THE EFFECT OF STRESS STATE ON THE SOIL-WATER CHARACTERISTIC BEHAVIOR OF A COMPACTED SANDY- CLAY TILL

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ABSTRACT A laboratory procedure is presented in this paper that accounts for the influence of the total stress state on the soil-water characteristics of a compacted fine-grained soil. Soil specimens were prepared to obtain stress states of 0 kPa, 25 kPa, 100 kPa and 200 kPa at three different initial water contents representing dry of optimum, optimum, and wet of optimum conditions. The soil-water characteristics of the specimens were then determined. The analysis of the results suggest that the stress state influences the soil-water characteristic behavior of specimens prepared at initial water contents dry of optimum in comparison to specimens tested at initial water contents optimum and wet of optimum. The unsaturated shear strength of specimens compacted with the three different initial water content conditions can be reasonably well predicted using the soil-water characteristic curves without considering the influence of the stress state for the net normal stress range used for the soil tested in this research program.

RÉSUMÉ Une procédure en laboratoire vérifiant l'influence de l'état de stresse total sur le comportement de la courbe caractéristique eau-sol d'un sol granuleux compacté est présentée dans cet article. Des échantillons de sol ont été préparés de façon a obtenir des états de stresse de 0 kPa, 25 kPa, 100 kPa et 200 kPa à trois différents contenus initiaux en eau représentant des conditions "sèches-optimum", "optimum" et "humides-optimum". Leurs caractéristiques eau-sol ont ensuite été déterminées. L'analyse des résultats suggère que l'état de stresse influence le comportement caractéristique eau-sol des échantillons préparés en conditions initiales en eau "sèches-optimum" en comparaison aux échantillons testés en conditions initiales en eau "optimum" et "humides-optimum". La force de cisaillement des échantillons insaturés compactés dans les trois différentes conditions de contenus initiaux en eau peut être raisonnablement bien prédite en utilisant les courbes caractéristiques eau-sol sans avoir à tenir compte de l'influence de l'état de stresse pour la marge nette de stresse normal utilisée pour le sol testé dans cette présente étude.

1. INTRODUCTION

Fredlund and Rahardjo (1993) have provided a rational approach to describe the engineering behavior of unsaturated soil in terms of two stress state variables, namely net normal stress, $(\sigma-u_a)$, and suction (u_a-u_w). However, this approach is time consuming and costly as extensive experimental studies are required. Simple relationships between the soil-water characteristic curve and saturated soil properties are now being used to predict/model the engineering behavior of unsaturated soils. Factors such as soil structure (and aggregation), initial moulding water content, void ratio, type of soil, texture, mineralogy, stress state, method of compaction, etc., can influence the soil-water characteristics of compacted fine-grained soils. Soil-water characteristic curves are commonly determined in the laboratory using a pressure plate apparatus without the application of any applied stress or confining pressure. However, under field conditions an in situ total stress exists in the soil. In order to assess and predict the engineering behavior of an unsaturated soil, it is important to test the specimen in the laboratory simulating the physical state and stress state conditions of the field.

A procedure is presented in this paper that takes into account the influence of the total stress state on the soil-water characteristic behavior of a compacted fine-grained soil. The soil specimens were first loaded and then unloaded using conventional consolidation apparatus to create a known stress history or stress state in the specimen. The soil-water characteristic curves were determined using a pressure plate apparatus.

Soil specimens were prepared by statically compacting a sandy-clay till in a mould and then subjecting them to a loading regime to obtain stress states of 0 kPa, 25 kPa, 100 kPa and 200 kPa at three different initial water contents representing dry of optimum, optimum, and wet of optimum conditions for each of the three stress states. The influence of stress state on the soil-water characteristic curve and the unsaturated shear strength behavior are discussed in this paper.

2. SOIL AND TESTING PROGRAM

A sandy-clay till obtained from Indian Head, Saskatchewan, was used in this testing program. The liquid limit and plastic limit are 35.5% and 16.8% respectively. Sand, silt and clay fractions are 28%, 42%, and 30% respectively. The AASHTO standard compacted maximum density is 1.80 Mg/m^3 at an optimum water content of 16.3%. The relative density of the soil solids is 2.73. Soil-water characteristic curves were determined on statically compacted specimens with a stress state of 0 kPa, 25 kPa, 100 kPa and 200 kPa. Three different initial water contents representing dry of optimum (i.e., 13% water content), optimum (16.3% water content) and wet of optimum (19.2% water content) conditions were used in this study.

