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Technical Note

A comparison between the undrained shear behavior of carbonate and quartz sands

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Abstract

Compared to quartz sand, the shear behavior of carbonate sand differs in appearance, origin, and kind. Carbonate sand is found mainly in the northern coast of the Persian Gulf and the Oman Sea. In this research, a comparison is made between the shear behavior of carbonate sand retrieved from the eastern region of the Chabahar Port, located north of the Oman Sea, and quartz sand obtained from Firoozkooh, north of Iran. Both carbonate and quartz sands have identical and uniform particle size distributions. A total of 4 one-dimensional consolidation tests, and 16 triaxial consolidated-undrained (CU) tests under confining pressures of 100, 200, 400, and 600 kPa were performed with initial relative densities of 20%-80%. The results indicated that despite their uniform properties, including size and grading, the two types of sand can differ in other properties as inherent interlocking, compressibility, stress-strain behavior, internal friction angle, changes in pore water pressure and stress path. For instance, Chabahar carbonate sand has more compressive potential than Firoozkooh sand because of the fragility of its grains. Moreover, the internal friction angle of carbonate sand is more than that of quartz sand. Quartz sand is more affected by initial relative density, whereas, carbonate sand is influenced by inherent packing.

Keywords: *Carbonate sand, Quartz sand, Shear behavior, Triaxial test.*

1. Introduction

Carbonate sands are known as problematic soils in civil engineering projects. The first problem concern with these soils occurred in 1961, during the installation of driven piles in Lavan Island of the Persian Gulf. During the pile driving process, a sudden free fall of the pile occurred [1].

Carbonate soils are defined as soils mainly derived from marine plants or animals, and are often composed of calcium carbonate compounds. Different origins and deposition conditions cause carbonate soils to have different characteristics [2, 3, 4]. Carbonate sediments are found in nature in many forms from non-cemented to cemented [5, 6].

The character of biogenic carbonate sands is quite different from that of quartz sands, yet our understanding of the monotonic and dynamic behavior of granular soils comes primarily from studies conducted on quartz sands of terrigenous origin. Conducting laboratory tests is an appropriate method to highlight the differences in terms of compressibility, volume changes, pore pressure changes and grain crushing during shearing, dilation, friction, and water permeation. Recent studies show that carbonate sands have larger inter-particle and intra-particle porosity, lower grain hardness, and a wider range of grain shapes compared to quartz sands [7, 8, 9, 10, 11, 12, 13, 14]. In addition, experimental researches show that carbonate sands mainly have higher compressibility, volume change, internal friction angle, and grain breakage than quartz sands [8, 15, 16, 17, 18, 19, and 20].

Carbonate grains generally have an angular, platy and needle shaped structure, whereas quartz grains are usually spherical and bulky. The stress among particles is greater on the platy and needle shaped grains, than the bulky grains of the same conditions. Volume change is therefore greater in carbonate soils due to grain abrasion and crushing [3, 4].

Studies associated with the crushing of the carbonate soils' particles are numerous. Many researchers reported that crushing reduces dilatant brittle behavior in favor of more contractive plastic shear response and maximum friction angles [12, 21, 22, and 23].

Several behavioral issues have been enumerated in previous literature for this type of soil without directly comparing it with quartz sand. Because the northern coasts

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of the Persian Gulf and Oman Sea contain carbonate soils, and because only few studies have been conducted on the soil of this region [20, 21, 24, 25], a carbonate sand sample has been chosen for comparison purposes in this research. A comparison between the shear behavior of the carbonate sand sample and a quartz sand sample of the same particle size distribution has been conducted using the consolidation and static triaxial undrained tests. The aim was to study the behavior of a type of carbonate sand, and assess the differences between carbonate and quartz sands.

2. Soil Characteristics

Two kinds of reconstitute carbonate and quartz sands have been used in this research. The used carbonate sand was obtained from Tang Port in the northern shore of the Oman Sea. Tang Port is a small port located 70 km west to the Port of Chabahar in the south eastern region of Iran. The Firoozkooh quartz sand was selected to compare the shear behavior of carbonate sand and quartz sand because it is a sand widely used in Iranian geotechnical researches (Fig. 1). The selected sample of the Firoozkooh sand was graded so it would have minimum difference with the Chabahar carbonate sand. After the sieving phase, some of the grains were removed from the sample in order to obtain the same particle size distribution with the Chabahar sand. Fig. 2 shows the particle size distribution of both sands (ASTM D422-63).

