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Assessment of Shear Strength Characteristic for Unsaturated Kaolin Clay in Qaime, Iraq

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ABSTRACT

In fact, the unsaturated soil test is not common in soil mechanics labs, and the unsaturated soils are feature higher strength and stiffness than saturated soil. The study focuses on the preparation of samples (kaolin from Qaime city), it uses the static compaction (one dimension) to keep on the samples initial water content, specific volume and degree of saturated constant. During the wet state, all samples appeared to have increasing water content, specific volume and degree of saturated by log time, and matric suction value was constant, during the equalization state this value was constant after about 40 hr., isotropic load was constant value (600) kPa and applied on a sample in each direction, during shearing loading for all case, the matric suction was constant value S (30, 60 and 90) kPa during testing. In this paper, the results of wetting stages showed the deviatoric stress increases with the increase in matric suction value. The axial and volumetric strain recorded the low value at S90 kPa because of the increasing matric suction value.

1. INTRODUCTION

The occurrence of unsaturated and saturated soil conditions in any geographical area is a direct function of active environmental factors such as evapotranspiration and rainfall. This soil covers a large part of the world and changing by the cycles of drying and wetting [1]. The behavior of unsaturated soil has not been widely investigated, this soil explained in the last twenty years, the unsaturated soils have become a very important subject inside geotechnical engineering, this division for the geomechanics have been slow to spread of practicing engineers, it is understood only with academic scholars and few specialists soil mechanicians, more often than in engineering practices, this soil is treated as fully saturated [2]. The concept of saturation is the moisture content within the soil particles. It can be divided into two types of soil, saturated soil and unsaturated soil (varying degree of saturation). In unsaturated soils, the pore pressure for water is usually negative, and the measurement of negative pore pressure directly is very difficult because of phenomenon of cavitation in the measurement system. During fully saturation pore water pressure in a sample is usually positive [3, 4].

2. BACKGROUND LITERATURE

The scientists in the unsaturated soil stage have completed significant advancements in the study of behavior unsaturated soil in some properties, such as matric suction, shear strength, volume change and water retention behavior.

2.1 Matric suction

The matric suction (S) is generally called as the change between pore-air Ua and pore-water Uw pressures in the unsaturated soil and are written as:

$$S = Ua - Uw \tag{1}$$

Matric suction is leading as component of suction in description of the mechanical behavior of unsaturated soil.

2.2 Shear strength

The stresses at any point of a mass section soil may be calculated the total principal stresses 1σ, 2σ, 3σ, which act at any point if the voids of the soil are filled by water under pore stress and the total principal stresses. Much investigational display that the unsaturated soil's shear strength is higher than that of the same soil in a saturated soil state at the same net stress value [5]. Using the values matric suction and net stress as the two stress state variables to explain unsaturated soils behavior, Fredlund and Rahardjo [6] suggested the following equation for shear strength.

$$\tau = c' + (\sigma - Ua) \tan\varphi' + (S) \tan\varphi \tag{2}$$

where, $(\sigma - Ua)$ net stress, τ , c' φ' and φ shear strength, cohesion and inter friction and inter friction at the suction.

Bishop (1959) putted the general equation to calculate the effective stress for unsaturated soil as below [7]: -

$$\sigma' = \sigma - \chi\, Uw - (1 - \chi)\, Ua \tag{3}$$

where, χ value is a parameter very important, it relies on degree saturation and differs from 0 (dry case) to 1 (fully saturated case).

(Khalili and Khabbaz, 1998) and (Khalili et al, 2004) related χ value to air-entry value (AEV) with matric suction according to [8, 9]:

$$\chi = (\frac{Ua - Uw}{(Ua - Uw)a})0.55 \quad (4)$$

where, (Ua-Uw) matrix suction value. (Ua-Uw) air entry value (AEV). The results showed that the effective stress parameter χ is not only associated with saturation in soil but also depends on kinds, hydraulic hysteresis, stress history, soil structure and other influences.

