

Article

The Effect of Moisture Content at Compaction and Grain Size Distribution on the Shear Strength of Unsaturated Soils

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Abstract: The soil moisture content at shearing and other factors, including dry density and grain size, influence its shear strength. This study investigated the effect of moisture content at compaction and grain size distribution on the unsaturated soil shear strength. Triaxial compression tests were performed in the laboratory using the modified triaxial apparatus on silica sands No. 3 and 6 without fines and with 20% fines to explore the unsaturated soil shear strength characteristics. Test samples were compacted and sheared at various combinations of the soil's optimum and residual moisture content. The analysis of the triaxial compression test results shows that moisture content at compaction and the grain size distribution influence the unsaturated soil shear strength. The test samples compacted at optimum moisture content showed higher peak shear strength when sheared at residual moisture content. Further, test results show that the test samples of soil without fines, when compacted at residual moisture content, show higher peak shear strength at optimum moisture content. The finding of this study endorses considering the moisture content at compaction for the geotechnical design of structures while predicting the soil shear strength.

Keywords: unsaturated soil; optimum moisture content; residual moisture content; suction; shear strength; triaxial compression test



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1. Introduction

Geotechnical engineering projects often include the construction of earth structures using compacted soils. The shear strength of the compacted soil is predicted based on laboratory testing carried out under similar conditions as expected in the field. The soil shear strength is influenced by various factors, including soil grain size, shape and distribution, dry density, and confining pressure [1]. The strength parameters improve with the increase in mean grain size and reduce with the increase in uniformity coefficient [2,3]. The soil with angular to sub-angular shaped grains exhibits higher shear strength parameters than soil consisting of rounded to subrounded shape particles [4].

Further, soil grain size distribution predominantly affects soil shear strength compared to its grain shape [5]. Soil dry density and confining stress also positively influence shear strength [6,7]. Soil shear strength also depends on soil moisture content during shearing [8]. A saturated soil with all the pores of the soil matrix filled with water (with zero suction) shows the lowest shear strength. As the moisture content reduces, making the soil unsaturated, the suction starts to develop and increases with the decrease in moisture content, causing an increase in soil shear strength up to a certain extent [9].

Considering the saturated condition of the soil, the Mohr–Coulomb failure envelope along with Terzaghi's effective stress concept [10], are generally used for describing the soil shear strength, as shown in Equation (1).

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

Defining the shear strength of soil in an unsaturated condition is more complicated. Various approaches, including the effective stress approach, independent stress variable

approach, and suction stress concept, have been adopted to predict soil shear strength in unsaturated conditions accurately. The effective stress approach incorporates the relationship defining the effective stress for unsaturated soil, as shown in Equation (2), proposed by Bishop [11].

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (2)$$

Parameter χ depends upon the degree of saturation of the soil and can also be related to soil air entry value and prevailing soil suction [12].

Fredlund et al. [13] proposed Equation (3) based on the independent stress state variable approach described by [14,15], which requires the independent stress state variables to interpret unsaturated soil shear strength considerably.

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (3)$$

Equation (3) supports that the shear strength of unsaturated soil increases linearly with the corresponding increase in suction. However, many experimental studies carried out in the past do not support the linearity of the failure surface in shear stress vs. matric suction planes [16,17].

The suction stress approach includes a relatively new concept of effective stress definition, as shown in Equation (4), under the framework of suction stress proposed by Lu and Likus [18].

$$\sigma' = (\sigma - u_a) - \sigma_s \quad (4)$$

The suction stress curve proposed by the author [18] can also describe the non-linearity of the failure surface in shear stress vs. matric suction planes. Considering the proposed suction stress curve, three types of soil behaviors are proposed for the soil shear strength as a function of suction. The suction stress curve supports the idea that if the suction keeps increasing beyond a specific range, depending upon the soil type, the shear strength of the soil either increases, remains almost constant, or decreases from a peak to a relatively constant value.

Previously, many researchers considered the saturated soil condition to explore the effect of the factors, including soil grain size and distribution, density, and confining pressure, on the soil's shear strength [19]. However, the effect of moisture content at compaction on the unsaturated soil shear strength has received less attention. As Vanapalli [20] stated, soil compacted at different initial water content should be considered different soil in terms of mechanical behaviors, even with the same soil type and size. Therefore, this study explores soil shear strength behavior when compacted at different moisture contents.

Further, it has been substantiated above from the literature review that suction positively influences the unsaturated soil shear strength. However, practical geotechnical problems are considered conservatively by ignoring the suction's effect [21] in predicting the soil's shear strength expecting the saturated condition of the soil to be achieved during the structure's design life. However, climatic conditions and the project's location do not always support this presumptive expectation. Therefore, this study considers the possibility of incorporating the positive effect of suction in the structure's geotechnical design.

In this study, the effect of the moisture content at compaction on unsaturated soil shear strength has been explored for the soils with different mean grain sizes and grain size distributions. The finding of this study allows the designer to vary the moisture content at compaction to achieve the required density and, eventually, the shear strength of the soil. Further, the viability of incorporating unsaturated shear strength, considering the positive influence of the suction, into the geotechnical design of the structure without compromising the safety requirement has also been studied.

This study employs the triaxial compression test to investigate the shear strength behavior of sandy soils and their mixture with non-plastic fines. The test samples were prepared at identical compaction ratios and consolidated at constant confining pressure before shearing. The finding of this study cannot be expanded to the other soil types

without proper investigations. The conclusions made from this study's findings are based on the laboratory elements test, and the validity is yet to be proved for field conditions.

2. Test Materials

This study used soil with different mean grain sizes and grain size distributions, including silica No. 3 and 6, which have mean grain sizes (D_{50}) of 1.5 and 0.3 mm, respectively, without fines and with 20% fines (DL-Clay). Silica No. 3 and 6 are uniformly graded sands with coefficients of uniformity (C_u) of 1.33 and 1.59, respectively. The addition of 20% fines to silica No. 3 and 6 alter their grain size distribution, which results in uniformity coefficients (C_u) of 64 and 14, respectively, for the said soils. The grain size distribution curves for the test soils have been shown in Figure 1a, where soil without fines and with 20% fines are designated as NF and WF, respectively.