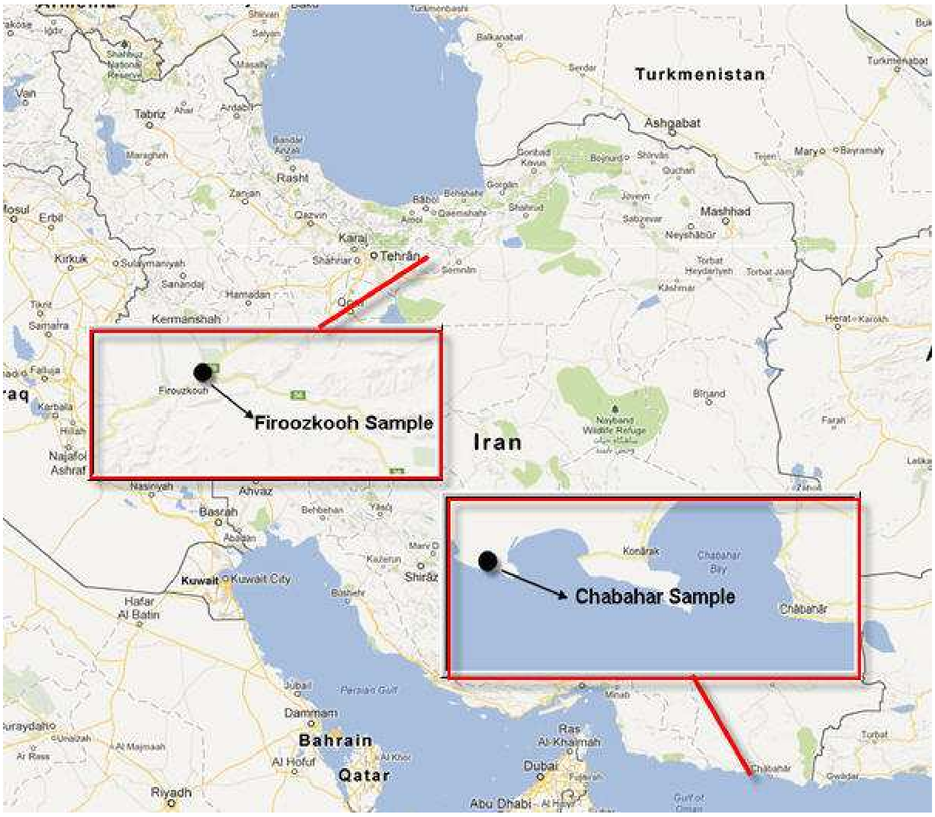

Fig. 1 The location of the studied soils

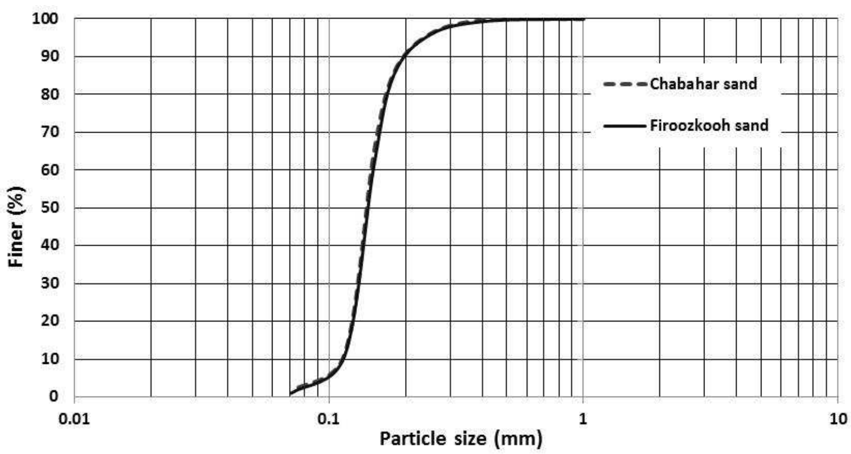

Fig. 2 Particle size distribution of sands

Since the carbonate calcium is known as an indicator in the shear behavior of carbonate sands [26], the equivalent carbonate content in sands was determined according to the BS-1377 standard (Table 1). This table also shows the other physical characteristics of the used carbonate and quartz sands such as specific gravity, minimum and maximum void ratio, coefficient of curvature and uniformity, and results of soils classification (ASTM D854). As seen in Table 1, the soil samples obtained from Chabahar and Firoozkooh are classified as extremely uniform sand by the Unified Soil Classification System (USCS). In order to determine the shape of soil grains, the electronic microscopic images (SEM) of the soils were prepared as well. Fig. 3a, b shows the electronic microscopic images of the aforementioned sands. According to Table 1 and Fig. 2, although these two types of sand have similar gradation and equal-sized grains, the maximum and minimum void ratios of Chabahar sand are approximately 13.5% and 20% more than those of Firoozkooh sand respectively. This emphasizes the significance of the geometry of grains on soil packing. Apparently, the diversity of the shape of grains of Chabahar carbonate sand prevents the soil from being compacted. Consequently, carbonate sands highly tend to create loose structures. As seen in Fig. 3a, Firoozkooh sand has voluminous grains with sharp corners and rough surfaces, while Chabahar sand is composed of a variety of planar grains with sharp corners and semi-spherical grains with relatively smooth surfaces. The illustration also shows a little bit of intra-granular and biological porosity.

Table 1 Physical properties of the sand studied

Sands	e_{max}	e_{min}	Cu	Cc	USCS	CaCo3 (%)	Gs
Chabahar	0.982	0.697	1.13	1.54	SP	46.7	2.72
Firoozkooh	0.865	0.580	1.13	1.54	SP	1.03	2.62