2.3 Volume change in unsaturated soil

Measurement of the sample's volume change is a significant subject when testing an unsaturated soils sample, there is a large variance after comparation saturated and unsaturated soil testing. In the saturation sample, the variation in void ratio causes the volume change inside the water phase, it is calculated clearly that the volume change for the sample is equal to volume change water. However, in an unsaturation sample, which may be measured as a three-phase as air, water and soil, the volume changes happen because of the variations in together gas and liquid phases, the total volume change of an unsaturated example is equal to the summation of the volume changes in air and water. This study used the triaxial equipment a single wall device used to complete all the test [10].

2.4 Water retention

Water retention behavior in the soil may be called as the association between suitable stress state variables (mostly suctions) and moisture content (or degree saturation). The quantity of water inside the void for the soil may be specified as gravimetric moisture content or degree saturation. Many studies explained that the shearing state was very important during comparison theoretical and experimental, the stress and the shear plane which have a large change from the field soil, during the evaluation, the shear strength obtained from triaxial tests are closer from the theoretical value [11, 12]. Huang et al. [13] explained the shear strength properties of unsaturated red clay, it developed a shear strength equation that may be simply applied in engineering practices, a sequence of the triaxial test for unsaturated and saturated red clay trials achieved by using the regular triaxial device, the data display that the top strength for the red clay increased slowly before the water content of 30% but reductions hard after that, the friction angle in particle red clay equal to unsaturated and saturated case, the cohesion in particle red clay for unsaturated is higher from saturated state, it changed in the resulted because of the matric suction. Many studies focused on the behavior clay soil by modified triaxial apparatus to test soil specimens under partially saturated state as a part of continually researches on unsaturated soils. These studies provided the new equipment for testing various kinds of hydromechanical loading counting drying and wetting stress paths under the suction and mean net stresses, the suction is scaled with axis translation technique [3, 14]. Many studies explained the impact of soil structure with different moisture content and initial stress on the shear strength for soils, they focus on the matric suction via using a high capacity tensiometer apparatus [15]. Some studies explained the association between a matric suction and a shear strength and separated in two portions, one portion is linear and non-linear, the point between the two portions is also defined as the highest point. Generally, when the matric suction increases, all the stress variables and the Young's modulus rise [16]. Vanapalli et al. [17], Fattah et al. [18] and AL-Ani et al. [19] mentioned great suction achieved at low moisture content in soil, but the osmotic suction dependent on the salt in liquid, the osmotic suction linked to the diffuse double layer in particle of soil while the matric suction essentially linked by the water-air interface (contractile skin). The matric and total suction distribution have a main influence on the stability for unsaturated soil, it affects on some properties as shear strength, seepage and stress, the soil water characteristic curve (SWCC) depended on the (AEV) and residual degree saturations, which are a main component of the distribution it [20]. Satyanaga et al. [21] explained that the water volume must be to reach at the equilibrium before increasing the suction value, the experiments confirmed that a significant drop in water volume is occasionally not consistent with the air pore value of the sample in suction state.

3. EXPERIMENTAL METHOED

3.1 Clay soil and case study

This study used clay to test isotropic and shearing after equalization state by triaxial apparatus, it does not contain highly expansive minerals and that test duration is reasonable [3, 22]. The kaolin clay is taken from Al-Qaim city near from Factory for Salt Resistant Cement. The location of the area study (34.25765381516885, 41.21690005302085) is about 320 W km from the city of Ramadi, the center of Anbar Governorate, see Figure 1 [23]. The chemical analysis of the kaolin is as shown in Table 1.

