. Osmotic Suctions of Several Salt Solutions.

Osmotic Suctions in kPa at 25°C							
Molality (m)	NaCl	KCl	NH ₄ Cl	Na ₂ SO ₄	CaCl ₂	Na ₂ S ₂ O ₃	MgCl ₂
0.001	5	5	5	7	7	7	7
0.002	10	10	10	14	14	14	14
0.005	24	24	24	34	34	34	35
0.010	48	48	48	67	67	67	68
0.020	95	95	95	129	132	130	133
0.050	234	233	233	306	320	310	324
0.100	463	460	460	585	633	597	643
0.200	916	905	905	1115	1274	1148	1303
0.300	1370	1348	1348	1620	1946	1682	2000
0.400	1824	1789	1789	2108	2652	2206	2739
0.500	2283	2231	2231	2582	3396	2722	3523
0.600	2746	2674	2671	3045	4181	3234	4357
0.700	3214	3116	3113	3498	5008	3744	5244
0.800	3685	3562	3558	3944	5880	4254	6186
0.900	4159	4007	4002	4384	6799	4767	7187
1.000	4641	4452	4447	4820	7767	5285	8249
1.200	5616	5354	5343	...	...	...	...
1.400	6615	6261	6247	...	...	...	...
1.500	...	...	...	6998	13391	7994	14554
1.600	7631	7179	7155	...	...	...	...
1.800	8683	8104	8076	...	...	...	...
2.000	9757	9043	9003	9306	20457	11021	22682
2.500	12556	11440	11366	11901	29115	14489	32776

Calibration for the Suction Wetting Curve

The calibration for the suction wetting curve for filter paper using salt solutions is based upon the thermodynamic relationship between total suction (or osmotic suction) and the relative humidity resulting from a specific concentration of a salt in distilled water. The thermodynamic relationship between total suction and relative humidity is given in Eq. (2).

In this study, NaCl was selected as an osmotic suction source for the filter paper calibration. Salt concentrations from 0 (distilled water) to 2.7 molality were prepared and filter papers were simply placed above salt solutions (in a non-contact manner) in sealed containers. The calibration test configuration adopted for this research is shown in Fig. 3. The filter paper and salt solution setups in the sealed containers were put in a constant temperature environment for equilibrium. Temperature fluctuations were kept as low as possible during a two week

equilibration period. A water bath was employed for this purpose, in which temperature fluctuations did not exceed $\pm 0.1^\circ\text{C}$.

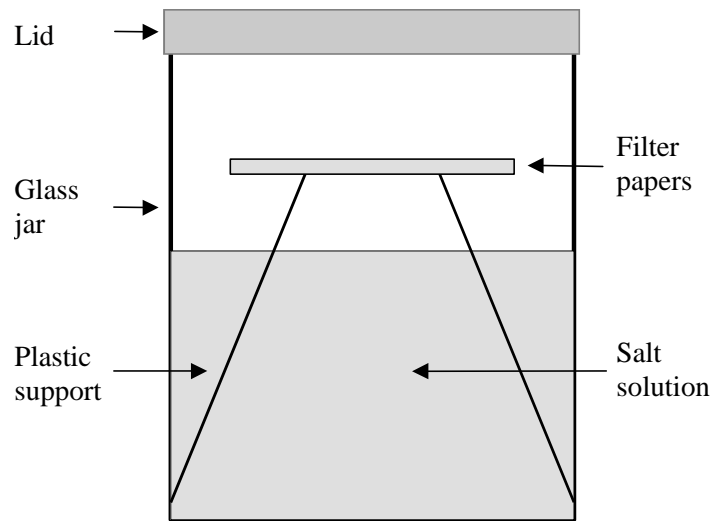


Figure 3. Total Suction Calibration Test Configuration.

Before commencing the filter paper calibration experiments and the soil suction measurements, all the items related to filter paper testing were cleaned carefully. Latex gloves and tweezers were used to handle the materials in nearly all steps of the experiment. The filter papers and aluminum cans for water content measurements were never touched with bare hands because oily hands may cause the filter papers to absorb more water. In addition, it is suggested that the filter paper water content measurements are performed by two persons in order to reduce the time during which the filter papers are exposed to the laboratory atmosphere and, thus, the amount of moisture lost or gained during measurements is kept to a minimum.

Experimental Procedure for Wetting Curve Calibration

The procedure that was adopted for the experiment is as follows:

1. NaCl solutions were prepared from 0 (i.e., distilled water) to 2.7 molality (i.e., the number of moles of NaCl in mass in 1,000 ml of distilled water).
2. A 250 ml glass jar was filled with approximately 150 ml of a solution of known molality of NaCl. Then, a small plastic cup was inserted into the glass jar to function as a support for filter papers. Two filter papers were put on the plastic cup one on top of the other. The glass jar lid was sealed tightly with plastic tapes to ensure air tightness. The configuration of the setup is depicted in Fig. 3.
3. Step 2 was repeated for each different NaCl concentration.