A conventional pressure plate apparatus does not allow specimens to be loaded externally during testing. A modified testing procedure was adopted for the testing program (i.e., the specimens had a known equivalent pressure). The meaning of the term equivalent pressure is detailed later in the paper. The void ratio versus stress relationship, both in loading and unloading conditions was determined through conventional oedometer testing using saturated soil specimens. Compacted specimens, 63.5 mm in diameter by 21 mm high with the required initial water content and density, were placed between filter papers and porous stones in consolidation rings and were loaded to 3.5 kPa. The specimens were submerged in distilled water with free drainage at top and bottom for about 36 hours. The degree of saturation of these specimens was determined using waxed trial samples, which were weighed in air and water. The degrees of saturation of all specimens were close to 99%. The specimens were removed from the oedometers and placed in the pressure plate apparatus. These specimens are referred to as specimens with 0-kPa equivalent pressure.

The procedure used for inducing a predetermined equivalent pressure is explained using Fig. 1. Figure 1 shows the void ratio versus stress relationship for a specimen with a water content equal to 16.3% (i.e., representing optimum water content conditions). This compacted specimen was placed in an oedometer, saturated under constant volume conditions and then loaded to 200 kPa (point A). The specimen was then allowed to swell under a nominal pressure of 3.5 kPa (point B). While the specimen had experienced a maximum preconsolidation pressure of 200 kPa, it had a void ratio corresponding to 100 kPa on the initial compression branch after swelling under the applied pressure of 3.5 kPa (point C). The **equivalent pressure** for this specimen is equal to 100 kPa.

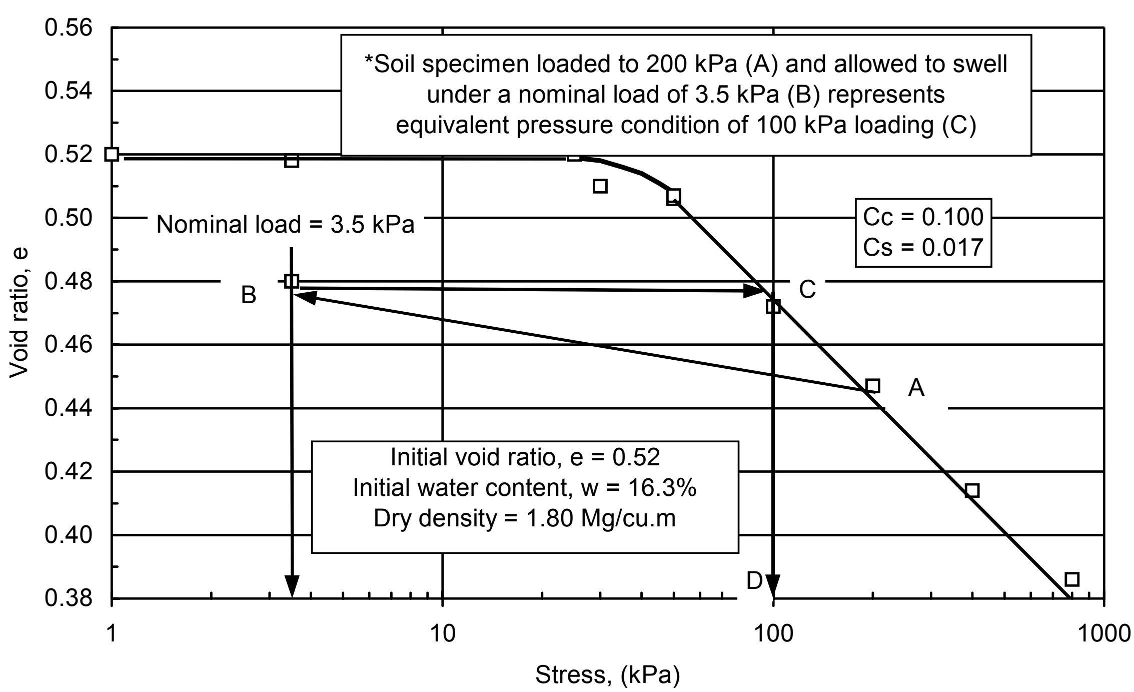

Figure 1. Void ratio versus the applied stress for an initial void ratio of 0.52.

