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EFFECT OF SILT CONTENT ON BEHAVIOUR OF SILTY SAND MIXTURES

Navid Khayat[1]

[1]Department of Civil Engineering, College of Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran

ABSTRACT: The anisotropy of sand has not been fully studied in terms of the effects of different silt content. This study investigates the effects on anisotropy in Tehran sand with various silt contents. The tests performed in this research include some Hollow Cylinder Torsion Shear Tests conducted on 400kPa confining stresses. The samples had 0, 15, 30, and 50 percent silt contents, and the effect of the inclination angle on the major principal stress "α" was investigated with a particular emphasis on silt content. The parameter "α" is considered as the key parameter that indicates the anisotropy characteristics, and can vary from 0° to 90°. According to the results, an increase of "α" leads to more contractive behaviours in the studied sands. In all samples, increasing the silt content up to 50% causes the strength to decrease.

Keywords: *Sand; Strength; Silt content; Anisotropy*

1. INTRODUCTION

In recent years, researchers have performed extensive and comprehensive studies on clean sand, determined different aspects of its behaviour in terms of its structure, and have made several general conclusions. However, the behaviour of clean sand containing silt is associated with several complications that make it difficult to understand.

Extensive studies have focused on the effects of inherent and induced anisotropy on the behaviour of clean sand [14]-[17]-[19]-[34].

Yamamuro and Lade (1998) extensively investigated the behaviours of sands containing small amounts of silt (7%)[28]. They concluded that when a small amount of silt is added to the host sand, the obtained sand-silt mixture exhibits the opposite behavior of that of pure sand. The sand under low confining pressure (25 kPa) is completely liquefied, and the strength of sand reaches zero. As the confining stress increases, the sand with 7% silt has more stable behaviour than that of pure sand with no liquefaction under high confining pressures. According to Yamamure and Covrt (2001), the behaviours of silt-sand mixtures with high amounts of silt (40%) are different from those of pure sand and those of silt-sand mixtures with small amounts of fine particles [29]. In these mixtures, like the sands with 7% silt, liquefaction occurs completely under 25 and 50 kPa confining stresses; however, as the confining stress increases, the behavior tends to be more stable. Such behaviours are similar to that of sand with 7% silt content but are still different from those of pure sand [29].

Parameter α° (the inclination of major principal stress with respect to the depositional (vertical) direction) is used to denote the rotation of principal stresses and parameter $b' = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ indicates intermediate stresses. Different principal stress directions and b' values can cause changes in soil behaviour. Thus, α° and b' are selected as the key parameters for studying the anisotropy of sands. In this regard, Hollow Cylindrical Torsional Shear (HCTS) is the best apparatus for studying these parameters [1]. HCTS has been used in several tests conducted on sands by different researchers to study the effects of parameters α° and b' more accurately. They generally came to the conclusion that sandy samples had softer behaviour as the values of α° and b' increased in undrained tests [32]. According to Symes et al. (1985), sandy samples exhibit more contractive behaviour as the α° and b' values increased [14]-[20]-[25].

Despite extensive studies conducted on the anisotropy effects of clean sand, there are few studies that have investigated its effects on the behaviour of sand-silt mixtures. Among recent relevant studies, Bahadori and Ghalandarzade (2008) studied the inherent anisotropic effects on the undrained behaviour of sands using HCTS[4]-[10].

In this research, the anisotropic behaviour of Tehran sand with different silt contents in 400 kPa initial effective confining stress are studied. A total of 12 tests are conducted on Tehran sand with silt contents of 0%, 15%, 30% and 50%. In these tests, the effects of the inclination angle of major stress and silt content are investigated.

2. MATERIAL AND METHODS

2.1 Material properties

Tehran sand, which is produced by crushing plants, this sand is greenish gray color. The physical characteristics and grading curves of this sand are shown in Fig. 1 and Table 1. The plasticity index of silt is less than 5% and can be addressed as non-plastic soil (see Table 2).