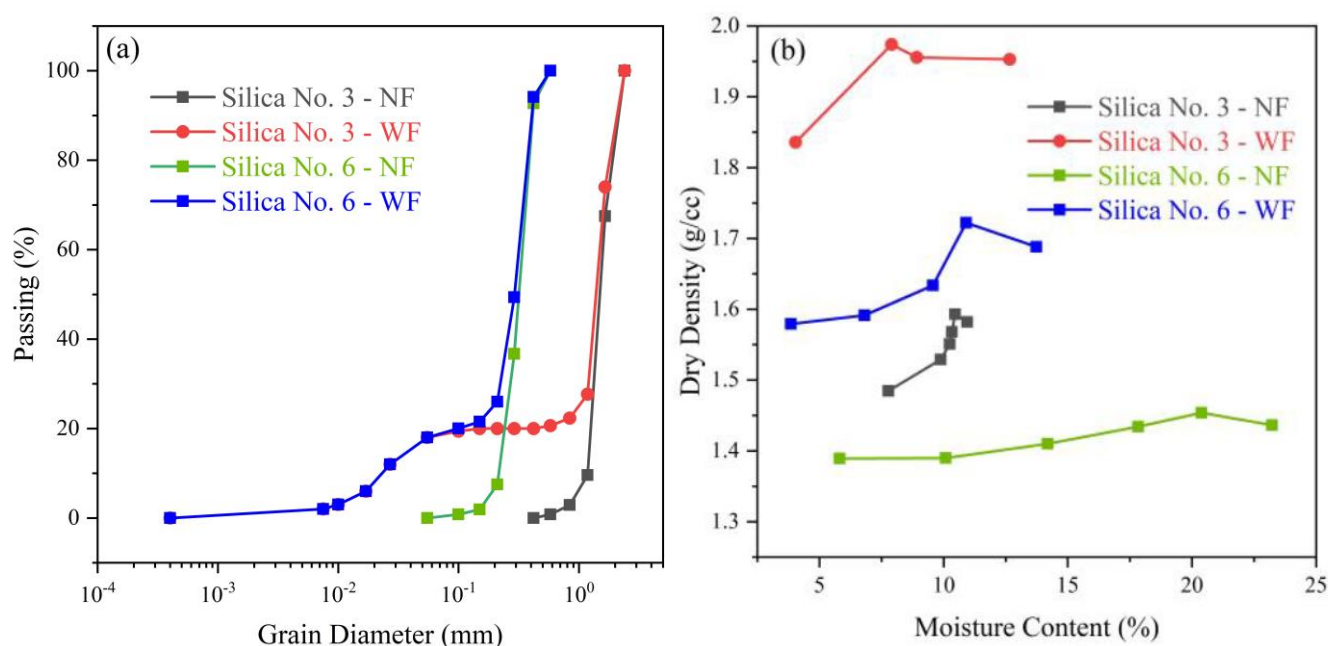


Figure 1. Physical properties of test materials. (a) Grain size distribution curves. (b) Dry density vs. moisture content curve.

The standard proctor test determines the maximum dry density and the optimum moisture content of the test materials. The test results showed that silica No. 3 has a maximum dry density of 1.59 g/cm^3 and an optimum moisture content of 10.5%.

The addition of fines results in a change in the grain size distribution of silica No. 3 and 6 to contain a wide range of grain sizes. This addition contributes to a smaller void ratio and less water content required to facilitate the soil particle rearrangement for denser packing under compaction force. So, as expected, with the addition of fines to silica No. 3, the maximum dry density increases to 1.97 g/cm^3 and the optimum moisture content decreases to 7.9%. Similarly, for silica No. 6, with the addition of 20% fines, the maximum dry density increases from 1.45 to 1.72 g/cm^3 and the optimum moisture content decreases from 20.1 to 10.9%. The effect of fine content addition on the compaction characteristic observed in this study is coherent with previous studies [22]. The maximum dry density and moisture content relationship for the test soils are shown in Figure 1b, whereas the index properties of the test material are shown in Table 1.

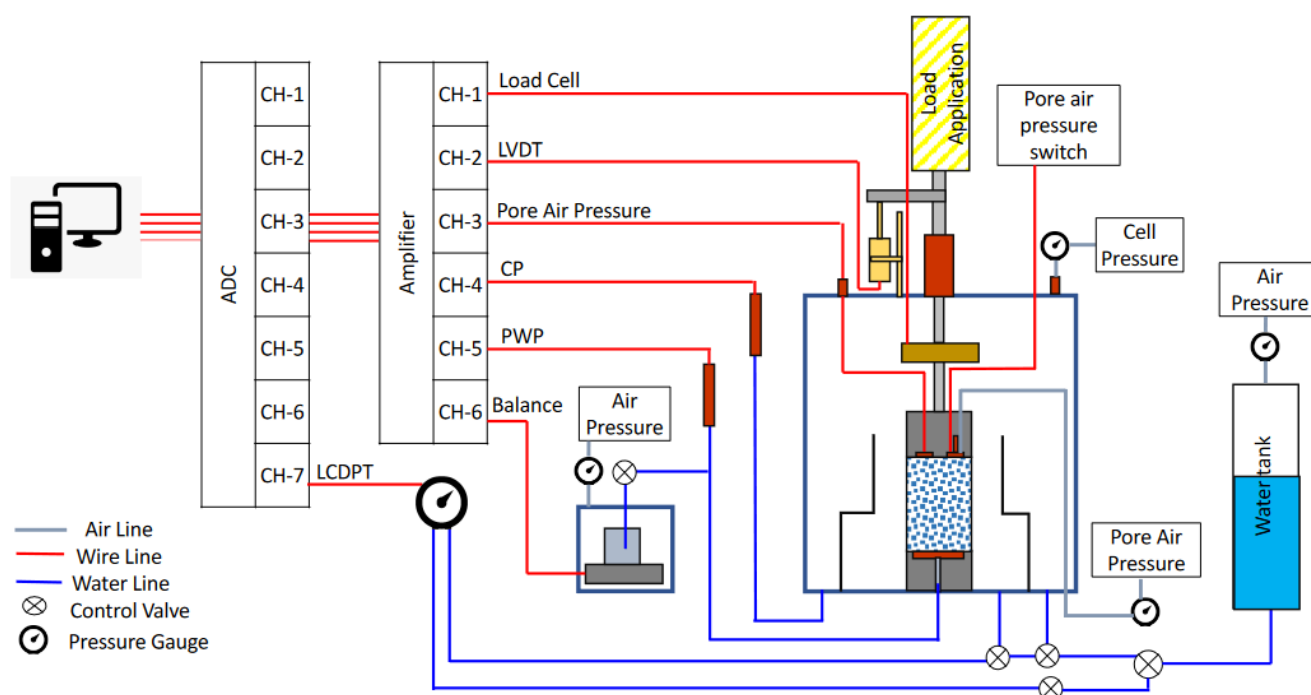
Table 1. Index properties of the test materials.

