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Stabilized marine and desert sands with deep mixing of cement and sodium bentonite

Mohammad Saberian*[1], Mojtaba Moradi[2], Ramin Vali[3] and Jie Li[4]

[1]School of Engineering, RMIT University, 376-392 Swanston Street, Melbourne, Victoria, Australia
[2]Department of Civil Engineering, Yazd University, Yazd, Iran
[3]Department of Civil Engineering, Mohajer Technical and Vocational College of Isfahan, Isfahan, Iran
[4]School of Engineering, RMIT University, 376-392 Swanston Street Melbourne, Victoria, Australia

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Abstract. Road construction is becoming increasingly important in marine and desert areas due to population growth and economic development. However, the load carrying capacity of pavement is of gear concern to design and geotechnical engineers because of the poor engineering properties of the soils in these areas. Therefore, stabilization of the soils is regarded as an important issue. Besides, due to the fuels combustion and carbonate decomposition, cement industry generates around 5% of global CO_2 emission. Thus, using bentonite as a natural pozzolan in soil stabilization is more eco-friendly than using cement. The aim of this research is to experimentally study of the stabilized marine and desert sands using deep mixing method by ordinary Portland cement and sodium bentonite. Different partial percentages of cement along with different weight percentages of sodium bentonite were added to the sands. Unconfined compression test (UCS), Energy Dispersive X-ray (EDX), and Scanning Electron Microscope (SEM) were conducted on the specimens. Moreover, a mathematical model was developed for predicting the strength of the treated soils.

Keywords: marine and desert sandy soils; deep mixing method; cement; sodium bentonite; unconfined compressive strength; mathematical model

1. Introduction

The rapid development of societies and the growing demand for transportation has led to a growing demand for the construction of high-quality pavements. Since the high values of departures and freights, an extension of road transportation system is regarded a significant matter. In this regard, construction of pavements in desert and marine regions is very demanding due to the problematic sandy subgrades with low rates of strength and cohesion. In these areas due to the uniform particle size distributions of the soils to deep depths, shallow stabilization of the soils is not efficient and reliable (Esmaeili and Khajehei 2016).

Cement stabilization has been proven to be very effective for improving the geotechnical properties of problematic soils (Pakbaz and Alipour 2012, Wong *et al*. 2013, Cong *et al*. 2014, Saberian and Khabiri 2016, Saberian and Rahgozar, 2016). Stabilized problematic soils with cement will introduce bind structure with few void ratios, leading to improvement of geotechnical properties such as unconfined compressive strength, cohesion, angle of internal friction, compaction, and CBR (Su 2009, Azadegan *et al*. 2013, Azadegan *et al*. 2014, Rahgozar and Saberian 2015, Rahgozar and Saberian 2016, Wong *et al*. 2016, Sukpunta and Jotisankasa 2016).

Deep mixed columns of admixture of cement and soil known as soil-cement columns are considered as an effective method to stabilize highway embankments, railroad subgrades, and soil (Ou *et al*. 2013, Ruggeri *et al*. 2014, Jiang and Han 2014, Ignat *et al*. 2015, Esmaeili and Khajehei 2016).

Based on a deep mixing method different percentages of cement (4, 6, 8, and 10%) at moisture contents of 30, 48, and 70% were added to the clay soil and various geotechnical laboratory tests were carried out on the specimens after 7, 14, and 28 days of curing. It was observed that by increasing the percentages of cement and decreasing the water moisture content, unconfined compressive strength, unit weight, liquid limit, compression index, and pre-consolidation pressure increased (Pakbaz and Alipour 2012). To improve the bending behavior of deep soil-cement columns, Sukontasukkul and Jamsawang (2012) studied the effects of addition of short steel fibers and propylene to the soil. To alleviate weakness and brittleness of the cement columns, different percentages of the fibers (0.5, 0.75, and 1%) were added to the soil. It was observed that although toughness and bending performance of the cement columns were improved by the addition of the fibers, a mixture of propylene fibers with soil improved the mentioned properties of the columns more than steel fibers. Sargent *et al*. (2013) added alkali activated waste binders to the depth of soft alluvial soil to enhance the durability and mechanical properties of the soil. It was found that the stabilized soil with alkali activated blast furnace slag indicated the most improvement of strength and durability.

*Corresponding author, Ph.D. Candidate
E-mail: s3609245@student.rmit.edu.au

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Moreover, due to the pozzolanic reactions of alkali activators, mechanical properties of the soils improved. Besides, although alkali activation resulted in a marginal increase in durability, additions of by-products improved the soil durability noticeably. Experimentally analysis of the cement stabilized clay soil strength was concluded that the application of pozzolanic additives increased substantially the strength properties of the soil such as unconfined compressive strength and secant modulus. The results led to offer an economical and environmental-friendly mix design (Cong *et al*. 2014).

Zhuang and Wang (2016) treated soft soil subgrade of railroad using deep cement columns. The results proposed that cement columns not only increased bearing capacity and decreased soft soil settlement, but they also accelerated the stabilization procedure. Investigation of treating soft grounds using cement columns indicated that ground settlement improved markedly because of increasing the length of columns (Yao *et al*. 2016). Esmaeili and Khajehei (2016) applied deep mixing cement by 10 cm diameters, 40 cm length, and 25 cm center to center spacing in groups by two different patterns of square and triangle forms into a loose sandy subgrade of the railway embankment. It was concluded that failure load increased 64% and crest settlement of embankment decreased 40% when using the square pattern compared with that of the untreated embankment. For triangular pattern, the failure load increased at 63% and crest settlement of embankment decreased by 12%. Therefore, the performance of triangular deep mixing cement columns was better than that of the square one.

