SHEAR STRENGTH BEHAVIOR OF AN UNSATURATED SILTY SOIL IN LOW AND HIGH SUCTION RANGE UNDER CONSTANT VOLUME CONDITONS

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ABSTRACT
This paper presents shear strength test results of a compacted, unsaturated silty soil determined using modified direct shear apparatus under constant volume conditions to study the influence of the soil structure both in low and high suction range. Three different compaction water contents representing dry of optimum, optimum and wet of optimum conditions were used to impart different soil structures to the silty soil. The results suggest that the shear strength behavior is significantly influenced by the soil structure in the low suction range (i.e., 0 to 180 kPa) for the soil tested. However, the soil structure does not have any influence on the shear strength behavior for suction values greater than 1,500 kPa. The shear strength of the soil is a constant value in the high suction range (i.e., from 1,500 to 300,000 kPa).

RÉSUMÉ
Cet article présente des résultats d'essai de résistance au cisaillement d'un sol limoneu compacté et non saturé déterminé à l'aide d'un appareil de cisaillement direct dans des conditions de volume constant pour étudier l'influence de la structure des sols tant pour des suctions de faible que de grande envergure. Trois teneurs d'eau de compaction représentant condition du côté sec, humide et à l'optimum ont été utilisées pour induire différentes structures au sol limoneu. Les résultats suggèrent que la résistance au cisaillement soit sensiblement influencée par la structure dans la gamme des faibles suctions (0 à 180 kPa) pour les sols utilisés. Cependant, la structure du sol n'a aucune influence sur la résistance au cisaillement pour des suctions au-delà de 1 500 kPa. La résistance au cisaillement du sol est un valeur constante à hautes suctions (c-à-d de 1 500 kPa à 300 000 kPa).

1. INTRODUCTION

Shear strength is an important engineering property required in the design of stability of slopes, retaining walls, bearing capacity of foundations, pavements and many other soil structures. In conventional engineering practice, soil is assumed to be in a state of saturated condition even though soils are mostly in a state of unsaturated condition. For this reason, the assumption of designing the soil structures based on saturated shear strength parameters is conservative to some degree.

In the last several decades, significant advancements were made with respect to our present understanding of the shear strength behavior of unsaturated soils (Bishop 1959, Bishop et al. 1960, Fredlund et al. 1978, Gan et al. 1988, Escario and Juca 1989, Fredulnd and Rahardjo, 1993, Wheeler and Siva Kumar 1992, Vanapalli et al. 1996, Blatz et al. 2002, Nishimura and Fredlund, 2003). More recently, several investigators have proposed semi-empirical procedures to predict the shear strength of unsaturated soils using the soil-water characteristic curve and the saturated shear strength parameters (Vanapalli et al. 1996, Oberg and Sallfors 1997, Khallili and Khabbaz 1998, Bao et al. 1998). These simple procedures are encouraging practicing engineers to take into account the contribution of soil suction in the shear strength of unsaturated soils.

There are several parameters that influence the shear strength behavior of an unsaturated compacted soil. Some of these parameters include type of soil, stress history, texture, compaction water, void ratio, soil mineralogy, method compaction and soil structure. Limited information is presently available in the literature to understand the influence of many of these parameters. Of the above, soil structure is one of the key parameters that has a considerable influence on the shear strength. The initial molding water content of the compacted soil influences the structure or the aggregation, which in turn has an influence on the shear strength behavior of an unsaturated soil. Earlier studies have shown that soils compacted at various “initial” water contents and to various densities should be considered as “different“ soils from a behavioural standpoint even though their plasticity and texture are the same (Fredlund and Rahardjo 1993, Vanapalli et al. 1996). For this reason, the shear strength behavior from one specimen to another will vary due to the differences in soil structure or aggregation.

This paper presents the test results of a compacted, unsaturated silty soil under constant volume conditions to study the influence of the soil structure on the shear strength behavior both in low and high suction range. Three different compaction water contents representing dry of optimum, optimum and wet of optimum conditions were used to impart different soil structures to the silty soil. Modified direct shear tests were used for determining the shear strength of soil specimens both in low and high suction range. Different techniques were used for the determination of shear strength in the low and high suction ranges. The shear strength was determined using axis translation technique in the low suction range. However, vapour pressure technique was used for determining the shear strength in the high suction range.