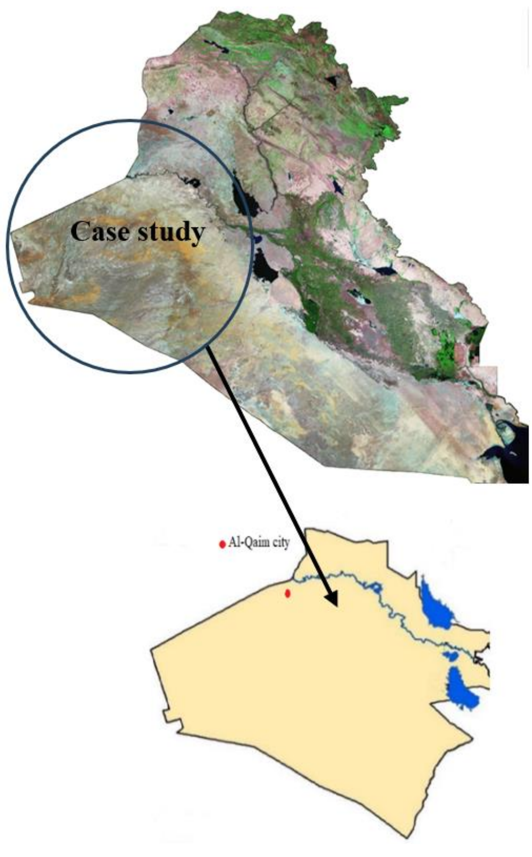

Figure 1. The study area and map details

Table 1. The percentage for components of kaolin clay

Components	Percentage
SiO_2	**47.5%**
Ai_2O_3	**30.5%**
Li_2O	**13.75%**
Fe_2O_3	**3.9%**
CaO	**3%**
SO_3	**0.98%**
MgO	**0.4%**

3.2 Procedure of modeling and compaction

The natural material was provided to the lab room as stone size greater than 150 mm, it was crushed by a hammer and divided into small stones or powder size less than 5 mm then passed a sieve (No.4), it was moved to an air-tight plastic bag then mixed 500g of clay dried by air with a bowl 125ml distilled water, the mix is stored in this air tight vessel for about (1-2) day to complete equilibrium then pass through sieve (No. 2). This method was depended from several researchers [3, 4, 14, 22, 24]. Multi-layer specimens were compacted by putting mixture kaolin clay and water inside the mold (1D Dimensionally) by using a marshal frame, the wet soil (50 g) placed inside split container and applied load (constant movement) by the arm, six layers were collected every in this mold, all layers have a high about (1.7 – 1.65) cm, the axial displacement rate was 1.5 mm/min, the top of surface for all layer was scarified before addition a new clay layer, the samples were prepared by a split mold (diameter 50mm and high 100mm). After compaction, the specimen was taken from mold by opening the screw in mold, the high and diameter of the sample were measured by spatial scale accuracy of 0.02 mm. Finally, using an electric balance the mass of the sample was calculated and placed on the cell apparatus, see Figures 2 and 3.

Figure 2. The specimen after compaction

Figure 3. A single-wall cell triaxial

3.3 Calculation by data test

The data were post-processed in a spread Excel sheet by using the equations shown below:

$$\upsilon = \frac{(Vo - \Delta V) * G * \rho w}{Ms} \quad (5)$$

$$q = \frac{F}{(Vo - \Delta V)} * (Ho - \Delta H) \quad (6)$$

$$\acute{p} = (\sigma_3 - Ua) + \frac{q}{3} \quad (7)$$

$$S_r = \frac{\frac{1}{\rho w} * (Mo - Ms) - \Delta Vw}{(Vo - \Delta V) - \frac{Ms}{\rho w * G}} \quad (8)$$

$$\varepsilon_a = -\ln(\frac{Ho - \Delta H}{Ho}) \quad (9)$$

$$\varepsilon_r = -\ln(\frac{Ro - \Delta R}{Ro}) \quad (10)$$

$$\varepsilon_V = -\ln(\frac{Vo - \Delta V}{Vo}) \quad (11)$$

$$\varepsilon_s = \frac{2(\varepsilon_a - \varepsilon_r)}{3} \quad (12)$$

The q deviator stress value, p net stress, s suction, S_r degree saturation, υ specific volume, F deviator force, V_O specimen volume at the start test, ΔV decrease of the specimen volume since the start test, H_O the length of a specimen at the start test, ΔH axial movement since the start test, Ro average radius of the specimen after equalization stage, ΔR average change in specimen radius (average area measured specimen cross-section), ρ_W water density, G specific gravity, Mo mass of the specimen at the start test, Ms the mass of solids within the specimen (at end test measure after oven-drying), ΔVw the decrease of pore water volume at start test, Ua air pressure, ε_a, ε_r, ε_v, ε_s true axial, radial, volumetric and shear strains.