| | Silica No. 3 | Silica No. 3 +20% DL-Clay | Silica No. 6 | Silica No. 6 +20% DL-Clay |
|--|-----------------|------------------------------|-----------------|------------------------------|
| Symbol | Silica No. 3-NF | Silica No. 3-WF | Silica No. 6-NF | Silica No. 6-WF |
| Mean Grain Size D ₅₀ (mm) | 1.5 | 1.5 | 0.3 | 0.3 |
| Fine Content (%) | 0 | 20 | 0 | 20 |
| Coefficient of Uniformity (Cu) | 1.33 | 64 | 1.59 | 14 |
| Maximum Dry Density (g/cm ³) | 1.59 | 1.97 | 1.45 | 1.72 |
| Optimum Moisture Content (%) | 10.5 | 7.9 | 20.1 | 10.9 |

3. Methodology

3.1. Apparatus

A modified triaxial apparatus was used in this study to investigate the strength characteristics of the test materials. The apparatus mainly consisted of a double-cell assembly with a loading arrangement and multiple electrical transducers for test parametrical data acquisition. Various components of the apparatus have been shown in Figure 2 and described below.

**Figure 2.** Schematic diagram of the modified triaxial apparatus.

The test sample was placed on the pedestal fixed in the base plate of the apparatus. The pedestal was equipped with a high air entry value ceramic disk at the top, and the bottom of the pedestal was connected to a porewater pressure transducer, supply, and drainage system. The pore water supply and drainage system also contained a weight balance to measure the quantity of water infiltrated or drained from the test sample.

A computer program was used to apply the axial load to the test sample using a servomotor jack unit through the top cap. The top cap also contained an electrical switch and transducer to control the supply and measure the pore air pressure. A load cell was fixed between the top cap and servomotor jack to measure the applied load. A linear variable differential transformer (LVDT) was attached externally to the axial loading arrangement to measure the vertical deformation. The volumetric strain was recorded with the help of a low-capacity differential pressure transducer (LCDPT) by considering the

difference in water head in double cell assembly. Cell pressure was applied as compressed air in the partially water-filled triaxial assembly and controlled manually with the help of a pressure regulator. The cell pressure was measured with an electrical transducer connected to the bottom plate of the apparatus. A set of amplifiers was used to collect the data from transducers and transmit it to a computer for recording using an analog-to-digital converter.

3.2. Testing Procedure

The test soil sample was prepared directly on the pedestal in five equal layers at a 90% compaction ratio using the wet-tempering method. A metallic mold (50×100 mm) and the rubber membrane placed inside under suction were used to prepare the test sample. The ceramic disk fixed at the top of the pedestal and the water lines connecting the pedestal to the pore water pressure transducer and the external weight balance was saturated before sample preparation. This saturation is necessary to accurately determine the pore water pressure/suction and the water drainage/infiltration to the sample.

The initial water content for test sample preparation was adopted as optimum or residual moisture content, per the test conditions discussed in the next section. The negative porewater pressure/suction exhibited by the unsaturated test soil sample just after the sample preparation was measured by the pore water pressure transducer and recorded. Suction in terms of negative pore water pressure offers less control over maintaining suction at the required level and may result in inaccurate data acquisition due to the formation of cavities. Therefore, the axis translation technique [23] maintained the suction per the test conditions requirement by varying the pore air pressure and keeping the pore water pressure above zero. Cell pressure was also increased with pore air pressure during the axis translation to avoid any volume change in the test sample.

After that, the test sample was isotopically consolidated at 50 kPa while maintaining the suction using the axis translation technique. The drainage valve was kept open during the consolidation stage. Then, the test sample was sheared under monotonic loading at 0.05 mm/min.

For the test sample initially prepared at the optimum moisture content and to be sheared at the residual moisture content, water was drained from the test sample under the suction after completing the consolidation process. For this purpose, suction was increased and maintained beyond the residual suction of the test soil by employing the axis translation technique. Then, sufficient time was allowed to complete the drainage process, i.e., no more increase in water in external weight balance was observed, before the application of the shearing load on the test sample.

Similarly, the sample's water content needed to be increased for the test sample initially prepared at residual moisture content and to be sheared at optimum moisture content. Water was infiltrated into the test sample from the bottom through the ceramic disk by applying air pressure to the external weight balance water container. The air pressure was kept low to infiltrate water into the soil sample at a slower rate for homogenous water distribution inside the test sample. Then, the sample was sheared under monotonic loading after attaining the required water content.

