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RESEARCH PAPER

Use of fine-grained soil for improvement of density and bearing capacity of aeolian sand

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Abstract
The existence of vast areas covered with aeolian sand in many regions of Iran has made the use of this type of soil inevitable in engineering projects. Considering the abundance of fine-grained soil in Khuzestan plain along with the aeolian sand, it is important to investigate the effect of the addition of fine-grained soil to aeolian sand to improve its dry density and bearing capacity. In the present research, different percentages of fine-grained soil were added to aeolian sand from Khuzestan plain to determine its effect on the maximum dry density (γ_{dmax}), optimum water content (ω_{opt}) and California bearing ratio (CBR) of the aeolian sand and fine-grained soil mixture. It was found that an increase in the percentage of fine-grained soil increased the γ_{dmax} and decreased the ω_{opt}. The CBR of the soil increased under tests performed at the optimum water content and decreased under saturated conditions. The highest CBR for penetrations of 2.5 and 5 mm ($CBR_{(2.5)}$ and $CBR_{(5)}$) when the samples were tested at an optimum water content was for the sample where the ratio of the dry weight of the fine-grained soil ($W_{S(F)}$) to dry weight of the aeolian sand ($W_{S(S)}$) is equal 40%. Comparison of the results of the current and previous research showed that, in areas such as the Khuzestan plain in which fine-grained soil is available, the use of such soil for improvement of aeolian sand is appropriate.

Keywords: Aeolian Sand, Fine-Grained Soil, Compaction Test, California Bearing Ratio, Dry Density, Optimum Water Content.

Introduction

Aeolian sand is a problematic soil type that covers large arid, semi-arid and coastal regions (Silva et al., 2023). As this soil type has a very low bearing capacity, it is necessary to improve it before beginning construction or using it as borrow material. The expansion of aeolian sand and the development of road and rail transportation lines in the areas covered with such material have prompted engineers to improve the engineering characteristics of this soil type.

Generally, aeolian sand does not exhibit plasticity properties and, because of its uniform grain size, it does not compact, which means it has a low bearing capacity (Arias-Trujillo et al., 2020) with the potential for collapse when becoming wet (Mohamedzein et al., 2019). Loose aeolian sand has the potential to liquefy when saturated and subjected to cyclic loading (Souza Júnior et al., 2020). Aeolian sand is a humogen, with circular grains of 0.08 to 0.4 mm in size (Das, 2007) that has a low water content (zero to 4%), a permeability of 0.00034 and 0.01 cm/s and a maximum water absorption of 1% (Al-Sanad et al., 1993; Abu Seif, 2013; Al-Taie, 2013). The specific weight of solid grains (Gs) of aeolian sand in Africa is 2.44 to 2.74 (Khan, 1982) and in Asia is 2.63 to 2.87 (Al-Ansary et al., 2012).
The chemical and mineralogical composition of aeolian sand grains vary depending on the

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location of the samples and their origin. However, quartz is the primary mineral, with minerals such as feldspar and calcite reported to occur in small amounts (Khan, 1982; Abu-Zeid et al., 2001; Al-Ansary et al., 2012; Padmakumar et al., 2012; Abu Seif, 2013; Al-Taie et al., 2013). The maximum dry density (γ_{dmax}) is reported to be 1.642 to 1.765 g/cm^3 and the optimum water content (ω_{opt}) to be 11% to 14.5% (Al-Sanad et al., 1993; Abu-Zeid et al., 2001; Al-Ansary et al., 2012; Elipe & Lopez-Querol 2014).

The shear strength of aeolian sand is affected by the friction component. It has generally been reported that this soil type has a cohesion (C) equal to zero and internal friction angle (φ) of 39° to 42° (Al-Sanad et al., 1993; Padmakumar et al., 2012; Al-Taie et al., 2013). A few studies have been conducted on the bearing capacity of aeolian sand by determining the California bearing ratio (CBR) and from compaction tests. Other studies have evaluated the strength of aeolian sand by performing uniaxial compressive strength (UCS) tests (Arias-Trujillo et al., 2020). In general, aeolian sand is a suitable material for building embankments and roads (Elipe & Lopez-Querol, 2014). However, when the sand is not confined, its geotechnical performance can be weak and improvement is recommended (Arias-Trujillo et al., 2020).

The engineering characteristics of aeolian sand can be improved by methods such as compaction, reinforcement, drainage and the addition of materials. Additives can improve the engineering properties of aeolian sand through physical, chemical or biological processes (Venda Oliveira et al., 2015; Abbasi & Mahdieh, 2018; Venda Oliveira & Rosa, 2020). The addition of lime, cement, bitumen and chemical additives are examples of ways to improve the engineering characteristics of this type of sand. Successful stabilization of aeolian sand and granular soil types using cement and lime have been reported (Al-Aghbari & Dutta 2005; Moosavi & Kalantari, 2011; AlKarni & ElKholy, 2012; Lopez-Querol et al., 2017; Silva et al., 2023). The use of bitumen alone or together with cement to stabilize aeolian sand also has been reported (Akili & Monismith, 1978; Al-Abdul et al., 1998; Al-Abdullah, 2006). Among a number of chemical stabilizers, polymer emulsions are widely used and have replaced other additives, especially traditional ones such as cement in recent decades (Onyejekwe & Ghataora, 2015). A number of studies have reported on the use of these emulsions for the stabilization of aeolian sand and granular soils (Lahalih & Ahmed, 1998; Freer-Hewish et al., 1999; Zandieh & Yasrobi, 2010; Onyejekwe & Ghataora, 2015).

