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SHEAR STRENGTH, COLLAPSIBILITY AND COMPRESSIBILITY CHARACTERISTICS OF COMPACTED BAIJI DUNE SOILS

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Abstract

Baiji city is a vital industrial centre in Iraq since it has the biggest oil refinery. Therefore, Baiji has become an attractive site for strategic construction projects. Dune sand covers about 220 km^2 of the area of Baiji city. However, few researches had attempted to study its behaviour. In this study laboratory tests were conducted to determine the shear strength, collapsibility and compressibility of the dune sand at its natural and compacted status. The effect of dry unit weight, moisture content, relative density and soaking on mechanical properties of dune soil was investigated. The results demonstrated that dry and soaked dune specimens tested at their in-situ condition exhibited similar volume changes during shear and identical friction angles. The results of shear tests of both of compacted soaked and unsoaked samples were identical. The collapse potential of dune soil is inversely proportional with the relative density. The minimum axial strain is observed when the samples are compacted to modified effort. The compression index of the compacted specimens is affected by moulding water content, while the rebound index is less sensitive.

Keywords: Dune sand, Compaction, Relative density, Collapsibility, Compressibility, Shear strength.

1. Introduction

Arid and semi-arid areas cover thirty percent of the world land surface [1]. In Iraq desert occupies more than half of the land surface. Sand dune covers about two million hectares of the Iraqi desert. It is mainly distributes in Baiji area and the west desert [2].

Nomenclatures

C_c	Compression index
C_r	Rebound index
D_r	Relative density, percentage
e_o	Initial void ratio
Pc	Preconsolidation pressure, kN/m^2

Greek Symbols

Δe_c	Change in void ratio resulting from saturation
$(\varepsilon_a)_{800}$	Axial strain at applied pressure (800 kPa), percentage
ϕ	Angle of internal friction, deg.
γ_d	Dry unit weight, kN/m^3
γ_{dmax}	Maximum dry unit weight, kN/m^3
γ_{dmin}	Minimum dry unit weight, kN/m^3
ω	Moisture content, , percentage

Abbreviations

CP	Collapse Potential, percentage
OMC	Optimum Moisture Content, percentage
SP	Poorly graded sand

Many researchers studied patterns, geomorphology, geographic distribution and geologic characteristics of Iraqi sand dune [3-7]. Other researchers investigated origin, nature, physical and mineralogical properties of dune [8-12]. Sedimentology, pedological and hydrological aspects of Iraqi dune was extensively studied [3, 4, 13]. The movement, extension, reclamation, fixation, controlling and stabilization of this soil are well documented in the literature [12, 14-16]. Some studies were directed to study environmental impacts and geological hazards of dune [17-19]. However, there is scarcity in the specialized literature concerning geotechnical characteristics of Iraqi dune soil.

Dune soil could be used in construction when compacted or mixed with additives [20-21]. Therefore, there is a need to conduct an investigation to study the relevant engineering properties of Iraqi dune soil.

In this study, laboratory tests were conducted to determine the shear strength, collapsibility and compressibility of the dune sand samples obtained from Baiji City. The effect of dry unit weight, moisture content, relative density and soaking on mechanical properties of dune soil was studied.

2. Geology and Geological Hazards of Baiji Sand Dune

Baiji city locates south of Makhul Mountain and west of Tigris River and borders by Wadi Tharthar on the west. The sand dune in Baiji area covers about (220) km^2 to the north and west, and extends to the south of the city, Fig. 1. Most of the dune sand is derived from the older formations such as Injana Formation (mainly contained from Sandstone) and Quaternary fans and terraces (mainly composed from fluvial, alluvial, sandy gravel deposits), the presence of sand dune as sheet of sand of Pleistocene and recent ages in the area of Baiji as a part of Mesopotamian plain [12, 22].

Sand dune in Baiji area causes many problems, such as accumulation of the moved sand on the railway, roads, sand and dust storms caused pollution and desertification. Baiji sand dune consists of three main parts. They are barchans belt, fixed dune and scattered patches. Barchans belt lies few kilometres to the northwest from Baiji city, while fixed dune belt locates around the south of Baiji and scattered patches of dune lies to west of the main belts [8, 23].