Szymkiewicz *et al*. (2012) studied the effects of grain size distribution and the amount of cement in deep cement columns on strength and behavior of treated sandy soils. Based on the results of unconfined compression tests they found that an even cement treated sand proposed similar hardening trend for all cement contents and soil with a larger distribution of grain size showed different hardening processes, depending on the cement content. Farouk and Shahien (2013) added different percentages of cement and different water-cement ratios to the silty sand soil extracted from Delta of the River Nile to improve the geotechnical properties of the soil and modeled a strip footing on the improved soil to investigate the interaction of the footing and the soil. It was concluded that unconfined compressive strength of the stabilized soil increased significantly and depending on the both number and the length of the soil-cement columns, settlement of the footing reduced up to 80%.

Pozzolan is a siliceous or siliceous and aluminous material which is very fine and it reacts with calcium hydroxide at ambient temperatures in the presence of water to create cemented compounds. To form calcium silicate hydrate (CSH: $3CaO{\cdot}2SiO_2{\cdot}3H_2O$) and calcium aluminate hydrate (CAH: $3CaO.Al_2O_3$), Ca^{2+} ions from ordinary Portland cement and sodium bentonite react with alumina and silica in the soil in a pozzolanic reaction. By passing adequate curing times, the compounds then crystallize, led to increasing soil strength (Dingwen *et al*. 2013, Iravanian and Bilsel 2014, Saberian and Rahgozar 2016, Kim and Kim 2016, Jahandari *et al*. 2017(a)).

Due to a reduction of both CO_2 emissions and costs, natural pozzolans such as sodium bentonite are substituted for cement. They can reduce the permeability of the soil and increase chemical resistance (Papadakis and Tsimas 2002, Gueddouda *et al*. 2010). The most significant features of natural pozzolans are that they are very fine and vitreous, and comprised mainly of silica (SiO_2) and alumina (Al_2o_3) in their oxide compositions. They are used to alleviate alkali silica reaction during the first step of curing of cement. The most important role of them is to neutralize the excessive alkalinity of cement with silica acid (H_2SiO_4) (Wong *et al*. 2013). Sodium bentonite is formed from volcanic ash alteration and can absorb aluminum silicate. Since it highly reacts with calcium hydroxide released from cement hydrolysis, it is utilized to partially replace cement in the production of cement. Therefore, it can improve and stabilize any soils. Moreover, due to its fineness, it acts as a filler to bond the cemented materials (Cristelo *et al*. 2012). Therefore, sodium bentonite can increase plasticity behavior and shear strength of soils (Worrall 1986).

Due to the fuels combustion and carbonate decomposition, cement industry generates around 5% of global CO_2 emission (Velosa and Cachim 2009, Khabiri 2010). Therefore, using bentonite as a natural pozzolan in soil stabilization is more environmentally friendly than using cement. On the other hand, for new applications of deep mixing method, sandy soils are the most suitable since the created materials can be compared to mortars (Szymkiewicz *et al*. 2012). Therefore, in this study, both marine and desert sandy soils were experimentally stabilized with ordinary Portland cement (C) and sodium bentonite (SB) to strength the soils. In order to determine the performance of both stabilized soils, the following properties of the materials and the stabilized specimens were measured after 28 curing days using unconfined compression test: unconfined compressive strength (q_u), failure strain (ε_f), brittleness index (I_B), resilient modulus (M_r), and secant modulus (E_s). Mathematical models for both marine and desert sands were developed to predict the compressive strength of the stabilized soils. It is worth adding that before UCS tests, the oxide compositions of all the materials used in this study were determined using X-Ray Fluorescence (XRF) test. Furthermore, the microstructures of the used materials in this study and the stabilized soils were investigated using SEM test. Also, Energy Dispersive X-Ray (EDX) test was conducted to obtain the chemical elements of the untreated and treated soils.

2. Properties of the materials

The desert sand and marine sand used in this study were sampled from Yazd and Mahshahr, Iran, respectively. Particle size distribution test was carried out on the sands according to ASTM D422-63 to determine the basic properties of the soils such as effective size, the coefficient of uniformity, and coefficient of curvature of the soils. Fig. 1 depicts the particle size distribution curves of the sands. The basic geotechnical and chemical properties of the soils are summarized in Table 1. It can be observed that both sands are poorly graded sands.

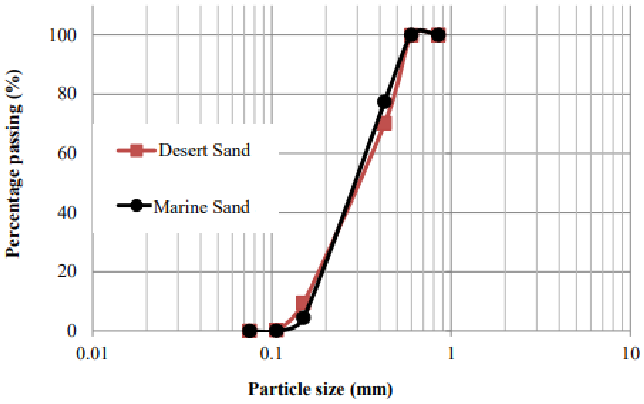


Fig. 1 Particle size distribution curves of desert and marine sands

Table 1 Basic geotechnical and chemical properties of the sands

Basic soil properties	Desert sand	Marine sand	Method
Unified Soil Classification	SP	SP	Unified Soil Classification System
Effective size, D_{10}	0.16	0.18	ASTM D422-63
Coefficient of uniformity, C_u	2.31	1.83	ASTM D422-63
Coefficient of curvature, C_C	0.74	0.89	ASTM D422-63
Natural moisture content, ω (%)	4-9	28–56	ASTM D2216-10
Specific gravity	2.66	2.35	ASTM D854-10
Bulk density, γ (kN/m^3)	16	15.3	ASTM D1557-07
Saturated density, γ_{sat} (kN/m^3)	18	17.1	ASTM D2435M-11
Cohesion, C (kPa)	0.1	0.45	ASTM D2435M-11
Angle of internal friction, ϕ (degree)	42	36	ASTM D2435M-11
pH	7.93	8.2	ASTM D4972-13
Electrical conductivity, ds/m	1.83	1.91	Shah and Singh (2004)
Na, Meq/Lit	5.5	10.1	ASTM D7503-10
Mg+Ca, Meq/Lit	11.2	15.6	ASTM D7503-10
Gypsum, Meq/Lit	0.2	0.5	ASTM D7503-10
Sum Cat	16.7	18.95	ASTM D7503-10
SAR	2.32	7	ASTM D7503-10

