Influence of Soil Type and Placement Conditions on Soil Suction in Compacted Expansive Soils

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ABSTRACT. *This study investigates the influence of the type of soil, compaction moisture content and dry density on soil suction in impact compacted expansive soils. Many samples which were obtained from five highly expansive soil types were tested. The soil types considered in this study included two natural from Sudan and three natural/artificial soil mixtures. An apparatus based on the axis-translation technique of suction measurement was developed and successfully used for laboratory testing. From analysis of the study results, it was concluded that for a given soil the suction is strongly influenced by the moisture content. The study also showed that at given moisture content, more plastic soils tend to yield greater suction values than less plastic soils. An empirical equation was proposed to relate soil suction, moisture content and soil type. The suction dry density relationship was investigated for samples from the two natural soils only and the trends obtained indicate that the influence of the dry density on soil suction is of secondary importance.*

RÉSUMÉ. *Cette étude analyse l'influence du type de sol, la teneur en eau et la densité sèche de compactage sur la succion et son impact sur les sols gonflants compactés. De nombreux échantillons qui ont été obtenus à partir de cinq types de sols très gonflants ont été testés. Les types de sols considérés dans cette étude sont de deux sites naturels du Soudan et de trois mélanges sites naturels et sols artificiels. Un appareil basé sur la technique de translation d'axe a été développé et utilisé avec succès pour les essais de laboratoire. A partir de l'analyse des resultants obtenus, on a conclu que, pour un sol donné la succion est fortement influencée par la teneur en eau. L'étude a également montré que pour une teneur en eau donnée, la succion est plus grande pour les sols plastiques que les sols moins plastiques. Une équation empirique a été proposée pour relier la succion du sol, teneur en eau et le type de sol. La relation succion densité sèche a été étudiée pour les échantillons provenant des deux sols naturels seulement et les tendances obtenues indiquent que l'influence de la densité sèche sur la succion du sol est d'une importance secondaire.*

KEY WORDS: *expansive soils, soil suction, compaction placement condition*

MOTS CLÉS: *les sols gonflants, la succion du sol, condition de placement de compactage*

1. Introduction

The importance of soil suction in the study of soil behaviour was known by soil scientists as early as 1935 but it was first introduced to soil mechanics in 1948 (Croney and Coleman, 1948). In an unsaturated soil, the pressure in the air phase (u_a) is different and always higher than the pressure in the water phase (u_w), because of the surface tension effects. The difference between these pressures is defined as the suction of the soil. The total suction present in a soil is made of two components; the matric suction and the osmotic suction. The matric suction develops from the particle surface and cation attractive forces of water and surface tension forces of water within the soil. The osmotic suction arises from the presence of soluble salts in the soil water. In the majority of previous studies on the volume change and shear strength characteristics of unsaturated soils, the matric suction component was mainly considered, while the osmotic component was either not considered or deemed to be insignificant.

The study described in this paper was undertaken to investigate the relationships between soil suction and some important soil properties such as moisture content, dry density and soil type in compacted expansive soils. To achieve this objective, it is necessary to employ a suitable method for measurement of the soil suction in the laboratory. A brief review of the soil suction measurement techniques in current use and the important findings of previous investigations on the influence of the above mentioned soil properties on soil suction is given in the following section.

2. Variations of Matric Suction with Soil Moisture Content, Soil Type and Dry Density; a Review

2.1. *Measurement of Soil Suction*

A great variety of techniques which can be used for the measurement of soil suction in the laboratory have been reported in literature. These techniques may be broadly divided into direct and indirect methods of matric suction measurement. In the direct measurements, the negative soil pore water pressure is directly measured and this requires a separation between the water phase and air phase normally by means of a ceramic disk. Examples of the direct matric suction measurements are the tension-meters and the null-type axis translation technique. Matric suction can be measured indirectly in the laboratory by the filter paper method. In this method, a dry filter paper is placed in contact with soil in a closed container and allowed to come into equilibrium with soil water.

2.2. *Soil Suction-Moisture Content Relationship*

Several studies have discussed the influence of the moisture content and dry density on suction for various soil types in their undisturbed and remoulded conditions and the main findings of these studies are presented here.

