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CONSTANT VOLUME SHEAR TESTS ON COMPACTED SILTY SOIL

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ABSTRACT: Most earth structures, such as embankments, roadways, foundations, slopes, and retaining walls, are commonly built above the groundwater table whenever possible, implying that the soil used in the construction of such structures is widely unsaturated in nature. The behavior of unsaturated soil is less predictable as compared to saturated soil. Usually, triaxial tests are carried out on unsaturated soils at various net axial stress and matric suction under constant confining pressure. There is limited research regarding the constant volume tests on unsaturated soil. In this study, a series of triaxial compression tests were performed under constant water content conditions using a double-cell triaxial test apparatus. The samples were prepared with an 80% degree of compaction and an optimum water content of 20%. All the soil specimens were consolidated isotropically under three different confining pressures of 100kPa, 300kPa, and 500kPa before being sheared with constant volume. The soil specimen's volume was controlled by manually altering the cell pressure during the shearing phase (depending on the volume change measurement). A pre-shear infiltration test was also carried out to understand the influence of matric suction in unsaturated soil when sheared with constant volume. The results show that the normally consolidated specimen exhibits anomalous behavior of sudden temporary drop in axial stress within the axial strain range of 0-2%, which can be attributed to the collapse of soil particles held together by suction.

Keywords: Unsaturated soil, Constant water content tests, Constant Volume, Isotropic Consolidation

1. INTRODUCTION

For most of their lifespan, earthen structures and slopes that have been engineered remain unsaturated. In recent years, it has become clear that unsaturated soil mechanics can shed light on how compacted soils behave in various situations, e.g., foundation engineering, retaining walls, earthen embankments and slopes, roads and pavements, mining engineering and underground pipelines [1-2]. In unsaturated compacted soils, the presence of matric suction can enhance the soil's shear strength and decrease its compressibility while also increasing the soil's effective stress. Additionally, suction helps maintain larger void and principal stress ratios at a given confining pressure [3]. Numerous experimental works have already been conducted to investigate unsaturated soil behavior [4-7].

Since rainfall and water infiltration are closely related to unsaturated slope failures, a thorough and in-depth seepage analysis is necessary to understand their behavior [8]. Both geotechnical and hydrological properties, such as the development of pore water pressure, rate of water infiltration, and the rate of change in shear strength, which is influenced by a change in matric suction, are significant when studying the behavior of unsaturated slopes [9]. Several researchers have conducted studies that have contributed to understanding how soil responds to rainfall infiltration, which results in instability [10-15].

Usually, triaxial compression tests on unsaturated soils are carried out under unconfined, constant confining pressure (low or high) or constant matric suction conditions. Few studies have been carried out regarding the constant volume, i.e., constant void ratio triaxial test on unsaturated soil [16-18]. For saturated soils, the requirement for constant volume is fulfilled by just doing undrained triaxial tests [19-21]. In the case of saturated soils, water movement (the volume of fluid entering or leaving the soil specimen) and volume change are directly related (assuming water to be incompressible). However, it is difficult to measure the volume change of the entire sample and the air and water volumes in the case of unsaturated soils [22].

In view of the above, this study investigates the mechanical behavior of unsaturated soil using triaxial compression tests executed with constant volume during shearing under constant water content conditions. A pre-shear infiltration test is also performed to study the effect of decreased suction on the instability of unsaturated soil.

2. RESEARCH SIGNIFICANCE

This research aims to better understand the response of unsaturated soil by conducting constant volume tests. Constant water content tests can simulate sudden failure conditions in the field. A pre-shear infiltration test simulates a soil slope's condition and failure mechanism following a rainy period in which the soil above the water table has been wet [23]. The existence of a state boundary surface for unsaturated soil can be validated with the help of constant volume tests [24].

3. TESTING PROGRAMME

The physical properties of soil, specimen preparation, test apparatus, and procedure will be discussed in this part.

3.1 Physical Properties of Soil

The fine soil used in this study is known commercially as DL Clay; it has low plasticity. The color of fresh, loosely deposited DL clay is yellowish-brown. DL clay is homogenous and easy to procure. It is classed as non-plastic silt (ML) by the USCS (Unified Soil Classification System) (ASTM D2487-11 2011) with 90% silt and 10% clay, and it has a larger grain size than ordinary clay. This soil has a uniform grain size distribution, with a mean D50 of about 0.03 mm [25].

