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THE EFFECT OF MATRIC SUCTION ON THE SHEAR STRENGTH OF UNSATURATED SANDY CLAY

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ABSTRACT: The shear strength parameters of the soil is the key engineering property required for the design of geotechnical structures and stability analysis. The shear strength of an unsaturated soil is controlled by matric suction. This research examined the effect of matric suction on the shear strength behavior of sandy clay using a series of experimental tests in the laboratory. The contact filter paper method was used to measure matric suction and the SoilVision knowledge-based system was used to give an approximation of the entire soil water characteristic curve (SWCC). The shear strength of the unsaturated sandy clay was examined using a series of unconsolidated undrained (UU) triaxial tests to identify the relationship between shear strength, cohesion, internal friction angle, and matric suction. The result shows that the shear strength of the soil increases as matric suction increases. It was found that when the matric suction is smaller than air entry value (AEV), the shear strength of the soil increases as matric suction increases and the increment is linear because the soil is in saturated conditions. At a certain matric suction value (on soil samples occurred at 40-600 kPa matric suction values), there is a significant increase in the shear strength of soil associated with the inter-particle force produced due to negative pore water pressure. Furthermore, at a high matric suction, the relationship between shear strength and matric suction tend to be stable as in a low water content, the matric suction is not transmitted effectively to the contact point of soil particles.

Keywords: Soil Water Characteristic Curve (SWCC), filter paper method, triaxial test, degree of saturation

1. INTRODUCTION

In unsaturated soil, mechanical behavior such as shear strength is controlled by two stress states variables which are net normal stress and matric suction [1]. Matric suction describes the potential of thermodynamic on the soil pore water. The potential of pore water decreases due to the evaporation of the soil mass, and it is accompanied by an increase in negative pore water pressure or matric suction [2]. The rate of the increase in the contribution of matric suction to shear strength is related to the rate of soil distortion which is a function of the water content [3]. Therefore, the change in the degree of saturation and matric suction causes the change in shear strength [4].

The determination of the shear strength parameters of unsaturated soil is very important to be used to solve geotechnical problems such as the slope stability analysis, designing retaining walls, soil excavation and embankment, and bearing capacity of shallow and deep foundation. The shear strength of unsaturated soil can be determined in a laboratory that applies a modified conventional direct shear device as described in [5],a suction controlled triaxial apparatus as described in [6], an unconfined compression test as described in [7], and unconsolidated undrained triaxial test as described in [8]. A direct measurement of the shear strength parameters of unsaturated soils is costly and time consuming, therefore, for practical purposes, the analysis is fairly based on the approximate soil properties [3].

Many shear strength equations that utilize semi empirical methods have been published to predict the unsaturated shear strength using SWCC (either directly or indirectly) and effective shear strength parameters [3], [9], [10], [11]. The Mohr-Coulomb theory applies effective stress state which is often used to predict saturated shear strength. Several published equations use hyperbolic and nonlinear failure envelopes as the behavior of unsaturated soil and saturated shear strength parameters to predict the unsaturated shear strength [10], [12], [13].

The undrained shear strength of Khon Kaen's compacted unsaturated soil was evaluated using triaxial (UU) test [8]. The samples were compacted at 85% of maximum dry density using the Proctor standard method. The drying soil water characteristic curve (SWCC) for the compacted Khon Kaen soil was determined using three methods, which were a hanging column method, a pressure plate method, and an isopiestic humidity method. The relationship between soil suction and the maximum unsaturated undrained shear strength of compacted Khon Kaen soil is a good non-linearly correlation.

The effect of matric suction on the shear strength of a highly plastic unsaturated compacted clay soil from Sudan was investigated [4]. Matric suction and drained shear strength were measured using the filter paper and the conventional shear box apparatus. It was found that the shear strength of unsaturated soils is dependent on the soil moisture condition, i.e. soil suction, and under the same applied vertical stress. The shear resistance and peak shear strength increases as matric suction increases and this increment is not linear. The lines representing the relationship between peak shear strength and matric suction for different values of vertical stress shows a sharp increase in shear strength for the first portion of the curve whereas the lines are almost parallel for high values of matric suction. The lines tend to curve as the matric suction approaches a specified value.

