Suction Study on Compacted Clay Using Three Measurement Methods

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An investigation was conducted to determine the effects of water contents and dry unit weights on measured suction pressures. The soil mixture used was a highly plastic clay with high shrink–swell potential. Four different configurations of soil specimen were compacted at two different water contents by using both standard and modified Proctor energies. The suction methods investigated in this study were pressure plate, filter paper, and thermocouple psychrometer. Matric and total suction parameters were compared, and their relationships to water content and dry unit weight were explored. The effectiveness of the filter paper method was recognized. The relationships of suction to moisture levels were confirmed and strengthened. The results indicate that effects of variations in dry unit weight on soil suction measurements may be neglected for disturbed samples in the field.

The concept of soil suction has been used by soil scientists and geotechnical engineers for many years. Soil suction can be described as a measure of a soil's need for water. Generally, the drier the soil, the greater its suction. The definitions of soil suction, its components, and the different potentials that make up the total potential of soil water have been given by the International Society of Soil Science (*1*). Soil suction may result from the attractive and repulsive forces between charged clay particles and polar water molecules, surface tension forces of water, solution potentials caused by dissolved ions, and gravity potential (*2*). In engineering problems, total suction is considered to be composed of matric suction and osmotic suction. Matric suction is believed to be caused by the clay and associated ions, and osmotic suction is a result of unbalanced ion concentrations in the pore water.

Devices generally used to measure soil suction include pressure plate apparatuses, tensiometers, heat dissipation sensors, pressure membrane apparatuses, gypsum blocks, centrifuges, fiberglass moisture cells, filter paper (the noncontact test), thermocouple psychrometers, and vacuum desiccators. The three last-named devices are used to measure total suction, whereas the first seven devices can be used to evaluate matric suction.

The relationship between dry unit weight and soil suction has been investigated and reported. In a work by Chu and Mou (*3*) matric suction was used to evaluate the swelling potential of clay soils. Their results showed that an increase in the dry unit weight with similar initial water contents resulted in an increase in soil suction. In other words, matric suction of compacted soils with the same water content increases as compaction energy increases. Croney et al. (*4*) indicated that matric suction is affected by the dry unit weight of an incompressible material. However, for a compressible compacted clay they found that matric suction was not affected by a change in dry unit weight.

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Campbell and Gardner (*5*) investigated the effect of bulk density on soil water potential, using thermocouple psychrometers. Their results showed there is apparently little change of water potential with bulk density except in a swelling clay subsoil. In 1972 Krahn and Fredlund (*6*) concluded that, for remolded compacted soils, the matric and total suction are dependent on the water content but are essentially independent of dry unit weight.

Based on a review of the literature, the relationship between soil suction and dry unit weight appears to be uncertain. However, it is clear that soil suction increases as water content decreases. To investigate further the correlations between initial conditions of soil samples and suction pressures, a testing program was designed and performed during this study.

MATERIAL

The soil chosen for testing was a highly active clay soil consisting of a mixture of 75 percent materials weathered from the Eagle Ford geologic formation and 25 percent bentonite clay. The Eagle Ford is a locally available material in the Dallas–Fort Worth area, and the bentonite was that commonly used for drilling fluids. The mixture was dark gray. It was passed through a No. 4 sieve and air dried. The results of clay mineralogy tests, x-ray diffraction, and differential thermal analysis indicated that the predominant mineral was montmorillonite.

According to the grain size distribution for the soil tested, 80 percent of the soil by dry weight was able to pass through a No. 200 sieve, and 20 percent was finer than 0.002 mm. The specific gravity was 2.72, and the average Atterberg limits included a liquid limit of 100 percent, a plastic limit of 24 percent, and a plasticity index of 76 percent. The average linear shrinkage was 19 percent. The standard Proctor maximum dry unit weight for this soil was found to be 14.9 KN/m^3 (94.5 pcf) at an optimum water content of 21 percent. The modified Proctor compaction parameters were 17.5 KN/m^3 (111.3 pcf) maximum dry unit weight and 15 percent optimum water content.

