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Effects of Texture and Carbonate Content on Internal Friction Angle for Soils of Northern Coasts of Persian Gulf

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Abstract

The present work is conducted to investigate the effect of texture and carbonate content on internal friction angle of carbonate soils. Carbonate soils are majorly found in the bed of shallow waters and also offshores in tropical regions. Recently there is a huge construction projects including oil and gas extraction platform and facilities, harbors, refineries, huge bridges and other big construction projects in many offshore and onshore areas around the world. One of these area is located on southern part of Iran. We collected soil samples from different parts of northern coasts of Persian Gulf, then the following experiments were performed, carbonate content, three-dimensional grain size, angularity, relative density & direct shear. The results showed that the average of internal friction angle of carbonate soil is higher respect to known silicate sands. This angle is affected by effective grain size, grain angularity, and calcium

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carbonate content. Based on the experimental results of this study, one of the results was that the internal friction angle of carbonate soils decreases as their effective size of soil aggregates increases.

Keywords: Internal friction angle; shear strength, Carbonate soils; Soil texture; Calcium carbonate content

Introduction

The bulk shear strength of soils is their internal strength in a unit surface area that resists against slip or failure of any internal plain. To analyze soil stability problems such as bearing capacity of shallow or deep foundations, slope stability, and lateral pressures on the retaining structures, it is necessary to have a comprehensive understanding of the shear strength nature. According to Mohr [1], material failure is controlled independently by neither maximum normal stress nor maximum shear stress; rather, a critical combination of these two factors as the relationship between shear strength and normal stress in the failure surface which is described in Eq. (1);

$$\tau_f = f(\sigma) \tag{1}$$

Where, τ_f is a shear strength, σ is normal stress. For most of the soil mechanics problems, the shear strength of failure surface can be accurately considered as a linear function of normal stress. This function is defined by Eq. (2) as the Mohr-Coulomb [2] failure criterion:

$$\tau_f = c + \sigma \tan\phi \tag{2}$$

Where, ϕ is internal friction angle, and c is soil cohesion.

Carbonate soils are classified as natural carbonate sediment of the continental crust that is formed in tropical climates in the continental plateau. The experimental results of triaxial tests on carbonate soil samples reveal that the shear strength angle is relatively high ($\phi > 45$) at low pressures, which decreases with an increase in the confining pressure (Vafaeian [3]). This finding can be expressed using Eq. (3);

$$\phi = a - b.\log\sigma'c \tag{3}$$

Where, σ'c is the confining pressure (kPa). Besides, a and b are the constant experimental values for the sands which are defined for the soil of the Bass Strait in Australia as following;

For Dr =50%	a=54	b=4.3	Poulos & Chua [4]
For Dr =78%	a=57	b=5	Poulos & Chan [5]
For Dr =85%	a=49.4	b=3.7	Poulos & Chua [4]

For the samples in North Ranking site in platform A of Austrian costs, Douri and Poulos [6] proposed Eq. (4):

$$\phi = 46.8 - 0.02\sigma'c \tag{4}$$

Where, σ'c varies between 0.1 and 0.4 MPa.

Hasanlourad et al. [7] studied the behavior of uncemented and cemented carbonate sands under shear load in Kish, Tonbak, Hormoz, and Rock Islands (south of Iran). Based on the results of monotonic triaxial tests conducted under constant conditions for different samples, various shear behaviors were monitored. They presented the internal friction angle (ϕ) of carbonate soils under confining pressures of 50-600 kPa on two loose and compacted conditions as in table 1.

Das [8] reported the ϕ for silicate sands under loose, medium and dense conditions for rounded and angular grains as written in table 2.

Baziar and Salehzadeh [9], show the variation range for ϕ of silicate sands with different relative densities (Figure1).

Table 1. Internal friction angle of uncemented carbonate soil under different confining pressures for loose and dense conditions (Hasanlourad et al. [7]).

Sand	Kish		Tonbak		Hormoz		Rock	
σ_3 (KPa)	loose	dense	loose	dense	loose	dense	loose	dense
50	44	46.76	45.4	51.26	46.87	52.88	45.6	52.77
100	44.04	47	44.2	49.2	44.6	50.11	45.6	50.45
200	42.24	45.29	-	-	43.26	47.89	43.9	47.79
300	41.72	44.52	43.33	47.17	42.77	45.99	42	45.58
400	41.88	43.4	-	-	42.42	44.52	40.32	43.48
500	41.24	43.19	41.4	44.38	41.07	43.4	39.18	42.48
600	40.54	42.35	40.16	43.3	40.78	42.43	38	41.4