The use of additives can incur problems such as high cost, lack of compatibility with some environments, fragile and reduced flexibility soil and lack of compatibility with the environment (Arias-Trujillo et al., 2020). Their improvement of soil properties can be affected by the type and number of additives and processing time (Homauoni & Yasrobi, 2011; Onyejekwe & Ghataora, 2016). For this reason, previous studies have used different types and percentages of additive along with different curing times to determine the effects of an additive on the engineering properties of soil. For example, Hamayouni & Yathrabi (2011) investigated the effect of adding poly methyl methacrylate and polyvinyl acetate on the bearing capacity of aeolian sand under modified compaction and CBR tests at different curing times. Their results showed that γ_{dmax} in the sample containing the highest percentage of polymer (5%) increased by about 3% when compared with the non-stabilized sample and that ω_{opt} did not change in non-stabilized or stabilized samples with different percentages of polymer. With an increase in the percentage of polymer, the CBR increased such that the highest value was for samples containing 5% additive. The curing time had a major effect on the CBR test results. The CBR for dry samples containing 5% polyvinyl acetate increased from 32% to 110% after 28 days. A significant decrease in CBR was observed in the saturated state compared to the dry state.

Lopez-Querol et al., (2017) investigated the effect of different percentages of Portland cement on the stabilization of aeolian sand in the Jeddah region of Saudi Arabia. They chose three cement contents (2%, 4% and 6% of dry weight of aeolian sand) and investigated their effects on γ_{dmax}, ω_{opt} and the bearing capacity under compaction and CBR tests. Their results showed an increase in the cement content linearly increased γ_{dmax} and linearly decreased ω_{opt}. They applied changes in the CBR test by introducing two indices called the “corrected bearing capacity number under confined conditions” and the “corrected bearing capacity number under unconfined conditions”. They suggested a linear and direct correlation between these two indices and the percentage of added cement.

Arias-Trujillo et al., (2020) investigated the effect of different amounts of vinyl acrylic polymer, a polymer emulsion, on improving the engineering characteristics of aeolian sand in Jeddah, Saudi Arabia. They chose three emulsion contents (0.5%, 1% and 1.5% of the dry weight of aeolian sand) and investigated their effects on γ_{dmax}, ω_{opt} and bearing capacity under compaction and CBR tests. Their results showed that changing the emulsion percentage had little effect on γ_{dmax}, but an increase in the emulsion percentage caused a linear decrease in ω_{opt}. The curing time had a great effect on the bearing capacity of the samples, such that an increase in the curing time and drying of the samples increased the CBR under both confined and unconfined conditions.

Uromeihy et al., (2015) used micro- and nano-clay particles to modify the geotechnical properties of aeolian sand. They mixed 0.5%, 1%, 2% and 4% micro- and nano-clay particles with aeolian sand and conducted compaction testing to investigate the effect of these amounts on the γ_{dmax} and ω_{opt} of the sand. They concluded that both micro- and nano-clays increased the γ_{dmax} and decreased the ω_{opt} of aeolian sand, but that the effect of nano-clay was greater than of micro-clay.

Eshraghi et al., (2019) investigated the effect of the addition of waste from stone-cutting factories (granite and travertine powder) for improving the engineering parameters of aeolian sand. They added 10%, 15%, 20% and 25% granite and travertine powders to the aeolian sand to determine their effects on the γ_{dmax}, ω_{opt} and bearing capacity of the aeolian sand under compaction and CBR tests. The addition of these materials increased the γ_{dmax} and decreased the ω_{opt} in samples containing 25% granite powder and 20% travertine powder. The highest CBR values were for the sample containing 15% granite powder and the sample containing 20% travertine powder.

In Iran, more than 47,000 km^2, which is equivalent to 2.9% of the total area of the country, are covered with aeolian sand (Abbasi, 2021). Considering the abundance and distribution of aeolian sand in Iran, it is necessary to study treatment methods to improve its bearing capacity and other engineering characteristics. Although the effects of additives such as cement, lime and polymer on the engineering characteristics of aeolian sand have been studied, Khuzestan plain has an abundance of aeolian sand as well as fine-grained soil. In the present research, the effects of the addition of fine-grained soil on improving the γ_{dmax}, ω_{opt} and bearing capacity have been investigated. Therefore, after sampling the aeolian sand and fine-grained soil of Khuzestan plain and determining their engineering characteristics, the aeolian sand was considered as the base soil and different percentages of fine-grained soil were added to it. The effect of the percentage of fine-grained soil on γ_{dmax}, ω_{opt} and the bearing capacity of aeolian sand were determined by conducting compaction and CBR tests.

Materials and Methods

Materials

The main materials used in this research were aeolian sand from Khuzestan province as the base soil and fine-grained soil. The aeolian sand was collected from the Um-al-Debs region to the north of the city of Bostan. Fine-grained soil collected from the same area was used to improve the engineering characteristics of the aeolian sand. The samples contained aeolian sand and different amounts of fine-grained soil. Table 1 shows the ratio of the dry weight of the fine-grained soil ($W_{S(F)}$) to dry weight of the aeolian sand ($W_{S(S)}$). For example, sample 2 is denoted as "S+0.2F" because it contains one dry weight unit of aeolian sand plus 0.2 dry weight unit of fine-grained soil ($W_{S(F)}$). In this sample, $W_{S(F)}/W_{S(S)}$ was equal to 20% and the ratio of the dry weight of fine-grained soil to the dry weight of the total soil used ($\frac{W_{S(F)}}{W_{S(S)}+W_{S(F)}}$) was equal to 16.67%.