In addition, X-Ray Fluorescence (XRF) test was performed using Bruker S4-Explorer X-Ray Fluorescence (1 kW) instrument to chemically analyze the materials used in this study. Oxide compounds of dry sands, ordinary Portland cement, and bentonite are given in Table 2.

From Table 2 it can be observed that ordinary Portland cement is mainly characterized by alumina (Al_2O_3), silica (SiO_2), quicklime (CaO), and ferric oxide (Fe_2O_3). This finding was also observed by Felekoğlu *et al.* (2009), and Saberian and Rahgozar (2016). In sodium bentonite, the essential pozzolanic compounds of Al_2O_3, SiO_2, and Fe_2O_3 were 17.29%, 62.38%, and 5.22%, respectively, making a total of 84.89%. ASTM C618 recommends that on the condition that the sum of these three compounds exceeds 70%, the material characterized as a natural pozzolan. Therefore, such an indication confirms that sodium bentonite is considered as a natural pozzolan. Based on the results of XRF on sands, It can be asserted that quartz

Table 2 Percentages of oxide compounds in dry sands, ordinary Portland cement, and sodium bentonite tested in this study, measured by X-ray fluorescence (XRF)

Oxide compound	Ordinary Portland cement (%)	Sodium bentonite (%)	Dry desert sand (%)	Dry marine sand (%)
CaO	61.24	3.45	9.64	0.37
SiO_2	19.36	62.38	61.77	87.67
Al_2O_3	4.92	17.29	6.52	5.12
Fe_2O_3	3.17	5.22	4.68	1.10
MgO	0.92	3.12	2.91	0.18
SO_3	2.05	0.11	7.68	0.15
K_2O	0.49	0.81	0.93	1.34
TiO_2	0.26	0.62	0.12	1.29
SrO	0.045	-	0.001	-
P_2O_5	0.12	0.12	0.13	0.81
Na_2O	0.082	4.97	0.48	-
MnO	0.19	0.04	0.018	-
ZnO	-	0.008	0.002	0.007
LOI	6.59	1.12	2.92	0.57
Total (%)	99.43	99.26	97.80	98.60

(SiO2) is the major mineral in the desert sand and marine sand at 61.77% and 87.67%, respectively.

3. Materials and methods

3.1 Added materials and sample preparations

To study the effects of deep mixing on the stabilized sands, different partial replacements of cement (C) 20, 30, 50, and 70% by 0.5 ratio of water/cement, and extra amounts of sodium bentonite (SB) at different percentages of 2, 3, 4, and 5% by dry weight percentages of soil were added to the soils and unconfined compression test was conducted on the specimens after 28 days of curing. It is worth adding that 2 kg of the soil were considered for each specimen and water content was calculated based on the weight of cement for each sample (Table 3). To eliminate any unexpected experimental errors each test was replicated three times on three different specimens and a mean result computed. Therefore, 96 specimens were totally prepared and tested (3 replicate per treatment×4 cement partial replacements×4 bentonite percentages×2 sands). Table 3 shows different percentages of additives.

3.2 Testing methodologies

UCS test is one of the most common tests for evaluation of strength of soils and determination of required contents of stabilizer agents. UCS test was carried out based on ASTM D1633-00 (standard test methods for compressive strength of molded soil-cement cylinders). The test

Table 3 Percentages of additives of the specimens

Cement (%)	Water/Cement	Water (gr)	Cement (gr)	Sodium bentonite (%)	Sand (%)
20	0.5	200	400	2, 3, 4, and 5	80
30	0.5	300	600	2, 3, 4, and 5	70
50	0.5	500	1000	2, 3, 4, and 5	50
70	0.5	700	1400	2, 3, 4, and 5	30

specimens were prepared by diameters and heights of 2.8 and 5.6 inches, respectively. Height to diameter ratio equaled 2.

Using VEGA3 TESCAN apparatus, the microstructures of air-dried untreated and stabilized sands were studied by Scanning Electron Microscope test. Furthermore, to obtain chemical elements of the admixtures, Energy Dispersive X-Ray (EDX) tests were conducted.

4. Results and discussion

4.1 Unconfined compression test

Tables 4 and 5 show the effect of adding different percentages of ordinary Portland cement and sodium bentonite after 28 curing days on the maximum unconfined compressive strength of stabilized desert and marine sands, respectively. Figs. 2 and 3 illustrate the effects of adding different percentages of bentonite (SB) (2, 3, 4, and 5%) and partial replacement of cement (C) by 20% after 28 curing days on the relationships between unconfined compressive stress and axial strain for stabilized desert sand and marine sand, respectively. The relationships between UCSs and axial strains for untreated sands are also presented in Figs. 2 and 3. Figs. 4 and 5 show the relationships between UCSs and axial strains for untreated sands and treated sands with different partial replacements of ordinary Portland cement and 5% bentonite. The maximum values of each specimen are also provided in the Figs. 2-5.

