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# Unconfined Compressive Strength of a Silty Soil and Kaolin below the Residual State

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## *Abstract*

Arid regions are widely distributed around the world. Soil water fluxes are related to the actual evaporation that is closely related to ground surface temperature and relative humidity. A soil can be dried such that its water content is below residual conditions. Of particular interest in this paper is the shear strength of very dry soils. This paper reports results on the relationship between total suction and shear strength beyond the residual water content state. This study involved performing unconfined compression tests for compacted, unsaturated soils and measuring the soil-water characteristic curves. A silty soil and kaolin were used in this test program. Two types of compacted, unsaturated soils were subjected to total suctions as high as 124,000 kPa and the shear strengths were measured. The soil-water characteristic curves were measured over a wide range of suctions. The residual state for the silty soil is clearly defined. The residual state for the kaolin is difficult to define. The shear strength in the residual state appears to increase slightly. This paper concludes that the failure envelope is essentially horizontal in the residual states.

## 1. *Introduction*

The fundamental theories for unsaturated behavior have become widely accepted in the geotechnical field. Unsaturated soil regions are generally located near ground surface. These regions are classified with in a saturated/unsaturated soil profile as following; dry soil with a discontinuous water phase, two phase zone

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with a continuous water phase, capillary fringe zone with discontinuous air phase, and saturated zone. The interface between the soil and the atmosphere produces a moisture flux boundary at ground surface. The assessment of appropriate boundary conditions at the ground surface is important. The geotechnical engineers have to solve practical problems involving unsaturated soils with highly negative pore-water pressures. The very high suction is produced by evaporation near ground surface. It is necessary to study the relationship between shear strength of an unsaturated soil and the evaporation process. Performance of a waste soil barrier systems is closely related to the change in shear strength of soils subjected to high suctions. Experimental relationship between shear strength and suction undergoing desiccation is needed in order to predict unsaturated soil property functions below residual state.

## 2. *Purpose of This Study*

This study involved performing unconfined compression tests for compacted, unsaturated soils subjected to high suctions. A silty soil and kaolin as fine-grain soils were used in this test program. Compacted unsaturated soil was desiccated using a relative humidity equilibrium technique until its water content was below residual water content. This study provides the relationship between total suction and shear strength of very dry compacted unsaturated soil. The results obtained from the unconfined compressive tests suggested that the shear strength has a relationship with the soil-water characteristic curve. This study concluded that the failure envelopes are essentially horizontal in the residual state of unsaturation.

## 3. *Literature*

### 3.1 *Evaporation at Ground Surface*

Recent studies provide design criteria and performance modeling for the estimation of evaporation rate for a composite soil cover system constructed on an acid generating waste rock dump in New Brunswick (Yanful, Bell and Woyshner, 1993). To prevent the movement of water into and through waste disposal facilities, compacted earth barriers intended to minimize the migration of contaminants from the facilities have became an essential component of the geotechnical design (Daniel, 1983). Silvestri, Soulie, Lafleur, Sarlis and Benkkouche (1990) mentioned that there are extensive settlement problems in lightweight structures related with soil volume changes beneath shallow foundations caused by precipitation and evapotranspiration balances. Engineered soil covers cannot be designed without evaluating the evaporation at the soil surface. Morris, Graham and Williams (1992) reviewed the occurrence and morphology of cracks in dry-climate regions of Australia and Canada. They mentioned that the settlement and cracks initially appear on the surface of the soil and propagate downward forming a cracked soil column with a desiccated surface crust. Reclamation operations for soft cohesive waste-disposal sites require the development of a desiccated surface crust with an adequate strength in order to support workers and equipment. A theory for modeling the consolidation and desiccation process of soft fine-grained soils after deposition was developed by Abu-Hejleh and Znidarcic (1995). Konrad and Ayad (1997) proposed a framework based on the theory of linear elastic fracture mechanics, showing the phenomenon of crack propagation for a cohesive soil under going desiccation.

