Soil-Suction Approach for Evaluation of Swelling Potential

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The use of soil water content as a major variable in the evaluation of the swelling potential of soils is a convenient and practical approach. However, findings from laboratory investigations are reported that indicate that including soil suction as an additional variable in test programs would provide further information that would aid in the analysis of test results and in obtaining a basic understanding of the fundamental principles that govern the swelling of expansive clays. This method is termed the soil-suction approach. Equipment and procedures developed for the direct determination of suction in soil specimens at existing density and water content, without going through the drying or wetting process required by certain methods of suction measurement, are described. Experimental data are presented to relate the suction of soil specimens determined by the soil-suction method to other variables that affect swelling potential. These variables include method of compaction, initial dry density, and initial water content. The effect of these variables on the swelling potential of an expansive clay is discussed in light of the soil-suction data obtained from the test specimens. It is concluded that the soil-suction approach is invaluable when applied to the study of the swelling characteristics of expansive clays.

In the geotechnical engineering field, it has long been recognized that the swelling of expansive clays caused by moisture changes may result in excessive heave and therefore in severe damage to overlying structures or pavements. In their efforts to gain knowledge of the behavior of expansive clays, various investigators have conducted extensive studies in the past two decades to evaluate the pertinent factors that influence swelling and to develop methods of analysis for predicting the amount of heave. These studies provide helpful information to design and construction engineers in formulating preventive measures to alleviate the potential problems related to volume change in expansive clays. Because these studies have a common objective--making the research findings immediately applicable to engineering practice--most of them are necessarily empirical in nature. As a result, there is still a lack of basic understanding of the fundamental principles that govern swelling and heave in expansive clays. In this regard, it is preferable to conduct research investigations by using a different and more basic approach in which soil suction is studied as a major variable in determining the behavioral characteristics of expansive clays.

The term soil suction refers to the negative pore-water pressure in partially saturated soils. In a soil formation, at a depth less than that of the groundwater table, the soil is partially saturated and may possess two components of soil suction--the matrix suction and the solute suction. The matrix suction, which is also called the matrix potential, matric potential, or capillary potential, arises from both the capillarity and the particle surface adsorption in a soil. On the other hand, the solute suction, which is sometimes identified as the solute potential or osmotic suction, is dependent on the concentration of soluble salts in the soil water. In most reports concerning the swelling of expansive clays, and in this paper, the term soil suction refers primarily to the matrix suction.

Studies of the volume-change characteristics of expansive clays based on changes in soil suction provide an insight into the fundamental mechanisms involved in heave. Furthermore, evaluating swelling potential by using soil suction as a major variable is often more advantageous than similar evaluations that use water content as the only variable to represent the changes in soil moisture. The significance of this can be explained by considering two test specimens of the same soil and the same water content. If there are discrepancies in the soil suction of the two specimens, their swelling characteristics are likely to be different even though their water contents are identical. For these reasons, soil suction has been included as an additional variable in the evaluation of swelling potential and in the analysis of heave as reported by a number of investigators (1-5).

The soil-suction approach was followed in conducting the laboratory investigations reported in this paper. Because of the importance of suction measurements in this study, the equipment and procedures for determining the soil suction in test specimens are described first. The method used in this study makes it possible to determine soil suction directly without going through the sorption or desorption process required in some methods of suction measurement. Finally, the compaction and swelling characteristics of an expansive clay are presented and discussed in light of the variations in the measured soil suction of the test specimens.

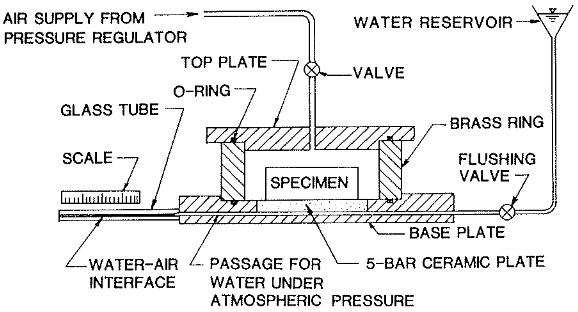
MEASUREMENT OF SOIL SUCTION

Since the type of soil suction covered in this study is primarily the matrix suction, the discussion of the methods of suction measurement does not include those for determining the solute suction of partially saturated soils. Although soil-suction measurements can be conducted either in the field or in the laboratory, this paper discusses laboratory measurements only.

