Eur. Phys. J. Plus (2018) **133**: 205
DOI 10.1140/epjp/i2018-12016-0

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Physical and mechanical properties of sand stabilized by cement and natural zeolite

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Received: 21 January 2018 / Revised: 15 April 2018
Published online: 31 May 2018

Abstract. Loose sands are prone to lose their shear strength when being subjected to static or cyclic loads. To this end, there exist several methods to improve the mechanical properties of sands, but the most crucial and viable approach is the one with the lowest harmful environmental impact both in production and recycling processes. In this regard, zeolite as a natural pozzolanic additive offers an eco-friendly improvement in strength parameters of cemented sandy soils. Thereby, in this study, a series of unconfined compressive strength (UCS) tests are conducted to evaluate the mechanical parameters of the zeolite-cemented sand. The results demonstrate a meaningful increase in the UCS of the treated sand samples for replacement of cement by zeolite at an optimum proportion of 40% in specimens with 14 and 28 days curing time. The effectiveness of the improvement process is demonstrated by the strength improvement ratio which was up to be 128% to 209% for the samples with 14 and 28 days curing time, respectively. With regard to the above results, zeolite can be introduced as a promising cement substitute in stabilization of sandy ground including backfills, roadbed, embankments, and other structural filling systems.

1 Introduction

Recently in the engineering practices, inevitable ongoing efforts have been devoted to improve loose sands due to their low shear strength. Those undesirable challenges for providing human accommodation mainly attributed to population growth, excessive housing demand, and low access to appropriate construction sites have led to high rise constructions with immense complexity, and changes in the behavior of soil beneath the foundations. As such, the most direct solution for improving the strength properties of low strength loose sandy soils is utilizing chemical stabilizers such as cement.

Among the geotechnical laboratory tests, of particular interest is unconfined compressive strength (UCS) test which offers a comparatively prevalent, efficient, fast and simple, low cost, and accurate solution for evaluating the efficiency of the conducted soil stabilization. Aside from the workability of the test, the resulted parameters from this test can be relied on for engineering design or safety assessment. In the past, a large number of studies have been carried out on contribution of additives to make artificial cemented soils samples strength in an unconfined compression test (*e.g.*, [1–13]). In this regard, researchers have found that the addition of cement to the sandy soils up to a certain amount improves the strength parameters of the soils.

Nowadays more than 3.2 billion tons of cement is produced annually in more than 150 countries with a rapid increase in demand. From carbon footprint aspect, about 650 to 920 kg of CO_2 is emitted by per each ton of cement production (depending on the applied level technology) through production process of clinker, and manufacturing energy consumption (fossil fuel or electric energy). Hence, the cement industry with 7% annual greenhouse gas emission plays a crucial role in CO_2 emission [14,15].

The International Energy Agency (IEA) in a report has revealed that the projected rise in the global energy demand would be more than double by 2040. The drastic changes in climate are the result of increasing greenhouse gas

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emissions, including CO_2, mainly attributed to irregular energy consumption. Thereby, the United Nations framework convention on climate change has committed the developed countries to reduce greenhouse gas emission levels under the Kyoto Protocol (1997).

As such, implementing green building materials to reduce or eliminate any more extreme harm to the environment is crucial. In terms of optimal and unobtrusive cement production, a surprising amount of cement additives have been developed to offset the environmental issues.

Several studies have been carried out to address the requirement for improving the mechanical behavior and compression strength of cemented sand by utilizing additives such as fiber, glass, silica fume, fly ash, rice husk ash, nanoparticle, and metakaolin (*e.g.*, [16–25]). It is worth mentioning that using cement additives leads to obtain the benefits of low potential energy consumption during production and to lower production costs accordingly. Other advantages include an increase in sulfate resistance, reduction of hydration process (reduced setting time), and as a consequence rising of the mechanical parameters besides reduction in the soil stiffness (reduction in the brittleness or plastic deformation).

Natural zeolite is a pozzolanic matter made up of volcanic material that contains large quantities of reactive silicon dioxide (SiO_2) and aluminum oxide (AL_2O_3). Calcium hydroxide ($Ca(OH)_2$) produced by the hydration of Portland cement reacts with zeolite, which causes chemical improvement in the interfacial microstructure between the blended cement paste [26–28]. Generally, natural zeolite which contains high pozzolanic activity leads to improve the mechanical strength and durability of cement and concrete properties [29–32].

In the first decades of the 20th century, the application of natural zeolite was begun in pozzolanic cement production. It is reported that in 1912, 25 percent of cement content was replaced by zeolite tuff in the construction of the 386 kilometer long Los Angeles Aqueduct, which led to approximately $1 million economic benefits [33]. As a flashy topic, several experimental studies were conducted on zeolites to examine its suitability as a permeable reactive barrier [34, 35], a landfill liner material with a mixture of bentonites [36–38], and even the geotechnical properties of natural zeolite-soil blends [39–41].

Based on the study presented by Hong *et al.* [40], the adsorption capacity of sand-bentonite backfills increases by adding zeolite up to 10% by weight, whereas it has a low amount of influence on backfills' compressibility and permeability. In other experiments conducted by Park *et al.* [42], clinoptilolite was added to the sand and used for constructing barriers where they were in contact with contaminated groundwater. The results proved high removal efficiency of the contaminants besides an increase in shear resistance of sand in direct shear tests.

The main scope of this study is increasing the compressive strength of loose sand by means of chemical reactions between cement, sand, and zeolite mixture. Thereby, detecting a natural pozzolanic substance and its properties in order to enhance the strength of cemented sand specimens is particularly important. For this purpose, a series of unconfined compressive strength tests were performed to investigate the mechanical behavior of the zeolite-cement-sand mixture. To the best of our knowledge, the studies on zeolite in the geotechnical field are very limited and mainly focused on improving concrete strength. However, this study clearly illustrates that this natural pozzolanic material has the potential of a) being cement supplementary b) costs reduction for its low price and availability c) enhancing the strength of the cemented sand samples. As a result, widespread use of this material in practice is feasible.