Wilson, Fredlund and Barbour (1997) presented a theoretical approach in which a Dalton-type mass transfer equation was used to predict the evaporative fluxes from non vegetated soil surfaces. It is important to realize that some of the water loss comes directly from the soil due to evaporation, and some comes indirectly from the soil through the plants (i.e., transpiration) (Silvestri, Soulie, Lafleur, Sarlis and Benkkouche, 1990). Direct evaporation of water from a soil surface is subjected to purely physical influences (i.e., temperature, relative humidity, wind and duration of daylight), whereas transpiration is basically a biological process, partly dependent on plant physiology and soil conditions. Barton (1979) suggested soil evaporation may be estimated on the basis of the humidity and the water content of the near surface soil. Hammel, Papendick and Campbell (1981) described actual evaporation from soil as a function of soil-water content and included the water flow processes in the soil with combined moisture and temperature gradients. Granger (1989) stated that evaporation from unsaturated soil surface is a function of the actual vapor pressure at the soil surface.

### 3.2 *Residual Stage of Unsaturation*

Unsaturated soil properties are closely related to the relationship between the amount of water in soils and soil suction. The relationship between the water content and soil suction is known as the soil-water characteristic curve. Its role is essential for unsaturated soil mechanics. The soil-water characteristic curve is studied adequately in order to develop predictive numerical models for unsaturated soil behavior. The amount of water in soil with increase suction is generally quantified in terms of volumetric water content, $\theta$, gravimetric water content, $w$, or degree of saturation, $S$. The entire suction range of the soil-water characteristic curve is required primarily to investigate evaporation process near ground surface.

An initially saturated soil specimen begins to desaturate as a result of an increase in suction in the soil. The desaturation stages, generally, are classified along the desorption branch of a soil-water characteristics curve; namely, the boundary effect stage, the transition stage (i.e., with primary and secondary transition portions) and the residual stage of desaturation (White, Duke and Sunada, 1970, Vanapalli, Fredlund, Pufahl and Clifton, 1996). White, Duke and Sunada (1970) have provided the original concepts for the different stages during the desaturation process. Vanapalli, Fredlund, Pufahl and Clifton (1996) developed different saturation stages on the soil-water characteristic curve in order to predict the shear strength in terms of soil suction.

In the boundary effect stage all soil pores are filled with water. The soil behavior can be explained using saturated soil mechanics in the boundary effect stage. The first important point on the soil-water characteristic curve is the air-entry value, $(u_a - u_w)_b$. This value of suction identifies the point at which air enters the largest pores of the soil. When suction is larger than the air-entry value, the soil starts to desaturate in the transition stage. The amount water in the soil decreases significantly with increasing suction in the transition stage. Eventually large increases in suction lead to a relatively small changes in water content in the residual stage of unsaturation.

A coarse-grained soil such as a gravel or sand shows a tendency to desaturate at a fast rate with increasing suction. Since the water storage ability depends on grain size distribution, the rate of desaturation decreases with an increase in fine content. The residual suction, $(u_a - u_w)_r$, can be expected to be higher for fine-grained soils. The suction corresponding to the residual water content approximates the wilting point of many plants. Fredlund (1998) mentioned that water in the liquid phase drains from most of the soil pores when the suction is less than 1500 kPa. He suggested that water content corresponding to a suction of about 1500 kPa may be used as the residual water content. van Genuchten (1980) indicated that a wilting point of 1500 kPa corresponds to the residual water content for practical field problems. The pore-water at suctions greater than the residual suction may move through the pores in the vapor phase.

When the wetted contact area has reduced significantly, the volume change of an unsaturated soil becomes negligible. The suction in the residual stage makes a small contribution to an increase in shear strength compared with the suction in the transition stage. Vanapalli, Fredlund and Pufahl (1999) concluded that soil-water characteristics are not significantly influenced either by the soil structure aggregation or the stress history in the high suction ranges (i.e., 20,000-1,000,000 kPa). Fredlund (1998) commented that the shear strength of an unsaturated soil remains essentially constant beyond residual state.