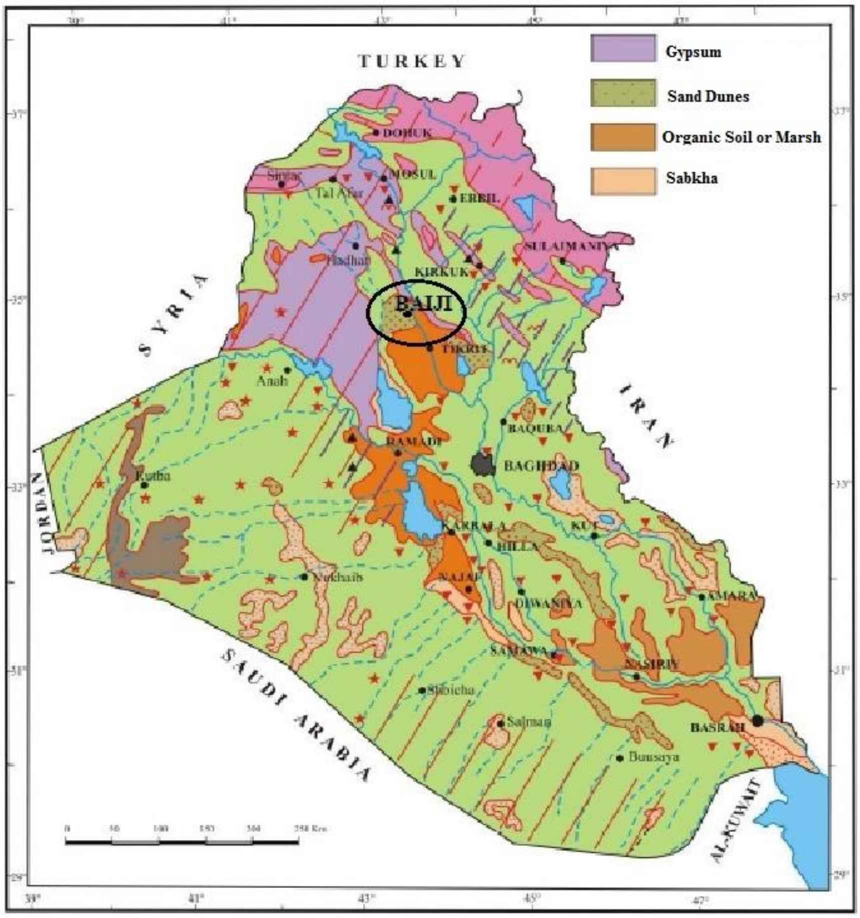


Fig. 1. Geographical distribution of sand dune in Iraq [18].

3. Samples Preparation

3.1. Correlation with dune morphology (Natural soil)

In general, dune sand in nature found dry, cohesionless and with low relative density. Loose sand is irregularly distributed on the windward slope of dune as well as throughout the leeward slope. Denser sand formed on the upper portion of the windward slope of dune just back from the crest. The transition from loose state to relatively dense state may be quite abrupt [24, 25]. The deposition of sand in the loosest form with relative density of less than 20% can be spreaded near the crest. At the deeper levels, the sand is compacted under the overburden pressure, therefore it is slightly more stable [25]. If the soil of dune is used in its natural state, it is necessary to determine the engineering properties of dune soil. To achieve this aim the following procedure was adopted in preparing the samples for the oedometer and shear tests:

First, minimum (γ_{dmin}) and maximum (γ_{dmax}) dry unit weights were determined. Then, five relative densities (D_r) were adopted to represent the field relative densities. They are listed in Table 1. The formula used for the calculation of dry unit weight (γ_d) is:

$$\gamma_d = \frac{(\gamma_{d\max}\gamma_{d\min})}{(\gamma_{d\max} - D_r(\gamma_{d\max} - \gamma_{d\min}))} \tag{1}$$

The oven dry soil required for a specific dry unit weight was prepared by dropping grains from a suitable height into the ring of the oedometer or the box of the direct shear device. It is important to note that both of the ring and the box is fitted in its device before the placing of the soil. Also, the soil must fill the ring or the box to achieve the specified dry unit weight, otherwise, the sample is rejected. For shear and oedometer tests, two identical groups of natural soil were papered. Each group consists of five sets of four similar specimens. These specimens were prepared according to the procedure outlined above. The soil in the first group was tested at their dry in-situ condition. While in the second group the soil was soaked in water to about two hours then tested.