The relationship between matric suction and the as-moulded moisture content of compacted soils has been studied in several previous investigations. Croney and Coleman (1960) determined the relationship between suction and moisture content for disturbed samples of a heavy clay soil and reported that a unique relationship exists between them. This conclusion was further confirmed for a highly plastic clay soil by Khrahn and Fredlund (1972). Snethen (1980) conducted a comprehensive study on undisturbed clay soil samples and proposed an empirical relationship between suction and moisture content which was found to be satisfactory for numerous clay soils having suctions in the range of 200-2000 kPa.

The dependence of the soil suction-moisture content relationship on the type of soil was considered in a number of previous studies. Aitchison and Richards (1965), undertook an investigation on moderately active undisturbed clays and the results obtained showed that for a given suction, the corresponding moisture content is higher in a soil of higher than of lower clay content. Olsen and Langfelder (1965), measured the suction in five compacted soils prepared at different moisture contents and found that the suction at particular moisture content could be related to the soil specific area.

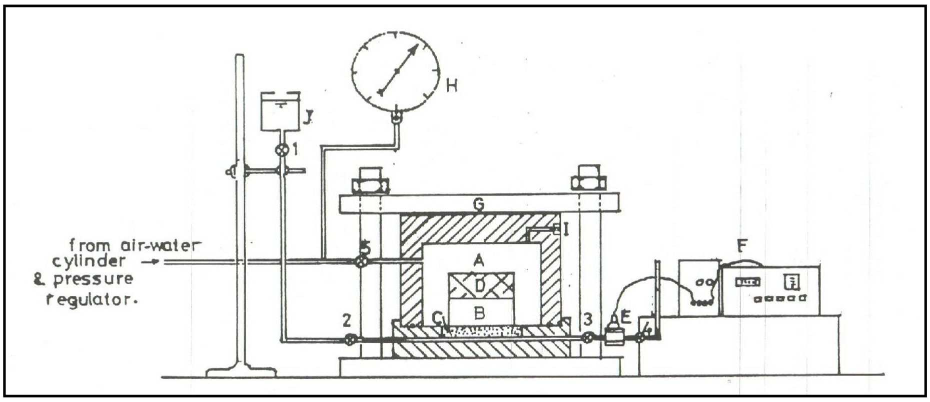
2.3. *Soil Suction-Dry Density Relationship*

Unlike the moisture content, there appears to be some inconsistency and disagreement in the findings of previous studies with regard to the effect of soil density on matric suction. Croney and Coleman reported that the matric suction is influenced by the soil dry density in incompressible or undisturbed soils but is not affected in compressible and disturbed soils. Taylor and Box (1961) measured the suction in soil samples with constant moisture contents and different dry densities and reported that higher densities tend to produce lower suction values. A variation of suction with dry density in two soils prepared by static and kneading compaction methods was reported by Mou (1981) who found that in both soils higher values of suction were measured in more dense samples at the same moisture content. Olsen and Langfelder (1965) and Krahn and Fredlund (1972) tested static and impact compacted soils respectively and concluded that the influence of dry density on matric suction did not appear to be significantly affected by the differences in soil density. Vanapalli et al (1999) measured soil matric suctions using the axis-translation technique for statically compacted clay till soil specimens and concluded that a unique relationship appears to exist between matric suction and the as-compacted moisture content. An interesting study was reported by Gibbs (1965) who related suction to both the moisture content and dry density and presented his results in iso-lines of equal suctions suggests that the influence of dry density on suction is dependent on the moisture content level.

3. Testing Program

3.1. *Matric Suction Measurement Method Adopted*

A schematic diagram of the apparatus developed in the present study for the measurement of soil suction is shown in Figure 1. In essence, it consists of a high entry ceramic plate on which the soil samples to be tested is placed within a closed high pressure chamber. There are provisions for measuring the chamber air pressure and the pore water pressure beneath the ceramic plate. The method is based on the null-type axis-translation technique which reverses the reference air pressure from atmospheric to above atmospheric causing the water pressure to change as it comes to equilibrium with the pore air pressure. In such system, the air pressure is varied and the soil water pressure varied by the same magnitude so the matric suction in the soil sample remains unchanged.



LEGEND
A : Pressure chamber — B : Soil sample — C : 15 bar ceramic plate
D : 1 kg seating load — E : Pressure transducer — F : Data logger
G : Supporting frame — H : Pressure gauge — I : Bleeding valve
J : De-aired water tank

Figure 1. *Setup of matric soil suction measurement apparatus developed*

3.2. *Soil Samples*

Five different soils were selected for testing in the present study in such a way that they would represent a wide range of expansive soils. These include two natural expansive clay soils taken from two different geographical regions in Sudan (designated as soils A and B), and three soils (designated as soils C, D and E) obtained by mixing soil A with a highly expansive artificial material in different proportions. The artificial material which is commercially known as "Surrey Powder" Bentonite was thoroughly mixed with soil A in three ratios (by dry mass) of 1:9, 2:8 and 3:7 for soils C, D and E respectively. Some of the basic engineering properties of the five selected soil types and soil mixtures are given in table 1.