### 3.3 *Shear Strength of Unsaturated Soil*

The relationship between soil suction and the shear strength of unsaturated soil is important for many geotechnical engineers. The concept of stress state variables to describe the unsaturated soil behavior were introduced by Fredlund and Morgenstern (1977). Fredlund, Morgenstern and Widger (1978) proposed a shear strength equation for unsaturated soils using two independent stress state variables, the net normal stress, $(\sigma - u_a)$, and the matric suction, $(u_a - u_w)$.

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)_b \tan\phi^b \qquad (1)$$

where, $\tau$ = shear strength, $c'$ = effective cohesion intercept, $\sigma$ = total normal vertical stress, $\phi'$ = effective angle of internal friction with respect to net normal stress, $u_a$ = pore-air pressure, $u_w$ = pore-water pressure, $\phi^b$ = angle of internal

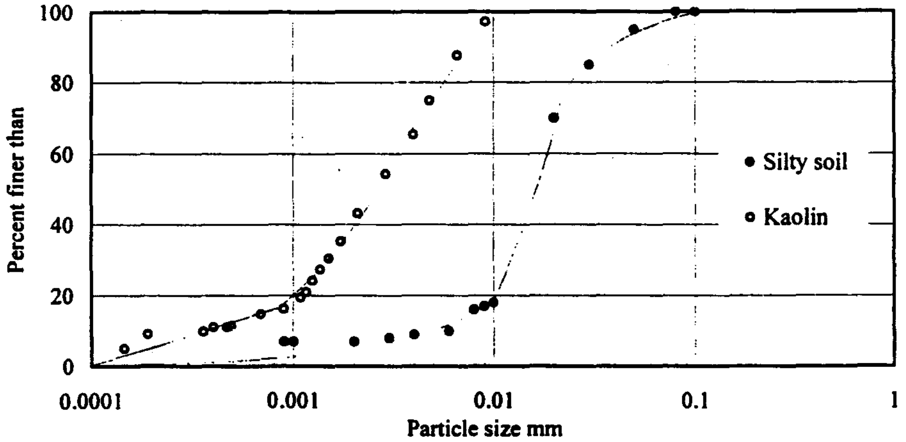

Fig. 1. Grain size distribution for a silty soil and a kaolin

friction with respect matric suction.

The unsaturated soil shear strength equation proposed by Fredlund, Morgenstern and Widger (1978) describes a planar surface tangential to the Mohr-Coulomb circles at failure. Fredlund, Rahardjo and Gan (1987) showed non-linear failure envelopes using a modified direct shear apparatus. The slope of the shear strength versus matric suction envelope can also be negative (Donald, 1956). Escario and Saez (1987) conducted direct shear tests on three compacted unsaturated soils by controlling suction up to 15,000 kPa. They found that the relationship between shear strength versus suction was non-linear. Escario and Saez (1987) have observed an increase in shear strength up to 11,000 kPa for the grey clay. However, for the suction range from 11,000 kPa to 150,000 kPa, a slow drop in shear strength was observed. Escario and Juca (1989) reported that direct shear strength of a clay sand increases up to a suction of 1,000 kPa. Beyond 1,000 kPa, the slope of the shear strength versus soil suction, $\phi^b$, appears to approach a negative value.

Mahalinga-Lyer and Williams (1985) carried out unconsolidated undrained triaxial tests on two lateritic soils. The results show that the slope, $\phi^b$, of the failure surface with respect to the matric suction decreases sharply in the suction range 0-1,000 kPa and then decreases slightly in the suction range 1,000-8,000 kPa for the lateritic soil developed on basalt. For the lateritic soil developed on sandstone, $\phi^b$, decreases sharply in the suction range 0-200 kPa and then decreases slightly in the range from 200 kPa to 1,800 kPa. They showed that the failure envelope with respect to the matric suction was non-linear for lateritic soils, and mentioned that suction has no effect on the shear strength when the degree of saturation was lower than 53-55 %.