Using a similar procedure, specimens of differing equivalent pressures as shown in Fig. 1 were prepared and used for testing. To use this procedure, the values of compression index, C_c and the swelling index, C_s, must be known. These values were measured from a separate laboratory-testing program for the three different initial water content conditions (Vanapalli, 1994).

The procedure described above is not suitable for preparing specimens at optimum and wet of optimum initial water contents with an equivalent pressure of 25 kPa. These specimens neither compress nor swell at these pressures. Hence, the specimens were loaded to 25 kPa, allowed to remain for a period of 36 hours and were then used for testing.

The specimens prepared, as detailed above, were used for measuring the soil-water characteristics using a pressure plate apparatus for the suction range from 0 to 1,500 kPa and osmotic desiccators for the range of suction values from 3,500 to 300,000 kPa. The combined results can be used to fit and plot the soil-water characteristic curve for the entire range of suction (i.e., from 0 to 1,000,000 kPa) (Fredlund and Xing 1994). However, soil-water characteristic curves obtained from pressure plate apparatus only are presented in this paper.

3. TEST RESULTS AND ANALYSIS

3.1 Soil-water characteristic curves

Soil-water characteristic curves developed for the specimens compacted dry of optimum with equivalent pressures of 0, 25, 100 and 200 kPa are shown in Fig. 2. At any particular value of suction, the specimens subjected to higher equivalent pressures have higher degrees of saturation. The desaturation characteristics of the soil-water characteristic curve are governed by the macro structure for the specimens prepared dry of optimum regardless of the increase in the equivalent pressures.

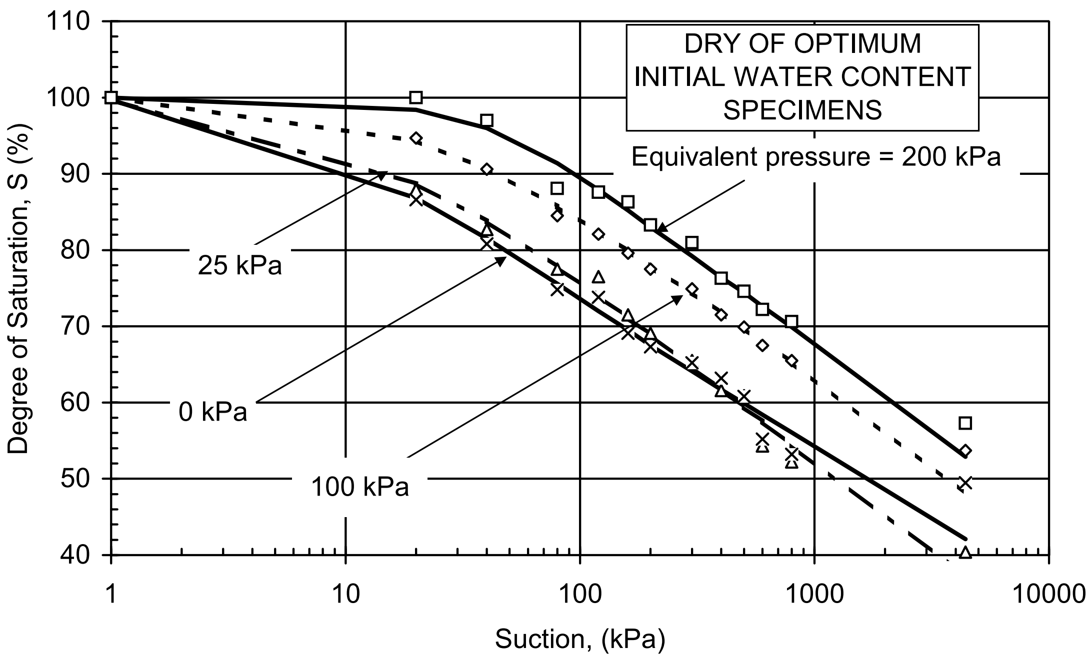

Figure 2. Soil-water characteristic curves for specimens compacted dry of optimum water contents.