In this paper, several laboratory tests were conducted to obtain the soil properties index. The filter paper contact method was used to measure the matric suction and the SoilVision knowledge-based system was used to give an approximation of the entire soil water characteristic curve (SWCC). Shear strength of unsaturated sandy clay was examined based on series of unconsolidated undrained (UU) conventional triaxial test to obtain the relationship between the shear strength, cohesion, internal friction angle, and matric suction.

2. SOIL WATER CHARACTERISTIC CURVE

The soil water characteristic curve (SWCC) is defined as the relationship between water content and suction. The water content is represented by three variables namely gravimetric water content, volumetric water content, and degree of saturation [9]. The SWCC plays an important role in determining hydro mechanical behavior in unsaturated soil and it can be used to estimate several functions such as hydraulic conductivity, water storage, and shear strength. The complete SWCC measurement (i.e., water content at many matric suction curves) takes a long time and is expensive, therefore, generally only a few data points are measured along the desorption curve. The curve fitting equation is then used to give an approximation of the entire SWCC of some measured data points. It is important to choose an appropriate equation that actually represents the point of measured data [14].

Fredlund et al. [15] proposed a method for estimating SWCC from the grain size distribution curve and volume-mass properties that have been compiled in the SoilVision knowledge-based system. The soil was assumed to be uniformly aligned and the particle size was assumed to be homogeneous. The predictions in the form of SWCC was derived from SWCC experimental data using best-fit analysis with formulas. SWCC predictions of the grain size distribution curve may be considered as a way of describing effective unsaturated soil behavior. The SWCC form is an input for numerical modeling of unsaturated soil.

3. SHEAR STRENGTH OF UNSATURATED SOIL

The shear strength equation for saturated soils was proposed by Terzaghi [16]. This equation uses Mohr Coulomb theory and is expressed as a linear function of effective stress as presented in Eq. (1).

$$\tau = c' + (\sigma_n - u_w)\tan\phi' \quad (1)$$

where τ is shear strength, c' is effective cohesion, ϕ' is effective angle of internal friction, σ_n is the total normal stress on the plane of failure, $(\sigma_n - u_w)$ is the effective normal stress on the plane of failure, and u_w is the pore water pressure.

Many practical problems in the field take into account unsaturated soil shear strength. A linear shear strength equation for an unsaturated soil was proposed by Fredlund et al. [17]. The equation is expressed in Eq. (2).

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (2)$$

where τ is shear strength of unsaturated soil, c' is effective cohesion, ϕ' is effective angle of frictional resistance for a saturated soil, ϕ^b is angle of frictional resistance related to the change of soil suction, $(\sigma_n - u_a)$ is net normal stress, u_a is pore air pressure, u_w is pore water pressure, and $(u_a - u_w)$ is matric suction. The first two terms on the right-hand side of the equation describe the conventional Mohr-Coulomb criterion for the strength of saturated soil. The third term captures the increase in shear strength with increasing matric suction in unsaturated soil.

Vanapalli et al. [3], Fredlund et al. [9] proposed a function for predicting the shear strength of an unsaturated soil using the entire soil water characteristic curve as presented in Eq. (3).

$$\tau = \left[c' + (\sigma_n - u_a)\tan\phi'\right] + \left[(u_a - u_w)\left\{(\Theta^\kappa)(\tan\phi')\right\}\right] \quad (3)$$

where κ is the fitting parameter, Θ is normalized volumetric water content similar to the degree of saturation, S. Equation (3) can also be written in Eq. (4).