The glass jars were inserted into large plastic containers and the containers were sealed with water proof tape. Then, the containers were put into sealed plastic bags for extra protection. After that, the containers were inserted into the water bath for an equilibration period. After two weeks of equilibrating time, the procedure for the filter paper water content measurements was as follows:

1. Before taking the plastic containers from the water bath, all aluminum cans were weighed to the nearest 0.0001 g. accuracy and recorded on a filter paper water content measurement data sheet, similar to the one provided in ASTM D 5298.
2. After that, all measurements were carried out by two persons. For instance, while one person was opening the sealed glass jar, the other person was transferring the filter paper, using tweezers, into the aluminum can very quickly (i.e., in a few seconds, usually less than 5 seconds). The lid was placed on each aluminum can immediately.
3. Then, the weights of each can with filter papers inside were very quickly measured to the nearest 0.0001 g.
4. Steps 2 and 3 were followed for every glass jar. Then, all the cans were put into the oven with the lids half-open to allow evaporation. All filter papers were kept at $105 \pm 5^{\circ}\text{C}$ temperature for 24 hours inside the oven. This is the standard test method for soil water content measurements. However, it is only necessary to keep the filter paper in the oven for at least 10 hours.
5. Before taking measurements, the cans were closed with their lids and allowed to equilibrate in the oven for about 5 minutes. Then, a can was removed from the oven and put on an aluminum block for about 20 seconds to cool down; the aluminum block acted as a heat sink and expedited the cooling of the can. This is to eliminate temperature fluctuations and air currents in the enclosed weighing scale. After that, the can with dry filter paper inside was weighed to the nearest 0.0001 g. very quickly. The dry filter paper was taken out of the can and the cooled can was also weighed very quickly.
6. Step 5 was repeated for every can.

Wetting Calibration Curve

A wetting curve was constructed from the filter paper test results by following the procedure described above. The curve obtained for Schleicher & Schuell No. 589-WH filter papers using sodium chloride salt solutions is depicted in Fig. 4. Figure 4 clearly shows the sensitivity of total suction to very small changes in filter paper water content values when the relative humidity approaches 100%. The reason behind this sudden drop in suction was briefly explained with Fig. 2 and it will be discussed in detail in the following paragraphs.

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

change in relative humidity is very small with respect to the change in total suction. For instance, a relative humidity of 94 percent at a temperature of 25°C corresponds

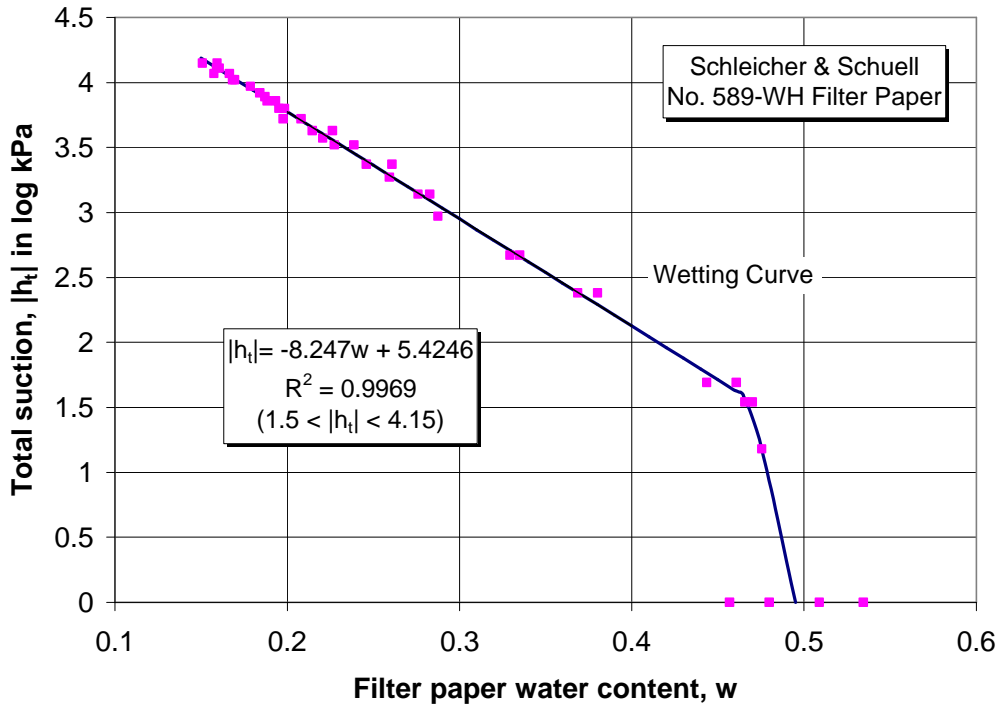


Figure 4. Filter Paper Wetting Calibration Curve.