Figures 3 and 4 show the variation of degree of saturation with respect to suction for optimum and wet of optimum initial water content specimens with different equivalent pressures. Regardless of the different equivalent pressures, soil-water characteristics of specimens with wet of optimum initial water contents appear to be the same (i.e., the soil-water characteristics appear to be independent of the stress history) (Fig. 4). The implications of this observation is that the desaturation characteristics are governed by the micro structure for wet of optimum water content specimens. The soil-water characteristic curve of the specimens compacted at optimum water content lies between that of specimens tested with dry and wet of optimum initial conditions (Fig. 3). More details of the influence of macro and micro structure on the soil-water characteristic behavior are available in Vanapalli et al. (1996a)

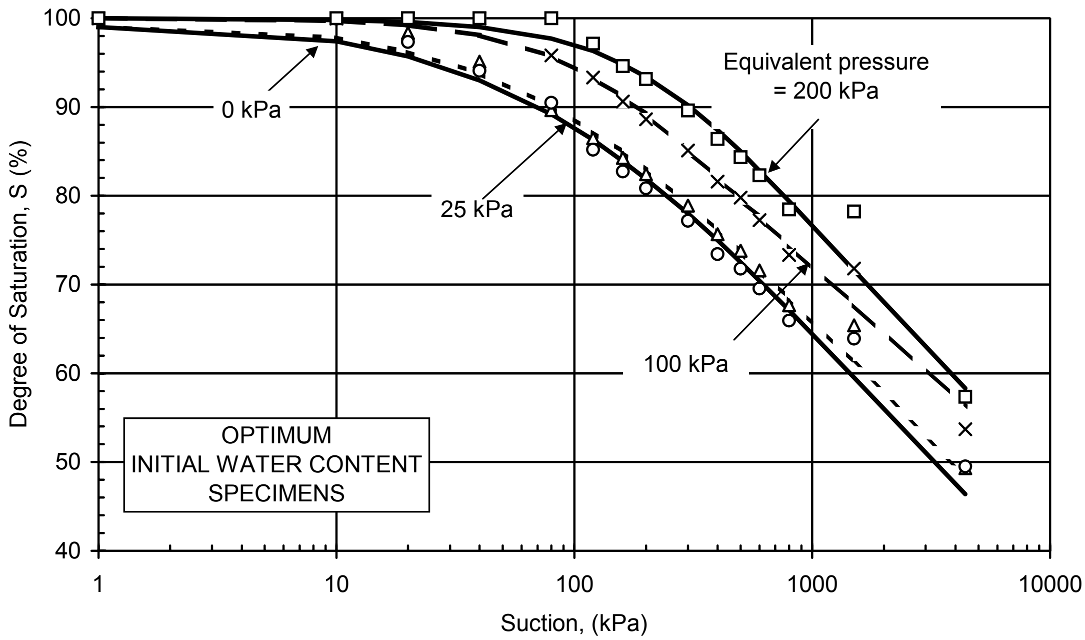

Figure 3. Soil-water characteristic curves for specimens compacted at optimum water contents.