3.3. Experimental Program

This study explores the effect of the moisture content at compaction on the shear strength of unsaturated soils. The soil's optimum and residual moisture content has been considered in this study as compaction or the shearing moisture content depending upon the test conditions. The optimum moisture content of the soil is generally obtained by performing the proctor test on the soil sample. Conventionally, the construction of geotechnical structures involves soil compaction at the same moisture content. On the other hand, the residual moisture content is the minimum moisture content that can be retained by the compacted soil when the suction keeps on increasing [24]. In this study, four series of triaxial compression tests following the Japanese Geotechnical Society Standard "JGS

0527-2009 were carried out considering the condition, i.e., the optimum moisture content (OMC) or the residual moisture content (RMC) for test sample compaction and shearing, as mentioned in Table 2.

Table 2. Details of the test series performed.

| Test Series | Name | Description | |
|-------------|---------|--------------------------------|------------------------------|
| | | Moisture Content at Compaction | Moisture Content at Shearing |
| 1 | OMC-RMC | OMC | RMC |
| 2 | RMC-RMC | RMC | |
| 3 | OMC-OMC | OMC | OMC |
| 4 | RMC-OMC | RMC | |

The triaxial compression test series defined in Table 2 followed the stress paths shown in Figure 3 for the respective test series.

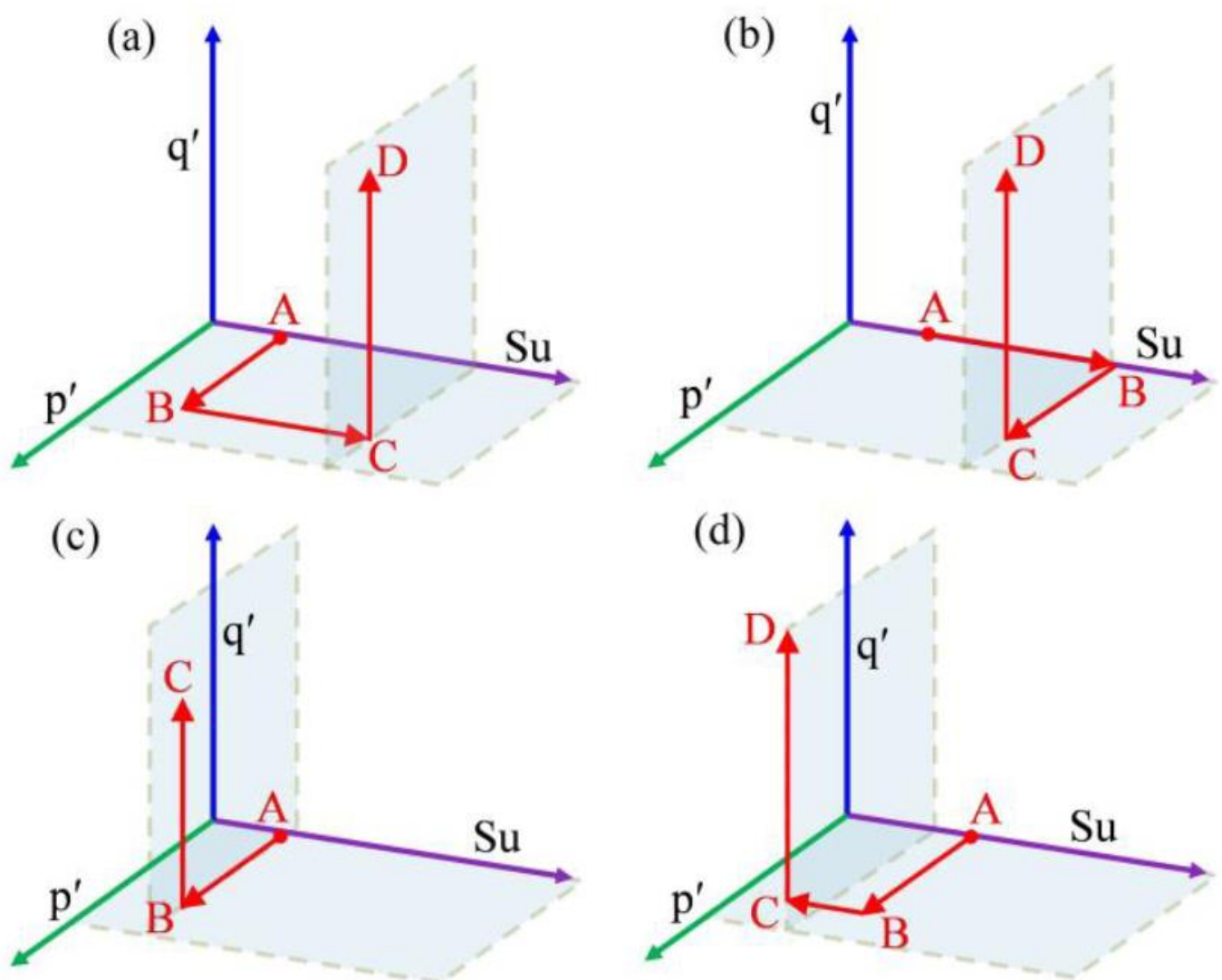


Figure 3. Stress path adopted for various test series. (a) OMC-RMC, (b) RMC-RMC, (c) OMC-OMC, (d) RMC-OMC.

The test series (1) was carried out by compacting the test soil sample at the optimum moisture content. The test sample at the OMC exhibited the initial suction as negative pore water pressure designated as pt. A in Figure 3a. The axis translation technique maintained the same suction in the test sample by controlling the pore air pressure. The same suction was maintained during the isotropic consolidation, which is shown as pt. A to B of the test sample. After the completion of the consolidation process, the residual moisture content condition was achieved for the test sample by increasing the suction, shown as pt. B to C, to drain the moisture content from the test sample. Suction was increased up to 25 and 50 kPa for the test soils without fines and with 20% fines, respectively, considering the residual suction of the respective materials [25,26]. The residual moisture content condition was achieved when the quantity of water in the external weight balance stopped increasing. The deviatoric stress is shown as pt. C to D and was then applied to shear the test sample. After the completion of the shearing process, the test sample was removed from the triaxial apparatus, and the moisture content of the test sample was determined by the oven-drying method. The moisture content obtained was recorded as the residual moisture content of the test soil.