Table 1 Physical characteristic of sands

Sand type	C_c	C_u	$FC(\%)$	$D_{50}(mm)$
Tehran sand	0.59	2.55	0.03	0.106

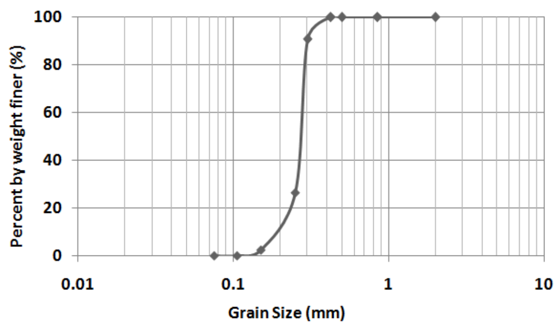


Fig. 1. Grain size distribution curves of Tehran sand

Table 2 Physical properties of silt

Plastic limit (%)	Liquid limit (%)	Plasticity index (%)
22	24	2

2.2 Maximum and minimum void ratios of sand-silt mixtures

An effective factor in the general behaviour of saturated sands in monotonic loading is soil relative density, which is a parameter that shows the sample's specifications at the end of consolidation stage. The samples prepared at low densities showed contractive behaviours in the drained tests; this behaviour causes excess pore water pressure in undrained tests, which reduces the effective confined stress. The change of stress-strain from the softening to hardening states is generally related mostly to the relative density, which is observed and reported by several researchers [5]-[7]-[8]-[16].

It is clear that adding silt to the host sand changes the maximum and minimum void ratios. The parameters related to soil density are needed to compare the test results; therefore, minimum and maximum void ratios should be obtained for different percentages of silt. In this research, ASTM 4253 and ASTM 4254 are used to measure the minimum void ratio ($e_{\min}$) (densest state) and maximum void ratio ($e_{\max}$) (loosest state), respectively. The obtained values are plotted in Fig. 2. For host sand, the minimum void ratios decrease as the silt content of the samples increases. This trend continues up 28 percentage fine content (FC); then, the void ratio increases as the silt content increases. The minimum achieved void ratio takes place in the fine contents, which will be called the threshold fines content.

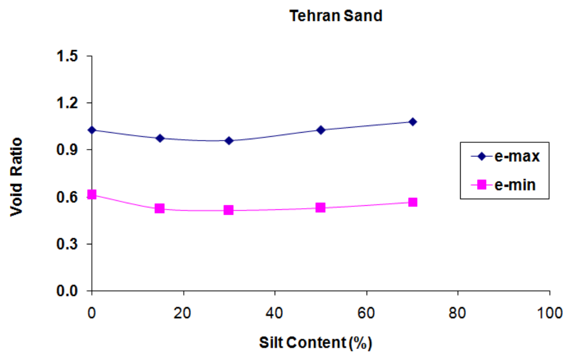


Fig. 2. Minimum and maximum void ratios for the Tehran sand-silt mixtures

2.3 Testing apparatus and method

In order to study the inherent anisotropy, a hollow cylinder torsional shear (HCTS) device was used. For better investigation of post peak response the device can perform both stress and strain controls. A closed loop control was applied to the machine to handle any type of desired stress history including major principal stress rotation and intermediate stress ratio. Four Electrical/Pneumatic [E/P] transducers were used to exert required pressure for the inner and outer cell pressure in addition to the torsion and axial load pneumatic actuators. An alternative DC motor for torsional strain control test was prepared in order to study the post peak behaviour. In the case of our tests, the motor was utilized since the strain control was adopted in order to study the softening response. The motor speed in all the tests remained constant and equal to 4 degree per minute. Eleven transducers were adjusted in order to measure different parameters continuously .Three water pressure sensors, two for inner and outer cell pressures and one for pore pressure, one vertical displacement sensor to measure axial strain, and one rotation angel sensor to measure torsional strain, two differential pressure sensors, two axial and torsional stress sensors and finally two limit switch sensors were set up. A computer program was utilized to control all test procedures by means of a PID control algorithm. Data logging device was the last part of the control system. The sample dimensions were 12 cm in height, 6 cm in inner diameter and10 cm in outer diameter.