Table 4 The unconfined compressive strength (kPa) of the stabilized desert sand

Sodium Bentonite (%)	Partial replacements of cement (%)			
	20	30	50	70
2	3617.83	2751.6	1987.26	1324.84
3	4178.34	3210.19	2343.94	1630.57
4	4840.76	3719.74	2751.59	1987.26
5	5859.87	4433.12	3312.10	2394.90

Table 5 The results of unconfined compressive strength (kPa) of the stabilized marine sand

Sodium Bentonite (%)	Partial replacements of cement (%)			
	20	30	50	70
2	2700.63	1987.26	1375.79	866.24
3	3261.14	2445.85	1732.48	1171.97
4	3872.61	2955.41	2191.08	1579.61
5	4359.94	3363.05	2394.90	1630.57

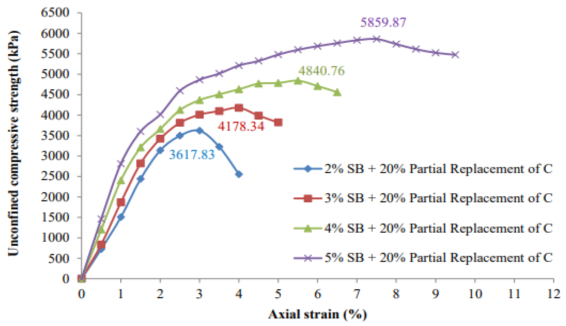


Fig. 2 The relationship between UCS and axial strain for stabilized desert sand with different percentages of bentonite and 20% partial replacement of cement after 28 curing days

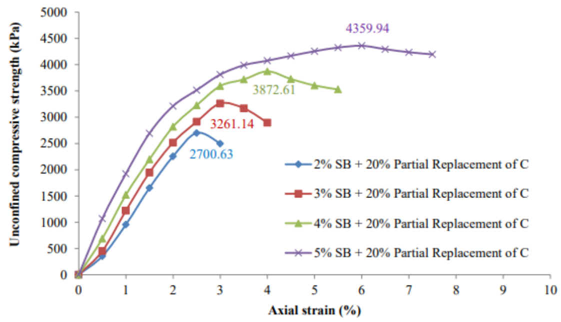


Fig. 3 The relationship between UCS and axial strain for stabilized marine sand with different percentages of bentonite and 20% partial replacement of cement after 28 curing days

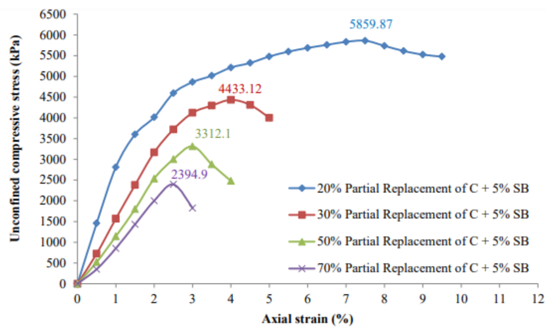


Fig. 4 The relationship between UCS and axial strain for stabilized desert sand with different partial replacements of cement and 5% bentonite after 28 curing days

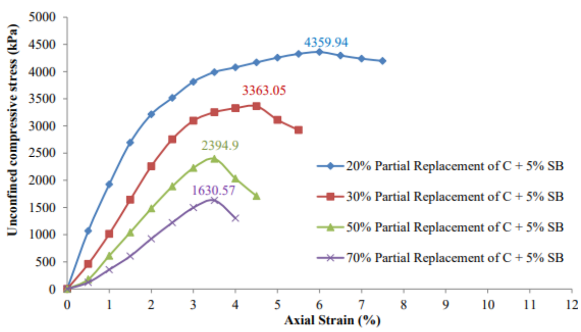


Fig. 5 The relationship between UCS and axial strain for stabilized marine sand with different partial replacements of cement and 5% bentonite after 28 curing days

According to ASTM D4609 (Standard guide for evaluating the effectiveness of admixture for soil stabilization), soil stabilization is effective enough if the resulting UCS is at least 345 kPa (50 psi) (Sariosseiri and Muhunthan 2009). As it can be seen from Tables 4-5, the UCS of all the specimens exceeded 345 kPa. For both desert and marine sands, it can be observed from the results that the test specimens with 5% sodium bentonite and 20% partial replacement of cement after 28 curing days had the highest UCS values at 5859.87 kPa and 4359.94 kPa, respectively. Also, for the specimens with similar percentages of additives, the UCS values of the treated desert sand are much higher than those of the treated marine sand. This is because the marine sand is weaker due to its higher natural moisture content. On the other hand, by increasing the percentages of bentonite and decreasing the partial replacements of cement, the UCS of both sands increased. As it is clear, sand plays as an aggregate in specimens. When an inappropriate amount of sand is used, pozzolanic reactions cannot lead to firm bindings between cement and sand aggregates. Therefore by increasing the partial replacement of cement, UCS of specimens decreased. Hashemi *et al*. (2012), Ata *et al*. (2015), Shooshpasha and Shirvani (2015), and Gupta and Kumar (2017) also reported similar trend.

4.2 Failure strain

The failure strains (ε_f) corresponding to the maximum UCSs of the specimens are provided in Table 6. Based on Table 6, the stabilized desert and marine sand specimens with 5% sodium bentonite and 20% partial replacement of ordinary Portland cement after 28 curing days had the highest failure strains at 7.5% and 6%, respectively. Moreover, by increasing the percentages of sodium bentonite, failure strain of the specimens increased. This indicates that adding sodium bentonite to the soils plays significant roles in increasing the plasticity and deformability of the specimens. This trend was also observed by Worrall (1986).

