Influence of Water Content on Matric Suction and Shear Strength of Unsaturated Compacted Silty Soil in Unconfined Conditions

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ABSTRACT: The shear strength of compacted structural backfills is usually measured in laboratory by preparing samples compacted to the same water content and dry density specified for the backfill. The backfill can be wetted, either due to rainfall or rising groundwater. The shear strength of unsaturated soil is commonly measured in the laboratory by performing the triaxial test in constant water content (CW) conditions. The CW triaxial test is a reasonable simulation of the condition of compacted soil for filled embankments. In this research, we have also conducted CW tests on unsaturated soil specimens prepared with various water content and tested under unconfined conditions to investigate the effect of water content on matric suction and shear strength of unsaturated soil. A linear relationship between water content and matric suction was observed whereas the relationship between water content and shear strength was non-linear. It was also observed that dry soil showed more suction, higher shear strength and more dilative behavior as compared to the wet soil.

1 INTRODUCTION

Construction of earth structures implicates the use of compacted soils. Knowing that most earth structures will remain unsaturated or in a near-saturated condition, investigating the soil behavior under different saturation states is paramount. In geotechnical problems like lateral earth pressure, bearing capacity and slope stability, the shear strength of compacted soils is primarily important. The shear strength of compacted structural fills is usually measured on laboratory samples compacted to the same moisture content and dry density specified for the fill. The fill can be wetted either by rainfall or raising groundwater. In addition, utility trenches, broken utility lines, street subgrades, permeable layers, gravel packed sub-drains, all act as subsurface conduits that lead water to fill. Many researchers such as Escario and Sa´ez (1986), Alonso et al. (1990), Fredlund & Rahardjo (1993), Maaˆtouk et al. (1995), Wheeler & Sivakumar (1995), Faroul and Lamboj (2004), Kwon et al. (2011) have studied the shear strength of unsaturated compacted soils. Fredlund & Rahardjo, (1993) states that the suction influences the shear strength of unsaturated compacted specimens. The shear strength of unsaturated soil is commonly measured in the laboratory by performing the triaxial test in constant water content (CW) conditions. The CW triaxial test is a reasonable simulation of the condition of compacted soil for embankments. The pore-air pressure is readily dissipated, and the pore-water pressure can vary according to the soil characteristics without a change in water content. The constant water content triaxial test is performed with an initial consolidation stage followed by a shear stage in which water is not allowed to drain out or into the specimen, and the air pressure is kept constant. For the CW triaxial test, with suction higher than 1 atm, the axis translation technique is usually applied. The axis translation technique applied by (Hilf, 1956) is commonly used in unsaturated soil mechanics for imposing matric suctions in samples. In this technique, the pore air pressure and the pore water pressure are raised by the same amount so that the matric suction (given by their difference) is kept constant. In this way, the pore water pressure can become positive, thus avoiding water cavitation inside the experimental setup. The use of the CW test for unsaturated soils seems to be a way to expand the use of unsaturated soil mechanics in practice, therefore, in this research, we have also conducted CW tests to determine shear strength of unsaturated soil.

The stress state in the surface layer of an embankment is under very low confining pressure conditions. From a practical standpoint, the test performed in unconfined conditions can also play an important role to get a thorough understanding of the mechanical behavior of unsaturated soils and to predict the stability and deformation of the surface layer in embankments. Since no confining pressure is applied to soil specimen in unconfined conditions, it is primarily the matric suction that controls the measured shear strength. There have been very few studies on unsaturated soils performed in triaxial test apparatus in unconfined conditions. Kato et al. (2002), Pineda et al. (2005), Chae et al. (2010), Kwon et al. (2011) have examined the behavior of unsaturated soil in unconfined conditions and tried to interpret the effects of matric suction and suction stress on the shear strength of the soil.

In this study, the influence of water content on matric suction and shear strength of unsaturated soil was studied in unconfined conditions (i.e. considering the surface of embankment). The matric suction was measured by placing soil specimens with varying water content on a saturated pedestal. It was observed that relationship between water content and matric suction was linear whereas a nonlinear relation between water content and shear strength was observed. It was also observed that the dry soil performed better than wet soil under the same testing conditions.

2 EXPERIMENTAL SETUP & METHODOLOGY

2.1 *Description of test device*

Figure 1 gives a schematic diagram of a modern unsaturated triaxial testing device for cylindrical specimens 5cm in diameter and 10cm in height.