Table 1 Physical Properties of DL Clay

Properties	Unit	Value
Specific gravity	g/cm^3	2.635
Percentage of fine content	%	99
Consistency	-	Non-Plastic
Maximum dry density, ρ_{dmax}	g/cm^3	1.55
Optimum water content	%	20

This soil is used because it has a lower initial matric suction than kaolin clay at the same degree of saturation. Table 1 and Fig.1 show the physical properties and compaction curve of DL Clay.

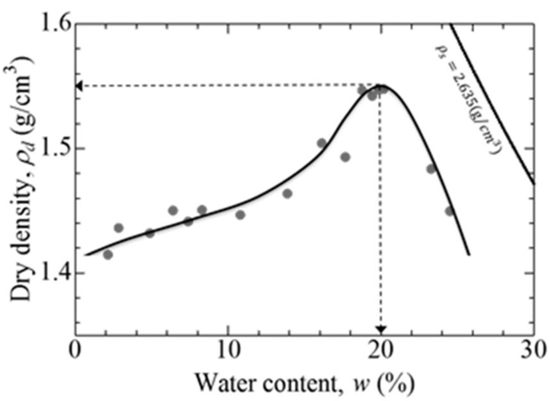

Fig. 1 Compaction curve for the studied soil [26]

3.2 Specimen Preparation

To achieve a uniform density along the specimens' length, the soil was compacted in five layers, each 2 cm thick, in a cylindrical mold with a diameter of 5 cm using a static compaction machine with a hydraulic jack [23]. The low energy of static compaction can provide a homogeneous density in the specimen, preventing the formation of a weaker zone [27]. Water was mixed with dry DL clay before compaction to make specimens at an optimum water content of 20%. The samples were compacted to 80% degree of compaction and had a dry density of $1.24g/cm^3$. During preparation, the specimens underwent a pre-consolidation pressure of about 210kPa and were initially 46.5% saturated with a void ratio of about 1.125. All specimens had initial matric suctions of ≈19-20 kPa, indicating that the preparation steps were always meticulously followed to maintain a suction condition of about 20 kPa. All prepared specimens were 10 cm in height and 5 cm in diameter, as shown in Fig. 2.

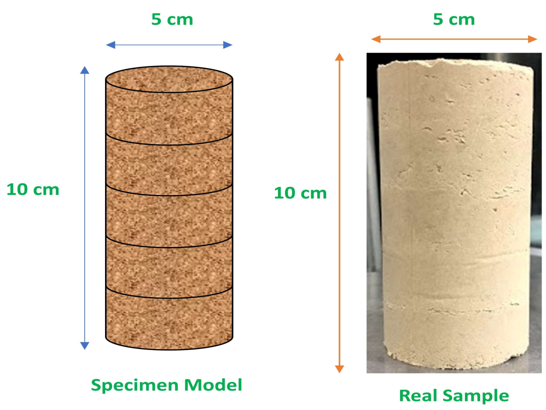

Fig. 2 Prepared sample

3.3 Test Apparatus

A strain-controlled triaxial equipment suited for evaluating unsaturated soils was utilized for this research. It comprises a double cell, pore water pressure (PWP), cell pressure, and pore air pressure (PAP) transducers. Loading system for exerting axial load, Low-Capacity Differential Pressure Transducer (LCDPT) to measure volume change, external Linear Variable Displacement Transducer (LVDT) to measure the vertical deformation of the specimens, and a suitable computer application to track test sequence and record experimental results. The triaxial device is coupled to a balance with an external load cell to quantify the amount of water drained or infiltrated into the specimen. Before commencing the experiments, the load cell and all the transducers were calibrated correctly according to standards. Fig. 3 depicts a schematic representation of the triaxial system employed in this study.

