EFFECT OF COMPACTION ON THE UNSATURATED SHEAR STRENGTH OF A COMPACTED TILL

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Abstract

An experimental program was undertaken on compacted clay till at three different initial water contents to study the unsaturated shear strength under drained and undrained loading conditions. The three different initial moulding water contents (dry of optimum, optimum, and wet of optimum) induced differing soil structures to the compacted soil. The research study presented in this paper shows that the variation in suction in a soil that arises due to the influence of soil structure is a function of the initial compaction water content. The influence of soil structure on the drained and undrained shear strength parameters in unsaturated conditions is reflected through the shear strength contribution due to suction.

Introduction

Compacted fine-grained soils are commonly used in the construction of geotechnical and geo-environmental structures. Both drained and undrained shear strength analyses of compacted soils are of significance in dealing with these structures.

The shear strength behavior of compacted soils in an unsaturated condition is significantly influenced by properties such as the initial moulding water content, stress state and soil structure. For example, a fine-grained soil compacted at various initial water contents and to various densities produce "different" soils from a soil mechanics behavioral standpoint even though their mineralogy, plasticity, and texture are the same. The engineering behavior will vary from one specimen to other due to differences in soil structure or aggregation which are related to the initial moulding water content. Limited information is available in the literature with respect to the influence of soil structure on the shear strength behavior of unsaturated soils in drained and undrained loading.

An experimental program was undertaken on a compacted clay till to study the shear strength in drained and undrained loading. The initial water contents were chosen to represent dry of optimum, optimum, and wet of optimum conditions. The influence of soil structure on the drained and undrained shear strength parameters in unsaturated conditions and the contribution of shear strength due to suction is presented in this paper.

Testing Program

The clay till used for the study has the following properties: liquid limit, w_L, equal to 35.5% and plastic limit, w_P, equal to 16.8%. The percentages of sand, silt, and clay are 28, 42, and 30 respectively. The specific gravity of soil is 2.73. The soil is classified as a CL. The AASHTO standard compacted density is 1.80 Mg/m^3 with an optimum water content of 16.3%. Three initial water contents were selected for preparing the soil specimens representing dry of optimum (initial water content of 13% and γ_d of 1.73 Mg/m^3), optimum (initial water content of 16.3% and γ_d of 1.80 Mg/m^3), and wet of optimum (initial water content of 19.2% and γ_d of 1.77 Mg/m^3). Statically compacted specimens were used for the study.

The effective saturated shear strength parameters were determined using conventional direct shear equipment in single stage, multistage and residual shear tests. The unsaturated shear strength was determined in multistage testing using modified direct shear equipment designed by Gan and Fredlund (1988). The drained unsaturated shear strength behavior was determined under three net normal stresses: 25, 100, and 200 kPa for a suction range of 0 to 500 kPa. Soil-water characteristics were determined using a pressure plate apparatus for the suction range of 0 to 1,500 kPa. To attain the suction versus degree of saturation relationship beyond 1,500 kPa (i.e., 4,500 to 300,000 kPa), osmotic desiccators were used. The undrained shear strength characteristics were studied using conventional undrained triaxial tests both in unconfined and confined loading conditions. The details of sample preparation and testing procedures are available in Vanapalli (1994).

Saturated Shear Strength Results

A narrow range of effective cohesion values were determined from the testing. This variation can be attributed to differences in strain rate, different direct shear equipment, type of testing procedures, and the possible variation in soil properties (Vanapalli 1994). The values of c' tended to zero with decreasing strain rates. The effective angle of shearing resistance, ϕ', is 23^o for all three different initial water contents and densities.

Shear Strength of Unsaturated Soil in Drained Loading Conditions

The shear strength mobilization with horizontal displacement in the modified direct shear tests for specimens tested with a net normal stress of 25 kPa at a suction value of 350 kPa is shown in Fig. 1. The strength increase is related to the initial water contents. A more comprehensive analysis with respect to shear strength is offered using the entire shear strength envelope shown in Fig. 2.

