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# An Experimental Investigation in Effect of Confining Stress and Matric Suction on the Mechanical Behavior of Sand with Different Fine Content

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***Abstract*—** This paper presents the results that the soil volumetric strain and shear strength are closely related to the confining stress and initial matric suction under constant water content testing on the specimens of unsaturated sand with clay and silt fines contents. The silty sand specimens reached their peak strength after a very small axial strain followed by a post-peak softening towards an ultimate value. The post-peak drop in stress increased by an increment of the suction, while there is no peak strength for clayey sand specimens. The clayey sand shows compressibility and possesses ductile stress-strain behaviour. Shear strength increased nonlinearly with respect to matric suction for both soil types. When suction exceeds a certain range, the effect of suction on shear strength increment weakens gradually. Under the same confining stress, the dilatant tendencies in the silty sand increased under lower values of suction and decreased for higher suction values under the same confining stress. However, the amount of contraction increased with increasing initial suction for clayey sand specimens.

***Keywords*—**Unsaturated soils, silty sand, clayey sand, triaxial test, constant water content.

## I. Introduction

IN the past two decades, significant development has been done in unsaturated soils studies. The first models were presented based on two stress state variables and regardless of effective stress in unsaturated condition as in [1], [2]. However, there were a number of models back to Bishop's [3] theory with regard to the degree of saturation tried to provide an equation for the consideration of effective stress and its effects on the behavior of unsaturated soils as in [4]-[6].

Net confining stress and matric suction have a significant influence on mechanics properties of unsaturated soils such as shear strength and volume change. Reference [7] used these independent stress variables to propose the shear strength relationship of unsaturated soils which is commonly applied in practical engineering problems. Several researchers suggested these variables as the critical state variables for unsaturated soils.

The experimental studies play an important role in identifying variables affecting the behavior of unsaturated soils. In these studies, the effects of suction, net stress, stress path, strain rate and also physical properties such as density, grain size and specimen preparation methods on mechanical behaviour of unsaturated soils have been discussed as in [8]-[11]. Being a time-consuming process is one of the main problems in performing unsaturated tests which can be reduced by conducting constant water content test (CW) as shown by many researchers [3], [12]-[14]. Furthermore, during rainfall, rapid failure may occur under undrained conditions which can be simulated by constant water content test.

Some previous research has studied the effect of fine content on the unsaturated mechanical behavior of soils, Although the studies have shown conflicting results, they revealed that the unsaturated mechanical behavior of soils is sensitive to the plastic and non-plastic fine content [15], [10], [16].

The results of an experimental program including a series of triaxial compression tests to study the effect of net confining stress and matric suction on the mechanical behavior of unsaturated clayey sand and silty sand are presented in this paper. Matric suction and volume changes during the shearing stage of constant water content triaxial tests were analyzed and discussed. The volume change behavior of unsaturated soils can be contractive or dilative under the influence of applied stress or suction changes. This behavior depends on the nature of the soil and loading and leads to failures and damages to foundations, buildings, and slopes.

## II. Test Program & Materials

Two different soil types were used for specimen preparation, the first type was a mix of 58% sand and 42% clay and the second type was a mix of 53% sand, 23% silt and 24% clay which are classified as SC and SM in Unified Soil Classification system respectively.

The physical properties of the base sand without fine are presented in Table I.

TABLE I
NATURAL VARIABLES OF THE CLEAN SAND

| $e_{min}$ | $e_{max}$ | $G_s$ | D50 (mm) | D10 (mm) | Fine percentage | Cu | Cc |
|---|---|---|---|---|---|---|---|
| 0.583 | 0.928 | 2.66 | 0.26 | 0.15 | 0 | 1.80 | 1.14 |

The soil specimens had a diameter of 39.1 mm and height of 80 mm. Triaxial soil specimens were compacted according to the standard proctor test at a low water content of 7% for silty sand or 8.4% for clayey sand specimens to achieve the desired initial suctions without any drying process. The classification properties of the soil and the physical properties

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of soil specimens are given in Table II.