TESTING PROGRAM

Four configurations of compacted soil were prepared and used in this study. These four configurations are referred to in this paper as Soils I, II, III, and IV. Soils I and II were compacted using standard Proctor energy levels. Soils III and IV were produced using modified Proctor compaction. Soils I and III, compacted at a water content of approximately 17 percent, had dry unit weights of approximately 14.5 KN/m^3 (92 pcf) and 17.4 KN/m^3 (111 pcf), respectively. Soils II and IV, molded at a water content near 22 percent, had dry unit weights of about 14.6 KN/m^3 (93 pcf) and 16.3 KN/m^3 (104 pcf), respectively. Soil III had the highest dry unit weight among the four configurations of compacted sample. Soils I and II had similar values of dry unit weight. A summary of the initial conditions of compacted soils is given in Table 1.

Swelling pressures obtained by the constant-volume swell pressure test on compacted samples ranged from 206 kPa (2.15 tsf) to 731 kPa (7.63 tsf). Volumetric swell, under free swell conditions, ranged from 13.0 to 21.2 percent. According to these results Soil III displayed the highest potential to undergo volume change and had the largest swell pressure. Soil II showed less potential to swell and had smallest swell pressure. Summaries of the physical properties of the test soils are given in Table 2.

Three devices, a pressure plate, filter paper, and a thermocouple psychrometer, were used to measure the soil suction. The thermocouple psychrometer and the filter paper were used to measure total suction of the soil. Matric suction was determined directly by the pressure plate method.

Pressure Plate Method

The apparatus used in the pressure plate method included 5- and 15-bar pressure plate extractors from Soil Moisture Equipment Corp., California. Four suction–water characteristic curves for Soils I, II, III, and IV were established with air pressures of 0.5, 1.0, 1.5, 2.0, 4.0, 6.0, 8.0, and 10.0 bars.

Filter Paper Method

The filter paper used in this study was Baxter grade 381 filter paper 55.0 mm (2.17 in.) in diameter. Filter papers were calibrated with NaCl solutions of various concentrations. A way to prepare the calibrating solutions of NaCl can be found elsewhere (*7*). The water potentials of NaCl solutions at different concentrations were provided in a work by Lang (*8*). In addition, information from a work by Frazer et al. (*9*) about vapor pressures of salt solutions can be used to evaluate the water potentials of NaCl solutions at various concentrations.

Figure 1 shows the calibration curve, $R^2 = 0.99$, for Baxter 381 S/P filter paper. NaCl solutions at 12 different concentrations were used to establish this curve. At each concentration there were at least three tests, and the average of those results was used to draw the calibration line.

Four suction–water characteristic curves for Soils I, II, III, and IV were obtained by the filter paper method. The soil specimens used were 25.4 mm (1 in.) high and 63.5 mm (2.5 in.) in diameter. To produce different water contents for each soil configuration, the soil specimens were wetted with varying amounts of distilled demineralized water or dried at room temperature for varying lengths of time. For Soils In and III the maximum amount of water added to the specimens was 45 mL (1.52 oz) and the maximum time used to dry the specimens was 24 hr. For Soils II and IV the maximum amount of water added was 30 mL (1.01 oz) and the maximum dry time was 72 hr. To ensure uniform water contents, the wet specimens were wrapped with plastic, sealed, and cured in a polystyrene thermal box for at least 2 days before suction testing.

TABLE 1 Initial Conditions of Compacted Soils

Initial Conditions	Soil Configuration I*	II*	III+	IV+
Water Content (%)	17	22	17	22
Dry Unit Weight (KN/m^3)	14.5	14.6	17.4	16.3

* Standard Proctor + Modified Proctor

TABLE 2 Physical Properties of Test Soils

Property	Soil Mixture
Liquid Limit (%)	100
Plastic Limit (%)	24
Plasticity Index (%)	76
Linear Shrinkage (%)	19
Specific Gravity	2.72
Silt and Clay < 0.074 mm (%)	80
Clay Fraction < 0.002 mm (%)	20

Property	Soil Configuration I	II	III	IV
Swell Pressure (kPa)	213	206	731	243
Free Swell (%)	15.2	13.0	21.2	18.4