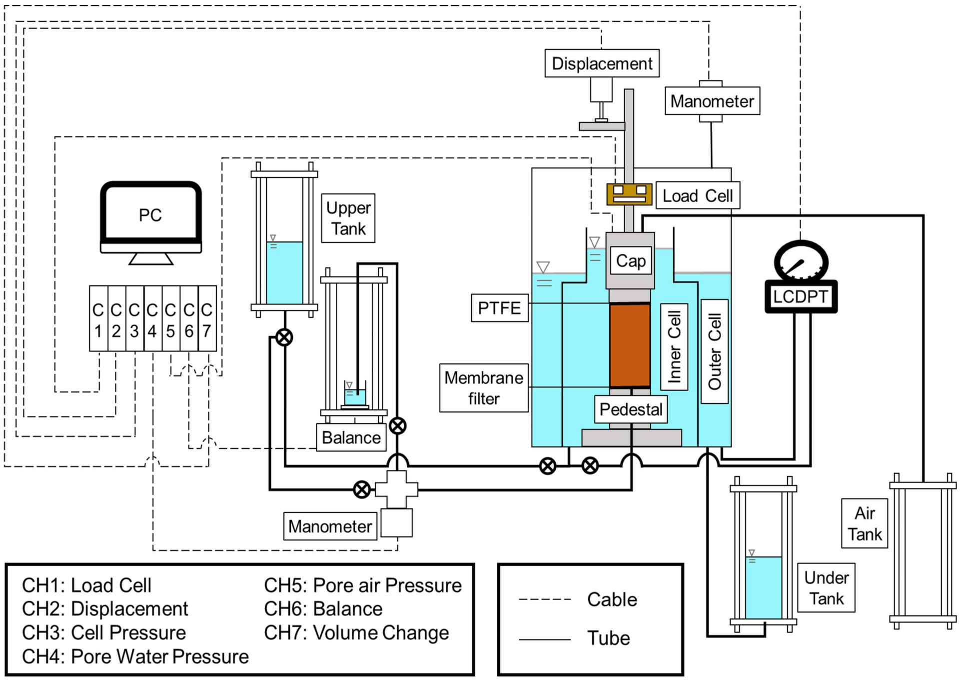

Fig. 3 Schematic diagram of triaxial apparatus

A thin membrane, "Supor 450", and a Polytetrafluoroethylene (PTFE) sheet were used to effectively control and measure the pore water and air. The thin membrane was put on the bottom pedestal to allow water to flow while blocking the air passage [28]. It had a pore size of 0.45 µm, a thickness of 140 µm, and an air entry value of 250 kPa. The PTFE sheet was glued to the underside of the top cap to prevent water flow into the top cap (Fig. 4). To reduce the amount of air in the pore air drainage line, a solenoid-controlled exhaust air valve is also installed within the top cap.

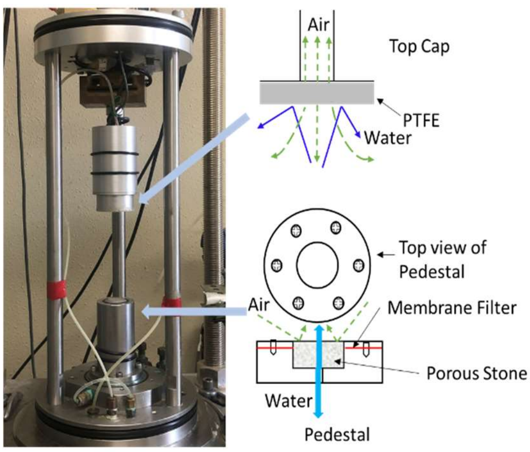

Fig. 4 Schematic of top cap and bottom pedestal

3.4 Test Procedure

The bottom pedestal was fully saturated before each test so that no air bubble was trapped inside the porous stone of the pedestal. The suction pump was used to apply vacuum pressure to de-air the water in the external upper and lower tanks for at least 24 hours.

After the specimen was prepared, it was wrapped in a rubber membrane using a membrane holder and set over a pedestal with a thin membrane to measure the initial suction value. After measuring initial suction, the Axis translation technique (ATT) was carried out to prevent the formation of cavities inside the pedestal, which would ultimately affect the reading of pore-water pressure. To make the pore water pressure zero, the pore air pressure and confining pressure were increased simultaneously, leaving the specimen volume unchanged [29]. During consolidation, the specimens were consolidated isotropically by applying the required net confining pressures of 100kPa, 300kPa, and 500kPa, to get the sample to the desired state before shearing. The drain valve was kept open throughout the consolidation phase to dissipate the excess pore water pressure. The load control system automatically controlled the axial stress to keep deviatoric stress (q) equal to zero.