TABLE II
PROPERTIES OF THE SOILS

| Properties | Clayey sand (SC) | Silty sand (SM) |
|---|---|---|
| Max dry proctor γ(KN/m$^3$) | 19.71 | 19.29 |
| Specimen dry γ(KN/m$^3$) | 16.96 | 17.94 |
| Specimen wet γ(KN/m$^3$) | 18.32 | 19.11 |
| $(Sr)_{initial}$ (%) | 39.36 | 37.73 |
| e | 0.56 | 0.46 |
| $G_S$ | 2.66 | 2.68 |
| $(\omega)_{opt}$ (%) | 9.58 | 10.21 |
| $(\omega)_{initial}$ (%) | 8.4 | 7 |
| Liquid limit (%) | 23.5 | 16 |
| Plastic limit (%) | 14 | - |
| Plasticity index (%) | 9.5 | NPI |

A double walled Bishop and Wesley type triaxial cell designed by VJ-tech is used for this study which is able to measure unsaturated soil volumetric changes and suction measurement. The apparatus test parameters such as load, cell, pore water, and pore air pressures are controlled by Clisp studio computer software.

### *A. Saturated Triaxial Testing*

A series of consolidated undrained triaxial shear tests (CU) were carried out on saturated specimens of two sands at effective consolidation pressures of 50, 100 and 200 kPa, with shearing at an axial strain rate of 0.08 mm/min (about 0.1%/min). The shearing stage was continued until the pore water pressure of the specimen remained constant and the specimens reached a critical state.

### *B. Unsaturated Triaxial Testing*

The CW triaxial test includes the three stages of suction equalization, isotropic consolidation, and shearing at constant water content.

In constant water content triaxial tests, the pore air can drain for the whole testing procedure; therefore, pore air pressure valve was fully open while the pore water is kept undrained to measure the pore water pressure during shear. The compacted specimens were equalized by using the method of wetting (water flows into the specimen). The specimens brought to desire initial matric suctions of 30, 100, 150 and 200 kPa and then left to equalize. For this purpose, an air pressure of 300 kPa was applied at the top of the specimens. Back pressures of 270, 200, 150 and 100 kPa were injected to the bottom of the specimen through a 5 bar high entry porous ceramic disk. After the equalization, the specimens were consolidated isotropically at net confining stress of 50 and 100 kPa and then sheared at constant water content. The shearing stage continued until reaching the critical state.

## III. TEST RESULTS

### *A. Saturated Soil Behavior*

The variations of deviator stress and pore water pressure with axial strain are presented in Fig. 1. Soil specimens reached a critical state by the deviator stress and pore water pressure became constant at axial strains of 20-25%. As shown in Fig. 1, the pore-water pressure rapidly increased at the start of loading and remained positive in all saturated specimens during the whole process of shear loading, meaning that the specimens behaved contractive from the beginning to the end of the tests. According to the test results, during loading, the pore water pressure increased as the confining stress increased.

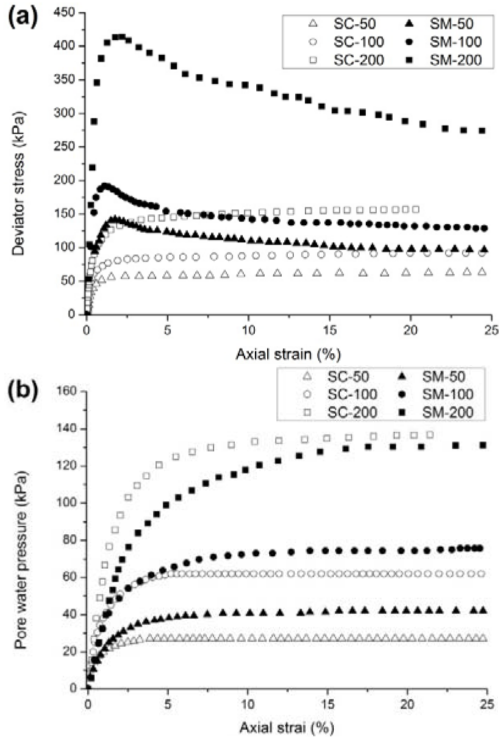



Fig. 1 (a) Deviatoric stress-strain curves and (b) pore water pressure-strain curves of CU tests

### *B. Unsaturated Soil Behavior*

Constant water content triaxial tests were continued until the deviator stress, volumetric strain and matric suction tended to constant values. Changes in pore water pressure cause matric suction vary during shearing in CW tests. The variations of deviator stress, volumetric strain and suction versus the axial strain during the shearing for the unsaturated specimens are shown in Figs. 3-6.