$$\tau = \left[c' + (\sigma_n - u_a)\tan\phi'\right] + \left[(u_a - u_w)\left\{(S^\kappa)(\tan\phi')\right\}\right] \quad (4)$$

The first part of the equation is the saturated shear strength. The second part of the equation is the shear strength contribution due to suction, which can be predicted using the soil water characteristic curve. Garven and Vanapalli [18] proposed κ as presented in Eq. (5).

$$\kappa = -0.0016 I_p^2 + 0.0975 I_p + 1 \quad (5)$$

where I_p is plasticity index. Tan ϕ^b in Eq. (2) is obtained by comparing Eq. (2) and Eq. (4) [7] as presented in Eq. (6).

$$\tan\phi^b = \left[S^\kappa\right](\tan\phi') \quad (6)$$

The term of matric suction in Eq. (2) is considered as a contribution to soil cohesion [19] as presented in the Eq. (7). It means that matric suction in unsaturated soils increases cohesion.

$$c = c' + (u_a - u_w)\tan\phi^b \quad (7)$$

where c is the total or apparent cohesion of an unsaturated soil. Rifa'i [20] proposed a non linear correlation between cohesion and matric suction expressed in Eq. (8).

$$c = c' + r_c\sqrt{(s - s_e)}.P_a \quad (8)$$

where c' is the cohesion of soil at saturated state, s is matric suction, s_e is the air entry value, P_a is atmospheric pressure, and r_c is a dimensionless evolution parameter of cohesion determined using Eq. (9) as follows :

$$r_c = r_k \frac{\sqrt{3}(3 - \sin\phi')}{6\cos\phi'} \quad (9)$$

where r_k is a dimensionless evolution parameter and ϕ' is internal friction angle of soil at saturated state.

4. EXPERIMENTAL METHOD

4.1 Soil Properties

The soil sample composition used in the research consists of 40% clay obtained in Piyungan Sub-district (Yogyakarta, Indonesia) and 60% sand obtained in Depok Sub-district (Yogyakarta, Indonesia). The soil contains 8.61% clay, 52.78% silt, and 38.61% sand fraction. The soil texture categorized as sandy lean clay soils (CL in USCS) was used in the research.

The soil samples were tested for its consistency, specific gravity, particle size distribution, and compaction to attain various parameters. The index properties of the soil are shown in Table 1. The particle size distribution data fitted using unimodal equation and was then compared to other results in SoilVision's database as shown in Fig.1. It is indicated that the soils registered in SoilVision have similar grain size distribution with the soil samples, however, the content of fine grain in the soil samples was higher.

Table 1. Index properties of the soil

Properties	Value
Specific Gravity, Gs	2.62
Liquid Limits, LL (%)	39.83
Plastic Limits, PL (%)	24.07
Maximum Dry Density, MDD (kN/m^3)	15.14
Optimum Moisture Content, OMC (%)	23.00
Soil fraction: Clay (%)	8.61
Silt (%)	52.78
Sand (%)	38.61
Soil classification:	CL(USCS)

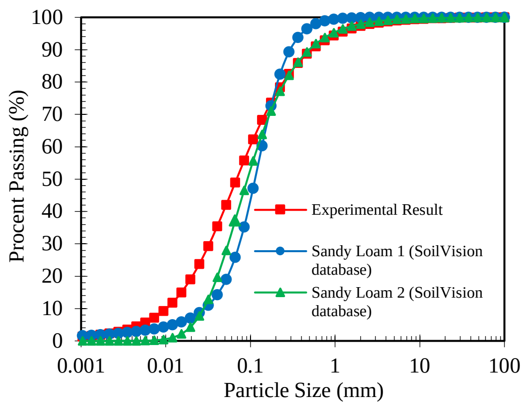

Fig.1 Comparison of grain size distribution between experimental results and the soil registered in SoilVision database

4.2 Testing Program

The soil sample was dried with oven, crushed using a rubber hammer, and passed through a 2 mm sieve. The soil was given different water contents, consequently, it had a degree of saturation of 50%, 60%, 70%, 80%, 90%, and 100%. The specimens were compacted statically to achieve the same dry density (15.14 kN/m^3). This test was intended to observe the change in shear strength of the soil by changing the matric suction for the same amount of soil solids per unit volume.