2 Experimental investigations

2.1 Description of materials used in laboratory testing

This study focuses on Babolsar sand that has been sampled from the southern shore of the Caspian Sea located in Mazandaran province. Figure 1 represents the Caspian sea, Baboolsar city, and sampling locations in the north of Iran. Also, in table 1 the basic properties, mineralogical composition, and morphological characteristics of Babolsar sand are given (*e.g.* [43,44]). According to the grain size distribution curve of the soil in fig. 2, the soil can be classified based on the Unified Soil Classification System (USCS) (ASTM D422, [45]) where poorly graded sand is referred with letter group symbol SP.

For the applicability of Portland cement type II in structures exposed to soil or water containing sulfate ions (ASTM C150/C150M-17, [46]) and its wide usage in the construction industry of northern parts of Iran, this type of cement has been provided from Mazandaran Cement Company for the experiments.

Natural zeolites can be found in zeolite-rich rock deposits at very low cost due to being easy mined and its availability. There are abundance worldwide zeolite reserves, while countries such as the US, China, Jordan, Turkey, Korea, and Cuba account for producing a considerable tonnage of that (USGS, [47]). Natural zeolites are also abundantly present in Iran. Based on recent explorations, the proven reserves of zeolite in Aftar mine, 30 km far from Semnan province in the central region of Iran, is over 600 thousand tons and currently, this mine provides 85 percent of total zeolite extracted in Iran. About general features of natural zeolite applied in this study, it is worth noting that the zeolite extracted from the Aftar mine, is of the clinoptilolite type, classified as low plasticity silt (ML) according to the Unified Soil Classification System (with $G_s = 2.2$), and it has light cream color. Figure 2 represents particle size distribution curves of the sand, the cement, and the zeolite used in this study. Furthermore, the physical characteristics

Fig. 1. (a) Caspian sea. (b) Baboolsar city location in the north of Iran. (c) Sampling location. (Note: The background map is adopted from Google Maps ©, 2017; geographical coordinate: 36°42′34.4″N 52°38′04.2″E.)

Table 1. Basic properties, mineralogical composition and morphological characteristics of Babolsar sand.

Basic properties	$(\gamma_d)_{\max}$	$(\gamma_d)_{\min}$	G_s	D_{50} (mm)	C_u
	17	15.1	2.78	0.24	1.8
Mineralogical	Quartz	Feldspar	Mica	Carbonate	Chlorite
	46%	27%	11%	16%	0
Morphological	Average shape factor		Average sphericity	Average roundness	
	0.89		0.71	4.86	

and the chemical composition of the cement and the zeolite are presented in table 2, respectively. A Scanning electron microscope (SEM) image of the employed zeolite is shown in fig. 3. As can be seen, the surface texture of the zeolite grains contains irregularities with tiny sharp edges such that the overall grain shape is semi-angular to semi-rounded with the interlocking potential of each individual grains edge.

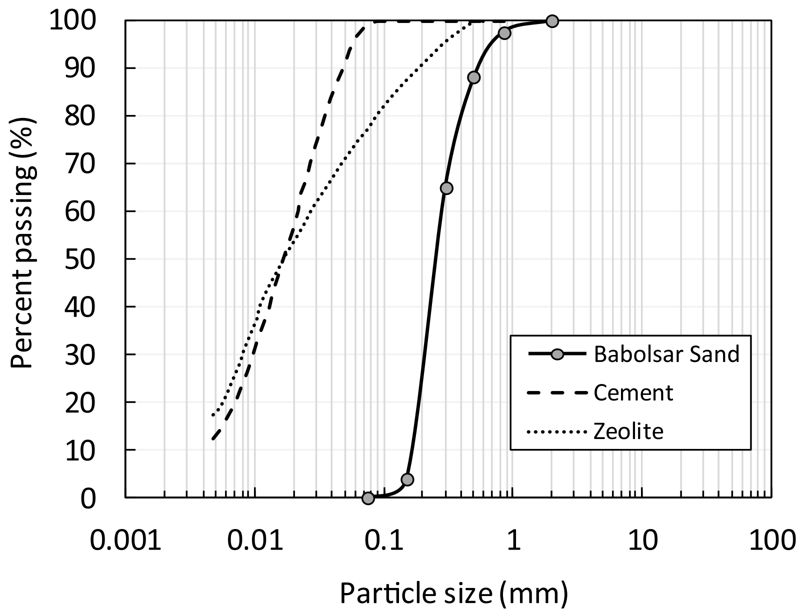

Fig. 2. Particle size distribution curves of Babolsar sand, cement and zeolite.

Table 2. Physical properties and chemical composition cement and zeolite. Note: Chemical compositions of NZ and Portland cement were determined according to ASTM C114-11 [48].

Details	Cement	Zeolite
SiO_2	21.90	67.79
Al_2O_3	4.86	13.66
Fe_2O_3	3.30	1.44
CaO	63.32	1.68
Na_2O	0.36	2.04
K_2O	0.56	1.42
MgO	1.15	1.20
SO_3	2.10	0.50
LOI (loss on ignition)	2.40	10.23
C_3S	47.98	–
C_2S	26.61	–
C_3A	7.30	–
C_4AF	10.04	–
Specific gravity	3.11	2.2
Blaine (m^2/kg)	305	400
Initial setting time (min)	115	–

2.2 Description of experiments, sample preparation, and testing procedure

The aim of the present investigation is to study the effect of different cement to zeolite ratios on the strength of sand-additive samples. A series of experiments include the unconfined compressive strength (UCS) test (conducted according to ASTM D2166, [49]) that has been performed to investigate the optimum proportion of zeolite as the supplementary of the cemented sand. The test is a quick, inexpensive, useful, and prevalent technique among the other geotechnical laboratory tests, which deserves the scope of this part of the current study. Unlike triaxial tests that include confining stresses, the UCS test preserves bonding or cementation between weakly cemented soil particles [50]. Laboratory tests on the Babolsar sand were conducted with cement ratios of 3% and 7% (relative to the dry soil mass) and replacement of cement by zeolite at the rates of 0, 20%, 40%, 60%, and 80%. The soil samples were prepared in a cylindrical shape with 49 mm diameter and 98 mm height (in the ratio 1:2). Table 3 represents a summary of unconfined compression strength tests used in this study.