Time to reach equalization depends on several factors such as unsaturated soil permeability initial matric suction, compaction condition, initial water content and the thickness of the porous ceramic disc. Fig. 2 shows the wetting process of specimens corresponding to 100 kPa suction during equalizing. It can be seen that the volume of water entering the clayey sand specimens is greater than silty sand specimens due to higher porosity they have.

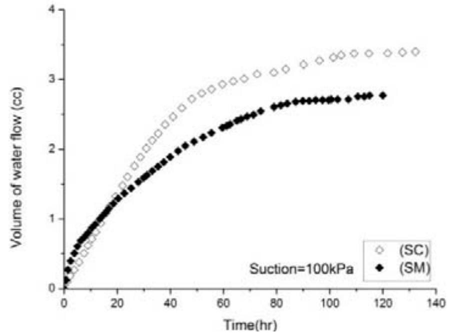



Fig. 2 Wetting curves during equalization

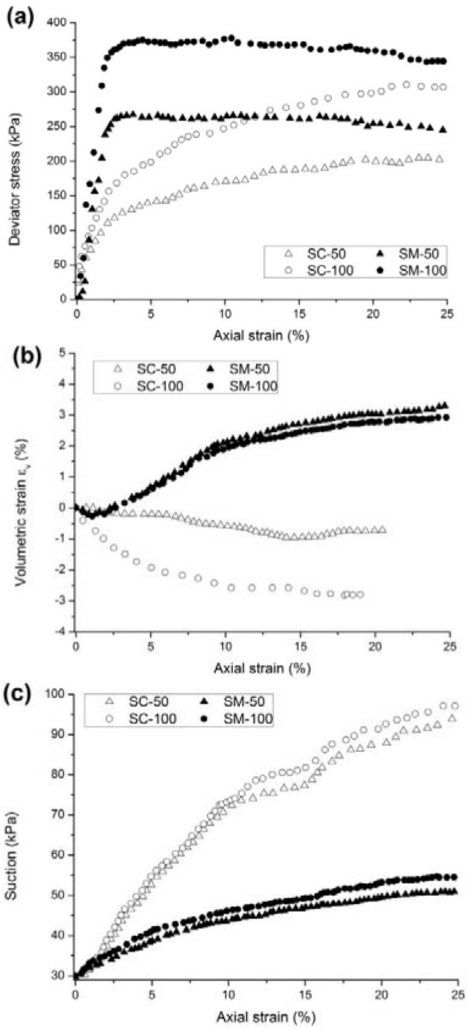



Fig. 3 (a) Deviatoric stress-strain curves, (b) volumetric strain-strain curves, and (c) suction-strain curves of CW tests at the initial matric suction of 30 kPa