Methods

In order to evaluate the effect of the fine-grained soil on the γ_{dmax}, ω_{opt} and bearing capacity of aeolian sand, granulation, hydrometry, specific gravity of the solid grains (Gs), Atterberg limits, standard compaction and CBR tests were conducted. These tests were performed in the laboratory using the standard methods presented in Table 2.

The CBR tests were performed in two modes. Both samples were prepared with the optimum water content and maximum dry density. In the first mode, the sample was subjected to CBR testing. In the second mode, the sample was initially placed in water for 96 h until fully saturated and then was subjected to CBR testing. The curves of force versus piston penetration then were drawn for all samples. The amount of force required for 2.5 mm and 5 mm of penetration was measured and divided by the standard stresses of CBR for these levels of penetration to determine $CBR_{(2.5)}$ and $CBR_{(5)}$. Development of the force-penetration curve revealed the behavior of the samples under dry and saturated conditions. The standard test recommendation is to report the larger measurement for penetrations of 2.5 and 5 mm as the CBR (ASTM D1883-16).

Results

Granulation, hydrometry, Atterberg limits and Gs

The results for determining the granulation, hydrometry and Atterberg limits of aeolian sand, fine-grained soil and combinations of these two (Table 1) are presented in Figure 1. The grain size of the aeolian sand samples was the same at 0.75 to 0.25 mm, which is classified as poorly grained soil.

Table 1. Characteristics of samples

Sample	Soil ID	$\frac{W_{S(F)}}{W_{S(S)}} \times 100$ (%)	$\frac{W_{S(F)}}{W_{S(S)} + W_{S(F)}} \times 100$ (%)
1	S	0	0
2	S+0.2F	20	16.67
3	S+0.3F	30	23.07
4	S+0.4F	40	28.57
5	S+0.5F	50	33.33
6	S+0.6F	60	37.5
7	F	100	100

Table 2. Test standards

	Test	Standard No.
1	Particle-Size Analysis	ASTM D 422-63
2	Specific Gravity of Soil Solids	ASTM D 854-14
3	Liquid Limit, Plastic Limit and Plasticity Index	ASTM D 4318-00
4	Compaction test	ASTM D 698-07
5	California Bearing Ratio (CBR)	ASTM D 1883-16

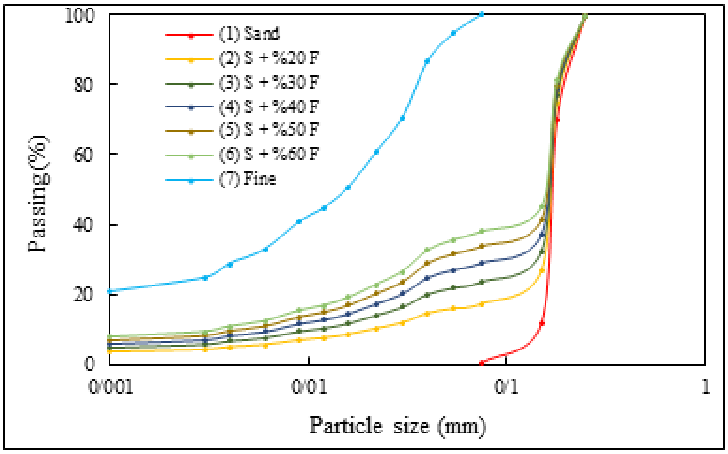

Figure 1. Granulation of aeolian sand, fine-grained soil and 5 samples mixed according to Table 1

The fine-grained soil added to the aeolian sand had a uniform size distribution and consisted of particles of 0.75 mm to >0.001 mm in size. The gradation chart of the samples that contain different percentages of fine-grained soil fall between the gradation charts for aeolian sand and fine-grained soil.

Table 3 shows the classification of the soil based on the Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) classifications. The aeolian sand was in the SP category and the fine-grained soil was in the CL category. Samples 1 was classified as SP and samples 2, 3, 4, 5 and 6 were classified as SM. According to AASHTO (Table 3), the aeolian sand was in group A-3, comprising fine sand having a uniform size. The fine-grained soil (sample 7) was in group A-4 and samples 2 and 3 were in group A-3 and samples 4 and 5 were in group A-2-4. Sample 6 was in group A-4 because the percentage of fine grains was more than 35%. The classification of all soil compositions (except sample 6) showed that the samples, despite having different percentages of fine-grained soil, remained in the category of granular soil.

Table 3 lists the results for the Atterberg limits, liquid limit (LL), plastic limit (PL) and plasticity index (PI). Aeolian sand does not have Atterberg limits. The PI of the fine-grained soil and the percentage of particles of less than 0.002 mm in size mean that the fine-grained soil has low plasticity and is inactive. By adding up to 30% fine-grained soil to the aeolian sand (samples 2 and 3), the resulting mixture will be non-plastic. Samples 4, 5 and 6 have a higher percentage of fine grains, making the soil slightly plastic. The PL of these three samples is 11% to 15% and the LL values are 18% to 19.5%. The PI was low at less than 10% for these three soil samples. Because the fine-grained soil was not active, its addition to aeolian sand in low percentages did not produce plastic soil. The larger amounts of the base soil placed the soil mixtures in the slightly plastic category.

The specific weight of the solid grains (Gs) of aeolian sand, fine-grained soil and the different soil compositions are presented in Table 3. The Gs varied from 2.63 to 2.72.