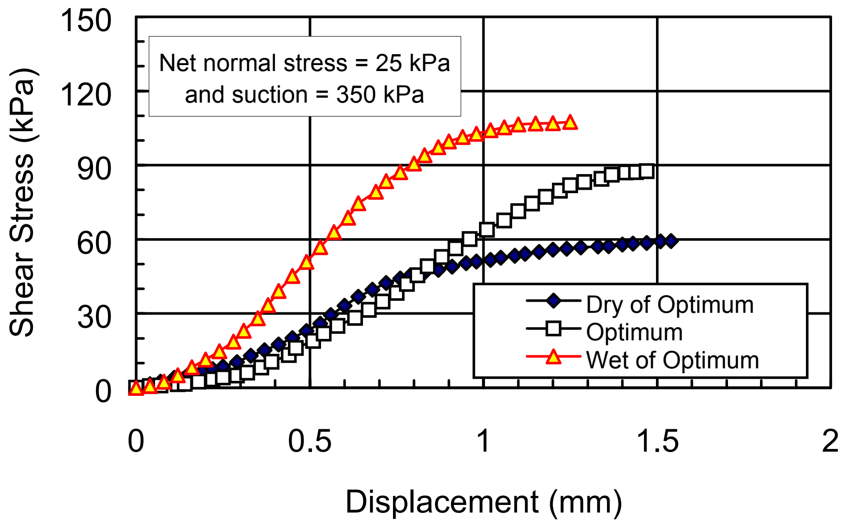

Fig. 1. Shear stress versus horizontal displacement relationship

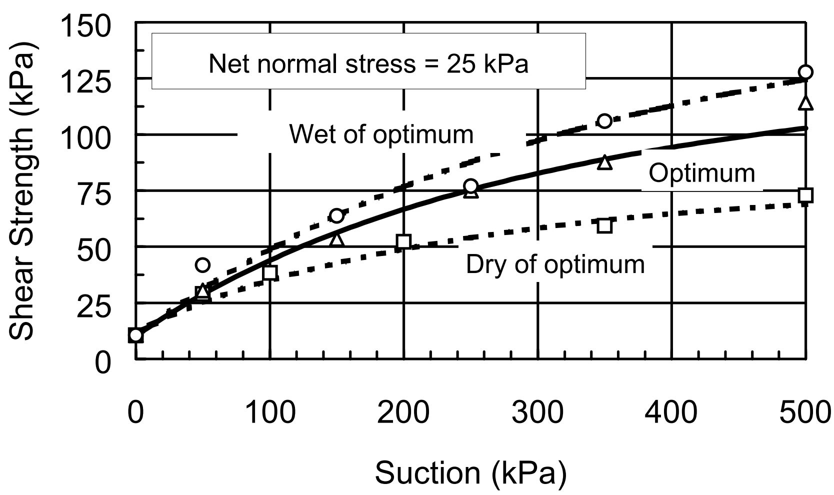

Fig. 2. Shear strength versus suction for three initial water contents

The variation of shear strength with respect to suction for the unsaturated soil specimens tested with three different initial water contents subjected to a net normal stress of 25 kPa is shown in Fig. 2. At any particular value of suction, the dry of optimum specimens have the lowest shear strengths. Specimens tested wet of optimum have the highest shear strength and the specimens tested at optimum water content lie in between that of dry and wet of optimum. Similar trends were observed for specimens tested with a net normal stress of 100 and 200 kPa for the three different initial water contents.

The shear strength behavior under drained loading conditions can be explained using the soil-water characteristics. Figure 3 shows the soil-water characteristics with a net normal stress of 25 kPa for the three different initial water contents. The macro pore structure present in the specimens dry of optimum facilitates easier drainage of water (i.e., desaturation) under an applied suction. In contrast to the dry of optimum specimens, the pore channels in the wet of optimum specimens are generally disconnected and offer greater resistance to water flow. The soil in this latter condition is more impervious since the micro structure dominates and provides resistance to the desaturation process. At any given value of suction, the specimens compacted wet of optimum have the highest degree of saturation while the specimens compacted dry of optimum have the lowest. In other words, the specimens tested at wet of optimum have more wetted interaggregate contact area in comparison to specimens that are dry of optimum. Suction as a stress state variable, transmits shearing stresses more effectively in specimens with greater water contents or higher degrees of saturation. Thus, the unsaturated shear strength in drained loading conditions is always higher in specimens at any given suction value in a specimen that has a higher degree of saturation or water content.