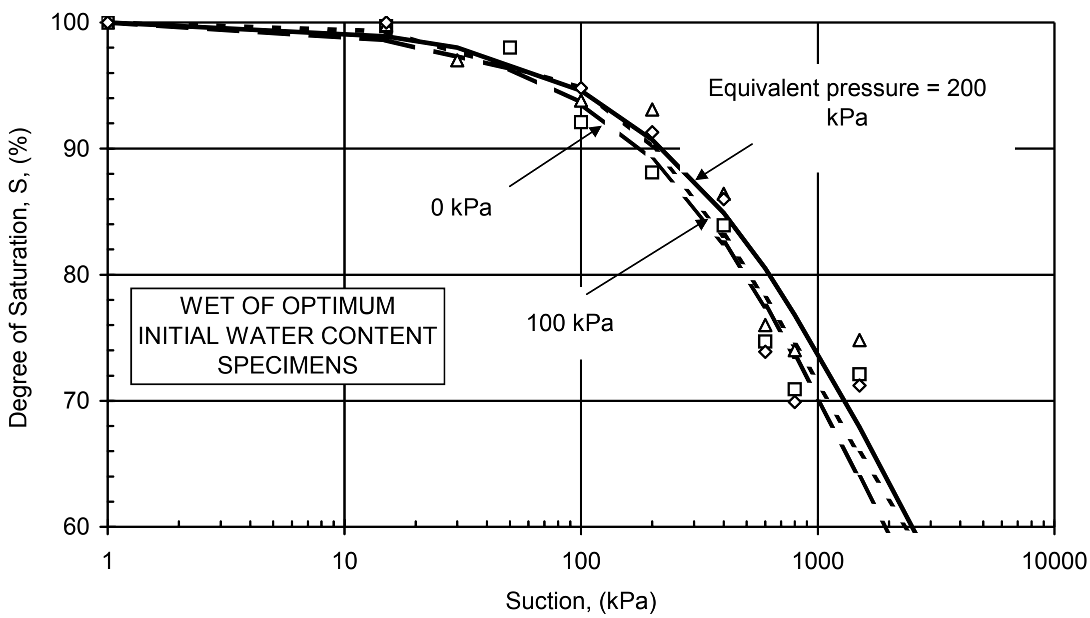

Figure 4. Soil-water characteristic curves for specimens compacted wet of optimum water contents.

3.2 Shear Strength

Shear strength equation for an unsaturated soil was proposed by Fredlund et al. (1978) as:

$$\tau_f = [c' + (\sigma_n - u_a) \tan \phi'] + [(u_a - u_w) \tan\phi^b] \quad \text{[Eq. 1]}$$

where:

τ_f = shear strength of an unsaturated soil,
c' = effective cohesion of the soil,
ϕ' = effective angle of shearing resistance for a saturated soil,
$(\sigma_n - u_a)$ = net normal stress,
$(u_a - u_w)$ = matric suction, and
ϕ^b = angle of shearing resistance relative to an increase in suction

The shear strength of unsaturated sandy-clay till specimens were predicted using the saturated shear strength parameters and the soil-water characteristic curve data measured on specimens as detailed earlier. The average saturated shear strength parameters for the soil tested with three different initial water contents in this research program were: c' equal 0 kPa and ϕ' equal 23.5 degrees (Vanapalli et al. 1996a).

Figure 5 shows the results of the predicted shear strength of specimens tested with initial water contents dry of optimum for various net normal stresses as solid lines while the measured shear strength values are shown as symbols. The net normal stresses, $(\sigma_n - u_a)$, chosen for the direct shear tests were identical to the equivalent pressures of the soil-water characteristic curves. More details of prediction procedures for shear strength are available in Vanapalli et al. (1996b) and Fredlund et al. (1996). Figure 6 shows the relationship between shear strength and net normal stress at different values of matric suction. The slope of these lines are equal to the effective angle of shearing resistance (ϕ'). These envelopes are essentially congruent within the limits of experimental error. The specimens tested with optimum and wet of optimum initial water contents also have shown similar trends. Thus, for all practical purposes the effective angle of shearing resistance, ϕ', is independent of the applied matric suction for the soil tested in this research program.