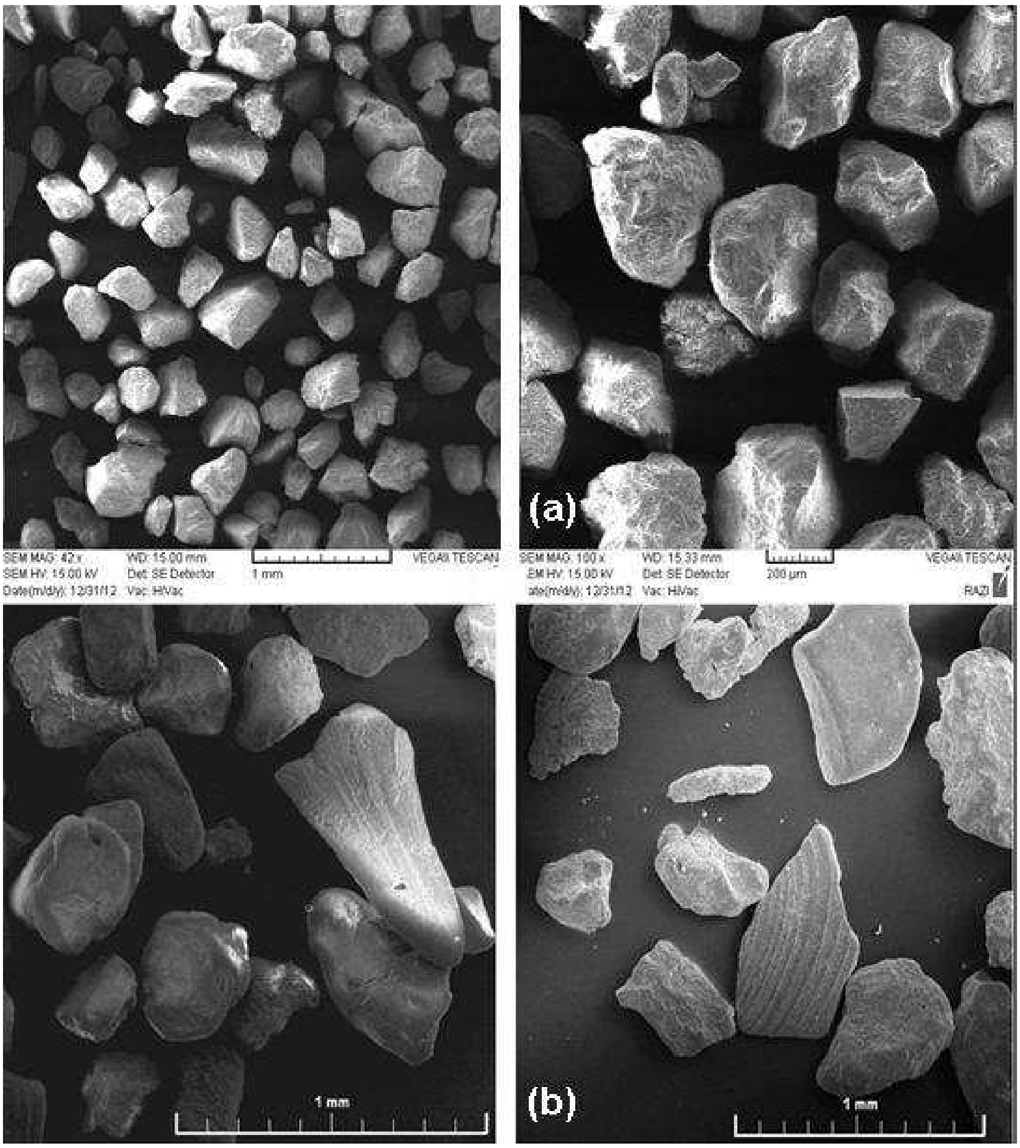

Fig. 3 Microscopic electronic image of sands: (a) Firouzkoh sand, (b) Chabahar sand

3. Test Programs

To compare shear behavior between the two sands, several one-dimensional consolidation and common triaxial tests were performed.

3.1. Consolidation tests

The compressibility of sands is usually tested using a one-dimensional or isotropic consolidation test. Consequently, 4 one-dimensional consolidation tests were performed on Firoozkooh and Chabahar sands in order to examine the compressibility of these sands (ASTM D2435). Two of the tests were performed on loosely packed samples with a relative density of 20%, and the other tests were performed on densely packed samples with a relative density of 80%. Cylindrical samples with 6 cm diameters and 2.5 cm heights were built on a layer using the dry deposition method. The samples were exposed to incremental loading caused by vertical stresses up to 4 MPa.

3.2. Triaxial tests

A total of 16 consolidated-undrained monotonic triaxial tests were performed (ASTM D7181-11). The samples were built with relative densities of 20% (earmarked with L in Table 2) and 80% (pre-consolidation) (earmarked with D in Table 2) using the dry deposition method. The cylindrical samples had diameters of 3.8 cm and heights of 7.6 cm. In order to obtain homogenous samples, the soil was divided into 3 layers. Each layer was separately cast with a specific weight ratio and was built by mild strokes of a plastic hammer on the sample mold. The samples were 95% saturated before the test. In order to accelerate the saturation of the samples, before allowing distilled water to pass the samples, they were targeted by carbon dioxide and were saturated under a back pressure of about 200 kPa. Experiments were carried out under confining stresses of 100, 200, 400 and 600 kPa. Table 2 summarizes the numbers and specifications of triaxial tests on the Chabahar (CH) and Firoozkooh (F) sands. In this table, each test is referred by a code.

Table 2 List of the triaxial performed tests

Test Code	σ_3	Relative Density	Sands
CHL100	100	20%	Chabahar
CHL200	200		
CHL400	400		
CHL600	600		
CHD100	100	80%	
CHD200	200		
CHD400	400		
CHD600	600		
FL100	100	20%	Firoozkooh
FL200	200		
FL400	400		
FL600	600		
FD100	100	80%	
FD200	200		
FD400	400		
FD600	600		

CH=Chabahar, F=Firoozkooh, L=Loose, D=Dense

4. Test Results

The results of the consolidation and triaxial tests are provided below separately. A comparison is also made between the test results.

4.1. Consolidation test results

Fig. 4a, b show the compressibility of dense and loose sands under one dimensional loading, as the void ratio is divided by the initial void ratio versus normal stress. As shown in these figures, the compressibility of loose carbonate sand is generally more than quartz sand under stressful conditions. The compressibility of dense samples is more analogous to the quartz sand, although by the end of the loading process, carbonate sand once again demonstrates a higher level of tendency towards contraction. This trend is more evident as stress is increased. When loose carbonate sand experiences vertical stresses of about 250 kPa, its compressibility is intensified; however, this trend begins under vertical stresses of about 2.5 MPa for dense samples. This behavior can be ascribed to the higher initial void ratio (Table 1) and fragility of carbonate sand grains, because carbonate sand grains have less stiffness (hardness of 3 for calcite and 7 for quartz on the Mohs scale) and weaker planar geometry (compared to volumetric geometry grains of quartz sand).

4.2. Triaxial stress-strain behavior

The deviatory stress $q = (\sigma_1' - \sigma_3')$ for the two types of sand under study is shown in Figs 5a, b, versus the axial strain. As seen in these figures, carbonate sands have generally more shear strength than quartz sands, both for dense and loose states. As expected, an increase in the values of initial density and confining stress leads to an increase in the maximum deviatory stress experienced by loosely and densely packed samples. The loosely packed samples of both types of sand show hardening behavior, while densely packed samples demonstrate softening behavior. Loose quartz sand strengthens at the beginning and then softens a little bit, and hardens again at the end. The sample under study, however, demonstrated a different behavior under confining stresses of 600 kPa as loose samples of carbonate sand showed very faint softening behavior at the end of loading.