The saturated shear strength as characterized by the shear strength parameters c' and ϕ' for all the specimens tested with three different initial water contents are the same. However, the shear strength in unsaturated conditions is different in each of the specimens due to the imparted soil structure (Fig. 1 and 2). The contribution of shear strength in unsaturated conditions due to the influence of soil structure is dependent on the value of ϕ^b, which is the frictional angle associated with suction. Figure 4 shows the variation of ϕ^b versus suction for specimens tested with different initial water contents with a net normal stress of 25 kPa. Similar trends were observed for specimens tested with net normal stresses of 100 kPa and 200 kPa with the three different initial water contents.

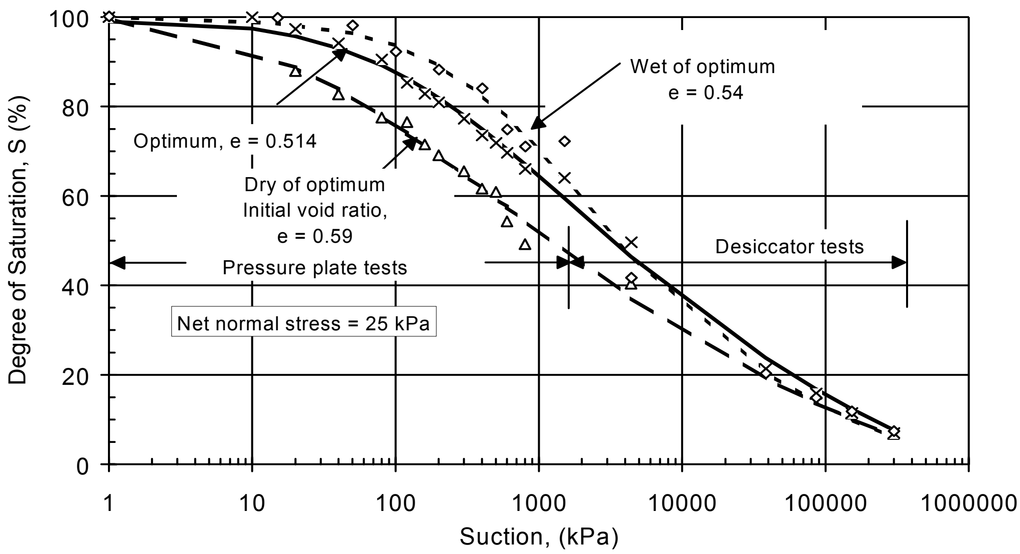

Fig. 3. Soil-water charatersistics for specimens compacted at three different initial water contents

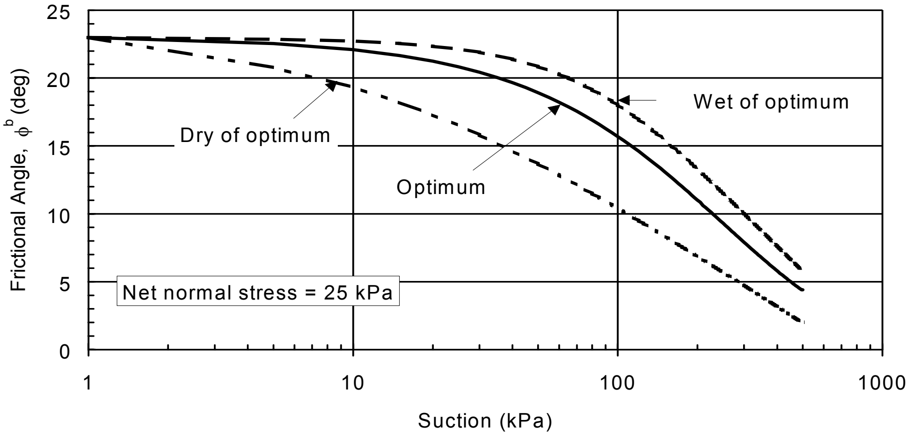

Fig. 4. Frictional angle, ϕ^b, versus suction for 25 kPa net normal stress for specimens with different initial water contents

Figure 5 shows the confined compression test results of specimens with the three different initial water contents. The initial matric suction values of the dry of optimum, optimum, and wet of specimens were 368, 152, and 68 kPa, respectively. Figure 6 shows the variation of shear strength with the applied confining pressure for triaxial specimens tested with known initial suction values in confined and unconfined loading.

