Suction Measurements on Compacted Till Specimens and Indirect Filter Paper Calibration Technique

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Standard AASHTO compacted specimens were used to provide a constant-suction environment for an indirect calibration of filter paper sensors. The suctions of the compacted till specimens were measured with tensiometers, thermal conductivity matric suction sensors, and psychrometers. The compacted specimens had essentially constant degrees of saturation at water contents greater than optimum. The matric suction of specimens compacted greater than optimum were observed to vary linearly with the water content and the void ratio (i.e., matric suction varies directly with dry density and inversely with water content). Filter paper sensors in good contact with specimens compacted greater than optimum were found to yield a more consistent calibration curve than filter paper sensors that were not in contact with the soil. Calibration curves obtained showed that the transition from where liquid flow is dominant to where vapor flow is dominant occurs at approximately 20 to 90 kPa.

The behavior of both saturated and unsaturated soils is affected by the pore-water pressures in the soil. Both positive and negative pore-water pressures have a major effect on the shear strength and volume change behavior of a soil. The effect of negative pore-water pressures on the hydraulic conductivity behavior of unsaturated soils has become increasingly important in analyzing geoenvironmental problems.

The measurement of positive pore-water pressures has become routine for engineering works such as embankments and dams. The measurement of negative pore-water pressures, however, has remained a research endeavor. The measurement of negative pore-water pressures over a wide range of values has proved to be difficult. Negative water pressures can range from 0 to 1 million kPa. The direct measurement of negative pore-water pressure is limited by the problem of cavitation. Water will cavitate when the vapor pressure is reached on an absolute pressure scale. As a result, the direct measurement of negative pore-water pressures by a tensiometer is now limited to pressures of less than 1 atm. Research at Imperial College, London, has involved the use of thin water films in a tensiometer to reduce the problem of cavitation. It is hoped that this research will provide a means of extending the range of negative pore-water pressure measurements beyond the present 1-atm constraint.

Various indirect methods of assessing the negative pore-water pressure in soils have been used for a number of years. These methods include moisture blocks, thermal conductivity sensors, blotting papers, filter papers, and psychrometers. All these methods have their own set of limitations. All methods, except the psychrometer method, rely on the absorbency properties of a sensor material and thus suffer from nonlinearity and hysteresis in the water-retention characteristics of the sensor medium. That is, the sensor materials generally display small water-content changes over large suction changes when in the high suction range.

Nevertheless, the filter paper method has some attractive features. It has been found to be applicable over a wide range of suctions. Filter paper provides an inexpensive sensor, and the methodology associated with its use is simple. The filter paper method, however, suffers from some procedural difficulties. Although the method is applicable to a wide range of suctions, the degree of accuracy is often inadequate. The filter paper method does not lend itself to automation processes, particularly in the area of data acquisition. The method is considered a destructive method in that the filter papers are not reusable.

The filter paper method is a technique that can be readily incorporated into routine site investigations. There has been considerable interest in the use of the filter paper method in several disciplines. Literature from early research (*1–5*) and from more recent research (*6–11*) into the filter paper method is listed in the References section. Recent experiences with studies related to airport pavement subgrades (*11*) and the movement of foundations of light structures (*9*) have indicated that the method deserves further consideration.

The objectives of this paper are (*a*) to determine the suction of compacted till specimens by using various suction measurement devices and (*b*) to evaluate an indirect method of calibrating filter paper sensors by using compacted soil specimens to provide constant suction environments. At present, the filter paper method has not gained wide acceptance in geotechnical engineering. The issues of whether the filter paper should be in contact with the soil or not in contact with the soil and of what suctions are measured in each case have been much debated. It is hoped that this study will assist in further resolving these questions related to the filter paper method.

PROGRAM FOR THE LABORATORY STUDY

The laboratory program involved (*a*) the measurements of suction in a set of standard AASHTO compacted till specimens and (*b*) using these compacted specimens to provide constant-suction environments for an indirect calibration of filter paper sensors.

Suction Measurement Devices

Suctions in the compacted till specimens were measured with the following suction measurement devices: jet-fill tensiometers, quick-draw tensiometers, MCS-6000 thermal conductivity matric suction sensors, and psychrometers.