The maximum inclination of principal stress (α°) and intermediate stress ratio (b') are considered the critical parameters in this research. Because the torsion sensor measures the torque (T) at any moment, the $\sigma_{Z\theta}$ (shear stress) value can be obtained using Eq (3), where r_i and r_o are the inner and outer radiuses of the samples, respectively. The value of σ_Z (vertical normal stress) must be kept constant, and therefore, the values of σ_θ and σ_r (circumferential and radial normal stress respectively) obtained through Eqs (1) and (2), respectively, are also kept constant. Furthermore, P_i and P_o (inner and outer water pressures) are computed using Eq (5), F_V (vertical force) is found using Eq (4) and principle stress can be measured by equation 6 to 8 [15].

$$\sigma_\theta = \sigma_Z - \frac{2\sigma_{Z\theta}}{\tan 2\alpha} \quad (1)$$

$$\sigma_r = \sigma_Z - \frac{\sigma_{Z\theta}(\cos 2\alpha - 2b + 1)}{\sin 2\alpha} \quad (2)$$

$$\sigma_{Z\theta} = \frac{1}{2}\left[\frac{3T}{2\pi(r_o^3 - r_i^3)} + \frac{T}{\pi(r_o^3 + r_i^3)(r_o - r_i)}\right] \quad (3)$$

$$\sigma_Z = \frac{F_V + \pi(P_o r_o^2 - P_i r_i^2) - A_r P_o}{A_S} \quad (4)$$

$$\begin{cases} P_i = \dfrac{\sigma_r(r_o + r_i) + \sigma_\theta(r_o - r_i)}{2r_i} \\ P_o = \dfrac{\sigma_r(r_o + r_i) + \sigma_\theta(r_o - r_i)}{2r_o} \end{cases} \quad (5)$$

2.4 Experimental Program

Sample preparation method used in this study was dry deposition method. That may alter the real anisotropy fabric; water sedimentation method was not used. Dry deposition method is able to create more uniform silty sand samples according to Miura and Toki (1982) suggestion which says pluviation methods create the most significant anisotropy [12].The sand was deposited into the frame through a funnel with a long tube. Carbon dioxide (CO_2) and deaired water are passed through the samples in their saturated states. The circulating time for the CO_2 considered in the tests conducted by Zlatovic and Ishihara (1997) were 30 minutes for clean sand and 8 hours for pure silt [33]. In the present study, the minimum and maximum times were 30 and 135 minutes for clean sand and the 50% silt mixture, respectively. After circulation of CO_2, the deaired water entered from the bottom similar to CO_2 but in the opposite direction of gravity and was seeped into all the voids in the sample. The saturation procedure continues as the confining pressure increased, and the pore water pressure was measured in several steps. If the B-value would exceed 0.95, then the sample is assumed to be completely saturated. At this time the saturation stage was completed and the sample should be consolidated. Because all the tests conducted in this research were of the Consolidated Undrained (CU) type, all drainage valves must be opened during consolidation and connected to the system. The amount of water discharged from the sample during consolidation could be measured by reading the burette numbers at the beginning and end of this stage. After consolidation the shear stage started at which the shear speed was four degrees per minute, the lowest speed that can be applied to the system. At the end of the test the porosity of the samples was measured.

3. RESULTS

The goal of this research was to study the influence of the amount of silt upon anisotropy features in sand-silt mixtures. For this purpose, sand were tested using 400-kPa initial confining stress and a silt content range of 0-50%.Also the Intermediate stresses parameter (b') in all tests was 0.5, Some information on these tests are given in Table 3.