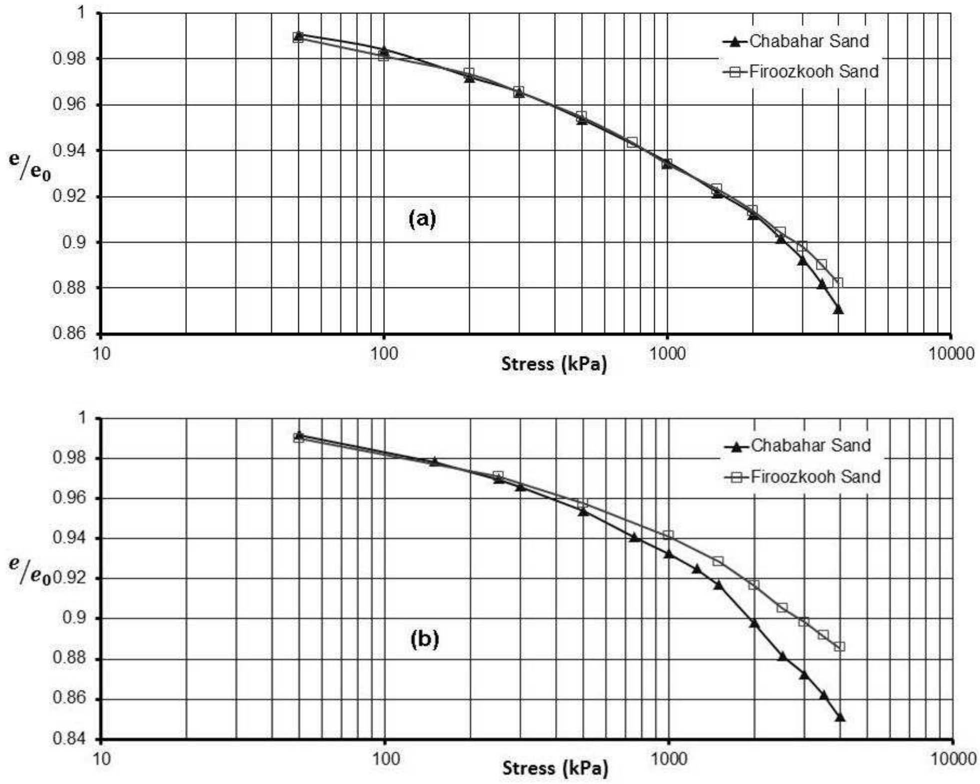

Fig. 4 Normalized void ratio versus normal stress: (a) densely packed samples, (b) loosely packed samples

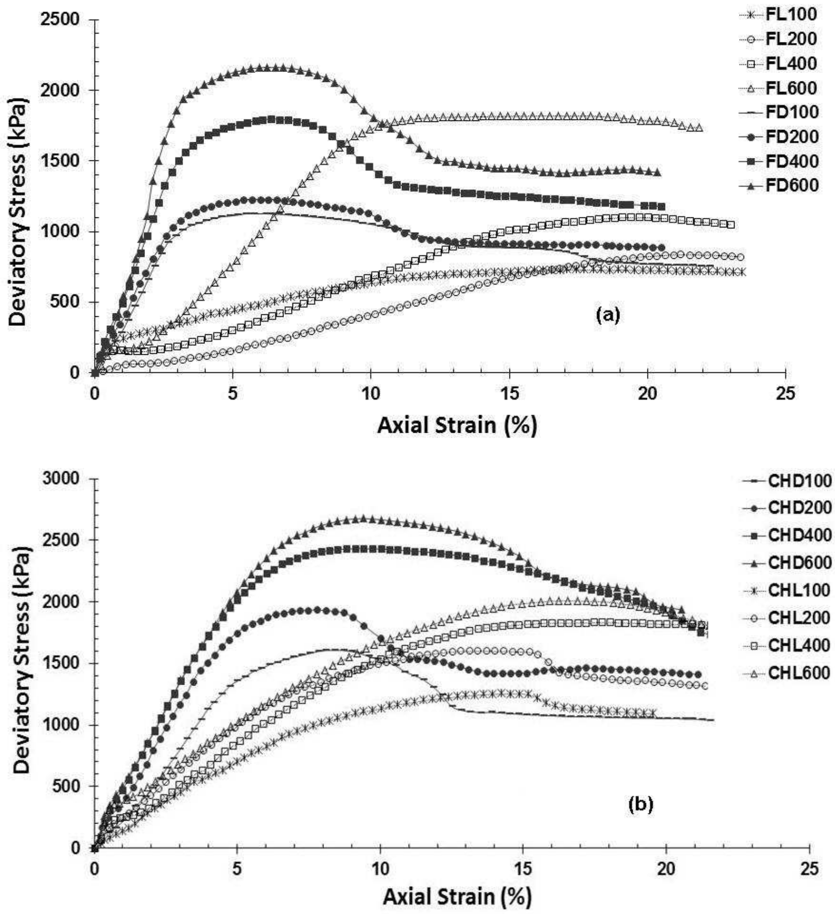

Fig. 5 Deviator stress versus axial strain: (a) Firoozkooh sand, (b) Chabahar sand

Fig. 6a provides the value of maximum shear strength (q) versus effective confining stress (p') at the peak point for both types of sand under loose and dense states. The maximum obtained shear strength of carbonate sand was more than that of quartz sand. The strength of loosely packed (Dr=20%) carbonate sand is in fact almost equal to the strength of densely packed (Dr=80%) quartz sand. This can be attributed to the special shapes of carbonate sands and the effect of an inherent interlocking of the soil, which yields a high level of strength even in the state of looseness. According to Fig. 6a, an increase in the effectiveness of confining stress leads to the growth of maximum shear strength of carbonate and quartz sands. In addition, a high level of confining stress reduces the increasing gradient of the Chabahar carbonate curve. Fig. 6b shows the values in Fig. 6a after normalization to the initial effective consolidation stress. This figure, which shows the failure envelope of the soil (Hvorslev surface), indicates that carbonate sands can generally absorb more stresses. In other words, when shear load is applied, pore water pressure variation (volume change tendency) takes place over a wider range in carbonate sand than quartz sand; so that even in a loose condition, carbonate sand exhibits a wider range of pore-water pressure variation and more effect of intrinsic interlock than the quartz sand in a dense condition. The resulted shear failure envelope for sands is presented in Table 3. Values of q and p' are independently calculated using Equ.1.

$$q = (\sigma_1' - \sigma_3') \;\; p' = (\sigma_1' + 2\sigma_3')/3 \tag{1}$$

Table 3 Failure envelope results for carbonate and quartz sands

Sands	Failure Envelope Equation
Chabahar Loose	$\frac{q'^{a}}{p_0'} = 1.62 \frac{p'^{b}}{p_0'}$
Chabahar Dense	$\frac{q'}{p_0'} = 1.84 \frac{p'}{p_0'}$
Firoozkooh Loose	$\frac{q'}{p_0'} = 1.46 \frac{p'}{p_0'}$
Firoozkooh Dense	$\frac{q'}{p_0'} = 1.66 \frac{p'}{p_0'}$

[a] $q' = (\sigma_1' - \sigma_3')$

[b] $p' = (\sigma_1' + 2\sigma_3')/3$

Table 4 Stress ratios (η_{PT}) of the present study sands and some other sands reported in literature

Reference	Relative density		Sands
	Dense	loose	
Hassanlourad et al. (2008)	1.52	1.46	Kish (carbonate)
	1.65	1.54	Hormoze (carbonate)
	1.73	1.68	Tonbak (carbonate)
	1.73	1.65	Rock (carbonate)
This study	1.31	1.1	Chabahar (carbonate)
	0.93	**0.67**	**Firoozkooh (quartz)**
Sharma and Ismail (2006)	1.51		Ledgepoint (carbonate)
	1.46		Goodwyne (carbonate)
Vaid and Chern (1988)	**1.2**		**Quartz sand**