Failure strains of the specimens with different partial replacements of cement and 5% bentonite are shown in Table 7. At a given percentage of bentonite (5%), increasing the partial replacements of cement from 20% to 70% led to decrease failure strains of the stabilized desert and marine sands from 7.5 to 2.5% and from 6 to 3.5%, respectively. It can be inferred that addition of cement increases the brittleness of the specimens. This trend was also observed by Pakbaz and Alipour (2012), Azadegan *et al*. (2013), and Eskisar (2015).

4.3 Secant modulus

Secant modulus (E_s) is defined as ratio of one half of the compressive strength to the axial strain corresponding to this stress (Cong *et al*. 2014). Table 6 provides secant modulus of the specimens with different percentages of bentonite (i.e., 2, 3, 4, and 5%) and 20% partial replacement of cement after 28 curing days. Based on the results, it can be seen that by increasing the percentages of bentonite from 2 to 5%, secant modulus of the stabilized desert and marine sands increased from 144.71 MPa to 279.04 MPa and from 108.01 MPa to 198.17 MPa, respectively. For both of the stabilized desert and marine sands with 20% partial replacement of cement and 5% sodium bentonite the highest E_s values were observed at 279.04 and 198.17 MPa, respectively.

Table 7 shows secant modulus of the specimens with different partial replacements of cement and 5% bentonite after 28 curing days. By increasing the partial replacements of cement from 20% to 70%, E_s values of the stabilized desert and marine sands decreased from 297.04 to 95.79 MPa and from 198.17 to 58.23 MPa, respectively. Similar to UCS results, E_s values of the treated desert sand specimens are higher than those of the marine ones. These trends were also observed by Mun *et al*. (2012) on the study of soil cement deep mixing wall in sand.

4.4 Brittleness index

From Figs. 2 and 3, it can be seen that by increasing the percentages of bentonite, failure strains increased. Therefore, the stabilized specimens with higher percentages of bentonite provided more ductile behavior. On the other hand, based on Figs. 4 and 5, it is obvious that by increasing the ordinary Portland cement, the treated specimens indicated brittle behaviors since at first there were steep linear elastic curves followed by elastic deformations (i.e., no plastic deformation) with no energy adsorptions before their quick fractures.

Brittleness index is known as difference between the peak and critical un-drained shear strengths normalized by the peak un-drained strength. It is an indicator for characterization of soil severity of strain softening and soil contractiveness (Bishop 1971)

$$I_B = \frac{(q_p - q_r)}{q_p} \tag{1}$$

where q_p and q_r are the peak stress and critical und-rained shear strength obtained from unconfined compressive strength curves, respectively.

Brittleness indexes of the specimens with different percentages of bentonite and 20% partial replacement of cement are given in Table 6. From Table 6 it can be seen that by increasing the sodium bentonite, brittleness index decreased. Moreover, the brittleness indexes of stabilized desert and marine sands with 5% bentonite and 20% partial replacement of cement were the least at 0.31 and 0.26, respectively. Thus, addition of sodium bentonite led to increase the ductile behavior of specimens.

Brittleness indexes of the specimens with different partial replacements of cement and 5% bentonite are provided in Table 7. By increasing the partial replacements of cement from 20% to 70% at a given percentage of bentonite (5%), the brittleness indexes of stabilized desert and marine sands increased from 0.31 to 0.85 and from 0.26 to 0.62, respectively. Also, it is obvious that the specimens of 20 and 30% partials replacement of cement, showed almost ductile behavior, however, the specimen of 50% partials replacement of cement provided ductile/brittle behavior and the specimen of 70% partials replacement of cement demonstrated brittle behavior. Therefore, addition of cement led to increase the brittle behavior of specimens.

Table 6 Failure strain, secant modulus, brittleness index, and resilient modulus of both stabilized sands with different percentages of bentonite and 20% partial replacement of cement after 28 curing days

Sodium bentonite (%)	Stabilized desert sand				Stabilized marine sand			
	ε_f (%)	E_s (MPa)	I_B	M_r	ε_f (%)	E_s (MPa)	I_B	M_r
2	3	144.71	0.79	517.31	2.5	108.01	0.64	403.68
3	4	189.92	0.55	586.71	3	130.44	0.40	473.18
4	5.5	242.03	0.33	669.05	4	138.30	0.27	549
5	7.5	279.04	0.31	795.42	6	198.17	0.26	609.43

Table 7 Failure strain, secant modulus, brittleness index, and resilient modulus of both stabilized sands with different percentages of partial replacement of cement and 5% bentonite after 28 curing days

Partial replacement of cement (%)	Stabilized desert sand				Stabilized marine sand			
	ε_f (%)	E_s (MPa)	I_B	M_r	ε_f (%)	E_s (MPa)	I_B	M_r
20	7.5	297.04	0.31	795.42	6	198.17	0.26	609.43
30	4	151.81	0.46	618.51	4.5	111.35	0.32	485.82
50	3	113.42	0.65	479.50	3.5	49.89	0.56	365.77
70	2.5	95.79	0.85	365.77	3.5	58.23	0.62	271

4.5 Resilient modulus

According to AASHTO Test Method T307 (2005), resilient modulus is a measure of the elastic response of soil to stress. moreover, this parameter is the stress ratio to recoverable strain on the 200th load repetition. Resilient modulus can be directly used for design of flexible pavements. It can be measured from the following equation proposed by Thompson (1966) based on UCS value as follows

$$M_r(MPa) = 0.124 \times UCS(kPa) + 68.8 \tag{2}$$

Based on Table 6, by increasing the sodium bentonite from 2 to 5%, resilient modulus of desert and marine sands increased from 517.31 to 795.42 MPa and from 403.68 to 609.43 MPa, respectively. On the other hand, from Table 7 it can be seen that by increasing the partial replacements of cement from 20% to 70%, resilient modulus of desert and marine sands decreased from 795.42 to 365.77 MPa and from 609.43 to 271 MPa, respectively.

