Triaxial Testing of Unsaturated Soils

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Abstract. This paper highlights the key features of triaxial testing of unsaturated soils. The modifications to a conventional triaxial apparatus and the test procedures for various unsaturated soil triaxial tests are described. Test results for an undisturbed residual soil tested under consolidated undrained (CU) and constant water content (CW) conditions at three different strain rates are presented. The test results showed that ϕ^b is not a constant, but decreases as matric suction is increased. The shear strength envelopes obtained from CU and CW tests at the three different strain rates are similar.

1 Introduction

The difference between behavior of saturated and unsaturated soils lies in the existence of suction in unsaturated soils. Soil suction has two main components matric suction and osmotic suction (solute suction). Often, osmotic suction does not feature in the constitutive relationships for unsaturated soils whereas matric suction is always a permanent fixture. Katte and Blight (2012) showed that changes in osmotic suction do not affect shear strength of a soil. Matric suction is pore-water pressure when referenced to air pressure. Edil et al. (1981) and Fredlund and Rahardjo (1993) showed that matric suction is the fundamental suction component that controls mechanical behavior of unsaturated soils. There are two ways to impose matric suction onto a soil specimen: (1) to use the axis-translation technique (Hilf 1956) or (2) to use the osmotic technique via a semi-permeable membrane. Due to the inherent difficulties in the osmotic technique, the axis-translation technique is often used in the triaxial apparatus. Using the axis-translation technique, the conventional triaxial apparatus for saturated soil tests can be easily modified for unsaturated soil testing by inclusion of pore-air pressure control.

This paper examines triaxial testing of unsaturated soils using the axis-translation technique for controlling of matric suction. Issues relating to the triaxial apparatus, test procedures and interpretation of test results are discussed. A series of triaxial test results for an unsaturated residual soil is also presented and discussed.

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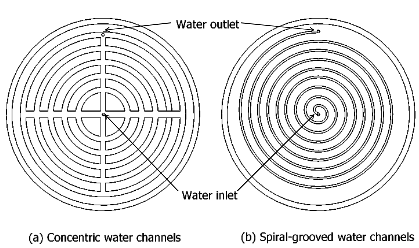
2 Triaxial Apparatus and Test Procedures

In testing unsaturated soil specimens, modifications have to be made to the conventional triaxial apparatus to apply/control matric suction and special considerations must be made for measurement of volume change. Similar to saturated soil triaxial testing, several different types of triaxial tests can be performed.

2.1 Application of Matric Suction

The simplest modification that can be incorporated into a conventional triaxial apparatus is to replace the bottom porous disk with a high air entry (HAE) ceramic disk. However the HAE disk will need to be sealed to the bottom platen such that any fluid movement will only be through the HAE disk. A water channel is usually etched into the platen so that the HAE disk does not experienced flexure cracks during air pressure application (Leong et al. 2004a). Possible configurations of etched water channels are shown in Fig. 1. A properly sealed HAE disk when fully saturated will only allow water to pass through but not air until its air entry value is exceeded. This effectively limits the maximum matric suction at which the soil specimen can be tested to 1500 kPa as this is the upper limit of currently available HAE disk. As the triaxial test duration for unsaturated soils tends to be much longer than saturated soils, air diffusion through the HAE disk and reappearing as air bubbles in the water volume below the HAE disk may be a problem. Flushing the air bubbles in the water volume may be facilitated if a spiral groove is etched into the bottom platen as illustrated in Fig. 1b.

The above arrangement may be improved with simultaneous application of pore-air and pore-water pressures at both the top and bottom platens. This can be achieved by having both coarse porous stone and HAE disks in both top and bottom platens. Possible arrangements of the filter elements are illustrated in Fig. 2.



(a) Concentric water channels (b) Spiral-grooved water channels

Fig. 1 Etched water channels in platen.