Table 1. Adopted relative densities [26].

D_r, %	0-20	20-40	40-60	60-80	80-100
States	Very loose	Loose	Medium	Dense	Very dense

3.2. Compacted specimens

Samples have been prepared at different moisture content and compacted to the corresponding dry unit weights. The soil was compacted using the standard and modified Proctor procedures. The compacted samples were extracted from compaction mold by pushing the test ring or box (of oedometer or direct shear) carefully to the required thickness. Then, the faces were trimmed and leveled. For shear and oedometer tests, two groups of specimens were compacted at optimum moisture content to the maximum dry densities obtained from standard and modified Proctor tests. The soil in the first group was tested at its initial placement condition (as compacted), while the second group was tested after soaking with water.

4. Testing Program

Classification tests were performed according to (ASTM D422), then minimum and maximum dry unit weight determination was fulfilled based on (ASTM D4254). Standard (ASTM D698) and modified (ASTM D1557) compaction tests were carried out to determine the moisture content-unit weight relationship.

Two series of shear tests were conducted using the direct shear apparatus (ASTM D3080). A calibrated proving rings of (200 kg) and (300 kg) capacity and (0.002 mm) precision dial gauge for vertical deformation reading were used, while for horizontal deformation a (0.01 mm) gauge was used. The rate of strain was (1.2 mm/min). In the first series, five sets of four samples each was prepared using the preparation procedure outlined in section (3.1). The samples were tested at dry condition. Identical samples were prepared and tested after soaking in water. In the other series, two groups of specimens were compacted to different moisture contents and dry densities. They were prepared with a size of (60x60x20 mm) using the preparation procedure outlined in section (3.1). The first group was tested with no addition of water, while the other group was soaked in water and then tested. All specimens were tested using normal pressure of 82.5, 165, 247.5 and 330 kPa for each set. The time of soaking in water was about two hours.

Compression and collapse tests were conducted using the standard front-loading oedometer (the sample size used was 76 mm in diameter by 19 mm in height).The double oedometer test was carried out according to the procedure of Jennings and Knight [27]. This procedure developed for assessing the response of a soil to wetting and loading at different stress levels. In this procedure two oedometer tests are carried out on identical samples, one being tested at its natural moisture content, whilst the other is tested under saturated condition, the same loading sequence being used in both cases. Samples were loaded progressively as in the consolidation test.

5. Results of Physical, Relative Density and Compaction Tests

According to unified soil classification system (ASTM D 2487) the soil of sand dune can be classified as poorly graded sand (SP). The specific gravity of this soil is 2.7. The values of γ_{dmax} and γ_{dmin} are 16.53 kN/m^3 and 14.30 kN/m^3 respectively. The optimum moisture content (*OMC*) and the maximum unit weight (γ_{dmax}) for standard and modified compaction tests are summarized in Table 2. It is noted that γ_{dmax} of dune sand is obtained when the soil is compacted using modified compaction test. When sand is air dried by using vibratory compaction, high unit weight was achieved than standard proctor compaction test; however, the difference is small.

Table 2. Summary of relative density and compaction tests.

Soil Property	OMC (%)	γ_{dmax} (kN/m^3)	γ_{dmin} , (kN/m^3)
Standard Compaction	15.00	16.42	-
Modified Compaction	11.50	17.55	-
γ_{dmax} and γ_{dmin} for dry soil	-	16.53	14.30