2. BACKGROUND

Shear strength behavior of several unsaturated soils is reported in the literature both in low and high suction ranges by several investigators (Gan et al. 1988, Escario and Juca 1989, Fredulnd and Rahardjo, 1993, Wheeler and Siva Kumar 1992, Vanapalli et al. 1996, Blatz et al. 2002 Nishimura and Fredlund 2003). There are also different approaches available in the literature to interpret the shear strength behavior of unsaturated soils (Fredlund et al. 1978, Toll 1990, Wheeler and Sivakumar 1992). However, there are limited studies available to understand the influence of soil structure on the shear strength behavior of unsaturated soils.

A compacted fine grained soil has two levels of structure; namely macro structure and micro structure. The macro structure is the arrangement of soil aggregates whereas the micro structure is the arrangement of elementary particles associations within the soil aggregates (Mitchell 1976). Typically, a fine-grained soil such as silt or clay compacted at dry of optimum has an open structure with large interconnected pore spaces among soil particles within the clods of finer particles. These large pores offer little resistance to drainage under an applied suction. However, specimens with wet of optimum initial water content have no visible interclod pores and offer more resistance to desaturation under an applied suction and exhibit an occluded structure. The threshold for the occluded structure and open states is believed approximately at optimum water content conditions (Marsall 1979). Some studies are available to understand the influence on soil structure on the soil-water characteristic curve behavior over the entire suction range of 0 to 1,000,000 kPa (Vanapalli et al. 1999).

In this paper, the focus of study is to understand the influence of the soil structure on the shear strength of an unsaturated silty soil both in low and high suction range. The low suction is considered to be in the range of 0 to 1,500 kPa; whereas suction values greater than 1,500 kPa is considered to be in the high suction range.

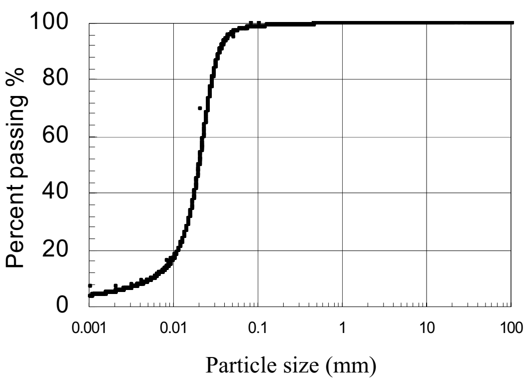

Figure 1. Grain size distribution of the silty soil.

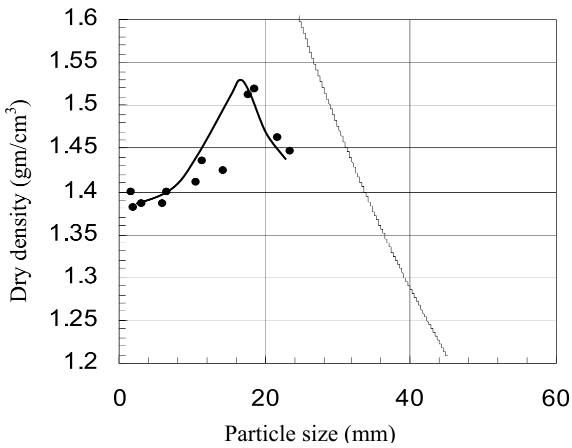

Figure 2. Proctor compaction curve

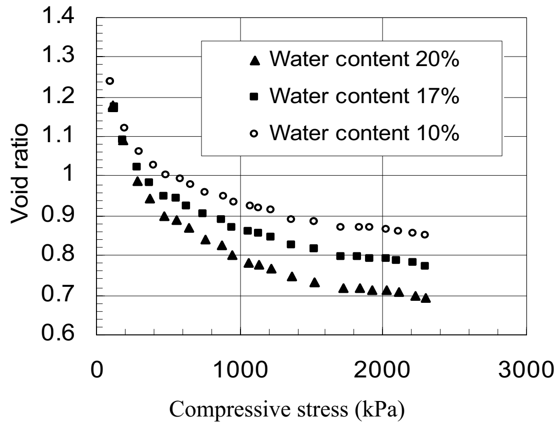

Figure 3. Compression curve.