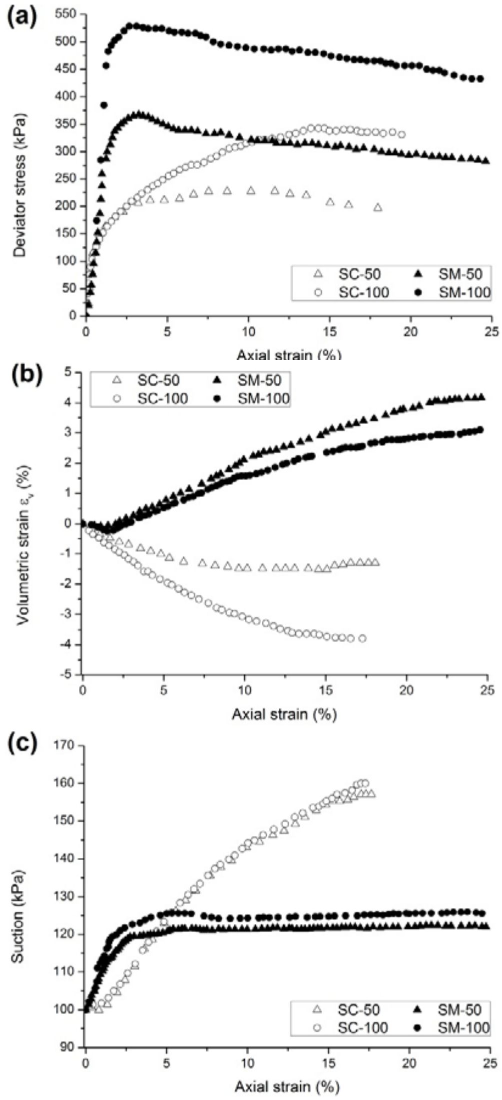
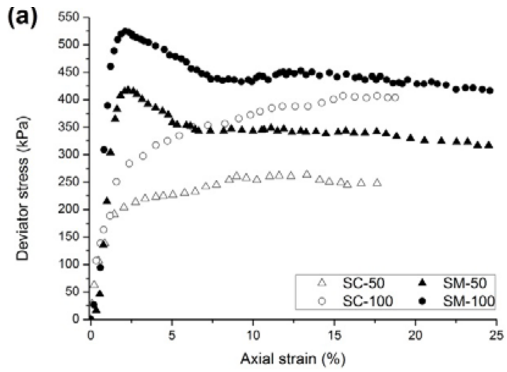



Fig. 4 (a) Deviatoric stress-strain curves, (b) volumetric strain-strain curves, and (c) suction-strain curves of CW tests at the initial matric suction of 100 kPa



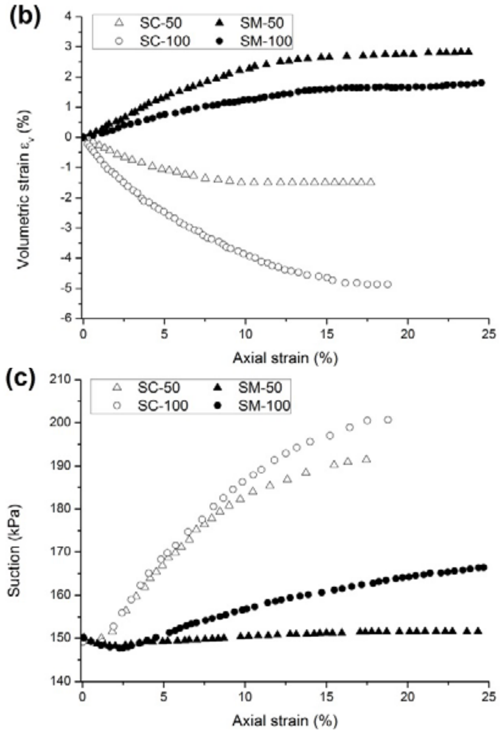



Fig. 5 (a) Deviatoric stress-strain curves, (b) volumetric strain-strain curves, and (c) suction-strain curves of CW tests at the initial matric suction of 150 kPa

## IV. Discussions

The strength of the unsaturated specimens was greater compared to the saturated ones at the same net confining stress. The deviatoric stress increases as net confining stress increases in tests with the same initial suction. Higher ultimate deviatoric stress and deviator stress at failure appeared in higher initial suction which is reflected as an increase in the shear strength of specimens. As can be seen in Figs. 3-6 (a) the influence of net confining stress on shear strength increase is more obvious than suction. Figures show the silty sand specimens acted typical of sand by approaching critical state with the shear strength reduction after peak strength due to dilation. The post-peak drop in strength increased with increase in initial suction, while no peak is observed in the stress–strain curves for clayey sand specimens.

### *A. Volume Change and Matric Suction Behavior*

In clayey sand specimens, the results indicated a tendency to lose pore air and reduce the total volume under the applied axial load. The matric suction increment caused a greater tendency to volume reduction in clay sand specimens. Volume change behavior of the silty sand specimens is a function of sand structure which indicates contraction initially and then dilation.