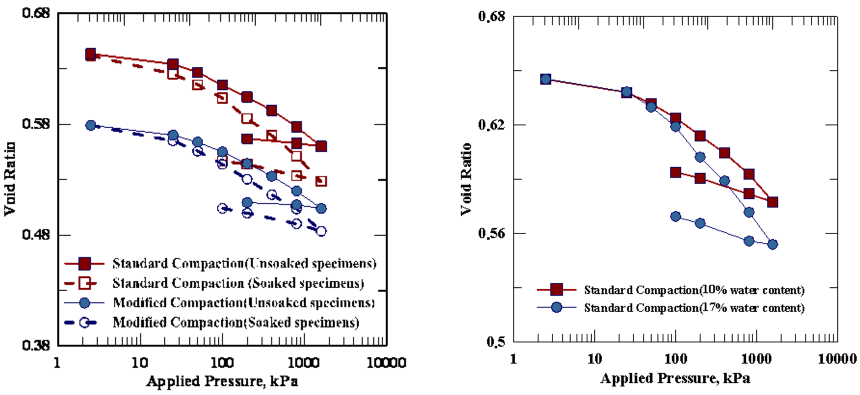
5.1. Compression tests result

The compression tests results are shown in Table 3 and Fig. 2. It is clear to note that the (as compacted) specimens are less compressible than the soaked specimens. They have low compression index (C_c), rebound index (C_r) and preconsolidation pressure (P_c). Furthermore, C_c was decreased about when the compaction effort increased.

Table 3. Results of compression test.

Compaction	γ_d, **kN/m**^{3}	ω **%**	e_o	P_e, **kPa**	C_c	C_r
			As Compacted Specimens			
Standard	16.44	14.5	0.642	68	0.045	0.007
Modified	17.50	11.5	0.579	70	0.041	0.003
			Soaked Specimens			
Standard	16.44	14.50	0.642	43	0.056	0.017
Modified	17.50	11.5	0.579	47	0.044	0.016

The effect of compaction moisture content on compressibility characteristics is clearly illustrated in Fig. 2. The results indicate that when the moisture content increased from dry side to wet side of the optimum, C_c increases from 0.035 to 0.050. This represents 40 % increase in compressibility due to the increase in moisture content. However, this is not significant since the initial compressibility is very low. Re-examination of Fig. 2 reveals that the rebound curves of dune soil are relatively flat with a very low rebound index from 0.0015 to 0.0016, and moisture content has low effect on the magnitude of C_r.



(a) Specimens compacted with different compaction efforts

(b) Specimens compacted with different moisture contents

Fig. 2. Compression tests result.

5.2. Results of collapse tests for natural specimens

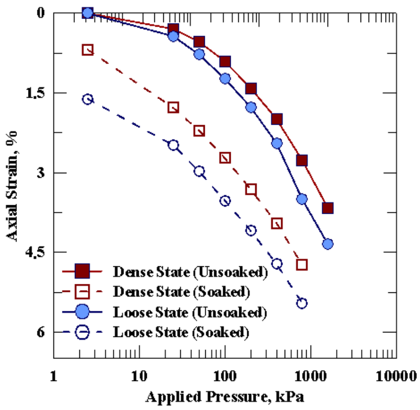
Table 4 summaries the result of collapse tests using double oedometer procedure. The value of deformation at any stress level at which the soil get saturated is obtained from the difference between the compression curves. Typical results from double oedometer test for loose and dense specimens are shown in Fig. 3. The collapse potential can be determined at any required stress level. Based on Jennings and Knight [27] the collapse potential was calculated using the following equation:

$$CP = \Delta e_c / (l+e_o) \qquad (2)$$

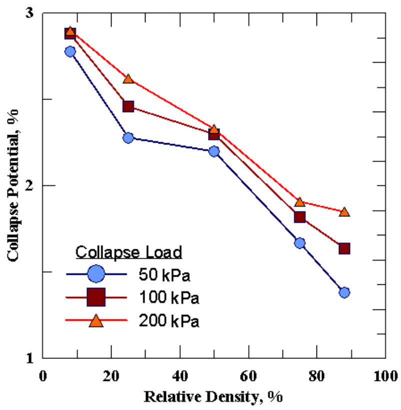
Where (Δe_c) is the change in void ratio resulting from saturation and (e_o) is the initial void ratio. Figure 3 is indicated that the collapse potential (CP) for each load increment, and the final strain (at 800 kPa). According to the ASTM D5333-1, the collapsibility of the natural dune sand can be classified as slight to moderate. The *CP* of this soil increases with the increase of soaking pressure.

Table 4. Results of collapse test using double oedometer procedure.