3. SOIL PROPERTIES, TEST PROGRAM AND PROCEDURE

3.1 Description of soil specimen

A non-plastic silty soil with a uniform grain size distribution was used in the test program (Figure 1). The optimum moisture content of the soil from the Proctor's compaction curve is equal to 17% (Fig. 2). The test program involved in the determination unsaturated shear strength behavior of the silty soil at three selected water contents that represent dry of optimum (i.e., 10%), optimum (i.e., 17%) and wet of optimum water content (i.e., 20%) conditions.

The soil specimens prepared at three different initial compaction water contents (i.e., dry of optimum moisture water content 10%, optimum moisture content 17%, and wet of optimum moisture content 20%) with their respective density conditions determined from Proctor's tests were subjected to static compression stress.

Figure 3 shows the relationship between the void ratio and static compression stress for the three tested specimens. These results suggest the void ratio of the soil specimen compacted at wet of optimum conditions reduces at a rapid rate in comparison to the other two water contents (i.e., optimum and dry of optimum water content conditions). Typically, for any fine-grained soil, the degree of saturation of specimens compacted at wet of optimum conditions is higher in comparison to specimens compacted at dry of optimum and optimum water content conditions. The initial matric suction of the specimen compacted at dry of optimum and optimum conditions will also be higher in comparison to specimens compacted at wet of optimum conditions. Due to this reason, specimens compacted with dry of optimum water content conditions offer more resistance to deformation under static compression loading in comparison to specimens compacted with optimum and wet of optimum water content conditions. In other words, the soil structure of specimens with higher water contents offer less resistance to deformation under an applied static compression stress in comparison to specimens with lower water contents.

In the present research program, the statically compacted specimens with "identical" initial void ratio of 0.89 (prepared by subjecting the specimens to static loading as detailed in Figure 3) with different initial compaction water content conditions (i.e., dry of optimum moisture water content, 10%, optimum moisture content, 17%, and wet of optimum moisture content. 20%) were used for determining the shear strength behavior both in low and high suction range using the modified direct shear test apparatus.

3.2 Procedure for the determination of shear strength using modified direct shear test apparatus in the low suction range

The statically compacted specimen prepared with an initial void ratio of 0.89 as detailed earlier was placed in the modified direct shear box and allowed to imbibe de-aired distilled water under constant volume conditions. Constant volume conditions were maintained by changing the normal stress on the specimen. The procedure is similar to the technique used for the determination of swelling pressure of expansive soils using conventional consolidation test apparatus under constant volume conditions. This technique facilitates the specimen to achieve fully saturated condition under constant volume conditions without changing the soil structure of the prepared compacted specimen. The saturated specimens were then subjected to a known value of matric suction using the axis translation technique in the modified direct shear test apparatus.

After ensuring equilibrium conditions, the specimen was sheared at a rate of 0.25 mm per minute. The shear strength of soil specimens were determined at different values of matric suctions (i.e., 20 kPa, 40 kPa, 80 kPa, 120 kPa and 180 kPa) using the modified direct shear test apparatus. The soil specimen was sheared over approximately 6 mm horizontal displacement or until a peak value of shear stress was observed. The total volume of soil specimens was maintained constant during the shearing of the specimen by changing the normal load on the specimens. The constant volume condition was checked by monitoring vertical displacement guage on the specimens. It was ensured that the vertical movement of the specimens was less than 0.01 mm throughout the shearing stage. The normal stress on the specimens which was varied to maintain a constant volume conditions during the shearing was not measured in this study.

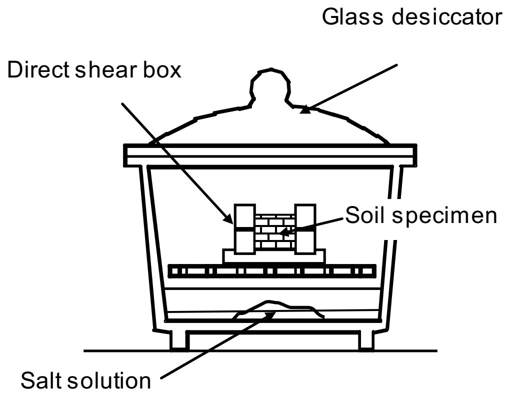

Figure 4. Illustration of vapor pressure technique.