Laboratory Methods

Commercially available pressure-plate devices are commonly used for the measurement of matrix suction in soils. This type of equipment as well as a pressure-membrane apparatus are specified in the American Society for Testing and Materials (ASTM) Standard Methods of Test (6) for determining the capillary-moisture relations of soils (ASTM D2325 and D3152). In a study of moisture variations in subgrade soils, Janssen and Dempsey (7) used Tempe cells for measuring soil suctions up to 100 kPa (14.5 lbf/in^2) and a pressure-plate apparatus for determining soil suctions greater than 100 kPa. The devices mentioned above are suitable for laboratory experiments to establish the suction and water-content relation of a given set of soil samples through a desorption or sorption process. If it is desired to measure the suction of a compacted or undisturbed soil sample at its existing density and water content without going through the desorption or sorption process, a different pressure-plate or pressure-membrane apparatus would be required. The use of a special apparatus for this purpose was reported by Johnson (4) and Olson and Langfelder (8). The equipment used in this study was also made specifically for direct

Figure 1. Pressure-plate apparatus for measurement of soil suction at existing water content and dry density.



measurement of the suction in a soil sample at its existing density and water content.

Study Method

The pressure-plate apparatus used in this study (see Figure 1) is somewhat similar to that used by Olson and Langfelder (8). The main difference between their method of suction measurement and that developed in this study is in the calibration of the apparatus before suction measurement. A brief description of the procedures, including preparation of the apparatus, calibration, and suction measurement, is presented below.

As necessary with all pressure-plate devices, it is essential to saturate the ceramic plate with deaired water and to remove any air entrapped in the system by prolonged evacuation. Before calibration, a moist paper towel is used to wipe the top of the ceramic plate. The first step in the calibration procedure is to open the flushing valve slowly in order to bring the water-air interface in the glass tube to the zero mark. Then a certain air pressure is applied to the chamber, and the new location of the water-air interface is recorded. This step is repeated for successive increments of chamber pressure so that a calibration curve can be prepared to relate the chamber pressure to the corresponding location of the water-air interface.

After calibration, the apparatus is ready for suction measurement. To obtain accurate results, it is essential that the placement of a soil specimen on the ceramic plate, the assembling of the apparatus, and the application of a desired air pressure to the chamber be completed as quickly as possible. Usually, the operation in this step requires less than 1 min. The water-air interface, which should be adjusted to the zero mark before the specimen is placed, will start to move away after placement of the specimen and application of the air pressure. The air pressure in the chamber should be adjusted as necessary to bring the water-air interface to the specific location indicated by the calibration curve. The adjustment of the chamber pressure is repeated until the water-air interface remains at a constant location for at least 10 min to make sure that an equilibrium condition has been reached. The chamber pressure under this condition is equal to the soil suction in the specimen.

When the suction measurement is completed, the chamber pressure is reduced to zero and the setup is disassembled. The soil specimen is then carefully removed from the ceramic plate. The thickness of the specimen is measured and its weight is determined before and after oven drying. The thickness and weight data are used in computing the density and the water content of the specimen after suction measurement. Information obtained from this study indicates that the dry density and the water content of the specimens after suction measurements are approximately the same as before the measurements.

Ceramic plates of any air-entry value can be installed in this equipment. The one used in this study is identified as a 500-kPa (5-bar) plate by the equipment supplier. The approximate rated air-entry value of this plate is 500 kPa (72.5 lbf/in^2). Experimental data from this study indicate, however, that the actual air-entry value exceeds 538 kPa (78.0 lbf/in^2). The reproducibility or repeatiblity of the suction values measured by this method was found to be satisfactory. Although only compacted soil specimens were used for the suction measurements in this study, the apparatus and procedures described above should be suitable for measuring the suction of undisturbed soil samples as well.

Experimental Data

Laboratory experiments were conducted to determine the effect of variations in density, water content, and other factors on the suction of an expansive clay. The sampled soil came from northeastern Texas. It is light brown in color, contains primarily montmorillonite clay minerals, and has the following physical characteristics: liquid limit = 49, plasticity index = 19, plastic limit = 30, specific gravity = 2.75, and 50 percent finer than 0.002 mm.

In this investigation, compacted soil specimens 35 mm (1.38 in) in diameter and approximately 14 mm (0.55 in) in thickness were used for suction measurements immediately after removal from the compaction mold. Soil compaction was achieved by two different methods--static compaction and kneading compaction. Kneading compaction was carried out by using the compaction rod of the Harvard Compactor developed by Wilson (9). In one test series for this study, the compactive effort was maintained constant for both the static and kneading methods; in other test series, the compactive effort was varied in order to obtain a specific density at a given water content.

The use of a constant compactive effort in the preparation of soil specimens results in the relations between density and water content that are shown at the bottom of Figure 2. In selecting the constant compactive effort for either static or kneading compaction, attempts were made to obtain curves for density versus water content somewhat similar to the curve obtained by the standard Proctor compaction method (AASHTO T99 and ASTM D698). As a result, a compaction pressure of 980 kPa (142 lbf/in^2) was used for static compaction, and in kneading compaction 20 blows were applied at a contact pressure of 690 kPa (100 lbf/in^2). The data shown in Figure 2 indicate that, although the densities of specimens prepared by kneading compaction are generally higher than those of specimens prepared by static compaction at similar water contents, their suction values are considerably lower.