Figure 5 depicts the test stages involved in the current research. During shearing, the drainage valve for the pore water pressure was kept closed while the pore air pressure was continuously drained and controlled. The soil specimens were sheared with a constant void ratio (constant volume) at a strain rate of 0.05 mm/min under constant water content conditions. When fill materials are compacted in the field, the excess pore-air pressure developed during compaction will vanish instantly, while the excess pore-water pressure will dissipate over time. A constant water content test (CWC) can simulate this condition [30]. The sample volume was kept constant by adjusting the confining pressure in response to the specimen's volume change (i.e., reading of the LCDPT value). The shearing phase was automatically terminated when the axial strain reached 15%, per the standards of the Japan Geotechnical Society [31].

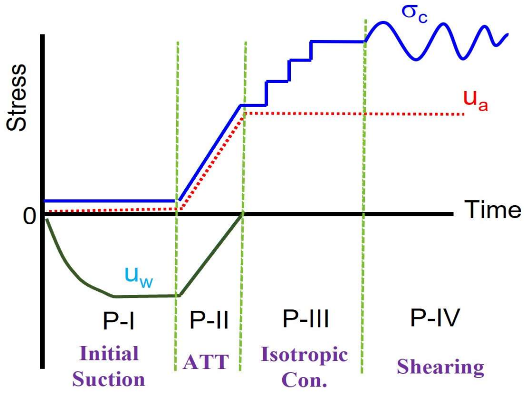

Fig. 5 Test phases involved.

For the pre-shear infiltration test, water in the soil sample was infiltrated through the waterline from the bottom pedestal, which was connected to a beaker and the pore water pressure transducer. The beaker was mounted on an external load cell and enclosed in a pressure chamber (balance). The infiltration rate was regulated by varying the pressure of air applied on top of the water surface in the beaker [27], [32]. For this test, when isotropic consolidation was achieved after initial suction measurement and ATT, the matric suction value of the soil sample was reduced to 5kPa. This was accomplished by carefully applying an infiltration pressure of 15kPa on balance to increase the pore water pressure. When no further change in the water flow entering the specimen was detected, the water infiltration step was completed. Following the infiltration stage, the pore water drainage valve was closed, and the specimen was subjected to shear with constant volume under constant water content conditions.

4. TEST RESULTS

Up to a 15% axial strain, the sample was sheared at a rate of 0.05% per minute. The water drain valve was closed while the air drain valve was open, so the shearing could be done in constant water content conditions. The cell pressure was adjusted manually in accordance with the LCDPT value to keep the void ratio of the sample constant since the samples had to be sheared with zero volumetric strain. Fig. 6 shows the constant void ratio of samples maintained during the shearing phase.

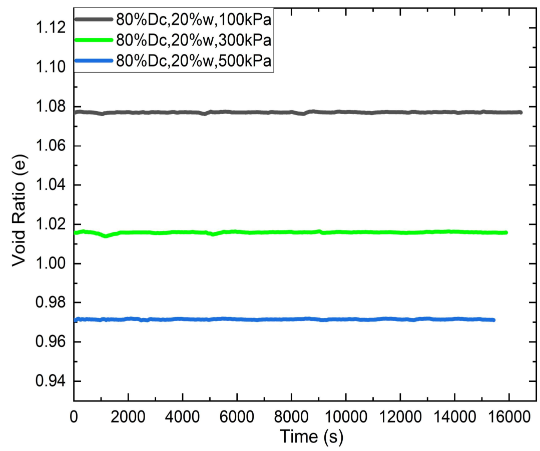

Fig. 6 Constant void ratio during shearing

Figure 7 shows the relationship between deviatoric stress and axial strain when sheared with constant volume. It can be observed that the deviatoric stress reaches a peak value within the axial strain range of 0-2% and then decreases afterward, exhibiting post-peak behavior. The shear strength is more significant for specimens consolidated under high confining pressure.