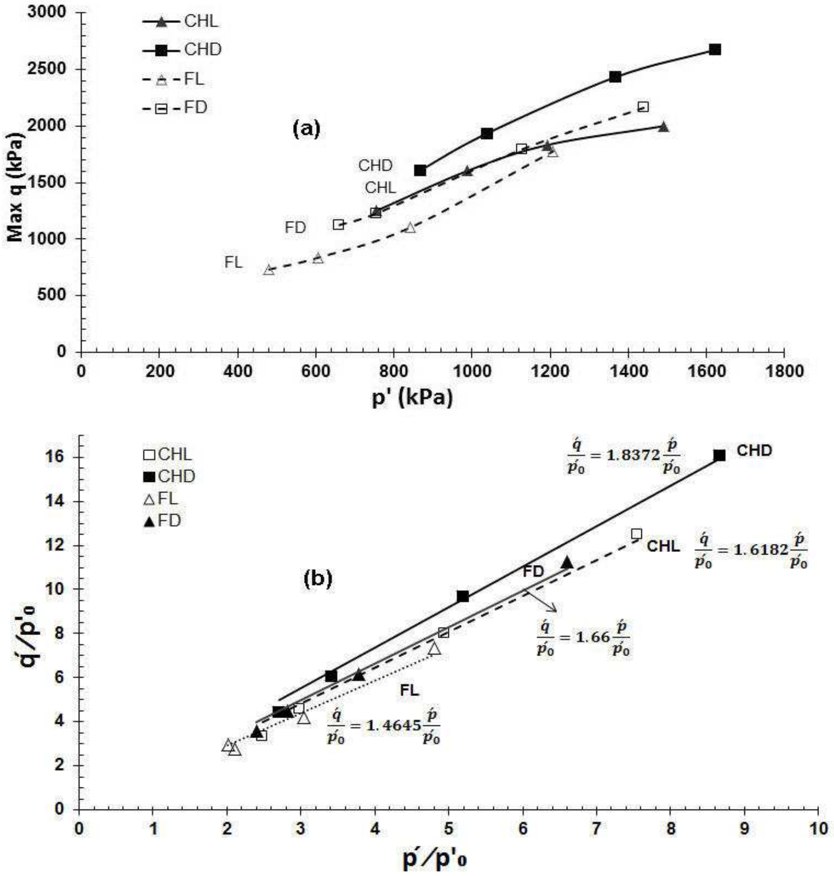

Fig. 6 (a) Maximum shear strength versus effective confining stress at peak point, (b) normalized shear strength versus effective stress to initial consolidation pressure

Fig. 7 shows the amount of strain at the peak point versus effective confining stress. According to this figure, in the state of looseness, mobilization of the maximum shear strength requires higher levels of strain. Also the strain equivalent to the maximum strength of quartz sand is more than that of carbonate sand. According to Fig. 7, it seems that the effect of an increase in the density of quartz sand is more severe than that of carbonate sand. In other words, the growth of density in quartz sand reduces the peak equivalent strain more than the carbonate sand does. Moreover, Fig. 7 implies that an increase in the effective confining of stress elevates the peak point strain in carbonate sand with more intensity when compared to quartz sand (about 2.5% to less than 1%).

Fig. 8 shows the discrepancy between the shear strengths (q) at the peak point and the end of the test (axial strain of 20%). As seen in this figure, in both states of looseness or denseness, the strength of carbonate sand is reduced more than the strength of quartz sand; however, an increase in the confining stress reduces the discrepancy between strengths of the two samples.

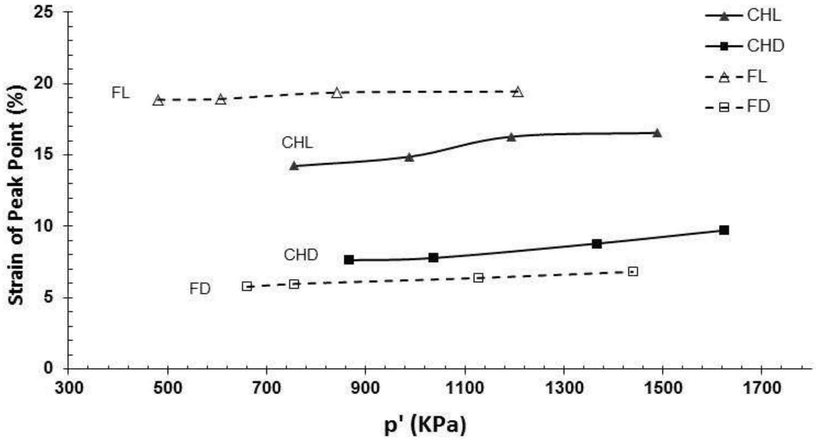

Fig. 7 Axial strain at peak point versus effective confining stress

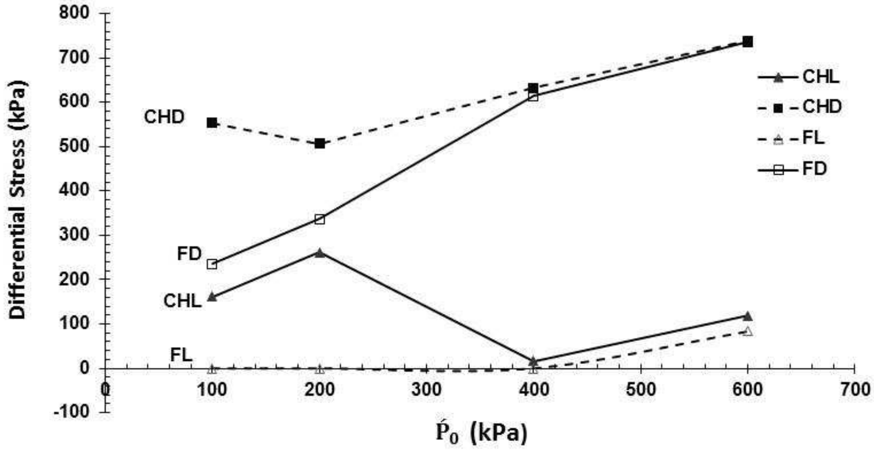

Fig. 8 The discrepancy between the shear strengths (q) at the peak point and end of the test (axial strain 20%)