To investigate the fluctuations in suction values caused by variations in the method of compaction as well as changes in the compaction water content, another test series was conducted by compacting soil samples at various water contents to a selected dry density regardless of the method of compaction. The measured suctions of two sets of soil specimens, one at a dry density of approximately 1.619 g/cm^3 (101.0 lb/ft^3) and the other at a dry density of approximately 1.539 g/cm^3 (96.0 lb/ft^3), are shown in Figure 3. This figure indicates that, for specimens at either of these dry densities, static

Figure 2. Compaction curves and suction versus water content for an expansive clay.

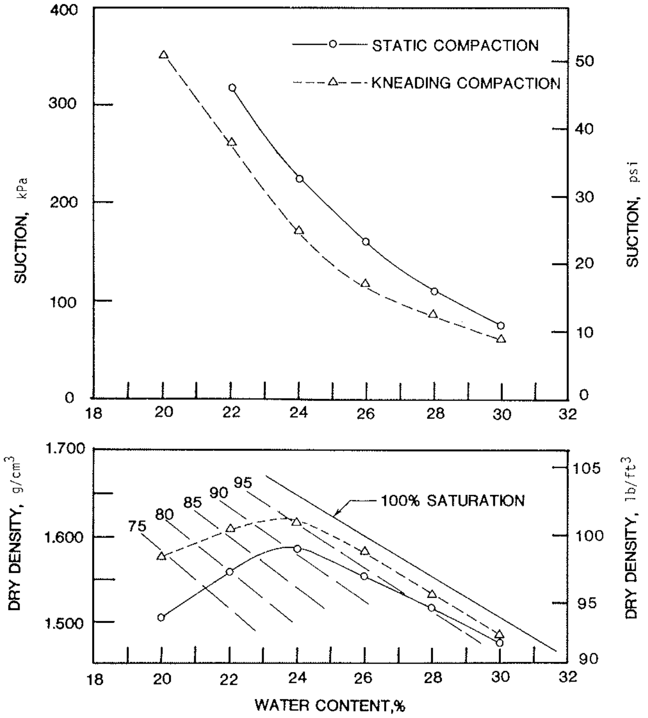
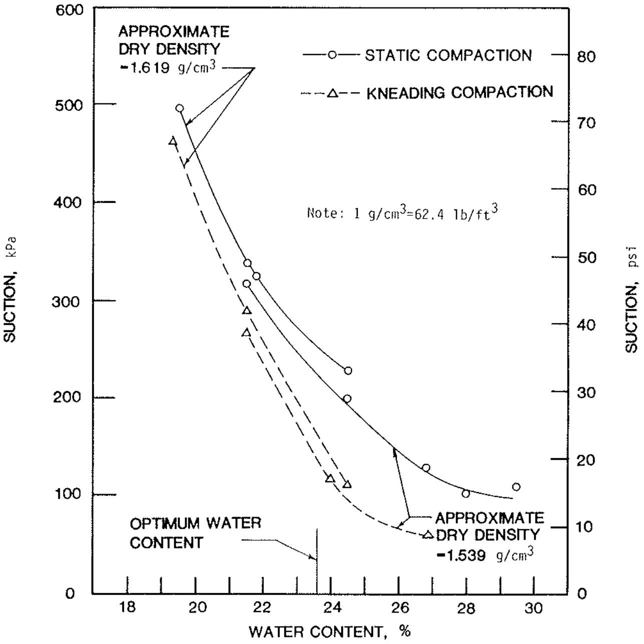


Figure 3. Suction versus water content for an expansive clay at two approximate dry densities.



compaction results in suctions that are consistently higher than those of specimens prepared by kneading compaction at similar water contents. Insofar as the effect of changes in the compaction water content is concerned, Figure 3 shows that a slight variation in the compaction water content on the drier-than-optimum side results in a substantial change in the soil suction. The combined effect on soil suction attributable to variations in both the method of compaction and the compaction water content can also be evaluated on the basis of the test data presented in Figure 3. In this respect, the data indicate that the difference in soil suction caused by the variation in the method of compaction is somewhat less at relatively low compaction water contents than at compaction water contents at or near the optimum.