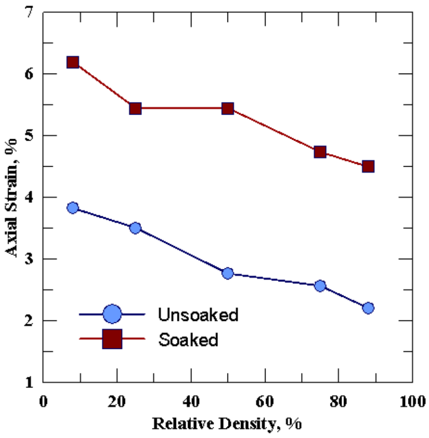
Applied Stress kPa	Property	Relative Densities				
		Very loose	Loose	Medium	Dense	Very dense
50	CP, %	2.78	2.28	2.20	1.67	1.38
100		2.88	2.46	2.30	1.82	1.64
200		2.90	2.62	2.33	1.91	1.85
unsoaked	$(\varepsilon_a)_{800}$,%	3.51	3.83	2.21	2.77	2.57
soaked		6.20	5.45	2.45	4.74	4.50



(a) Stress-strain curves



(b) Collapse potential- Dr



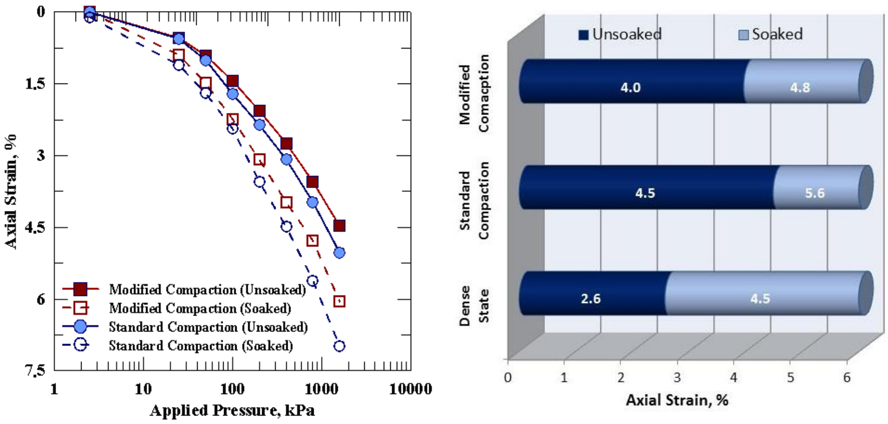
(c) Axial strain vs. D_r

Fig. 3. Collapse tests results from double oedometer procedure.

Figure 3 shows the effect of vertical pressure and relative density (*Dr*) on *CP* and the axial strain of the dry and soaked dune samples. As it is expected, increasing of relative density resulted in decreasing in collapse potential. It is attributed to the reduction in void ratio of the specimens with increasing *Dr*. However; a considerable increase in the axial strain due to soaking (about 55%) can be seen from Fig. 3. The axial strain is decreased with increasing the relative density as it shown in Fig. 3.

5.3. Results of collapse tests for compacted specimens

Figure 4 shows the results. The results reveal that the behaviour of the dune samples compacted with Proctor efforts is resemble the behaviour of the natural specimen (vibratory compaction), where small collapse potential was recorded in both cases. A comparison between the axial strain values (at applied pressure of 800 kPa) of the natural dense specimens and compacted specimens at standard and modified efforts is shown in Fig. 4. It is noted that the minimum axial strain of dune sand is obtained when the soil is compacted at modified compaction effort. Consequently, dry sand specimens prepared by vibratory compaction shows low axial strain than specimens prepared at standard proctor compaction effort. Furthermore, the difference between axial strains of specimens compacted with vibratory and modified compaction is minimal.



