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Effect of Zeolite on the Compaction Properties and California Bearing Ratio (CBR) of Cemented Sand

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Abstract

This research investigates the impact of zeolite on the compaction properties and California Bearing Ratio (CBR) of cemented sand. For this purpose, firstly, sand, cement (2, 4, 6, and 8% by the sand dry weight), and zeolite (0%, 30%, 60%, and 90% of cement content, as a replacement material) are mixed. Then, various cylindrical samples with sizes of 101×116 mm and 119×152 mm are prepared for compaction and CBR tests, respectively. After curing for 28 days, the samples are tested according to the standards of compaction and CBR tests. The results depict that the use of zeolite reduces Maximum Dry Density (MDD) while it increases Optimum Moisture Content (OMC) of cemented sand. Furthermore, the inclusion of zeolite up to 30% of cement content contributes to the highest CBR values due to the pozzolanic and chemical reactions. Finally, some correlations with high correlation coefficients are proposed between the CBR and MDD of zeolite-cemented sand.

Keywords: cement, sand, California bearing ratio, standard proctor compaction test, zeolite

1. Introduction

The loose sandy soils generally have low strength and high potential for settlement. The replacement of this type of soil with high quality materials for the desired engineering features will often lead to economic and environmental problems. Consequently, in such circumstances, appropriate methods such as reinforcement, drainage, lowering of groundwater table, and chemical stabilization can be employed to enhance the properties of loose sand. Methods of chemical stabilization are generally recommended to enhance soil properties because of their appropriate performance [1]. The success of chemical stabilization of soil depends on the soil type, the required strength and durability of the stabilized layer, as well as the content and type of the stabilizer. For the application of a suitable stabilizer, particular attention should be given to the appropriate reactivity between soil and agent and also to the environmental effects of the stabilizer. The most widely used stabilizer known for the treatment of sand is cement. The impact of cement percentage and curing time on the stress-strain behavior of artificially cemented sand has been investigated in the past by several investigators. According to their results, the key parameters influencing the strength of cemented sand are cement content, porosity, and moisture content. Al-Aghbari et al. [2] examined the effect of ordinary Portland cement on sandy soil and concluded that by increasing the cement percentage, Maximum Dry Density (MDD) increased and Optimum Moisture Content (OMC) reduced to an extent which was more pronounced for higher cement contents. Rasouli et al. [3] expressed that by stabilizing the sand below the foundation with

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cement, the bearing capacity of the foundation was enhanced to an acceptable level. Hasanzadeh and Shooshpasha [4] reported that the addition of cement to sandy soil decreased the displacement at failure. However, it improved ultrasonic pulse velocity and Unconfined Compressive Strength (UCS) of soil.

In spite of many advantages, applications of cement for soil stabilization causes several detrimental impacts on the environment, including the dust generation in conjunction with the excavation of raw materials for the manufacture of cement, the threat to human and animal health, the harm to the most nutritious layers of soil, and the emission of greenhouse gases such as nitrous oxide (N_2O) and carbon dioxide (CO_2) [5]. Total energy consumption in cement manufacturing is about 5 TJ per 1000 ton. In addition, each ton of cement releases approximately 1 ton of CO_2 into the atmosphere [6]. Researchers have so far suggested many solutions to decrease the carbon emissions, energy usage, and contamination associated with cement manufacturing [7-9]. The adoption of natural pozzolans such as zeolites (as a partial replacement for cement) can be regarded as a suitable and sustainable option to confront the problems caused by cement consumption. Zeolites as natural pozzolans are aqueous aluminum silicates with elements of alkali and alkaline earth. Their composition consists of a framework of AlO_4 and SiO_4 tetrahedrons connected to corners of each other by exchanging oxygen atoms. In tetrahedral sites, the replacement of Si^{4+} by Al^{3+} leads to more negative charges and a better cation exchange capacity [10].