The difference in the suctions of soil specimens compacted by different methods of compaction was also observed by Olson and Langfelder (8). This difference can be explained on the basis of the variation in soil fabric of the compacted specimens. Lambe (10) conducted a study of the structure or fabric of compacted clays. Detailed discussions concerning soil fabric and its effect on volume change and other behavior characteristics of clays were presented by Mitchell (11). According to the findings reported by these and other investigators, it is understood that, for a given method of compaction and at a specific compactive effort, the soil fabric of a compacted clay depends on the water content during compaction. For compaction at relatively high water contents, the soil fabric of compacted clays might approach the dispersed type because of the significant reorientation of soil particles during compaction. On the other hand, compaction at relatively low water contents might result in a soil fabric close to the flocculated type because there is much less reorientation of soil particles than in compaction at high water contents. For a given compaction water content, however, kneading compaction is expected to cause more orientation of soil particles than static compaction. Consequently, the soil fabric is likely to be different in specimens compacted by the two methods used in this study. This difference in soil fabric is believed to be the primary cause of the discrepancies in the soil suctions of the specimens prepared by the two methods of compaction.

As various investigators, including Wilson (9), have discussed, if one desires to select a method of laboratory compaction that simulates the field compaction of clays effected by commonly used compaction equipment, kneading compaction would certainly be preferable to static compaction. In this study, however, both kneading and static compaction were used for specimen preparation in order to conduct laboratory investigations of soil fabric as one of the variables affecting soil suction.

INVESTIGATION OF SWELLING CHARACTERISTICS

The laboratory experiments discussed here were conducted primarily to assess the relative merits of the soil-suction approach to evaluating swelling potential. For this purpose, a laboratory swell-testing program was planned, and the results were analyzed so as to determine the potential benefits, if any, of including soil suction as one of the variables in the investigation of all factors that influence the swelling of expansive clays.

Test Methods

It is not the purpose of this study to compare the advantages and disadvantages of different laboratory test methods for evaluating swelling potential. Nevertheless, three test methods were used in this study in order to demonstrate the possible discrepancies in the percentage of swell obtained from the different methods of test. A brief description of each test method is presented below. In all of these methods, a surcharge pressure of 6.9 kPa (1 lbf/in^2) was applied on the specimen during the test.

Method 1

Method 1 involves the complete immersion of a test specimen in water in order to measure the change in the height of the specimen while the diameter of the specimen is maintained constant. The term consolidometer swelling test is sometimes used in referring to this type of test. Holtz (12) suggested a similar test method for determining both one-dimensional swell and the swelling pressure under the condition of no volume change. It should be noted, however, that the experiments performed in this study were intended to determine the one-dimensional swell only. In other words, specimens subjected to test method 1 were permitted to swell immediately after immersion. This type of test has been used by various investigators, including Seed and others (13), to determine the one-dimensional swell of expansive clays.

Method 2

The only difference between methods 1 and 2 is in the manner in which water is allowed to flow into the originally unsaturated specimen. In method 1, water may flow into the test specimen through either the top or the bottom; in method 2, water is permitted to flow only through the bottom of the specimen. The purpose of controlling the flow in test method 2 is to reduce the amount of air that may be entrapped in the specimen during immersion.

Method 3

Method 3 is the controlled-suction test developed by Chu and Mou and explained in detail elsewhere (14). As shown in Figure 4, the test apparatus is equipped with a device for controlling the suction in the specimen during the test so that it is possible to determine the swelling of a soil specimen when its suction changes. [The tension in the water inside the base chamber can be regulated by using a simple device such as the one shown (adjusting ΔH_1 and ΔH_2 to obtain the desired tension) or other pressure-control devices. If high surcharge pressure is to be applied on the specimen, a support (not shown in the figure) should be provided inside the base chamber for the ceramic plate, to avoid possible damage.] The test used by Escario and Saez (15) is similar in principle to this method. The controlled-suction test can be used to evaluate the volume-change characteristics of soils caused by the repeated application of wetting and drying cycles (14). This paper, however, presents only the test data concerning the percentage of swell attributable to an increase in water content accompanied by a decrease in suction.

Test Results

The expansive clay described previously was used in the laboratory experiments to study swelling characteristics. Again, soil specimens were prepared by either static or kneading compaction to desired dry densities at various water contents. To determine the length of the storage period between specimen preparation and the beginning of a swelling test, a sufficient number of soil specimens were prepared by using each of the two methods of compaction. These identical specimens were stored for different lengths of time at constant water content and were then used for suction measurements. Several sets of specimens compacted at various water contents to selected densities were used in this test series. However, Figure 5 shows only the curves that represent the data obtained from two sets of soil specimens prepared by the two methods of compaction. For each method of compaction, the curve shown illustrates the typical relation between storage time and the corresponding suction.