Compaction test

The results of the compaction test are presented in Figure 2. This graph shows the changes in dry density versus the moisture content. The values of γ_{dmax} and ω_{opt} are presented in Table 3. The γ_{dmax} for aeolian sand was 1.69 g/cm^3 and the ω_{opt} was 14%. A significant increase in the γ_{dmax} can be observed in sample 2 compared to sample 1, but the ω_{opt} in sample 2 decreased. An increase in the fine-grained soil content in samples 3 to 5 caused a continuous increase in γ_{dmax}. The highest value of γ_{dmax} was for the sample containing the highest percentage of fine grains (sample 6) which had a γ_{dmax} of 2.06 g/cm^3. The ω_{opt} of the samples did not change substantially with an increase in the fine-grained content and ranged from 9.5% to 10%. The 22% increase in γ_{dmax} and a 32% decrease in ω_{opt} for sample 6 compared to only aeolian sand shows the significant effect of the addition of fine-grained soil on the γ_{dmax} and ω_{opt} of the aeolian sand. Figure 3 shows the γ_{dmax} and ω_{opt} values plotted versus $W_{S(F)}/W_{S(S)}$ for the samples. From this figure, it was possible to propose an experimental relationship between γ_{dmax} and $W_{S(F)}/W_{S(S)}$ for the range of soil and soil contents in the present research as:

$$\gamma_{d\max} = 1.72 + 0.61\,\frac{W_{S(F)}}{W_{S(S)}} \quad (1)$$

Table 3. Classification of samples based on USCS and AASHTO and Gs values, γ_{dmax} and ω_{opt} of samples

Sample	USCS	AASHTO	LL (%)	PL (%)	PI (%)	Gs	γ_{dmax} (g/cm^3)	ω_{opt}(%)
1	SP	A-3	-	-	-	2.70	1.69	13.9
2	SM	A-3	-	-	-	2.69	1.88	9.2
3	SM	A-3	-	-	-	2.68	1.90	9.7
4	SM	A-2-4	18	11	7	2.68	1.94	10.3
5	SM	A-2-4	19	14	5	2.68	2.04	9.5
6	SM	A-4	19.5	15	4.5	2.67	2.06	10.0
7	CL	A-4	28	18	10	2.63	1.91	12.7

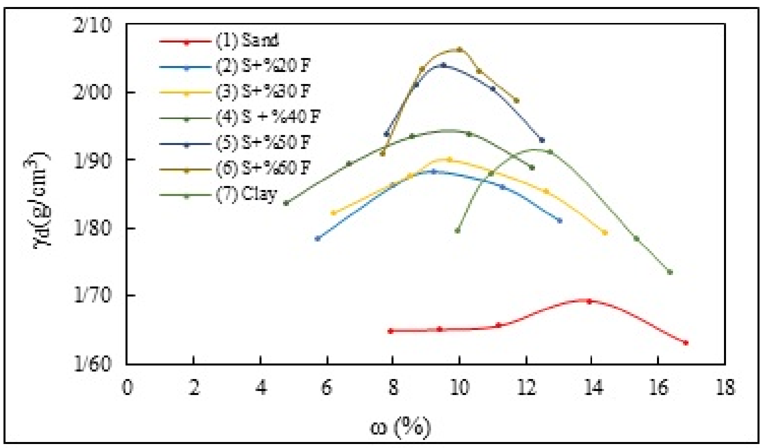

Figure 2. γ_{dmax} vs. ω_{opt}

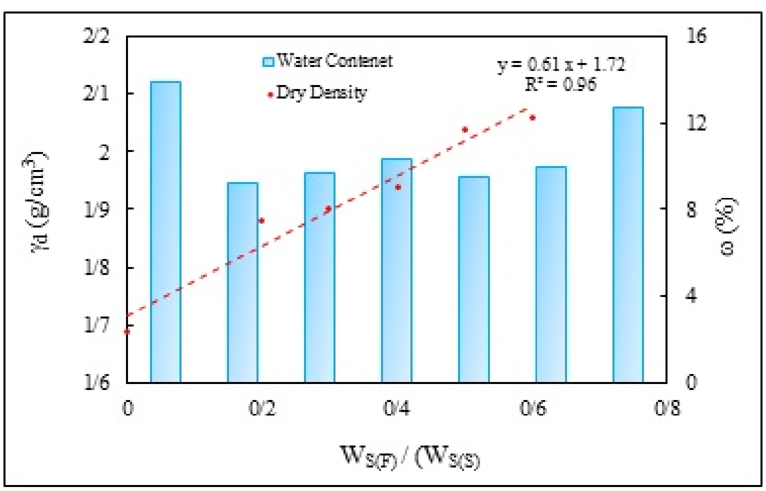

Figure 3. Changes in γ_{dmax} and ω_{opt} vs. $W_{S(F)}/W_{S(S)}$

CBR test

The results of the CBR tests are presented in Table 4. For each soil sample, the values correspond to penetrations of 2.5 and 5 mm under both optimum water content and saturation conditions. As can be seen, the highest CBR values were for samples 3 and 4.

CBR test at optimum water content

Figure 4 shows the curve of force versus penetration in the CBR test along with the γ_{dmax} and ω_{opt}. The force required for penetrations of 2.5-mm and 5-mm are shown and the CBR values are reported as $CBR_{(2.5)}$ and $CBR_{(5)}$. These values for the tested samples have been compared in Figure 5.