4. RESULT AND DISCUSSION

The air entry value (AEV) in this study was used 100 kPa for the system, the specimen was located directly on an air entry filter, it puts a rubber membrane around a specimen. The loading in test S30, S60 and S90 were approved on the specimens during the pore air and water pressure concurrently while cell pressure was constant at (600) kPa. Despite the rate of loading on the hydromechanical behavior particularly in the little suction value, the rate of loading (10 -20 kPa/hr) had to be forced because of some subjects on electrical power cut and safety, the high rate of loading, i.e., bigger than the dissipation of the pore water pressure, the suction value is constant value during the loading and stay to end test.

4.1 Compaction and equalization state

Through the initial equalization test, the all specimens in this study displayed a rise in degree of saturation, water content and the specific volume, it increased by increasing matric suction value (30,60 and 90) kPa with respectively. The behaviours of unsaturated soil during the equalization test are qualitatively to the behaviours saturated soil, while on the wetting state, the data depends on significantly of volumetric behaviour and suctions value. Figures 4, 5, 6 and Table 2 illustrated the rise in degree of saturation, water content and specific volume by time in the equalization period for the three specimens confirmed in the triaxial unsaturated soil system. After nearly 40 hrs., the average of specimen volume variation and pore water volume change reduced indicating that equilibrium state was approximately attained.

Table 2. Degree of saturation, water content and specific volume values after compaction and after equalization

Sample	After Compaction Stage			After Equalization Stage		
	Sr	**W**	**V**	**Sr**	**W**	**V**
S30	0.53	0.229	2.188	0.627	0.299	2.316
S60	0.519	0.221	2.174	0.606	0.279	2.269
S90	0.527	0.224	2.173	0.605	0.27	2.231

Isotropic loading in test S (30, 60 and 90) kPa were automatically achieved but not displayed in this study as figure, both water and air pore pressure raised (at the same time) while maintaining suction value constant at (30, 60 and 90) kPa, a rate of the loading was (10-20) kPa/hr., a decision was complete to divide the isotropic loading stage into sub-stages with a rest period after each one to allow for equilibrium, after this stage, the shearing loading is starting.

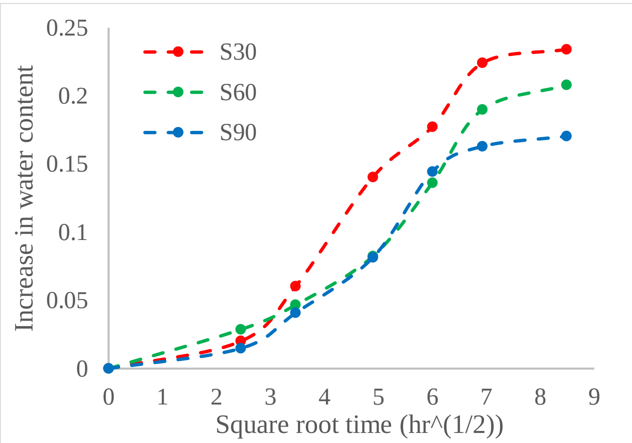

Figure 4. Relationship between water content and time

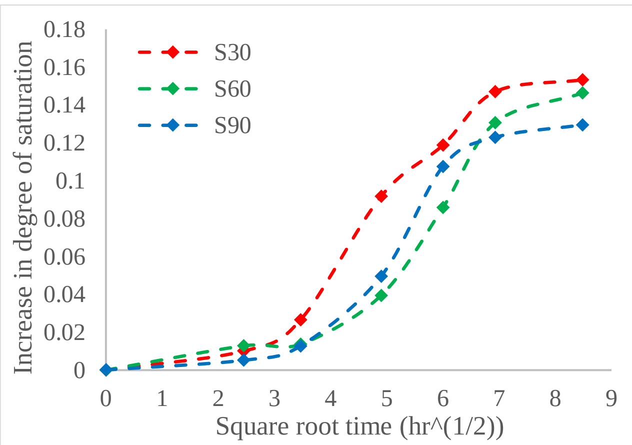

Figure 5. Relationship between degree of saturation and time

The rate for degree of saturation water content and specific volume was (15.3, 14.6 and 12.9) % (23.4, 20.7 and 17.03) % (0.055, 0.041 and 0.025) with (30, 60 and 90) kPa suction respectively. The change for degree saturation, water content and specific volume through wetting 30kPa is significantly lower than that of 60 and 90kPa due to the low suction value, this mean the soil is near saturation state.