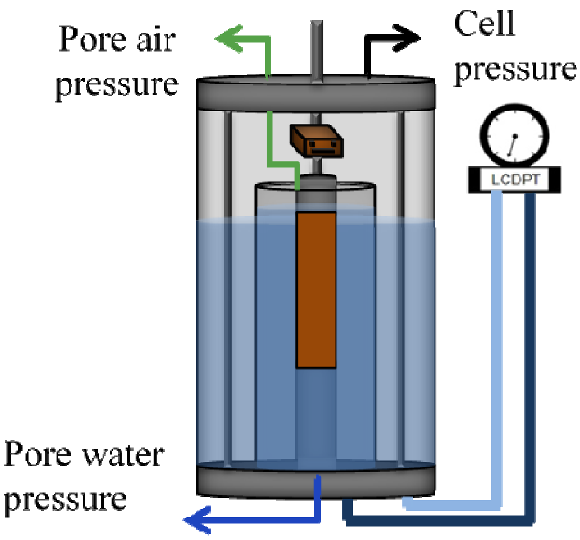

Figure 1. Schematic diagram of triaxial cell

In order to separate the routes for the measurement and the control of the pore air pressure and the pore water pressure, a membrane filter and a PTFE (polytetrafluoroethylene, known as Teflon) sheet were used. The PTFE sheet was placed on the top of the specimen to cut off the flow of water and to measure the air pressure. The membrane filter was installed in the lower pedestal to cut off the flow of air and to measure the water pressure. The thin membrane filter with pores of 0.45mm has air entry value of 420kPa. For fully undrained tests, no pore water was allowed to flow out in both the isotropic consolidation and monotonic shearing process. The salient feature of this triaxial apparatus is that both pore air and water pressures can be measured separately. Pore air pressure transducer was installed in the top cap and connected to air regulator in order to give continuously supply of the air throughout the test. In addition to this, a solenoid valve was also installed in the air drainage line inside the top cap to control drained/undrained pore air. The change in volume of the specimen during the triaxial tests was measured as the change in the water level in the inner cell by LCDPT (Low capacity differential pressure transducer). The monotonic loading was applied under strain-controlled conditions. The vertical load of the soil specimen was measured by the inner load cell. The cell pressure and pore water pressure was measured by cell and pore water pressure transducers. All instruments were connected with dynamic strain amplifiers which were then connected to A/D board and finally to PC. The dynamic strain amplifiers have a voltage range of 0~10V and PC has a software for controlling instruments.

2.2 *Soil properties*

The silty soil known as "DL clay" in Japan was tested in this study. DL clay is homogenous and easy to obtain. It is larger in grain size than average clay and is composed of 90% silt and 10% clay. The soil density is 2.635g/cm^3 and the liquid limit is non-plastic. The reason for using this clay is that it has lower initial suction than that of kaolin clay under the same degree of saturation. The physical properties of DL clay are summarized in Table 1.

Table 1. Soil Properties

Properties	Unit	Value
Density of soil particle, ρ_s	g/cm^3	2.635
Consistency	-	NP
Maximum dry density, ρd_{max}	g/cm^3	1.538
Optimum water content	%	21.5
Maximum particle size, d_{max}	mm	0.039
Coefficient of permeability k_s	m/s	6.68 x 10^{-7}

2.3 *Specimen preparation*

The soil specimens used in this research were prepared by the static compaction method. The purpose of using static compaction as opposed to dynamic compaction is to obtain a more homogeneous specimen in terms of density (Rasool, 2015). Initially two soil specimens, each having height 10cm and diameter 5cm was prepared with the same density. In order to check the homogeneity of the specimen along its length, the first specimen was prepared by putting whole mixed soil inside the mold and compacted statically. While the other specimen was prepared by putting soil in a layer of 2cm as shown in Table 2, both specimens were then cut into 2cm slices. Density and water content of each layer was calculated.

This showed that specimen prepared in layers was more homogenous throughout its height than the other specimen.

Table 2. Specimens Preparation

Height	Without Layer		In Layer	
	ω(%)	ρ(g/cm^3)	ω(%)	ρ(g/cm^3)
2cm	21.27	1.305	20.60	1.296
2cm	21.09	1.291	20.64	1.295
2cm	20.87	1.285	20.77	1.294
2cm	20.49	1.285	20.54	1.295
2cm	20.26	1.262	20.42	1.297

Therefore, the specimens used in this study were prepared by putting soil in a layer of 2cm and compacting statically in order to get a homogenous sample. Prior to performing the compaction, the dry DL clay was mixed well with water to make up a water content of 0%, 7%, 10%, 15%, 20%, 25% and 28%. After mixing with the water the specimens were statically compacted in a layer of 2cm (each) in a special apparatus with a hydraulic jack in order to obtain homogeneity. The specimens were compacted to achieve a degree of compaction of about 80%. The pre-consolidation pressure on the soil at the time of sample preparation was more than during test process, therefore the soil used is termed as over consolidated soil. According to Nishimura (1999), unsaturated soils near the ground surface & artificially compacted soils are commonly over-consolidated due to changes in the environment.