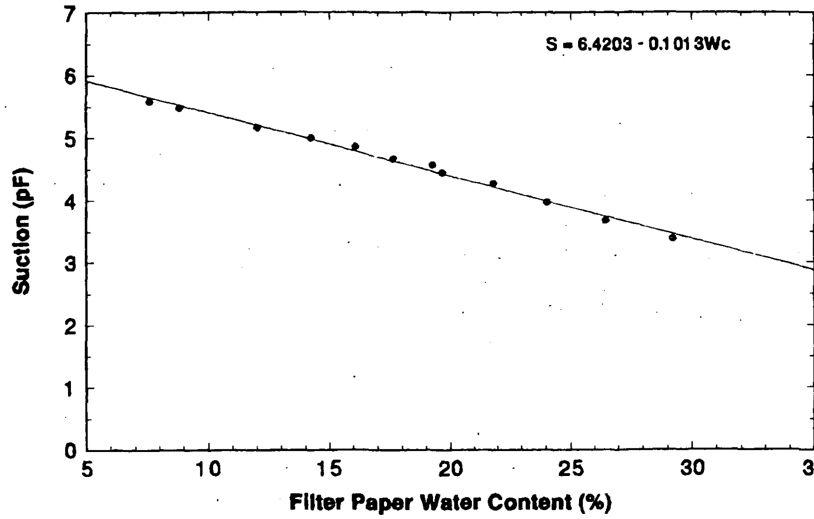

FIGURE 1 Calibration line for Baxter 381 S/P filter paper.

Thermocouple Psychrometer Method

A WESCOR HR-33T Dewpoint microvoltmeter with a PS-10 psychrometer switch box was used during this investigation. The thermocouple psychrometers used were Wescor PCT-55 with a SUREFAST connector in which a chromel-constantan junction is enclosed in a ceramic cup. The HR-33T permits water potential to be determined with a variety of sensors in either the dew point or the psychrometric mode. Generally, the two modes should give similar readings in a controlled-temperature environment in the laboratory. The advantage of the dew point mode may be that the voltage is more sensitive to water potential and less sensitive to temperature. According to a work by Briscoe (*10*), because the dew point mode provides a continuous output instead of the falling plateau given by the psychrometric mode accurate measurements may be easier to obtain. However, the accuracy of the instrument depends on the correct setting of the cooling coefficient (*11*).

In this research all readings from thermocouple psychrometer method were taken at both dew point and psychrometric modes. The suction pressure reported was an average of the values obtained from these two modes. Solutions of NaCl at seven different concentrations were used to establish the calibration curves of used thermocouple psychrometers. Each psychrometer had its own calibration curve. Typical calibration curves of a thermocouple psychrometer from the two different output modes, psychrometric and dew point, are shown in Figure 2.

The way in which soil specimens of each soil configuration were prepared at different water contents was the same in this case as for the filter paper method; however, the maximum amounts of water and drying time were different from those of the filter paper method. Because of the lower capacity of the thermocouple psychrometers used, this suction method was unable to work well with samples that were too dry or too wet. In other words, thermocouple psychrometers do not work well for soils with very low or very high suction pressures. In this method the maximum amount of water used was 25 mL (0.85 oz) for Soils I and III and 20 mL (0.68 oz) for Soils II and IV. The maximum drying time for samples was 2 hr for Soils I and III and 36 hr for Soils II and IV.

RESULTS AND ANALYSIS

Twelve suction–water characteristic curves for the four configurations of compacted soil were determined with three suction measurement methods. For each soil configuration a total of three suction–water characteristic curves were established.

Thermocouple Psychrometer

Thirteen psychrometers were used, and at least two psychrometers were used to establish a suction–water characteristic curve for each soil configuration. A comparison of suction–water characteristic curves for the four configurations of soil is shown in Figure 3. These results consist of 102 points, and every point was the average of the two suction values obtained by the psychrometric and dew point modes. The logarithmic unit pF is used because the water contents can be linearly related to suction values in pF units and because of the wide range of values usually measured. A pF unit is the logarithm of the negative water pressure (in centimeters). The range of water content covered by the thermocouple psychrometer method was approximately 15.5 to 40 percent, and suction pressures ranged from 3.3 to 4.7 pF. The results showed that soil samples with water contents ranging from 17 to 30 percent were generally able to provide positive and reliable readings with psychrometers during the study.