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Tensiometers are limited to a matric suction value of approximately 90 kPa. The MCS-6000 thermal conductivity matric suction sensors are reliable in the range from 0 to 300 kPa. Psychrometers start to become reliable at a suction near 100 kPa and measurements can be made up to 8000 kPa. Suctions of interest in geotechnical engineering generally range from 0 to 1500 kPa.

Soil Selected for the Study

The soil used in the laboratory tests program was a till from the Qu'Appelle Moraine east of the city of Regina in Saskatchewan, Canada. The grain size distributions of the till show 37 percent sand, 34 percent silt, and 29 percent clay. The till has a liquid limit of 38 percent and a plastic limit of 16 percent. Distilled water was added to the till to yield a set of samples with water contents ranging from 8 percent to 25 percent. Standard AASHTO compacted specimens were prepared from these samples for the testing. The compaction characteristics of the soil are presented in Figure 1. The till has a maximum dry density of approximately 1860 kg/m^3 and a corresponding optimum water content of approximately 15 percent.

Different suction values were obtained by compacting the till at various water contents. In other words, the suctions in the compacted specimens were not directly induced or controlled as in a pressure plate device. The matric suction or the total suction values, or both, in each specimen were measured with one or more of the following devices: jet-fill tensiometer, quick-draw tensiometer, MCS 6000 sensor, or psychrometer.

Filter Paper Selected for the Study

Schleicher Schuell No. 589 white ribbon filter paper was used in the laboratory tests. The filter papers had a diameter of 55 mm. The filter papers were pretreated by being dipped in a fungicide, drip dried, and over dried overnight. The fungicide was a mixture of 3.5 g of a technical-grade of pentachlorophenol (i.e., 86 percent by weight of pentachlorophenol) in 100 g of ethyl alcohol, which yielded a 3 percent "penta" solution.

A scanning electron micrograph of a Schleicher Schuell No. 589 white ribbon filter paper is shown in Figure 2. A scanning electron micrograph of a Whatman filter paper is also shown for comparison. The two types of filter paper appear similar in the scanning electron micrographs. The similarity of the filter papers has great implications with respect to the calibration of filter papers for suction measurements.

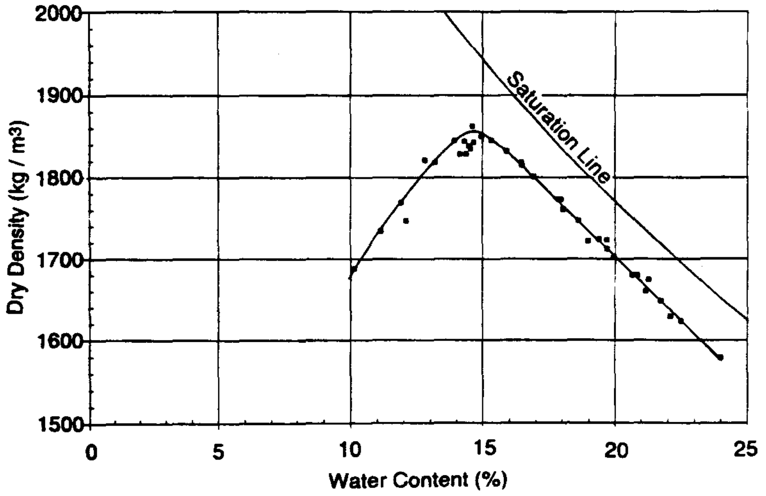


FIGURE 1 Compaction characteristics of till.