Table 4. CBR test results at optimum water content and under saturated conditions

Sample	Optimum water content		Saturation condition	
	$CBR_{(2.5)}$	$CBR_{(5)}$	$CBR_{(2.5)}$	$CBR_{(5)}$
1	29	19	27	22
2	31	26	18	25
3	22	30	22	29
4	32	36	18	19
5	20	30	18	20
6	20	26	21	24

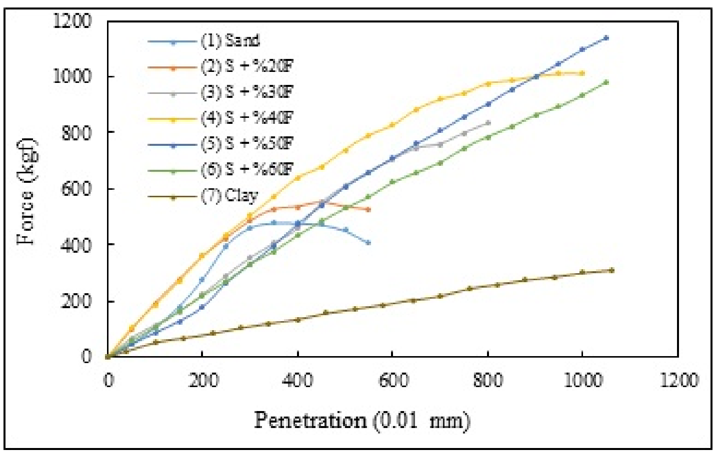

Figure 4. Force-penetration in CBR test for samples at optimum water content

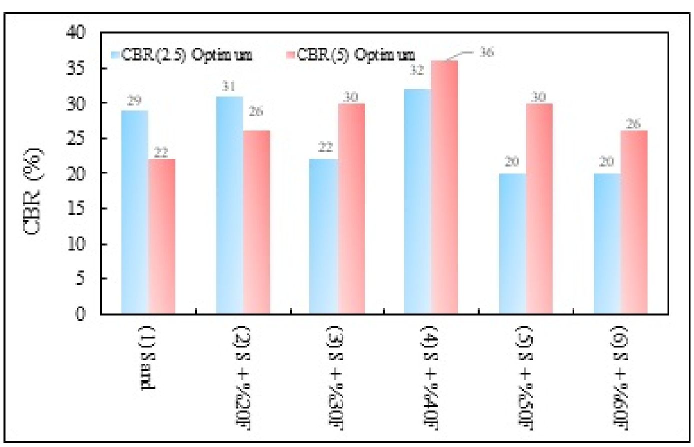

Figure 5. Values of $CBR_{(2.5)}$ and $CBR_{(5)}$ of samples tested at optimum water content

Figure 4 shows that the initial slope of the force-penetration diagram for samples 1 and 2, which had the lowest fine-grain contents, was higher than for the other samples and the $CBR_{(2.5)}$ values for these samples was higher than for the other samples. The trend of the chart changed with an increase in $W_{S(F)}/W_{S(S)}$. Initially, the slope of the force-penetration at the beginning of the graph decreased slightly, then the slope remaining constant up to a penetration of about 10 mm. This made the $CBR_{(2.5)}$ values for samples 3 to 6 lower than for samples 1 and 2, but the $CBR_{(5)}$ for samples 3 to 6 increased compared to samples 1 and 2. It can be concluded that the increase in the fine-grained content caused linearization of the course of change in the force-penetration diagram.

The graph for sample 4, where $W_{S(F)}/W_{S(S)}$ = 40%, was higher than the other graphs as the values of $CBR_{(2.5)}$ and $CBR_{(5)}$ for this sample were higher than for the other samples. The samples tested at the optimum water content (samples 1 and 2) had the lowest fine-grained contents. These samples showed good resistance to the initial forces but, with an increase in the force applied to about 500 kgf, they experienced a significant loss in strength. At even with lower force values, the penetration of the piston into the sample continued. With an increase in the percentage of fine grains, the relationship between strength and penetration increased linearly, but the graph for sample 4 was higher than for those of other samples. Figure 5 shows that $CBR_{(5)}$ changed for the six samples that were bell-shaped and its maximum value was for sample 4.

CBR test under saturation condition

Figure 6 shows the force-penetration diagram for the CBR test under saturated conditions. The $CBR_{(2.5)}$ and $CBR_{(5)}$ values were extracted from this figure and are compared in Figure 7. The force-penetration diagrams for samples 1, 2 and 3 show a decreasing trend after reaching a maximum point, while the graphs for samples 4, 5 and 6 continued to increase. Sample 1 did not contain fine-grained soil; thus, when the force reached 500 kgf, the slope of the graph became negative. Samples 2 and 3 reached maximum force at 750 kgf and then the slopes of their graphs became negative. The slope of the initial part of the force-penetration diagram for sample 1 was higher than for the other samples for a penetration of less than 3 mm; however, before reaching 5 mm of penetration, the slope for sample 1 became negative. This indicates that the $CBR_{(2.5)}$ for sample 1 was higher than for the other samples.

Figure 7 shows that the changes in $CBR_{(2.5)}$ differed for the different samples, but no specific trend was observed with an increase in the percentage of fine grains. The highest value was for sample 1, followed by sample 3.