From the results shown in Figure 3 it was found that suction increases with a decrease in soil moisture content. In addition, it appears that total suction pressure is not significantly affected by a change in dry unit weight of remolded soils. According to the analysis of the *t*-statistic for the equality of intercepts and slopes, there is no evidence that the four regression lines shown in Figure 3 differ at a 0.05 level of significance.

Filter Paper Method

To measure total suction, the filter papers used were suspended above the soil specimen in a container for a minimum of 7 days.

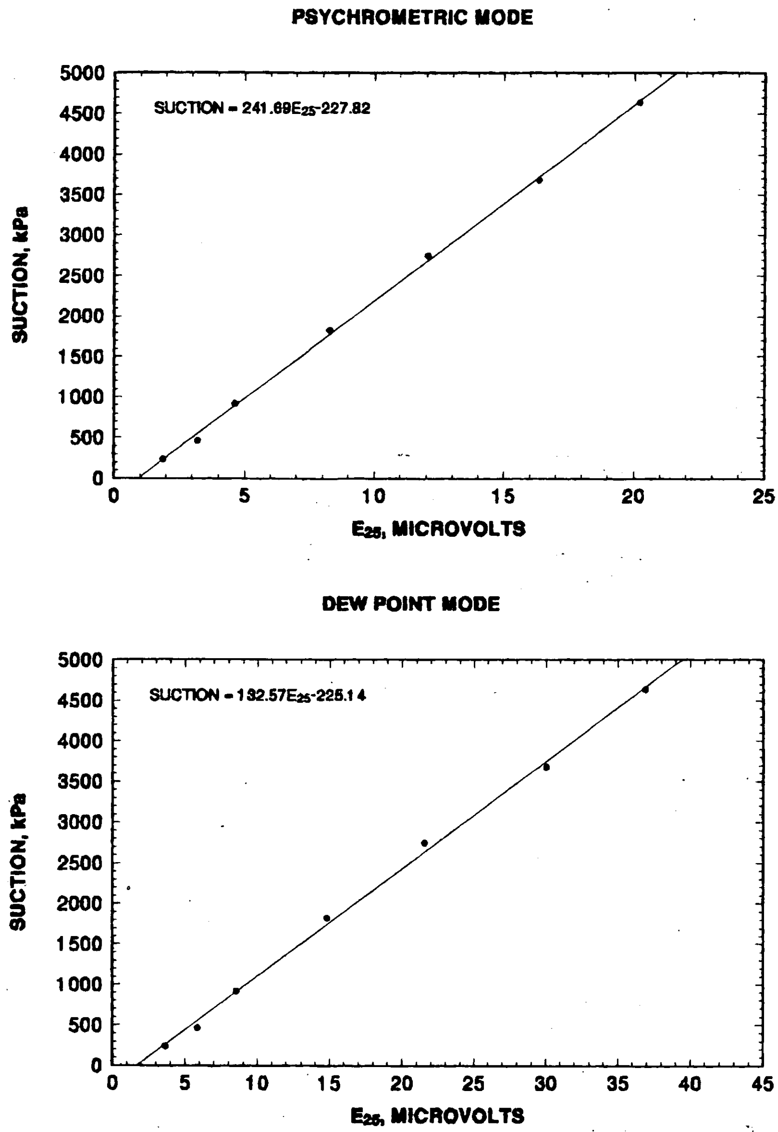

FIGURE 2 Typical calibration lines of psychrometer from two different output modes.

Theoretically, the equilibrium water content of the filter paper corresponds to the total suction of the soil when the filter paper is not in contact with the soil.

It was found that there were no good linear correlations between suction and water content for samples having water contents higher than 33 percent. Results showed considerable variability and unreliable outputs at these low suction values. It should be pointed out that great care must be taken when doing this test, especially for wet samples.

