E3S Web of Conferences **382**, 02007 (2023) https://doi.org/10.1051/e3sconf/202338202007
UNSAT 2023

Effect of the optimum and residual moisture content on the strength characteristics of unsaturated sands

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Abstract. Soil exists mainly in unsaturated conditions. Therefore, accurate prediction of the soil shear strength for unsaturated conditions also becomes equally important for the geotechnical design of earth structures. This study primarily investigates the effect of the moisture content of unsaturated soil on its shear strength. The strength characteristics of silica sands with different grain sizes were studied using the modified triaxial apparatus and analytical methods. For this purpose, four series of triaxial compression tests on silica sands were performed by varying the moisture content of the test sample at compaction and shearing as optimum or residual moisture content. The test results showed that the test sample sheared at optimum and residual moisture content exhibited higher shear strength when the sample was initially compacted at residual and optimum moisture content, respectively. The moisture content at compaction and the soil grain size considerably influence the shear strength of unsaturated sandy soils. Furthermore, the analytical method used in this study for unsaturated soil shear strength prediction does not account for the effect of initial moisture content in predicting unsaturated soil shear strength.

1 Introduction

The conventional approach of predicting the soil shear strength for saturated conditions incorporating Terzaghi's effective stress approach is well established. However, the prediction of soil shear strength for the unsaturated condition is still a subject of significant discussion.

The naturally existing soils do not remain saturated and experience moisture content change under varying weather conditions. The partially water-filled pores of soil create a negative pore water pressure when the soil is unsaturated. This negative pore water pressure is known as suction ($u_a - u_w$) and which is defined as the difference between pore air and pore water pressure. A change in the moisture content of the soil results in a change in the soil suction, which directly influences the soil shear strength [1-3].

Various approaches to predict soil shear strength for unsaturated conditions consider suction a vital parameter. For example, Bishop [4] used effective stress approach for unsaturated soil shear strength prediction, and the author defined the effective stress as Eq. 1.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (1)$$

The parameter χ indicates the degree of saturation of the soil and is equal to unity for fully saturated soils. Further, χ is related to the air entry value of the soil [5]. For predicting unsaturated soil shear strength, considering the independent stress state variable approach [6,7], Eq. 2 has been proposed [8].

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

In the above equation increase in shear strength with the increase in suction relates to $tan\varphi^b$. Initially, researchers experimentally determined the linear increase in soil shear strength at the rate of φ^b with a corresponding increase in suction [9]. But later, it was observed that beyond a specific range of suction, φ^b decreases [10].

Suction stress depends upon the micro-level inter-particle and grain-to-grain forces transfer in the soil matrix. Effective stress defined by [11] incorporates the concept of suction stress (Eq. 3). The author proposed a suction stress curve based on the concept of suction stress to illustrate soil shear strength response to a wide range of suction.

$$\sigma' = (\sigma - u_a) - \sigma_s \quad (3)$$

Further, the unsaturated soil shear strength is estimated by employing the soil suction and its volumetric water content relation [12], called the soil water characteristic curve (SWCC). This relation shows that soil water content responds to the change in suction up to residual conditions. After achieving the residual moisture content, the rate of change of moisture content of the soil with a corresponding increase in suction is

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minimal. The water content of the soil in this condition is known as residual moisture content.

The density also influences the soil shear strength as the soil shear strength improves with an increase in its density [13,14]. Previous studies focused on studying the strength characteristics of soil under the framework of maximum dry density and optimum moisture content achieved in laboratory testing [15].

In this study, efforts have been made to explore another aspect of unsaturated soil shear strength, i.e., the effect of soil moisture content at compaction and shearing on its shear strength. For this purpose, modified triaxial apparatus has been used to carry out laboratory determination of the shear strength of the test soil samples.