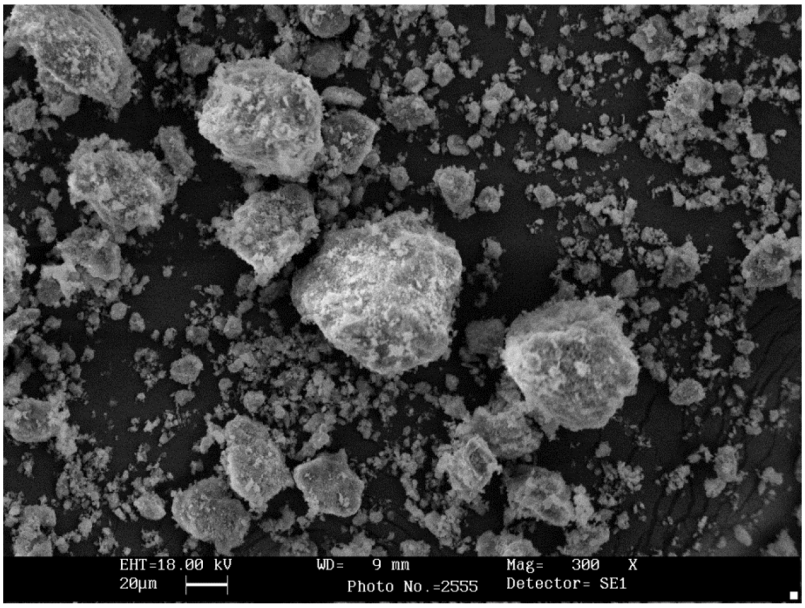

Fig. 3. Scanning electron microscope (SEM) image of zeolite (type of clinoptilolite) with magnification of 300 times.

Table 3. Summary of unconfined compression strength tests used in this study. Note: sign of negative (−) denotes a decreasing trend in strength value and sign of positive (+) denotes an increasing trend in the strength value of specimens in association with cemented sand specimens.

No.	Series	Sand (%)	Cement (%)	Zeolite (%) (replacement)	Curing days	Axial strain at peak strength (%)	Strength increase ratio, q_R	Deformability index, D
1	A	97	3	0	7	1.2	1	1
2	A	97	3	20	7	1.3	−0.78	1.08
3	A	97	3	40	7	1.35	−0.56	1.12
4	A	97	3	60	7	1.5	−0.33	1.25
5	A	97	3	80	7	2	−0.11	1.67
6	B	97	3	0	14	0.7	1	1
7	B	97	3	20	14	0.8	+1.11	1.14
8	B	97	3	40	14	0.9	+1.28	1.28
9	B	97	3	60	14	1	+1.02	1.42
10	B	97	3	80	14	1.3	−0.57	1.85
11	C	97	3	0	28	0.8	1	1
12	C	97	3	20	28	0.9	+1.09	1.12
13	C	97	3	40	28	1.1	+1.28	1.37
14	C	97	3	60	28	1.3	+1.03	1.62
15	C	97	3	80	28	1.7	−0.56	2.12
16	D	93	7	0	7	0.9	1	1
17	D	93	7	20	7	1	−0.81	1.11
18	D	93	7	40	7	1.15	−0.59	1.27
19	D	93	7	60	7	1.4	−0.39	1.55
20	D	93	7	80	7	1.7	−0.14	1.88
21	E	93	7	0	14	0.5	1	1
22	E	93	7	20	14	0.6	+1.4	1.2
23	E	93	7	40	14	0.7	+2	1.4
24	E	93	7	60	14	0.9	+1.13	1.8
25	E	93	7	80	14	1.1	−0.46	2.2
26	F	93	7	0	28	0.8	1	1
27	F	93	7	20	28	0.85	+1.36	1.06
28	F	93	7	40	28	0.9	+2.09	1.12
29	F	93	7	60	28	1	+1.11	1.25
30	F	93	7	80	28	1.2	−0.58	1.5

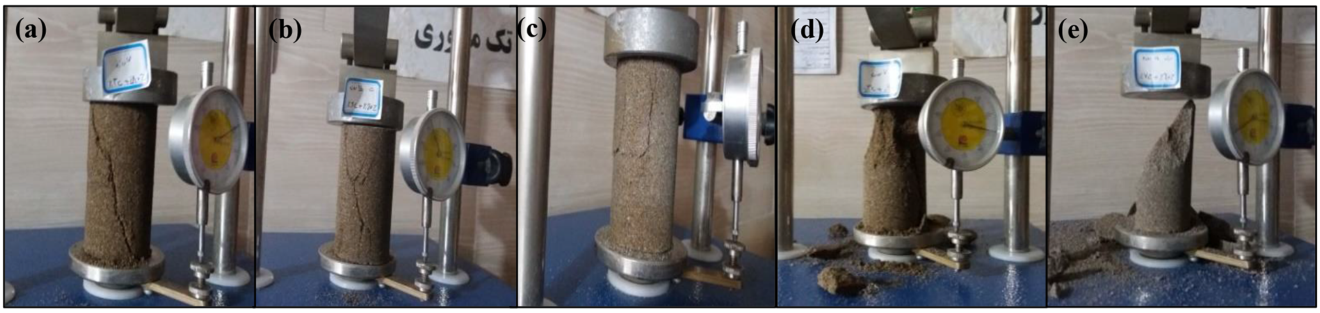

Fig. 4. Failure types of stabilized samples (a) cemented sand, zeolite replacement by cement (b) 20% (c) 40% (d) 60% (e) 80%.