3.3 Procedure for the determination of shear strength using modified direct shear test apparatus in the high suction range

A different technique known as vapour pressure technique was used for determining the shear strength in the high suction range (i.e., greater than 1,500 kPa). In the vapour pressure technique a known relative humidity environment is created such that high suctions can be achieved in the soil specimens under controlled conditions.

The soil suction may be determined by the measurement of the vapour pressure in equilibrium conditions with the soil water (Edlefsen and Anderson 1943). The value of soil suction can be calculated simply knowing the relative humidity. Equation (1) can be used to determine the soil suction, if the temperature is 20 degrees

$$\psi = -135022 \ln(RH) \quad (1)$$

where:
ψ : soil suction or total suction (kPa), RH : relative humidity (%).

Table 1. Summary of salt solutions used in test program.

Chemical symbol	Relative humidity %	Soil suction kPa
K_2SO_4	98	2830
KNO_3	95	6940
$NH_4H_2PO_4$	93	9800

In the test program, a controlled relative humidity environment was achieved by using three different kinds of salt solutions in glass desiccators. The three different salt solutions used were potassium sulfate (K_2SO_4), potassium nitrate (KNO_3), and ammonium dihydrogenphosphate ($NH_4H_2PO_4$). Each of these salt solutions is capable of inducing a different suction value. Table 1 summarizes the relative humidity and soil suction corresponding to each salt solution. Figure 4 illustrates the details of equipment assembly for vapour pressure technique.

The direct shear box along with the soil specimen was placed in the glass desiccator to achieve desired high suction in the soil specimen through equilibration under controlled relative humidity environment (Fig. 4). The direct shear box assembly with the soil specimen was placed in the glass desiccator that had a volume equal to 4400 cc. The mass of the direct shear box assembly with the soil specimen was measured at regular intervals until it is a constant value. The soil specimen attains a constant mass value in approximately one month. The direct shear box along with the equilibrated soil specimen with the desired suction value was then transferred to modified direct shear test apparatus. The remainder of the testing details are similar to the procedures detailed for the determination of the shear strength of soil in the low suction range.

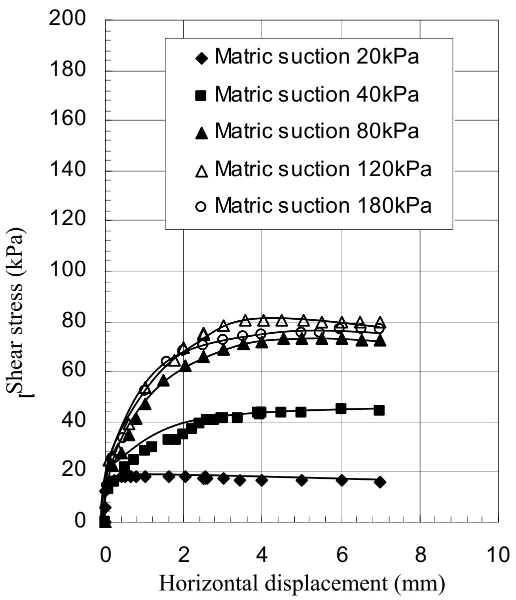

Figure 5. Shear stress-displacement relationships in low suction range (Initial water content = 10%)

4. TEST RESULTS

4.1 Shear stress versus horizontal displacement relationship in the low suction range

The relationship between the shear stress and horizontal displacement for soil specimens of different initial compaction water contents under constant volume conditions in the low suction range (i.e., 20 to 180 kPa) are presented in Figures 5, 6 and 7. The stress-strain curve behavior is typically hyperbolic in nature for the specimens tested. The shear stress increased at a faster rate at low shear strains. There is a non-linear increase in the shear stress with an increase in the matric suction. In other words, the rate of shear strength contribution was higher in specimens tested with low matric suction values (i.e., for matric suction values lower than 80 kPa) in comparison to specimens tested with matric suction values in the range of 120 to 180 kPa. The non-linear increase in the shear strength for specimens tested with low suction range is consistent with the observations of other investigators (Gan et al. 1988, Vanapalli et al. 1996, Khallili and Khabbaz 1998).