2.4 *Selection of strain rate during shear*

The shear strength test of unsaturated soils is commonly performed at a constant strain rate. An appropriate strain rate must be selected prior to commencing a test. In constant water content test which is also a type of undrained test, the selection of strain rate must ensure equalization of induced pore pressure throughout the specimen (Rahardjo, 1993). Gibson & Hankel (1954) and Bishop & Henkel (1962) presented test data showing the variation in strength with strain rate. Satija & Gulhati (1979) concluded from their test data that deviatoric stress is not sensitive to the effect of varying strain rates. The author has also performed a separate series of constant water content test at a strain rate of 0.025, 0.05, and 0.08mm/min to observe the effect of strain rate on the mechanical behavior of unsaturated DL clay. The strain rates were corresponding to the motor speed of 100, 200, and 300rpm of strain-controlled loading system. It was observed that the shear strength of unsaturated DL clay was not sensitive to the effect of varying strain rate. The criterion used to select an appropriate strain rate was that the shear strength should remain constant when sheared at rates below the selected displacement rate and equalization of induced pore pressures took place. Based on described criteria, strain rate of 0.05mm/min was selected and soil specimen in further test series were sheared at the same strain rate

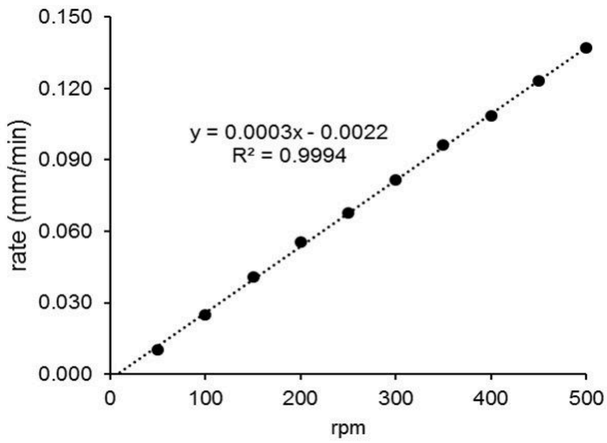

Figure 2. Strain rate vs rpm of motor for loading system

3 EXPERIMENTAL RESULTS

3.1 *Initial suction*

The initial suction of unsaturated soil was measured by placing soil specimen made with varying water content on a saturated pedestal. In this process pore air pressure was drained and pore water pressure was accurately measured in form of negative pressure or suction. The previous researchers show that initial suction influences the behavior of unsaturated soil. However, the suction depends on the pore-water distribution and water content. Figure 3 shows the variation of the monitored values of initial suction with a time of statically compacted specimens with a water content of 0, 7 10, 15, 20, 25 and 28% when they were set in the triaxial apparatus. Due to different values of water content, the initial suction varies and we can see that the higher the water content less is the initial suction and less is the time required for stabilizing initial suction and vice versa. The less time in stabilizing initial suction is due to use of a thin membrane filter with air entry value of 420kPa.

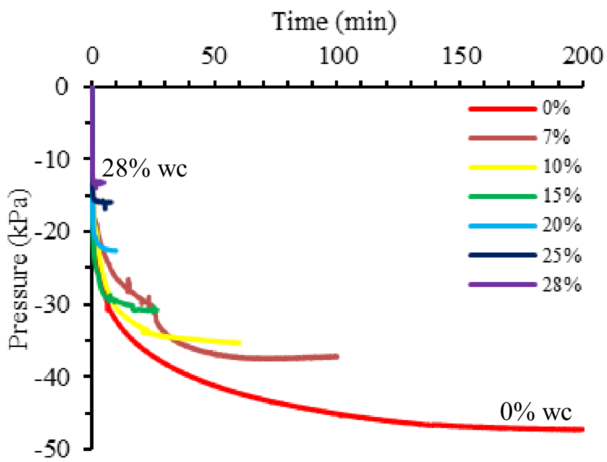

Figure 3. Measurement of initial suction.