to a total suction value of 8,488 kPa. Since the total suction values in engineering practice are often represented in logarithmic scales (i.e., pF or log kPa), the total suction values in log kPa units versus relative humidity were plotted in Fig. 2 in order to see the effect of the logarithmic scale on the relationship. From the figure, it is seen that total suction decreases dramatically when relative humidity approaches 100 percent.

Different concentrations of sodium chloride solutions were plotted against corresponding osmotic (or total) suction values both in kPa and log kPa units at 25°C in Figs. 5 and 6, respectively. As expected, the trend of the curves are similar to the trend of the curves obtained for relative humidity versus total suction for both kPa and log kPa units in Figs. 1 and 2, respectively. For example, a high concentration salt solution at a constant temperature in a closed container has low relative humidity above its surface.

Figure 7 depicts a plot of the wetting curve in kPa units versus filter paper water contents obtained in this research. In other words, if the suction values in Fig. 4 are plotted in kPa units, Fig. 7 is obtained. From the figure, the sensitivity of the filter paper water contents and total suction relationship can clearly be seen at very low suction values. From the relationships between total suction and relative humidity (i.e., Figs. 1 and 2), total suction and salt solutions (i.e., Figs. 5 and 6), and total suction and filter paper water contents (i.e., Figs. 4 and 7) it can be concluded

that the dramatic decrease in total suction at high water contents depends on the nature of the relationship between total suction and relative humidity from Kelvin's equation and on the use of the logarithmic scale for total suction. In addition, soils

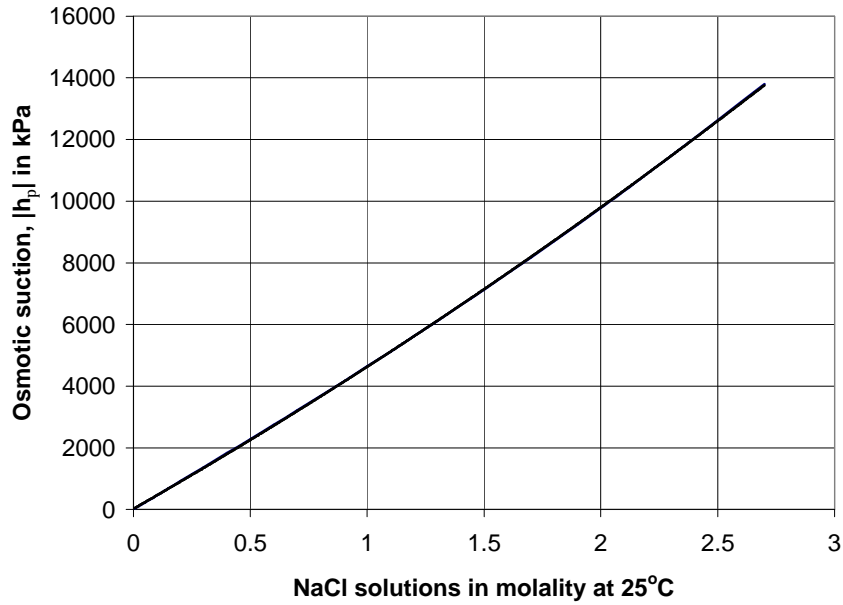


Figure 5. Osmotic Suction versus NaCl Solutions.