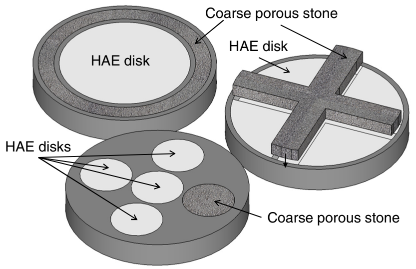


Fig. 2 Possible arrangement of high air entry (HAE) disk and coarse porous stone on the same platen.

2.2 Volume Change Measurement

Unlike saturated soil triaxial testing, the presence of air makes volume measurement of an unsaturated soil specimen difficult. This is further compounded by the fact that unsaturated soil is usually stiffer and has smaller volume changes. Laloui et al. (2006) had categorized volume change measurement of unsaturated soil specimen into three categories: (i) Cell liquid measurement; (ii) Direct air-volume and water-volume measurements, and (iii) Direct measurements on the specimen.

In cell liquid measurement technique, the volume of the confining liquid moving in and out of the triaxial cell is measured. This technique is affected by compressibility of the cell wall, volume expansion of the confining fluid to temperature, adsorption of water by the cell wall and accuracy of volume measurement.

These problems can be overcome by adopting a double-walled cell (e.g. Wheeler 1988), correcting volume expansion of the confining fluid due to temperature fluctuations (Leong et al. 2004b), minimizing the liquid volume using an inner cylinder (e.g. Bishop and Donald 1961, Aversa and Nicotera 2002, Toyota et al. 2001), using wall materials that are more resistant to water adsorption and adopting accurate liquid volume measurement such as high accuracy differential pressure transducer, respectively.

In direct air-volume and water-volume measurements, the volumes of air and water draining from the soil specimen are measured separately. This is possible when both air and water phases are continuous which in reality does not occur at the same time. As air volume is severely affected by pressure and temperature, correction of air volume to a standard pressure and temperature is needed.

For direct measurements, local displacement transducers mounted on the specimen (e.g. Leong et al. 2011), non-contact transducers such as proximity transducers (e.g. Fredlund and Rahardjo 1993, Leong et al. 2006), laser techniques (e.g. Romero et al. 1997) or digital imaging technique may be used. However volume is estimated from the measurements which may translate to error of the order of the volume change in unsaturated soils.

2.3 Test Procedures

There are several unsaturated soil tests that can be conducted using the triaxial apparatus: Consolidated drained test, constant water content test, consolidated undrained test with pore-pressure measurements and undrained test.

For the consolidated drained (CD) test, the soil specimen is first consolidated to the net confining pressure and matric suction. The soil specimen is then sheared at a slow rate where net confining pressure ($\sigma_3 - u_a$), pore-air (u_a) and pore-water (u_w) pressures and hence matric suction ($u_a - u_w$), are maintained constant. This test is also commonly known as constant suction (CS) test. For the constant water (CW) test, the soil specimen is first consolidated to the net confining pressure and matric suction similar to the consolidated drained test. The soil specimen is then sheared where net confining pressure and pore-air pressure are maintained constant but pore-water pressure is undrained. The pore-water pressure can be measured but accuracy of the pore-water pressure measurement will depend on the pore-water pressure system to be free from diffused air and the response time to be unaffected by the HAE disk. For the consolidated undrained (CU) test, the soil specimen is first consolidated to the net confining pressure and matric suction similar to the consolidated drained test. The soil specimen is then sheared under undrained conditions with respect to the air and water phases. The pore-air and pore-water pressures are measured during shearing. However, it is difficult to maintain fully undrained condition for the air phase as air may diffuse through the pore water, the rubber membrane and water in the HAE disk. For the undrained test, the soil specimen is sheared at its initial water content and matric suction. Either unconfined or confined compression test may be performed. For the unconfined compression (UC) test, the soil specimen is sheared at a high strain rate typically 1.2 mm/min until failure to maintain undrained conditions. The pore pressures are usually not measured during the test. Similar to the saturated soil unconfined compression test, the undrained shear strength is taken as half of the unconfined compressive strength. For confined compression (undrained) test, a confining pressure is applied to the unsaturated soil specimen. The undrained shear strength of the soil increases as confining pressure is increased due to a reduction in soil specimen's volume. The matric suction of the soil decreases with an increase in degree of saturation and the undrained shear strength approaches that of a saturated soil specimen. A summary of the triaxial tests for unsaturated soils is shown in Table 1.