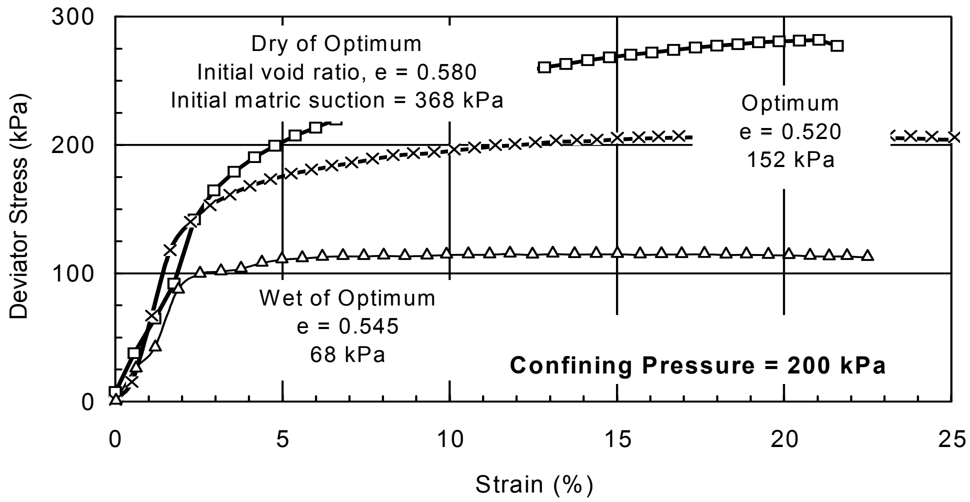

Fig. 5. Stress versus strain relationships of confined compression tests

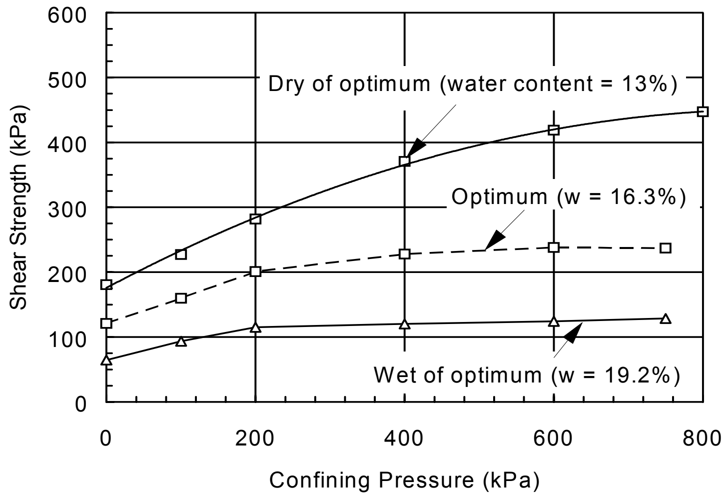

Fig. 6. Variation of shear strength with confining pressure

The trend of results in Fig. 5 and 6 are opposite to that of drained test results shown in Fig. 1 and 2. The specimens tested with lower water contents had lower strengths in drained loading while the strengths were higher in undrained loading conditions. Such contradiction in behavior requires some discussion.

In the research study as described in this paper, the densities and initial water contents are the same both in drained and undrained loading. A comparison of the contribution to strength due to suction both in drained and undrained loading is required to understand the influence of soil structure on the shear strength.

Before the comparisons are undertaken the procedure for predicting the nonlinear variation of shear strength contribution due to suction is briefly detailed for one series of undrained test results obtained from specimens prepared at optimum initial water content and tested in confined and unconfined loading conditions. For this series of tests a horizontal failure envelope was obtained beyond a confining pressure of 400 kPa (Fig. 6). It can be inferred that the specimens were saturated and may have a suction value close to zero for the specimens tested with confining pressures higher than 400 kPa. The measured and predicted degrees of saturation using the theory of undrained pore pressure parameters for confining pressures higher than 400 kPa were close to 100% (Vanapalli 1994).