All test results are presented in the form of stress-strain and effective stress path curves. According to these curves, the sample behaviours are similar to those of dense sands based on the classification of undrained sand behaviour in most conducted tests, according to Yoshimine et al. (1998) [34]. The significance of the strength of the deviator stressing phase transformation point is evident in this figure. According to Figs. 3 through 6, the sample strengths (deviator stressing phase transformation and failure points) decrease as α° increase, which indicate that the soil becomes softer. Increasing the silt content up to the threshold level will cause the strengths to decrease, and this reduction is more obvious for the 50% silt case (Figs. 6). In these samples, the test conditions were the same, and the silt percentage increased as the density increased, but unexpectedly, strength did not increase. For example, in test No.7, the value of D_r is 76, but in test No.28, which contains 50% silt, its value is 99, 6.

Table 3. Characteristics of the tests

Test No.	FC (%)	α°	e	D_r	(e_f)	(e_c)
7	0	15	0.711	76.0	1.83	0.71
8	0	30	0.712	75.8	1.83	0.71
9	0	60	0.718	74.3	1.85	0.72
16	15	15	0.600	83.0	1.25	0.84
17	15	30	0.610	80.7	1.27	0.85
18	15	60	0.606	81.6	1.26	0.84
25	30	15	0.560	89.3	0.98	0.92
26	30	30	0.563	88.6	0.98	0.93
27	30	60	0.567	87.7	0.99	0.93
28	50	15	0.530	99.6	0.76	0.88
29	50	30	0.534	98.8	0.77	0.88
30	50	60	0.537	98.2	0.77	0.89

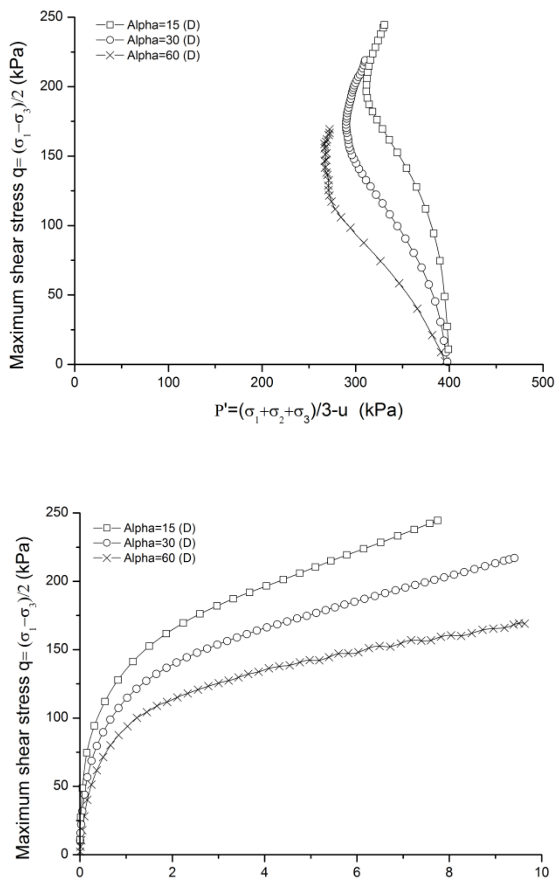


Fig. 3. (a) Stress path and (b) stress–strain curves in Tehran sand subjected to an initial effective stress of 400 kPa (FC(%) = 0)