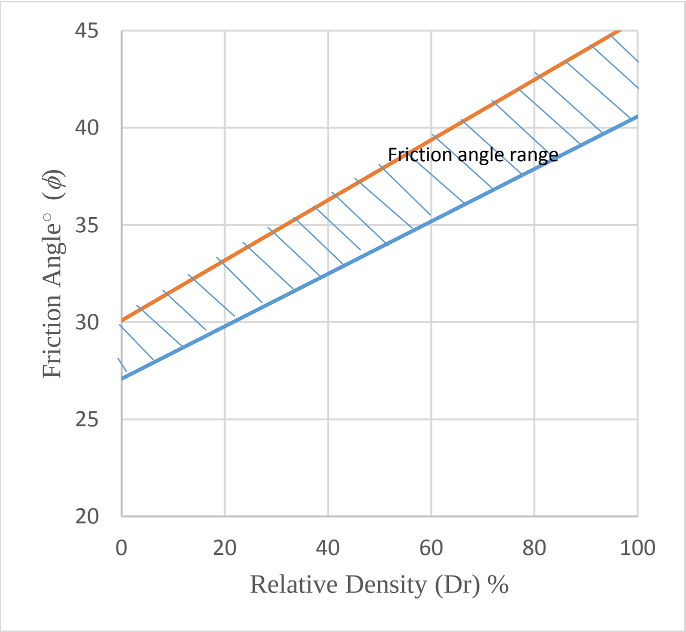

Figure 1. Internal friction angle range of silicate sands for different relative densities (Baziar and Salehzadeh [9])

Table 2. Internal friction angle for silicate sands for rounded and angular grains for loose, medium and dense condition (Das, [8]).

Soil Type	ϕ
Rounded Sand	
loose	27- 30
medium	30- 35
dense	35 - 38
Angular Sand	
loose	30 - 35
medium	35 – 40
dense	40 - 45
Gravel with Sand	34 - 48
Silt	26 – 35

Compared to silicate sands, carbonate sands possess some special features. Although, they have a slightly higher specific unit weight than silicate sands, they have high porosity due to the presence of intergranular and intragranular pores. This is the reason why they have a relatively lower dry densities compare to silicate sands (Vafaeian [3]).

In terms of their origin and engineering behaviors, carbonate soils are also different from silicate soils. Considering their origin, these soils are the remnants of sea creatures, have a chemical origin, or physically transported to the sedimentary environment. The most important feature of these soils is their grain fragility against the applied loads depending on the shape of their grains and intergranular pores. The fragmentation and the induced volume change poses some negative issues in engineering structures such as piling and foundations. However it should be noted that particle breakage of carbonate sand particles happen in different confining pressure based on their geological and geographical condition. In some cases particle breakage may happen under confining pressure of higher than 1Mpa (Shahnazari and Rezvani [10]). So far, some unusual feature of foundations and their poor performance have been reported in carbonate soils (API [11]). Usually carbonate soils are defined as soils containing a considerable share of carbonate compounds (CO_3 > 50%). Four major characteristics were introduced for carbonate soils in the First Australian Carbonate Sediment Conference (Semple [12]): 1) Each grain is mainly a part of bioclasts and has weak material; 2) Cementation degree is considerable varying in these soils; 3) Generally, because of their high intergranular and intragranular porosities and fragility, these soils have high compressibility; and 4) The grain type, grain size distribution, cementation degree, and mechanical properties such as strength, compressibility, and permeability in these soils vary in short distances, where these variations are significance in behavior prediction of geotechnical structures. Due to the high diversity of these soils in different parts of the world, different behaviors are reported and no comprehensive information is available for them. Most of the research works conducted on these soils are in African coasts, Mexic, Philippine, Australia, India, North Sea, Persian Gulf and South China Sea. In this regard, the first practical work about these soils was performed in 1965 Lavan Island (McClelland [13]).

According to previous studies (Golightly and Hyde [14], Hull et al. [15], and Shambhu et al. [16]) it is known that the corresponding ϕ of bioclastic sands with peak shear strength is higher than that of

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quartz soils. Moreover, it is reported that ϕ' decreases with an increase in confining pressure for both quartz soils (Vesic and Clough [17]; Bolton [18]) and carbonate soils (Airey et al. [19]; Poulos et al. [20]; Datta et al. [21]).

Salehzadeh and Ghazanfari [22] studied undrained and drained shear behavior of carbonate soils of Kish Island of Persian Gulf of Iran and reported that for the increasing of confining pressure, the decrease in shear strength for loose specimens is greater than that for denser specimens. Shahnazari, and Rezvani [10] studied the effect of different parameters on carbonate sand crushing in Hormoz Island and Bushehr Port using the monotonic triaxial tests under both drained and undrained conditions.

The present study was conducted to investigate the effect of texture (grains shape and size) and carbonate content on shear strength of carbonate soils in northern coasts of Persian Gulf. The shear strength of more than 50 sand samples was measured using direct shear test. Carbonate soil samples were collected from some coasts and southern islands of Iran. Grain size distribution (sieve test), determination of calcium carbonate content, relative density, specific bulk, measuring grains length, width, and thickness, and finally, direct shear tests were also carried out in the present study. As mentioned before carbonate sands have a wide range of geotechnical engineering indexes and parameters (such as shear strength) regarding their geographical location. This fact is an obstacle in front of people who try to develop different engineering

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structures in offshore or onshore areas which their soils is carbonate sand. Results of research will help them to have a better knowledge on shear strength of these soils.