Table 1 Different triaxial tests for unsaturated soils.

Test method	Consolidation			Shearing			Stress analysis
	σ_3	u_a	u_w	σ_3	u_a	u_w	
CD/CS	Applied	Applied	Applied	Maintained	Maintained	Maintained	SSV*
CW	Applied	Applied	Applied	Maintained	Maintained	Measured	SSV
CU	Applied	Applied	Applied	Maintained	Measured	Measured	SSV
UC	No	No	No	-	-	-	Total
Undrained	No	No	No	Applied	-	-	Total

*SSV – Stress state variables

For triaxial testing of unsaturated soils, the three commonly performed tests are the constant suction (CS) test, the constant water content (CW) test and the consolidated undrained (CU) test. The simplest way of interpretation of the CS, CW and CU tests is to use the extended Mohr-Coulomb shear strength equation (Fredlund et al. 1978):

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

where τ is shear strength, c' is the effective cohesion, σ is the normal stress, u_a is pore-air pressure, u_w is pore-water pressure, ϕ' is effective friction angle, ϕ^b is the angle describing the rate of increase in shear strength due to matric suction. The angle ϕ^b is not a constant and generally decreases as matric suction decreases.

Using Eq. 1, the stress paths for the CS, CU and CW tests are shown in Fig. 3. For simplicity, ϕ^b is assumed to be constant in Fig. 3.

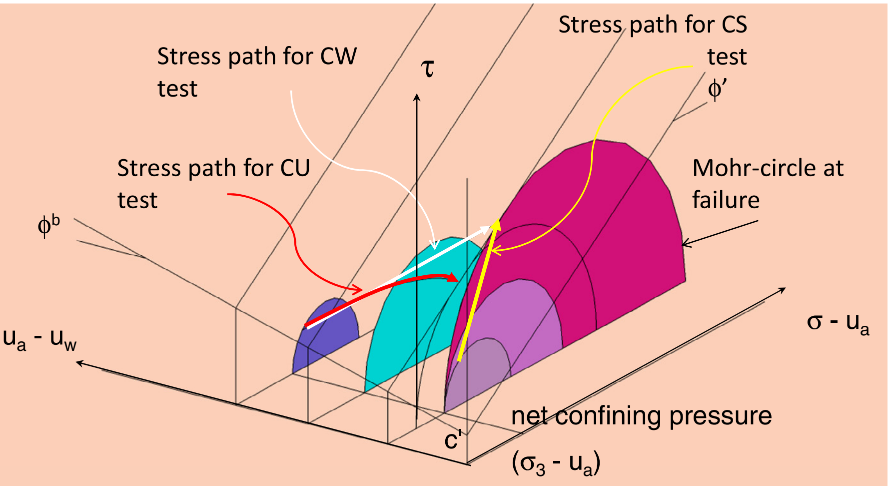


Fig. 3 Stress paths for CS, CU and CW tests.

3 Test Programme

A test programme was set up to study the shear strength of unsaturated residual soils from Bukit Timah Granite formation of Singapore. Undisturbed residual soil samples were obtained using Mazier samplers. Quantification of the shear strength behavior of unsaturated soils requires a number of identical soil specimens to be tested. Residual soil samples are seldom homogeneous and this poses a challenge to the test programme. Furthermore, CS test requires the soil specimen to be sheared at very slow strain rates thus increasing the duration of each test. To overcome these difficulties, multi-stage shearing test using cyclic loading procedure as described by Ho and Fredlund (1982) was adopted in the test programme. The triaxial tests performed were CW and CU tests. Different shearing rates were used to investigate the effect of shearing rate on shear strength of the unsaturated residual soils.