### 4. *Test Procedure*

A silty soil and kaolin were used in this test program. The silty soil is non-plastic soil and the kaolin is a fine-grain cohesive soil. Grain size distributions for both soils are shown in Fig.1. The two fine – grain soils were compacted statically. Each soil specimen had a height of 100 mm and a diameter of 50 mm. The initial water contents of the silty soil and the kaolin were 9.6 % and 31.7 %, respectively. All soil specimens were placed directly into a temperature and relative humidity controlled chamber in order to apply a high total suction. The chamber used in this test program could control the relative humidity in a range from 20 % to 90 % at a temperature of 30 °c. The thermodynamic relationship between soil suction and the partial pressure of the pore-water vapor can be written as follows:

$$\psi = -\frac{RT}{v_{w0}w_v}\ln\left(\frac{\overline{u_v}}{\overline{u_{v0}}}\right) \tag{2}$$

where, $\psi$ = soil suction or total suction (kPa), $R$ = universal (molar) gas constant [i.e., 8.31432 $J/(molK)$], $T$ = absolute temperature [i.e., $T = (273.16 + t^\circ)(K)$], $t^\circ$ = temperature $(^\circ c)$, $v_{w0}$ = specific volume of water or the inverse of the density of water [i.e., $1/\rho_w$ $(m^3/kg)$, $\rho_w$ = density of water, $w_v$ = molecular mass of water vapor (i.e., 18.016 $kg/kmol$), $\overline{u_v}$ = partial pressure of pore-water vapor (kPa), $\overline{u_{v0}}$ = saturation pressure of water vapor over a flat surface of pure water at the same temperature (kPa).

The term, $u_v/u_{v0}$ is called relative humidity, RH(%). If a temperature of 20 °c is used as the reference, the above equation (2) can be written to give a fixed relationship between total suction (in kPa) and relative vapor pressure (i.e., relative humidity).

$$\psi = -135022\ln\left(\frac{\overline{u_v}}{u_{v0}}\right) \tag{3}$$

Figure 2 shows a plot of relative humidity versus total suction. Fredlund and Xing (1994) mentioned that there is a maximum total suction value corresponding to a zero relative humidity in any porous medium. The total suction corresponding to zero relative humidity or zero water content is approximately 1,000,000 kPa. This value is supported experimentally for a variety soils (Croney and Coleman, 1961).

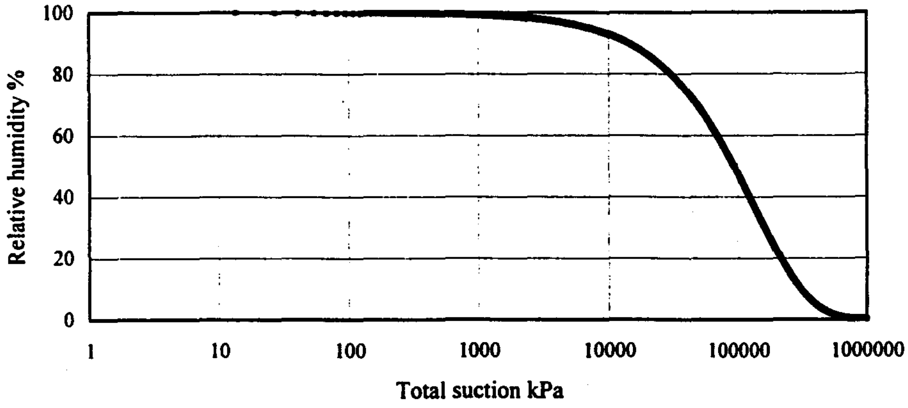

Fig. 2. Relationship between relative humidity and total suction

The test program selected relative humidity of 80 %, 70 %, 60 %, 50 % and 40 %. Each soil specimen was subjected to the relative humidities for a month. For example, a relative humidity of 80 % and 40 % corresponds to a soil suction of 30,000 kPa and 124,000 kPa, respectively. Desaturation of a soil started as a result of evaporation in the relative humidity chamber. After the soil specimen had reached equilibrium with the selected relative humidity, an unconfined compression test was conducted at a rate of axial strain of 0.5 mm per minute.