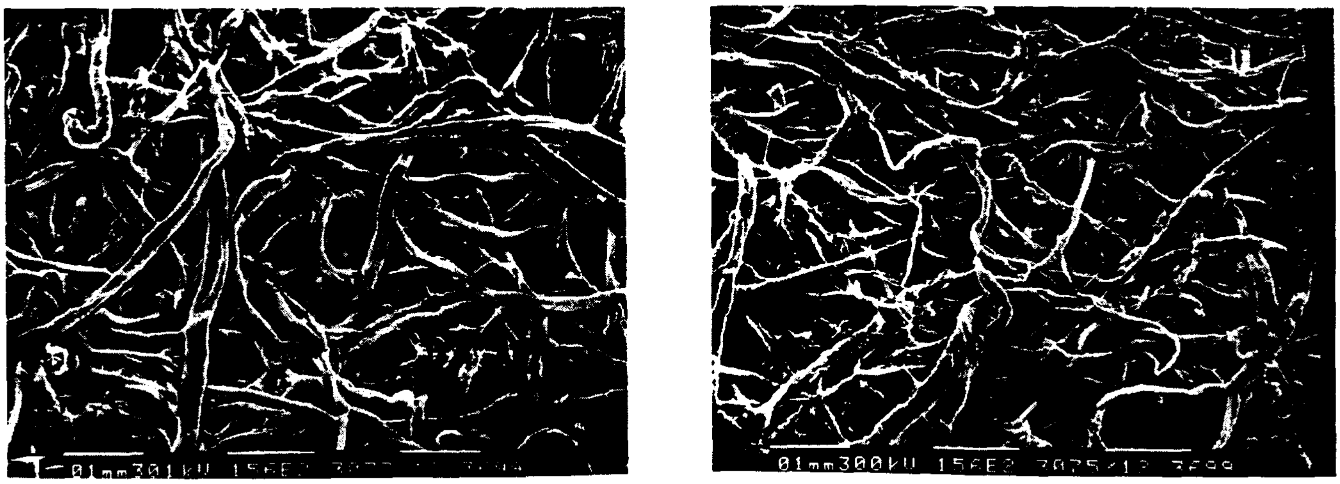


FIGURE 2 Scanning electron micrographs: *left*, Schleicher and Schuell No. 589 filter paper; *right*, Whatman filter paper.

Installation Procedures for Filter Paper Sensors

The jet-fill tensiometers, quick-draw tensiometers, or MCS-6000 thermal conductivity matric suction sensors were snugly fitted into a hole drilled into the compacted specimens (Figures 3–5). The psychrometers were installed in sets of three (Figure 6). These sensors (i.e., jet-fill tensiometers, quick-draw tensiometers, MCS-6000 sensors, and psychrometers) are subsequently referred to as reference sensors.

Installation of Good-Contact Filter Papers in Standard AASHTO Compacted Specimens

Two installation procedures were used. In the first procedure a vertical cut was made in the compacted specimen at a distance of approximately 3 cm on either side of the reference sensor (Figure 3). In the second procedure a single horizontal cut was made at a distance of approximately 2 cm below the tip of the sensor (Figure 4). The cut was made either with a bow saw equipped with a piano wire for moist specimens or a with a hacksaw blade for drier specimens.

A triple sandwich filter paper sensor was installed in each cut. The specimen was held together with masking tape, then wrapped with Saran wrap and aluminum foil followed by an outer layer of masking tape. The specimen was then placed in a styrofoam chest packed with styrofoam chips and left to equilibrate with time.

Installation of Noncontact Filter Papers in Standard AASHTO Specimens

Three vertical holes surrounding the reference sensor were drilled into one end of a compacted specimen by a 22.23-mm (⅞-in.) drill bit. A plastic hair roller was installed in each hole (Figure 5). A sin-

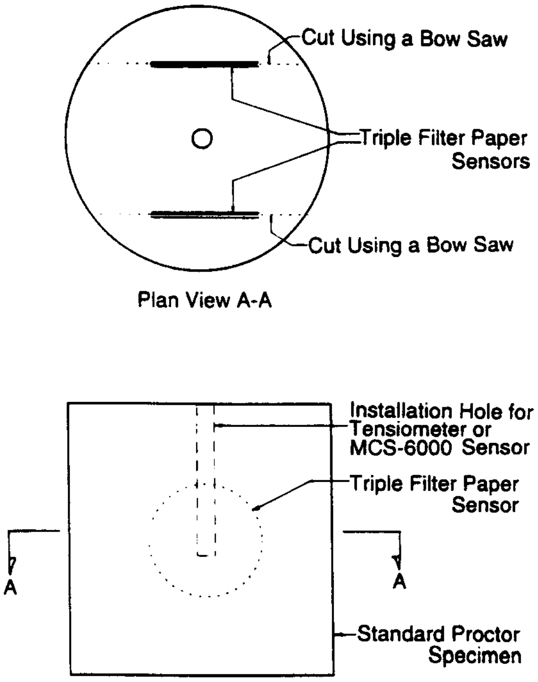


FIGURE 3 Setup 1 for calibration of good-contact filter paper sensors in standard Proctor specimens.