3.1 Triaxial Apparatus Set-Up

The triaxial apparatus used is shown schematically in Fig. 4. Air pressure is supplied via a coarse porous stone in the top platen and pore-water pressure is controlled by a digital pressure volume pressure controller (DPVC) through a 5-bar HAE ceramic disk in the bottom platen. The modified triaxial apparatus is equipped with a 3 kN submersible load cell, a pair of local displacement transducers (LDT) for measurement range of 0 – 0.4 mm (details can be found in

Leong et al. 2011), an internal submersible linear variable transformer (LVDT) with measurement range of ±2.5 mm, an external LVDT for axial strain measurements at large strain levels (range = ±15 mm) and a pair of proximeter transducers for radial strain measurements (range = ±1.5 mm).

3.2 Properties of Soil Tested

The residual soil specimens tested were from depths of 2 to 3 m. The average initial water content and the average void ratio of the undisturbed residual soil sample were 42% and 1.3, respectively. The residual soil was classified as silt with low plasticity (ML) according to USCS with LL=45% and PL=30%. The sand and fines content of the residual soils were 45% and 55%, respectively. Table 2 summarizes the basic properties of the residual soils. The effective shear strength parameters of the saturated residual soil obtained from CU test are c' = 10 kPa and $\phi' = 33^{o}$.

3.3 Test Procedures

Soil specimens of 50 mm diameter and 100 mm height were trimmed from 70 mm diameter undisturbed Mazier residual soil samples. The trimmed specimen was placed on the base pedestal of the triaxial apparatus fitted with a 5-bar high air entry ceramic disk. The specimen was then enclosed in a rubber membrane and the top cap fitted with a coarse porous disk was lowered onto the specimen. The triaxial apparatus's top cap was rigidly connected to the piston. After securing the rubber membrane on the top cap and the pedestal with O-rings, local displacement transducers (LDT) were attached to the specimen for axial strain measurements and proximity sensors were positioned for radial strain measurements. The specimens were saturated in the triaxial cell prior to consolidation to ensure that the specimen starts from a fully saturated condition. Full saturation was assumed when pore-water pressure parameter B measured was greater than 0.96 (Head 1980). After saturation, the soil specimens were isotropically consolidated to the in situ effective confining pressure and subsequently at the required net confining pressure (σ_3-u_a) and matric suction (u_a-u_w) via the axis-translation technique. For the application of matric suction, a constant air pressure of 450 kPa was supplied at the top of the soil specimen through a porous disk and water pressure was controlled via a digital pressure volume controller (DPVC) through a 5-bar high air entry ceramic disk. The amount of water flowing out of the soil specimen during matric suction equalization was monitored via the DPVC. Matric suction equalization was assumed to have been completed when the amount of water flowing out of the soil specimen had become negligible. The soil specimens were tested under two different test conditions: consolidated undrained test (CU) and constant water content test (CW). Multi-stage shearing test was carried out under net confining pressure of 50 kPa in four stages at initial matric suctions of 50 kPa, 100 kPa, 200 kPa and 400 kPa. Matric suction was applied by reducing the pore-water pressure while the pore-air pressure was maintained at 450 kPa. At the end of each matric suction equalization stage, the specimen was sheared until failure was imminent and then unloaded before imposing the next required matric suction. Three different strain rates (0.5 mm/min, 0.1 mm/min and 0.006 mm/min) were used. In CU test, both pore-air and pore-water pressures were not allowed to drain during shearing. In CW test, air was allowed to drain freely, but, pore-water pressure was undrained during shearing. The variations of pore-air and pore-water pressures during shearing were recorded. At the end of the test, water content was measured to obtain the variation of water content with respect to the applied matric suction.