Soil designation	A	B	C	D	E
Soil Type	black cotton soil	black cotton soil	Mixture of soil A and SPB(*) in 9:1 ratio	Mixture of soil A and SPB(*) in 8:2 ratio	Mixture of soil A and SPB(*) in 7:3 ratio
Passing No. 200 sieve	68	-	71.2	74.4	77.6
Liquid Limit, LL %	77.0	63.0	87.0	98.0	120.0
Plasticity Index, PI %	43.2	35.9	51.6	59.2	79.8
Specific gravity G_s	2.70	2.71	2.83	2.93	2.97

SPB(*) = Surrey Powder Bentonite

Table 1. *Summary of the basic index properties of the soil types tested*

The various compaction placement conditions i.e. moisture content (w) and dry density (γd) considered in the experimental program carried out on the samples tested from different soil types are summarised in table 2. In total, forty four different compacted soil samples were tested in the various test series considered in this study.

Test Series	Suction-moisture content		Suction-dry density	
Soil type	Range of w (%)	γd (kN/m^3)	Range of γd (kN/m^3)	w (%)
A	23.9 - 34.5	13.3	12.2 – 15.0	29.3
B	24.0 – 33.2	13.4	13.9 – 16.3	23.4
C	29.0 – 37.8	13.2	-	-
D	31.1 – 39.7	13.1	-	-
E	32.4 – 45.0	13.0	-	-

Table 2. *Compaction placement conditions of the soil samples.*

3.3. *Sample Preparation and Testing Procedure*

3.3.1. *Sample Preparation*

For each soil type a number of samples were prepared in the laboratory by the impact compaction method at different moisture contents but approximately same dry density. In addition, samples of soils A and B were prepared at the same moisture content but different dry density values. Immediately after being compacted to the specified placement conditions, the soil samples were carefully wrapped in aluminium foil, tied firmly in plastic bags and stored to cure for a minimum period of one week prior to testing. After being prepared and cured, the soil samples were tested in the suction measurement apparatus developed.

3.3.2. *Testing Procedure*

The testing methodology followed in this study is similar to that proposed and described in details by Gibbs and Coffey (1969). The test procedure involves the saturation of the ceramic plate with de-aired water and the placement of soil sample to be tested on it. A 1Kg. seating load is placed on the specimen to ensure good contact between the soil specimen and the saturated ceramic plate. The apparatus is then quickly assembled and a sufficiently high air pressure is applied in the pressure chamber and pore water pressure in the system is recorded using a pressure transducer until equilibrium is reached. Once the maximum pore pressure is reached, the data logger is set to register the decrease in pore water pressure at suitable time intervals. The test is then left and observed frequently until no further reduction in pore water pressure is noted i.e. the system reached equilibrium. The measured matric suction value is taken as the difference between the air pressure applied in the chamber and the recorded pore water pressure. The maximum suction value of the soil sample under test occurs when an equilibrium state is established throughout the system.

3.4. *Test Results*

The measured soil suctions were plotted against the elapsed time for all tests and a typical suction versus time curves for the samples of soil A compacted at approximately equal dry densities but different moisture contents are shown in Figure 2. The time required for equilibrium varied between 2 and 9 hours, but for most samples tested the maximum suction was reached in 3 to 6 hours time.

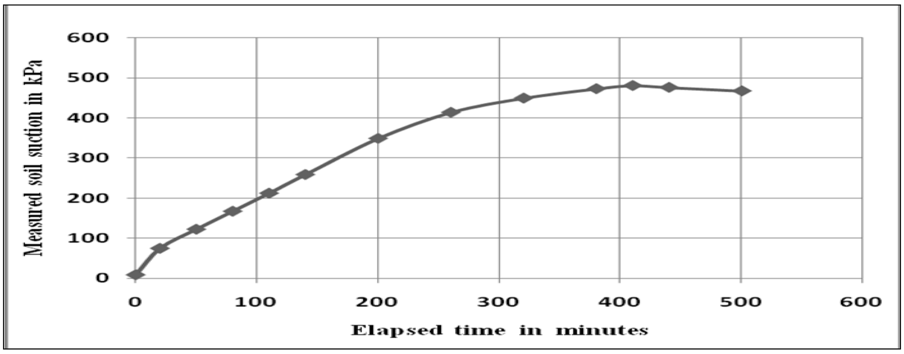


Figure 2. *Typical soil suction versus elapsed time curve for a compacted sample*