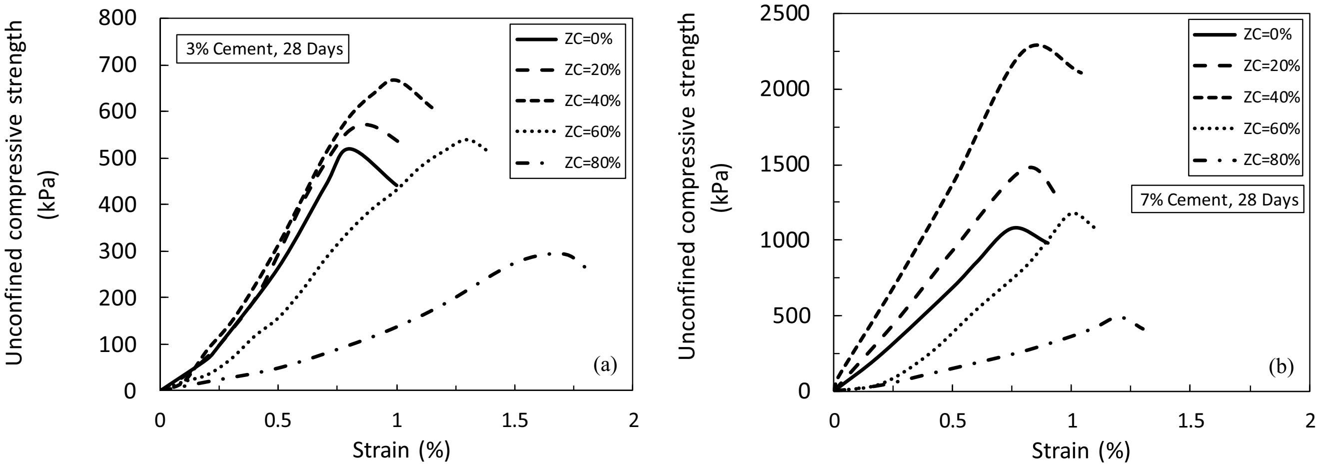

Fig. 5. Stress-strain curves of zeolite-cemented sand samples under 28 days curing time.

Initially, the sand was dried in an oven for 24 hours and then mixed gradually with cement and zeolite mixture (based on the scheduled ratio). Then, clean water with 10% ratio of the dried soil was continuously added to the soil and mixed well to form a homogeneous paste. Regarding the compaction method proposed by Ladd [51], the mixture was dispersed in three separate layers in the mold and compacted before casting the upper layer. The surface of the lower layers was slightly scarified to improve the interlock between the layers. To minimize friction between the mold and the sample, before pouring the mixture into the mold, the inner surface of the mold was lubricated. As a result, no crack was observed in the sample due to the mold removal. After 6 hours and reaching the initial set, the mold was removed and the samples were cured in plastic bags for 7, 14, and 28 days in a room with $23 \pm 2\,^{\circ}$C temperature and above 95% relative humidity. After curing, the samples were placed under vertical automatic loading at a rate of 1 mm/min without any hit and vibration. Liu and Evett [52] reported that failure in UCS test occurs in the form of either the largest amount of load per unit area or the load per unit area at 15% axial strain. Figure 4 shows failure types of stabilized samples with various zeolite and cement contents.

3 Results and discussion

3.1 Investigation of stress-strain behavior

To investigate the behavior of the stabilized soil through the UCS test, analyzing the stress-strain curves is particularly important. Figure 5 shows unconfined compression test of the stabilized specimens cured in 28 days both with 3% and 7% cement content and various zeolite to cement ratios (series C and F of tests from table 3). As it can be seen, with a constant cement content (for instance, 3%), increasing the percent of zeolite to cement content causes the rise of strain value in proportion to the peak stress. Once the cement content increases, the maximum strain value rises as well leading to a reduction in the peak axial stress. This means that enhancing the percent of zeolite to cement content derives failure in the higher strains due to the plastic behavior of zeolite-cemented sand samples. Figure 4 plots failure types of the stabilized sample with 7% cement content, which indicates that an increase in the zeolite rate decreases the brittle behavior of the sample (plastic deformation). Although 7% cement content is followed by the highest cracks, rising the percent of zeolite to cement content from 0% to 80% (fig. 4(a)–(e)) leads to the cracks

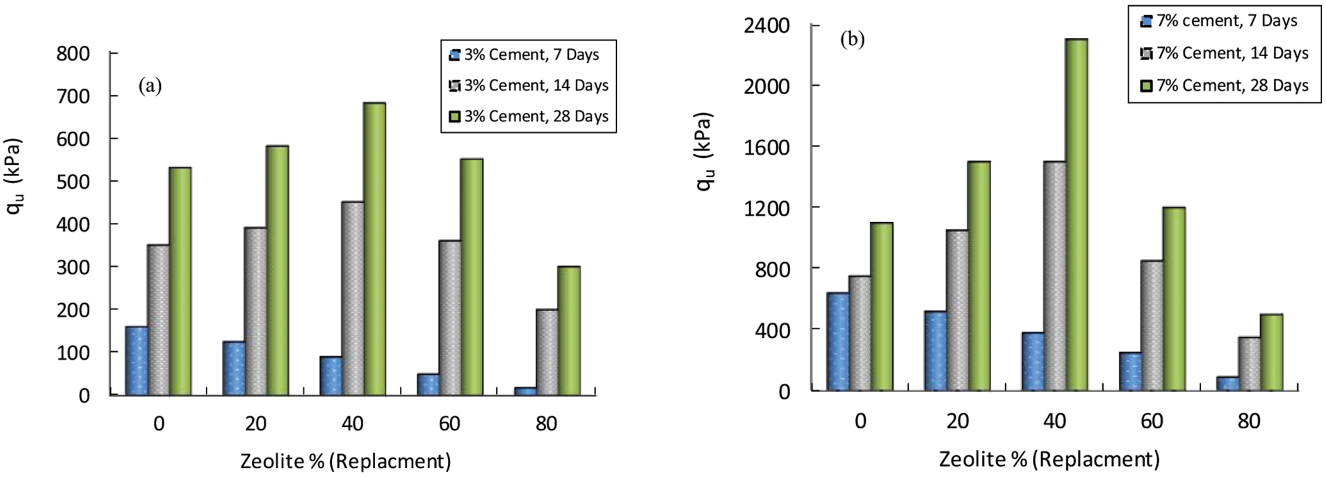

Fig. 6. Effects of zeolite on unconfined compression strength of cemented sand samples.

reduction (brittle behavior reduction). With regard to several researchers exploration, there are two parameters that affect the relation between this mechanism and adding soil additives as they can be seen in the following: 1) additive properties (such as material, surface roughness, length, and content), and 2) the surface shearing force attributed to the soil cohesion and the particle size distribution [53].