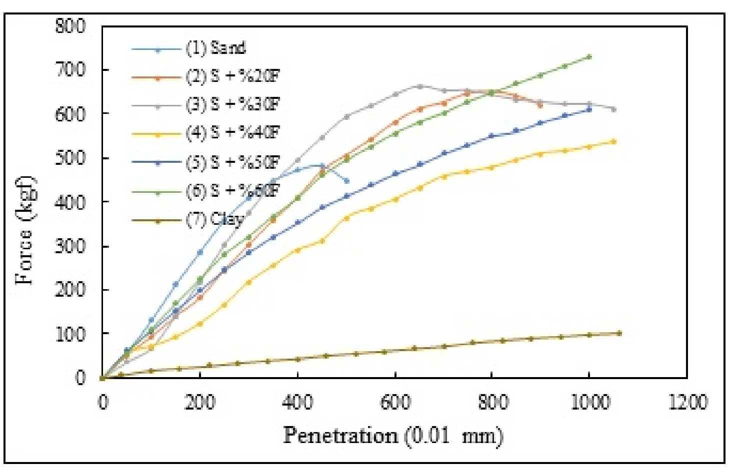

Figure 6. Force-penetration diagram from CBR test for saturated samples

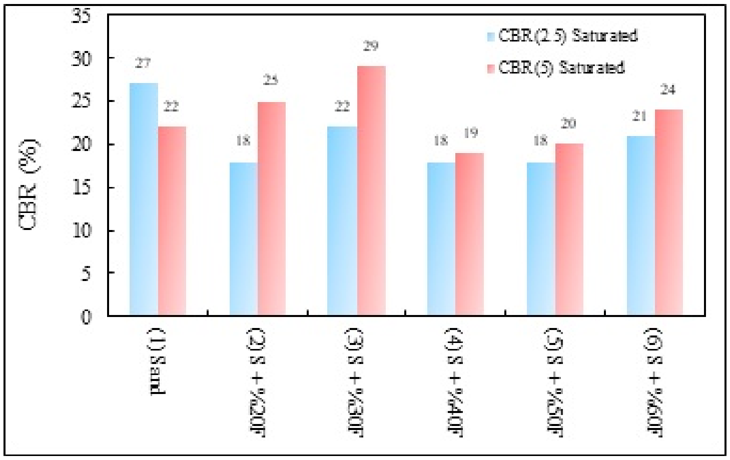

Figure 7. Values of $CBR_{(2.5)}$ and $CBR_{(5)}$ for samples tested at saturation condition

For the other samples, the values of $CBR_{(2.5)}$ were very similar. Changes in $CBR_{(5)}$ exhibited a bell shape, with the highest value recorded for sample 3.

One positive effect of the addition of fine-grained soil to aeolian sand can be seen in the behavioral difference of sample 1 (aeolian sand without fine grains) compared to the other samples. In sample 1, the soil reached its maximum strength after a specific level of stress and then significantly lost strength. This trend was not observed in samples containing fine-grained soil. Those samples showed a continual increase in strength with an increase force.

Discussion

Figure 8 shows the percentage of change of γ_{dmax} and ω_{opt} for the samples. Parameters $\Delta\gamma_{dmax}$ and $\Delta\omega_{opt}$ could be determined as:

$$\Delta\gamma_{dmax} = \frac{\gamma_{dmax} - \gamma_{dmax(S)}}{\gamma_{dmax(S)}} \times 100 \quad (2)$$

$$\Delta\omega = \frac{\omega_{opt} - \omega_{opt(S)}}{\omega_{opt(S)}} \times 100 \quad (3)$$

where γ_{dmax} and $\gamma_{dmax(S)}$ are the maximum dry density for each sample and the maximum dry density of the base soil (aeolian sand), respectively, and ω_{opt} and $\omega_{opt(S)}$ are the optimum water content of each sample and optimum water content of the base soil, respectively.

This figure shows that, for an increase in the percentage of fine grains from 10% to 60% ($10\% \leq W_{S(F)}/W_{S(S)} \leq 60\%$), the value of $\Delta\gamma_{dmax}$ was 11.4% to 21.89% and the highest value was for sample 6. In addition, for an increase in the percentage of fine grains, the range of change in $\Delta\omega_{opt}$ was -25.90% to -33.81%, with the highest percentage of decrease for samples 2 and 5. Decreasing the percentage of ω_{opt} by increasing the fine-grained content increased the usability of this additive for dry areas such as the Khuzestan plain, but produced a significant increase in γ_{dmax} . The addition of fine-grained soil to aeolian sand changed the structure of the soil, reduced the void spaces and increasing the dry density of the samples. Figure 8 shows that sample 5 at $W_{S(F)}/W_{S(S)}$ = 50% can be considered as the best option considering both γ_{dmax} and ω_{opt}.

In Figure 9, $\Delta CBR_{(2.5)}$ and $\Delta CBR_{(5)}$ were calculated using Eqs. (4) and (5) and are presented as a percentage for samples under dry and saturated conditions as:

$$\Delta CBR_{(2.5)} = \frac{CBR_{(2.5)} - CBR_{(2.5)_{(S)}}}{CBR_{(2.5)_{(S)}}} \times 100 \quad (4)$$

$$\Delta CBR_{(5)} = \frac{CBR_{(5)} - CBR_{(5)_{(S)}}}{CBR_{(5)_{(S)}}} \times 100 \quad (5)$$

where $CBR_{(2.5)}$ and $CBR_{(5)}$, are the values for penetrations of 2.5 and 5 mm. respectively, and $CBR_{(2.5)(S)}$ and $CBR_{(5)(S)}$ are the values for the base soil for penetrations of 2.5 and 5 mm, respectively.