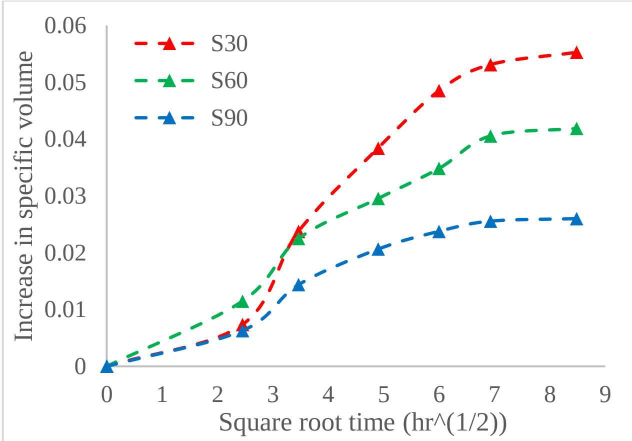

Figure 6. Relationship between specific volume and time

4.2 Shearing state

All samples started from A and reached at B during isotropic loading, and then the sample started from B (after equalization end) to reached C (end the test) during sharing test. The stress path was illustrated in Figure 7. The maximum mean stress p' of soil samples increases with the increase deviator stress q and these values were (41.65, 53.34 and 83.16) kPa.

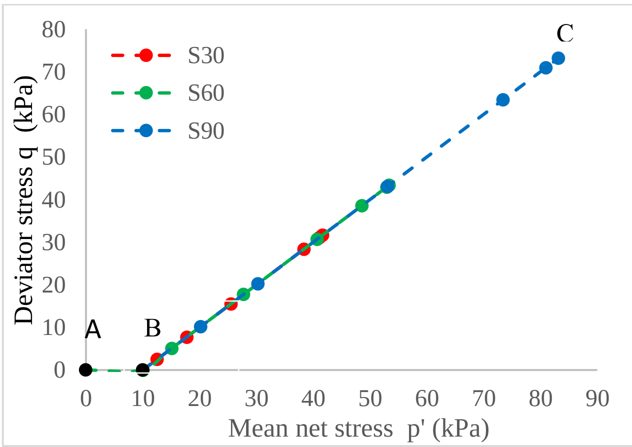

Figure 7. Stress path samples

Figures 8 and 9 display the investigational change of deviator stress q, true axial strain ε_a and true volumetric strain ε_v at the shearing test of all samples S (30, 60 and 90). Both true axial strain ε_a and true volumetric strain ε_v increased with increasing deviator stress q. The shear strength for unsaturated soil is measured via two variables mean net stress and matric suction, the influence matric suction is explained with applying three matric suctions value. The maximum deviatoric stress rises to 31.65 kPa, 43.34 kPa and 73.16 kPa with increased matric suction S (30, 60 and 90) kPa when the specimen exposed constant close pressure of 600 kPa, respectively. Figure 10 displays true volumetric strain ε_v and true axial strain ε_a for the shearing test of all samples S (30, 60 and 90), the soils increased both strains with decreased the matric suction value.