Zeolites have a high metal absorbing potential and are commonly used in gravel and bentonite as absorbents for the removal of ammonium and heavy metals. Hence, they are appropriate to increase contaminant inhibition by absorption. Considering the comparatively limited resources of silica fume and fly ash and also the similarity between the pozzolanic activities of zeolite and them, researching the impact of zeolite as an acceptable choice for substituting a certain quantity of cement in engineering projects may be considered to be of high significance. Yukselen-Aksoy [11] found that zeolites are mechanically stable and are appropriate for use in landfill liner and embankment materials. Grela et al. [12] showed that zeolite can also be received from waste materials such as fly ashes. The use of zeolite can reduce the unavoidable environmental issues associated with the production of cement such as CO_2 release and consumption of energy. Therefore, the substitution of cement with zeolite is regarded in this research.

Several researchers have conducted extensive investigations on soil stabilization using zeolite. Mola-Abasi and Shooshpasha [13] proposed a polynomial model using Group Method of Data Handling (GMDH) for the UCS prediction of zeolite-cemented sand mixtures. Mariri et al. [14] depicted that the incorporation of zeolite in cemented loess can improve the strength remarkably. Rajabi and Ardakani [15] reported that with increasing zeolite content and the curing time, the UCS of sandy clay and clayey sand increased 2.5 and 4 times the initial soil strength, respectively. Although numerous investigations have been performed about the impact of zeolite on the concrete industry, little emphasis has been devoted to the influence of natural zeolite on the soil features, particularly the compaction properties and CBR of cemented sand. Hence, this issue is investigated in this study. Furthermore, being environmentally friendly with unique physiochemical properties and having appropriate distribution of zeolite in Iran have been among the chief reasons of selecting zeolite in the present research.

2. Materials and Methods

2.1. Sand

The sand in this study is collected from the coastal zone of Babolsar city, Mazandaran province, Iran. This sand is categorized as poorly graded sand (SP) using the Unified Soil Classification System (USCS) [16] with a mean grain size (D_{50}), specific gravity (Gs), coefficient of curvature (C_c), and coefficient of uniformity (C_u) of 0.21 mm, 2.73, 1.04 and 1.29, respectively. Table 1 presents the chemical composition of this sand.

Table 1 Chemical characteristics of Babolsar sand

Chemical name	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	Na_2O	MgO	SO_3	TiO_2	P_2O_5	L.O.I.
Percent (%)	42.8	7	3.71	1.34	23.3	1.37	3.35	0.21	0.79	0.2	15.69

2.2. Cement

The ordinary cement utilized in the tests is type II Portland cement based on ASTM C150 [17]. This cement is known as modified Portland cement and is supplied from Mazandaran cement company, Iran. The Gs and Blaine of this cement is 3.15 and 305 m^2/kg, respectively. The physical and chemical characteristics of the cement are presented in Table 2.

Table 2 Physical and chemical properties of Portland cement type II

Parameters	Value
Autoclave expansion (%)	0.05
Initial setting time (min.)	115
Compressive strength after 3 days (kg/cm^2)	185
Compressive strength after 7 days (kg/cm^2)	295
Compressive strength after 28 days (kg/cm^2)	397
SiO_2 (%)	21.90
Al_2O_3 (%)	4.86
Fe_2O_3 (%)	3.10
K_2O (%)	0.53
CaO (%)	63.30
MgO (%)	1.20
SO_3 (%)	2.04
Na_2O (%)	3.07

**Documentation of Mazandaran cement company laboratory test results*

2.3. Zeolite

From an economic point of view, there are various natural zeolite resources in Iran, making it cost-effective. In this study, the natural clinoptilolite type of zeolite obtained from the Semnan company in Iran with Blaine of 400 m^2/kg, specific weight of 11900 N/m^3, and Gs of 2.20 is used. The color of the used zeolite is a light cream and is categorized as ML based on the USCS [16]. The gradation curves of Babolsar sand, cement, and natural zeolite are depicted in Fig. 1. Table 3 presents the chemical properties of zeolite.