(a) **Axial Strain versus applied pressure**

(b) **Axial strain for different compaction states**

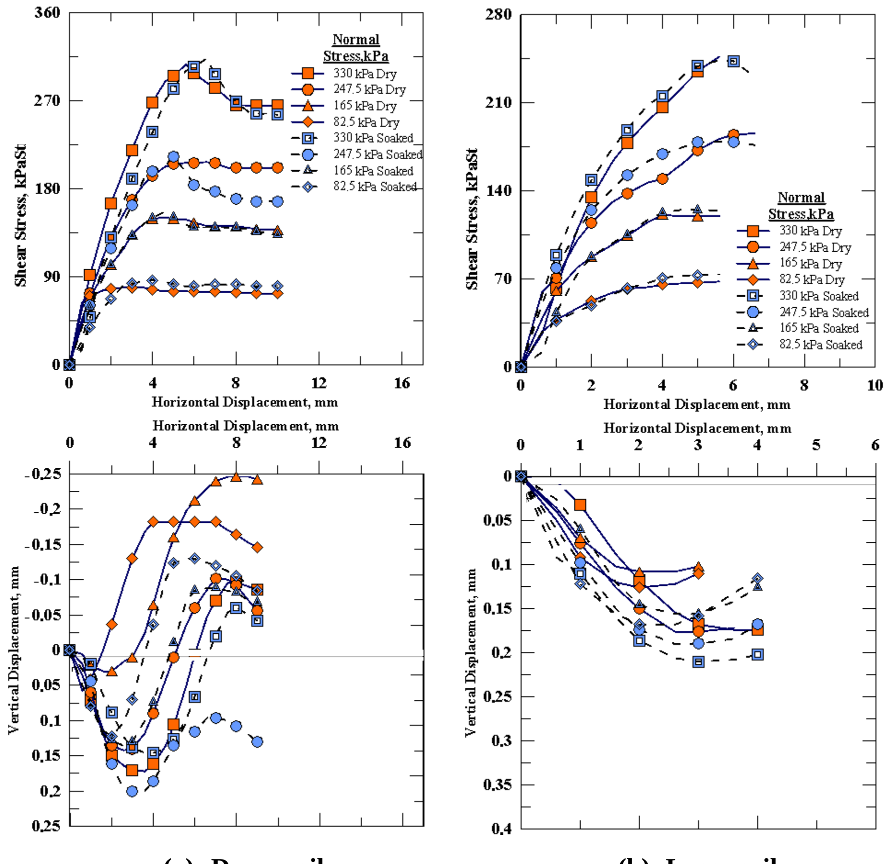
Fig. 4. Results of collapse tests for compacted specimens.

5.4. Direct shear tests for natural specimens

The stress-strain curves for dry and soaked specimens prepared at loose and dense states are shown in Fig. 5. It is demonstrated that these curves behave similarity for granular soil. The shearing stress at loose state is increase with increase displacement until failure, unlike the shear stress of dense sand that increases from zero to a peak value and then gradually decreases to an ultimate or residual value. Dry and soaked specimens tested at their dry in-situ condition exhibited similar volume changes during shear. The volume of the dense specimen decreases (up to 3 mm of horizontal displacement) and dilates (about 6 mm of horizontal displacement). While the volume of loose specimen decrease with increase horizontal displacement.

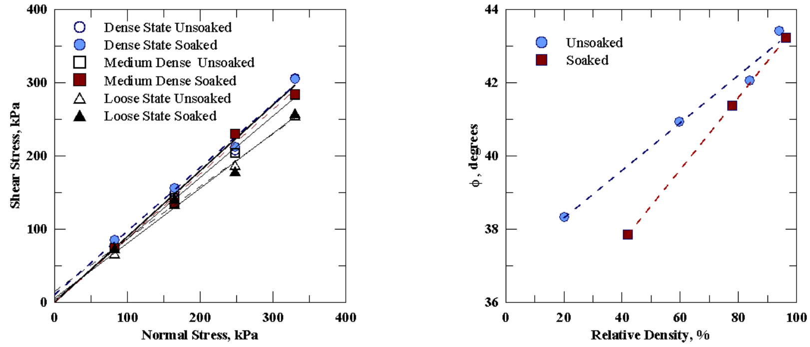
The strength envelopes for sand tested are given in Fig. 6. The cohesion parameter is varied from (0 to 10) kPa for dune soil tested at dry and soaked conditions. Moreover, soaked and unsoaked specimens showed slightly identical friction angles for both loose and dense specimens ranged from (35^{o} to 36^{o}) for loose state and (41^{o} to 42^{o}) for dense state. The decrease in the coefficient of friction (*tan* ϕ) for dune sand due to soaking fall between (0 to 6) %.

The angle of internal friction correlated well with the relative density as shown in Fig. 6. The angle of repose was determined for dune soil. It is found that, the value of the angle of repose is equal to 31^{o}. It is interesting to note that the angle of internal friction of the dune soil at loose state is greater than that of the angle of repose. It is because the slope of slip face of dune will have an angle of repose varies from 30 ^{o} to 35 ^{o}, depending on the type of material, relative density, particle shape and surface roughness, [26, 28].