A conventional triaxial (UU) apparatus was used in this study. The specimens were molded in cylindrical shape with a diameter of 35 mm and a height of 70 mm. The weight of the soil required to fill the mold cylinder to achieve the dry density of 15.14 kN/m^3 is calculated for each water content. The soil sample was compacted statically at 3 layers by dividing the required soil weight on the same cylinder of the same mold. All specimens were prepared with the above method, on the same dry density but at six different moisture levels. Three normal stresses 100 kPa, 140 kPa, and 180 kPa were applied for each specimen with different water contents. Furthermore, the result was analyzed to determine the peak shear stress at each normal stress.

Eight specimens were prepared with the same method and molded in cylindrical shape with a diameter of 64 mm and height of 30 mm. The weight of the soil required to fill the mold cylinder to achieve the dry density of 15.14 kN/m^3 is calculated for each water content. All specimens were prepared on the same dry density but at eight different water content, therefore, it had a degree of saturation of 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. The filter paper method was chosen for this study because it could be used to determine the overall matric suction and was easy to perform. The filter paper used in this study is Whatman 42. The testing procedure follows ASTM D5298-03 [21] guidelines with appropriate calibration curves.

5. RESULT AND DISCUSSION

5.1 Soil Water Characteristic Curve of Sandy Clay

The filter paper test results were used to plot the relationship between the degree of saturation and matric suction (SWCC). The SoilVision knowledge-based system was used to give an approximation of the entire SWCC using proper curve fitting equation which represents measurable data points. In this study, Van Genuchten's equation shown in Fig. 2 was used. The water entry value (AEV) and residual suction value (S_r) of sandy clay were 21.5 kPa and 70.000 kPa respectively. Figure 2 shows the occurred soil desaturation process and the various stages of saturation. Vanapalli et al. [3] have identified three desaturation stages i.e. the boundary effect stage, the transition stage, and the residual stage of unsaturation.

At the boundary effect stage, all soil pores are filled with water (i.e., the water meniscus in contact with the soil particles or aggregates are continuous). In other words, the soil is in a saturated condition and the area of water is not reduced at this stage. At SWCC, this stage is bounded by AEV, which is a suction value that declares the entry point of air in the largest soil pores. At the transition stage, the soil starts to desaturate. Due to the increase in matric suction, the water content in the soil starts to reduce significantly. Some water in contact with soil particles decreases due to the sustainability of the desaturation (i.e., the water meniscus area in contact with the soil particle is not continuous and starts to decrease). Eventually, the large increase in suction leads to a slight change in water content (degree of saturation). At the residual stage of unsaturation, a slight change in water content causes a large change of matric suction because there was only a little amount of water found at this stage (i.e., the water meniscus is small). The water content in the soil at the beginning of this stage is generally referred as the residual water content.

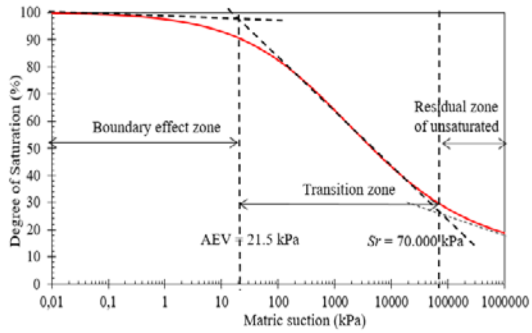

Fig.2 The process of soil desaturation of sandy clay

The soil water characteristic curve (SWCC) of sandy clay (Experiment result), the SWCC of soil collection SoilVision database that has the same particle distribution (Sandy Loam 1 and 2) and the SWCC prediction (using Fredlund and Wilson eq., Tyler and Wheatcraft eq., Arya and Paris eq.) are shown in Fig.3.