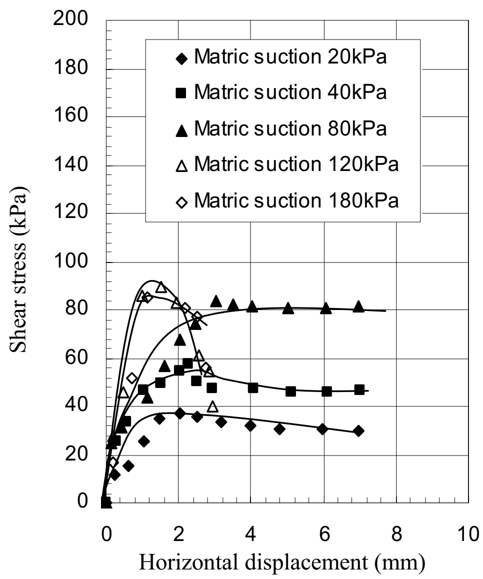

Figure 6. Shear stress-displacement relationships in low suction range (Initial water content = 17%)

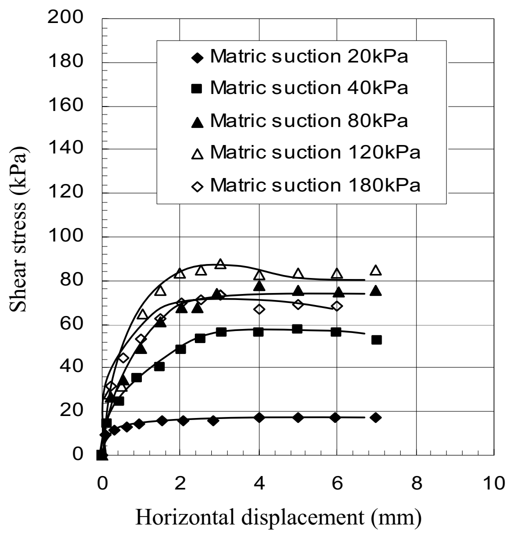

Figure 7. Shear stress-displacement relationships in low suction range (Initial water content = 20%)

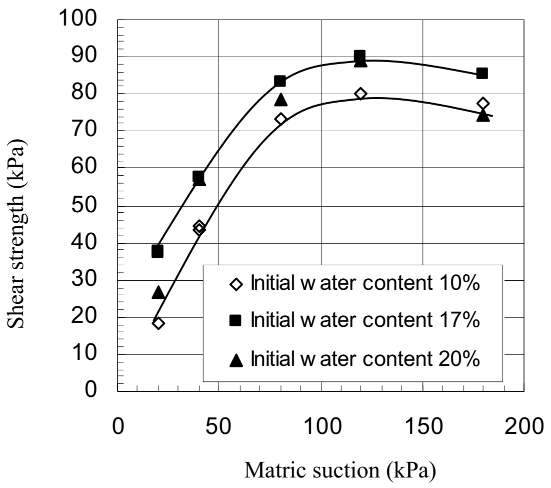

Figure 8. Variation of shear strength with matric suction for specimens tested with different initial water contents (low suction range)

4.2 Influence of soil structure on the shear strength behavior in the low suction range

Figure 8 shows the variation of shear strength with respect to matric suction for the soil specimens compacted with three different "initial" water contents (i.e., dry of optimum water content, 10%; optimum water content, 17%; and wet of optimum water content, 20%) using the test results shown in Figures 5, 6 and 7 in the low suction range (i.e., 0 to 180 kPa). The shear strength of soil specimens compacted with optimum and wet of optimum water contents is higher than soil specimens compacted with dry of optimum water content conditions. In other words, at any particular matric suction value, the specimens tested at dry of optimum water content conditions (i.e., 10%) have the lowest strengths. Shear strength of specimens tested with water contents representing optimum and wet of optimum and water contents is higher. This behavior can be attributed to the influence of soil structure of specimens with wet and optimum water contents. The specimens with higher water contents have more interaggregate contact points that are wet and matric suction can more effectively contribute to an increase in shear strength. The dry of optimum water content specimens have a lower storage capacity and hence have lesser wet interaggregate contact points. Due to this reason, shear strength contribution due to matric suction is less effective in comparison to specimens compacted with optimum and wet of optimum conditions. Similar observations were reported based on the test results undertaken on a glacial till in the matric suction range of 0 to 500 kPa (Vanapalli et al. 1996)