(a) Dense soil **(b) Loose soil**

Fig. 5. Direct shear test result.

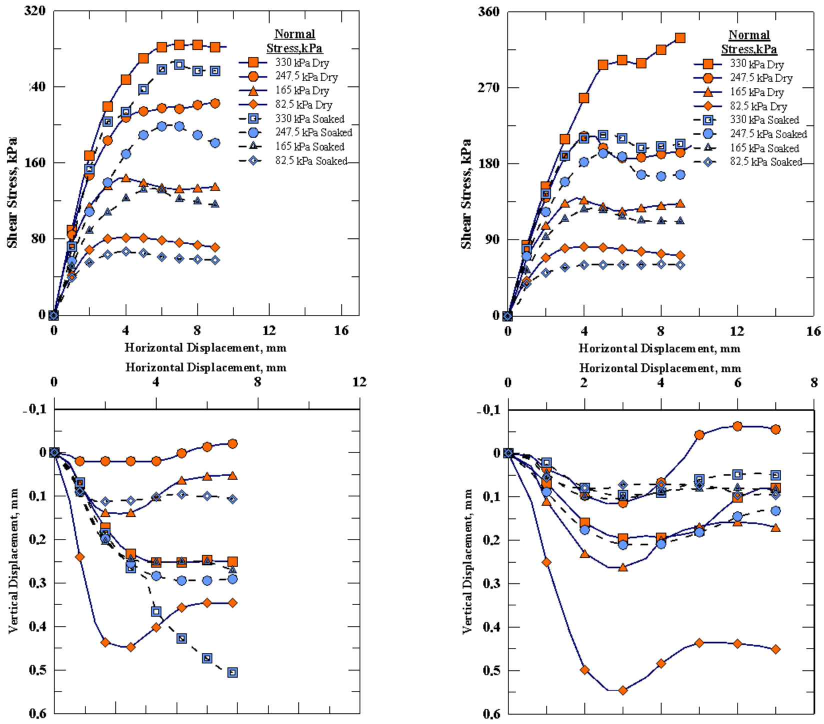


(a) **Mohr envelops** (b) **ϕ vs D_r**

Fig. 6. Mohr envelops, ϕ and D_r of natural dune sand.

5.5. Direct shear tests for compacted specimens

Figure 7 gives a summary of direct shear test results for compacted soil. It can be seen that, the results of shear tests on soaked samples are mostly similar with unsoaked. The angle of internal friction decreases by 1 to 2 degrees due to soaking. Moreover, the apparent cohesion is diminished when the soil is soaked.



(a) **Standard compaction** (b) **Modified compaction**

Fig. 7. Direct shear test result compacted dune sand.

The general behaviour of the compacted sand during direct shear tests is approximately similar to that of the natural dense specimens, whereas a peaked stress-strains curves reveal an initial volume decrease followed by an increase in the thickness of the specimen prior to failure at peak stress. Furthermore, the angle of internal friction for the soil in both cases fills in the range between (40 to 43) degree.

6. Conclusions

Strength, collapsibility and compressibility tests were carried out on dune soils obtained from Baiji city. Tests were performed on natural and compacted specimens. Based on the results the following conclusions are made:

- The compression index of the compacted dune soil increase with increase of molding water content. The change in moisture content merely effect on the magnitude of rebound index. Furthermore, when the compaction effort increased from standard to modified compression index value of dune soil was occurred by about 21%.
- The collapse potential and the axial strain of dune soil decreases with decrease of soaking pressure and with increase the relative density. The minimum axial strain got when the soil is compacted using modified compaction test. Air dried specimen shows low axial strain rather than specimens compacted at standard proctor effort.
- Dry and soaked dune specimens tested at in-situ condition exhibited similar volume changes during shear and almost identical friction angle. The angle of internal friction increases with increases relative density. For compacted soil, the shear test on soaked samples is almost identical with unsoaked samples. The angle of internal friction decreases by 1 to 2 degrees due to soaking. Moreover, the apparent cohesion is diminished when the soil is soaked. The general behaviour of the compacted sand during shear test is approximately similar to that of the natural dense specimens. Finally, the angle of internal friction of dune sand at loose state is greater than that of the angle of repose.

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