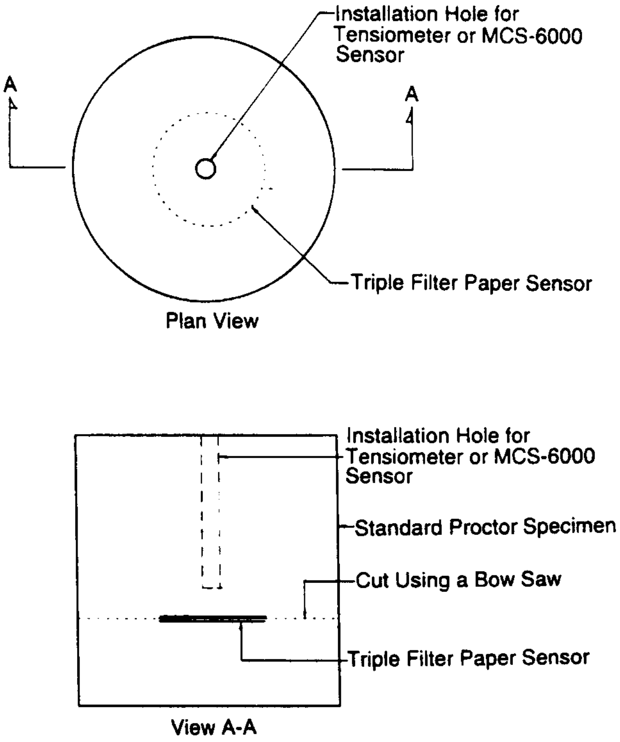


FIGURE 4 Setup 2 for calibration of good-contact filter paper sensors in standard Proctor specimens.

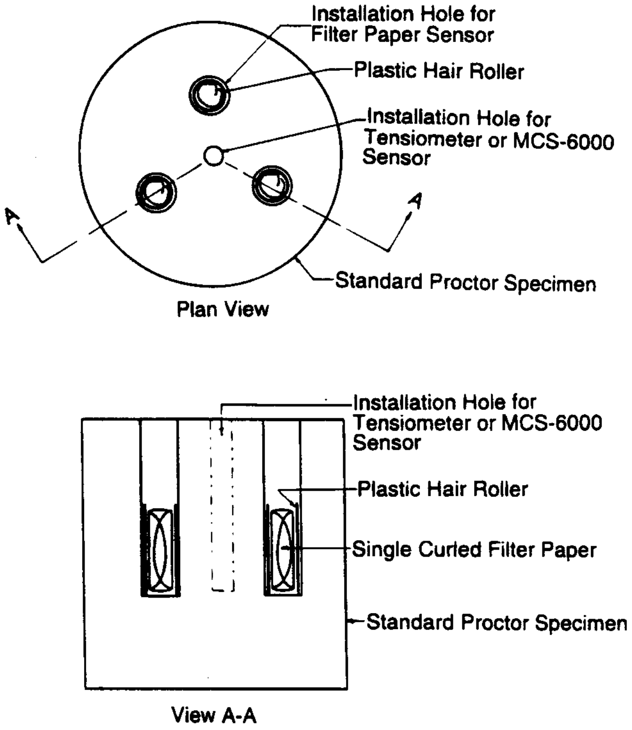
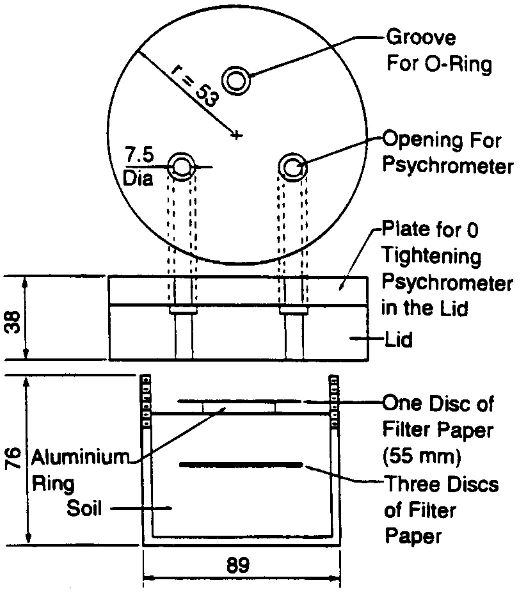