While the shear strength increased for all specimens with different "initial" compaction water contents up to 120 kPa matric suction value, there was drop in shear strength observed for specimens tested with matric suction values greater than 120 kPa. Similar trends of decrease in shear strength were reported by other investigators at large suction values for fine-grained soils (Escario and Juca 1989). The decrease in shear strength can be attributed to reduction in contribution of matric suction as the effective wet contact area reduces as the suction increases. For the silty soil tested, it is likely that at suction values of 120 kPa and higher, the effective wet contact area to transmit the matric suction reduces. For this reason, there is a drop in shear strength contribution due to matric suction beyond a value of 120 kPa. This behavior was observed for all the tested specimens irrespective of the initial compaction water contents.

4.3 Shear stress versus horizontal displacement relationship in the high suction range

Figures 9, 10 and 11 show the relationships between the shear stress and horizontal displacement for specimens tested with three different initial compaction water contents under a constant total volume with high soil suctions (i.e., in the range of 1,500 to 10,000 kPa). All the soil specimens have relatively low water contents because of high suctions.

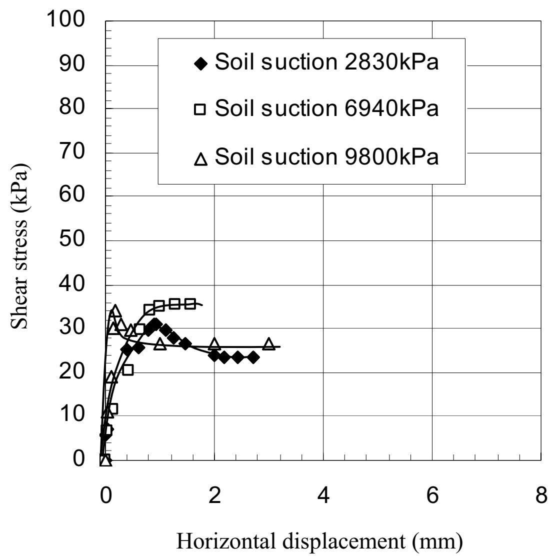

Figure 9. Shear stress-displacement relationships in high suction range (Initial water content = 10%)

The shear stress versus horizontal displacement relationships as shown in Figs. 9, 10 and 11 attain peak values with horizontal displacements less than 2 mm. A relative steady state was observed in shear stress values for displacements in the range of 2 to 6 mm for most of the specimens tested. The soil specimens tested high suctions exhibited both peak and residual strength values. The shear stress versus horizontal displacement relationships are approximately similar for all the specimens tested with different initial compaction water content conditions and suction values.

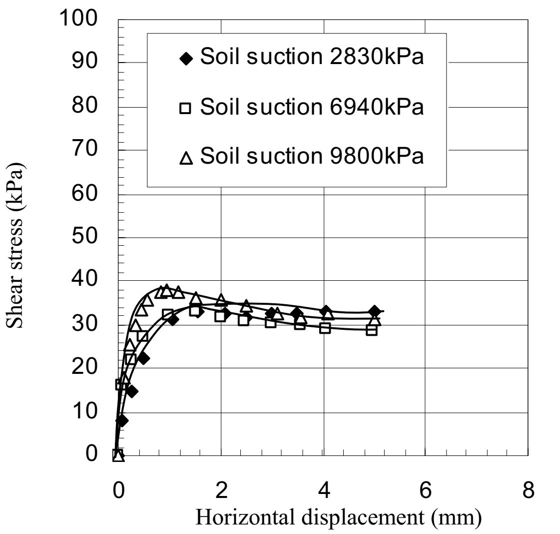

Figure 10. Shear stress-displacement relationships in high suction range (Initial water content = 17%)

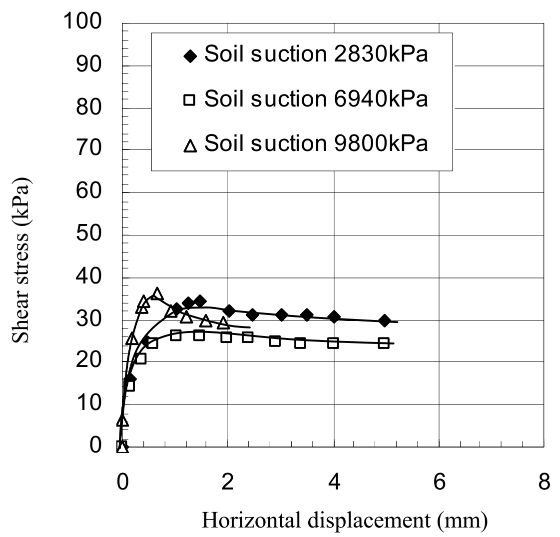

Figure 11. Shear stress-displacement relationships in high suction range (Initial water content = 20%)