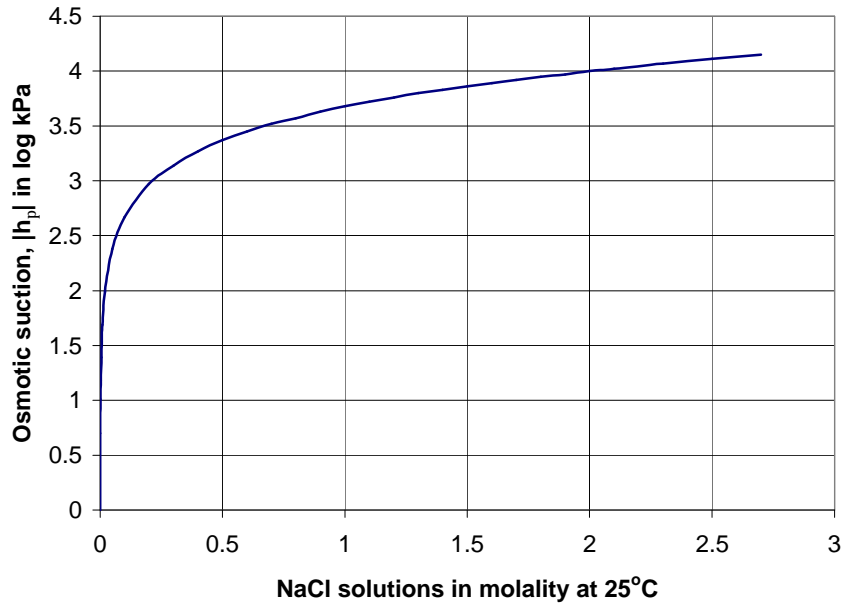


Figure 6. Osmotic Suction versus NaCl Solutions at 25°C.

tend to absorb more water for a small change in suction at very low suction values (Baver et al. 1972), and since filter papers, like soils, are porous materials they are very sensitive for absorbing water at low suction values.

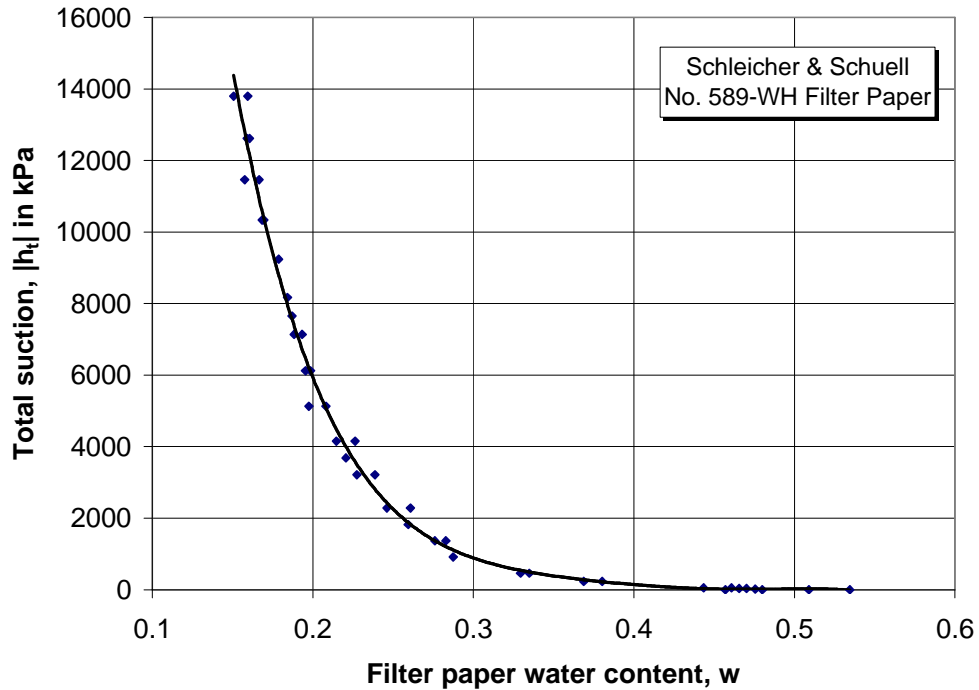


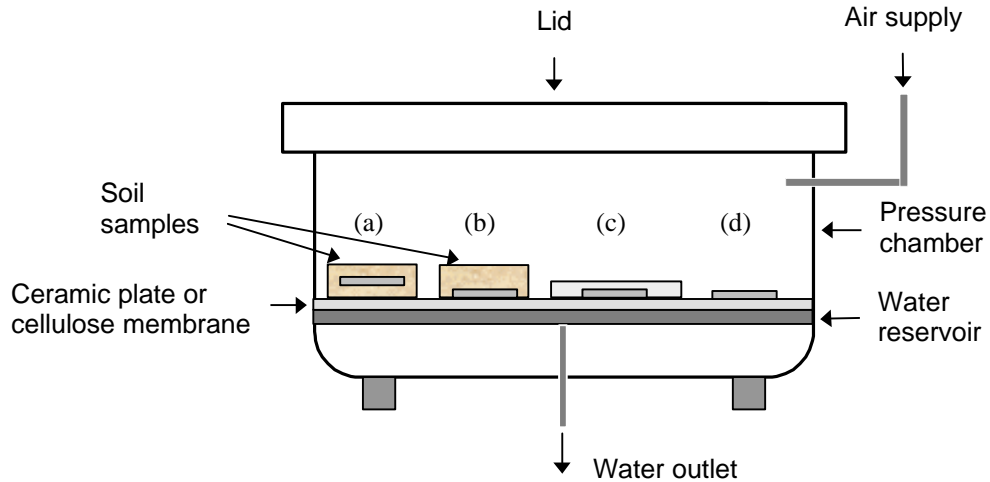
Figure 7. Filter Paper Wetting Calibration Curve in kPa Units.