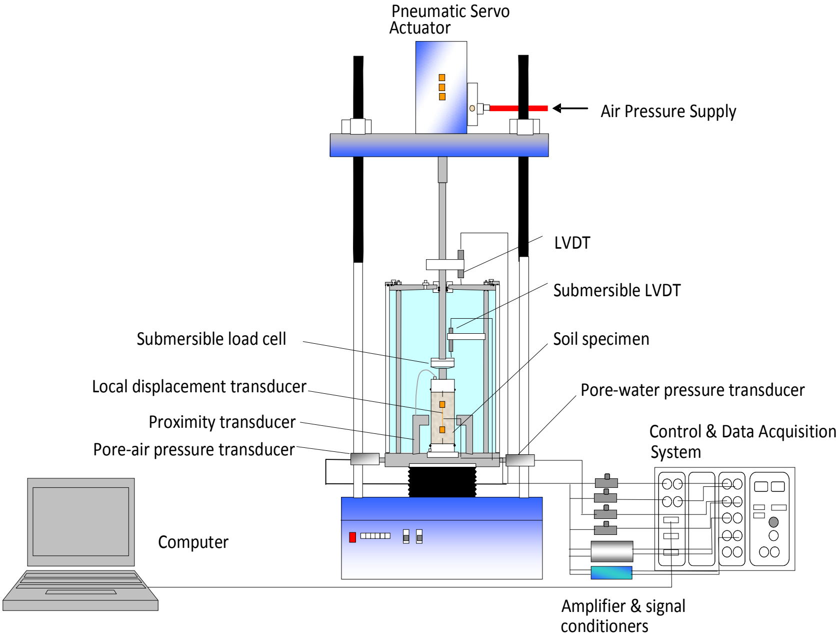


Fig. 4 Modified triaxial test set-up (from Leong et al. 2006)

Table 2 Summary of basic properties of undisturbed residual soil.

Soil properties	Value
Depth (m)	2.0-3.0
Liquid limit (%)	45
Plastic limit (%)	30
Plasticity index (%)	15
Sand (%)	45
Silt (%)	35
Clay (%)	20
Specific gravity	2.74
Unified Soil Classification System (USCS)	ML (Low plasticity silt)

3.4 Test Results and Discussion

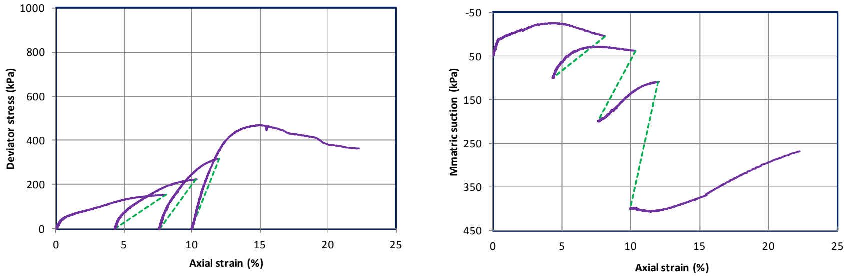
The deviator stress and matric suction versus axial strain relationships are shown in Figs. 5 and 6 for the CU and CW tests, respectively. Figs. 5 and 6 show that the deviator stress increased significantly with the increase in initial matric suction. Matric suction decreased with axial strain and reached a constant value near the failure strain. Generally, the deviator stress versus axial strain relationship at slow strain rate was observed to be stiffer than that at faster strain rate in both CU and CW tests.

For CU tests, pore-water pressure increased with axial strain for all the tests. However, different behaviors of pore-air pressure changes with axial strain were observed during shearing. For the specimen tested at strain rate of 0.5 mm/min, pore-air pressure increased during shearing for all shearing stages at different initial matric suctions. For the specimen tested at strain rate of 0.1 mm/min, no change in pore-air pressure was measured during shearing. For the specimen tested at strain rate of 0.006 mm/min, pore-air pressure decreased with axial strain. This is because when the specimen was sheared under undrained pore pressures condition at a slow strain rate, pore-air could diffuse into pore-water and as a result, decreasing pore-air pressure was measured during shearing.