4.6 Mathematical model

The results of UCS test showed that partial replacements of cement and sodium bentonite had significant effects on the strength of the stabilized sands. In other words, a small difference in percentages of cement and/or bentonite had substantial influences on the performance of soil-cement-bentonite-mixtures.

Consoli *et al*. (2010), Cong *et al*. (2014), Saberian *et al*. (2017a) and Saberian *et al*. (2017b) proposed a power function (Eq. (3)), since it had the most adaptation to fit the experimental relation between UCS (q_u) and cement content. Taking ratio of SB/C (sodium bentonite/cement) as a variable, Eq. (3) can be used to develop equations for predicting UCS of the both stabilized sands after 28 curing days. The relationship between UCS and the variable of SB/C can be expressed as Eq. (4).

$$q_u = a \times C^b \tag{3}$$

$$q_u = a \times \left(\frac{SB}{C}\right)^b \tag{4}$$

where a (in kPa) and b (dimensionless parameter) are fitting parameters and SB/C is the percentages of sodium bentonite/partial replacements of cement.

Table 8 summarizes the values of SB/C ratio and UCSs of the stabilized sands after 28 days of curing based on the UCS laboratory test results. It also provides predicted UCS values of the specimens calculated from Eqs. (5) and (6) as well as deviation of each value. Fig. 6 shows the mathematical models of both sands on the basis of q_u-(SB/C) after 28 curing days.

Table 8 Values of the SB/C ratio and UCS for both sands

SB/C	Desert sand			Marine sand		
	Actual UCS (kPa)	Predicted UCS (kPa)	Deviation (%)	Actual UCS (kPa)	Predicted UCS (kPa)	Deviation (%)
0.1, (2/20)	3617.83	3199.57	11.56	2700.63	2398.19	11.19
0.0667, (2/30)	2751.6	2445.48	11.12	1987.26	1787.31	10.06
0.04, (2/50)	1987.26	1741.16	12.38	1375.79	1233.04	10.37
0.0285, (2/70)	1324.84	1390.82	4.9	866.24	964.05	11.29
0.15, (3/20)	4178.34	4187.58	0.22	3261.14	3219.04	1.29
0.1, (3/30)	3210.19	3199.57	0.33	2445.85	2398.19	1.94
0.06, (3/50)	2343.94	2279.56	2.7	1732.48	1655.09	4.46
0.0428, (3/70)	1630.57	1821.71	11.72	1171.97	1295.13	10.5
0.2, (4/20)	4840.76	5068.57	4.7	3872.61	3966.73	2.43
0.1334, (4/30)	3719.74	3873.98	4.14	2955.41	2956.29	0.02
0.08, (4/50)	2751.59	2759.13	0.2	2191.08	2039.52	6.91
0.0571, (4/70)	1987.26	2205.82	10.99	1579.61	1596.62	1.07
0.25, (5/20)	5859.87	5877.66	0.3	4359.94	4664.32	6.98
0.1667, (5/30)	4433.12	4491.49	1.3	3363.05	3475.44	3.34
0.1, (5/50)	3312.1	3199.57	3.39	2394.9	2398.19	0.13
0.0714, (5/70)	2394.9	2558.53	6.83	1630.57	1877.88	15.16

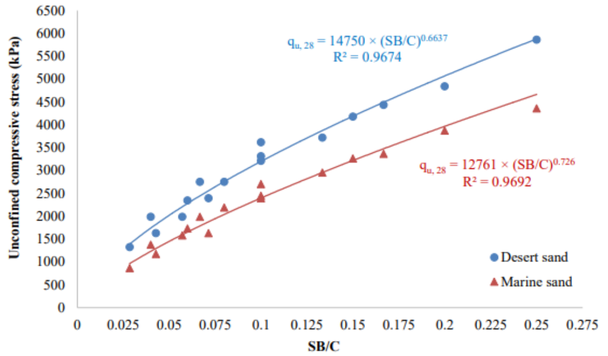


Fig. 6 Fitted curves of UCS development in the stabilized sands using the SB/C ratio hypothesis

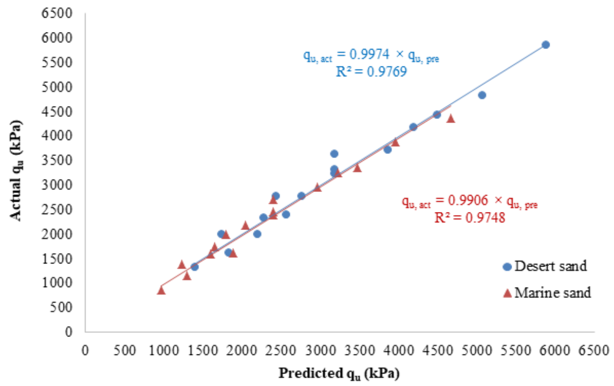


Fig. 7 Actual values of UCSs of the stabilized desert sand and marine sand versus those predicted UCSs values by Eqs. (5) and (6), respectively

Based on the mathematical model and Fig. 6, two equations can be obtained to estimate UCSs for the sands stabilized with different percentages of bentonite and different partial replacements of cement. The results are presented by Eqs. (5) and (6). The mean values of desert and marine deviations were measured at about 5.42% and 6.1%, respectively.

$$q_u = 14750 \times \left(\frac{SB}{C}\right)^{0.6637}, R^2 = 0.9674 \text{, Mean deviation} = 5.42\% \quad \text{Desert sand} \tag{5}$$

$$q_u = 12761 \times \left(\frac{SB}{C}\right)^{0.726}, R^2 = 0.9692 \text{, Mean deviation} = 6.07\% \quad \text{Marine sand} \tag{6}$$

Eqs. (7) and (8) show good correlation between the laboratory results of UCSs after 28 curing days and the predicted values given by the predicted Eqs. (5) and (6).