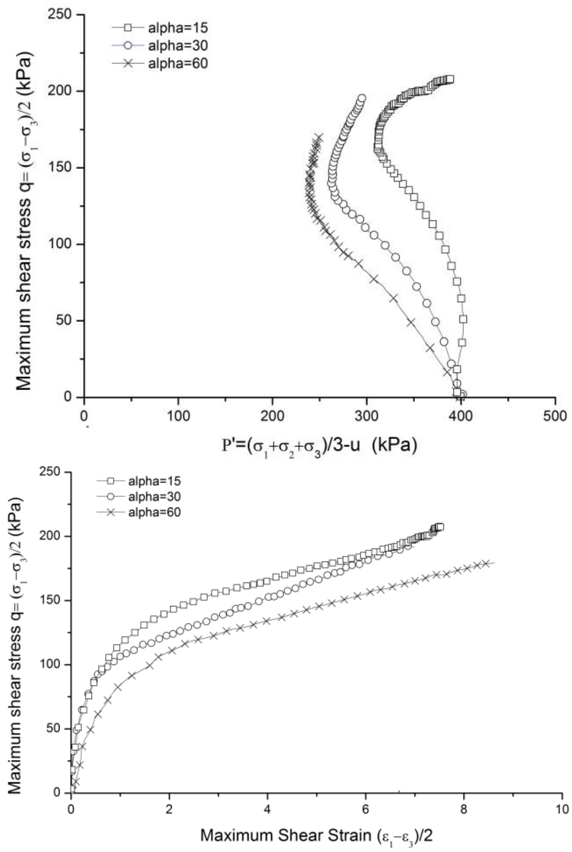


Fig. 4. (a) Stress path and (b) stress–strain curves in Tehran sand subjected to an initial effective stress of 400 kPa (FC(%) = 15%)

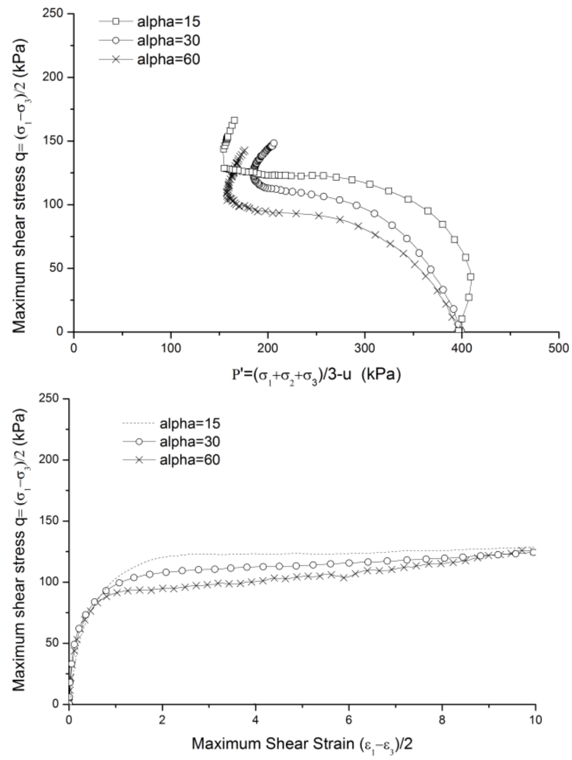


Fig. 5. (a) Stress path and (b) stress–strain curves in Tehran sand subjected to an initial effective stress of 400 kPa (FC(%) = 30%)