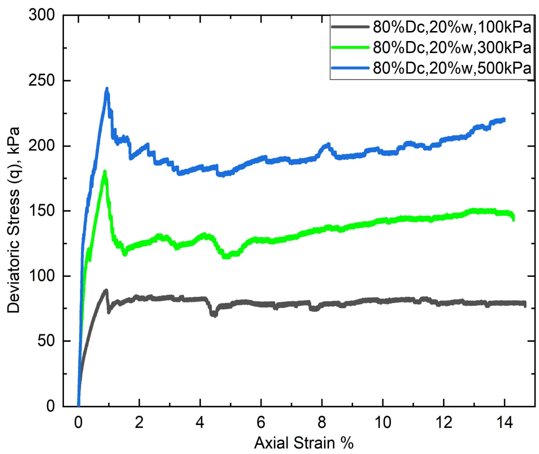

Fig. 7 Stress-Strain behavior

Figure 8 shows unusual behavior over an axial strain range of 0-2%. The effective stress gradually grows, abruptly lowers, then gradually increases, and decreases again until the specimen reaches the critical condition. The abrupt loading impact may have caused this phenomenon during shearing, which could have triggered the suction-held soil particles to collapse and reorient quickly [24]. However, as the confining pressure decreases, the unusual behavior is minimized, as seen from the stress paths depicted in Fig. 9. It should be noted that the samples consolidated with 300 and 500kPa are normally consolidated as the confining pressure is greater than the pressure experienced during sample preparation. In comparison, the sample consolidated with 100kPa is lightly over-consolidated as the confining pressure is less than the pressure for sample preparation. The critical state line (C.S.L) has a slope of 1.3.

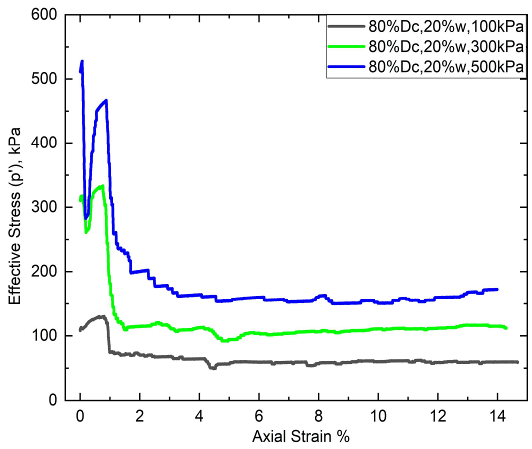

Fig. 8 Effective Stress Vs. Axial Strain

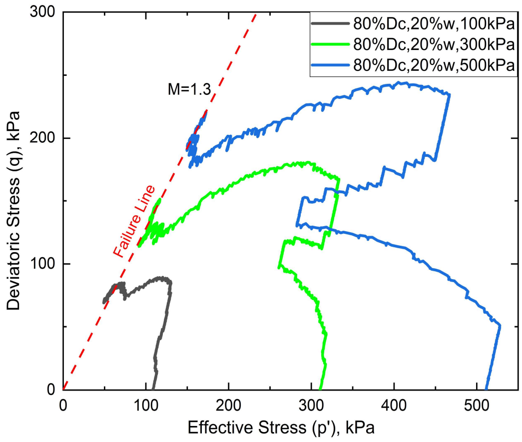

Fig. 9 Stress paths of specimens

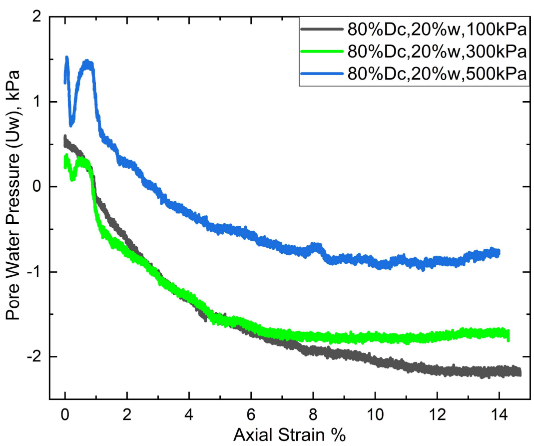

Fig. 10 Pore water pressure during shearing

Pore water and air pressure were reduced throughout the shearing phase, as shown in Fig. 10 and Fig. 11, respectively. However, the drop in pore water pressure was more significant than in pore air pressure. As a result, there was a modest rise in matric suction, as shown in Fig. 12. Since the water drainage valve was closed and a fixed void ratio was kept during the testing, the degree of saturation of the samples remained almost constant throughout the shearing.