Calibration for the Suction Drying Curve

Pressure plate and pressure membrane devices were employed in the drying filter paper calibration. A schematic drawing of a pressure plate or pressure membrane apparatus is depicted in Fig. 8. For the drying suction calibration of the filter paper, a contact path is provided between the filter paper and the measuring device so as to eliminate the osmotic suction component of total suction. In other words, if transfer of the soil water is allowed only through fluid flow, dissolved salts will move with the soil water, and the measuring device will not detect the osmotic suction component.

Pressure plate and pressure membrane devices operate by imposing a suction value (i.e., applied air pressure minus water pressure at atmospheric condition) on a given specimen which can be a soil or filter paper. The filter paper is put into the suction measuring device in a manner that ensures good contact with the porous plate or cellulose membrane. In this process, the main concern is to make sure that an intimate contact is provided between the water inside the filter paper and the water inside the porous disk so that transfer of the water is allowed only through continuous water films. To investigate the degree of contact between the filter paper and porous disk, the testing procedure and setup as depicted in Fig. 8 were

undertaken in this study. Three different soils (i.e., a fine clay, sandy silt, and pure sand) were used in the calibration process of filter papers in order to investigate the role of soils in establishing a good contact between the filter paper and porous disk.



- (a) One filter paper between two larger size protective filter papers embedded into the soil sample.
- (b) One filter paper makes contact with the porous plate or membrane and covered on top with a larger size protective filter paper in the soil sample.
- (c) One filter paper makes contact with the porous plate or membrane and covered on top with two larger size protective filter papers.
- (d) One filter paper on the porous plate or membrane.

Figure 8. Schematic Drawing of a Pressure Plate or Membrane Device.

Experimental Procedure for Drying Curve Calibration

The procedure that was adopted for the experiment is as follows:

1. Prior to each test, the porous disk or membrane and the soils were saturated with distilled water at least one day in advance, so that all the pores were fully saturated with water.
2. The testing configuration as in Fig. 8 was established using one of the soils (i.e., fine clay or sandy silt or pure sand). Figure 8 explains how the filter papers, soil, and protective papers were arranged in the experiment. The soil specimens with the filter papers were placed on the saturated disks and the level of distilled water on the plate was raised enough to cover all of the filter papers. All of the air bubbles were eliminated during placement of the filter paper, soil, and protective paper arrangement on the ceramic disk by carefully pressing the bubbles out to the edges of each. The air bubbles were pressed out of the sample using a small diameter glass pipe and a large diameter glass cylinder.

3. After the pressure chamber was tightened, with the influence of the applied air pressure the water inside the soil specimen and filter papers were forced out through the porous plate or membrane and collected in a graduated cylinder until a suction equilibrium between the soil and filter papers and the applied air pressure was established.

An equilibration period between 3 and 5 days is commonly suggested for matric suction measurements using pressure plates and membranes (ASTM D 5298, Houston et al. 1994, Lee 1991). The equilibrating periods used for this study varied between 3, 5, and 7 days depending on the testing set up. For instance, when filter papers were embedded in the soil, equilibrating periods were 7 days for the fine clay and 5 days for the sandy silt set up, but the equilibrating period was 3 days when filter papers embedded in the pure sand or when only filter papers were used. However, all the three soils were also tested with filter papers inside in the same pressure chamber to check the differences between the filter paper water contents. To obtain the filter paper water contents, the same procedure described in the Wetting Curve Calibration Procedure was followed.

Drying Calibration Curve

A drying curve was established from the filter paper test results by following the procedure described above. The curve obtained for Schleicher & Schuell No. 589-WH filter papers using both pressure plate and pressure membrane devices is depicted in Fig. 9. Each data point on Fig. 9 is an average of at least three tests and each test data is an average of at least four filter papers. The standard errors for the straight line and curved portions of the drying curve are 0.135 and 0.116 log kPa units, respectively. The standard error for the straight line portion of the wetting curve is 0.044 log kPa. With the pressure membrane the highest matric suction obtained was 4,570 kPa and suctions below 150 kPa were obtained using the pressure plate apparatus. The corresponding wetting calibration curve is also shown in Fig. 9. It plots below the drying suction curve, as is expected of the hysteresis process.

Very high filter paper water contents were obtained when all the three soils were used as in the set up (a) as shown in Fig. 8. However, the filter paper water contents were all comparable as obtained from the set ups (b), (c), and (d) as in Fig. 8. The results from (b) were slightly wetter than (c) and the results from (d) were slightly drier than (c). In obtaining the calibration curve, the filter papers from the set up arrangements (b), (c), and (d) were used.