As shown in figures, in the silty sand specimens level of dilatancy is closely related to the initial suction and confining stress. In a certain range, the greater initial suction, the more obvious dilatancy phenomenon. When the suction reaches a certain level, the dilatancy phenomenon is gradually weakened with an increase in the suction. Under the same suction, the dilatancy phenomenon induced by lower confining stress is more apparent.

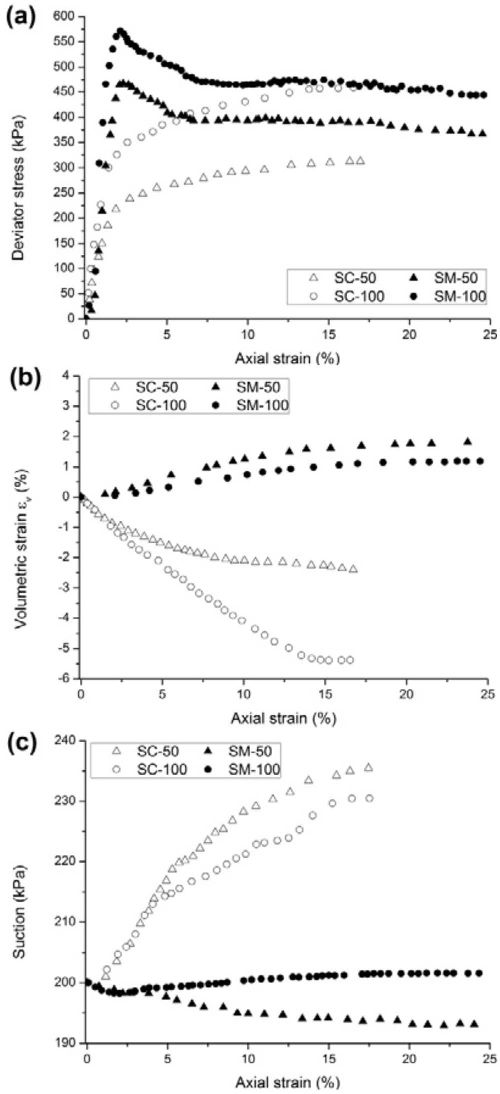



Fig. 6 (a) Deviatoric stress-strain curves, (b) volumetric strain-strain curves, and (c) suction-strain curves of CW tests at the initial matric suction of 200 kPa

Above-mentioned phenomenon shows that dilatancy increases with the increase of the suction under the given normal stress. It may be due to that the high suction makes soil particles become more closely packed and bonded together and form larger particles as similar sand particles called aggregate, Therefore, under the action of shear stress, particles overturning (dilatancy) more likely happen between particles than shearing. The trend of dilatancy is particularly significant at high suction under low confining stress, at low suction, under high confining stress the volumetric strain behaves mainly compressive which appears to agree closely with the literature such as [10].

One of the features observed in constant water tests is that the pore water pressure changes in the specimen during the shearing which directly changes the matric suction during the test (pore air pressure keeps constant). The nature of matric suction changes during constant water testing is not yet known. The test results showed that the fine content (clay or silt) of the soil specimens does not have a significant effect on the pore water pressure changes, and these changes are mostly under the effect of the specimens' initial suction.

As can be seen from Figs. 3-6 (c), there is an increase in the matric suction from the initial matric suction as shearing progressed. The suction has been increased with a descending rate under applied axial load until reaching failure. According to this figure, at the same initial matric suction, the matric suction variation of the specimens performed under 100 kPa net confining stress is more obvious than specimens under 50 kPa. In addition, at all amounts of confining stress, a larger variation was observed for the samples with the lower initial suctions. The variation in matric suction of clayey sand specimens is greater than silty sand specimens. When suction reached 150 kPa and above, high suction leads to a very small degree of saturation, and it causes the enhancive effect of suction on granular shear strength to weaken significantly, therefore, the dilatancy degree reduced accordingly.