4.3 Pore water pressure changes

Changes of excess pore water pressure are dependent on the volumetric behavior of sands. Factors affecting the volumetric behavior of sands include: particle size distribution, initial relative density, confining stress, geometry and stiffness of grains, and type of constituent minerals. Particle size distribution of Chabahar carbonate and Firoozkooh quartz sands are the same, while other characteristics of these sands differ from each other. Therefore, these two types of sand are expected to show different volumetric behaviors under different pore water pressures. Changes of excess pore water pressure in these sands are shown in Fig. 9a, b. As seen in these figures, when axial strain acts, both sands show a contractive behavior and induce positive pore water pressure at the beginning. Afterwards, they show dilative behavior and induce negative pore water pressure. This behavior is seen in both loose and dense sand samples. Reduction in the initial density and an increase in the confining stress levels lead to an increase in the contraction and a decrease in the dilation portion of the sands. In addition, loose samples show a volumetric behavior similar to dense samples; however, the volumetric behavior of the sands differs in the loose samples and induces a smaller negative pore water pressure under the same amount of confining stress. Nevertheless, the resultant behavior of all samples was found to be negative pore water pressure at the end of the tests. The question that may be raised is: Why do the loose samples show dilative behavior? To answer this question, it can be argued that loose samples show dilative behavior because of the uniformity of their particle size distribution. Uniformly distributed sands, or sands that are not properly graded show less contraction as they are sheared.

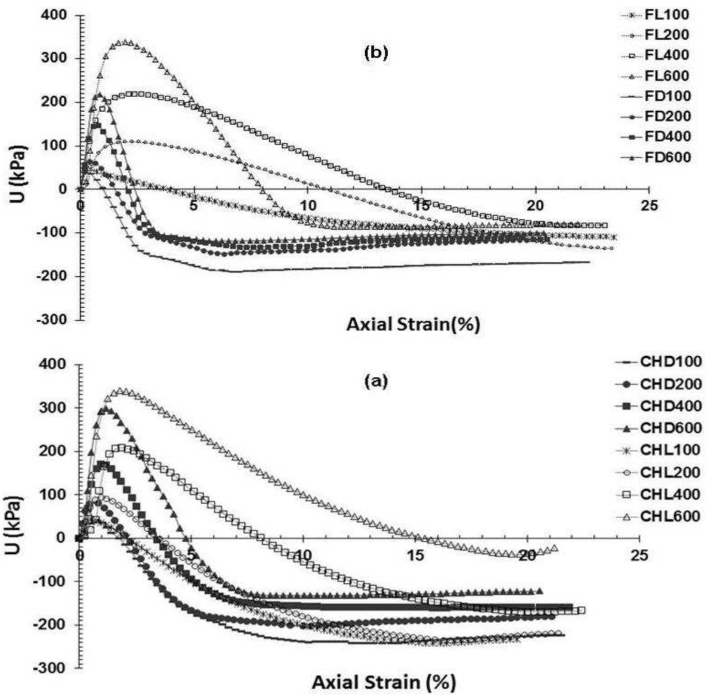

Fig. 9 Changes of excess pore water pressure versus axial strain: (a) Firoozkooh sand, (b) Chabahar sand

An analysis of pore water pressure changes on densely packed quartz and carbonate sands indicates that carbonate sand tends to generate more positive and negative pore water pressure than quartz sand (Fig. 10a); however, loose samples show a slightly different behavior. It can be explained that carbonate sand tends to induce more negative pore water pressure up to maximum confining pressure of 400 kPa, while quartz sand tends to induce more negative pore water pressure under confining pressure of 600 kPa (Fig. 10b). This reflects the dominating effect of inherent interlocking on the carbonate sand; however, excessive confining stress (600 kPa) can probably crush the grains of loosely packed carbonate sand and negate the effect of interlocking.

4.4 Stress path

In Fig. 11a, b the stress paths $(p'-q)$ of carbonate and quartz sands are shown for the loose and dense states. As seen in Fig. 11, the difference between the stress paths in loose and dense quartz sands is more than that of carbonate sands. As the relative density increases, the effect of confining stress applied to quartz sand becomes more evident than in carbonate sand. Regarding the carbonate sands it can be mentioned that at the beginning of stress path, loose and dense samples show contrary behavior and it seems that the samples are misplaced; however, the behavior of the samples is correct along the stress path. Apparently, the effect of relative density on carbonate sand is negated because of an inherent packing and perhaps particle breakage. Hence, the stress paths of loose and dense samples of carbonate sand are more alike than those of quartz sand. In other words, carbonate sand has a tendency to show dilative behaviors even in a state of looseness.