The suction–water characteristic curves of Soils I, II, III, and IV are shown in Figure 4. The results include 147 points with suction pressures ranging from 3.3 to 5.3 pF and water contents ranging from 13 to approximately 41 percent. The four linear regression lines appear to have similar slope and have an average R^2 value of 0.82. It was found that total suction was not significantly influenced by a variation in dry unit weight of soil specimens tested by the filter paper method. From the analysis of the t-statistic using a 0.05 level of significance, there is insufficient evidence to reject the null hypotheses about the equality of intercepts and slopes of the regression lines shown in Figure 4.

A comparison between the average values of the four total suction curves (in kilopascals) from the thermocouple psychrometer and filter paper methods is illustrated in Figure 5. The results show that these methods gave nearly the same values for samples that had similar water potentials. It also appears that suction increased rapidly as the water contents of samples became lower than 22 percent. On the other hand, soils showed little change in suction when their moisture contents were higher than certain values, in this case approximately 30 percent.

From this study it was found that the filter paper method has three distinct advantages with respect to the thermocouple psychrometer method. These advantages are that (*a*) it is relatively simple, (*b*) it

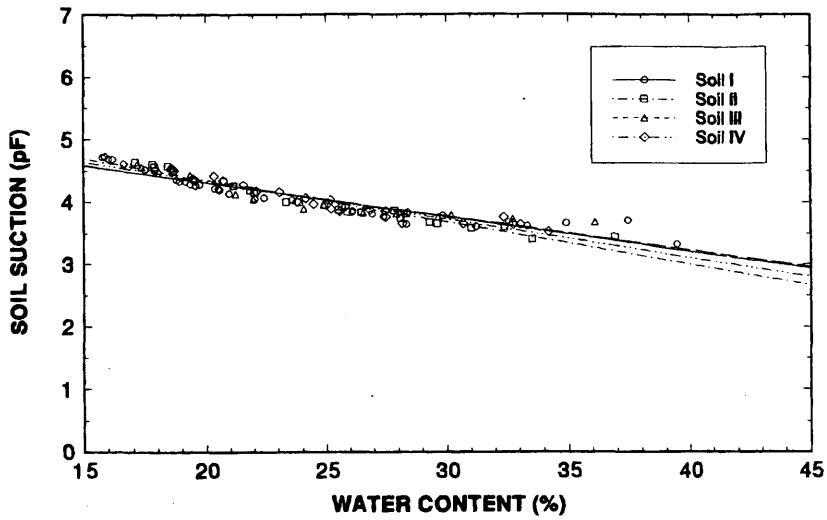

FIGURE 3 Relationships between suction and water content for four configurations of soil determined by thermocouple psychrometer.

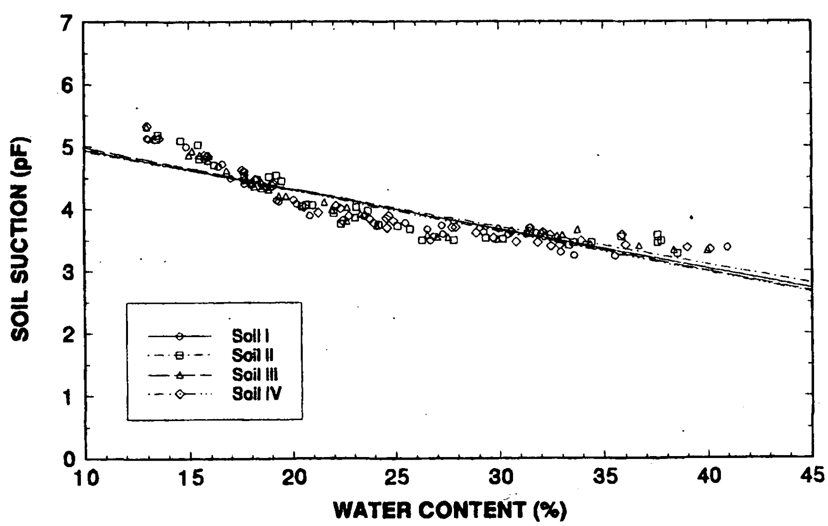

FIGURE 4 Relationships between suction and water content for four configurations of soil determined by filter paper method.

is an inexpensive test method to determine total suctions of soil samples, and (*c*) it has a wider range of measurable suction than the psychrometer method. However, compared with those of the psychrometer method, the results from the filter paper method generally exhibit more scatter. Therefore, to achieve best results using the filter paper method it is necessary to prepare more tests for every soil sample.