3.2 Effects of zeolite on cemented sand strength

As a means of supplementing, figs. 6(a) and (b) show the effect of increasing zeolite to cement ratio on the compressive strength of the stabilized samples. The graph contains maximum axial stress of all samples with 3% and 7% cement contents cured for 7, 14, and 28 days. As such, fig. 6 outlines that increasing zeolite to cement ratio of samples (in both defined cement contents with curing time of 7 days) decreases their compressive strength due to the incomplete pozzolanic reaction in the mixtures. Moreover, enhancing the percent of zeolite to cement content in the 14 and 28 days' samples leads to initial rising of the compressive strength, which follows by further reduction. It is interesting to note that the highest compressive strength can be obtained in an optimum replacement ratio of 40%. Thereby, increasing the cement content from 3% to 7% with 40% zeolite rate (as a cement additive) and 28 days curing time shows up to 238% enhancement in strength.

In case of adding 60% zeolite in proportion to cement content, the strength rate of samples with 28 days curing time and 7% cement content increases up to 9%, whereas the improvement is only 2% for the ones with 14 days curing time and 3% cement content. As such, the results reveal that the compressive strength of the cemented sand samples has an upward trend by adding zeolite up to 60%, but the specimens with 80% zeolite to cement ratio have lower strength compared with the cemented sand specimens.

It is worth noting that the selected percentages of cement content in this study are based on the average cement content extracted from prior researches on soil-cement, which was 7% at the maximum rate. However, laboratory studies have reported a broader range from 1% to 12% cement content for soil-cement stabilization (*e.g.*, [7,54]). While high percentages of cement are used for practical purposes such as constructing backfills, sub-base of road and railroads, etc., potential issues such as the material costs (global price of cement) and the heat generated through hydration should be overwhelmed.

3.3 Strength and deformation characteristics

As indicated earlier, reviews of various additives' impacts on cemented sand samples have shown that adding a specific amount of zeolite (in proportion to the percent of cement amount) can improve the mechanical strength of the samples [19,21–24]. In this paper, regarding an increase in the strength rate, q_R can be used as an index parameter to gain an understanding of the replacing impact of cement with zeolite on a cemented sand sample.

An increase in the UCS due to the inclusion of zeolite-cement is quantified by q_R in eq. (1) (defined as the ratio of UCS for a stabilized zeolite-cemented sand specimen divided by that of a cemented sand specimen):

$$q_R = \frac{\text{UCS}_{(S\text{-}C\text{-}Z)}}{\text{UCS}_{(S\text{-}C)}}\,. \quad (1)$$

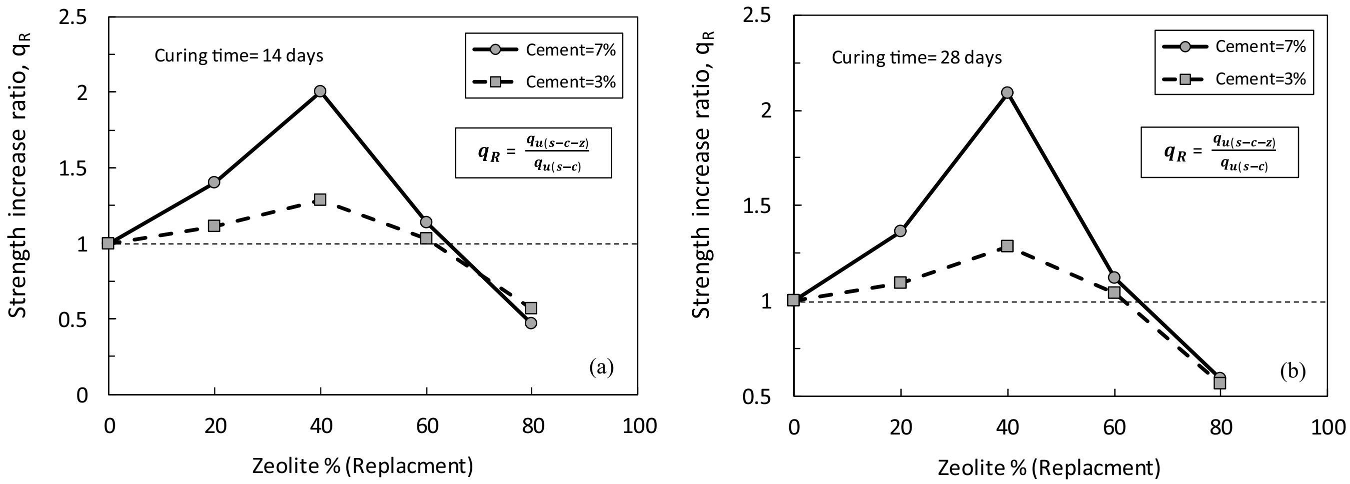

Fig. 7. Variation strength increase ratio *versus* zeolite content (a) 14 days curing time (b) 28 days curing time.