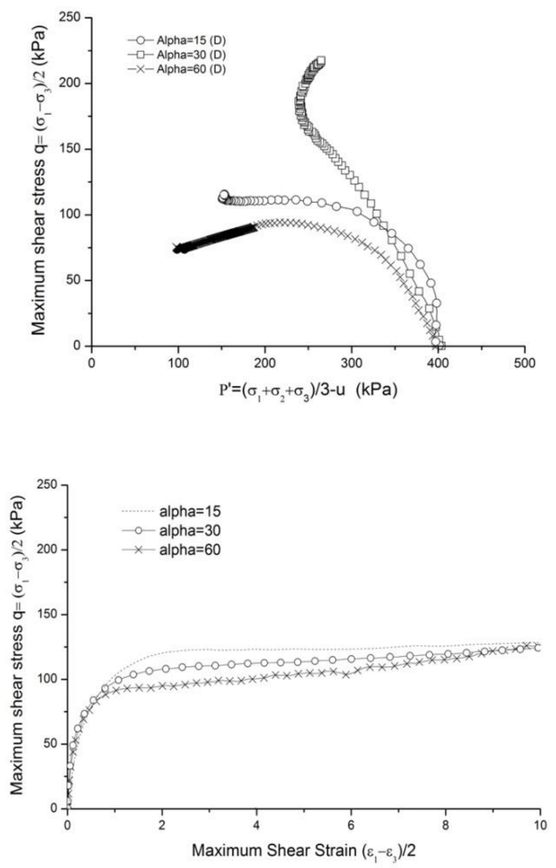


Fig. 6. (a) Stress path and (b) stress–strain curves in Tehran sand subjected to an initial effective stress of 400 kPa (FC(%) = 50%)

4. DISCUSSING AND STUDYING THE STRESS PATHS

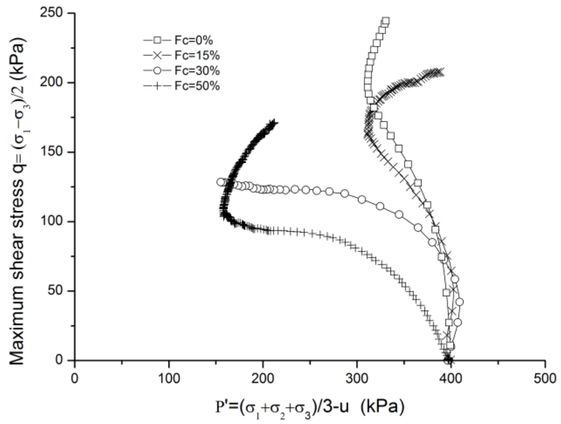
4.1 Effect of inclination angle (α°) on the sand's behaviours

In Figs. 3 through 6, the strength of samples (deviator stressing phase transformation and failure strength) is reduced as α° increase, which indicates that the soil becomes softer. This behaviour has been described by Yoshimine and Ishihara (1998) for Toyoura sand and by Bahadori and Ghalandarzadeh (2008) for a Firoozkuh sand-silt mixture [4]-[32]. It seems regardless of type of sand, similar behaviour can be observed in all studied cases here.

4.2 Effect of non-plastic fines content on the sand's mixture behaviours

The effect of nonplastic fines on the behaviour of saturated sand has been studied by many researchers [6]-[13]-[23]-[29]-[32]. Adding different amounts of nonplastic silt considerably changes the sand behaviour, and these changes are difficult to describe. Pitman et al. (1994) concluded that when silt was added to Ottawa sand, it became less collapsible in undrained triaxial compression tests. However, others found that nonplastic silt may decrease the strength (Troncoso and Verdugo, 1985; Sladen et al., 1985) [18] - [24]. Ishihara (1993) and Verdugo and Ishihara (1996) showed that the increased silt content increased the potential for sand to exist in nature in a contractive state, which includes the possibility of flow failure or liquefaction [9] - [28]. Yamamuro and Lade (1997, 1998) and Lade and Yamamuro (1997) observed that increasing the amount of nonplastic silt in Nevada sand increased the volumetric contractive character in both drained and undrained triaxial tests, even when the overall density increased [30]. Among the problems involved in these studies is the impossibility of fixing at least one of the parameters in sand-silt mixtures. In the present study, the method proposed by Bahadori and Ghalandarzadeh (2008) [4] was applied to address this problem. Based on this method, if the same conditions are considered in sampling and testing, then increasing the silt increases the density and decreases the strength. Thus, while the sample densities are equal, the sample with higher silt content has lower strength.