The degree of saturation versus suction variation (i.e., the wetting soil-water characteristic curve) can be obtained from the undrained triaxial test results. The change in degree of saturation and suction in the undrained triaxial specimens due to the applied confining pressures can be computed from knowledge of the initial conditions of the soil using a marching forward technique. This procedure is detailed in Fredlund and Rahardjo (1993). This technique is not required if the suction and degree of saturation are measured at failure conditions. The soil-water characteristic generated from the undrained tests along with the saturated shear strength parameters was used for predicting the shear strength of unsaturated soils under undrained loading conditions using either Eq. 1 or Eq. 2. These equations are described in the following section of this paper.

There is a good correlation between the predicted and measured variation of shear strength with suction for the specimens compacted at optimum initial water contents. More details of the procedure and the test results are available in Vanapalli and Fredlund (1997). Figure 7 shows the variation of ϕ^b versus suction for these test results.

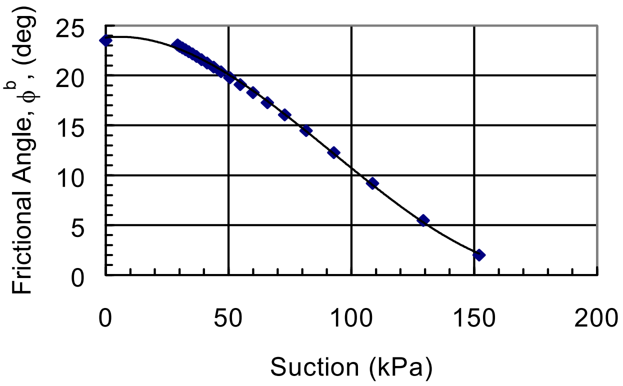

Fig. 7. Variation of frictional angle, ϕ^b, from undrained triaxial shear tests

Comparison of shear strength contributions due to suction in drained and undrained loading conditions

The shear strength of an unsaturated soil can be predicted using one of the following equations:

$$\tau = \left[c' + (\sigma - u_a)\tan\phi'\right] + (u_a - u_w)\left[\left(S^{\kappa}\right)(\tan\phi')\right] \tag{1}$$

$$\tau = \left[c' + (\sigma - u_a)\tan\phi'\right] + (u_a - u_w)\left[\left(\frac{(S - S_r)}{(100 - S_r)}\right)(\tan\phi')\right] \tag{2}$$

where:

κ = fitting parameter
S_r = residual state of saturation

The first part of each equation represents the saturated shear strength, when the pore-air pressure, u_a, is equal to the pore-water pressure, u_w. The second part of each equation is the shear strength contribution due to the soil suction. The information that is needed for predicting the unsaturated shear strength from [1] or [2] is the soil-water characteristic and the saturated shear strength parameters. The fitting parameter, κ, is required to obtain a correlation between the predicted and measured shear strength. The residual state of saturation, S_r, can be estimated from the soil-water characteristic data using a graphical procedure. More details of these equations and procedures are available in Vanapalli et al. (1996) and Fredlund et al. (1996). The unsaturated shear strength of several soils including the clay till used in this study has been successfully predicted using these equations.

The resulting structure or aggregation in a specimen is a function of initial water content and has a considerable influence on the nature of the interphase contact area (i.e., wetted area of contact) that develops in an unsaturated soil. The unsaturated shear strength both in drained and undrained loading is directly dependent on the interphase contact area that is available to transmit the suction as a stress state variable. The variation of this interphase contact area with respect to suction can be interpreted using the soil-water characteristic curve. The normalized wetted area of contact is represented as a dimensionless number, S^{κ}, from [1] or $\{(S-S_r)/(100-S_r)\}$ from [2].