Direct shear test apparatus

Direct shear tests apparatus was used in the present study. The size of specimen was 100mm×100mm and the tests were conducted according to ASTM D: 3080-90.

Sampling and index tests

Soil samples were collected from different parts of northern coasts of Persian Gulf such as Bandar Abbas, Bushehr Port, and Qeshm, Hormoz, and Hengam Islands, where a large number of construction activities is undergoing (Figure 2). All samples were un-cemented and collected in disturbed condition from shallow depth (less than 1m). After performing different index tests such as mechanical grain size distribution, calcium carbonate concentration, specific bulk, relative density some other tests were conducted to determine grain morphology conditions (spherical, plate, needle, and blade form). The further investigations were conducting about 50 direct shear tests on specimens.

Sieve analysis was carried out using the sieves with standard sizes (ASTM D421, D422) for all soil samples. According to the Unified Standard Soil Classification (USCS), the collected soils typically are poorly graded coarse, average, and fine sands (sp). The soils samples also consist of aggregates larger than 4.75 mm. The soil samples had natural aggregates with different grain sizes (0.5-12 mm). To evaluate the different effects of aggregate size, six groups (Table 3) of samples were prepared with selected particle sizes. The range of particle size in these 6 samples were narrower than the original samples by selecting aggregates only between two consecutive sieves (e.g., sieves 8# and 16#)

Figure 2. Map of Hormoz strait in Persian Gulf and sampling location of carbonate soils

Table 3. Specification of samples with selected gradation curve

Sieve No.					
< 16	16 - 8	8 - 4	4 – ¾″	¾″ – ½″	200 - 4
					Sample 6
				Sample 5	
			Sample 4		
		Sample 3			
	Sample 2				
Sample 1					
< 1.18	1.18- 2.36	2.36-4.75	4.75- 9.5	9.5- 12.7	.075-4.75
Aggregates Size (mm)					

The calcium carbonate content of the soil specimens was determined using the Bernard Calcimeter instrument (Pansu &

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Gautheyrou [23]). To precisely measure carbonate calcium ($CaCO_3$) content in these soils, using a ceramic mortar, the soil samples were ground as a fine-grained powder (smaller than sieve #200). 1 mol. of pure calcium carbonate which is 100.0872 gr can produce 22.4 liter of CO_2 gas when reacted with sufficient amount of hydrochloric acid (Eq. (5)). Using the Bernard Calimeter, 1.0, 0.5, and 0.25 gram of pure calcium carbonate sample were mixed with hydrochloric acid and the volume of released gas was measured. Then, an equivalent amount of the calibrated weight (0.25 gr) of the carbonate soil was prepared and tested. Again, the volume of the released gas was measured. In this way, the carbonate calcium content of each soil was determined.

$$CaCO_3+2HCl \longrightarrow CaCl_2 + CO_2 + H_2O \tag{5}$$

The results showed that calcium carbonate content of the collected samples varies from 45% to 95%.

The specific bulk of the samples was measured using the powder under sieve #200. The carbonate soils have different levels of intra granular pores leading to high errors in measurements unless the air bubbles are removed from them. The specific bulk of the collected samples was within 2.65 to 2.8 while it is 2.63 to 2.67 for silicate sand. This result seems reasonable considering the specific bulk of calcite mineral (CaCO3) and quartz mineral (SiO2) which is 2.7 and 2.65, respectively.

In this research the shear strength and Internal friction angle of all samples were studied for different specimen at medium relative density (D_r) of 50%. The minimum and maximum dry density (γ_{dmin} & γ_{dmax}) of all samples were measured in accordance with (ASTM

D4254, D4253). Target medium relative density was calculated by Eq. (6);

$$Dr_{50}\ \% = \frac{\gamma_{d50} - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}} * \frac{\gamma_{dmax}}{\gamma_{d50}} \tag{6}$$

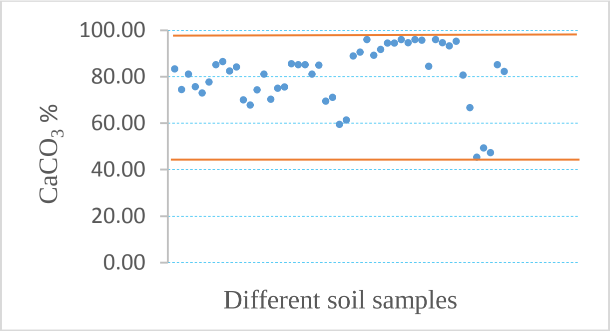
Calculated dry density of different soils (γ_{d50}) was between 0.73 to 1.7 gr/cm^3. The minimum γ_{d50} (0.727 gr/cm3) was for carbonate soil of Hormoz island with grain size of 9.5- 12.7 mm, 75% $CaCO_3$ and the specific bulk of 2.76. The maximum γ_{d50} (1.70 gr/cm3) was for carbonate soil of Qeshm island with grain size of less than 1.18 mm, 85% $CaCO_3$ and the specific bulk of 2.70 . The results of index tests are shown in Figure 3.