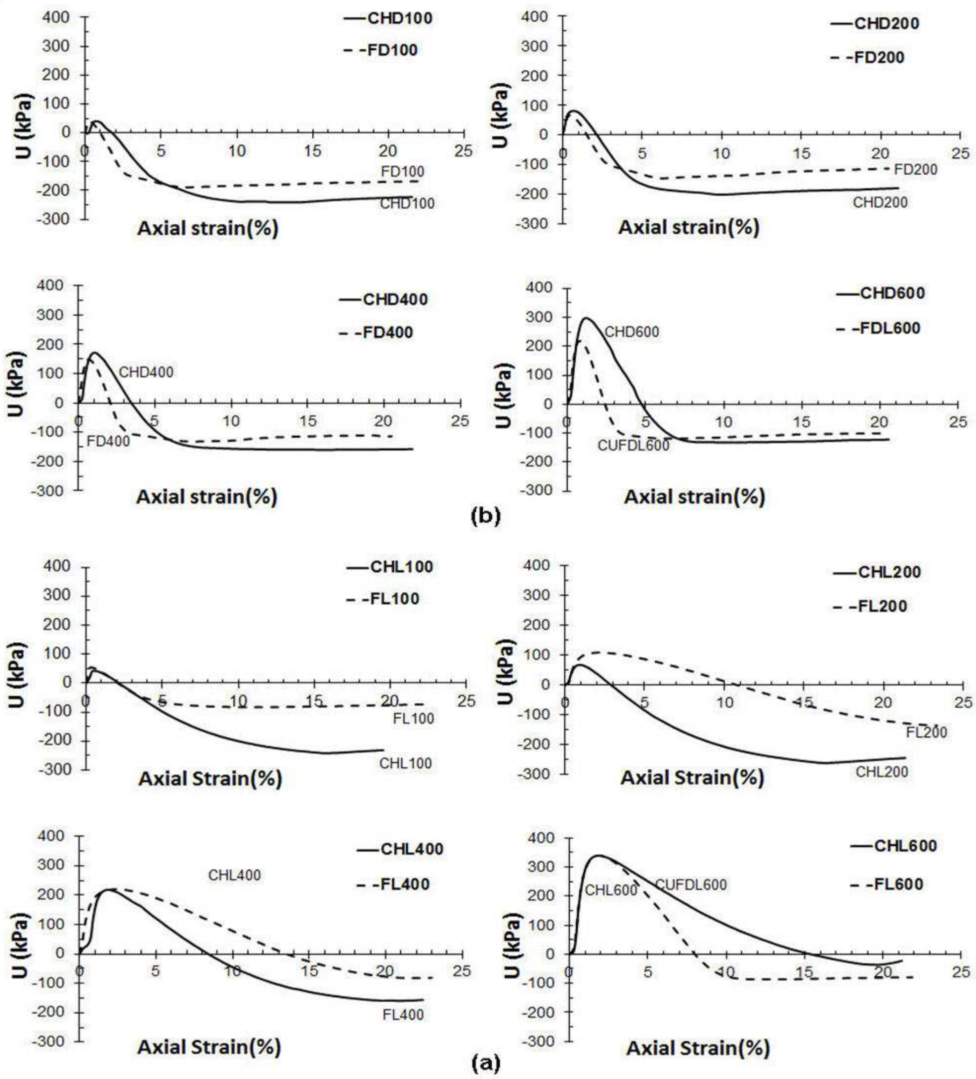

Fig. 10 Changes of excess pore water pressure versus axial strain: (a) densely packed samples, (b) loosely packed samples

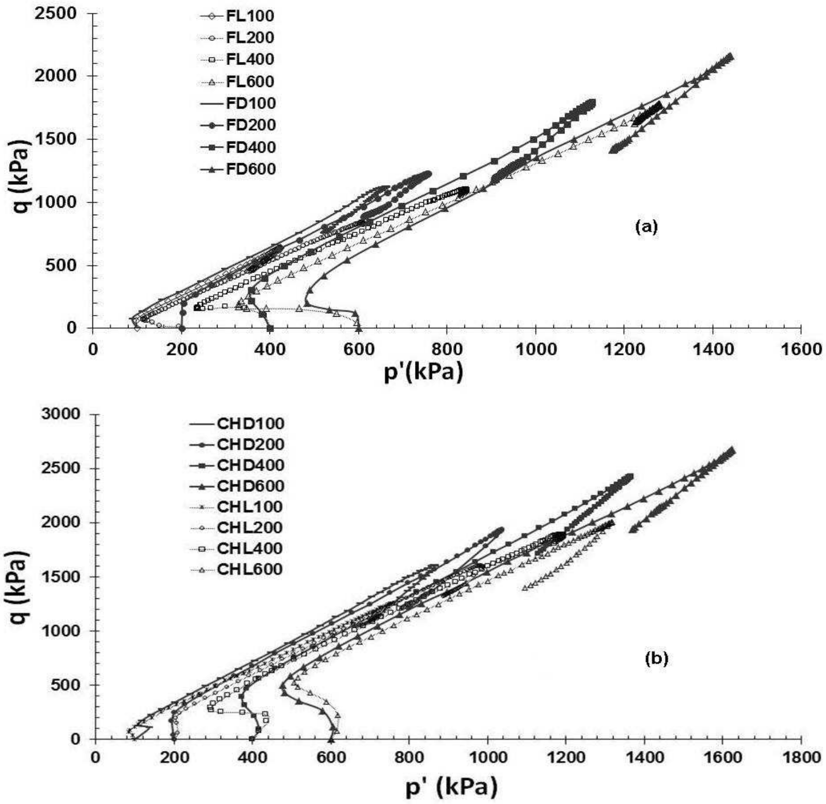

Fig. 11 Stress path of the studied sands: (a) Firoozkooh quartz sand, (b) Chabahar carbonate sand

4.5 Effective internal friction angle

In order to compare the undrained shear strength differences of carbonate and quartz sands, the effective internal friction angle, which is determined by measurements of pore water pressures during testing and effective stress calculations, has been evaluated for both sands.

Fig. 12 shows effective internal friction angle (ϕ') versus average effective confining stress (p'). As expected, the effective internal friction angle of carbonate sand is more than that of quartz sand. An increase in the confining stress leads to a decrease in the internal friction angle of both types of sand. The internal friction angle of loosely packed carbonate sand (relative density of 20%) is almost equal to densely packed quartz sand (relative density of 80%). That is to say, the inherent interlocking of carbonate sand is as effective as the 60% increase in the relative density of quartz sand. On the other hand, internal friction angle of the Chabahar carbonate sand is tighter than carbonate sands found in other parts of the Persian Gulf [19, 22, 23]. This can be ascribed to the uniform gradation of the Chabahar carbonate sand compared to carbonate sands obtained from other parts of the Persian Gulf. In addition, the internal friction angles of both densely and loosely packed samples of Chabahar carbonate sand are more than those of Firoozkooh quartz sand.

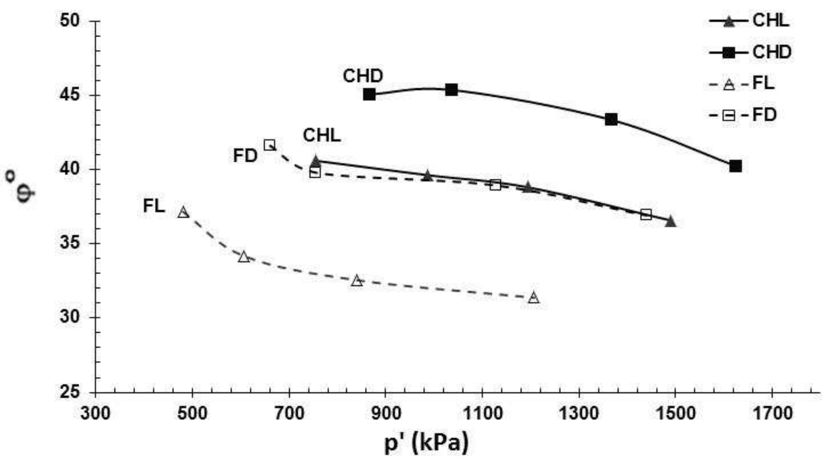

Fig. 12 Effective angle of internal friction versus average effective confining stress

In general, the angle of internal friction is made up of inherent internal friction, dilation, and grains breakage [21, 27]. In undrained testing, the dilation parameter is omitted ($\varepsilon_v = 0$) while the other two parameters are taken into account. Since the stiffness of carbonate sand grains is less than that of quartz sand, it experiences more breakage. Therefore it can be argued that some parts of the internal friction angle of carbonate sand are related to particle breakage, while others to inherent friction.