The test samples were sheared at optimum and residual moisture content, initially prepared at optimum moisture content. Similarly, the test samples were prepared at residual moisture content and sheared at residual and optimum moisture content. The strength characteristics of unsaturated soil determined through laboratory testing were also compared with the results of the analytical method for predicting unsaturated soil shear strength.

2 Test material

Silica sand no. 3, 6, 7, and 8 were used in this study to explore their strength characteristics in the laboratory. The mean grain size (D50) for silica no. 3, 6, 7, and 8 is 1.5, 0.3, 0.15, and 0.08 mm, respectively (Fig. 1). These soils are mostly uniformly graded with a coefficient of uniformity ranging from 1.33 to 2.00. Silica no. 3 and 6 do not have any fine content, while silica no. 7 and 8 have fine content of 10 and 30 %, respectively.

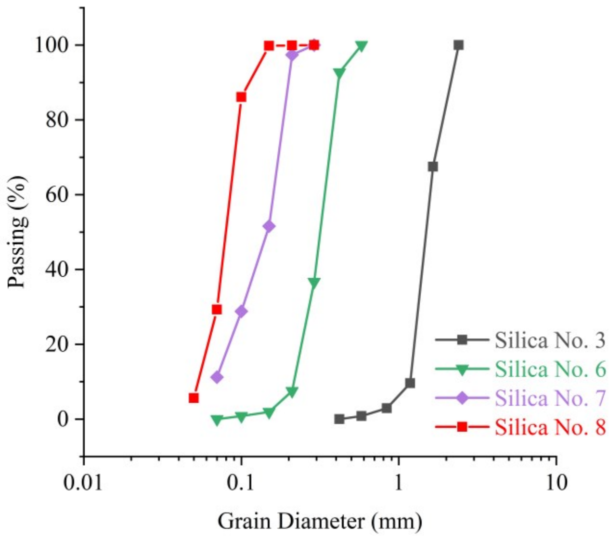

Fig. 1. Grain size distribution curves of the test materials

The standard proctor tests determined the maximum dry density and the optimum moisture content of the test materials. The test results show that the maximum dry density decreases from 1.59 to 1.44 g/cm^3 with a corresponding increase in optimum moisture content from 10.5 to 21.8 %, as the mean grain size decrease for silica no. 3 to 7 (Fig. 2). Silica no. 8, containing 30 % fines, shows maximum dry density and optimum moisture content of 1.48 g/cm^3 and 20.5 %, respectively. Table 1 contains the index properties of the test materials.

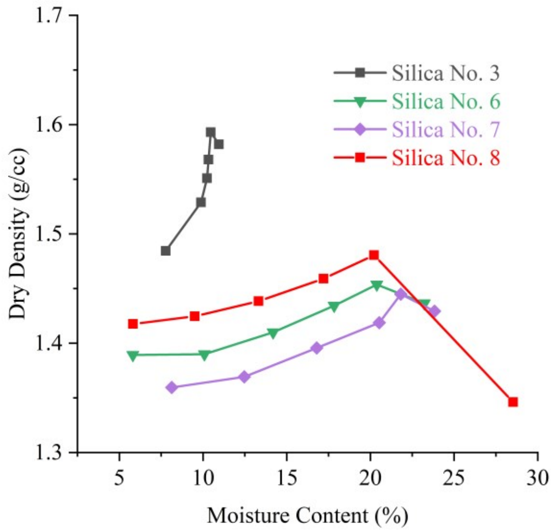

Fig. 2. Optimum moisture content vs dry density curve

3 Methodology

3.1 Apparatus

The strength characteristics of the silica sands were explored using modified triaxial apparatus (Fig. 3). Details of the various components of the apparatus are given below.