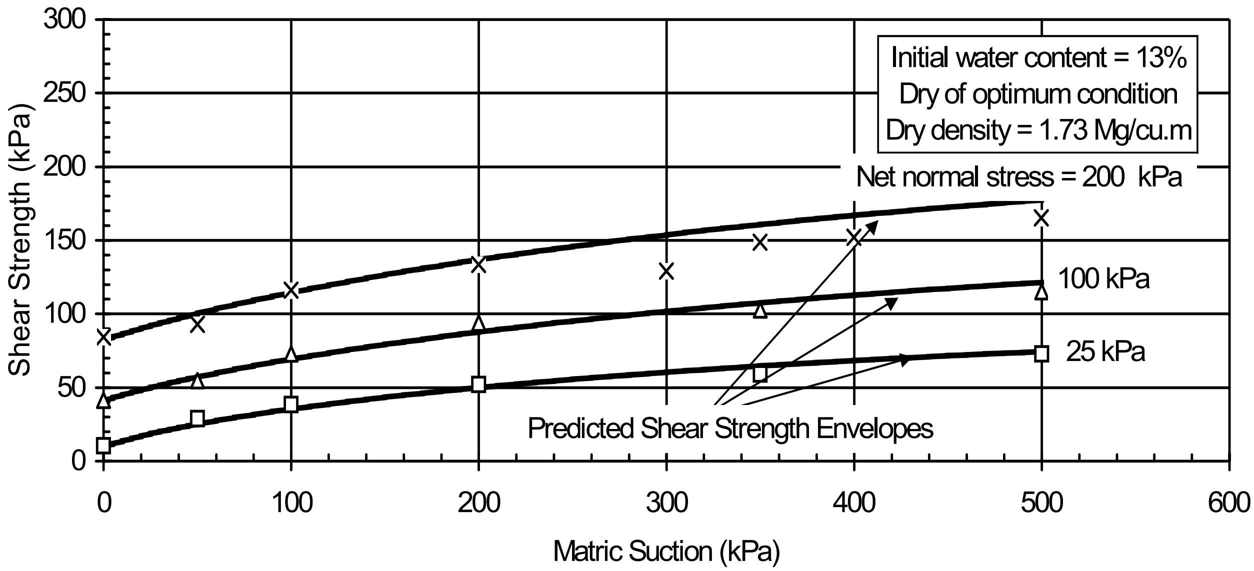

Figure 5. Variation of shear strength with matric suction under different net normal stresses with initial water contents dry of optimum.

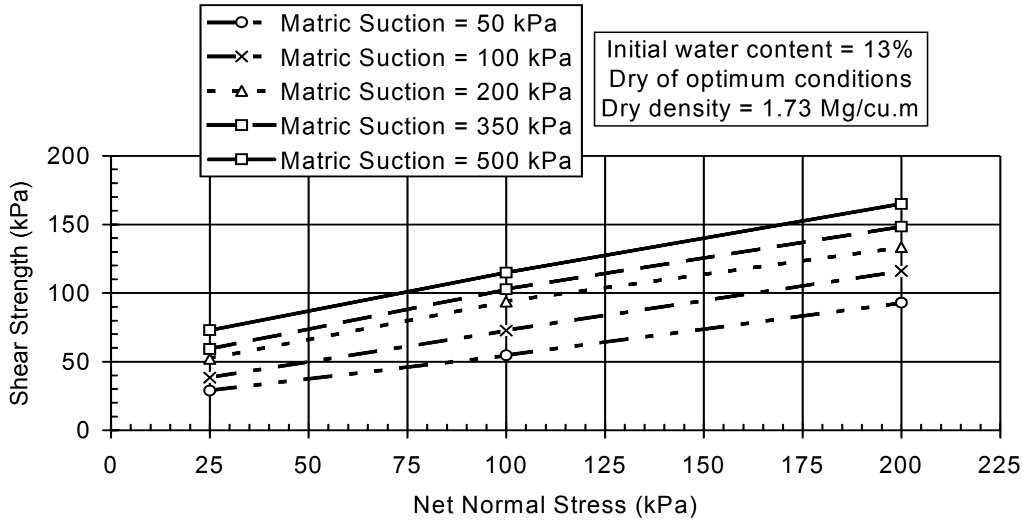

Figure 6. Variation of shear strength with net normal stress under different matric suctions for specimens with initial water contents dry of optimum.

3.3 A simple procedure for predicting shear strength

The shear strength contribution due to suction can be more accurately estimated using the soil-water characteristic curve that has been determined taking into account the influence of stress state. However, a simpler method can be used in the prediction of shear strength using the soil-water characteristic curve that is conventionally measured without the application of any applied stress. The proposed simple prediction procedure is described using [Eq. 1]. The first part of [Eq. 1] (i.e., [c' + ($\sigma_n - u_a$) tan ϕ']) is the saturated shear strength, wherein the influence of the net normal stress, which is the stress state, is taken into account. This is a valid assumption in the proposed method because the effective angle of shearing resistance, ϕ', is independent of the applied matric suction at least for the soil tested in this research study. The second part of the [Eq. 1], [($u_a - u_w$) tanϕ^b], is the shear strength contribution due to matric suction. Figures 7, 8 and 9 show the predicted shear strength, using this simple method, as continuous lines and the measured shear strength values as symbols.