The variations of strength ratio *versus* zeolite content for 3% and 7% cement content samples with 14 and 28 days curing times are shown in fig. 7. Also, table 3 shows the calculated values for all data. As it can be seen in the plot, for cemented sand samples with 40% zeolite to cement ratio, the q_R amount was increased up to 2.09 and 1.28 times, respectively, for 7% and 3% cement contents (28 days curing time). In addition, for 14 days curing samples with 7% and 3% cement contents, the q_R was, respectively, increased by 2 and 1.28 times. The improvement through increasing cement content from 3% to 7% at a constant zeolite value of 40% was 63% for the 28 days curing time samples (fig. 7(b)), and 56% for the 14 days curing time specimens (fig. 7(a)). This can be attributed to the greater reaction of zeolite with calcium hydroxide ($Ca(OH)_2$) in the cemented sample, together with the decrease in porosity of the sample, which results in its strength improvement. For samples with more than 40% cement replacement by zeolite, the process of stabilization has a downward trend, such that for 80% cement replacement by zeolite, the improving rate is less than that of cemented sand samples, which results in falling of the associated curve below the dashed line, which illustrates a clear strength reduction. This reduction is due to the restriction of pozzolanic reaction resulted from higher cement content replacement by zeolite. Immediately after mixing Portland cement with water, water is saturated with calcium hydroxide and changes to cement paste. The microscopic study of hardening cement paste indicates that calcium hydroxide crystals, which are sometimes quite large, are surrounded by a homogeneous mass called cement gel. Generally, the cement gel tends to make tubular or chain structures at least until the capillary voids have enough space for these structures. In this study, 40% is determined as the optimum content for replacing cemented sand by zeolite. Increasing this ratio results in filling the gap between the capillary voids with zeolite and its sedimentation in the form of a gel, which makes a barrier for creating the calcium silicate hydrates (C–S–H) gel as the main cohesion and strength in the cement paste. Hence, although adding zeolite as cement replacement has a major effect on the strength improvement of zeolite-cemented sand, it should be limited to 40%, within the circumstances specified in the present study. Increasing the amount of zeolite causes a downward trend in the strength of the 7 days curing time samples due to incomplete pozzolanic reactions; therefore, plotting the related data in fig. 7 is ignored.

Maher and Ho [16] found that mixing 1% glass fiber with 4% cemented Ottawa sand results in an approximate q_R of 1.5. Kumar *et al.* [55] showed that adding 1% polyester fiber and clay with 10% sand causes an approximate q_R of 1.2. However, the obtained q_R value in this study (see table 3) for the purpose of stabilization was more than 2 for 40% replacement of cement with zeolite both in 14 and 28 days curing time samples, which is greater than the obtained values by other researchers.

As seen in fig. 5, increasing the zeolite rate causes rising of the axial strain at the peak strength compared with the cemented sand specimens. Therefore, it can be said that the addition of zeolite to the samples enhances deformability (plastic behavior) and postponing of the samples' failure rate (brittle behavior reduction). Thus, the concept of ductility is used to determine the performance of zeolite-cemented sand. Ductility is a physical property for structural material to evaluate the ability of a material for undergoing inelastic deformation without any significant loss in resistance prior to collapse. Ductility behavior is commonly defined for metals but the mechanism of this behavior can be considered the same as the deformability index defined by Park [13]. Park [13] demonstrated that ductility can be defined as the ratio of the final deformation (or deflection) at the ultimate state to that of the yield state.

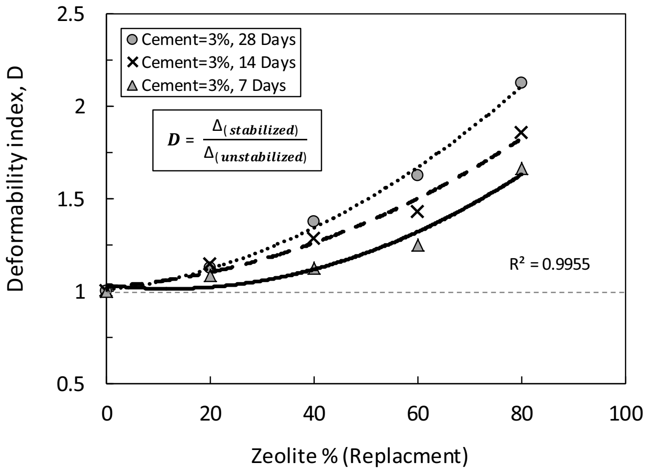

Fig. 8. Variation of deformability index *versus* zeolite content for stabilized specimens with 3% cement content.

Unlike the triaxial tests, determining the ultimate state and yield state is complicate in the UCS tests. Thereby, axial strain at the peak strength and axial strain at the ultimate (or steady) state are applied to define the Deformability index. In fact, this index is useful when either a peak stress or a residual state is not clearly observed.

Avoiding the possible confusion of the readers, the ductility mechanism used in the UCS test samples is named deformability index in this text. This parameter in the UCS tests is defined as axial strain at the peak strength of zeolite-cemented sand on the axial strain at the peak strength of cemented sand specimens which abbreviates by D and represents ductility behavior (eq. (2)). Therefore, the definition and mechanism of both parameters (ductility and deformability) are the same. This study follows the deformability index term proposed by Park [13] to define the ductility of zeolite-cemented sand as follows:

$$D = \frac{\Delta_{(s\text{-}c\text{-}z)}}{\Delta_{(s\text{-}c)}}, \quad (2)$$

where $\Delta(s\text{-}c\text{-}z)$ is the axial strain at the peak strength of zeolite-cemented sand specimens and $\Delta(s\text{-}c)$ is the axial strain at the peak strength of cemented sand specimens. The strain-based index, D, can be determined by comparing the axial strain at the peak strength of any stabilized specimens with zeolite to that of specimens without zeolite content. The index, D, was calculated and summarized for different zeolite and cement contents. The axial strain at the peak strength is shown in table 3.

Evaluation of ductility or deformability of cemented sand stabilized by various zeolite contents can be carried out by applying D index. Figure 8 shows the D index rate against zeolite replacement rate for the 7, 14, and 28 curing times samples with 3% cement content. As it can be seen, the D rate increases by rising zeolite replacement rate, whereas it obtains the highest rate for 28 days curing time compared with the other two considered curing times. In fact, the D rate is related to the amount of zeolite, cement, and curing time.