At the end of the unconfined compression test, the water content of the soil specimen was measured in order to evaluate the soil-water characteristic curve. The soil-water characteristics curve for the two soil were measured using a pressure plate apparatus, glass desiccator containing saturated salt solutions (i.e., vapor equilibrium technique) and relative humidity technique. The above mentioned three methods were used to develop the soil-water characteristics curve over the entire soil suction. The air pressure in the pressure plate apparatus was increased to a maximum of 490 kPa. The vapor equilibrium technique (relative humidity technique) was used to impose suction larger than 490 kPa. Five different salt solutions were used in the glass desiccator: lithium chloride ($LiCl \cdot H_2O$), magnesium chloride ($MgCl_2 \cdot 6H_2O$), magnesium nitrate ($Mg(NO_3)_2 \cdot 6H_2$), sodium chloride ($NaCl$) and potassium sulphate ($KSO_4$). The above five salt solutions controlled the atmospheric humidity in the glass desiccator (Yong, 1967).

## 5. *Experimental Results and Interpretation*

### 5.1 *Soil-Water Characteristic Curve*

The soil-water characteristic curve can be described as a measure of the

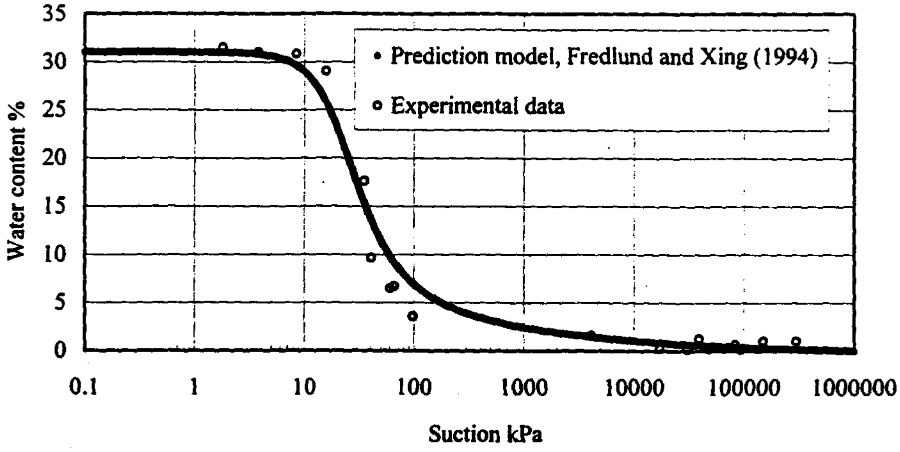

Fig. 3. Soil-water characteristic curve for a silty soil

water-holding capacity (i.e. storage capacity) of the soil, when subjected to various values of suction. The distribution of the soil, water and air phases changes as the stress state changes (e.g. shear strength, volume change). Changes in these phases (soil, water and air) take on different forms and influence the engineering behavior of unsaturated soils.

The relationship between amount of soil water and soil suction was evaluated using a pressure plate apparatus, salt solution desiccator and a relative humidity chamber. The soil-water characteristic curves for a silty soil and a kaolin were tested from a saturated condition to a totally dry condition (i.e. for soil suctions ranging from 0 to 1000,000 kPa) and are shown in Figs. 3 and 4. The soil-water characteristic curve for the kaolin is different from the soil-water characteristic curve of the silty soil. The key features of the soil-water characteristic curve are the air-entry value, the residual water content and the slope of the straight line portion of the desorption branch. The air-entry value for the two soils can be obtained by extending the constant slope portion of the soil-water characteristic curve to intersect the suction axis at saturated condition. Evaluated air-entry value for the silty soil and the kaolin are 10 kPa and 100 kPa, respectively. When matric suction exceeds the air-entry value, desaturation starts in the liquid phases. The soil dries rapidly with increasing suction. The slope of branch in the transition stage for the silty soil is larger than that of the kaolin. The rate of desaturation is higher for the silty soil.

