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Shear Strength Behavior and Soil Water Retention Curve of a Dual Porosity Silt-Bentonite Mixture

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Abstract. *Evaluation of soil shear strength is an important step in the stability analysis of earth structures, foundations and natural slopes. The shear strength profile of unsaturated soil is dictated by the suction profile. This profile depends on the evaporation rate, depth of the water table and the soil water retention curve. In this paper, the soil water retention curve of a dual porosity silt-bentonite mixture is determined; employing the vapor equilibrium method and osmotic suction technique, and the validity of these approaches is examined against the results from the filter paper technique. Besides, the effect of the stress state on the suction value is studied employing the filter paper method. Furthermore, the shear strength response of the material is evaluated for a wide range of suction values (0-287MPa) employing the direct shear apparatus. Results of direct shear tests show that the expansive clay behaves like a normal consolidated soil at suction values less than, or equal to, 20.5MPa, while its behavior is similar to the heavily over consolidated soils for suction more than 20.5MPa.*

Keywords: *Shear strength; Expansive clay; Soil water retention curve; Dual porosity.*

INTRODUCTION

Shear strength forms a fundamental engineering property in the design of numerous geotechnical structures, such as foundations, embankment dams, pavements and retaining structures. Besides, suction has a significant effect on the shear strength features of medium to fine grained soils. Therefore, considerable experimental research has been done on the shearing response of unsaturated soils.

Some researchers resorted to triaxial tests to study the effect of suction on the shear strength parameters of soils [1-13]. Others selected direct shear apparatus to investigate the role of suction in controlling the shear strength of different soils [14-18].

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The importance of matric suction in the stability of residual soil slopes in Singapore where shallow slides are frequent was illustrated by Rahardjo et al. (1995) [19]. Results of Oloo (1996) tests showed the importance of matric suction in the bearing capacity of pavement structures [20]. Rassam and Williams (1997) considered a suction profile and demonstrated that the stability was enhanced by about 25% when the matric suction contribution to shear strength was taken into account in the calculation [21]. Adams and Wulfsohn (1998) concluded from the results of their tests that shearing under confining stresses greater than the matric suction of the soil caused pore water pressure to increase, with corresponding loss of strength at the critical state of agricultural soils [22]. These soils also have strength significantly lower than that defined by the critical state line, when sheared under zero confining stress. Lee et al. (2005) centered their study on understanding the effect of net normal stresses on the shearing response and Soil Water Retention Curve (SWRC) of unsaturated soils [11]. Shimizu et al. (2006) studies confirmed the effect of the drainage condition in the results of shear tests [23].

Furthermore, the nonlinearity of shear strength versus suction envelope has been related to the soil-water retention curve by some other researchers [2-5,24-29].

Despite the huge amount of research on the shear response of unsaturated non-expansive soils, little work has been done to date on the shear strength behavior of expansive unsaturated clays. Expansive clays, beside collapsible clays [30], are among problematic soils, and exhibit certain characteristics such as considerable swell-shrinkage behavior and crack propagation during the drying-wetting process. Kim and Oneill (1998) employed a field test program to evaluate the effect of seasonal moisture changes on the unit shear stress acting on the sides of a drilled shaft in expansive clay [31]. Miao et al. (2002) considered the effect of number of drying-wetting cycles on the hysteresis loop of the SWRC of expansive clay [32]. They proposed a hyperbolic model to simulate the shear strength of these soils. More recently, Zhan and Ng (2006) carried out some direct shear tests on slightly expansive natural and remolded clays. The results demonstrated that the dilatancy of soil increases with an increase in suction [33]. The axis translation technique was used in this research and the tests were performed in the range of low suction values (0 to 200 kPa).

It is worth noting that highly expansive clays usually include extremely fine grained montmorilonite particles, with air entry values more than the range of suction values covered using the axis translation technique. Besides, in engineering practice, soils are usually compacted at water contents close to the optimum value, leading to a bimodal pore size distribution curve (dual porosity structure). Dual porosity clays are composed of the clay aggregates that, in turn, include considerable clay platelets. While the fabric of the aggregates makes the macro-structure of the soil, arrangement of clay platelets forms the micro-structure of the clay.

With this background, lack of information about the shearing response and retention curve of compacted expansive clays is still evident, especially for the high range of suction values. In this paper, the shear strength features and SWRC of an expansive dual porosity silt-bentonite mixture is studied, utilizing the osmotic method and vapor evaporation techniques.