In most samples, $\Delta CBR_{(2.5)}$ was negative for the optimum and saturation conditions. This indicates that the addition of fine-grained soil to aeolian sand reduced the $CBR_{(2.5)}$ and reduced the piston penetration resistance compared to aeolian sand alone at low penetrations. In all samples, $\Delta CBR_{(5)}$ for the optimum and saturation conditions was positive. This indicates that $CBR_{(5)}$ for most samples was higher than for aeolian sand alone. In other words, the addition of fine-grained soil to aeolian sand increased the piston penetration resistance compared to aeolian sand alone at penetrations of 5 mm and over. The greatest change was for sample 4 at the optimum water content state. In that sample, $W_{S(F)}/W_{S(S)}$ = 40% and $\Delta CBR_{(5)}$ reached 60% .

A comparison of the results of the samples under saturation and optimum water content conditions generally showed that the addition of fine-grained soil to aeolian sand under saturated conditions had little effect on the CBR. However, materials at the optimum water content that were subjected to loading could have a significant effect on the bearing capacity of aeolian sand. For samples loaded under the saturated condition, with the addition of fine-grained soil, the rate of water drainage decreased. This could be a reason for the decrease in the CBR of the samples mixed with fine-grained soil. When the samples were subjected to the test at the optimum water content, the presence of fine-grained materials reduced the void spaces in the sample, which increased its density. As a result, the CBR of the sample increased.

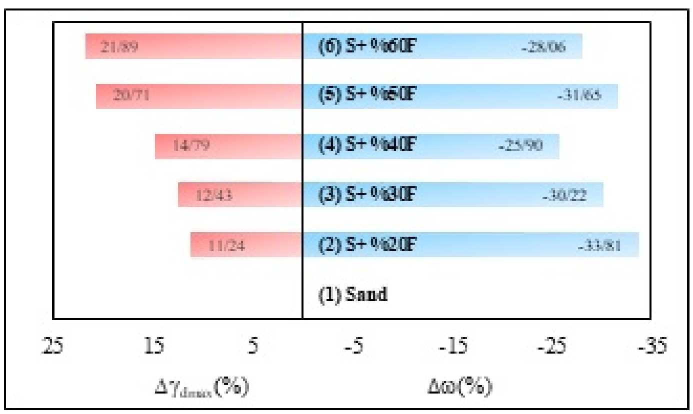

Figure 8. Ratio of change in γ_{dmax} and ω_{opt}

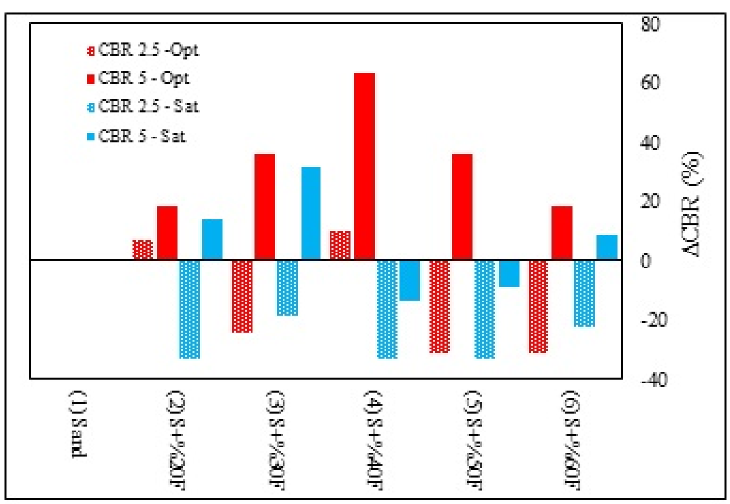

Figure 9. ΔCBR for different CBR tests

Table 5 summarizes previous researches in which different additives were used to improve the γ_{dmax} and ω_{opt} of aeolian sand. Figure 10 compares the values obtained for these parameters. It can be seen that the addition of fine-grained materials to aeolian sand increased the γ_{dmax} of the mixtures more than other additives. Eshraqi et al., (2019) added travertine and granite powder to aeolian sand and reported a γ_{dmax} that was about 7% higher than the value obtained in the present research, but the advantage of fine-grained soil is its availability, especially in areas such as the Khuzestan plain. The change in ω_{opt} in all cases was 8% to 14%, which indicates that the results of the present research with a ω_{opt} of 10% are suitable. In hot and dry regions, reducing the ω_{opt} by adding a suitable additive is a strong point for soil compaction.

Table 6 compares the CBR for samples under both optimum water content and fully saturated conditions with the results of previous research on aeolian sand. Figure 11 is based on the data of Table 6. A comparison of the results shows that the CBR obtained under saturation was about 30% higher than the for research of Hamayun & Yasrobi, (2011). The CBR obtained for the sample under the optimum water content was similar to those of previous research, except for that reported by Eshraqi et al., (2019), which was about 18% higher than the value reported herein.

Comparison of the results of the present research with those of previous research shows that the addition of fine-grained soil to aeolian sand increased the γ_{dmax} and the CBR and reduced the ω_{opt}.