Table 1. Index properties of test materials

	Silica No. 3	Silica No. 6	Silica No. 7	Silica No. 8
Mean Grain Size D50 (mm)	1.5	0.3	0.15	0.08
Fine Content (%)	0	0	10	30
Coefficient of Uniformity (Cu)	1.33	1.59	2.00	1.49
Maximum Dry Density (g/cm^3)	1.59	1.45	1.44	1.48
Optimum Moisture Content (%)	10.5	20.1	21.8	20.5

The modified triaxial apparatus consisted of a double-cell assembly to precisely measure the volume change of the test sample using a low-capacity differential pressure transducer (LCDPT). The test soil sample was placed on the bottom metallic pedestal, which was equipped with a ceramic disk with a high air entry value of 100 kPa. The purpose of this ceramic disk was to allow the flow of water (infiltration/drainage) while restricting the flow of air. Porewater pressure was measured using an electric transducer attached to that system. This system was also equipped with an external

 https://doi.org/10.1051/e3sconf/202338202007

weight balance to measure the quantity of drained/infiltered water from the test soil sample.

Suction was controlled by varying the pore air pressure. In addition, the top cap was equipped with a supply and measurement system for air pressure and a PTFE filter to constrain water flow to the air supply system.

Axial loading was applied and measured using a servomotor jack unit and load cell. A linear variable differential transformer (LVDT) was attached to the axial loading arrangement to record the axial displacement. Cell pressure was applied and measured by a compressed air supply and an electric transducer.

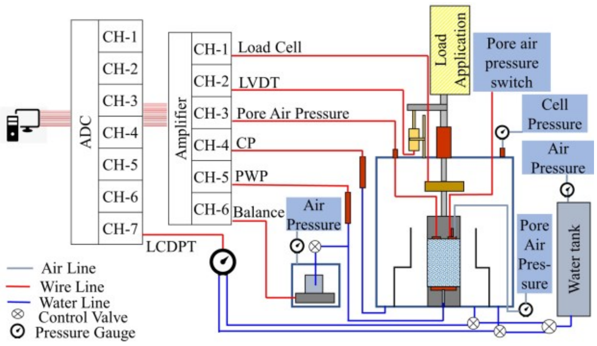

Fig. 3. Schematic diagram of modified triaxial apparatus [16]

All the transducers transmit the data to a computer program through amplifiers and analogue to digital converters. The axial loading was applied through the same computer program using the load control box and digital-to-analogue converter. The application of air pressure and cell pressure was controlled with the help of manual pressure regulators.

3.2 Testing procedure

To accurately determine pore water pressure, it is necessary to saturate the ceramic disk fixed in the pedestal and connecting water lines before carrying out the triaxial compression test. The saturation of the said system was carried out in two steps. Initially, the pedestal was placed underwater in a vacuum chamber for 24 hours under a negative pressure of 101.3 kPa. The pedestal was then fixed in the triaxial cell and inundated. Next, an air pressure of 200 kPa was applied to the triaxial cell to saturate connecting water lines by allowing the backflow of water through the pedestal. Sufficient time was allowed for the backflow of water to saturate all the water lines.

The test sample was directly prepared on the pedestal in five equal layers using the wet temping method. The moisture content for test sample preparation was adopted per the test condition, which has been discussed under the experimental program subheading. As the test soil sample was prepared in unsaturated conditions, the pore water pressure transducer experienced suction (negative pore water pressure). Later, based on the axis translation technique [17], suction was controlled by applying and controlling the pore air and pore water pressure.

The test sample underwent drained consolidation after managing the suction at the required level using the axis translation technique. Then, The water drainage/infiltration was allowed from the test sample depending upon the test conditions before applying monotonic shearing to the test ample.

3.3 Experimental program

The experimental program was devised to explore the strength characteristics of the test materials for different conditions of moisture content at compaction and shearing. For this purpose, test samples were compacted and sheared at various combinations of optimum moisture content (OMC) or residual moisture content (RMC). Four test series were carried out to obtain desired information. Details of the test series are tabulated in Table 2.