OSMOTIC METHOD

In the osmotic method, a polyethylene glycol (PEG) solution was used to apply the suction. A semi-permeable membrane separates macromolecules of the solution from unsaturated soil [34,35]. The osmosis process allows water to exchange across the membrane with the amount of water swap depending on the macromolecule concentration. PEG with a molecular weight of 6000 Da (1 Da = $1.6605*10^{-24}$ g) was selected in this study. The relationship between PEG concentration and the amount of suction is given by [36,37]:

$$s = 11c^2, \tag{1}$$

where s is the suction in MPa and c is the concentration of PEG in gr of PEG per gr of water. Temperature affects the relationship between suction and PEG concentration, and Equation 1 is valid when the temperature is maintained at 20 ± 1.5°C and for suction less than 8.5 MPa [38].

VAPOR EQUILIBRIUM TECHNIQUE

The vapor equilibrium method has been founded on the Kelvin equation for perfect gases, that is:

$$s = -\gamma_w \frac{RT}{Mg} \ln(\text{RH}), \tag{2}$$

in which s is suction (kPa), R is universal constant for perfect gases (8.31 $\text{J}^{-1}.\text{mol}^{-1}.\text{K}^{-1}$), γ_w is the unit weight of water (9.81 kN/m^3), g is the gravitational constant (9.8 m/sec^2), M is the molecular weight of water ($18*10^{-3}$ kg.mol^{-1}), T is absolute temperature (K) and RH is relative humidity (%). Thus a constant value of total suction (the thermodynamic potential of the soil pore water relative to a reference potential of free water) will be imposed on a soil sample placed near to a saturated salt solution in an airtight chamber. Different total suctions can be imposed by employing different solutions. It is worth mentioning that the uncertainty in the relative humidity imposed by a salt solution is between 1 and 2%. Therefore, the validity of the saturated vapour equilibrium technique is limited to suction more than 10 MPa [39].

MATERIAL

An artificially prepared highly expansive silt-bentonite mixture was employed to study shearing response and SWRC behavior. Forty percent of the material consisted of Xeuilley silt from east France. X-ray diffractometry demonstrated that this silt contains 60% quartz, 20% montmorilonite and 11% feldspar with the remaining part containing kaolin and mica. The commercially available bentonite contains more than 80% calcium montmorilonite. The maximum particle size used to prepare the samples was 400 μm (obtained by sieving). Table 1 shows the physical characteristics of the material.

SAMPLE PREPARATION METHOD

The silt-bentonite mixture was blended to the desired water content and stored in a humid chamber. After

Table 1. Physical properties of silt-bentonite mixture.

Liquid limit (%)	87
Plasticity index (%)	22
Specific gravity	2.67
Initial dry density (kN/m^3)	14.5
Initial water content (%)	15
Pressure for static compaction (kPa)	2000
Optimum water content in static compaction (%)	23
Maximum dry density in static compaction (kN/m^3)	17.8
Free swelling (%)	26
Swelling pressure (kPa)	350

48 hours, the soil was compacted in the shear box to the required dry unit weight, employing a strain control compaction machine with a rate of 0.1 mm per minute. All samples were prepared to, nominally, the same initial dry unit weight and moisture content prior to testing. This is important to avoid any difference in the fabric of samples resulting from different compaction moisture content.

Fourteen specimens, 169 mm in diameter and 10 mm in height, were prepared and tested in the direct shear apparatus. The dry unit weight was in the range of 14.5 to 15 kN/m^3 and the variation in moisture content was in the range of 14.5 to 15.5%. Eleven samples were put in airtight chambers beside different salt solutions for at least four weeks to impose different suction values, using the vapor equilibrium technique. Table 2 shows salt types and their corresponding suction values. Samples were weighed sequentially during these four weeks to ensure suction equalization by monitoring variations in the weight of samples. Other samples (three specimens) were inundated in the shear box to perform shear tests in a saturated condition. Moreover, several smaller samples with diameter of 38 mm and height of 10 mm were prepared by the same procedure to determine SWRC and also to measure the suction values of the material under different stress states.

Table 2. Salt solutions and their corresponding suction values.

Salt	Suction Value (MPa)
LiCl	287.9
$MgCl_2$	152.9
K_2CO_3	113.2
$MgNO_3$	83.6
NaCl	38.9
KCl	20.5
KNO_3	8.5

SOIL WATER RETENTION CURVE (SWRC)

The association between moisture content and suction is referred to as the SWRC. To study the hydro-mechanical behavior of multiphase media, such as saturated and unsaturated soils, one needs to know the characteristics of the material. SWRC parameters can represent these characteristics.

For gap graded soils with two or more pore structures, the corresponding SWRC can be bimodal or multimodal. For dual porosity soils, with suction surpassing the first air entry value, air starts to fill the macro-pores. At this stage, the micro-pores remain saturated until the suction reaches the second bubbling pressure. Therefore, more parameters are needed to describe the whole bimodal SWRCs, which are residual degrees of saturation for micro-pores $(S_r)_{rm}$ and the bubbling pressure of micro-pores $(u_a - u_w)_{bm}$. To make a distinction between parameters of macro-pores and micro-pores, parameters of the first part of SWRC are recognized by capital M: $(u_a - u_w)_{bM}$ for the bubbling pressure of macro-pores, and $(S_r)_{rM}$ for the residual degree of saturation for macro-pores.