Pressure Plate Method

A comparison of soil–water characteristic curves of the four configurations of soil is shown in Figure 6. It appears that a variation in dry unit weight has no effect on the matric suction of compacted soils. From the results of the *t*-statistic at a 0.05 level of significance there is no evidence to suggest that the slopes and intercepts of these regression lines are different. Because of limitations on its capacity, the pressure plate was unable to determine soil–water characteristic curves for high suction pressures. However, it worked well for low suction pressures. The results of this test show that the highest water content obtained during testing was 42 percent and the lowest water content was approximately 23 percent, with the respective matric suctions ranging from 2.71 to 4.01 pF.

Curves showing average total suction, matric suction, and the difference between total and matric suctions for Eagle Ford clay including 25 percent bentonite appear in Figure 7. The results indicate that the shapes of the total suction and the matric suction curves are similar. The total suction curves shown in Figure 7 were obtained by taking the average of suction values (in kilopascals) of the psychrometer and filter paper methods for all soil configura-

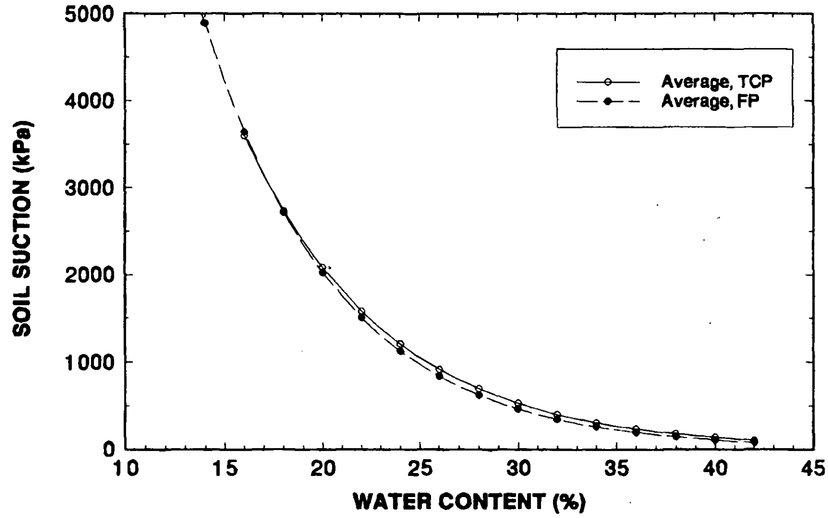

FIGURE 5 Comparison of average total suction from filter paper (FP) and thermocouple psychrometer (TCP) methods.

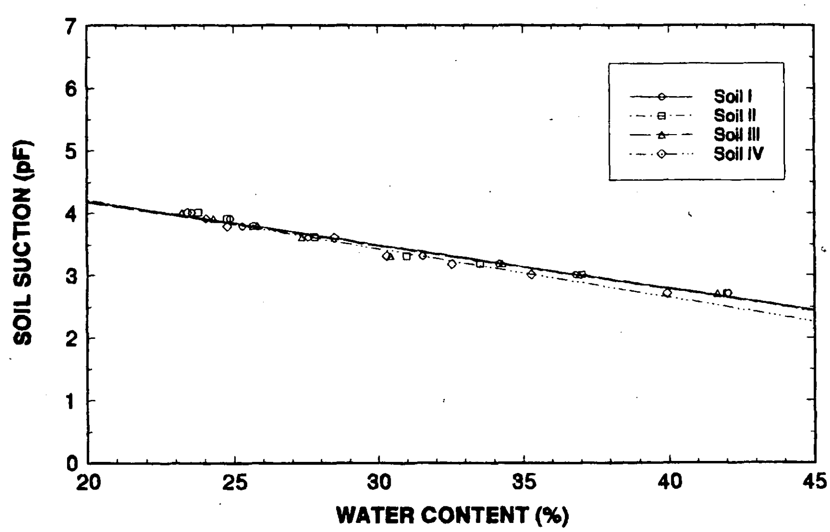

FIGURE 6 Relationships between suction and water content for four configurations of soil determined by pressure plate method.

tions. It appears that the difference between the total suction and the matric suction curves increases as water content decreases. In other words, osmotic suction increases with a decrease in water content. It also appears that the values of osmotic suction were lower than those of matric suction at high suction levels but became similar or higher for the wet samples.