It is of interest to note that different trends of variation are indicated by the two curves. Although a gradual and consistent increase in suction with time is shown by the curve for the specimens prepared by kneading compaction, the curve for the specimens molded by static compaction shows an abrupt increase and decrease in suction within one day after specimen preparation. Since the relations between suction and storage time found in other sets of soil specimens are similar to those illustrated in Figure 5, the difference between the two curves noted above is apparently related to the variation in the method of compaction (the effect of the variation in compaction method on the soil structure or fabric of the compacted clay has already been discussed).

In view of the continuous change in soil suction immediately after compaction, it was decided to follow the common practice of storing the specimens for several days before using them for swelling tests. The data shown in Figure 5 indicate that the soil suction in compacted specimens would have

Figure 4. Controlled-suction test apparatus used in method 3 tests.

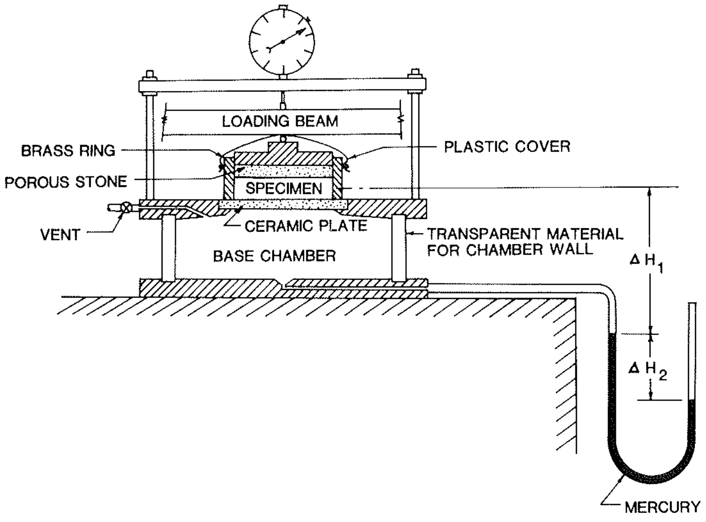
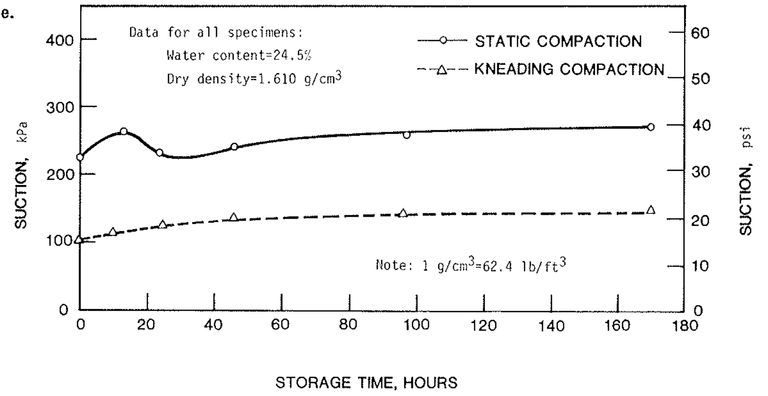


Figure 5. Changes in suction of compacted soil specimens with time.



reached a fairly constant level after a storage period of four or five days. Consequently, a minimum storage period of four days was used in this study to allow time for the soil specimens to reach a uniform and stable moisture condition before the beginning of the swelling test.

Experimental data obtained from the swelling tests by using the three methods previously described are summarized in Table 1 for specimens subjected to each method of compaction. The last column of the table gives the percentage of swell, which is often referred to as free swell. These data indicate that the percentages of swell determined by the three test methods for nearly identical specimens are somewhat different. For example, specimens S7, S8, and S9 were compacted at similar water contents to almost the same dry density. The values of percentage of swell obtained by the three test methods on these specimens are, however, considerably different. In Table 1, discrepancies among the three specimens are also noticeable in regard to the degree of saturation

Table 1. Data for test specimens prepared by static compaction and kneading compaction.