It is worth noting that several other studies have been performed on bimodal SWRCs in recent years [40-42].

Testing Program

Desorption and sorption branches of the SWRC of a silt-bentonite mixture were determined in terms of gravimetric moisture content, w, and also degree of saturation S_r, using osmotic suction for suctions less than or equal to 8 MPa, also employing the vapour equilibrium method for suction values more than 8.5 MPa.

The filter paper technique was employed to validate the results. Samples and Whatman No. 42 filter papers were placed in a container for at least two weeks until they reached a state of equilibrium with the relative humidity in the measuring chamber. Moisture contents of the samples and papers were measured and their suction values were determined based on the standard curve [43].

A petroleum product named kerdane was employed to determine the volume of voids and hence the variation of volume during free wetting and drying processes. The Kerdane contact angle is more than 90°, and therefore, it is a non wetting fluid. Samples were weighed in a wetted situation and while samples had been submerged in Kerdane. The total volume of the samples was then determined using the Archimedes rule. Having the total volume of the sample, together with the water content and weight of the soil specimen, the unit weight of the soil and, subsequently, the void ratio, is determined.

Results and Discussion

The results of the drying branch were compared with the results from the filter paper test (Figure 1). There is a difference between the results of the filter paper and the osmotic method in the first portion of SWRC, as shown in the figure. This difference indicates the difference between total and matric suctions of the soils measured using filter paper and osmotic methods, respectively.

Figures 2 and 3 show the experimental data points describing the variation of degree of saturation versus suction during desorption and sorption processes, respectively. The SWRC parameters determined from these figures are presented in Table 3. These bimodal SWRCs imply that micro-pores can be desaturated, even in highly expansive clayey soils.

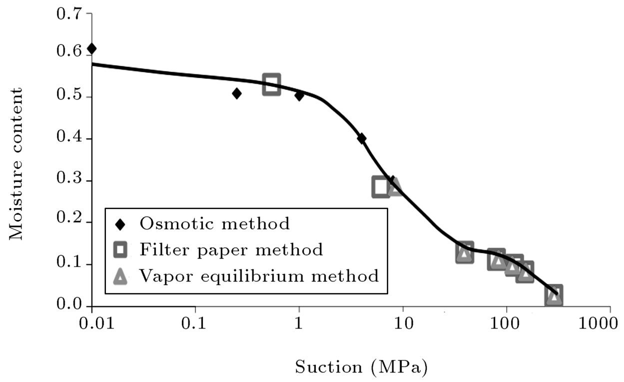


Figure 1. Drying branch of SWRC, osmotic technique, vapour equilibrium methods and filter paper tests results.

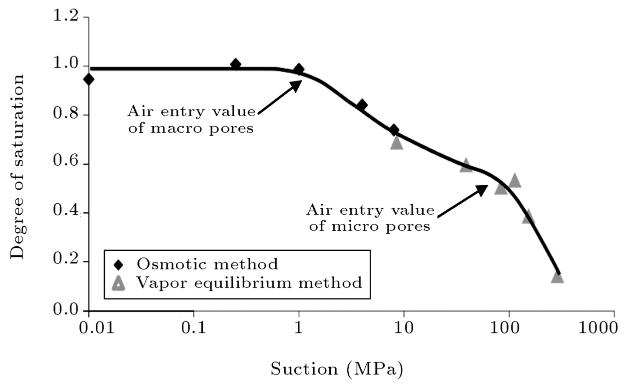


Figure 2. Drying branch of SWRC: variation of degree of saturation with suction.

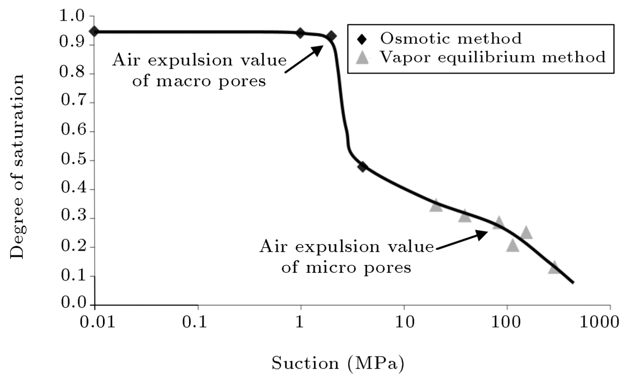


Figure 3. Wetting branch of SWRC: variation of degree of saturation with suction.