CONCLUSIONS

Discussions and analyses for test results during this study were presented. The soil mixture used was a highly plastic clay with high shrink–swell potential. According to analyses of clay mineralogy tests, the predominant mineral appeared to be montmorillonite. Four configurations of compacted soil were prepared and used in this study. For each soil configuration suction–water characteristic curves were determined with a specific filter paper, with thermocouple psychrometers, and with a pressure plate apparatus.

On the basis of the results and discussions presented, the following conclusions are drawn:

1. From suction–water characteristic curves of the four configurations of soil tested it appears that suction pressure decreases with increasing soil water content and increases rapidly in dry soils with little decrease in water content.
2. Both matric suction and total suction are not significantly affected by a change in the dry unit weight of compacted soils used in this study. In other words, effects of variations in dry unit weight

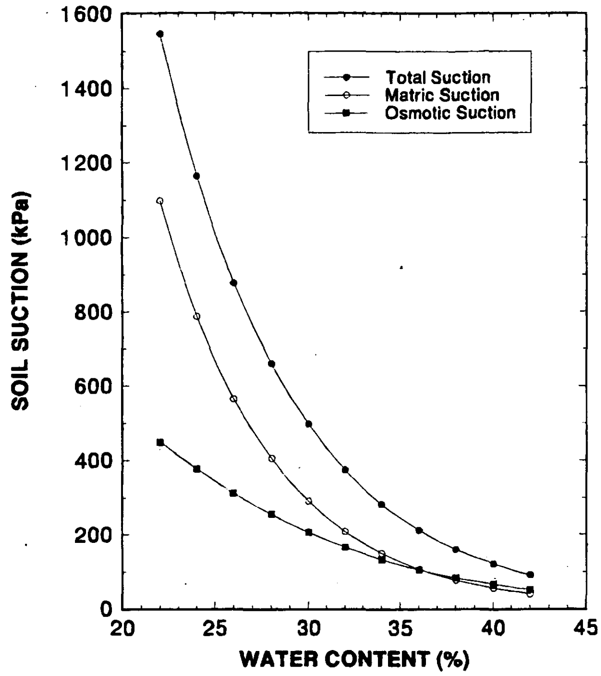

FIGURE 7 Average total, matric, and osmotic suction pressures for Eagle Ford clay including 25 percent bentonite.

on soil suction measurements may be neglected for remolded soil samples.

3. The advantages of the filter paper method in measuring total suction of soil samples are that (*a*) it is relatively simple, (*b*) it is an inexpensive test method, and (*c*) it is capable of measuring a wide range of suction potential. However, compared with those of the thermocouple psychrometer method, the results of the filter paper method generally exhibit more scatter. Inasmuch as a small difference in handling test samples may produce a large difference in results, special care must be taken during the filter paper test. Regardless of the high and low suction levels, the psychrometer method is generally able to provide very positive and reliable results for daily suction readings in the laboratory and for field applications.

4. Because of the capacity of the pressure plate apparatus used, including 15- and 5-bar extractors, it was not possible to provide the measurement of matric suction in the range of high pressures. However, the pressure plate apparatus can provide a very good and reliable matric suction measurement for moister soil conditions. The problems of conducting tests on clay soils with the pressure plate apparatus can include the following: (a) the initial conditions of soil specimen can be changed over a long period for equilibrium, (b) the sample size may be too small and thus unrepresentative for undisturbed soils, and (c) this method cannot be used practically in the field.

5. The difference between total suction and matric suction, as the osmotic suction, increases with decreasing soil water content. Osmotic suction is lower than matric suction at high suction levels but becomes similar or higher for wet samples. At high water contents the values of both matric and osmotic suctions are usually small. Practically speaking, the moisture effects of clay are much more important at low moisture levels and are believed to contribute the most to swell potential.

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