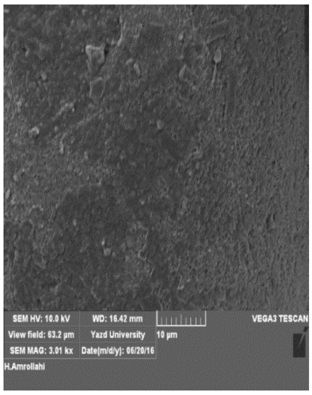
$$q_{uact,28} = 0.9974 \times q_{upre}, R^2 = 0.9769 \quad \text{Desert sand} \tag{7}$$

$$q_{uact,28} = 0.9906 \times q_{upre}, R^2 = 0.9748 \quad \text{Marine sand} \tag{8}$$

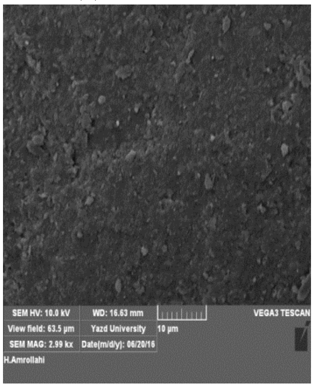
4.7 Scanning Electron Microscope test

Fig. 8 (a)-8(d) show the scanning electron micrographs (SEM) of the air dried marine sand, desert sand, stabilized marine sand with 20% partial replacement of cement and 5% bentonite after 28 curing days, and stabilized desert sand with 20% partial replacement of cement and 5% bentonite after 28 curing days, respectively. It is clear that the marine sand was composed of evener and finer particles, led to propose lower UCS, E_s, and M_r values than that of the desert one. Based on the stabilized figures, it can be concluded that both stabilized sands were characterized by well-structured matrixes with very small pores, due to the pozzolanic reactions of cement and bentonite, and as a result of the bentonite filling a large fraction of the voids, however, just a few more voids were observed in the stabilized marine, led to propose lower UCS, E_s, and M_r values than that of the desert one.

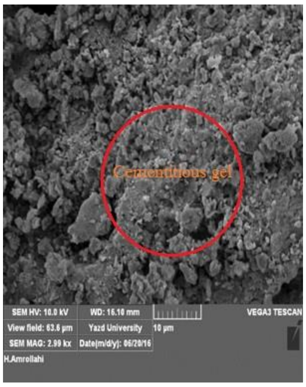
On the other hand, soil stabilization occurs via time-dependent pozzolanic reactions that happen over a time span of days to years, depending on reactant supply. By an addition of sufficient quantity of the chemical additives into the soils, pH of the soils increases significantly, leading to increasing the solubility of



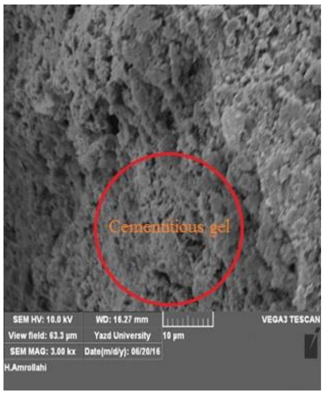
(a) Marine sand



(b) Desert sand

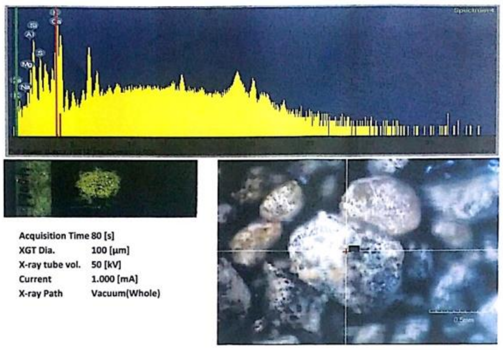


(c) Stabilized marine sand with 20% partial replacement of cement and 5% bentonite



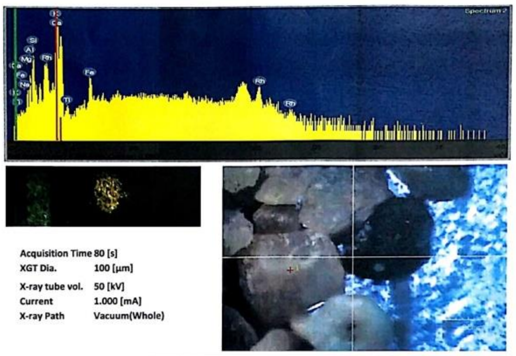
(d) Stabilized desert sand with 20% partial replacement of cement and 5% bentonite

Fig. 8 Scanning electron micrographs



Elem.	Line	Mass[%]	3sigma	Atomic[%]	Intensity[cps/mA	Formula	Mass[%]	Molecule[%]
12 Mg	K	0.86	0.28	0.72	2.75	MgO	**1.43**	1.88
13 Al	K	1.47	0.13	1.1	17.11	Al2O3	**2.78**	1.44
14 Si	K	6.88	0.18	4.96	160.89	SiO2	**14.72**	12.98
16 S	K	0.59	0.03	0.37	46.98	SO3	**1.46**	0.97
19 K	K	0.31	0.03	0.16	18.97	K2O	**0.37**	0.21
20 Ca	K	31.11	0.27	15.71	2169.06	CaO	**43.52**	41.13
22 Ti	K	0.09	0.02	0.04	4.67	TiO2	**0.14**	0.09
25 Mn	K	0.04	0.01	0.01	4.06	MnO2	**0.06**	0.04
26 Fe	K	1.11	0.04	0.4	148.14	Fe2O3	**1.59**	0.53
37 Rb	K	0.03	0.01	0.01	6.86	Rb2O	**0.04**	0.01
38 Sr	K	0.1	0.01	0.02	21.13	SrO	**0.12**	0.06
O		23.65	0.32	29.92				
L.O.I		33.76		46.58			**33.76**	40.65