Table 3. Parameters of SWRC of silt-bentonite mixture.

Parameter	Drying Branch	Wetting Branch
$(u_a - u_w)_{bM}$ (MPa)	1	2
$(u_a - u_w)_{bm}$ (MPa)	100	100
$(Sr)_{sm}$	50	25
$(Sr)_{rM}$	50	25
$(Sr)_{rm}$	1	1

EFFECT OF STRESS STATE ON THE SOIL SUCTION

To study the influence of stress state on the suction of dual porosity soils, the relationship between the compaction pressure and the total suction of the material was studied. Three compaction pressures were selected: 800, 1000 and 1200 kPa. The total suction of the compacted samples was measured using the filter paper technique. The suction measurements and the initial dry densities are plotted in Figure 4.

As seen from these figures, the iso-suction curves are inclined beyond the optimum water content, thus indicating the dependence of the suction on the applied load. On the dry side of the optimum moisture content,

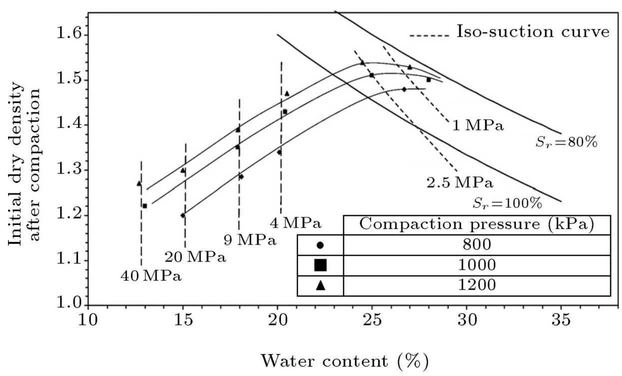


Figure 4. Static compaction curves with iso-suction curves.

the suction does not depend on the initial dry density of the soil, and the iso-suction curves are parallel to the vertical-axis. Some other researchers have reported similar results for compacted clayey materials [44-46].

The results imply that the loading mechanism only affects the macro porosity, which does not contain free water at high suctions, and the moisture is generally held inside the micro pores (aggregates). In other words, suction is controlled by the microstructure on the dry side of the optimum, which means pore water pressure does not vary during the loading process if suction values are big enough. It may, therefore, be concluded that at high suction values, one may shear the samples quickly in a direct shear test under consolidated drained conditions without worrying about pressure equalization throughout the specimen.

It is worth noting that Rahardjo et al. (2004) demonstrated that the response of the pore-water pressure or the matric suction in constant water tests is not related to the volume change of the dual porosity clayey soil during shearing [10], which confirms the aforementioned conclusion.

DIRECT SHEAR TESTS

The shear strength of soils is recognized based on the critical state concept. The critical state is a failure condition under which the soil under loading conditions deforms with no further change in volume [47]. The critical state theory has been extensively used to establish models for simulating the elastic-plastic behavior of unsaturated soils [5,28,48-52], but experimental work is relatively limited, especially for expansive soils.

Testing Program

Fourteen direct shear tests were performed under saturated and unsaturated conditions. Different suction values were imposed on eleven samples employing the vapor equilibrium technique. Samples were put in the direct shear apparatus following the suction equalization phase. Then, different net vertical stresses (difference between normal stress and pore air pressure) were applied to the specimens. Quick shearing of the unsaturated samples (suction values of more than or equal to 20.5 MPa) started when the compaction process was completed. Suction values of the samples were checked at the end of the shear phase, utilizing the filter paper method. The discrepancy from the initial suction was negligible. A similar method was used by Blatz et al. (2002) to perform triaxial shear tests on a sand-bentonite mixture [53]. Moreover, three other samples were inundated in the shear box in order to carry out slow shear tests under satur5ated conditions (rate of horizontal displacement = 0.036 mm/min). Table 4 demonstrates the outline of tests.

Table 4. Outline of the direct shear tests.

Number	Net Vertical Stress (kPa)	Suction (MPa)	Type of the Test
1	50	0	Slow
2	100	0	Slow
3	150	0	Slow
4	100	20.5	Quick
5	200	20.5	Quick
6	400	20.5	Quick
7	100	38.9	Quick
8	100	83.6	Quick
9	100	113.2	Quick
10	100	152.9	Quick
11	150	152.9	Quick
12	50	287.9	Quick
13	100	287.9	Quick
14	150	287.9	Quick

Results and Discussion

Results from saturated tests are presented in Figure 5. The signs for vertical strain are expressed as positive for dilation and negative for contraction of the samples. Vertical strain versus horizontal normalized