Test series (2) was carried out by compacting the test sample at residual moisture content determined at the end of test series (1) for the respective test soil. The test sample exhibited the initial suction at RMC, designated as pt. A in Figure 3b. Then, the test sample suction was increased to 25 or 50 kPa, shown as pt. A to B, as in test series 1 for the respective soil, using the axis translation technique. After that, the test sample was isotopically consolidated, shown as pt. B to C, and then deviatoric stress was applied to shear the test sample, which is shown as pt. C to D.

While carrying out test series (3), the test sample was compacted at the optimum moisture content, as shown in Figure 3c. After maintaining the initial suction using the axis translation technique such as the test series (1), the test sample undergoes isotropic consolidation, shown as pt. A to B. Then, the test sample was sheared under the deviatoric stress, which is shown as pt. B to C.

The test sample was compacted at residual moisture content for test series (4). The axis translation technique was used to maintain the suction equal to the initial suction designated as pt. A and the then test sample was isotopically consolidated, which is shown as pt. A to B at the same suction, as shown in Figure 3d. The water was infiltrated to increase the moisture content of the test sample by applying air pressure to the water contained in the external weight balance chamber. The air pressure for water infiltration was kept low at around 10 kPa for uniformly distributing the water inside the test sample. The optimum moisture content of the test sample was achieved when the desired quantity of water infiltrated, considering the record of external weight balance. Then, suction was maintained as the initial suction shown as pt. B to C, which was observed as the initial suction for the test series 1 for respective soil tests before applying the deviatoric stress, which is shown as pt. C to D, for shearing of the test sample.

4. Discussion of Test Results

The modified triaxial apparatus has been used in this study to explore the shear strength behavior by carrying out triaxial compression tests. This study aimed to investigate the effect of moisture content at compaction and shearing and grain size distribution on the shear strength of unsaturated soils. For this purpose, four triaxial compression test series were performed for the test samples initially compacted at the optimum or residual moisture content. The test results showed that moisture content at compaction and grain size distribution significantly influenced the shear strength of unsaturated soils, which has been discussed hereunder.

The test results showed that unsaturated test soils exhibited higher peak shear strength at the residual moisture content when the test samples were compacted at the optimum moisture content compared to the test sample compacted at the residual moisture content. For instance, OMC-RMC and RMC-RMC samples consisting of silica No. 3-NF show a peak deviatoric stress of 175 and 173 kPa with a maximum volumetric strain of 3.7 and 4.5%, as shown in Figure 4 [27]. However, a vast difference in peak deviatoric stress was observed for silica No. 3-WF OMC-RMC and RMC-RMC samples. For these samples, peak deviatoric stress increased to 407 and 192 kPa, respectively, with a corresponding volumetric strain of 8.2 and 4.5%.

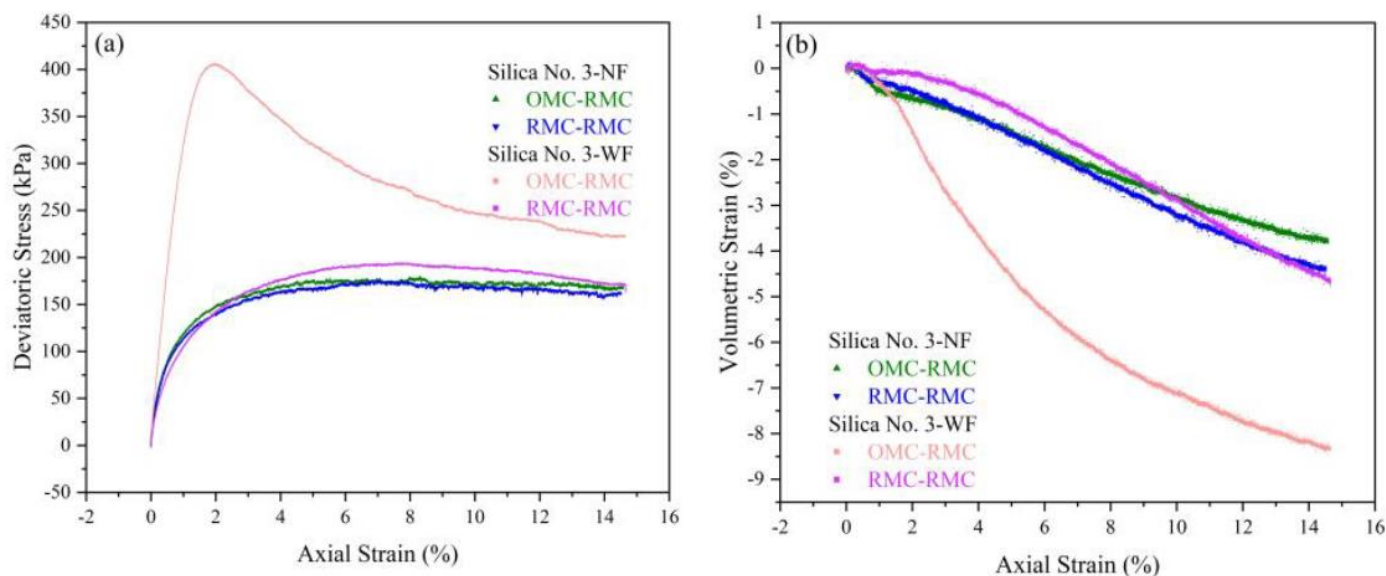


Figure 4. Silica No. 3-NF and silica No. 3-WF OMC-RMC and RMC-RMC samples. (a) Deviatoric stress vs. axial strain. (b) Volumetric strain vs. axial strain.

Similarly, OMC-RMC and RMC-RMC samples consisting of silica No. 6-NF show a peak deviatoric stress of 165 and 154 kPa with a maximum volumetric strain of 2.0 and 2.7%, as shown in Figure 5 [27]. A considerable increment in peak deviatoric stress was observed for silica No. 6-WF OMC-RMC and RMC-RMC samples. Peak deviatoric stress for these samples increased to 272 and 200 kPa, respectively, with a corresponding volumetric strain of 6.0 and 3.4%.