4. Discussion of Study Results

4.1. *Performance of the Developed Suction Measurement Apparatus*

The significance of the soil suction variable in the analysis of volume change and shear strength of unsaturated soils is very well known; but the difficulties involved in its measurement has obstructed its wide use in routine testing. The experience gained from the present study has shown that the axis-translation provides a reliable and practical technique of suction measurement, suitable for use in an ordinary soil mechanics laboratory. Of the various methods based on this technique, the exposed-end plate test adopted, has proved to be a simple, relatively fast and inexpensive test for soil suction measurement. The apparatus developed in this study has adequately performed throughout the testing program undertaken. Though the designed testing apparatus is capable of handling very high air pressures (up to 1500 kPa), the maximum suction measured in this investigation was about 1000 kPa due to some difficulties experienced in maintaining a stable high pressure in the laboratory.

4.2. *Soil Suction-Moisture Content Relationship*

To study the relationship between soil suction and moisture content, the measured suction values were plotted against the corresponding as-compacted moisture content values as shown in Figure 3. The general trend of the suction-moisture content relationship indicated in this figure for the different soil types is, as anticipated, non-linear and inverse with the higher suctions being associated with the soil samples of lower moisture contents and vice versa. For the less plastic soils (soils A, B and C), the suction-moisture content is hyperbolic with greater (steeper) curve slopes at the lower than at a higher moisture content. For the more plastic soils (soils D and E), the suction- moisture content relationship appears to be linear.

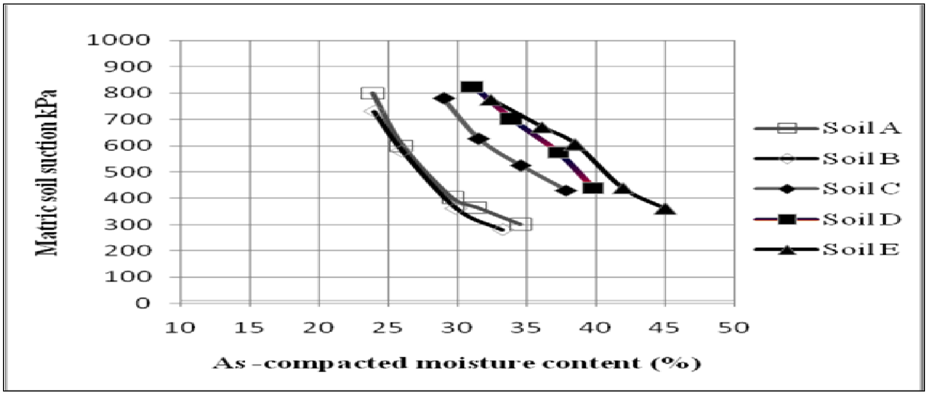


Figure 3. *Soil suction versus compacted moisture content for tested soil samples*

To mathematically define the relationship between soil suction and moisture content, the test data for each soil type was analysed using statistical regression method. It was found that for a given soil a simple relationship exists between the logarithm of soil suction ($u_a - u_w$) and as-compacted moisture content (w) and can be expressed as follows:

$$\text{Log}\,(u_a - u_w) = b - m^*w \qquad [1]$$

The constants "b" and "m" in equation [1] are the y-intercept and the slope of the best-fit regression lines of the suction-moisture content relationship. Somewhat different b and m values were obtained from data analysis for the natural and mixed soil groups as given in table 3. The fact that different values of m and b were obtained for the five soils tested indicates that the suction-moisture content relationship is soil type dependent. The slopes and y-intercept values of the regression lines are practically equal for the different soils in the same group.

Soil group	Slope m		Intercept b	
	range	average	range	average
Natural soils (soils A and B)	0.045 – 0.047	0.046	3.91– 4.01	3.96
Mixed soils (soils C, D, E)	0.028 – 0.030	0.030	3.70– 3.90	3.81

Table 3. *Computed values of the slope and intercept for the two soil groups*

An attempt was made to relate both the soil suction and compaction moisture content to the soil type through the plasticity index (PI) parameter which reflects the composition. The soil suction values were plotted against the moisture content of the compacted samples representing the five soil types with PI ranging from 35.9 to 79.2% and moisture contents in the range of 26-34% as shown in Figure 4.