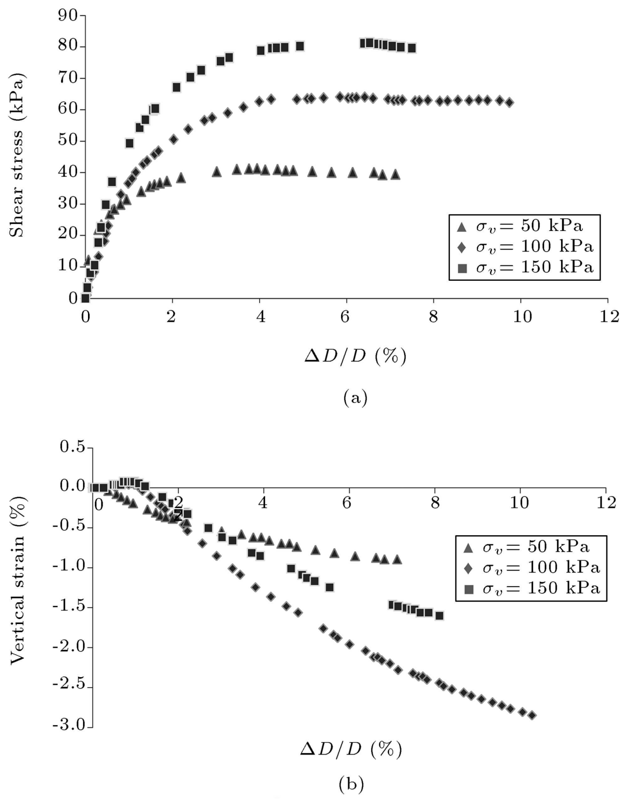


Figure 5. Results of saturated direct shear tests. (a) Shear stress versus normalized horizontal displacement; (b) vertical strain versus normalized horizontal displacement.

displacement curves does not exhibit critical state behavior, and contraction of the samples continues even after the critical state occurrence in the space of the shear stress. The internal friction angle and effective cohesion of the material under a saturated condition is equal to 21.8°and 20 kPa, respectively. Shear stress-horizontal normalized displacement curves under a saturated condition, and for suction values of 20.5 MPa (Figures 5 and 6), show strain hardening behavior until they reach a plateau with no further change in shear stress, which implies a critical state situation. Therefore, at relatively low suction values, the behavior of samples is similar to the characteristics of a normally consolidated soil. Samples that are under greater net stresses tend to contract more. It means that the volume change of the samples in the range of low suction values is governed by the value of net vertical stress.

Figure 7 shows the shearing behavior of some samples under net vertical stress of 100 kPa and at suction values of 38.9, 83.6 and 113.2 MPa. The post softening behavior of these samples includes a second drop in the shear stress at high strain levels (Figure 7). This behavior is a specialty of extremely fine grain soils, such as montmorillonite [54].

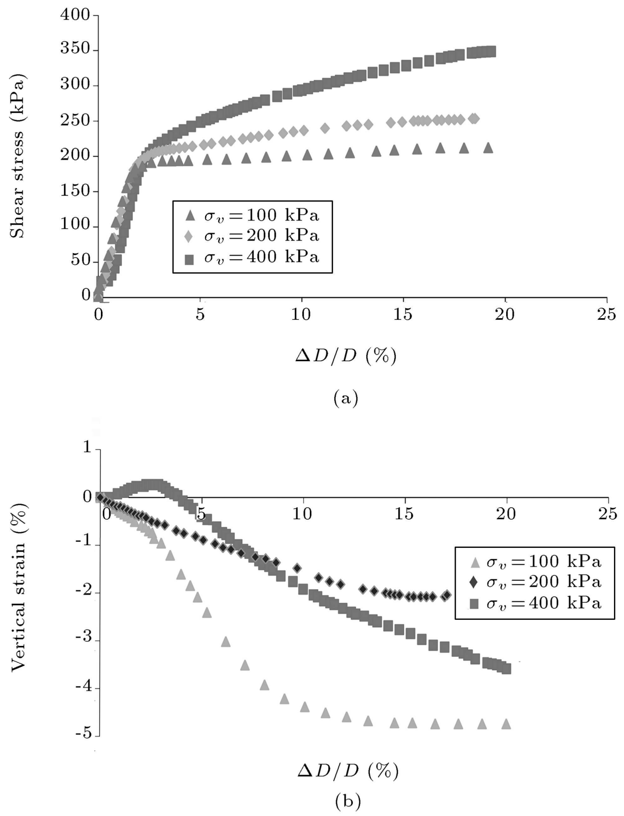


Figure 6. Results of direct shear tests at suction equal to 20.5 MPa. (a) Shear stress versus normalized horizontal displacement; (b) vertical strain versus normalized horizontal displacement.