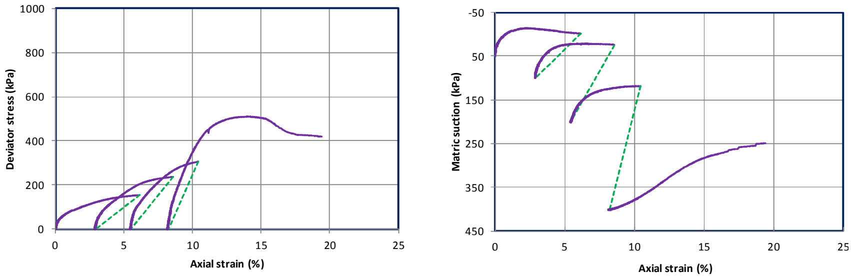
For CW tests, pore-water pressure increased with axial strain while pore-air pressure was maintained constant with during shearing. Difference in pore-pressure conditions gave different trends in the variations of matric suction with axial strain for CU and CW tests (Figs. 5 and 6). The variation of matric suction with axial strain at different strain rates showed similar trend for each type of test except for the test at initial matric suction of 400 kPa.

Using $\phi' = 33^o$, the total cohesion intercepts for the CU and CW tests at different strain rates were obtained as illustrated in Fig. 7 for the tests at strain rate of 0.5 mm/min. The total cohesion intercepts obtained from CU and CW tests were plotted against matric suctions at failure in Fig. 8. Fig. 8 shows that the total cohesion intercepts fall within a narrow band indicating that the CU and CW tests gave similar relationships with matric suctions for the three strain rates. The relationship of total cohesion intercept with matric suction is the shear strength envelope on the zero net confining pressure plane. The shear strength envelope on the zero net confining pressure plane gives the relationship of ϕ^b with matric suction. Fig. 8 shows that ϕ^b is not a constant. The angle ϕ^b is approximately equal to ϕ' at low matric suctions and reduces as matric suction increases.

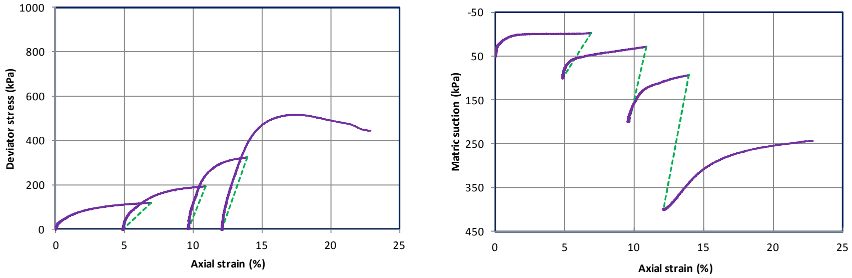
The strains measured using the LDT and proximity transducers are not discussed due to space constraint.