The definition of the residual water content is not easy, as the shape of the soil-water characteristic curve varies depending on soil properties. An empirical, graphical procedure has been suggested for the residual state (Vanapalli, Fredlund and Pufahl, 1999). The residual state of saturation can be defined as the point where the line extending from 1000,000 kPa along the curve intersects the previous tangent line. The silty soil shows a residual water content of 2.5 % and a residual

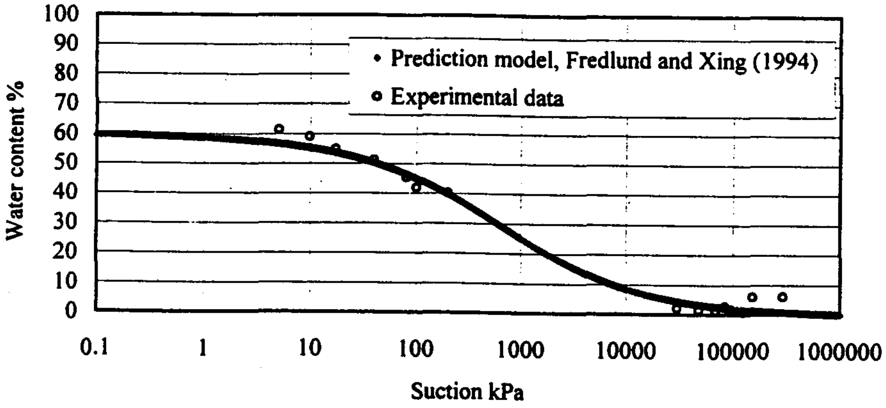

Fig. 4. Soil-water characteristic curve for a kaolin

suction of 200 kPa using above mentioned graphical procedure. On the soil-water characteristic curve of the kaolin there is not a clear point, where the residual suction can be found. A decrease in the water content continues with soil suction. In other words, the soil-water characteristic curve of kaolin has no distinct breaking point in the high suction range.

### 5.2 *Unconfined Compressive Strength and Failure Envelope*

Unconfined compressive test results for the silty unsaturated soil and the kaolin unsaturated soil subjected to a high suction are summarized in Tables 1 and 2. The initial relative humidity selected in this test program is less than 80 %. Soil suction corresponding to this relative humidity is larger than 30,000 kPa. An unconfined compressive test was performed on a specimen with the initial water content in order to compared the results with the compressive strength of the unsaturated soil subjected to higher suctions. Total suction in Tables 1 and 2 is computed using a relative humidity versus total suction theoretical Eq.2.

The water content of the soil specimen decreases with increasing total suction or decreasing relative humidity. The decrease of water content with total suction, however, is not significant. Desaturated silty soil and kaolin are in the residual state of saturation. The decreasing in the axial strain at failure was noticed during compression testing. A decrease in the axial strain at failure is predictable due to a decreasing wetted area of contact between soil particle due to the high suction. Below the residual stage water content, when deviator stress reached to peak, there is similarity in the axial strain regardless of soil suction value.

The relationship between unconfined compressive strength and total suction is presented in Figs. 5 and 6. The shear strength of the desaturated silty

Table 1 Summary of unconfined compression test for a silty soil

| Relative humidity % | Total suction kPa | Unconfined compressive strength kPa | Water content % | Axial strain at failure % |
|---|---|---|---|---|
| 80 | 30000 | 32.4 | 0.304 | 0.14 |
| 70 | 48000 | 38.8 | 0.269 | 0.19 |
| 60 | 69000 | 58.3 | 0.188 | 0.15 |
| 50 | 94000 | 59.2 | 0.158 | 0.32 |
| 40 | 124000 | 39.8 | 0.105 | 0.29 |
| Initial condition | 41 | 28.8 | 9.6 | 0.56 |

In case of "Initial condition", suction means matric suction.