FIGURE 5 Setup for calibration of noncontact filter paper sensors in standard Proctor specimens.



All Dimensions in mm.

FIGURE 6 Lucite container for filter paper calibration when psychrometers are used as reference sensors.

gle filter paper sensor was curled with tweezers to fit inside each hair roller. The specimen was then wrapped in Saran wrap and aluminum foil and tightly bound with masking tape. The specimen was left to equilibrate in a styrofoam chest filled with styrofoam chips.

Installation of Good-Contact and Noncontact Filter Paper for Calibration Using Psychrometers

Two slices of soil cut from a standard AASHTO compacted specimen were trimmed to fit into a Lucite container. Each slice was approximately 3 cm thick. A triple sandwich, good-contact filter paper sensor was placed between the slices. The two slices of soil were pressed tightly together inside the Lucite container. This procedure ensured good contact between the filter paper sensor and the soil. A single noncontact filter paper sensor was also installed by placing the filter paper on an aluminum ring placed on the surface of the soil. The setup is shown in Figure 6.

The Lucite container was fitted with three psychrometers and placed in a steel beaker immersed in a water bath for equilibration (Figure 7). The temperature of the water bath was maintained at 24°C.

PRESENTATION OF RESULTS

The suction-versus-compaction water-content relationship for the standard AASHTO compacted till specimens is presented in Figure 8. The curve in Figure 8 is not a soil-water characteristic curve because the relationship was obtained from a set of nonidentical specimens. Also shown in Figure 8 are the total suction and matric suction curves obtained from another study on a similar till (*12*).

Calibration data obtained from the triple sandwich, good-contact filter paper sensors are presented in Figure 9. The water-content data for all three filter papers in each of the triple sandwich sensors were similar.

Calibration data from the noncontact single filter paper sensor are presented in Figure 10. The calibration was conducted from low suction values of less than 10 kPa to suction values of approximately 1000 kPa. In retrospect, the calibration by the sorption procedure (i.e., noncontact filter paper) would be more meaningful if it were restricted to high suction values.

DISCUSSION OF RESULTS

Results of suction measurements on the compacted till are discussed, followed by a discussion of the results of the calibration of the filter paper sensors. The filter paper calibration curves obtained from this study are compared with currently available calibration curves. The merits or demerits of the indirect calibration procedure are discussed.

Suction Measurements on the Compacted Till

The suction-versus-compaction water-content data (Figure 8) show that the suctions measured in the compacted till specimens have values comparable with those obtained from previous tests on a simi-

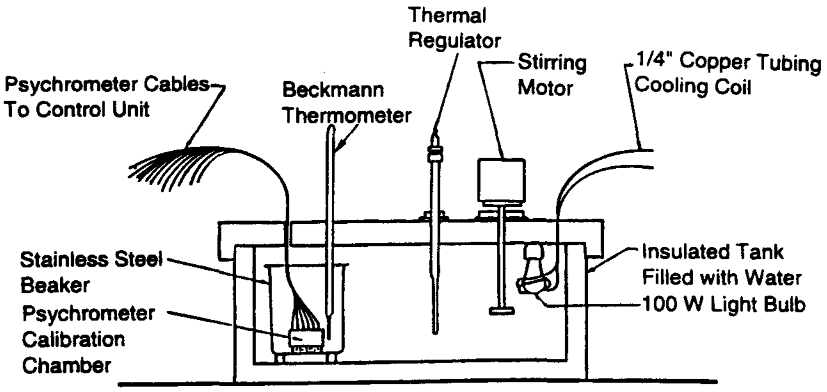


FIGURE 7 Water bath for calibration with psychrometers (*12*).