These three curves are started from the numerical value of 1 for the cemented sand samples and have upward trend by increasing the zeolite amount. Although 40% zeolite replacement leads to the highest strength among the considered specimens, the D index has an upward trend by increasing the zeolite up to 60% and 80% (deformation enhancement or brittle behavior reduction). The specimens with 3% cement content and 40% zeolite replacement, have respectively the D indexes 2.12, 1.85, and 1.67 times more formable than the cemented sand samples with 28, 14 and 7 days curing time. Precisely, the D index increases from 7 to 14 days curing time up to 10%, and from 7 to 28 days curing time up to 27%. These enhancements are due to improvement in the microstructure of the specimens attributed to the secondary reactions between the sample's particles and followed by the production of C–S–H gel. For all curves, the coefficients of determination values (R^2) were greater than 0.95, which indicates that the regression lines fit the data properly.

3.4 Effect of curing time on compressive strength and modulus deformation

In order to increase the compressive strength of the specimens, of particular importance is the curing time, whereas there are effective parameters on the UCS rate of the given samples including water to cement ratio, particle size, types and amounts of additives, and the partial replacement of cement by mineral admixtures.

As the strength characteristics of soils treated with a stabilizer are associated with time due to the continuing hydration/pozzolanic reactions, studying time-strength development is essential for such materials [56,57].

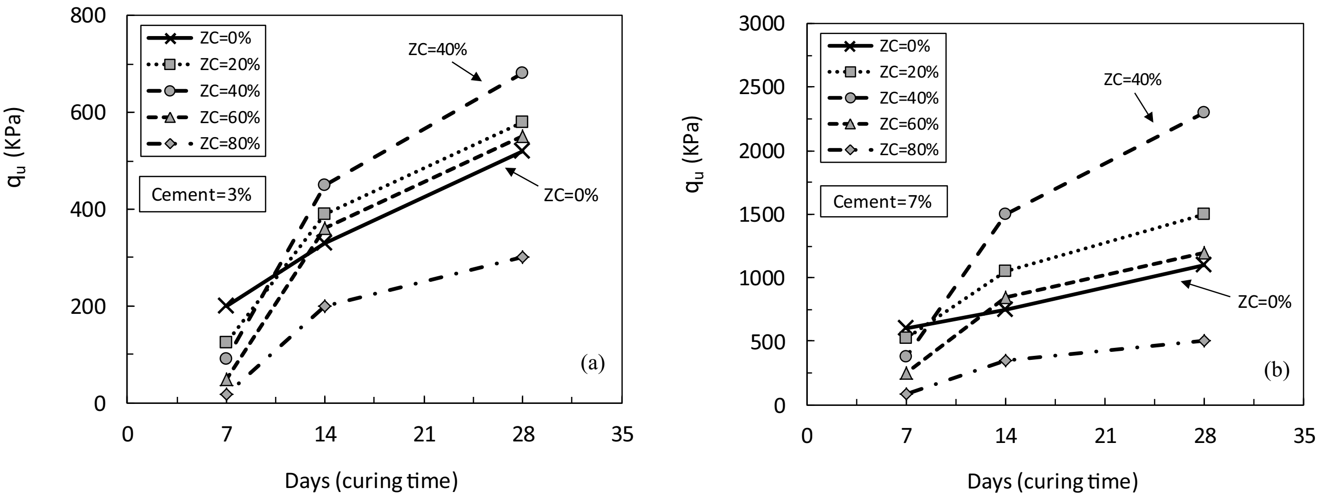

Fig. 9. Effect of curing time on unconfined compressive strength of zeolite-cemented sand samples (a) 3% cement content (b) 7% cement content.

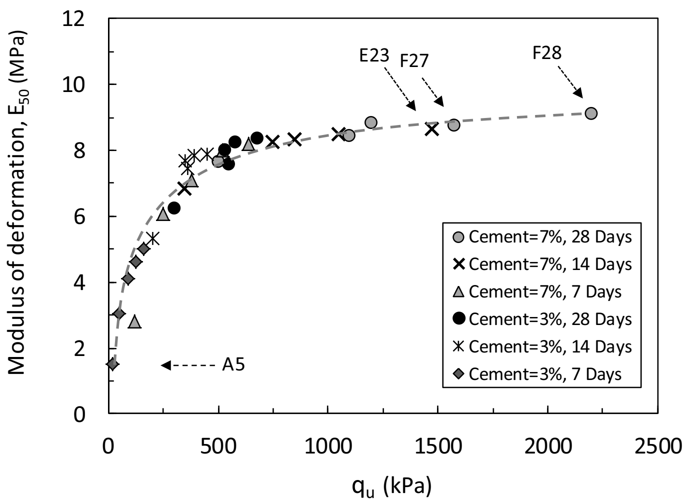

Fig. 10. Modulus of deformation *versus* unconfined compressive strength of zeolite-cemented sand samples.

It is obvious that the chemical reaction of cement is time-dependent. Accordingly, fig. 9(a) and (b) are drawn to evaluate the effect of setting the time on the strength of the zeolite-cemented sand samples. Setting time is defined as a specified time required for concrete or mortar to change from liquid state to plastic state and plastic state to solid state (the hardened paste) so that the surfaces become sufficiently rigid to withstand a definite amount of pressure. The initial hardening time of cement-zeolite paste is known as "setting time" of cement-zeolite. It is noteworthy to mention that extending the curing time rises the samples' strength. Although the strength increases in a linear trend for cemented sand samples, it is nonlinear for the specimens where the cement content has been replaced by zeolite. Roughly speaking, the strength rises with a steep slope through changing the curing time from 7 to 14 days, but it becomes gentle thereafter. The specimens with 40% replacement of cement by zeolite have the greatest strength rising both by extending the curing time from 7 to 14 and 14 to 28 days due to the pozzolanic reactions between zeolite and cement. For 3% cement content samples shown in fig. 9(a), the differences between 20%, 40%, and 60% cement replacement by zeolite are approximately in the same range compared with cemented sand samples, thus the amount of scattering in the graphs' data is lower. However, the difference is more pronounced in 7% cement content samples and a greater rate of scattering is observed.