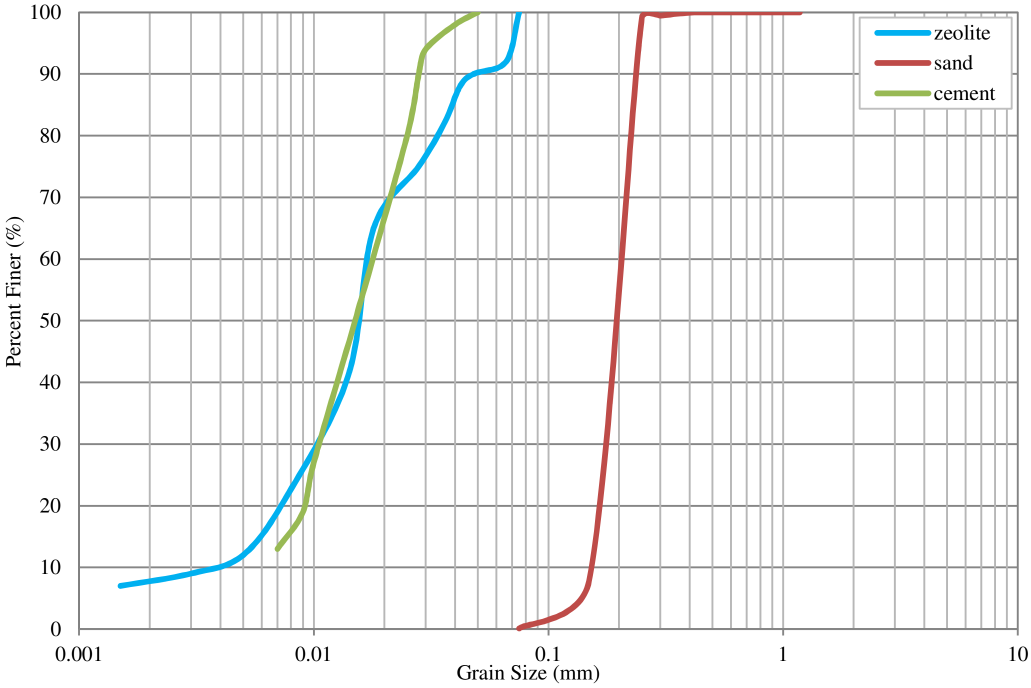

Fig. 1 Gradation curves of cement, zeolite, and Babolsar sand

Table 3 Chemical properties of zeolite

Component	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	SO_3	Na_2O
Content (%)	67.40	10.80	0.84	0.19	1.20	0.33	0.47	3.70

**Documentation of Semnan zeolite company laboratory test results*

3. Sample Preparation

The MDD and OMC of the samples are determined by carrying out a set of standard proctor compaction experiments using ASTM D698 [18]. To prepare specimens, sand, cement (2, 4, 6, and 8% by the dry weight of the sand), and zeolite (0%, 30%, 60%, and 90% of cement content, as a replacement material) are blended with different water amounts (10 to 24% of the weight of the mixture). The mixture is then put into a standard mold in three layers, with each layer compacted by 25 rammer blows falling down from a 0.3 m distance. Moisture content and weight of specimens are determined following compaction phase. Standard proctor compaction experiments are carried out on three similar specimens for each combination of variables, and then the average value of the findings is recorded. Fig. 2 shows the sample preparation for compaction test.

Fig. 2 The standard proctor compaction test

The CBR tests are applied as the conventional technique of pavement design in different countries or even as the primary approach for subgrade characterization. To obtain the efficient percentage of the zeolite required to enhance the soil strength characteristics, the CBR tests are regarded in the present investigation. In order to prepare samples, the pre-calculated amounts of sand, cement, zeolite, and water are blended until a uniform mixture is obtained. During the mixing process, considerable care is made to ensure a homogenous mixture. CBR specimens are prepared using the modified proctor method in a mold with 152 mm diameter and 178 mm height. The samples are packed to a height of 119 mm in five layers using 2700 kN-m/m^3 effort. The height of the packed mixture allows 59 mm of free board space for placing the surcharged load as required by ASTM D1883 [19]. The testing equipment used for CBR tests has a 28 kN capacity of proving ring, and 0.01 mm accuracy of a dial gauge for reading of displacement. The samples are stored under a steel weight surcharge of 4.5 kg, put in plastic bags for preventing moisture loss, and kept for 28 days for curing. After curing, the samples are soaked in water for 96 h to obtain maximum saturation prior to CBR tests. The values of CBR of the specimens are achieved by dividing the stress needed to induce a standard piston to penetrate 2.54 and 5.08 mm in the compacted sample at the rate of 1.25 mm/min. Fig. 3 indicates the CBR test. The details of samples are presented in Table 4.