Figure 4 illustrates scanning electron microscopy (SEM) images of a carbonate soil sample. As shown in the figure, the grains of these soils have angular corners and rough surfaces where the diameter and depth of pores at higher magnifications prove such rough surfaces that are effective in the increased ϕ of the carbonate soils.

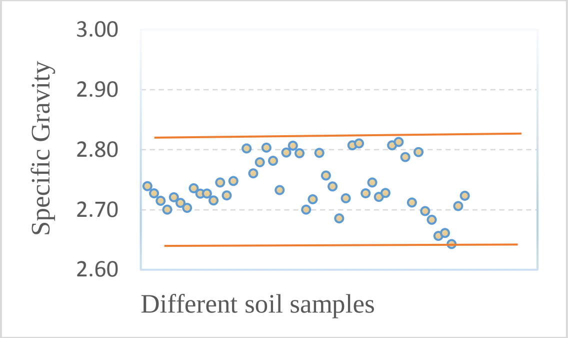
Shape index determination

One of the main parameters which describes the texture of aggregate is shape index. In this regard, grains are classified into four groups: spherical, planar, needle-form, and blade form particles (Tucker, [24]). The shape index which proposed by Hashemnejad et al. [25] as in Eq. (7), is the sum of length-to-width (L/W) and length-to-thickness (L/T) ratios:

$$\text{shape index} = \frac{L}{W} + \frac{L}{T} = L\left(\frac{T+W}{W*T}\right) \tag{7}$$



a)



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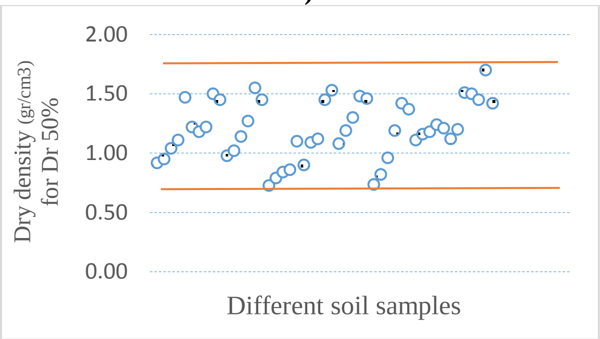

c)

Figure 3. a) Carbonate calcium content; b) specific bulk; c) dry density of the collected soil samples at Dr = 50%.

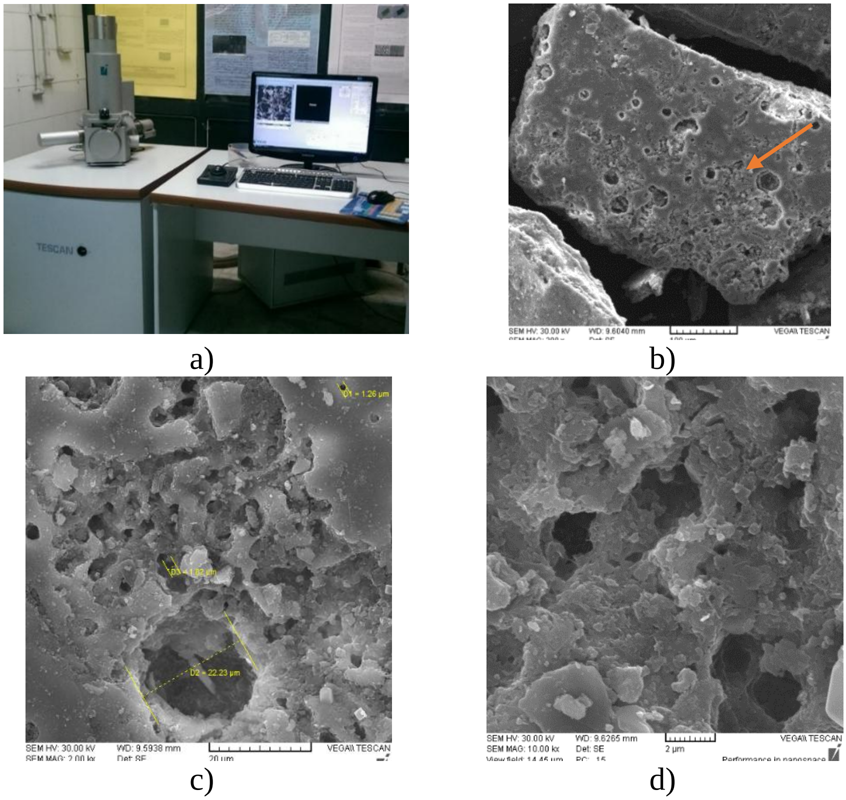

Figure 4. Illustrations of a) Scanning electron microscopy (SEM, TESCAN); Hormoz aggregates < sieve 16, b) rough surface of aggregate magnified up to 300×; and c) aggregate surface magnified up to 2000× with a cavity diameter of 22.23 μm. d) Aggregate surface magnified up to 10000×