		Before Test				After Test			
Specimen No.	Method of Swelling Test	Suction (kPa)	Dry Density (g/cm^3)	Water Content (%)	Degree of Saturation (%)	Dry Density (g/cm^3)	Water Content (%)	Degree of Saturation (%)	Swelling (%)
Static Compaction									
S1	1	345	1.529	21.6	74.5	1.446	30.2	92.1	5.75
S2	1	366	1.554	21.6	77.7	1.480	29.8	95.7	5.10
S3	1	503	1.618	19.6	77.8	1.490	28.9	94.1	8.60
S4	3	503	1.614	19.7	77.9	1.500	28.9	95.7	7.56
S5	1	442	1.620	20.3	80.5	1.511	29.7	100.0	7.25
S6	1	318	1.617	22.8	90.5	1.538	28.1	98.2	5.10
S7	1	352	1.625	21.9	87.9	1.538	27.9	97.9	5.73
S8	2	352	1.606	21.9	85.5	1.527	28.2	97.2	5.13
S9	3	352	1.618	21.7	86.4	1.550	28.1	100.0	4.41
S10	1	387	1.619	21.4	84.9	1.529	28.1	96.9	5.90
S11	1	228	1.598	25.3	97.6	1.551	27.8	98.9	3.70
S12	2	228	1.587	25.7	98.6	1.548	28.0	99.0	2.20
S13	3	228	1.588	25.7	97.7	1.556	27.7	100.0	1.90
S14	3	469	1.678	21.0	92.0	1.578	26.2	97.8	6.10
S15	3	469	1.683	21.4	93.0	1.598	26.3	100.0	4.50
S16	2	469	1.675	21.2	94.6	1.561	27.2	98.4	8.90
S17	1	442	1.685	21.4	93.4	1.572	27.3	100.0	7.19
S18	1	414	1.679	21.0	91.3	1.580	26.8	100.0	6.36
S19	1	469	1.710	21.4	97.3	1.596	26.4	100.0	7.09
Kneading Compaction									
K1	1	262	1.509	21.4	71.6	1.469	29.2	92.1	2.83
K2	1	283	1.570	21.5	79.0	1.524	27.6	94.8	3.20
K3	1	483	1.607	19.1	74.3	1.502	28.0	92.7	7.07
K4	1	359	1.609	20.3	79.3	1.534	26.6	92.7	5.02
K5	1	193	1.611	23.6	92.5	1.572	26.2	96.7	2.50
K6	1	310	1.618	21.4	85.3	1.567	26.0	95.2	4.33
K7	2	310	1.620	21.7	86.8	1.588	25.8	97.7	3.38
K8	3	310	1.638	21.9	89.0	1.590	26.3	100.0	3.05
K9	1	124	1.593	25.7	99.2	1.582	27.2	100.0	1.70
K10	2	124	1.593	25.5	97.3	1.583	26.4	99.2	0.70
K11	3	124	1.591	25.2	95.9	1.585	26.2	98.9	0.60
K12	3	503	1.670	19.6	84.1	1.572	26.6	98.1	6.21
K13	1	503	1.668	19.0	81.2	1.556	26.4	95.0	7.33
K14	1	310	1.668	21.1	90.2	1.609	24.7	96.5	3.73
K15	2	345	1.667	21.2	90.6	1.574	26.4	97.8	5.40
K16	1	510	1.691	19.5	85.9	1.574	26.1	97.0	7.40
K17	1	317	1.692	21.6	95.6	1.627	25.1	100.0	4.06

Note: 1 kPa = 0.145 lbf/in^2; 1 g/cm^3 = 62.4 lb/ft^3.

Figure 6. Water content and percentage of swell versus soil suction as determined by method 1 tests for specimens with dry densities of 1.610 ± 0.015 g/cm^3 (100.4 ± 1.0 lb/ft^3).

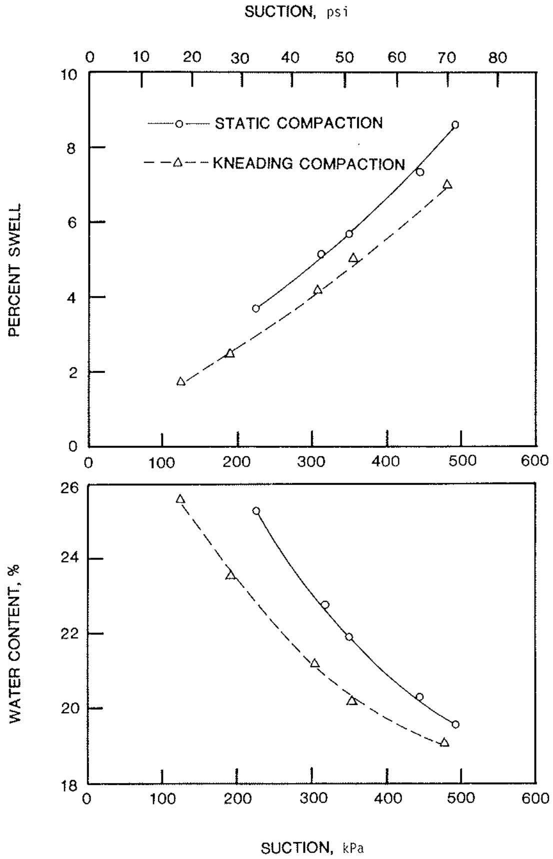
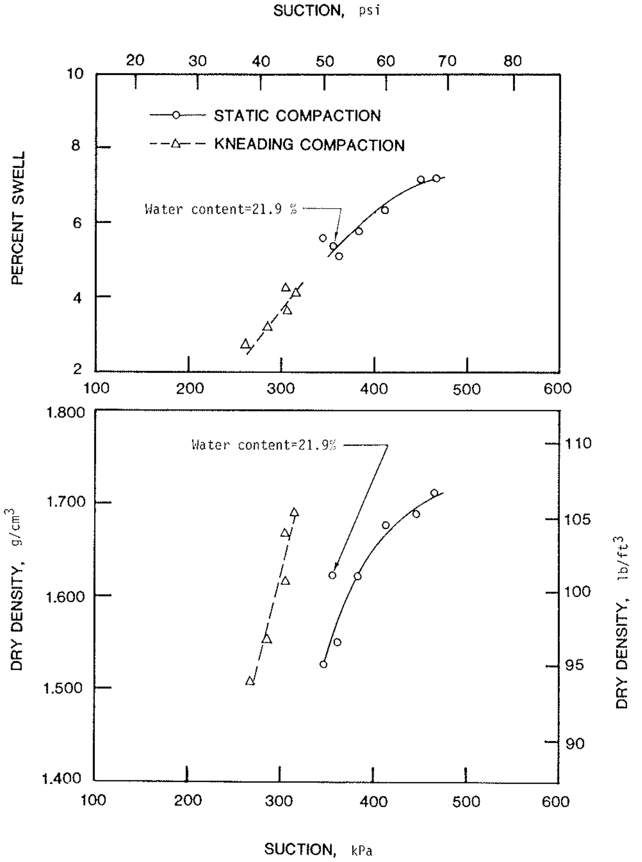