The relationship for $\tan\phi^b / \tan\phi'$ versus $\{(S-S_r)/(100-S_r)\}$ for specimens tested both in **drained** and **undrained** loading conditions is shown in Fig. 8. In spite of different soil structures resulting from different initial water contents and stress states there is a unique relationship between these two variables within the limitations of experimental errors. It seems apparent that the influence of soil structure is directly reflected in the suction values of compacted soils. A similar unique relationship will be obtained for $\tan\phi^b / \tan\phi'$ versus S^{κ} relationship as $\{(S-S_r)/(100-S_r)\}$ is equal to S^{κ}. These unique relationships between $\tan\phi^b / \tan\phi'$ versus $\{(S-S_r)/(100-S_r)\}$ or $\tan\phi^b / \tan\phi'$ versus S^{κ} are useful for further simplifying the interpretations of shear strength of unsaturated soils.

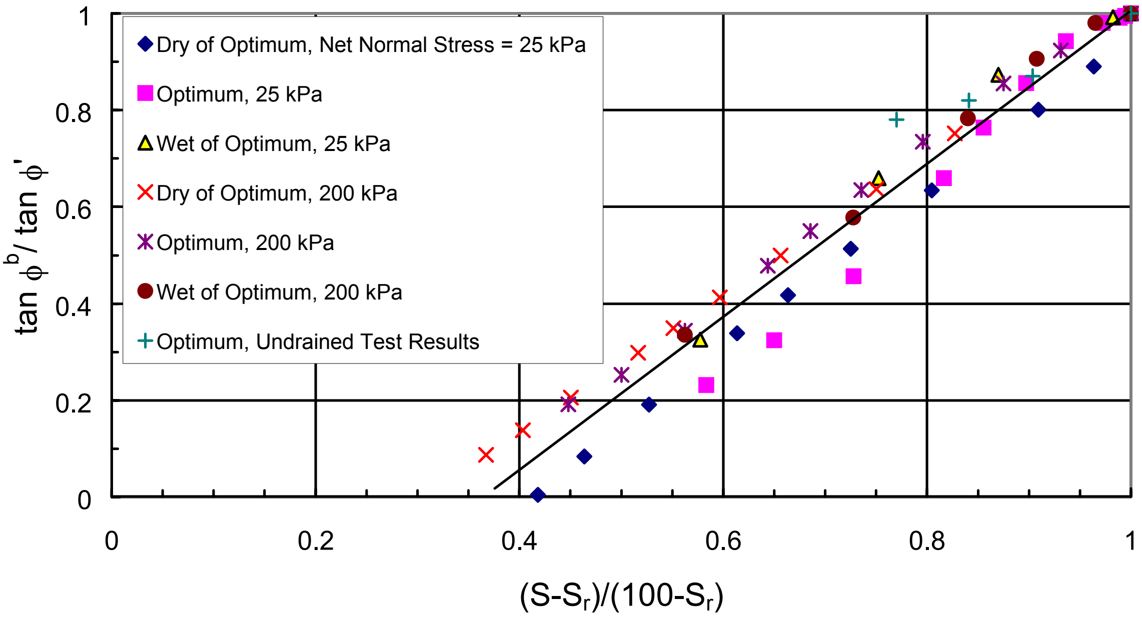

Fig. 8. Variation of tan ϕ^b/ tan ϕ^b versus $(S-S_r)/(100-S_r)$ relationship for drained and undrained shear test results for the clay till

Summary and Conclusions

The influence of soil structure on the drained and undrained shear strength characteristics of statically compacted clay till with three different initial water contents representing dry of optimum, optimum, and optimum water contents have been presented and discussed in this paper. The drained and undrained shear strengths and the soil-water characteristics are different due to the varying soil structures in the specimens. The results of this study support the contention that the resulting soil structure in a compacted soil is a function of initial compaction water content. The influence of soil structure on the drained and undrained shear strength parameters in unsaturated conditions is reflected in shear strength contribution due to suction (i.e., ϕ^b values). In spite of varying soil structures resulting due to different initial water contents, there appears to be a unique relationship between tan ϕ^b/ tan ϕ' versus $\{(S-S_r)/(100-S_r)\}$ or tan ϕ^b/ tan ϕ' versus S^{κ} for the clay till tested. More studies are required on different compacted soils to verify these relationships.

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