Table 2 Summary of unconfined compression test for a kaolin

| Relative humidity % | Total suction kPa | Unconfined compressive strength kPa | Water content % | Axial strain at failure % |
|---|---|---|---|---|
| 80 | 30000 | 551 | 2.16 | 1.34 |
| 70 | 48000 | 763 | 1.56 | 1.4 |
| 60 | 69000 | 608 | 1.21 | 1.32 |
| 50 | 94000 | 986 | 0.95 | 1.73 |
| 40 | 124000 | 1000 | 0.88 | 1.43 |
| Initial condition | 900 | 394 | 31.7 | 3.31 |

In case of "Initial condition", suction means matric suction.

soil and kaolin increases slightly with suctions in the suction range from 30,000 kPa to 124,000 kPa. In the residual stage of saturation, there is a slight increase in shear strength of soil related to essentially no change in water content (i.e., no change in wetted area of contact) with increasing of soil suction. The angle of friction, $\phi^b$, with respect to suction are computed from unconfined compressive strength versus suction relationship shown in Figs 5 and 6. The angle of friction, $\phi^b$, for the silty soil and kaolin are 0.02 degrees and 0.3 degrees, respectively. The failure envelope shows an essentially horizontal line in residual stage.

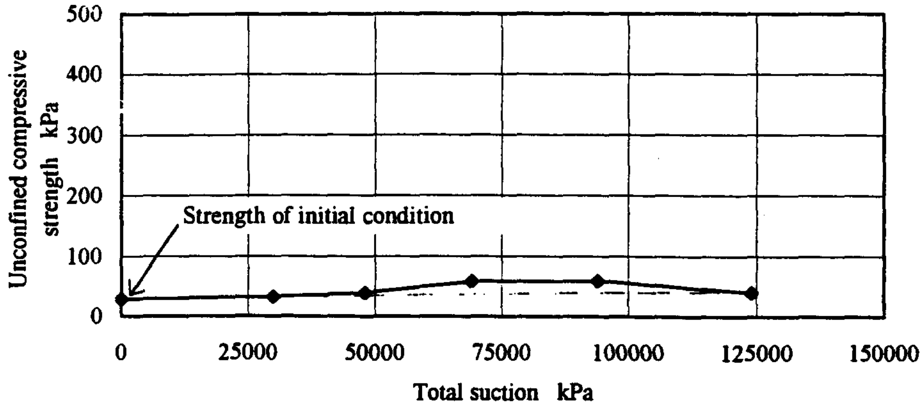

Fig. 5. Relationship between unconfined compressive strength and total suction for a silty soil

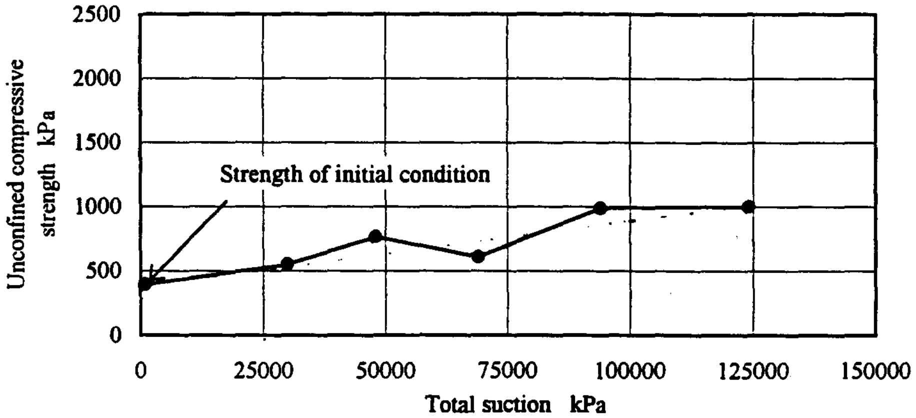

Fig. 6. Relationship between unconfined compressive strength and total suction for a kaolin

## 6. *Conclusions*

The soil-water characteristic curve and the unconfined compressive strength under the residual state of unsaturation were obtained for a silty soil and a kaolin during this study. The soil-water characteristic curve was obtained using a pressure plate apparatus, vapor pressure equilibrium technique and relative humidity equilibrium technique. The shear strength of an unsaturated soil subjected to high suction increases slightly with increasing suctions. An essentially horizontal envelope was obtained in the residual state of saturation. The soil-water characteristic curve in entire suction range (i.e. 0-1000,000 kPa) is essential to the prediction of unsaturated soil shear strength.

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