Table 2. Details of the experimental program

Test Series	Name	Description	
		Initial Moisture Content	Moisture content at shearing
1	OMC-RMC	OMC	RMC
2	RMC-RMC	RMC	
3	OMC-OMC	OMC	OMC
4	RMC-OMC	RMC	

The residual moisture content of the test sample was achieved by applying the suction above the residual suction of the respective test material. 25 kPa suction was applied to achieve the residual moisture content of test soils, considering the residual suction of the test materials and the apparatus limitations [18-19]. All the test samples were prepared same compactin ratio at optimum or residual moisture content depending upon the test conditions and isotropically consolidated before shearing. Fig. 4 shows the stress path adopted in this study for carrying out the defined test series.

Fig. 4(a) shows the stress path adopted for test series (1), for which the test samples were prepared at optimum moisture content. Suction exhibited by the test sample at optimum moisture content as negative porewater pressure was maintained using the axis translation technique. The test sample was isotopically consolidated with the opened drainage valve (A to B). Then the suction was increased to 25 kPa (B to C) to drain water from the test sample to achieve residual moisture content condition. Drainage was completed when no more increase in water amount was recorded in the external weight balance. Next, monotonic loading (C to D) was applied to shear the sample under the same suction. The moisture content of the sheared test sample was measured by the oven drying method after the completion of the test and recorded as the residual moisture content of the test material.

Fig. 4(b) shows the stress path adopted for the test series (2), for which the test sample was prepared at residual moisture content as measured from the test series (1). Suction was increased to 25 kPa (A to B) before isotropic consolidation (B to C), and after completion of the consolidation, the test sample was monotonically sheared (C to D).

Fig. 4(c) shows the stress path adopted for the test series (3), for which the test sample was prepared at optimum moisture content. Similarly, after controlling the initial suction using the axis translation technique, the sample underwent isotropic consolidation (A to B) followed by monotonic shearing loading (B to C).

For the test series (4), as shown in Fig. 4(d), the test sample was prepared at residual moisture content. After applying the axis translation technique to maintain initial suction, the test sample was consolidated (A to B). Then the water was infiltered in the test sample through the pedestal ceramic disk to increase the moisture content of the test sample up to optimum moisture content by applying the back pressure on the external weight balance chamber. Infiltration pressure was kept low to allow more time (around 24 hours) for the homogenous moisture distribution throughout the sample. Suction was controlled equal to the initial suction of the sample prepared at OMC (B to C) observed in the test series (1) and (3), and then the test sample was sheared under monotonic loading (C to D).

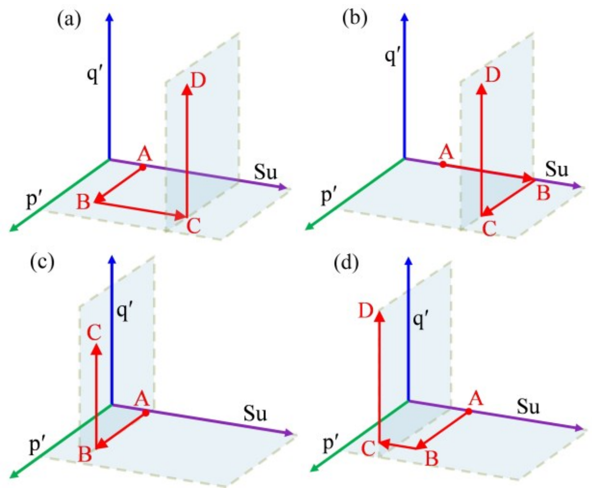

Fig. 4. Stress path for various test series

4 Discussion of Test results

Four triaxial compression test series were carried out to study the effect of moisture content at compaction and shearing on the shear strength of unsaturated soil. All the test samples were prepared directly on the pedestal at a 90% compaction ratio and isotopically consolidated at 50 kPa.

4.1 Effect of moisture content at compaction on shear strength at residual moisture content

In the first two test series, the test samples were prepared at optimum or residual moisture content and sheared at residual moisture content. From a practical standpoint, preparing the test sample at residual moisture content delegates the water scarcity condition in the project area.