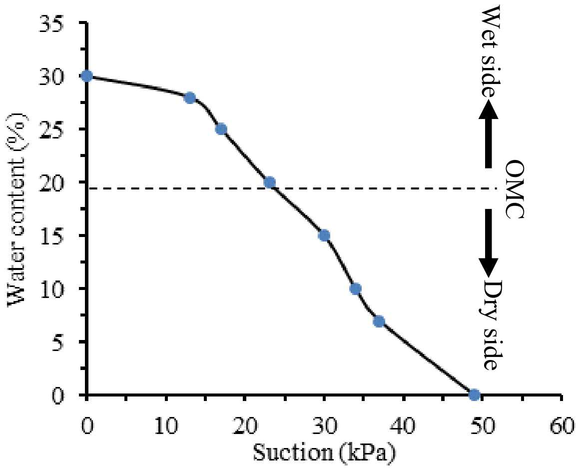

Figure 4. Relationship between water content and suction

Figure 4 shows the relationship between the water content and matric suction and it shows the convergence value of the initial suction and water content. We can see that initial suction converged to about 47, 38, 31, 23, 16 and 13 (kPa) against moisture content of 0, 7, 10, 15, 20, 25 and 28 (%) respectively. From Figure 2 and Figure 3 it is understood that suction of unsaturated soil decreases as the water content increases.

3.2 *Shear process*

After measurement of initial suction, the soil specimens were moved to shear process under no confining pressure. Pore air pressure was drained whereas pore water pressure was undrained during the shear process and the shearing was carried out at a strain rate of 0.05mm/min.

3.2.1 *Shear strength behavior*

Figure 5 shows the relationship between deviatoric stress and axial strain during shearing of seven cases of unsaturated soil specimens. The soil used in this study was over-consolidated soil, for such soils, a peak soil behavior was observed followed by post-peak response of specimens, same kind of response can also be seen in the figure. The peak deviatoric stress obtained against water content of 0, 7, 10, 15, 20, 25 and 2 % was 4, 18, 31, 46, 45, 38 and 27kPa respectively. The maximum deviatoric stress obtained among seven specimens was 46kPa at a water content of 15% and 45kPa at a water content of 20kPa. The optimum water content of studied soil from Standard Proctor test was 20%. From this, it can be understood that maximum shear strength is obtained at a value close to optimum water content ratio. The response of pore water pressure transducer showing increase in pore water pressure during the shearing process in constant water content conditions is shown in Figure 6. Generally, it can be observed that pore water pressure was developed in specimens prepared on the dry side of OMC, however, with increase in water content, the pore water pressure decreased. The maximum pore water pressure was developed in specimen prepared at 0% wc.