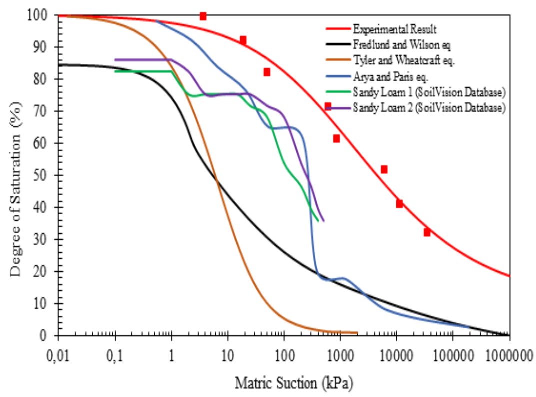

Fig.3 The soil water characteristic curve (SWCC) of experimental result, the soils are collected from SoilVision database that has similar particle distribution and SWCC prediction

The SWCC prediction using the Arya and Paris eq. appears to be approaching the SWCC from experiment result, compared to the other prediction results and the SWCC from experimental result is higher than the SWCC predicted results. This indicates that the experimental result are still required as a comparison to SWCC prediction results. The graphic gap due to the plasticity and the presence of fine grained of the soil samples is high [22].

5.2. Shear strength of unsaturated sandy clay

The variation of shear strength related to matric suction for specimens tested with the normal stresses of 100 kPa, 140 kPa, and 180 kPa are shown in Fig. 4. At the beginning of the curve up to the air entry value (AEV), the soil is in saturated condition. At this stage, the shear strength of the soil increases as matric suction increases in the linear form. Furthermore, in the matric suction between 40-600 kPa, a visible significant increase of soil shear strength was found. The soil begins to desaturate, the air starts to enter most of the soil pores and the water content decreases.

The high increase in shear strength of soil is associated with the inter-particle force produced due to the negative pore water pressure. The inter-particle forces depend on the particle size and these forces on the clay are higher than on silt and sand [23]. When the matric suctions are high (i.e. above 600 kPa), the relationship between shear strength and matric suction tend to be stable, this is indicated by a flat curve. This is due to the fact that when water content was low, the matric suction was not transmitted effectively to the contact point of soil particles. Furthermore, a large increase in matric suctions does not result in significant increase in shear strength.

The relation of shear strength to normal stresses at some variations of matric suction are shown in Fig. 5. The soil shear strength increases as normal stresses increase at a similar matric suction value. At low matric suction, the increase of normal stress leads to the shear strength increase which is not significant. The significant increase of shear strength occurs in matric suction of 40-600kPa. At a matric suction of above 600kPa, the increase of shear strength tends to be stable. It is identical to the relationship between shear strength and matric suction in Fig. 4 and it can be associated with the previously described reason**.**

The comparison between measurement of shear strength in the laboratory and the prediction of shear strength using Eq. (2) are shown in Fig. 6. The Prediction of shear strength is carried out by giving u_a equal to zero, κ obtained by Eq. (5) and tan ϕ^b obtained by Eq. (6) as entry data at Eq. (2). Both the measurement results and the prediction show the nonlinear relationship between the shear strength and matric suction although the shear strength equation developed by Fredlund et al. [17] show a linear equation. Several results of the research also show the same thing i.e. the relationship between shear strength and matric suction was nonlinear in overall matric suction [22], [24].

The nonlinear relationship between cohesion and matric suction from experimental result are shown in Fig.7. Initially, the curve is linear in shape, a sharp increase occurs in the matric suction between 40-600 kPa and the curves tends to be flat at matric suction above 600 kPa. It is identical to the relationship between shear strength and matric suction in Fig. 4 and it can be associated with the same reason described previously.