Fig. 7 shows the variation of peak shear strengths of the unsaturated specimens with initial matric suction under different net confining stress. The maximum value of shear stress was strongly influenced by the matric suction. It can be seen that the peak shear strength nonlinearly increases with an increase in matric suction. The shear strength enhancement with a suction increase was weakened gradually when suction exceeds a certain range.

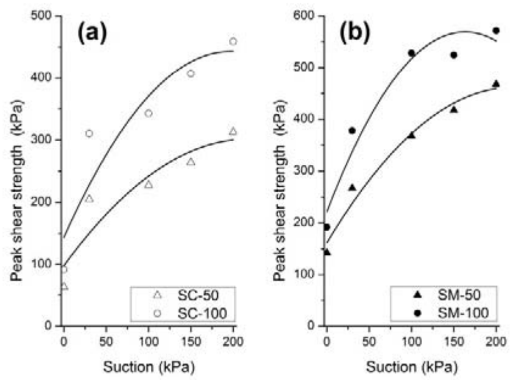



Fig. 7 Nonlinear relationship between peak shear strength and initial matric suction for (a) SC and (b) SM

Table III contains the state properties of the specimens resulted from performed CW tests. The results indicate under the same initial suction, the greater the confining stress is, the specimens reached the critical state at greater strength and the effect of dilatancy is reduced. Under the same confining stress, in clayey sand specimens, the greater the initial suction is the more obvious dilatancy phenomena, However, it is opposite in silty sand specimens. It shows that the clay content has a great influence on the dilatancy effect of soil.

TABLE III
ULTIMATE STATE PROPERTIES OF SPECIMENS FOR CW TESTS

| Test | Ultimate suction (kPa) | Ultimate deviator stress (kPa) | Ultimate specific volume (1+e) | Ultimate degree of saturation ($S_r$) |
|---|---|---|---|---|
| SC30-50 | 93.10 | 192.51 | 1.47 | 64.87 |
| SC30-100 | 97.78 | 307.39 | 1.444 | 66.68 |
| SC100-50 | 158 | 196.64 | 1.52 | 49.23 |
| SC100-100 | 160 | 331.03 | 1.475 | 53.64 |
| SC150-50 | 191.48 | 247.98 | 1.53 | 45.87 |
| SC150-100 | 200.63 | 403.80 | 1.50 | 52.2 |
| SC200-50 | 230.67 | 312.57 | 1.54 | 42.23 |
| SC200-100 | 235.36 | 458.64 | 1.52 | 50.66 |
| SM30-50 | 52.47 | 244.95 | 1.57 | 59.93 |
| SM30-100 | 55.91 | 341.37 | 1.56 | 64.47 |
| SM100-50 | 122 | 282.61 | 1.51 | 50.52 |
| SM100-100 | 126 | 432.34 | 1.42 | 61.63 |
| SM150-50 | 151.88 | 316.60 | 1.48 | 45.76 |
| SM150-100 | 167.28 | 416.17 | 1.39 | 55.64 |
| SM200-50 | 192.23 | 366.54 | 1.46 | 42.11 |
| SM200-100 | 201.53 | 444.23 | 1.30 | 52.79 |

## V. CONCLUSIONS

This paper experimentally investigates the effects of matric suction and confining stress on the mechanical behavior of the mixtures of one host sand and two types of fines. The tests include consolidated undrained tests on saturated specimens and constant water content tests on unsaturated specimens under suction-controlled conditions.

Based on results, the following conclusions can be drawn:

- The test data from both soil types indicate a nonlinear increase in shear strength as a result of higher values of initial suction. However, when suction exceeds a certain range, the effect of suction on shear strength increment is weakened gradually.
- In the silty sand specimens, dilatancy increases with the increase of the suction under the given normal stress, therefore, under the action of shear stress, particles overturning (dilatancy) more likely happen between particles than shearing. The trend of dilatancy is particularly significant at high suction under low confining stress, at low suction, under high confining stress the volumetric strain behaves mainly compressive.
- The net confining stress causes an increase in shear strength and according to the results, its influence on shear strength increase is more obvious than suction.

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