Based on these results, as the strength development of stabilized soil mixtures is time-dependent, the strength development of the cemented sand treated with zeolite is remarkably influenced by curing time. Ahmadi and Shekarchi [58] indicated that the increase in strength is probably due to time-dependence of pozzolanic reactions that result in the formation of various compounds, namely, calcium silicate hydrates (C–S–H), calcium aluminates hydrates (C–A–H), and calcium aluminum silicate hydrates (C–A–S–H). In essence, the presence of these compounds accounts for developing the mixtures' strength.

A similar behavior is observed between E_{50} and q_u, as can be seen in fig. 10. One half of the axial strain at the peak strength of the specimens was used to calculate the secant elastic modulus (modulus of deformation) and then compared with unconfined compressive strength (UCS). As fig. 10 illustrates, the outputs produced by all tests fall within a narrow band, which has a linear pattern in low compressive strength condition (lower than 500 kPa), and a nonlinear trend in higher strength range. The nonlinear trend is attributed to the compressive strength improvement of the cemented sand samples for increasing the amount of cement replacement by zeolite up to 40%. However, continuing this replacement up to 60% and 80% decreases the compressive strength of the samples or in other words, ceasing the zeolite addition prior to 60% and 80% results in rising of the strength. Thereby, changes of E_{50} against q_u are nonlinear in different ratios of cement replacement by zeolite. Conversely, numerous studies revealed that adding additives to cemented soils results in a linear relation between E_{50} and q_u. For instance, Ayeldeen and Kitazume [59] explored that the compressive strength of a stabilized soil with 15% cement content would increase by 240% by adding 0.5% fiber polymer. Accordingly, they proposed a linear relationship with different percentages of fiber polymer and cement content.

The compressive strength of series A (especially sample A5 according to table 3) shows that a sample with 7 days curing time, 3% cement content, and 80% cement replacement by zeolite, is the minimum among the defined samples, which falls greatly below the regression line (see fig. 10). In contrast, the highest compressive strength is recorded for 7% cement content samples with 20% and 40% zeolite addition (F27 and F28), which is far apart from the other data. As such, the E_{50} rate is dependent directly on zeolite content, cement amount, and last but not least the curing time.

4 Conclusion

In this study, a series of experiments were conducted for evaluating the mechanical behavior of zeolite-cemented sand mixtures through unconfined compressive strength (UCS) tests. Accordingly, 30 different UCS tests were performed to investigate the impact of adding zeolite to cemented sand samples and also, to determine the optimum proportion of cement replacement by zeolite among 0, 20, 40, 60, and 80% percent for cemented sand samples containing 3% and 7% cement content (relative to dry soil mass).

The following conclusions can be summarized based on the experimental results of this study:

1) Replacing cement by zeolite up to 40% causes the increase of compressive strength in the 14 and 28 days curing time samples up to 128% to 209%, respectively, attributed to the pozzolanic activity of zeolite and reduction in hydration reaction in this period. As a result, it is demonstrated that the optimum zeolite content determined in this study is 40%.

2) Although exerting 40% replacement of cement by zeolite increases the q_R of samples with both 7% and 3% cement contents respectively up to 2.09 and 1.28 times (with 28 days curing time), but continuing the zeolite addition as cement replacement decreases the q_R of cemented sand samples thereafter.

3) Adding zeolite to cemented sand samples increases the axial strain at the peak strength compared to cemented sand specimens. Therefore, adding zeolite to specimens improves their behavior from brittle state to plastic state (postponing the failure rate). The deformability index shows the plastic behavior of samples, which is 1.12, 1.37, 1.62, and 2.12 times of the cemented sand samples due to respectively 20%, 40%, 60% and 80% zeolite addition to 28 days curing time samples with 3% cement content.

4) Changes of secant elastic modulus (E_{50}) against unconfined compressive strength (q_u) are nonlinear for different cement replacement by zeolite. This nonlinear trend is due to the incredible compressive strength improvement of the cemented sand samples resulted from increasing the cement replacement by zeolite up to 40% in 14 and 28 days curing specimens.

5) As a natural pozzolanic material, zeolite is a promising cement additive in the cemented sand samples. Zeolite in comparison with cement has less environmental impacts, setting time (regarding its mixing time), and difficulties in compaction for its high workability. The lower price of zeolite rather than cement (global cost) results in reducing project costs. Zeolite has advantages of reducing greenhouse gas emissions especially CO_2, decreasing cement consumption, saving remarkable amounts of energy required for cement production, besides participation in sustainable development. Consequently, utilizing zeolite instead of cement can be facilitated to stabilize the sandy ground such as backfills, roadbed, embankments and other structural fill applications.

Nomenclature

C	Cement content
C_u	Coefficient of uniformity
D	Deformability index
D_r	Relative density
D_{50}	Mean effective diameter
G_s	Specific gravity
q_R	Strength increase ratio
q_u	Unconfined compressive strength
R^2	Coefficient of variation
$\mathrm{UCS}_{(S\text{-}C\text{-}Z)}$	Unconfined compressive strength of the zeolite-cemented sand specimens
$\mathrm{UCS}_{(S\text{-}C)}$	Unconfined compressive strength of the cemented sand specimens
Z	Replacement of cement by zeolite
$\Delta(s\text{-}c\text{-}z)$	Axial strain at peak strength in zeolite-cemented sand specimens
$\Delta(s\text{-}c)$	Axial strain at peak strength in cemented sand specimens
$(\gamma_d)_{\max}$	Maximum dry unit weight
$(\gamma_d)_{\min}$	Minimum dry unit weight

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