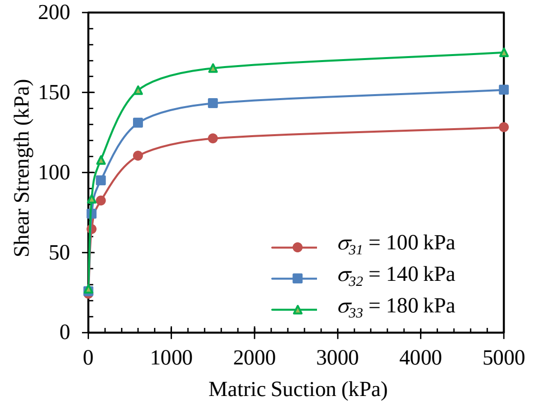

Fig.4 Variation of shear strength related to matric suction

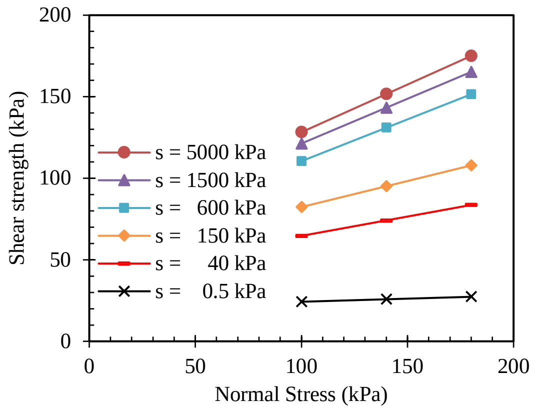

Fig.5 The relationship of shear strength with normal stresses at some variations of matric suction

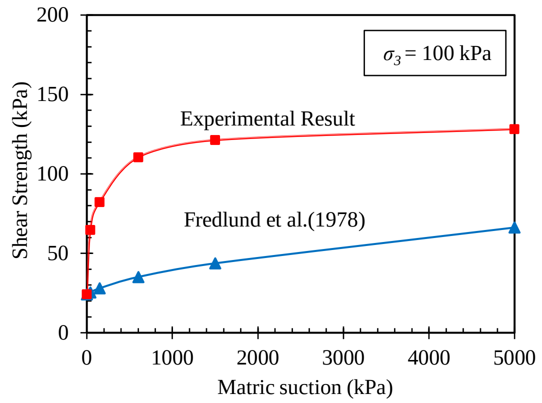

Fig.6 Comparison of shear strength between predictions and experimental results at various matric suctions

The comparison of measure and predicted results of the cohesion to matric suction are shown in Fig. 7. The cohesion was predicted using two equations, i.e. Eq. (7) and Eq. (8). The Rifa'i equations or Eq. (8) was obtained by providing the value of r_k equals one, κ was obtained by Eq. (5). The Ho and Fredlund equation or Eq. (7) results in a linear relationship of cohesion to the matric suction. This is not in agreement with the experimental results. The Rifa'i equation produces linear cohesion on the matric suction below 40 kPa and nonlinear cohesion on the matric suction above 40 kPa. This was similar to the measurement result. The cohesion of the soil under the air entry value equals the saturated soil cohesion. The increase of soil cohesion along with the increase of matric suction at nonlinearly occurs in matric suction at above of the air entry value.