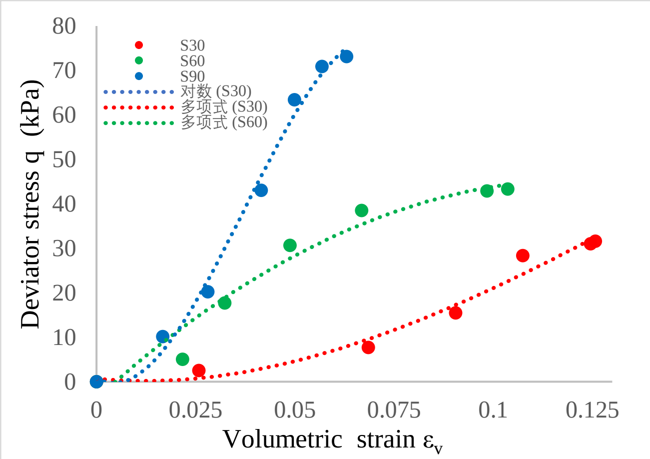

Figure 8. Relationship between deviator stress q and true volumetric strain ε_v

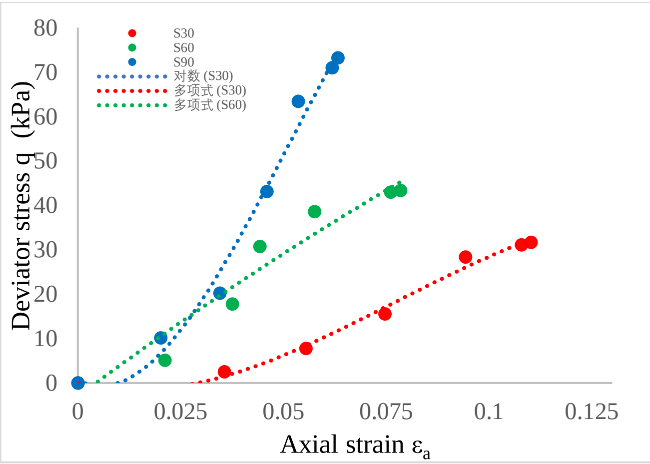

Figure 9. Relationship between deviator stress q and true shear strain ε_s

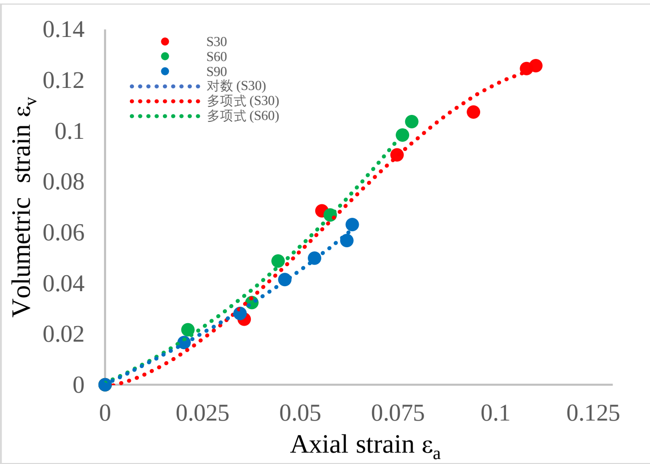

Figure 10. Relationship between true volumetric strain ε_v and true shear strain ε_s

Figures 11 and 12 display the difference in specific volume, mean net stress and degree saturation through testing the matric suction S (30, 60 and 90) kPa. From this test, the behavior is clear during the increase the matric suction.

The peak of shear strength for unsaturated clay increases with increasing a suction value. These behaviours usually were nonlinear that corresponds to drainage from the soil sample. the geometries of a particle clay and water molecular were variation behaviours in unsaturated test, the moving of water out a sample because of suction concept, it contributes to increase force and finally contribute to shear strength [25]. From the results, it can be concluded that increasing the cohesion between soil particles can be resulted from increasing the matric suction concentration of the clay which provided an inter bond between the particles of soil. Also, decreasing the thickness of the double layer causes a reduction in the antiparticle's repulsion force and an increase in the attraction force between the particles of soil.