Further, the test results showed that unsaturated soils exhibit higher or nearly equal peak shear strength at the optimum moisture content when the sample is compacted at the residual moisture content compared to the sample prepared at the optimum moisture content. OMC-OMC and RMC-OMC samples consisting of silica No. 3-NF show a peak deviatoric stress of 154 and 190 kPa with a maximum volumetric strain of 3.5 and 4.3%, as shown in Figure 6. The almost identical peak deviatoric stress of 192 and 191 kPa was observed for silica No. 3-WF OMC-OMC and RMC-OMC samples, respectively, with a corresponding volumetric strain of 4.2 and 2.5%.

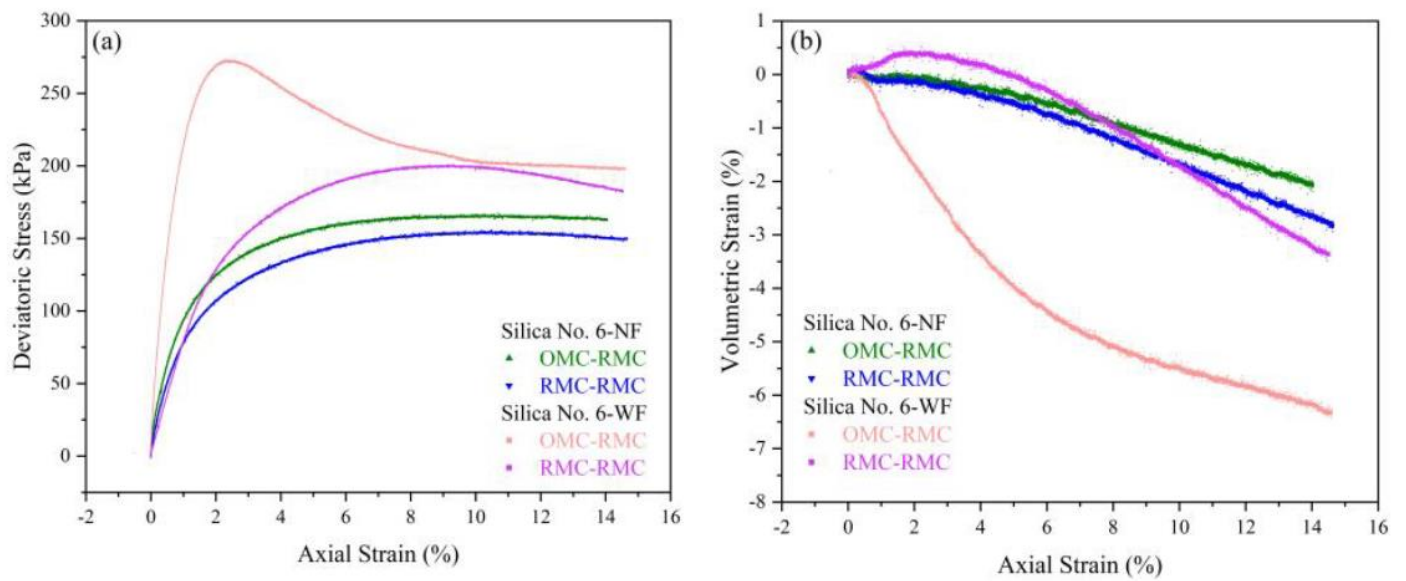


Figure 5. Silica No. 6-NF and silica No. 6-WF OMC-RMC and RMC-RMC samples. (a) Deviatoric stress vs. axial strain. (b) Volumetric strain vs. axial strain.

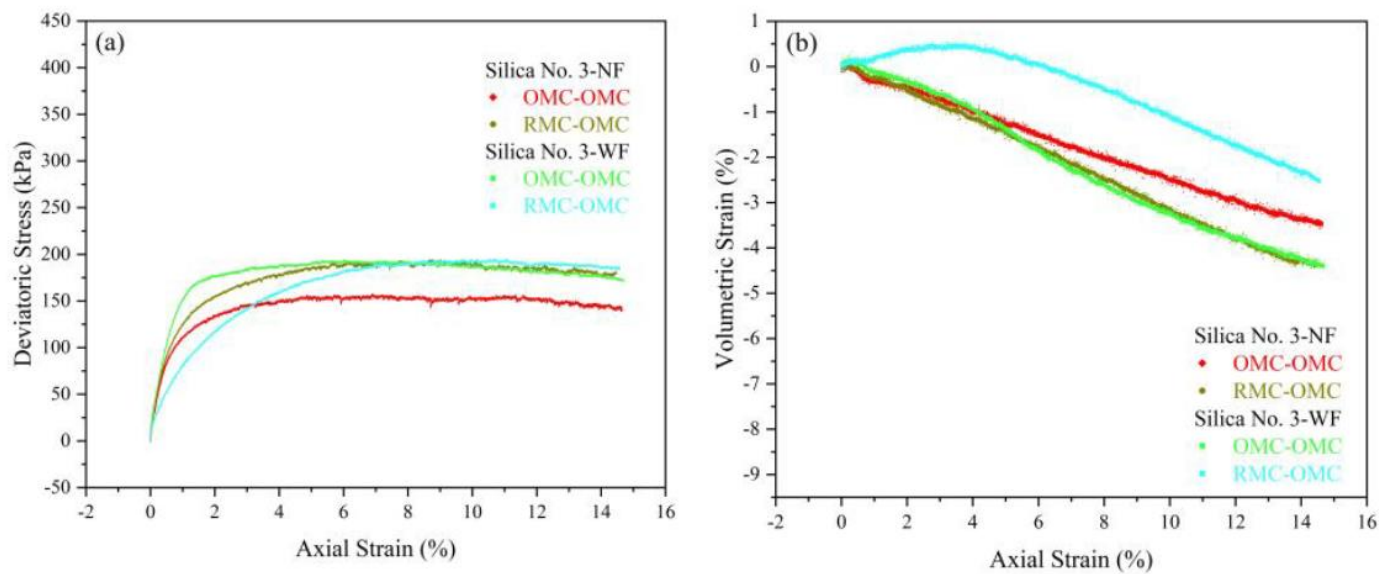


Figure 6. Silica No. 3-NF and silica No. 3-WF OMC-OMC and RMC-OMC samples. (a) Deviatoric stress vs. axial strain. (b) Volumetric strain vs. axial strain.