The triaxial compression test results show that the peak deviatoric stress of OMC-RMC samples ranges from 175 to 165 kPa for silica no. 3, 6 & 7 with maximum volumetric strain ranges from 2 to 3.7 % [16]. Silica no. 8 (having 30 % fines) shows peak deviatoric stress of 195 kPa with a maximum volumetric strain of 4 % for OMC-RMC samples. Peak deviatoric stress and maximum volumetric strain of RMC-RMC samples range from 173 to 162 kPa and 4.5 to 1.5 %, respectively, in decreasing order with the decreasing mean grain size from silica no. 3 to 8 (Figs. 5 and 6).

The peak deviatoric stress of OMC-RMC samples remains higher than RMC-RMC samples in the increasing order from 2 kPa for silica no. 3 to 33 kPa for silica no. 8.

The stress-strain curves show that stress increases with the increase in strain until reaching a fair constant peak value except for silica no. 8 (containing 30 per cent fines). Silica no. 8 OMC-RMC and RMC-RMC samples experience 32 and 12 kPa decrement, respectively, from peak to residual deviatoric stress.

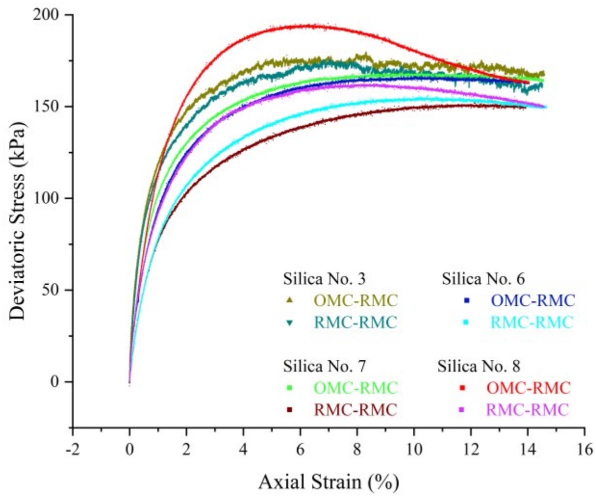

Fig. 5. Deviatoric stress vs axial strain of OMC-RMC and RMC-RMC samples

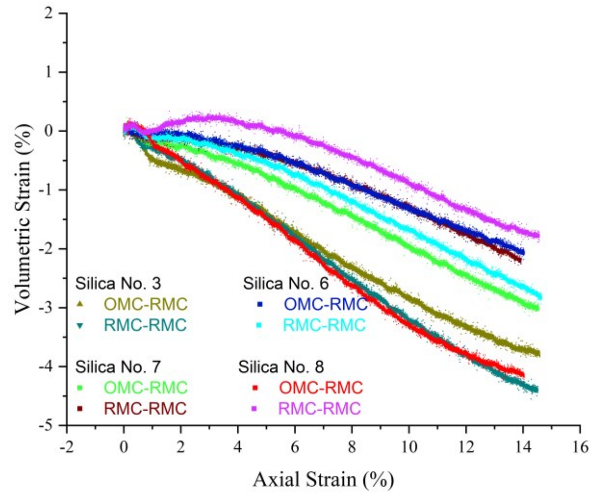

Fig. 6. Volumetric strain vs axial strain of OMC-RMC and RMC-RMC samples

A comparison of OMC-RMC and RMC-RMC samples' peak deviatoric stress shows that the difference increases with the decrease in the mean grain size of the test soils because of the increasing effect of the initial moisture content on the test sample's structure formation for the same. (Fig. 7).