Where, L, W, and T are the length, width, and thickness of each aggregate, respectively. According to the shape index classification by Tucker, [24] and shape index equation (7) it can be concluded that for a spherical grain, shape index is 2 while for needle samples this index would be very larger than 2. Shape index determination of the grains was carried out by three-dimensional measurements of each aggregate using Eq. (7) and shown in Figure 5. The minimum and maximum shape indexes of the collected samples were in range of 2 to 9, respectively.

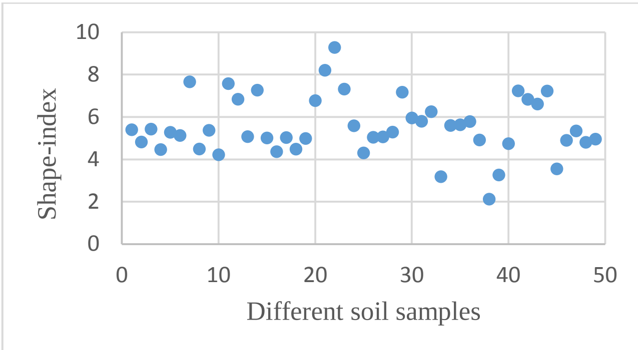

Figure 5. Shape index of the collected soil samples.

Determination of effective grain size

Size of aggregate is another parameter which describes its texture. Hashemnejad et al. [25] proposed Eq. (8) to define effective (dominant) grain size for each soil:

$$\text{Effective size} = 0.1\left(\frac{d_{min}+D_{10}}{2}\right) + 0.2\left(\frac{D_{10}+D_{30}}{2}\right) + 0.3\left(\frac{D_{30}+D_{60}}{2}\right) + 0.4\left(\frac{D_{60}+d_{max}}{2}\right) \quad (8)$$

Where, D_{10}, D_{30}, and D_{60} are the diameters of grain size less than 10, 30, and 60%, respectively. Besides, D_{min} and D_{max} are the minimum and maximum grain sizes. For six categories of soil which are described in Table 3, the effective size was calculated using Eq. (8). The results of sieve test shows that aggregates of all specimens had the minimum and maximum effective grain sizes of 0.5 and 6.5 mm, respectively (Figure 6).

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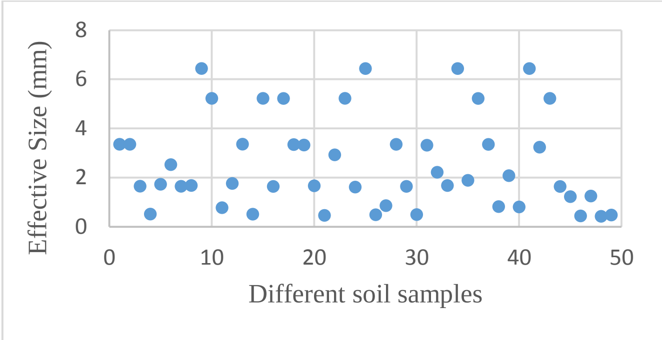

Figure 6. Effective grain size of the soil samples.

Determination of aggregate angularity

Aggregate angularity of specimens was also investigated as a parameter which describes texture. Using the aggregate images in JMicrovision software, the angularity of each soil group is determined. The radius of the sharpest corner was measured for each grain. Then, the radius of the largest circle inscribed in the grain was determined using the software. Finally the mean grain angularity was estimated using the output of the software based on the Eq. (9) which proposed by Friedman & Sanders [26].

$$p = \frac{r}{R} \tag{9}$$

Where, r is the radius of the sharpest corner, R is the radius of a largest circle inscribed in the aggregate, and p is the angularity. Figure 7 shows the estimation process of angularity of the aggregates using Eq. (9). As Results for all specimens are shown in Figure 8, it is concluded that angularity of the specimens varies from 0.34 to 0.83, where 1 stands for the minimum angularity (most rounded).

Figure 7: Measuring the radius of the sharpest corner of angular aggregate and the radius of circle inscribed in the aggregate using JMicrovision software.