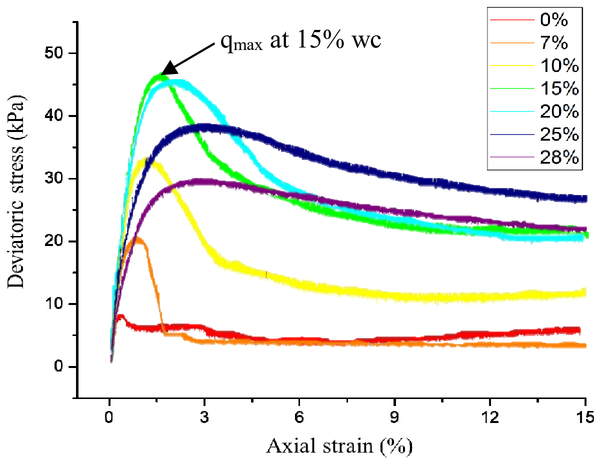

Figure 5. Relationship between deviatoric stress and axial strain

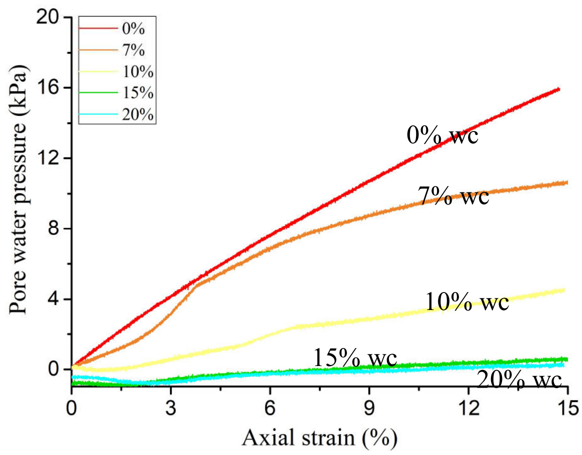

Figure 6. Relationship between Pore water pressure and axial strain

Figure 7 shows the water content – suction – deviatoric stress relation. In this figure we can see that deviatoric stress increase with increase in matric suction but as the suction increase beyond a certain value the deviatoric stress decrease. Similarly, we can see increase in deviatoric stress with a decrease in water content but when the water content was increased beyond a certain value the deviatoric stress decreased. Generally, it is thought that the deviatoric stress increase as the suction increase and water content decrease but the test results have shown that relationship between matric suction and deviatoric stress is nonlinear. The deviatoric stress increase up to the certain value of matric suction after which it decrease. This behavior can be explained by bulk and meniscus water concept given by Karube & Kato (1994). Meniscus water results in increase in strength of the soil whereas the bulk water has little effect. In other words, water in soil specimen affects the strength increase as meniscus water up to optimum water content, after this bulk water is more than meniscus water, as a result, the shear strength gradually decreased.

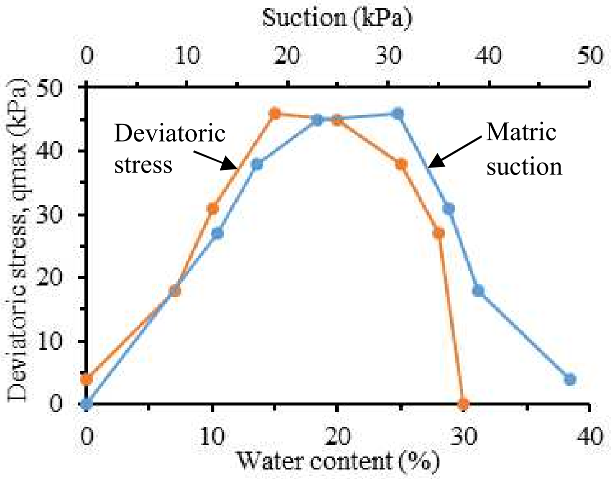

Figure 7. Water content – suction – shear strength relationship

3.2.2 *Volume change behavior*

Figure 8 shows the volume change behavior of specimens during the shearing process. The soil used in this study was overconsolidated soil, in such soils, the applied pressure during element test is less than past pressure and have a high degree of compaction. Due to a high degree of compaction the soil shows dilative behavior, therefore, the test soil also showed dilative behavior and we can see from the figure that dilation increases with increase in axial strain. In order to differentiate the volume change behavior, the specimens with water content less than optimum moisture content are termed as dry specimens (i.e, 7%, 10%, 15%) and specimens with higher water content than optimum moisture content are termed as a wet specimen (i.e. 25%, 28%).

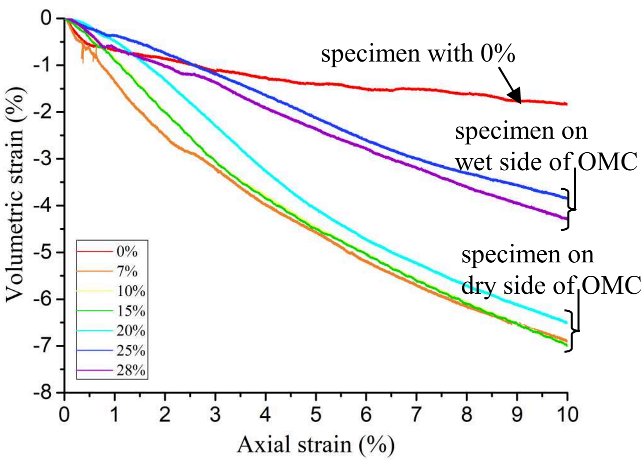

Figure 8. Volume change behavior

We can see that the volume change for the dry specimens was larger than that of wet specimens because the dry specimens showed more shear strength, therefore, volume change was also more for dry specimens. In addition to this, the volume change behavior of all specimens on the dry and wet side of optimum moisture content (respectively) was also same. The specimen with 0% water content also showed some deformation, as this specimen was fully dried and showed very small strength and brittle behavior during shearing, therefore, it showed very less volumetric deformation.

4 CONCLUSIONS

In this study, we carried out a series of constant water content tests on soil specimens prepared on the dry, optimum and wet side of optimum moisture content to study the effect of water content on matric suction, shear strength and deformation behavior considering the surface layer of the embankment. It was found that matric suction decrease with increase in water content, higher the suction more is the time required to stabilize. From the test results, it can be concluded that the dry soil showed better performance as compared to wet soil under same conditions used in this program. It showed high initial suction, more dilative behavior, and high shear strength. This suggested that surface layer of embankment should be compacted on the dry side of optimum moisture content to get better performance during the service life.

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