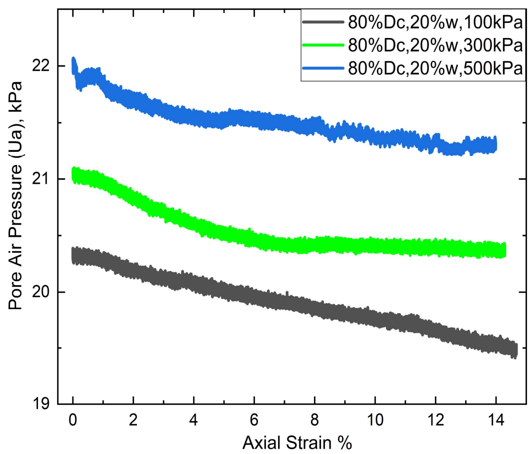

Fig. 11 Pore air pressure during shearing

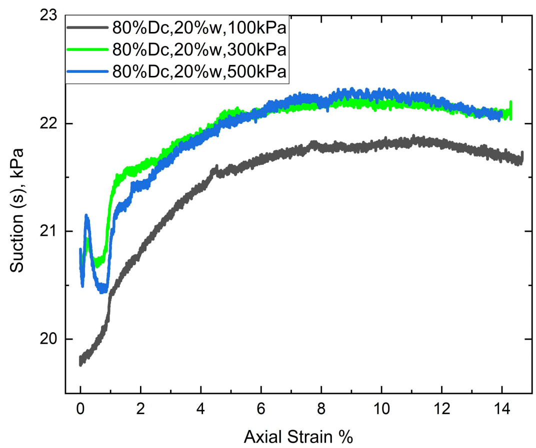

Fig. 12 Suction during shearing

A pre-shear infiltration test was conducted to authenticate the suction-based assumption devised for the unusual behavior of effective stress during the 0-2% axial strain range. This test replicates the state and mechanism of failure of a soil slope following a period of rain during which the soil above the water table undergoes a wetting process. The pore water pressure was increased before beginning the shear stage to reduce matric suction. Attempts were made in a few early trial tests to infiltrate water into specimens without increasing the pore water pressure; however, only a small volume of water could be injected into the samples, which needed to be increased. As a result, water infiltration was conducted by lowering the matric suction (from 20kPa to 5kPa). This was attained by exerting 15kPa infiltration pressure on the balance. The volume of infiltrated water into the specimen was 22cm3 in 3 hours when matric suction was reduced to 5kPa from 20kPa. The degree of saturation was increased from 46.5% to 76%.

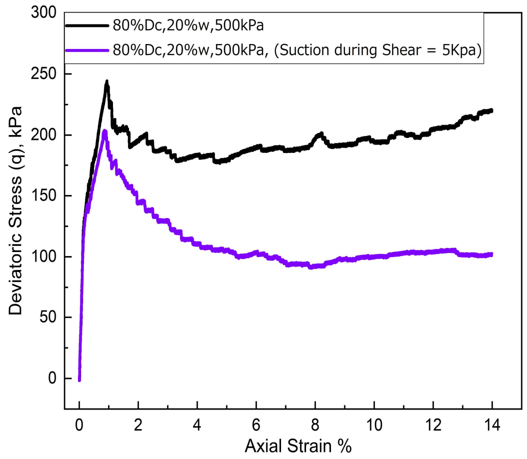

Fig. 13 Stress-strain behavior during a pre-shear infiltration test

It is evident from Fig. 13 that as matric suction reduces, so does the overall stiffness and strength. This is due to the effect of matric suction on interparticle contact forces, which tends to maintain the soil structure. However, with a decrease in matric suction, it can be observed that the unusual behavior within the axial strain range of 0-2% has reduced, as can be seen in Fig.14 and Fig.15. This confirms the hypothesis about the unusual behavior of mean effective stress. The soil particles held together by suction may collapse briefly and re-orient upon applying a sudden load. This phenomenon can be one of the reasons for the very premature failure of slopes following an earthquake during a non-rainy period.