Soil Total and Matric Suction Measurements

Soil total suction measurements are similar to those measurements in the filter paper calibration testing. The same testing procedure can be followed by replacing the salt solution with a soil sample.

Soil matric suction measurements are also similar to the total suction measurements except that an intimate contact should be provided between the filter

paper and the soil. A suggested testing procedure for soil total and matric suction measurements using filter papers is outlined in Appendix.

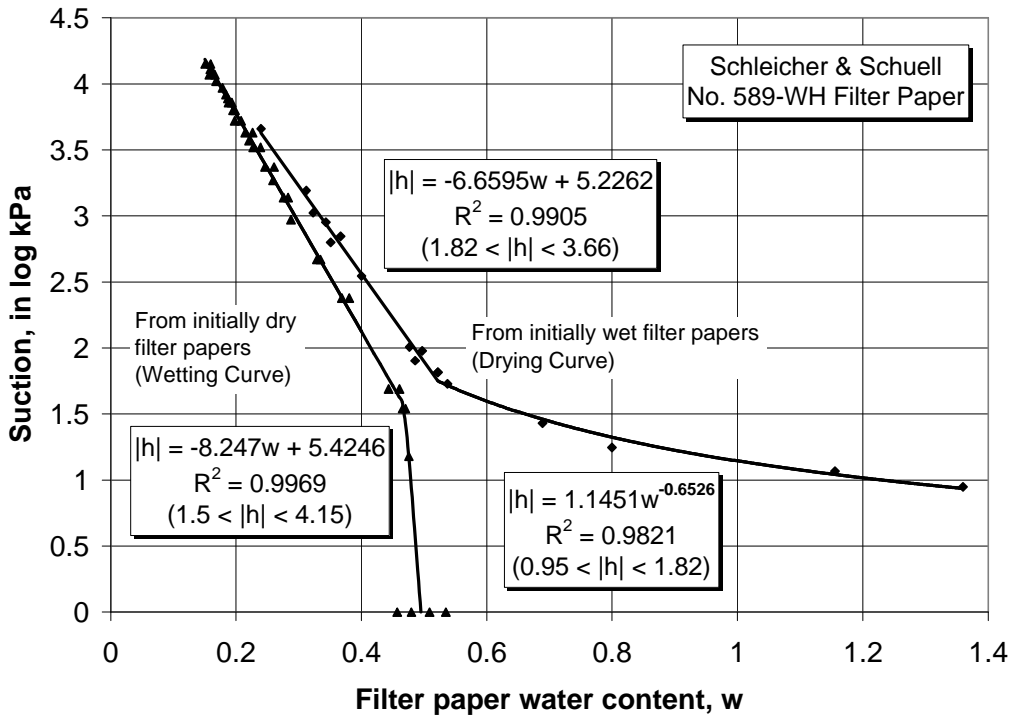


Figure 9. Drying Suction Calibration Curve along with Wetting Suction Curve.

Discussion

The dramatic decrease of total suction at high filter paper water contents is related to the nature of Kelvin’s equation and to the use of the logarithmic scale (i.e., log kPa or pF). These results conclude that the filter paper method can give reliable wetting suction results up to a point. In other words, with the Schleicher & Schuell No. 589-WH filter papers reliable wetting suction measurements can be taken at and above 1.5 log kPa (2.5 pF), but below about 1.5 log kPa wetting suction results cannot be relied upon because a small error in measuring water content can result in a large error in the inferred suction. Therefore, a best fit line up to 1.5 log kPa was made to plot Fig. 4, below which there is a sudden drop in the wetting suction.

In the drying filter paper calibration testing, filter papers are initially fully saturated and with the application of air pressure the water inside the filter paper is driven out, which is a drying process. However, the soil matric and total suction measurements follow a wetting process with the filter paper method. Because of hysteresis, the wetting suction calibration curve must always plot below the drying calibration curve. A final point; because both the matric and total suction measurements are wetting processes, they should, by these arguments, both be determined from the wetting calibration curve.

Acknowledgements

The authors wish to thank Dr. Hsiu-Chung Lee for helping with the total suction calibration testing and Dr. Seong-Wan Park for helping with the matric suction calibration testing.