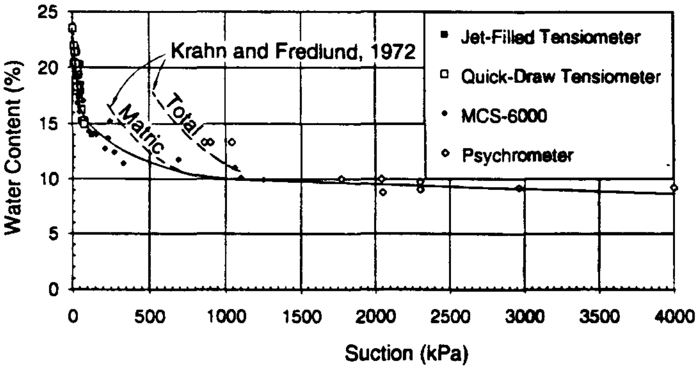


FIGURE 8 Water-content–suction relationship for compacted till.

lar till (*12*). The psychrometer readings appear to correspond well to the total suction curve from the previous study (*12*).

The suction-versus-compaction water-content data, along with the void ratio and the degree-of-saturation versus compaction water-content relationships, are shown side by side in Figure 11 for comparison. The void ratios and degree-of-saturation values were calculated from the compaction data in Figure 1.

Figures 8 and 11 show that the matric suction of the compacted specimens varied inversely linearly with compaction water content up to the optimum water content of 15 percent. At compaction water contents less than the optimum water content the matric suction values increased rapidly with a decrease in water content. The matric suction value at the optimum water content was approximately 80 kPa.

Results of Calibration for Filter Paper Sensors

The calibration curve for the good-contact filter paper sensor can be fitted by a bilinear curve (Figure 9). There appears to be significant scatter near the break in the calibration curve. The calibration data for the noncontact filter paper sensors also appear to fit a bilinear curve (Figure 10). The data from the noncontact filter paper sensors appear to be more scattered than the data for the good-contact filter paper sensor.

The water contents of the filter papers in good contact with the soil (Figure 9) were in better agreement with the suction values measured by the reference sensors than the water contents of the filter papers not in contact with the soil (Figure 10) for suction values of the compacted till below 100 kPa (i.e., above the optimum water content of the till).

It would appear that above the optimum water content of the till, there is a direct transfer of water via the liquid phase. In other words, conductive flow is more efficient and reliable in the equilibration process at water content above the optimum.

Below the optimum water content the results obtained for the noncontact filter paper sensors do not appear to be inferior to the results obtained for the good-contact filter paper sensors. Below optimum water content the water is tightly bound to the soil particles. Liquid flow is small in comparison with the vapor flow. Consequently the variations in the water content as a result of liquid flow are small. The small liquid flow may be one reason for the seemingly smaller scatter, regardless of whether the filter paper is good contact with the soil. The differences may also be exaggerated because of the use of a logarithmic scale for suctions.

The greatest scatter in the calibration data for the filter paper sensors occurs near the break in the bilinear curve. This is more obvious for the noncontact filter paper sensors (Figure 10) The scatter could be due to liquid flow being prominent in some instances and not in others at suction values near the break in the calibration curve. For the noncontact filter paper sensor it would appear to be more meaningful to restrict the calibration for suctions greater than 100 kPa.