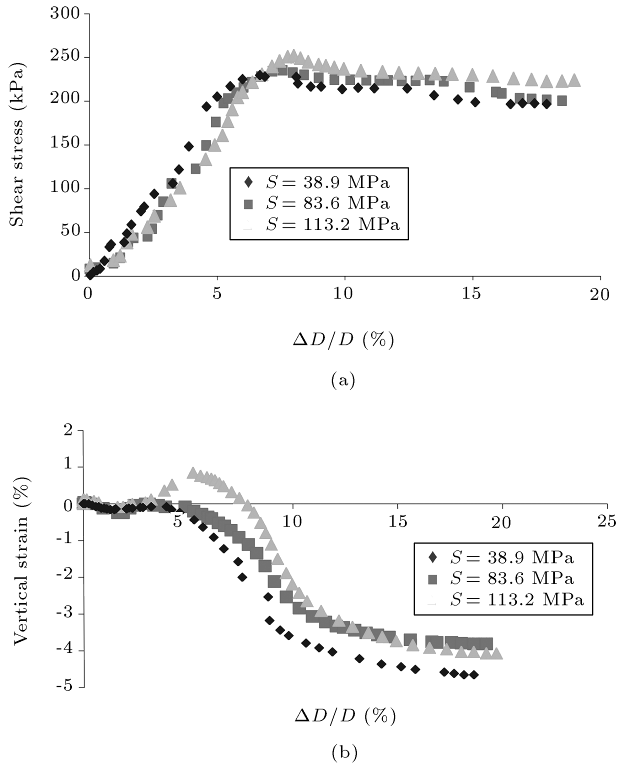
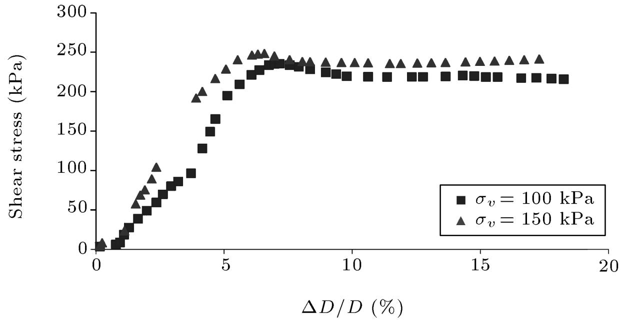


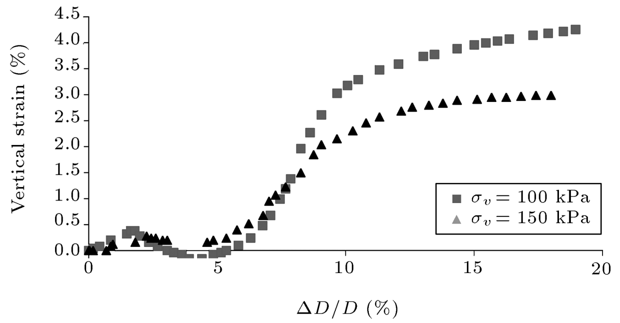
Figure 7. Results of direct shear tests at net stress equal to 100 kPa for different suction values. (a) Shear stress versus normalized horizontal displacement; (b) vertical strain versus normalized horizontal displacement.

At high suction values, the compacted specimens exhibit characteristics of a heavily over consolidated soil with post softening behavior after peak shear strength (Figures 8 and 9). These specimens also show an increase in total volume after an initial contraction during shearing. This behavior can be attributed to the influence of suction on the structure of the samples. Surpassing the air entry value corresponding to the micro-pores, suction causes the dispersed texture of the clay particles to change to a flocculated structure. Changing the structure of the soil from a dispersed arrangement to a flocculated fabric will shift the normal consolidation line to the right side [55] and, thus the yield stress of the soil increases significantly (Figure 10). Alonso et al. (1995) also performed several drying-wetting tests on the compacted expansive clayey soils in an oedometric condition under different applied stresses [56]. The results indicated that the drying induced accumulated shrinkage increased the over-consolidation ratio. Therefore, structured clay shows a behavior similar to heavily over consolidated soils.

The variation of shear strength with suction for net vertical stress equal to 100kPa is shown in Figure 11. The nonlinear envelope approaches a plateau with no further change in the shear strength for a wide range of suction values. Rassam and Williams (1999) reported similar results for tailing soils [7].