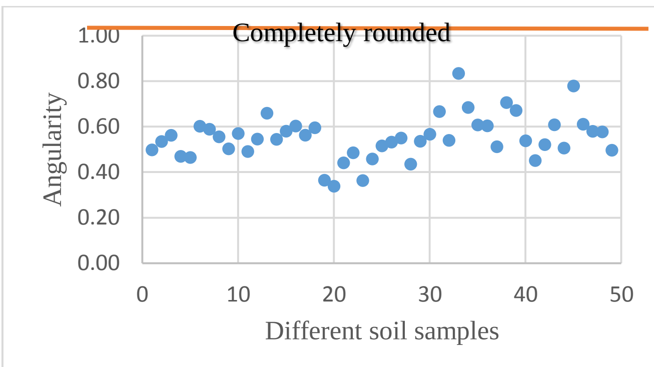

Figure 8. Angularity of the extracted soil specimens (1 stands for the minimum angularity).

Determination of Internal Friction angle (ϕ) of carbonate soils

Three stages direct shear tests were performed on different soil specimens which prepared with relative density (D_r) of 50%. For each stage, the vertical force was increased twice. Some tests were carried out both in dry and saturated conditions. However as samples were coarse-grained, the results were almost identical for two conditions. Therefore all other remained tests were carried out on dry condition. All tests were performed with the lowest speed of shearing (defined by ASTM, 0.51 mm/min).

Discussion and results

Internal friction angle (ϕ) was determined as the slope of a line prepared by best fitting the shear stress versus vertical stress at three points. Calculated ϕ for all tested carbonate samples are shown in Figure 9. The average calculated ϕ for all specimens is about 45.1° which is remarkably higher than the reported value for silicate sands.

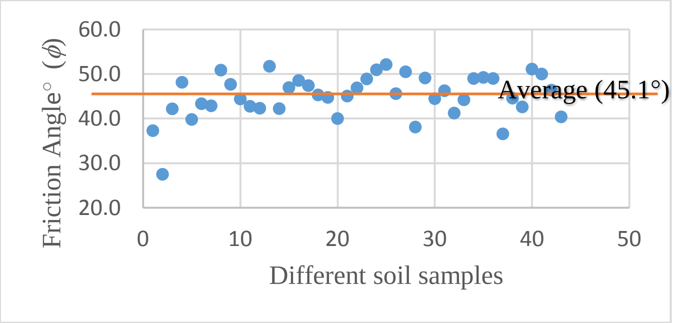

Figure 9. Internal friction angle of the extracted soil samples.

Figure 10 presents variations of ϕ for soils samples with different effective sizes. As it can be seen, ϕ of the carbonate soils and, consequently, their shear strength reduces with an increase in their effective grain size. As shown in this figure, for effective grain sizes below 1 mm, the average internal friction angel for all soil samples is about 50° for D_r=50%. With increase of the soils effective grain size, internal friction angle decreases to less than 40°. This trend is contrary to the behavior of silicate soils, for which the increase in aggregate size results in an increase in their Internal friction angle as reported by Das [8] (see Table 2) and Vangla and Latha [27]. It seems that, in compare to silicate soils, carbonate soils have a different behavior. This can be due to the lower relative density, larger inter granular free space and a greater porosity of coarse-grained carbonate soils (see fig. 3-c), as a result, coarse-grained carbonate soils have less frictional surfaces and less internal friction angle.

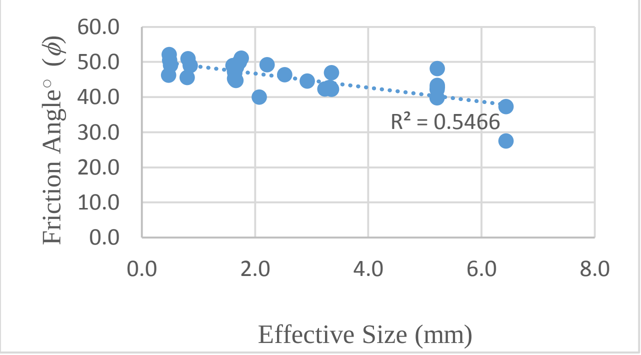

Figure 10. Variations of ϕ for carbonate soils with their effective grain size.

Figure 11 shows the effect of angularity on internal friction angle (ϕ) of aggregates with different sizes. As deduced from the figure, for soils with an aggregate size smaller than 1 mm, the angularity of the aggregates has a lower impact on internal friction angle, which varies from 46 to 50° for fine-grained soils with different angularity levels. An increase in the effective grain size for different angularity levels, clearly, cause a significant decrease in internal friction angle. In addition, with an increase in the effective grain size, soils with angularity above 0.6 have the minimum ϕ (< 30°) while for soils with angularity 0.4-0.5 a higher ϕ is observed. The effect of angularity on ϕ is higher when aggregates have higher angularity value.