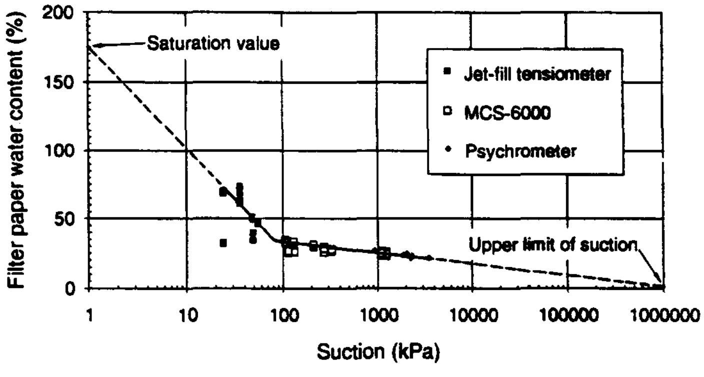


FIGURE 9 Data from calibrations of good-contact filter paper sensors, considering data from all three filter papers of each triple sandwich sensor.

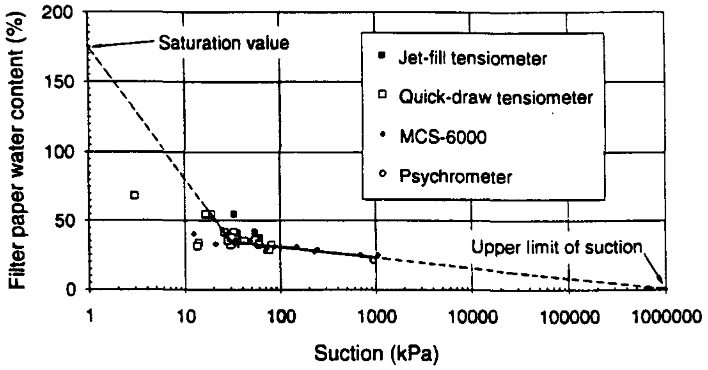


FIGURE 10 Data from calibrations of noncontact filter paper sensors.

Comparison of Filter Paper Calibration Curves

The calibration curves obtained for the good-contact filter paper sensors and the noncontact filter paper sensors are shown in Figure 12 along with some calibration curves previously obtained by others (*13,14*) for the same brand of filter paper.

There appear to be considerable variations in the calibration curves in Figure 12. There could be several reasons for the variations. First, the calibrations covered a time span from 1968 to the present. The characteristics of the Schleicher Schuell filter papers could vary over this time period. Second, the pretreatments given to the filter papers were not the same, although the same fungicide was used in each case. In the present study the treated filter papers were oven dried. The filter papers in the other calibrations (*13,14*) were air dried. The oven drying was supposed to assist in suppressing the hysteresis effects. Third, the contact of the filter paper with the soil in each case varied widely. In one case (*13*), only one calibration curve was presented, presumably applicable to both good-contact and noncontact situations. In another case (*14*) a filter paper was placed at the bottom of the soil specimen, separated from the soil by a paper towel, and a second filter paper was laid on the surface of the soil. The filter paper at the bottom of the soil was deemed to have good contact with the soil, and the filter paper laid on the soil surface was considered to be in uncertain contact with the soil.

It appears that the breaks in all the calibration curves fall between 20 and 90 kPa. This suggests that the transition from liquid flow being dominant to vapor flow being dominant occurs near 20 kPa to 90 kPa.

The low suction portion of the calibration curve for the noncontact filter paper (Figures 10 and 12) may not be meaningful, as the calibrations were obtained by a sorption process. The sorption process is more appropriate for high suction values.

Validity of the Calibration Curves from This Study

The calibration curve in Figure 9 for the good-contact filter paper sensors is applicable for assessing both matric suctions and total suctions in any soil. This is because the water contents of the good-contact filter paper in Figure 9, which correspond to matric suction values, were equated to matric suctions of the compacted till specimens.

The calibration curve for the noncontact filter paper sensors in Figure 10 is strictly valid only for the measurement of changes in