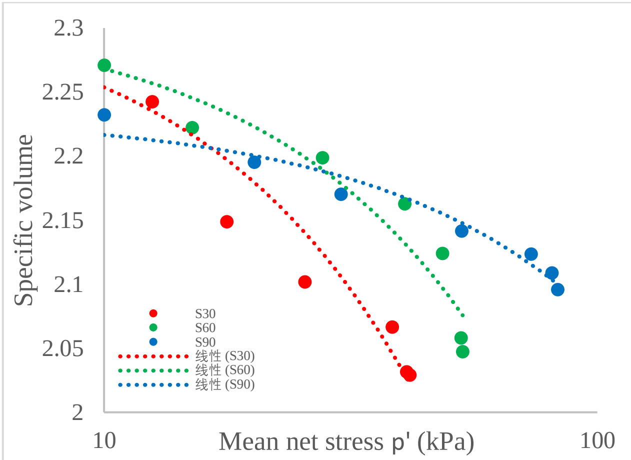

Figure 11. Relationship between specific volume and mean net stress

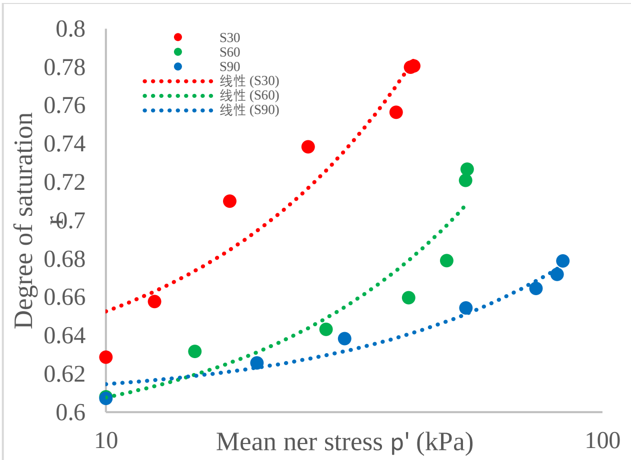

Figure 12. Relationship between degree of saturation and mean net stress

5. CONCLUSIONS AND REMARKS

1) After about 40 hrs, the specimens reached the equilibrium condition, and all test on the soil were achieved after this stage.

2) The peak of deviatoric stress happens at a high matric suction value with a constant confining pressure value.

3) During the shearing test, the curves degree saturation and specific volume were very clear, the signifying that the behavior for soil was mainly elastic.

4) From the curve mean net stress, degree saturation and specie volume displayed with the real that the volumetric

compressibility of pore space (void in structure soil) is bigger from the amount of water flowing out a specimen during the loading wet state.

5) For triaxial loading, it is observed that the increasing for specific volume water (Vw) was very little during shearing test.

REFERENCES

[1] Wheeler, S.J., Sharma, R.S., Buisson, M.S.R. (2003). Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. Géotechnique, 53(1): 41-54. https://doi.org/10.1680/geot.2003.53.1.41

[2] Solowski, W.T. (2008). Unsaturated soils: Constitutive modelling and explicit stress integration. Doctoral dissertation, Durham University. http://etheses.dur.ac.uk/2083/.

[3] Raveendiraraj, A. (2009). Coupling of mechanical behaviour and water retention behaviour in unsaturated soils. Doctoral dissertation, University of Glasgow. http://theses.gla.ac.uk/717/.

[4] Zhang, H., Hu, J., Li, Z., Zheng, B., Jin, H., Chou, Y., Li, H., Lu, M., Yang, S. (2025). Measurement and modeling of excess pore-water pressure in warm saturated frozen soil based on dynamic loading effect. Alexandria Engineering Journal, 110: 132-144. https://doi.org/10.1016/j.aej.2024.10.007

[5] Fredlund, D.G., Morgenstern, N.R., Widger, R.A. (1978). The shear strength of unsaturated soils. Canadian Geotechnical Journal, 15(3): 313-321. https://doi.org/10.1139/t78-029

[6] Fredlund, D.G., Rahardjo, H. (1993). Soil mechanics for unsaturated soils. John Wiley & Sons. https://doi.org/10.1002/9780470172759

[7] Kohgo, Y., Nakano, M., Miyazaki, T. (1993). Theoretical aspects of constitutive modelling for unsaturated soils. Soils and Foundations, 33(4): 49-63. https://doi.org/10.3208/sandf1972.33.4_49

[8] Khalili, N., Khabbaz, M.H. (1998). A unique relationship for χ for the determination of the shear strength of unsaturated soils. Geotechnique, 48(5): 681-687. https://doi.org/10.1680/geot.1998.48.5.681

[9] Khalili, N., Geiser, F., Blight, G.E. (2004). Effective stress in unsaturated soils review with new evidence. International Journal of Geomechanics, 4(2): 115-126. https://doi.org/10.1061/(ASCE)1532-3641(2004)4:2(115)

[10] Alabdullah, J. (2010). Testing unsaturated soil for plane strain conditions: A new double-wall biaxial device. Dissertation, Faculty of Civil Engineering, Bauhaus-University, Weimar.