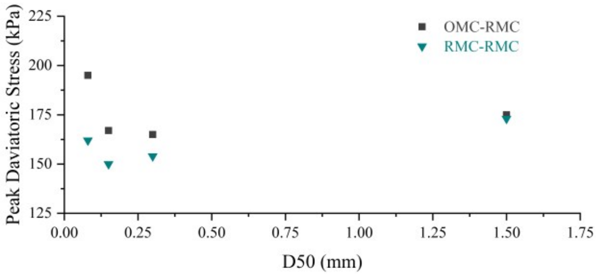

Fig. 7. Comparison of peak deviatoric stress of OMC-RMC and RMC-RMC samples

4.2 Effect of moisture content at compaction on shear strength at optimum moisture content

In the second two series, the test samples were prepared at optimum or residual moisture content and sheared at optimum moisture content.

The triaxial compression test results show that the peak deviatoric stress of OMC-OMC samples ranges from 154 to 164 kPa, and maximum volumetric strain ranges from 3.5 to 0.8 % for silica no. 3, 6, 7, and 8. Further, the test results show that the peak deviatoric stress and maximum volumetric strain RMC-OMC samples range from 157 to 192 kPa and 1.7 to 4.3 %, respectively, for the test soil samples (Figs 8 and 9).

The peak deviatoric stress of RMC-OMC samples remains higher than OMC-OMC samples in the decreasing order from 36 kPa for silica no. 3 to 7 kPa for silica no. 7 and for silica no. 8 RMC-OMC sample shows peak deviatoric stress 33 kPa higher than the respective OMC-OMC sample.

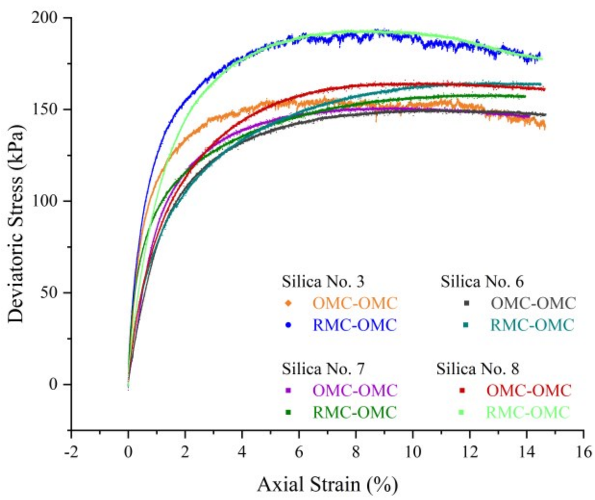

Fig. 8. Deviatoric stress vs axial strain of OMC-OMC and RMC-OMC samples

The comparison of peak deviatoric stress of OMC-OMC and RMC-OMC samples have been shown in Fig. 10. The comparison shows the difference in peak deviatoric stresses for OMC-OMC, and RMC-OMC samples decreased with a decrease in grain size from silica no. 3 to 7 but again increases for silica no. 8, which contains 30 % fines.