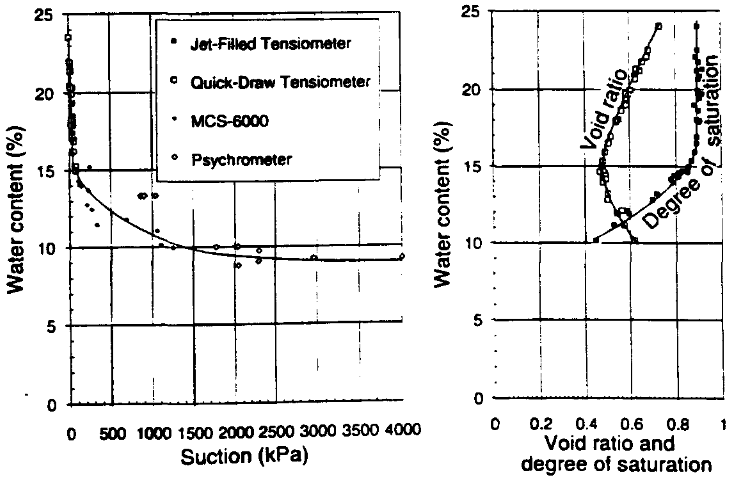


FIGURE 11 Relationship between (*left*) suction–water-content relationship and (*right*) degree of saturation (and void ratio) versus water-content relationship for compacted till.

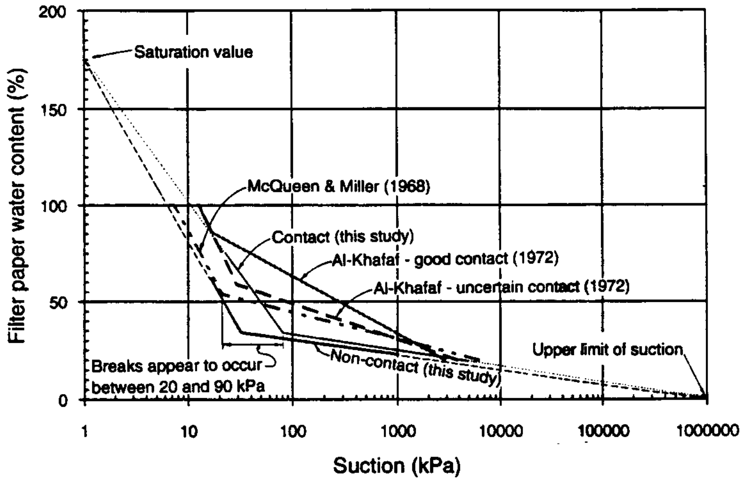


FIGURE 12 Comparison of calibration curves for Schleicher Schuell No. 589 filter paper sensors.

matric suction and preferably only in the same soil (i.e., till) that was used in the calibration. The water contents of the filter paper in Figure 10 correspond to the total suctions of the soil. The suction values in Figure 10, on the other hand, were matric suction values of the soil, which were measured with tensiometers or MCS-6000 thermal conductivity sensors. The water contents of the filter paper sensor corresponding to the total suctions of the soil were equated thus with the matric suctions of the soil. This procedure is inconsistent, and a separate evaluation of the osmotic suctions is required.

Consequently, psychrometers should be used only for the calibration of noncontact filter paper sensors. If filter paper in contact with the soil were calibrated by use of a psychrometer for assessing the suction in the soil, the water content corresponding to unknown matric suctions in the filter paper would be equated with the total suctions of the soil unless, of course, a separate evaluation of the osmotic suction were also conducted. At low water contents the extent of the contact between the soil and the filter may not be significant because the water flow will be restricted to the vapor phase.

CONCLUSIONS

The suction values were found to vary inversely linearly with compaction water contents in till specimens compacted at water contents wetter than optimum. The matric suction value at optimum water content was approximately 80 kPa for the till.

Compacted soil specimens at constant suction can be used for the calibration of filter paper sensors. The calibration, however, should be conducted in such a manner that the water contents of the filter paper sensors corresponding to matric suction values are referenced to matric suction values of the compacted soil specimens. Similarly, the water contents of the filter paper sensors corresponding to total suction values should be referenced to total suction values of the compacted soil specimens. The filter paper sensors, when calibrated appropriately, can be used for both matric suction and total suction measurement within the appropriate range of calibration values.

Calibration results for the filter paper sensors appear to have less scatter when the filter paper sensors are in good contact with the soil than when the filter papers are not in contact with the soil.

The transition from liquid flow being dominant to vapor flow being dominant in the filter paper occurs at near 20 kPa to 90 kPa.

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