[11] Chen, H.M., Ban, F.Q., Liu, X.W. (2006). Relationship between water content ω and unsaturated soil shear strength indices c and Φ. Journal of Hefei University of Technology, 29(6): 736-738.

[12] He, Y., Yu, Z.P., Zhang, Z., Chen, B., Zhang, K.N. (2022). Effects of rainfall on mechanical behaviors of residual-soil landslide. Frontiers in Earth Science, 10: 925636. https://doi.org/10.3389/feart.2022.925636

[13] Huang, F., Zhuo, L., Zhang, K. (2022). A study on the shear strength characteristic of unsaturated red clay. World Journal of Engineering and Technology, 10(4): 714-727. https://doi.org/10.4236/wjet.2022.104046

[14] Al-Sharrad, M.A. (2013). Evolving anisotropy in unsaturated soils: Experimental investigation and constitutive modelling. Doctoral dissertation, University of Glasgow. http://theses.gla.ac.uk/3828/.

[15] Marinho, F.A., Oliveira, O.M.D., Adem, H., Vanapalli, S. (2013). Shear strength behavior of compacted unsaturated residual soil. International Journal of Geotechnical Engineering, 7(1): 1-9. https://doi.org/10.1179/1938636212Z.00000000011

[16] Abd, I.A., Fattah, M.Y., Mekkiyah, H. (2020). Relationship between the matric suction and the shear strength in unsaturated soil. Case Studies in Construction Materials, 13: e00441. https://doi.org/10.1016/j.cscm.2020.e00441

[17] Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. (1999). The influence of soil structure and stress history on the soil–water characteristics of a compacted till. Géotechnique, 49(2): 143-159. https://doi.org/10.1680/geot.1999.49.2.143

[18] Fattah, M.Y., Ahmed, M.D., Mohammed, H.A. (2013). Determination of the shear strength, permeability and soil water characteristic curve of unsaturated soils from Iraq. Journal of Earth Sciences and Geotechnical Engineering, 3(1): 97-118.

[19] AL-Ani, S.M., Karkush, M.O., Zhussupbekov, A., Al-Hity, A.A. (2021). Influence of magnetized water on the geotechnical properties of expansive soil. In Modern Applications of Geotechnical Engineering and Construction: Geotechnical Engineering and Construction, pp. 39-50. https://doi.org/10.1007/978-981-15-9399-4_5

[20] Hafiz, H., Kechik, F., Ibrahim, A., Misnon, N., Daud, M., Abu Hassan, Z. (2024). Exploring the soil-water retention characteristics for unsaturated soil using coconut shell waste for subgrade improvement. The Open Civil Engineering Journal, 18: e18741495284385. https://doi.org/10.2174/011874149528438524030407125 1

[21] Satyanaga, A., Bairakhmetov, N., Kim, J.R., Moon, S. W. (2022). Role of bimodal water retention curve on the unsaturated shear strength. Applied Sciences, 12(3): 1266. https://doi.org/10.3390/app12031266

[22] Al-Sharrad, M.A., Al-Ani, S.M., Zedan, A.J. (2015). A modified suction-controlled triaxial equipment. Al-Nahrain Journal for Engineering Sciences, 18(2): 152-158.

[23] Enad, A.A., Ahmed, S.M., Mohammed, A.K., Mohammed, A.S. (2024). Influence of feldspar addition on the geotechnical properties of expansive soil in Rahhaliya, Iraq. Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials, 34(2): 143-148. https://doi.org/10.18280/rcma.340203

[24] Sivakumar, R., Sivakumar, V., Blatz, J., Vimalan, J. (2006). Twin-cell stress path apparatus for testing unsaturated soils. Geotechnical Testing Journal, 29(2): 175-179. https://doi.org/10.1520/GTJ14014

[25] Lu, N. (2020). Unsaturated soil mechanics: Fundamental challenges, breakthroughs, and opportunities. Journal of Geotechnical and Geoenvironmental Engineering, 146(5): 02520001. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002233