Figure 7. Dry density and percentage of swell versus soil suction as determined by method 1 tests for specimens with water contents of 21.3 ± 0.3 percent (except as noted).



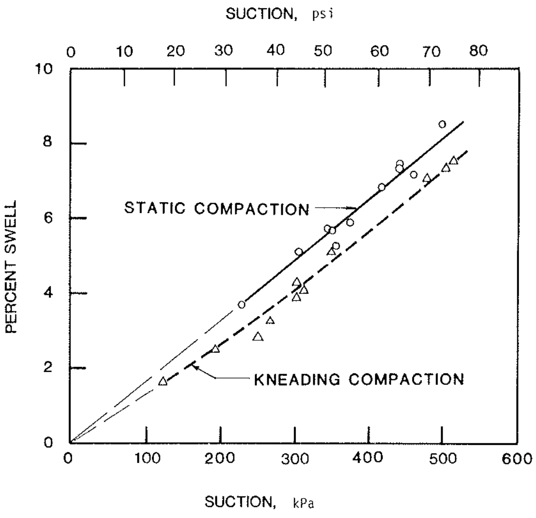
after the swelling tests. Regardless of the observed discrepancies among the three methods of test, the data obtained from these test methods indicate a similar trend of variation in percentage of swell as a result of a deviation in several factors, including initial water content and dry density. For this reason, the discussion of the findings that follows refers only to the data obtained from test method 1.

The effect of the variation in initial water content on percentage of swell is shown in Figure 6. The data shown in this figure were obtained from tests on specimens that had almost the same dry density before the swelling tests. As expected, an increase in the initial water content of the specimens results in a decrease in the suctions of these specimens and therefore a corresponding decrease in the percentage of swell. The figure also indicates that specimens prepared by static compaction show a consistently higher percentage of swell than specimens prepared by kneading compaction.

The general effect of initial dry density on the percentage of swell in a soil is well recognized by practicing engineers. The specific relation between initial dry density and percentage of swell has been studied by a number of investigators, including Vijayvergiya and Ghazzaly (16) and Brackley (17). The limited data on this relation determined in this study are shown in Figure 7. In general, an increase in the dry density of specimens that have similar initial water contents results in an increase in both suction and percentage of swell.

In view of the fact that percentage of swell depends primarily on the suction of the soil specimens before the swelling tests, it is of interest to study the relation between percentage of swell and suction regardless of the cause of the change in soil suction. To this end, all test data, including those shown in Figures 6 and 7, were used in the preparation of Figure 8 to illustrate the general relation between percentage of swell and initial soil suction. Although the test results shown in this figure are inadequate for making definite conclusions, the graphic representations appear to indicate that, for a given soil and for specimens prepared by a specific method of compaction, there is a unique relation between the variation in percentage of swell and the changes in initial soil suction regardless of the cause for the suction change (i.e., a change in the initial dry density or a variation in the initial water content). Furthermore, for specimens prepared by either method of compaction, Figure 8 indicates that the plotted line or curve representing the experimental data tends to reach the origin of the graph as shown by the thin dashed lines. This relation is obviously in compliance with the basic principle that there will be no swell attributable to moisture change if the initial moisture condition of the soil is represented by zero suction. The analysis of swelling potential according to the initial suction in the soil, as shown in Figure 8, is believed to be a useful approach in pursuing laboratory investigations of the swelling characteristics of expansive clays. This method of study has been referred to in this paper as the soil-suction approach.