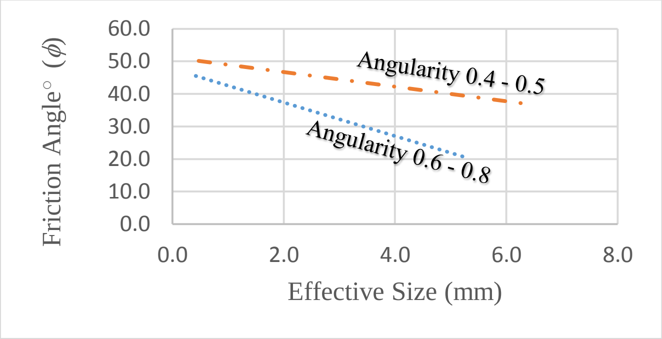

Figure 11. Variations of ϕ with the effective grain size for different angularity levels (The minimum angularity = 1).

Figure 12 reveals the effect of shape index on internal friction angle (ϕ) of all samples. As it can be seen in this figure, although test were performed on samples with wide range of shape index (3.2-9.3) this parameter doesn't have any considerable effect on soil internal friction angle.

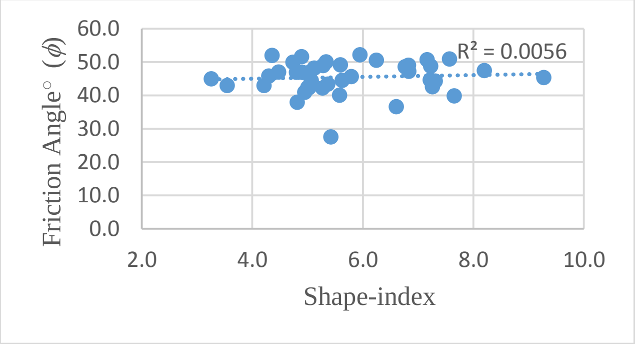

Figure 12. Variation of ϕ with shape index

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Effect of calcium carbonate content on internal friction angle (ϕ)is shown for different effective aggregate sizes in Figure 13. This figure is drawn for all specimens with different angularities and shape indexes. As illustrated in the figure, for soils with an effective grain size of less than 1 mm and carbonate content of more than 45%, ϕ is about 50°. The calcium carbonate content has a relatively small effect on ϕ and this effect is almost constant for different effective sizes. Decrease of internal friction angle is almost 5 degrees for all ranges of effective sizes when carbonate content decreases from a value of $CaCO_3$ > 90 % to 45 % < $CaCO_3$ < 69 %.

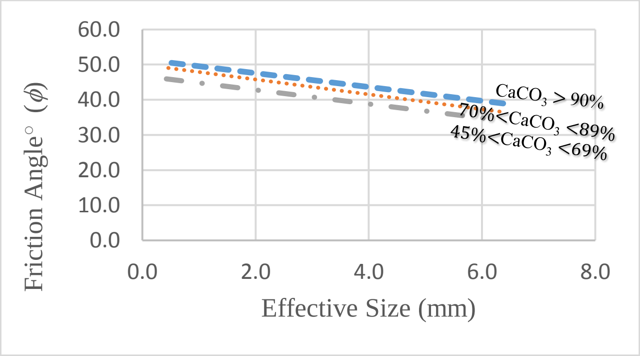

Figure 13. The variations of ϕ with the effective grain size for different calcium carbonate contents

Figure 14 shows the comparison of internal friction angle of carbonate soils and Firozkoh silicate sand (between two consecutive sieves (e.g., sieves 16# and 30#)). As shown, the internal friction angle of most carbonate soils is higher than the silica sample. This can be related to the rugged, pitted, and rough surfaces of carbonate soils.