4.6 Phase transformation point

Phase transformation point is the point at which contractive behavior is replaced by dilative behavior. In other words, at this point the tendency towards positive pore water pressure is shifted to negative pore water pressure. This point is equivalent to the highest positive pore water pressure in the curve associated with the changes of pore water pressure. The variation of (U/P') versus initial confining stress for the points on the phase transformation line are shown in Fig. 13. According to these diagrams, the amount of positive pore water pressure exerted on loosely packed samples is greater than the densely packed samples of any of the two kinds. The amount of positive pore water pressure for carbonate sand in a dense state is more than that of quartz sand. Nonetheless, in a loose state, this trend is inversed and the amount of positive pore water pressure for carbonate sand becomes less than that of quartz sand. As was mentioned earlier, this suggests that the effect of relative density on quartz sand is more than carbonate sand. In other words, this indicates that the inherent interlocking of carbonate sand is more effective than that of quartz sand. An increase in the confining stress exerted on loosely and densely packed carbonate sand leads to an increase in the stress ratio (U/P') at the phase transformation point; however, the result of this ratio is almost equal in both states for quartz sand. That is to say, an increase in the initial confining stress does not change the result of ratio for quartz sand.

Fig. 14 depicts the changes of ($\eta_{PT} = q/p'$) versus confining stress. According to this figure, even in the state of looseness, carbonate sand has a larger stress ratio than densely packed quartz sand (about 1.6 times). Sharma and Ismail [5] analyzed the behavior of undrained Goodwyne and Ledge point carbonate sands and stated that the stress ratio ($\eta_{PT} = q/p'$) of carbonate sands at the phase transformation point is more than that of quartz sands. This implies that the cyclic strength of carbonate sand is more than that of quartz sand [28]. The average stress ratios ($\eta_{PT} = q/p'$) of the aforementioned sands and other types of sands are given in Table 3.

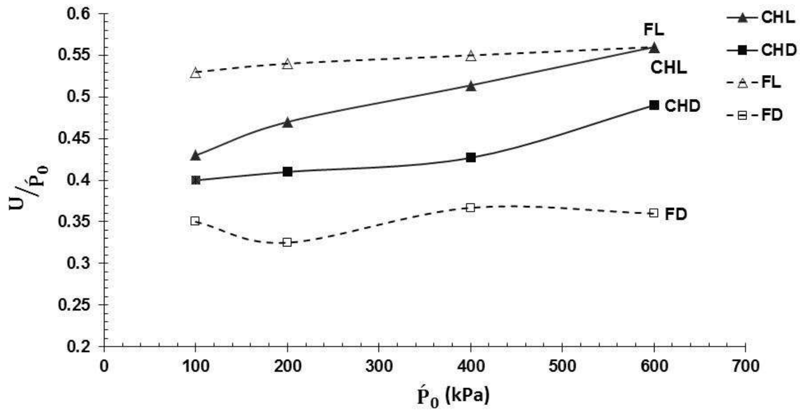

Fig. 13 The changes of (U/P') ratio at the phase transformation point versus initial confining stress

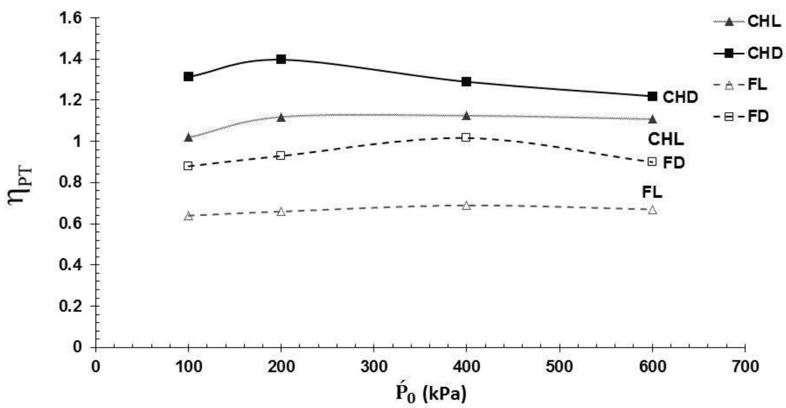

Fig. 14 Stress ratio (η_{PT}) at the phase transformation point versus initial confining stress

5. Conclusion

Using the consolidation and triaxial tests, this research studied the compressibility and consolidated- undrained shear behavior of two kinds of quartz and carbonate sands that had the same particle size distribution, initial relative density, confined pressure, and different particle shapes and mineralogy. Results of the aforementioned tests are as follows:

1. The minimum and maximum void ratios of carbonate sand were 20% and 13.5% more than those of quartz sand. The specific gravity of carbonate sand was approximately 3.8% more than that of quartz sand. This reflects the porous structure tendency of carbonate sand due to its planar shape of grains.
2. The one-dimensional consolidation test showed more compressibility of carbonate sand compared to quartz sand, especially in the loose state. This can be attributed to the fragility of the carbonate sand grains. However, a slight difference was observed between densely packed samples. This indicates that carbonate sand has more potential for settlement than quartz sand, especially in the state of looseness.
3. In the triaxial tests, carbonate sand illustrated more shear strength than quartz sand. Furthermore, the post-peak decline in the strength (strain softening) of carbonate sand is more than that of quartz sand.
4. Due to the uniform particle size distribution of sands under study, the behavior of the two sands were contractive (positive pore water pressure) at the beginning and were dilative (negative pore water pressure) afterwards. The range of pore water pressure changes (from positive pressure at the phase transformation point to negative pressure at the end of the test up to axial strain of 20%) in carbonate sand was wider than that in quartz sand, although this trend was somewhat defied in loose state.
5. The discrepancy between the stress paths of dense and loose samples of carbonate sand was less than that of quartz sand. This confirms that the effect of soil density on carbonate sand is less pronounced.
6. The effective angle of internal friction of carbonate sand was approximately 5 degrees more than that of quartz sand. An increase in the confining stresses leads to a reduction in the angle of internal friction of both sands. Moreover, results of the tests indicated that the angle of internal friction of the loosely packed carbonate sand with an initial relative density of about 20% was almost equal to the angle of internal friction of quartz sand with a relative density of 80%. This may be because of the planar and needle shapes of carbonate sand grains and an inherent interlocking.

The ratio of shear stress to confining pressure of carbonate sand at the phase transformation point was obtained to be 1.5 times more than that of quartz sand. This shows that carbonate sand has a higher level of cyclic strength.

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