Table 5. γ_{dmax} , ω_{opt} and additive type for present and previous research on aeolian sand

	Researcher	Additive	γ_{dmax} (g/cm^3)	ω_{opt} (%)
1	Present research	Fine grained soil	2.04	10.0
2	Uromeihy et al. (2015)	Nano clay	1.88	13.5
3	Esragi et al. (1390)	Travertine	2.19	8.0
4	Lopez-Querol et al. (2017)	Portland cement	1.72	12.9
5	Arias-Trujillo et al. (2020)	Polyvinyl acrylic	1.78	11.0
6	Homauoni and Yasrobi (2011).	Poly Methyl Methacrylate	1.87	14.0

Table 6. CBR and additive type in present and previous research on aeolian sand

	Researcher	Additive	CBR (Saturation)	CBR (Optimum)
1	Present research	Fine grained soil	39	31
2	Eshragi et al. (1390)	Travertine	46	-
3	Homauoni and Yasrobi (2011).	Poly Methyl Methacrylate	40	24
4	Hazirbaba (2019).	Polyperypilen	38	-

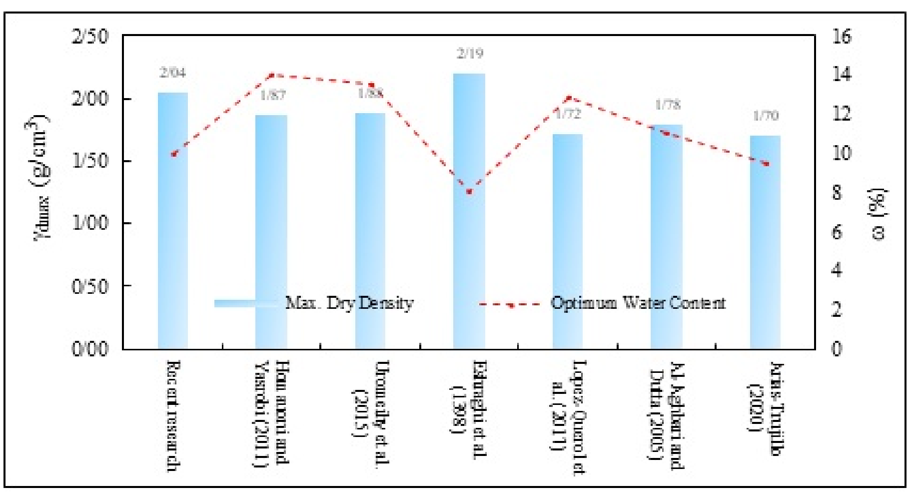

Figure 10. Comparison of γ_{dmax} and ω_{opt} in current and previous research on aeolian sand

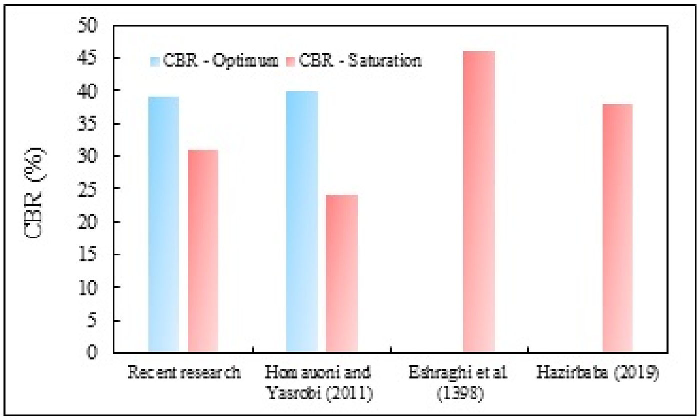

Figure 11. CBR under optimum and saturated conditions in current and previous research on aeolian sand

As this type of soil is in abundance in areas such as the Khuzestan plain, it should be possible and more suitable than other additives to use them to improve the parameters of aeolian sand. The addition of fine-grained material to aeolian sand changed the structure of the soil from granular to composite. This change in the structure has reduced the void spaces and increased the bearing capacity of the soil.

Conclusion

In the present research, aeolian sand from Khuzestan province were used as the base soil to which fine-grained soil, also available in this region, were added to improve the properties of the aeolian sand. Samples with different percentages of fine-grained soil were subjected to granulation, hydrometry, Atterberg limits, specific gravity of solid grains (Gs), density and CBR tests. The effects of these different percentages of fine-grained soil on the maximum dry density, optimum water content and CBR were determined and the following results were obtained:

The granularity of aeolian sand is generally poor. It is classified as SP and A-3 while the fine-grained soil is classified as CL and A-4 (USCS and AASHTO). The plastic limit and the liquid limit of the fine-grained soil were 18% and 28%, respectively.

The maximum dry density had a linear relationship with $W_{S(F)}/W_{S(S)}$ and the highest maximum dry density was for the sample where $\frac{W_{S(F)}}{W_{S(S)}} = 60\%$. The maximum dry density of this sample was 22% higher than the maximum dry density of aeolian sand alone.

The addition of fine-grained soil reduced the optimum water content of the aeolian sand. The optimum water content of 14% of aeolian sand fell to less than 10% in most samples with the addition of fine-grained soil. A decrease of about 26% occurred for the optimum water content.

The CBR of the 5-mm penetration zone in the samples containing fine-grained soil was higher than that of aeolian sand. The highest CBR for penetrations of 2.5 and 5 mm when the samples were tested at an optimum water content was for the sample where $\frac{W_{S(F)}}{W_{S(S)}} = 40\%$.

The addition of fine-grained soil to the aeolian sand for the samples under saturation had little effect on the bearing capacity of the soil.

A comparison of the results of the current and previous research showed that the addition of fine-grained soil increased the maximum dry density and CBR of aeolian sand and reduced the optimum water content. In areas such as the Khuzestan plain, where aeolian sand and fine-grained materials are both found, the use of fine-grained soil to improve the maximum dry density and CBR is suitable.

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