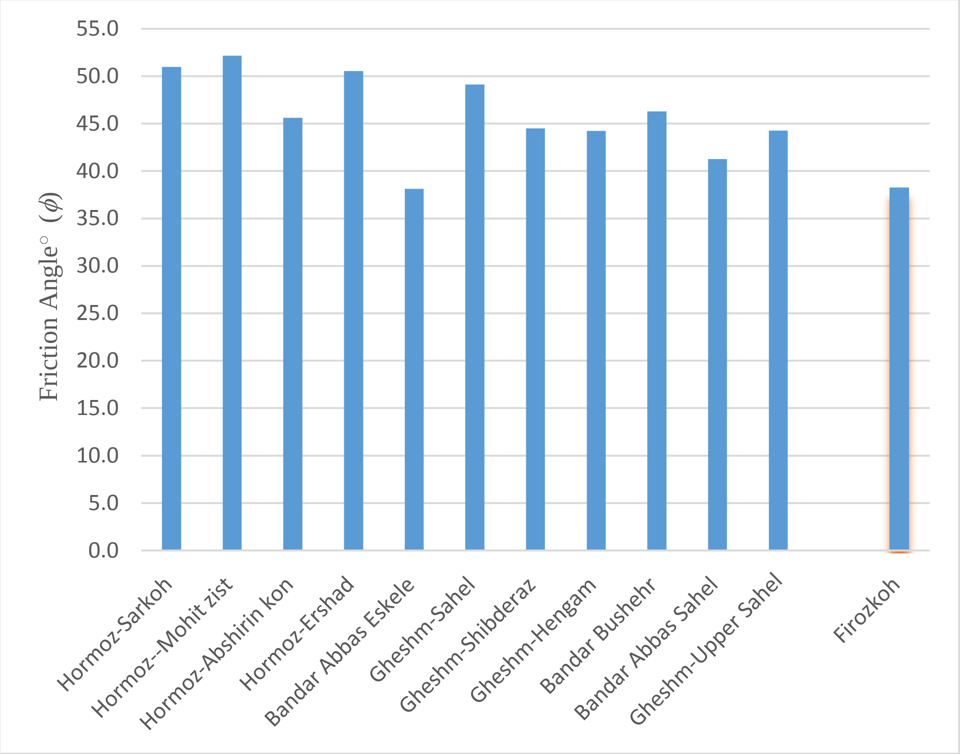

Figure 14. Comparison of internal friction angle of carbonate soils and Firozkoh silicate sand (between two consecutive sieves (e.g., sieves 16# and 30#))

Figure 15 shows the comparison of shear stress to strain of carbonate soils and one sample of silicate soil, obviously, all carbonate soils have a higher peak stress than silica sand of the same size. This can also be due to rugged and pitted surfaces in carbonate soils.

It has been previously observed that, in contrast to silicate soils, by increasing grain size, carbonate soils have a lower internal friction angle but both groups, by increasing their angularities, have increased friction angle and shear strength.

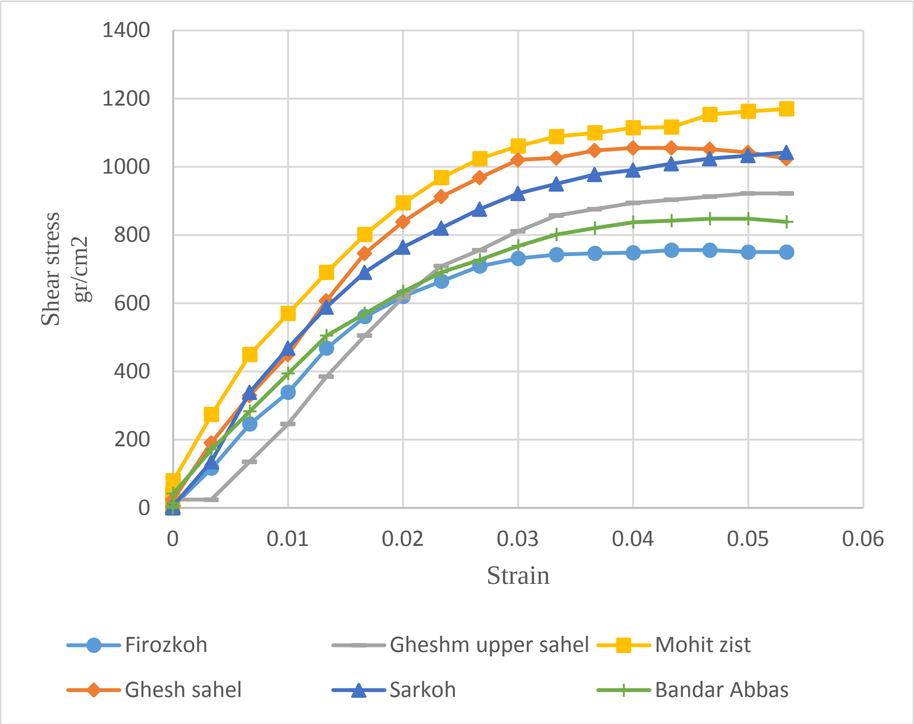

Figure 15. Comparison of shear stress to strain of carbonate soils and Firozkoh silicate sand (between two consecutive sieves (e.g., sieves 16# and 30#))

Conclusion

Considering the high diversity of the carbonate soils and their different behavior under various conditions, determination of effective parameter on internal friction angle (ϕ) of this types of soil is the main objective of this experimental research. Different samples of carbonate soils mainly with a biologic origin were collected from northern coasts and islands of Persian Gulf. Then, after performing grain size analysis and classification, preparing specimens with selected grain size distributions, determination of $CaCO_3$ content, angularity and shape index of aggregates, the internal friction angles (ϕ) of the soil samples at relative density of 50% were measured. The main conclusions of this study can be explained as:

1. Generally, carbonate soils, due to its rugged and rough surfaces, have a higher internal friction angle.
2. The internal friction angle (ϕ) of carbonate soils decreases as their effective size of soil aggregates increases.
3. Internal friction angle (ϕ) considerably decreases when angularity value of aggregates increases (the minimum angularity=1). This decrease is bigger for soils with bigger effective size.
4. In compare to other parameters, shape index has less effect on internal friction angle of carbonate soils ($R^2 = 0.0056$).
5. Internal friction angle (ϕ) reduces with the simultaneous increase in the effective size and angularity level.
6. Internal friction angle (ϕ) values of aggregates increase with increasing of the $CaCO_3$ content.

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