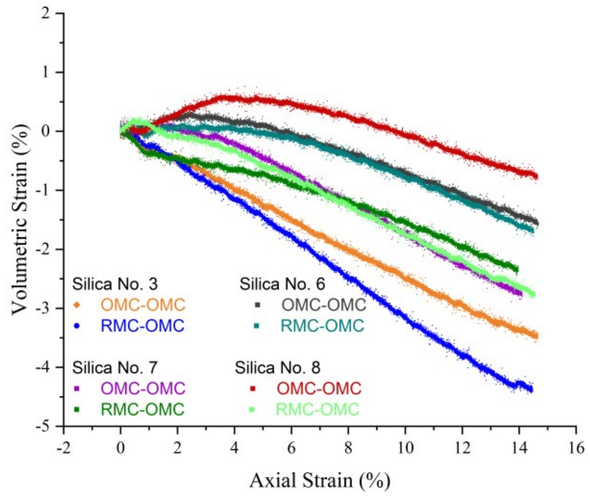

Fig. 9. Volumetric strain vs axial strain of OMC-OMC and RMC-OMC samples

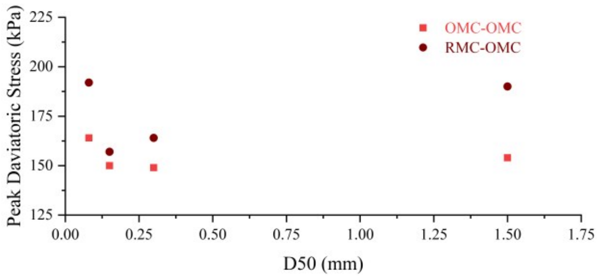

Fig. 10. Comparison of peak deviatoric stress of OMC-OMC and RMC-OMC samples

4.3 Comparison of peak deviatoric stress from experimental and analytical data

In this study strength characteristics of test materials have been studied for different moisture content conditions and corresponding suction. However, this study did not observe a noticeable relation between the soil shear strength and the particle size, as observed by [20] for saturated soils, because of the additional influence of the suction on the unsaturated soil shear strength.

The degree of saturation of soil and suction remains an essential input parameter in various approaches adopted by many researchers to predict the unsaturated shear strength of the soil. For example, a similar relation was proposed by Valanapali [21] as in Eq. 4 to predict the shear strength of unsaturated soil.

$$\tau = c' + (\sigma - u_a)tan\varphi' + (S^k)(u_a - u_w)tan\varphi' \qquad (4)$$

Where K is unity for no plastic soils. The angle of internal friction was calculated for the OMC-OMC sample by analyzing the triaxial compression test results for each test soil, considering the cohesion intercept zero. Based on this friction angle, deviatoric stress was predicted for the OMC-RMC condition for the respective soil by employing Eq. 4.

When suction is higher than the residual suction for silica sands, the degree of saturation approaches zero. So, Eq. 4 could not predict the shear strength contribution at high suction involving the product of the degree of saturation and suction, as shown in Fig. 11.

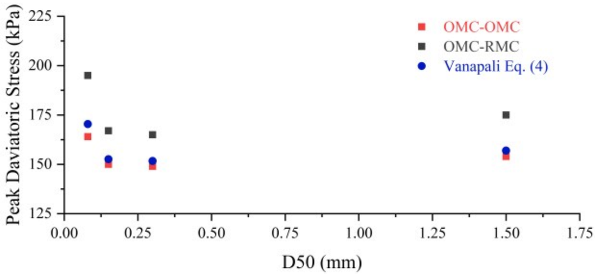

Fig. 11. Comparison of peak deviatoric stress experimental and analytical results

5 Conclusions

The strength characteristics of the unsaturated silica sand have been explored in this study, focusing on the effect of moisture content at compaction and the moisture content at shearing using the modified triaxial apparatus. Triaxial compression tests were carried out on silica sands no. 3, 6, 7, and 8 having mean grain size 1.5, 0.3, 0.15, and 0.08mm. Test samples were compacted and sheared at various optimum and residual moisture content combinations. The analysis of the triaxial compression test shows that the test samples sheared at residual moisture content showed 3 to 33 kPa high deviatoric stress for test samples initially compacted at optimum moisture content. Further, the test results reveal that the test samples sheared at optimum moisture content show 7 to 36 kPa high shear strength for the samples initially compacted at residual moisture content. At shearing, OMC-RMC samples undergo more suction, revealing more peak deviatoric stress than OMC-OMC samples for the corresponding test soils. The difference increases with a decrease in mean grain size of the test soils because of their higher residual suction. However, the analytical methods used in this study predicted 18 to 24 kPa less shear strength for residual moisture conditions than experimental results (test sample compacted at optimum moisture content). Therefore, the analytical method couldn't translate the effect of initial moisture content in predicting soil shear strength.