OMC-OMC and RMC-OMC samples consisting of silica No. 6-NF show a peak deviatoric stress of 149 and 164 kPa with a maximum volumetric strain of 1.5 and 1.7%, as shown in Figure 7. A minor difference in peak deviatoric stress was observed for silica No. 6-WF OMC-OMC and RMC-OMC samples, where peak deviatoric stress increased to 168 and 174 kPa, respectively, with a corresponding volumetric strain of 4.0 and 2.2%.

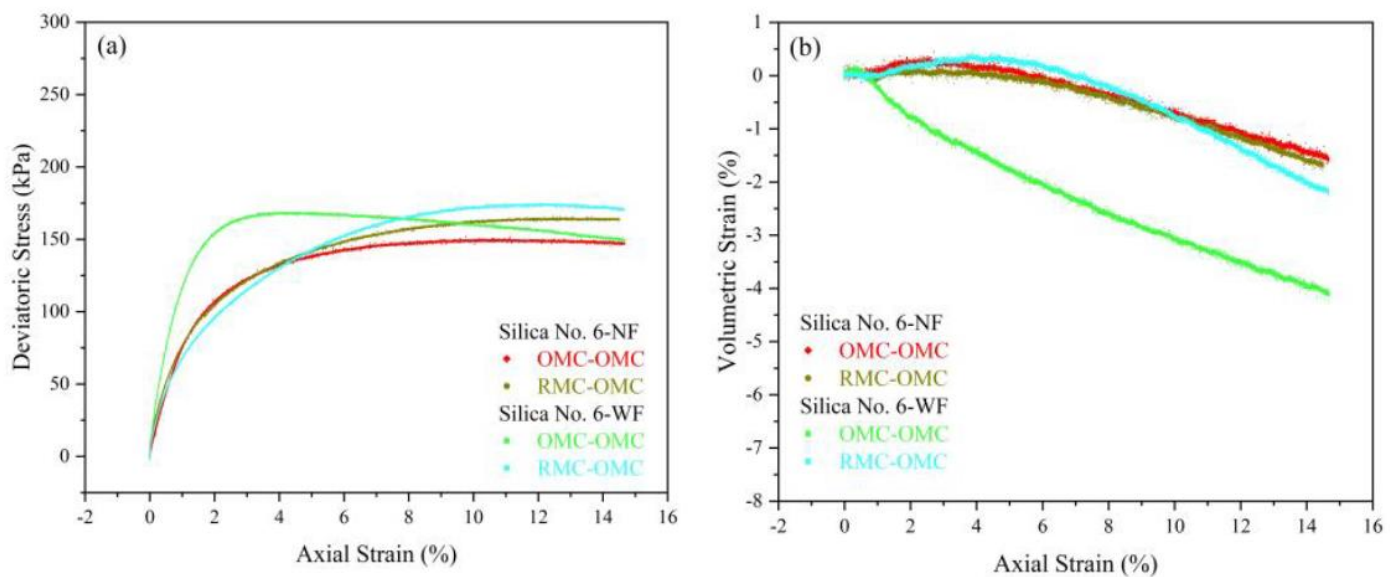


Figure 7. Silica No. 6-NF and silica No. 6-WF OMC-OMC and RMC-OMC samples. (a) Deviatoric stress vs. axial strain. (b) Volumetric strain vs. axial strain.

Figure 8 shows the summary of peak deviatoric stress for different test soils sheared under various test conditions. The figure depicts that the reduction in peak deviatoric stress from OMC-RMC to RMC-RMC samples increased with the decrease in mean grain size, i.e., silica No. 3 to 6 if the test soil did not contain any fines. The trend of the reduction in peak deviatoric stress from OMC-RMC to RMC-RMC samples became the opposite with the addition of fines, i.e., the reduction in peak shear strength increased with the increase in mean grain size from silica No. 3 to 6. For example, silica No. 3-NF with a larger mean grain size of 1.5 mm showed a lesser reduction of 2 kPa in peak deviatoric stress from the OMC-RMC to RMC-RMC sample. The same soil with 20% fines added (silica No. 3-WF) showed the highest value of peak deviatoric stress of 407 kPa for the OMC-RMC sample and showed the most significant value of strength reduction of 215 kPa from the OMC-RMC to RMC-RMC sample. On the other hand, the peak deviatoric stress difference between the OMC-RMC and RMC-RMC samples increases from 11 to 72 kPa for silica No. 6, with the addition of fines.

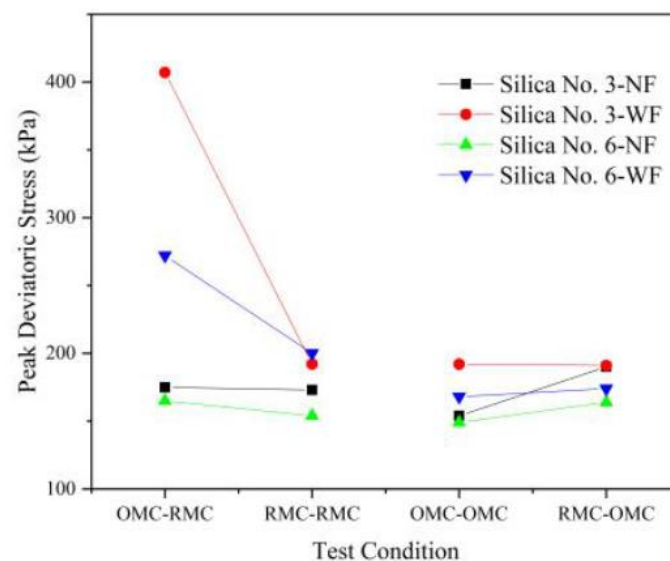


Figure 8. Summary of the peak deviatoric stress of the test materials for various conditions.