Figure 8. Suction versus percentage of swell as determined by method 1 tests for specimens with different dry densities and water contents.



CONCLUSIONS

On the basis of the experimental data and other information presented above, the following general conclusions can be made:

1. A pressure-plate apparatus and the procedures for measuring the suction of soil specimens developed in this study were found to be satisfactory for the direct determination of the suction of soil specimens at the existing dry density and water content.
2. The use of static as well as kneading compaction for specimen preparation results in a different soil structure or fabric of the compacted specimens. This difference in soil fabric is reflected in the measured soil suctions and the percentage of swell determined by the laboratory experiments in this study. This finding indicates that any difference in the soil fabric of expansive clay formations may be a significant factor that affects the swelling characteristics of the clay formations. In this respect, the measurement of soil suction would provide helpful information in the investigation of the volume-change behavior of expansive clays.
3. Although using soil water content as a major variable in the evaluation of swelling potential is a convenient and practical approach, findings from the laboratory investigations indicate that it is very useful to include soil suction as an additional variable for similar purposes. This study verifies that the soil-suction approach is invaluable in the analysis of experimental data and the determination of the swelling characteristics of expansive clays.

REFERENCES

1. G.D. Aitchison and B.G. Richards. The Fundamental Mechanisms Involved in Heave and Soil Moisture Movement and the Engineering Properties of Soils Which Are Important in Such Movement. Proc., 2nd International Research and Engineering Conference on Expansive Clay Soils, Texas, 1969.
2. J.E. Jennings. The Prediction of Amount and Rate of Heave Likely to Be Experienced in Engineering Construction on Expansive Soils. Proc., 2nd International Research and Engineering Conference on Expansive Clay Soils, Texas, 1969.
3. J.E. Jennings and others. An Improved Method for Predicting Heave Using the Oedometer Test. Proc., 3rd International Conference on Expansive Soils, Haifa, Israel, 1973, pp. 149-154.
4. L.D. Johnson. Influence of Suction on Heave of Expansive Soils. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Miscellaneous Paper S-73-17, 1973.
5. L.D. Johnson. Evaluation of Laboratory Suction Tests for Prediction of Heave in Foundation Soils. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Tech. Rept. S-77-7, 1977.
6. Annual Book of ASTM Standards. ASTM, Philadelphia, Part 19, 1979.
7. D.J. Janssen and B.J. Dempsey. Soil Water Properties of Subgrade Soils. Univ. of Illinois, Urbana-Champaign, Final Rept., 1980.
8. R.E. Olson and L.J. Langfelder. Pore Water Pressure in Unsaturated Soils. Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, New York, Vol. 91, No. SM4, July 1965.
9. S.D. Wilson. Small Soil Compaction Apparatus Duplicates Field Results Closely. Engineering News Record, 1950, pp. 34-36.
10. T.W. Lambe. The Structure of Compacted Clay. Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, New York, Vol. 84, No. SM2, 1958.
11. J.K. Mitchell. Fundamentals of Soil Behavior. Wiley, New York, 1976.
12. W.G. Holtz. Suggested Method of Test for One-Dimensional Expansion and Uplift Pressure of Clay Soils. In Special Procedures for Testing Soil and Rock for Engineering Purposes, ASTM, Philadelphia, Special Tech. Publ. 479, 1970, p. 198.
13. H.B. Seed, R.J. Woodward, and R. Lundgren. Prediction of Swelling Potential for Compacted Clays. Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, New York, Vol. 88, No. SM3, 1962, p. 53.
14. T.Y. Chu and C.H. Mou. Volume Change Characteristics of Expansive Soils Determined by Controlled Suction Tests. Proc., 3rd International Conference on Expansive Soils, Haifa, Israel, 1973, pp. 177-185.
15. V. Escario and J. Saez. Measurement of the Properties of Swelling and Collapsing Soils Under Controlled Suction. Proc., 3rd International Conference on Expansive Soils, Haifa, Israel, 1973, pp. 195-200.
16. V.N. Vijayvergiya and O.I. Ghazzaly. Prediction of Swelling Potential for Natural Clays. Proc., 3rd International Conference on Expansive Soils, Haifa, Israel, 1973, pp. 227-236.
17. I.J.A. Brackley. Swell Pressure and Free Swell in a Compacted Clay. Proc., 3rd International Conference on Expansive Soils, Haifa, Israel, 1973, pp. 169-176.

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