The sample strengths decreased in the silt-sand mixtures as the silt content increased (Fig. 7). The decreasing strength as silt is added to the host sand can be explained by Tavanayagan's classification (1999) [21]. According to Fig. 8, the void ratios of host sands are tested in the range of Tavanayagam's classification case (i); however, with 15% silt content, the intergranular void ratio $\left(e_c\right)$ approached $e_{\max,HS}$ (Fig. 8), which is more similar to that observed in Tavanayagam's classification case (ii). In this latter case, the finer grains may support a coarse grain skeleton that is otherwise unstable. These grains act as a load transfer vehicle between some of the coarse grain particles in the soil matrix, while the remaining fine particles fill in the voids. In this case, the shear strength is derived from a combination of friction along coarse grain contacts and fine particles. In this structure, e_c increased, which decreased the strength of the samples. This behaviour is evident as the silt percentage in the mixtures increases and leads to an increase in relative density. Increasing the amount of silt content to 30% caused the intergrain void ratio increased; the relative density does not increase because its threshold percentage was 28%. Thus, an inter-fine-particle void ratio is used to explain its behaviour, which is similar to case (iv-2) and shown in Fig. 8. Moreover, the inter-fine-particle void ratio in the mixture with 30% silt content is greater than that of a sample with 15% fine particle content. When the silt content is increased to 50% in all mixtures, e_f is smaller than ($e_{\max,HF}$),and ($FC_{th} < FC$); thus, their behaviours are similar to Tavanayagan's classification case (iv-2). In this case, the fine particles carry the contact and shear forces, while the coarse grains act as reinforcing elements embedded within the finer grain matrix. In this situation, the main bearing structure changes from sand to silt, and because the strength of silt is less than that of sand, increasing the silt up to 50% decreases the strength of the mixture.



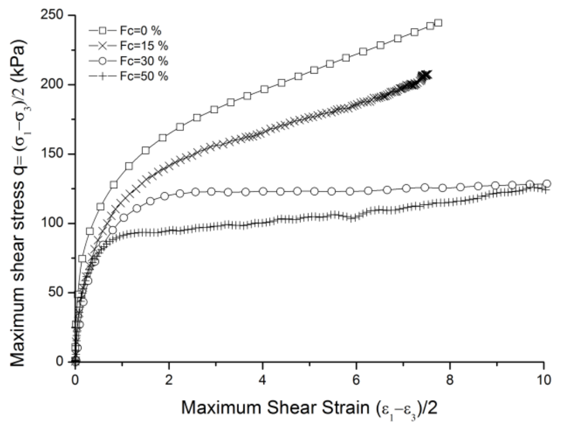


Fig. 7. Stress path and stress-strain curves in Tehran sands with different silt contents at α = 15.

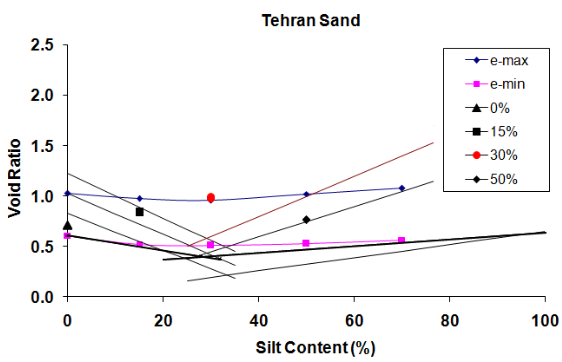


Fig. 8. Intergranular matrix phase diagram for Tehran Sand

5. CONCLUSION

1) As α° increases, the strengths of the samples of host sand and silt-sand mixtures decrease, i.e., the soil becomes softer. Such behaviours have also been observed by Yoshimine et al. (1998); Bahadori and Ghalandarzadeh (2008) and khayat et al (2014)[34]-[4]- [10].

2) As the silt content in mixtures increases, the relative density also increases, but this increase does not increase the mixture strength. An increase in relative density is one of the most marked phenomena that indicate that the index of the relative density (or void) is not a suitable index for evaluating the behaviour of silt-sand mixtures.

3) In all mixtures, increasing the silt content up to 50% causes the strength to decrease. This decline in strength may be justified by parameters $\left(e_c, e_f\right)$, which are defined by Tavanayagam (1999) [21].

6 .ACKNOWLEDGMENT

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Corresponding Author: Navid Khayat