4.4 Influence of soil structure on the shear strength behavior in the high suction range

Figure 12 shows the variation of shear strength with respect to high soil suction (i.e., 1,500 kPa to 10,000 kPa range) for all the specimens tested with three different initial compaction water content conditions. The shear strength is approximately constant in the high soil suction range. In other words, there is a unique shear strength envelope for constant volume direct shear tests (i.e., a horizontal envelope) for the soil tested in the high suction range. The test results suggest the shear strength behavior is independent of the influence of soil structure in the high suction range.

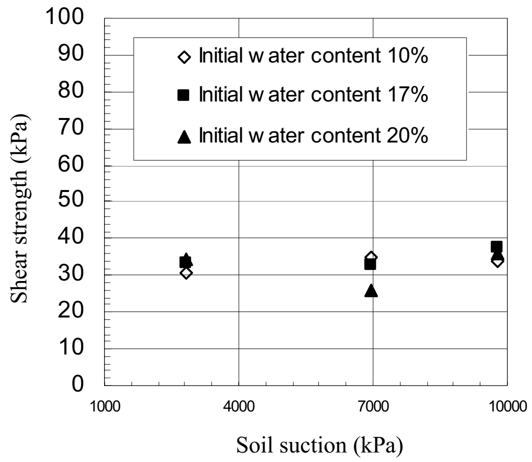

Figure 12. Variation of shear strength with soil suction for specimens tested with different initial water contents (high suction range)

4.5 Shear strength behavior over a large suction range

Figure 13 shows the shear strength results determined using modified direct shear apparatus both in the low and high suction range (i.e., from 20 to 10,000 kPa). There is a non-linear increase in the shear strength behavior under constant value conditions in the low suction range of 20 to 120 kPa for all the specimens tested with different initial compaction water contents. However, the contribution of shear strength due to matric suction starts dropping for suction values greater than 120 kPa. This behavior is consistent for all the specimens tested with different soil structures. It appears; at the matric suction value of 120 kPa there is not enough wet interaggregate area to transmit suction effectively as a stress state variable. From this value of suction value, shear strength contribution due suction decreases. At high suction values, as discussed earlier, there is a further drop in the shear strength. The shear strength envelope in the high suction range of 1,500 to 10,000 kPa is unique for all the three series of test results with different soil structures. In other words, the influence of soil structure is observed only in the low suction region but not in high suction range.