(a) Strain rate = 0.5 mm/min

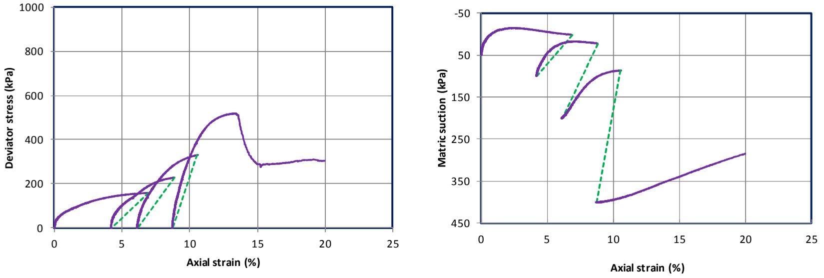


(b) Strain rate = 0.1 mm/min

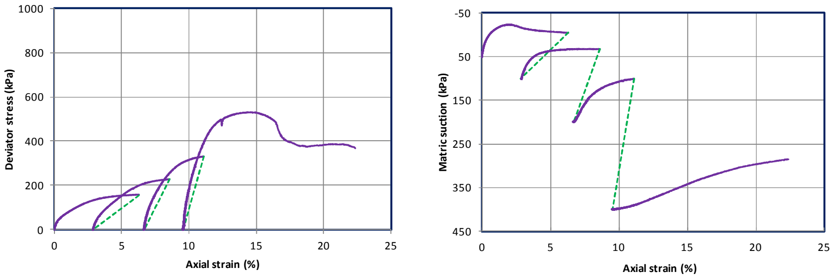


(c) Strain rate = 0.006 mm/min

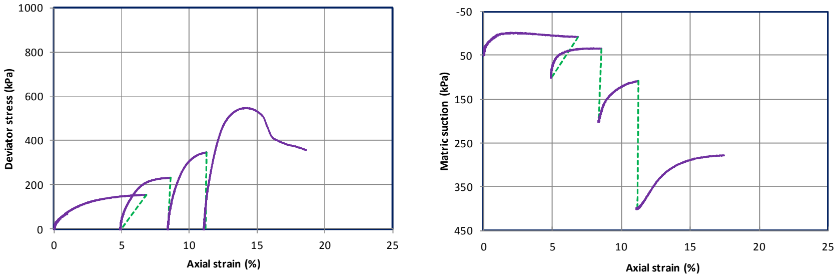
Fig. 5 Variation of deviator stress and matric suction with axial strain for CU test.



(a) Strain rate = 0.5 mm/min

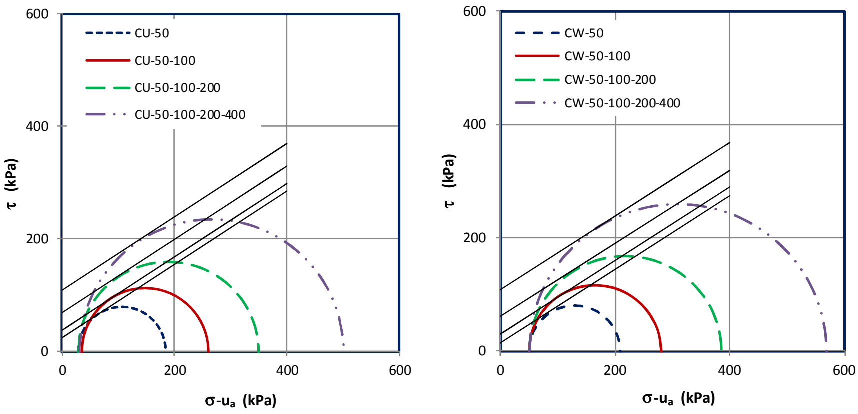


(b) Strain rate = 0.1 mm/min



(c) Strain rate = 0.006 mm/min

Fig. 6 Variation of deviator stress and matric suction with axial strain for CW test.



(a) CU test (b) CW test

Fig. 7 Interpretation of for CU and CW tests at strain rate of 0.5 mm/min.

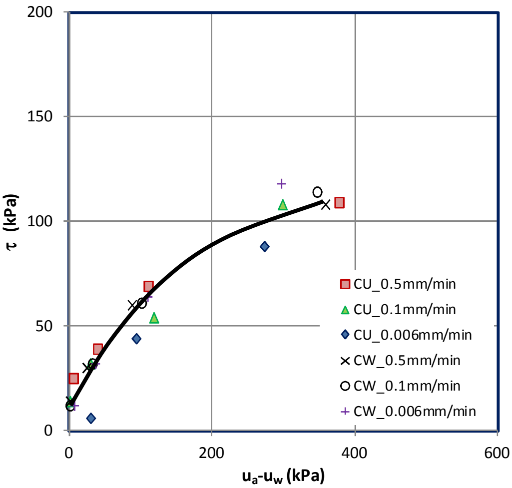


Fig. 8 Shear strength envelope on the zero net confining pressure plane.

4 Conclusion

Key modifications of the triaxial apparatus were highlighted. Different types of triaxial tests for unsaturated soils and their interpretation were discussed. Consolidated undrained (CU) and constant water content (CW) test results for an undisturbed residual soil were presented. The test results showed that ϕ^b is not a constant and decreases as matric suction is increased. The shear strength envelopes obtained from CU and CW tests are similar. Usually CW test is preferred as the test results for the CU test showed some discrepancies in the measurement of air pressure due to diffusion of air during the test.

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