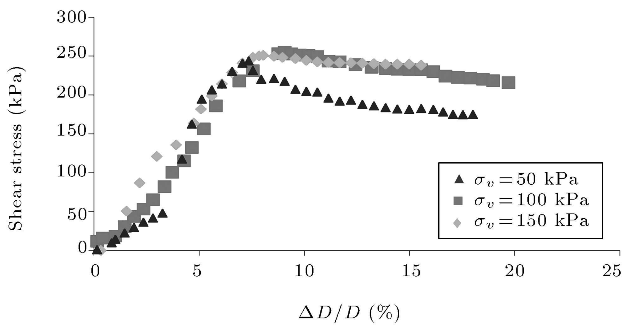


(a)

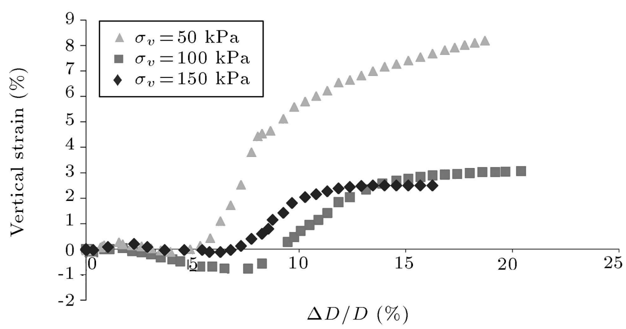


(b)

Figure 8. Results of direct shear tests at suction equal to 152.9 MPa (a) Shear stress versus normalized horizontal displacement; (b) vertical strain versus normalized horizontal displacement.



(a)



(b)

Figure 9. Results of direct shear tests at suction equal to 287.2 MPa. (a) Shear stress versus normalized horizontal displacement; (b) vertical strain versus normalized horizontal displacement.

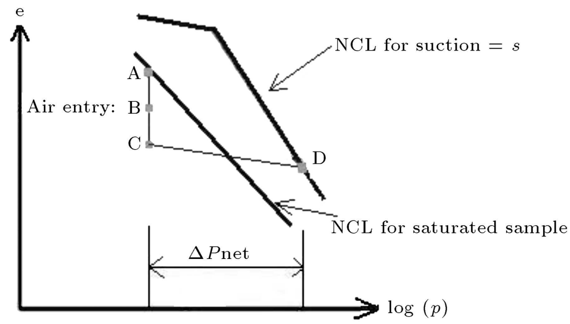


Figure 10. Schematic sketch of the suction induced hardening (AC: suction increase, CD: increase in net stress).

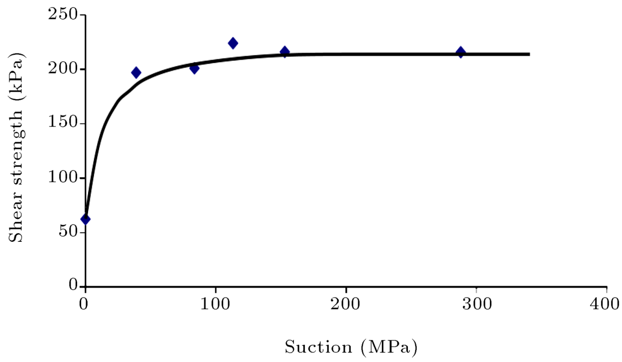


Figure 11. Variation of shear strength with suction at net stress equal to 100 kPa.

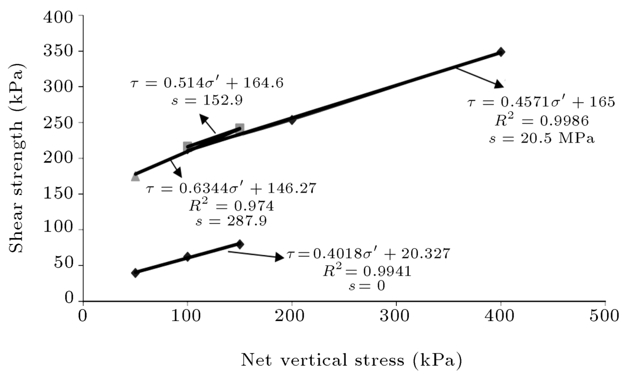


Figure 12. Critical state line for different suction values in the net stress space.

Figure 12 shows the critical state lines for different suction values. The slopes of these lines represents the friction angle (Ø′) of the soil at different suction levels. Figure 13 demonstrates the variation of Ø′ with suction. It is clear that the effective internal friction angle increases significantly with suction changes, and it was assumed that its variation with suction is linear. Lee et al. (2005) reported an exponential increase in Ø′ with suction for weathered granite [11].

An effective stress principle can bring together all experimental data around a unique critical state line.

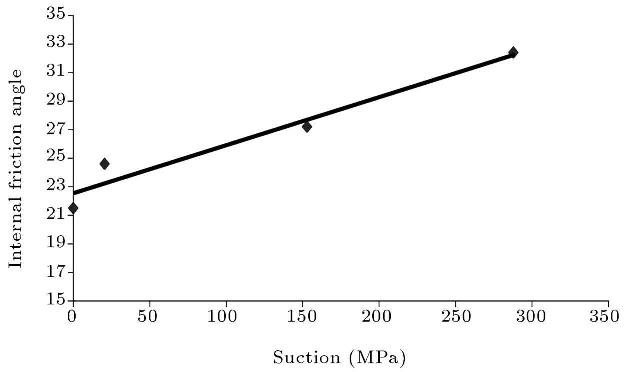


Figure 13. Variation of internal friction angle with suction.