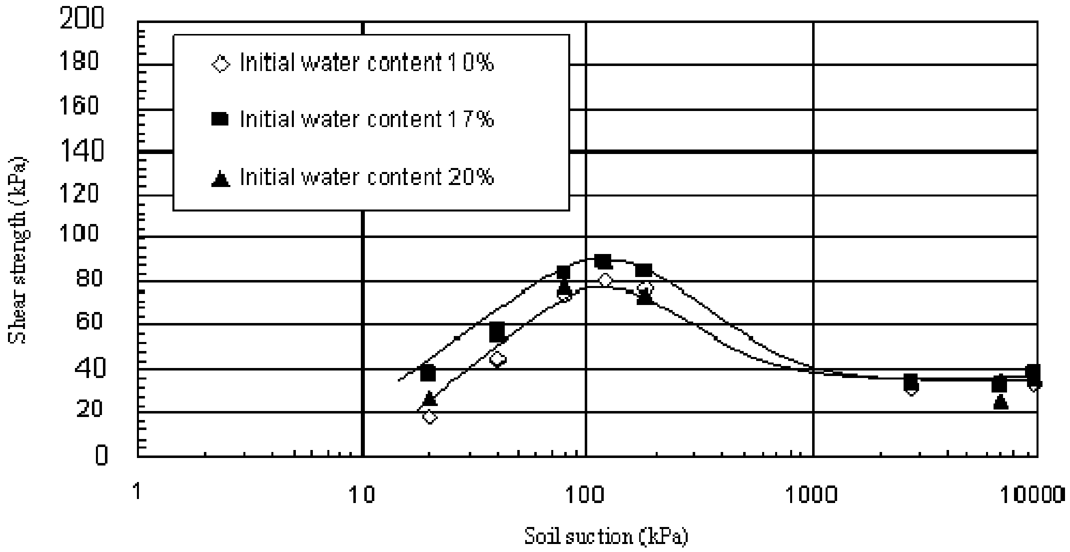

Figure 13. Variation of shear strength with soil suction considering both low and high suction ranges

4.6 Constant stress direct shear strength results in the high suction range.

Another series of shear strength tests were conducted to determine the shear strength behavior of the same silty soil in the high suction range (from 1,500 kPa to 300,000 kPa) using modified direct shear test apparatus. This series of tests were conducted on specimens compacted with an initial water content equal to 17% with a constant vertical stress of 100 kPa.

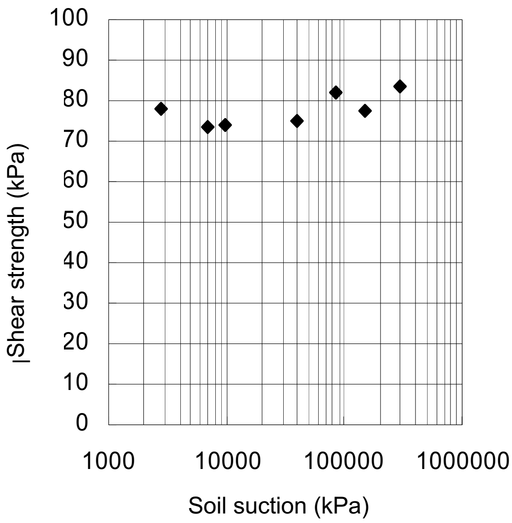

Figure 14. Variation of shear strength with respect to soil suction from constant stress direct shear tests

To achieve suction values higher than 10,000 kPa in the soil specimens, additional salt solutions were used. The different salt solutions used were, sodium chloride (NaCl), magnesium nitrate ($Mg(NO_3)_2 6H_2O$), magnesium chloride ($MgCl_2 6H_2O$), lithium chloride (LiCl).

The shear strength of all soil specimens in the suction range of 1,500 to 300,000 kPa was essentially constant (Figure 14). These test results suggest that the shear strength envelope of the tested silty soil is essentially horizontal (i.e., the shear strength is the same in the high suction range) irrespective of the different testing procedures.

5. SUMMARY AND CONCLUSIONS

The focus of the study presented in this paper is towards understanding the influence of the soil structure on the shear strength of an unsaturated silty soil both in low and high soil suction range. Three different initial compaction initial water contents (i.e., dry, optimum and wet of optimum) were used in the study to achieve differing soil structures. Shear strength was determined on statically compacted specimens at a constant void ratio of 0.89 but with different initial compaction water contents (i.e., dry optimum, optimum and wet optimum) using modified direct shear test apparatus. The shear strength of the soil was determined using axis translation technique in the low suction range and vapour pressure technique in the high suction range. The shear strength of all specimens was determined maintaining constant volume conditions during the shearing stage. A non-linear shear strength failure envelope was observed for all the three series of tests in the low suction range. The specimens tested with higher initial compaction water contents (i.e., optimum and wet of optimum conditions) exhibited a higher strength in the low suction range. Higher shear strength of specimens compacted with higher water contents can be attributed to the availability of larger wetter aggregate contact area points along which matric suction was more effectively communicated towards the contribution of increase in shear strength. In other words, soil structure has a considerable influence on the shear strength behavior in the low suction range. The shear strength envelope is essentially horizontal in the high suction range (i.e., 1,500 to 10,000 kPa) from constant volume modified direct shear tests. Similar trends of results were observed from constant load modified direct shear tests for the suction range of 1,500 to 300,000 kPa.

In summary, for the tested silty soil, shear strength increases non-linearly up to a suction value of 120 kPa. There is a drop in the shear strength for higher suction values. However, the shear strength for the soil attains a constant value for suction values greater than 1,500 kPa irrespective of the initial compaction water content of the tested specimens.

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