References

1. Y. Kim, S. Jeong, J. Kim, *Coupled Infiltration Model of Unsaturated Porous Media for Steady Rainfall*, Soils and Foundations, **56** (2016).
2. A.M. Rasool, J. Kuwano, *Influence of Matric Suction on Instability of Unsaturated Silty Soil in Unconfined Conditions*, International Journal of GEOMATE, **14** (2018).
3. S. Ravindran, I. Gratchev, *Estimation of Shear Strength of Gravelly and Sandy Soils from Shallow Landslides*, International Journal of GEOMATE, **18** (2020).
4. A.W. Bishop, *The Principle of Effective Stress*, Teknisk Ukeblad, **39** (1959).
5. N. Khalili, M.H. Khabbaz, *A Unique Relationship for χ for the Determination of the Shear Strength of Unsaturated Soils*, Geotechnique, **48** (1998).
6. D.G. Fredlund, N.R. Morgenstern, *Stress State Variables for Unsaturated soils*, Journal of the Geotechnical Engineering Division, **103** (1977).
7. H. Rahardjo, Y. Kim, A. Satyanaga, *Role of Unsaturated Soil Mechanics in Geotechnical Engineering*, International Journal of Geo-Engineering, **10** (2019.
8. D.G. Fredlund, N.R. Morgenstern, R.A. Widger, *The Shear Strength of Unsaturated Soils*, Canadian Geotechnical Journal, **15** (1978).
9. D.Y. Ho, D.G. Fredlund, *A Multistage Triaxial Test for Unsaturated Soils*, Geotechnical Testing Journal, **5** (1982).
10. K.M. Gan, *Direct Shear Strength Testing of Unsaturated Soils*, M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Canada, (1986).
11. N. Lu, W.J. Likos, *Suction Stress Characteristic Curve for Unsaturated Soil*, Journal of Geotechnical and Geoenvironmental Engineering, **132**, (2006).
12. D.G. Fredlund, A. Xing, M.D. Fredlund, S.L. Barbour, *The Relationship of the Unsaturated Soil Shear Strength to the Soil-Water Characteristic Curv*, Canadian Geotechnical Journal, **33** (1996).
13. K. Farooq, J.D. Rogers, M.F. Ahmed, *Effect of Densification on the Shear Strength of Landslide Material: A Case Study from Salt Range, Pakistan*, Earth Science Research, **4** (2015).
14. M.A. Sadek, Y. Chen, J. Liu, *Simulating shear behavior of a sandy soil under different soil conditions,* Journal of Terramechanics, **48** (2011).
15. B. Alshameri, A. Madun, I. Bakar, *Comparison of the effect of fine content and density towards the shear strength parameters,* Geotechnical Engineering, **48** (2017).
16. W. Ahmad, U. Taro, M. Umar, *Comparison of the Shear Strength of Unsaturated Sandy soils at Optimal and Residual Moisture contents*, International Journal of GEOMATE, **24** (2023).
17. J.W. Hilf, *An Investigation of Pore Water Pressure in Compacted Soils*, Ph.d. Thesis, Department of Civil Engineering, University of Colorado Boulder, pp.1-105 (1956).
18. J.P. Wang, N. Hu, B. François, P. Lambert, *Estimating Water Retention Curves and Strength Properties of Unsaturated Sandy Soils from Basic Soil Gradation Parameters*, Water Resources Research, **53** (2017).
19. T. Junfeng, U. Taro, T. Shangning, H. Dong, X. Jiren, *Water Movement and Deformation in Unsaturated Multi-layered Slope Under Heavy Rainfall*, International Journal of GEOMATE, **19** (2020).
20. R. Alias, A. Kasa, M.R. Taha, *Particle Size Effect on Shear Strength of Granular Materials in Direct Shear Test,* International Journal of Civil and Environmental Engineering, **8** (2014).
21. S.K. Vanapalli, *Shear Strength of Unsaturated Soils and its Applications in Geotechnical Engineering Practice,* In Proc. 4th Asia-Pacific Conf. on Unsaturated Soils, 23-25 November 2009, New Castle, Australia, (2009).