References

- Al-Khafaf, S. and Hanks, R. J. (1974). "Evaluation of the Filter Paper Method for Estimating Soil Water Potential," *Soil Science*, Vol. 117, No. 4, pp. 194-199.
- Baver, L. D., Gardner, W. H., and Gardner, W. R. (1972). *Soil Physics*, John Wiley & Sons, Inc., New York.
- Chandler, R. J. and Gutierrez, C. I. (1986). "The Filter Paper Method of Suction Measurements," *Geotechnique*, Vol. 36, pp. 265-268.
- Fawcett, R. G. and Collis-George, N. (1967). "A Filter-Paper Method for Determining the Moisture Characteristics of Soil," *Australian Journal of Experimental Agriculture and Animal Husbandry*, Vol. 7, pp. 162-167.
- Fredlund, D. G. and Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*, New York: John Wiley & Sons, Inc.
- Gardner, R. (1937). "A Method of Measuring the Capillary Tension of Soil Moisture Over a Wide Moisture Range," *Soil Science*, Vol. 43, No. 4, pp. 277-283.
- Goldberg, R. N. (1981). "Evaluated Activity and Osmotic Coefficients for Aqueous Solutions: Thirty-six Uni-Bivalent Electrolytes," *Journal of Physics and Chemistry Reference Data*, Vol. 10, No. 3, pp. 671-764.
- Goldberg, R. N. and Nuttall, R. L. (1978). "Evaluated Activity and Osmotic Coefficients for Aqueous Solutions: The Alkaline Earth Metal Halides," *Journal of Physics and Chemistry Reference Data*, Vol. 7, No. 1, pp. 263-310.
- Hamblin, A. P. (1981). "Filter Paper Method for Routine Measurement of Field Water Potential," *Journal of Hydrology*, Vol. 53, No. 3/4, pp.355-360.
- Hamer, W. J. and Wu, Y.-C. (1972). "Osmotic Coefficients and Mean Activity Coefficients of Uni-Univalent Electrolytes in Water at 25°C," *Journal of Physics and Chemistry Reference Data*, Vol. 1, No. 4, pp. 1047-1099.
- Houston, S. L., Houston, W. N., and Wagner, A. M. (1994). "Laboratory Filter Paper Measurements," *Geotechnical Testing Journal*, GTJODJ, Vol. 17, No. 2, pp. 185-194.
- Lang, A. R. G. (1967). "Osmotic Coefficients and Water Potentials of Sodium Chloride Solutions from 0 to 40°C," *Australian Journal of Chemistry*, Vol. 20, pp. 2017-2023.
- Lee, H. C. (1991). "An Evaluation of Instruments to Measure Soil Moisture Condition," *M.Sc. Thesis*, Texas Tech University, Lubbock, Texas.
- McKeen, R. G. (1980). "Field Studies of Airport Pavement on Expansive Clay," *Proceedings 4th International Conference on Expansive Soils*, Vol. 1, pp.242-261, ASCE, Denver, Colorado.
- McQueen, I. S. and Miller, R. F. (1968). "Calibration and Evaluation of a Wide-Range Gravimetric Method for Measuring Moisture Stress," *Soil Science*, Vol. 106, No. 3, pp. 225-231.

- Schofield, R. K. (1935). "The pF of the Water in Soil," *Transactions, 3rd International Congress of Soil Science*, Vol. 2, pp. 37-48.
- Swarbrick, G. E. (1995). "Measurement of Soil Suction Using the Filter Paper Method," *First International Conference on Unsaturated Soils*, Eds.: E. E. Alonso and P. Delage, Vol. 2, Paris, 6-8 September, ENDPC, pp. 701-708.

Appendix. Soil Suction Measurements

Soil Total Suction Measurements

Glass jars that are between 250 to 500 ml volume size are readily available in the market and can be easily adopted for suction measurements. Glass jars, especially, with 3.5 to 4 inch (8.89 to 10.16 cm) diameter can contain the 3 inch (7.62 cm) diameter Shelby tube samples very nicely. A testing procedure for total suction measurements using filter papers can be outlined as follows:

Experimental Procedure

1. At least 75 percent by volume of a glass jar is filled up with the soil; the smaller the empty space remaining in the glass jar, the smaller the time period that the filter paper and the soil system requires to come to equilibrium.
2. A ring type support, which has a diameter smaller than filter paper diameter and about 1 to 2 cm in height, is put on top of the soil to provide a non-contact system between the filter paper and the soil. Care must be taken when selecting the support material; materials that can corrode should be avoided, plastic or glass type materials are much better for this job.
3. Two filter papers one on top of the other are inserted on the ring using tweezers. The filter papers should not touch the soil, the inside wall of the jar, and underneath the lid in any way.
4. Then, the glass jar lid is sealed very tightly with plastic tape.
5. Steps 1, 2, 3, and 4 are repeated for every soil sample.
6. After that, the glass jars are put into the ice-chests in a controlled temperature room for equilibrium.