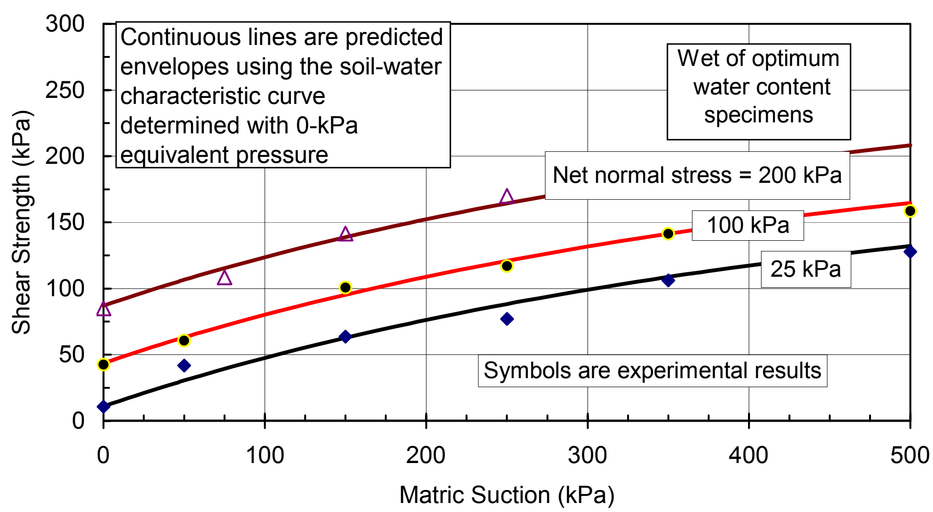

Figure 7. Predicted shear strength envelopes using the soil-water characteristic curve measured without considering the influence of stress state and measured shear strength values for specimens with wet of optimum initial water contents.

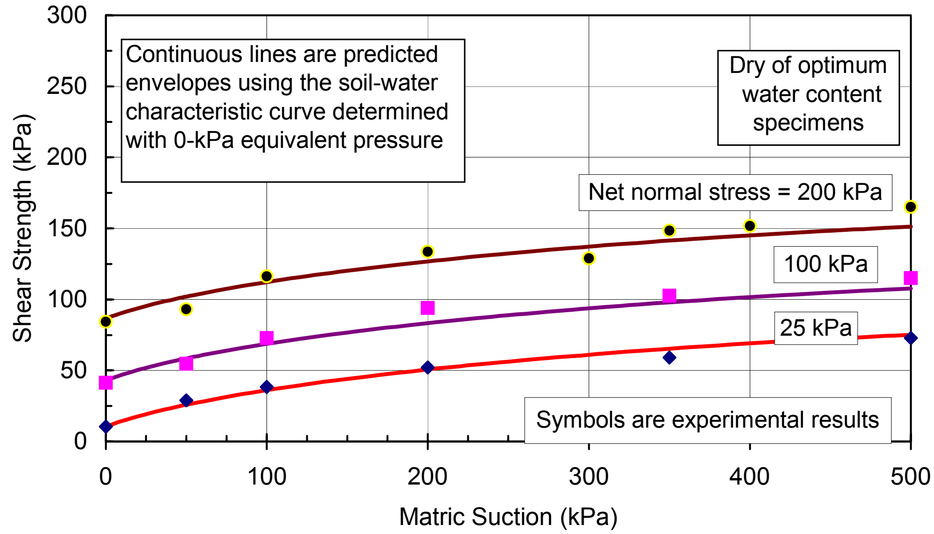

Figure 8. Predicted shear strength envelopes using the soil-water characteristic curve measured without considering the influence of stress state and measured shear strength values for specimens with dry of optimum initial water contents.