(a) Stabilized desert sand



Elem.	Line	Mass[%]	3sigma	Atomic[%]	Intensity[cps/mA]	Formula	Mass[%]	Molecule[%]
12 Mg	K	1.32	0.28	1.09	4.49	MgO	**2.19**	2.77
13 Al	K	1.22	0.13	0.91	15.09	Al2O3	**2.31**	1.16
14 Si	K	2.93	0.13	2.09	74.14	SiO2	**6.27**	5.33
16 S	K	0.08	0.01	0.05	7.53	SO3	**0.19**	0.12
19 K	K	0.09	0.02	0.05	6.74	K2O	**0.11**	0.06
20 Ca	K	35.42	0.26	17.71	2850.04	CaO	**49.55**	45.1
22 Ti	K	0.02	0.02	0.01	0.84	TiO2	**0.03**	0.02
25 Mn	K	0.01	0.01	0.01	1.63	MnO2	**0.02**	0.01
26 Fe	K	0.13	0.02	0.05	17.61	Fe2O3	**0.18**	0.06
38 Sr	K	0.02	0.01	0	4.63	SrO	**0.03**	0.01
O		19.65	0.28	24.61				
L.O.I		39.11		53.43			**39.11**	45.36

(b) Stabilized marine sand

Fig. 9 EDX results of the air dried samples stabilized with 20% partial replacement cement and 5% bentonite after 28 days of curing.

silica/alumina compounds present in the soils minerals and results in the formation of cementing agents (Fig. 8 (c) and 8(d)). As it was mentioned, the growth of the geotechnical properties is the result of pozzolanic reactions during the curing periods. So that the reaction of quicklime (CaO) with water, forms hydrated (slaked) lime ($Ca(OH)_2$). Then, the hydrated lime is dissolved into the water and the concentrations of hydroxyl $(OH)^{-1}$ and calcium (Ca^{2+}) ions are increased. In the presence of water, pozzolans (compounds usually consisting of silicates, alumina and/or alumino-silicates) react with calcium hydroxide forming the calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH), and calcium aluminate silicate hydrate (CASH). Therefore, stabilization of the soils occurs during the reactions because of ion exchange reactions during the curing time and properties of the soils are improved by the creation of extra bonds due to the pozzolanic reactions (Jahandari *et al*. 2017c). Similar results can be observed in SEM arising from other studies of stabilized sand with cement and fiber (Marri *et al*. 2014), and stabilized sand with bentonite (Saba *et al*. 2014).

4.8 Energy dispersive X-Ray (EDX) test

Fig. 9(a) and 9(b) represents the results of Energy Dispersive X-ray (EDX) test on the air dried desert and marine sands stabilized with 20% partial replacement of ordinary Portland cement and 5% sodium bentonite after 28 curing days, respectively.

From Fig. 9 it can be seen that the both stabilized desert and marine sands comprised high amounts of aluminum (Al), calcium (Ca), oxygen (O), and silicon (Si) which constituted 63.11% and 59.22% of total weight percentages of the specimens, respectively. These elements contribute most to pozzolanic reactions for formation of CAH and CSH crystals, which are the main cementation products in the treated soils (Jahandari *et al*. 2017b, Saberian and Rahgozar 2016). Since sum of the elements in the stabilized desert sand was more than those of the elements of the marine one, the stabilized desert sand exhibited higher values of UCS, E_s, and M_r.

5. Conclusions

In this study, a number of important parameters and properties were studied through laboratory experiments, which include curing time, oxide compounds, UCS, E_s, ε_f, I_B, and M_r. The objective of this research was to study of the effects of sodium bentonite as a natural pozzolan and partial replacement of cement on the properties of marine and desert sands after 28 days of curing. In addition, a mathematical model was used to develop equations for predicting the UCS values of the stabilized sands based on the SB/C ratio.

• Based on XRF test, since the sum of Al_2O_3, SiO_2, and Fe_2O_3, which made up 84.89%, exceeded 70%, sodium bentonite is considered a natural pozzolan. Moreover, quartz (SiO_2) was the major mineral in desert and marine sands at 62.38% and 61.77%, respectively.

• By increasing the percentages of bentonite and decreasing the partial replacements of cement, the UCS, E_s, and M_r of both sands increased.

• From UCS test, it was observed that the test specimens with 5% sodium bentonite and 20% partial replacement of cement after 28 curing days had the highest UCS values at 5859.87 kPa and 4359.94 kPa, respectively.

• For the specimens with a given percentages of additives, the UCS, E_s, and M_r values of treated desert sand were higher than those of the treated marine sand. This could be contributed to higher natural moisture content of the marine sand.

• Adding sodium bentonite to the soils played significant roles in increasing the deformability of specimens. Although, adding cement increased the brittleness of specimens.

• From the mathematical model, good correlations between the laboratory results of UCS test after 28 curing days and the UCS values given by the predicted equations were observed ($R^2 > 0.96$).

• From SEM test, the marine sand was composed of evener and finer particles, led to propose lower UCS, E_s, and M_r values than that of the desert one. Moreover, both stabilized sands were characterized by well-structured matrixes with very small pores, due to the pozzolanic reactions of cement and bentonite, and as a result of the bentonite filling a large fraction of the voids.

• From EDX test, the stabilized desert sand and marine sand comprised high amounts of aluminum (Al), calcium (Ca), oxygen (O), and silicon (Si) which constituted 63.11% and 59.22% of total weight percentages of the specimens, respectively. These elements contribute most to pozzolanic reactions for formation of CAH and CSH crystals, which are the main cementation products in the treated soils.

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