Bishop (1959) suggested the following effective stress expression for unsaturated soils [57]:

$$\sigma_v' = \sigma_v + \chi s, \tag{3}$$

in which σ_v' is the effective vertical stress, σ_v is net vertical stress, s is suction and χ is effective stress parameter, being 0 for completely dry soil and 1 for fully saturated soil. This parameter strongly depends on the soil structure. The shear strength of unsaturated soil is determined as follows:

$$\tau = \sigma_v \tan\varphi'(s) + \chi s \tan\varphi'(s) + c', \tag{4}$$

where $\varphi'(s)$ is the effective internal friction angle, and c' is the effective cohesion of the soil. Furthermore, the shear strength of saturated soils is expressed by:

$$\tau_0 = \sigma_v \tan\varphi' + c'. \tag{5}$$

The effective stress parameter is determined with respect to a reference point (saturated condition) from Equations 4 and 5 as follows:

$$\chi = \frac{\tau - \tau_0 - \sigma_v(\tan\varphi'(s) - \tan\varphi')}{s\tan\varphi'(s)}. \tag{6}$$

Figure 14 shows the variation of effective stress parameter (χ) with suction. Variation of φ' with suction was considered during the calculation of χ. Parameter χ controls the contribution of suction to shear strength. For the high range of suction values tested in this study, the values of χ are relatively small; however, due to the very high values of suction, the total contribution of suction, χs, is very significant (Figure 11). Effective vertical stresses for all tests were determined using the corresponding χ values. Figure 15 shows the critical state line in the space of effective stress. The parameters of the line were determined using linear regression on all data and assuming a constant intercept (c') of 20 kPa.

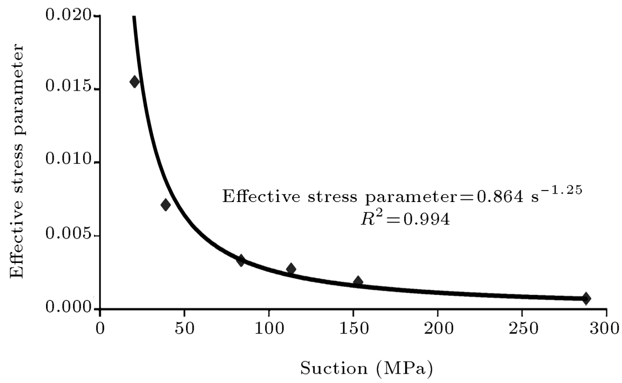


Figure 14. Variation of effective stress parameter with suction.

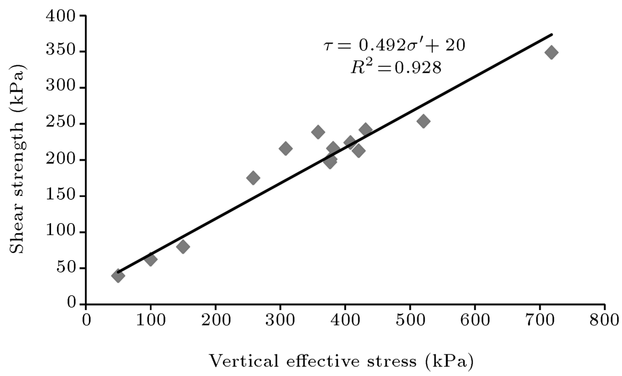


Figure 15. Critical state line in the effective stress space: $c' = 20$ kPa; $\phi' = 26.5$.

CONCLUSION

To investigate the structure of the soil, bimodal SWRC of an expansive dual porosity silt-bentonite mixture was studied, employing the osmotic method and the vapor equilibrium technique. Results were verified by comparing results from a filter paper test.

Saturated slow and unsaturated, fast, direct, shear tests were carried out to determine shear strength features of expansive soil. It is recommended to perform direct shear tests in which the suction can be measured or controlled, in order to ensure constant suction throughout the test.

The results indicate that for all suction values, the soil shear strength increases with the net vertical stress. Also, dilation of the soil specimens occurred only at suctions more than the air entry value of micropores.

The strain hardening-softening behavior of the samples and also the volume change of specimens during shearing can be explained by considering the soil structure to consist of soil aggregates made up of finer particles. It was concluded that soil aggregates, rather than soil particles, govern the volume change, and the pore water pressure responses of the compacted expansive silt-bentonite mixture at high suction levels.

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