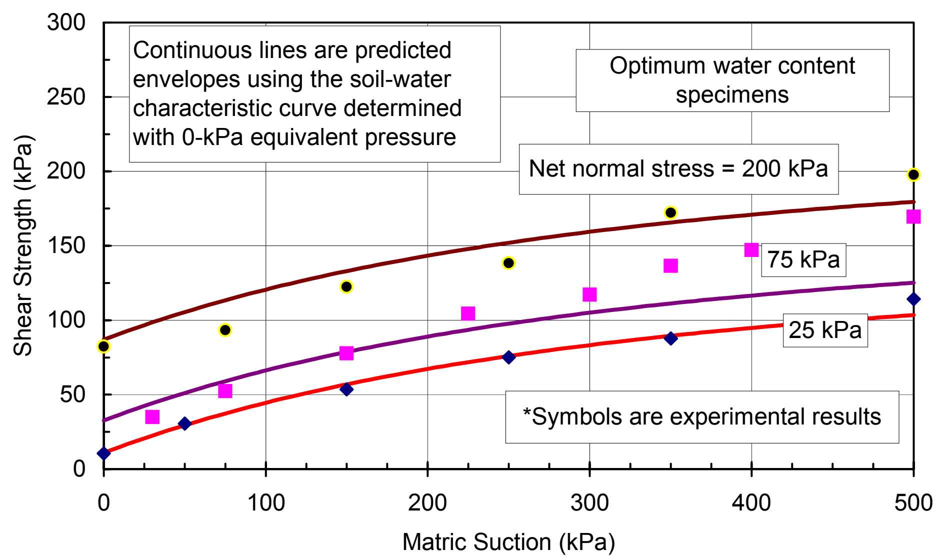

Figure 9. Predicted shear strength envelopes using the soil-water characteristic curve measured without considering the influence of stress state and measured shear strength values for specimens with optimum initial water contents.

The micro structure of the soil apparently governs the soil-water characteristic curve and the shear strength behavior, and the stress state has little or no influence (Fig. 4 and Fig. 7). However, for specimens with initial water contents dry of optimum, the macro structure and the applied stress state govern the desaturation characteristics and the shear strength behavior (Fig. 2 and 8). The behavior of specimens compacted at optimum initial water contents lie in between these two water content conditions (Fig. 3 and 9). There is a good comparison between the predicted and measured values for all the specimens tested with different initial water content conditions. The proposed simple method predicts lower values of shear strength and is, therefore, conservative. Such simple approaches seem to provide reasonable results and are encouraging especially for practicing engineers.

4. SUMMARY AND CONCLUSIONS

A procedure is presented in this paper that accounts for the influence of the total stress state on the soil-water characteristics of a compacted fine-grained soil. Soil specimens with stress states of 0 kPa, 25 kPa, 100 kPa and 200 kPa were prepared on statically compacted specimens at three different initial water contents representing dry of optimum, optimum, and wet of optimum conditions using the procedure described earlier. Their soil-water characteristics were subsequently determined in a pressure plate apparatus. The analyses of these results suggest that the applied stress state influences the soil-water characteristic behavior of specimens tested with initial water contents dry of optimum. However, the soil-water characteristic curve is not significantly influenced by the stress state for specimens compacted at initial water contents wet of optimum. The soil-water characteristic behavior of specimens compacted at optimum water content lie between these two water content conditions. The shear strength contribution due to suction can be more accurately estimated using the soil-water characteristic curve that has been determined taking into account the influence of stress state. However, the shear strength of specimens compacted with different initial water contents can be reasonably well predicted using the soil-water characteristic curves that have been determined **without** considering the influence of the stress state of soils for a net normal stress variation of 25 to 200 kPa for the soil tested in this research program. This approach underestimates the shear strength and is, therefore, conservative. More studies are necessary on other fine-grained compacted soils to develop a better understanding of the influence of stress state on the soil-water characteristics and on the unsaturated shear strength.

5. REFERENCES

Fredlund, D.G., Morgenstern, N.R., and Widger, R.A. 1978. The shear strength of unsaturated soils. Canadian Geotechnical Journal, **15**: 313-321.

Fredlund, D.G. and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John-Wiley & Sons Inc., New York.

Fredlund, D.G. and Xing, A. 1994. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal. **31**: 517-532.

Fredlund, D.G., Xing, A., Fredlund, M.D., and Barbour, S.L. (1996). The relationship of the unsaturated soil shear strength to the soil-water characteristic curve. Canadian Geotechnical Journal. **33**: 440-448.

Vanapalli, S.K. 1994. Simple test procedures and their interpretation in evaluating the shear strength of an unsaturated soil. Ph.D. thesis, University of Saskatchewan, Saskatoon, Canada.

Vanapalli, S.K., Fredlund, D.G., and Pufahl, D.E. 1996a. The relationship between the soil-water characteristic curve and the shear strength of a compacted glacial till. Geotechnical Testing Journal, GTJODJ, **19**: 259-268.

Vanapalli, S.K., Fredlund D.G., Pufahl, D.E., and Clifton, A.W. 1996b. Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, **33**: 379-392.