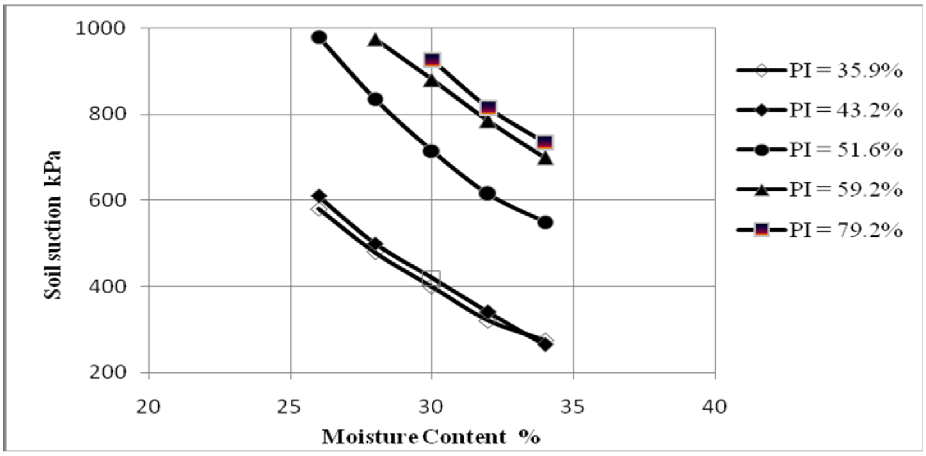


Figure 4. *Effect of soil plasticity on soil suction-moisture content relationship*

It is clear that the soil suction is strongly influenced by soil plasticity such that for given moisture content, the corresponding soil suction is higher in a soil of higher than of lower plasticity index. Similar trends of suction-moisture content relationship were obtained when the liquid limit was used instead of the plasticity index.

A more useful correlation between the soil suction ($u_a - u_w$), moisture content (w) and soil type was obtained upon incorporation of the liquid limit (LL) and specific unit weight (specific gravity, G_s) as soil type indicatives. Based on test data analysis for 44 different soil samples, it was found that the soil suction-moisture content-soil type relationship, graphically shown in Figure 5, can mathematically be described by a single equation as follows:

$$\text{Log}\,(u_a - u_w) = 0.867\,[LL / (w^*G_s)] + 1.89 \qquad [2]$$

In this equation, ($u_a - u_w$) is expressed in kPa and w and LL in percent. A reasonably high coefficient of correlation (R = 0.85) was obtained from the regression analysis of the test data. In fact, both the PI and LL parameters were considered in analysis but the LL gave a better correlation coefficient than the PI.

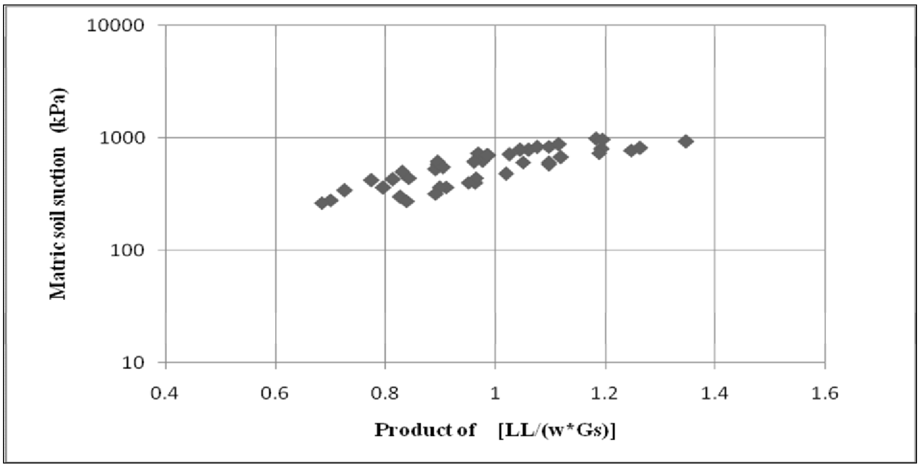


Figure 5. *Relationship between soil suction, soil moisture content and soil type*

Equation [2] may therefore be used to estimate soil suction from known values of moisture content, liquid limit and specific unit weight of the soil if it cannot be measured directly. However, more test data would certainly be required to verify the applicability and usefulness of equation [2] for wider ranges of soil suctions and for soil types different from those covered in the present study.