Researchers suggest a minimum equilibrating period of one week (ASTM D 5298, Houston et al. 1994, Lee 1991). After the equilibration time, the procedure for the filter paper water content measurements can be as follows:

1. Before removing the glass jar containers from the temperature room, all aluminum cans that are used for moisture content measurements are weighed to the nearest 0.0001 g. accuracy and recorded.
2. After that, all measurements are carried out by two persons. For example, while one person is opening the sealed glass jar, the other is putting the filter paper into the aluminum can very quickly (i.e., in a few seconds) using tweezers.
3. Then, the weights of each can with wet filter paper inside are taken very quickly.

4. Steps 2 and 3 are followed for every glass jar. Then, all cans are put into the oven with the lids half-open to allow evaporation. All filter papers are kept at $105 \pm 5^\circ\text{C}$ temperature inside the oven for at least 10 hours.
5. Before taking measurements on the dried filter papers, the cans are closed with their lids and allowed to equilibrate for about 5 minutes. Then, a can is removed from the oven and put on an aluminum block (i.e., heat sinker) for about 20 seconds to cool down; the aluminum block functions as a heat sink and expedites the cooling of the can. After that, the can with the dry filter paper inside is weighed very quickly. The dry filter paper is taken from the can and the cooled can is weighed again in a few seconds.
6. Step 5 is repeated for every can.

After obtaining all of the filter paper water contents an appropriate calibration curve, such as the one in Fig. 4, is employed to get total suction values of the soil samples.

Soil Matric Suction Measurements

Soil matric suction measurements are similar to the total suction measurements except instead of inserting filter papers in a non-contact manner with the soil for total suction testing, a good intimate contact should be provided between the filter paper and the soil for matric suction measurements. Both matric and total suction measurements can be performed on the same soil sample in a glass jar as shown in Fig. A1. A testing procedure for matric suction measurements using filter papers can be outlined as follows:

Experimental Procedure

1. A filter paper is sandwiched between two larger size protective filter papers. The filter papers used in suction measurements are 5.5 cm in diameter, so either a filter paper is cut to a smaller diameter and sandwiched between two 5.5 cm papers or bigger diameter (bigger than 5.5 cm) filter papers are used as protectives.
2. Then, these sandwiched filter papers are inserted into the soil sample in a very good contact manner (i.e., as in Fig. A1). An intimate contact between the filter paper and the soil is very important.
3. After that, the soil sample with embedded filter papers is put into the glass jar container. The glass container is sealed up very tightly with plastic tape.
4. Steps 1, 2, and 3 are repeated for every soil sample.
5. The prepared containers are put into ice-chests in a controlled temperature room for equilibrium.

Researchers suggest an equilibration period of 3 to 5 days for matric suction testing (ASTM D 5298, Houston et al. 1994, Lee 1991). However, if both matric and total suction measurements are performed on the same sample in the glass jar, then the final equilibrating time will be at least 7 days of total suction equilibrating period. The procedure for the filter paper water content measurements at the end of the equilibration is exactly same as the one outlined for the total suction water content measurements. After obtaining all the filter paper water contents the appropriate calibration curve may be employed to get the matric suction values of the soil samples.

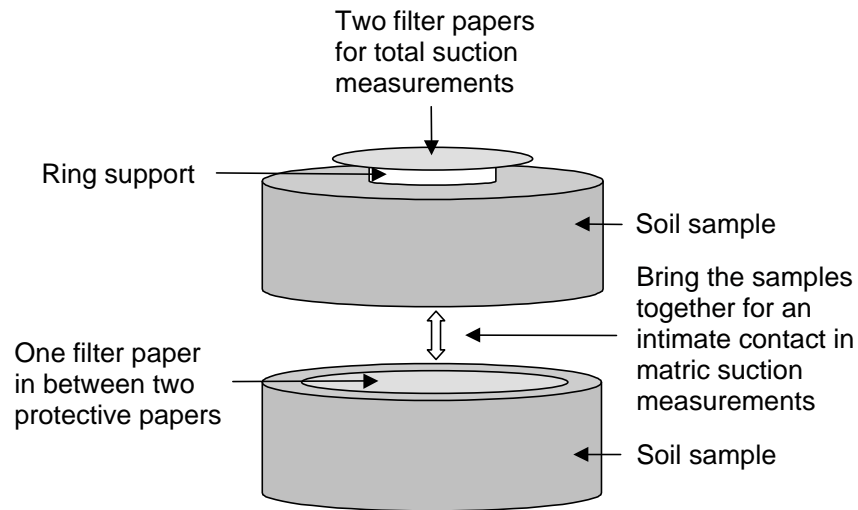


Figure. A1. Total and Matric Suction Measurements.