Similarly, a precise analysis of the difference in peak deviatoric stress between the RMC-OMC and OMC-OMC samples showed that the difference increased with the increase in the mean grain size of the test soil if it did not contain fines. On the other hand, the difference decreased with the increase in the mean grain size of the test soil containing fines. For instance, silica No. 6-NF shows the slightest difference of 15 kPa in peak deviatoric stress between the OMC-OMC and RMC-OMC samples and silica No. 6-WF shows the most significant difference of 6 kPa for the same conditions.

The following discussion explains the difference in peak deviatoric stress for the OMC-OMC, OMC-RMC, RMC-RMC, and RMC-OMC samples observed, as presented in Figure 8. The soil shear strength is affected by the coordination number of the soil particles in a granular mix [28], which is further proportional to the density/void ratio [29] and the grain size distribution [30] of the granular mix. The addition of fines increases the soil's grain size distribution and decreases its void ratio causing an increase in the soil shear strength of the test samples comprising silica No. 3-WF and silica No. 6-WF, as compared to silica No. 3-NF and silica No. 6-NF, respectively, for the respective test conditions.

This study compares unsaturated soil shear strength for test samples initially compacted with different moisture contents but at identical dry densities for each soil type, resulting in similar coordination numbers. At the micro level, the moisture content at compaction influences the soil structure affecting the soil shear strength. Therefore, it is postulated that soil structure development according to moisture content at compaction and the suction at shearing constitutes the mesomechanism for the variation of peak deviatoric stress encountered for different soil types under different test conditions.

OMC-RMC samples exhibited more peak deviatoric stress than OMC-OMC samples experiencing more suction at shearing, the respective test soils. The difference between OMC-OMC and OMC-RMC samples' peak deviatoric stress is higher for soils having fine content because of their higher residual suction. The test soils exhibited lower peak deviatoric stress for RMC-RMC samples for the respective soils as compared to OMC-RMC samples. This difference can be attributed to the initial moisture content's effect on the test sample's structure formation. As the moisture content at compaction predominantly affects the formation of the structure of the soil containing fines, the difference in peak deviatoric stress is prevalent for the same soils. The existence of brittle structures in OMC-RMC samples comprising soil containing fines is also supported by their significant difference in peak and residual deviatoric stress. The peak deviatoric stress of the RMC-OMC samples is more than the RMC-RMC samples for the soil without fines. It is hypothesized that an increase in water content increases the cohesion intercept of the sandy soils, as observed by [8]. On the other hand, the peak deviatoric stress of the RMC-OMC samples is less than the RMC-RMC samples for the soil containing fines. This is because an increased moisture content caused softening of the samples' fine content. Developing peak deviatoric stress at higher strain for RMC-OMC samples of the soils containing fines supports this interpretation.

From the practical engineering design point of view, a comparison of the triaxial compression test results of OMC-OMC, OMC-RMC, RMC-RMC, and RMC-OMC samples endorse that, for silica sand No. 3 and 6 mixed with fines and without fines, the shear strength of the RMC-RMC samples can be considered in the geotechnical design of the project, where an increase in the moisture content of the soil is unexpected. For silica sand No. 3 and 6 mixed with fines, the shear strength of the RMC-OMC can be incorporated into the geotechnical design for the project where an increase in the soil's moisture content is anticipated up to the soil's optimum moisture content. For the silica sand No. 3 and 6 without fines, the shear strength of the RMC-RMC samples can be employed for the same conditions.

5. Conclusions

A modified triaxial apparatus has been used in this study to explore the shear strength behavior by carrying out triaxial compression tests. The main objective of this study was to investigate the effect of moisture content at compaction and shearing and grain size distribution on the shear strength of unsaturated sandy soils. Considering the different scenarios of compaction and shearing moisture content as the optimum moisture content (OMC) and the residual moisture content (RMC), four triaxial compression test series (1) OMC-RMC, (2) RMC-RMC, (3) OMC-OMC, and (4) RMC-OMC, were carried out. The conclusions are summarized below.

- 1- The moisture content at compaction and the grain size distribution significantly influenced the test soil's shear strength.
- 2- Test samples comprising silica No. 3 and 6 exhibited higher shear strength when mixed with fines for the respective test condition.
- 3- Test soil samples sheared at residual moisture content exhibited higher peak deviatoric stress when compacted at the optimum moisture content. With a decrease in the mean grain size of the test soils, the difference increased from 2 to 11 kPa for the soils without fines, and for soils containing fines, this difference decreased from 215 to 72 kPa.
- 4- Test soil samples compacted at the residual moisture content exhibited higher peak deviatoric stress when sheared at the optimum moisture content. With a decrease in the mean grain size of the test soils, the difference decreased from 36 to 15 kPa for the soils without fines, and for soils containing fines, this difference increased from 1 to 8 kPa.
- 5- From the practical design point of view, if an increase in the soil's moisture content is unexpected in the field, then OMC-OMC and OMC-RMC can delegate the short-term and long-term conditions, respectively, and RMC-RMC can represent both short-term and long-term conditions. On the other hand, RMC-RMC and RMC-OMC can symbolize short-term and long-term conditions, respectively, if climatic/ground conditions support the water content increment up to the soil's optimum moisture content. A comparison of the triaxial compression test results of OMC-OMC, OMC-RMC, and RMC-RMC samples endorse that:
 - a. For silica sand No. 3 and 6 mixed with fines and without fines, the shear strength of the RMC-RMC samples can be considered in the geotechnical design of the project, where an increase in the moisture content of the soil is unexpected.
 - b. For silica sand No. 3 and 6 mixed with fines, the shear strength of the RMC-OMC can be incorporated into the geotechnical design for the project where an increase in soil's moisture content is anticipated up to the soil's optimum moisture content. For silica sand No. 3 and 6 without fines, the shear strength of the RMC-RMC samples can be employed for the same conditions.

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