4.3. *Effect of Dry Density on Soil Suction*

The study on the influence of dry density on soil suction was limited on tests performed on samples from the two natural soils (A and B) compacted at constant moisture contents and dry density values ranging between 1.22 and 1.63Mg/m^3. The suction versus dry density results for arbitrary moisture contents of 29.3% for soil A and 23.4% for soil B were plotted as shown in Figure 6. It can readily be noted in Figure 6 that for soil A, the dry density does not seem to have an influence on suction for the moisture content considered as virtually suction values of the same order (475-480kPa) were measured in the samples with dry density ranging from 1.22 to 1.49Mg/m^3. For soil B samples, the dry density appears to have some effect on soil suction, such that the suction generally tends to be higher in samples of lower density. Such a trend in the suction-dry density relationship was previously reported by Gibbs (1965), but an opposite trend of suction increasing with density at the same moisture content was suggested by Mou (1981).

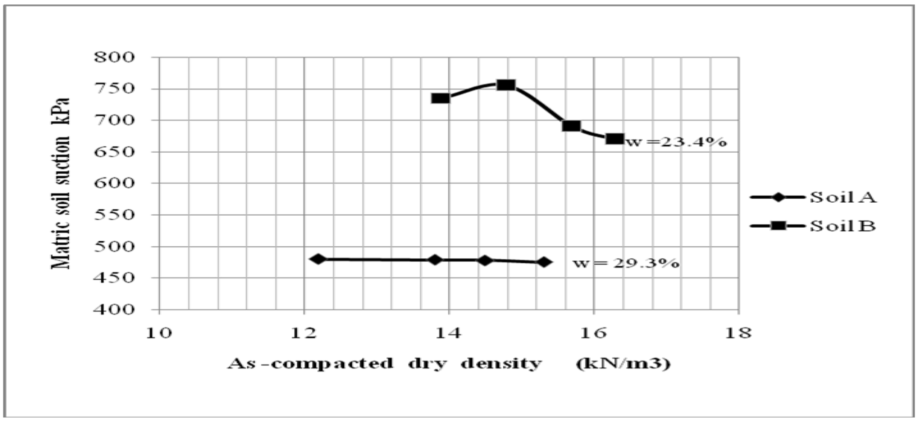


Figure 6. *Soil suction versus compacted dry density for samples from soils A and B.*

Compared to the order of measured suction magnitude in tested samples (about 700kPa), the suction changes due to differences in the dry density are relatively small. Therefore, the test results suggest an insignificant effect of density on soil suction of the two compacted expansive soils tested. This conclusion is consistent with the findings of previous studies such as Croney and Coleman (1960), Olsen and Langfelder (1965) and Krahn and Fredlund (1972). Due to the limited number of tests performed in the present study, one cannot confirm, or otherwise, the existence of a unique suction-moisture content relationship that holds over a wide range of moisture conditions which is totally independent of dry density. In fact, the test data reported by Gibbs (1965) clearly demonstrate that the dry density may have a significant effect on soil suction in soil samples compacted at or dry of optimum moisture content which contradicts the existence of such a suction-moisture content relationship.

5. Conclusions

An apparatus based on the null-type axis-translation technique was developed and successfully used for laboratory measurement of soil suction in the present study. From studying the influence of moisture content, dry density and soil type on soil suction using compacted samples from five different expansive soils, the following findings were revealed:

i. For a given soil, the matric soil suction is strongly and inversely related to the as-compacted moisture content. A simple relationship which appears to hold for highly expansive soils was established between the logarithm of soil suction and moisture cont in a given soil.

ii. The magnitude of soil suction is significantly influenced by soil plasticity. At given moisture content, more plastic soils tend to give higher soil suction values than less plastic soils.

iii. Based on analysis of test data of samples representing the various soil types tested, a simple empirical equation was developed to relate soil suction, moisture content and soil type for the compacted expansive soils tested. The validity of this equation needs to be verified for soil types and conditions different from those considered in this study.

iv. Although the suction-dry density relationship was not fully investigated, the trends obtained for the tested compacted natural soil samples indicate that the influence of dry density on soil suction is of secondary importance.

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