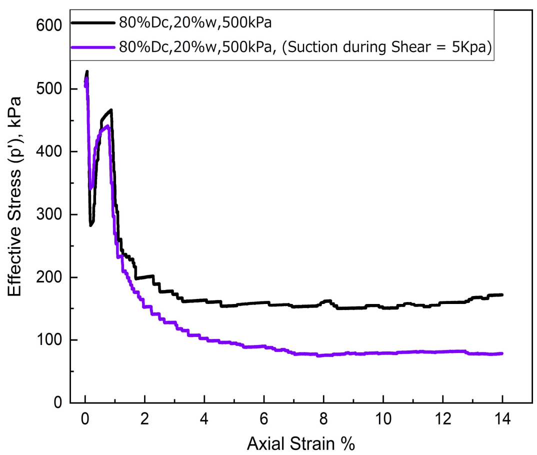

Fig. 14 Effective Stress Vs. Axial Strain during a pre-shear infiltration test

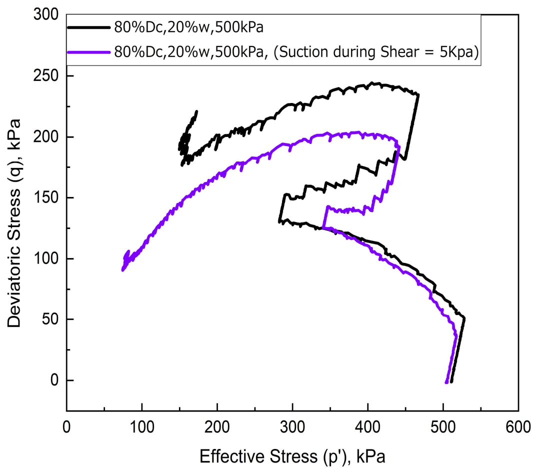

Fig. 15 Stress paths of specimens during a pre-shear infiltration test

Figure 16 depicts a 3D illustration of the relationship between deviatoric stress, mean effective stress, and the void ratio at failure. The state boundary surface (SBS) is formed by all the stress paths on the same failure plane. SBS distinguishes between achievable and impossible stress states. It can also be noted that the constant volume test generates contour-like lines, which aid in determining the geometry of the state boundary surface.

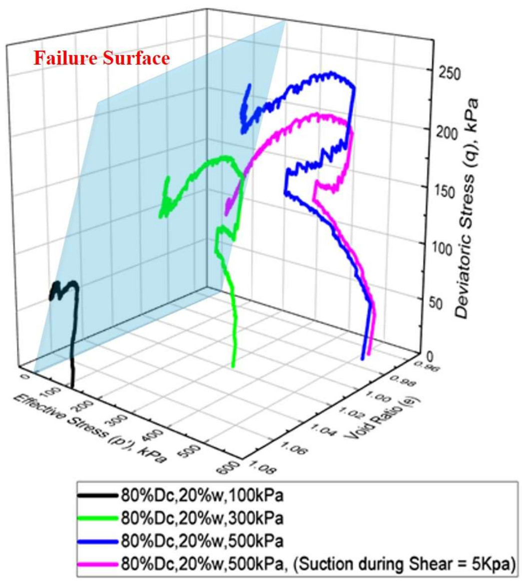

Fig. 16 Stress paths followed in p'eq space.

5. CONCLUSIONS

In this study, constant volume shearing tests were carried out to explore the mechanical behavior of compacted silty soil under constant water content conditions. The following conclusions can be drawn from this study:

- To maintain a constant specimen volume during shearing, the cell pressure was manually adjusted, corresponding to the change in volume indicated by LCDPT.
- The deviatoric stress reaches a peak value within the axial strain range of 0-2% and then decreases afterward, exhibiting post-peak behavior. The effective stress also exhibits unusual behavior (increased and decreased twice) within the axial strain range of 0-2%.
- The matric suction slightly increased during shearing due to decreased pore water pressure.
- The overall shear strength decreased with a decrease in matric suction. However, as matric suction reduces, there is a drop in the unusual behavior observed within the axial strain range of 0-2%.
- Constant volume tests present contour lines, which help define the state boundary surface.

6. ACKNOWLEDGMENTS

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