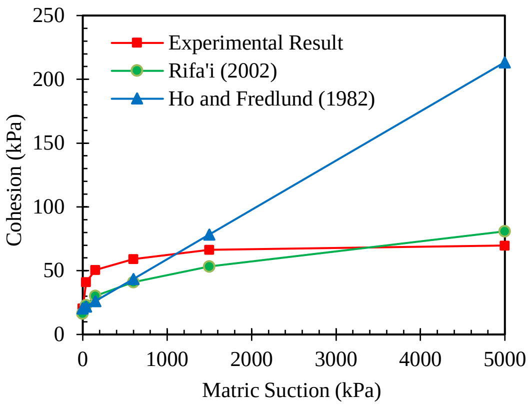

Fig.7 Comparison of cohesion between predictions and experimental results at various matric suctions

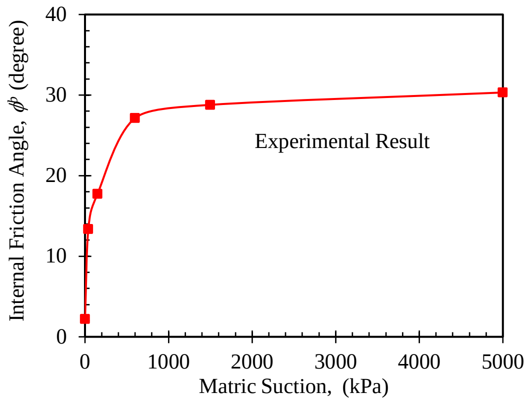

Fig.8 The relationship between internal friction angle and matric suction

The nonlinear relationship between the internal friction angle (ϕ^b) of unsaturated sandy clay and matric suction are shown in Fig. 8. There is a significant increase in internal friction angle at the beginning of the curve. This is indicated by a sharply increasing curve up to the matric suction of 40-600 kPa. Curves tend to be flat at the higher matric suction while the curve tends to be linear at the matric suction under AEV. It is identical with the relationship between shear strength and matric suction in Fig. 4, and it can be associated with the previously described reasons. A study carried out by Fredlund et al. [25] concluded that the ϕ^b angle (internal friction angle related to the change of matric suction) is equal to ϕ' (effective angle of internal friction) at low matric suction when the soil remains saturated, the ϕ^b angle reduces to a relatively constant value as matric suction exceed the AEV due to desaturation commences.

6. CONCLUSION

Several methods have been used to measure matric suction. Filter paper contact method has been carried out to measure the matric suction of sandy clay. The SoilVision knowledge-based system was used to give an approximation of the entire soil water characteristic curve (SWCC) using a proper curve fitting equation which represents measurable data points. In this study, Van Genuchten’s equation was used. Based on the results of SWCC, the air entry value (AEV) and residual suction value (S_r) of sandy clay were determined as 21.5 kPa and 70.000 kPa respectively.

A conventional triaxial (UU was selected to measure the shear strength of the tested soil samples. The filter paper contact method and the conventional triaxial (UU) were performed on compacted soil samples at the same maximum dry density and different water contents.

The results show that unsaturated shear strength of soil depends on soil moisture conditions i.e. matric suction. Under the same normal stress, the shear strength increases when the matric suction increases and the increase is nonlinear as reported by previous studies on highly plastic compacted clay [4]. When the matric suction is smaller than air entry value (AEV), the shear strength of the soil increases as matric suction increases and the increment is linear. Furthermore, in the matric suction between 40-600 kPa, a visible significant increase of soil shear strength was found.

The high increase in soil shear strength is associated with the inter-particle force produced by negative pore water pressure. The inter-particle forces depend on the particle size and these forces on the clay were higher than on silt and sand**.** At a high matric suction, the relationship between shear strength and matric suction tend to be stable as in a low water content, the matric suction is not transmitted effectively to the contact point of soil particles. Moreover, a large increase in matric suctions do not result in a significant increase in shear strength.

The shear strength of the soil increases as normal stresses increase at the similar of matric suction value. It was found that the soil cohesion and internal friction angle increase as matric suction increases and this increment is nonlinear. It could be stated that the increase in soil shear strength due to increase of matric suction is a result of the increase in soil cohesion and internal friction angle of the soil. This is in contrast to previous studies conducted on highly plastic compacted clay [4] which states that the increase in soil shear strength due to the increase of matric suction is the result of the increase in soil total cohesion.

7. ACKNOWLEDGEMENTS

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