Table 4 Details of the samples

Variables	Description of samples
Type of soil	Poorly graded sand
Cement agent	Portland cement-type II
Zeolite type	Natural cilnoptilolite
Cement content	2, 4, 6, and 8% by the dry weight of the sand
Zeolite content	0%, 30%, 60%, and 90% of cement content (as a replacement material)
Size of compaction samples	101 mm diameter and 116 mm height
Size of CBR samples	152 mm diameter and 119 mm height
Curing time	28 days

Fig. 3 The CBR test

4. Results and Discussion

The results found by performing standard proctor compaction and CBR experiments on sand with various percentages of zeolite and cement are presented in this section.

4.1. Results of standard proctor compaction experiments

Fig. 4 depicts the dry density-moisture content variation for sand with various cement percentages found by standard proctor compaction experiments (C = cement). As observed, the inclusion of cement to sand results in the rise of MDD and the reduction of OMC. The MDD increase is due to the higher Gs of cement (3.15) than sand (2.73) and its smaller particles which can reduce the pores between the sand grains. Cement influences the sand characteristics by enhancing the matrix of the stabilized sand. This phenomenon occurs because the cementation products fill up the pore spaces of sand, therefore generating a binding impact on the soil particles. The compaction couples with stabilization so that the pore spaces of the sand are refined, hence improving the properties of sand. This results in a denser state of the stabilized sand after compaction. The reduction of OMC may be ascribed to water self-desiccation because the relative humidity inside the paste reduces as no flow of water to the cement paste is permitted [7].

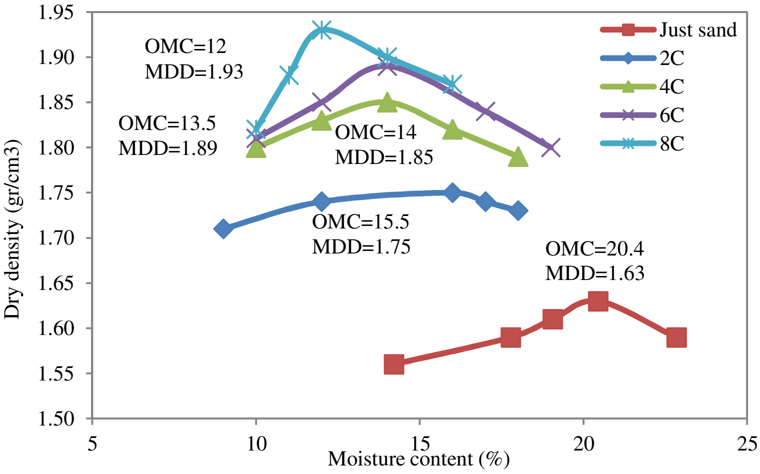

Fig. 4 The variation of dry density against moisture content for cement stabilized sand

Figs. 5-8 show the dry density-moisture content variation for sand-zeolite-cement mixtures (Z = zeolite). As seen, MDD decreases with replacing cement by zeolite due to the lower Gs of zeolite in comparison with sand and cement. For example, the MDD values of 0.4C3.6Z and 4C are 1.70 and 1.85 gr/cm^3, respectively. In other words, the replacement of 90% of cement by zeolite leads to 8% decrease in MDD. Yilmaz et al. [20] have also indicated that the existence of zeolite in the soil composition lowers MDD. Considering environmental impacts of zeolite and its lower cost than cement, the MDD reduction by replacing cement with zeolite is not considerable. In addition, materials with low values of Gs such as zeolite can be effective as backfill for retaining structures because they apply less lateral earth pressure. It can also be seen in Figs. 5-8 that OMC grows with the increment of zeolite percentage. Zeolites have a honeycomb-like structure with small channels and pores, which results in a large surface area and high ability to adsorb water. Thus, OMC increases with the addition of zeolite to cemented sand [21]. A summary of MDD and OMC values obtained from the standard proctor tests is indicated in Table 5.

Table 5 The MDD and OMC values for different samples

Serial number	Cement content (%)	Zeolite content (%)	MDD (gr/cm^3)	OMC (%)
Just sand	0	0	1.63	20.4
2C	2	0	1.75	15.5
1.4C0.6Z	1.4	0.6	1.73	15.8
0.8C1.2Z	0.8	1.2	1.71	16.2
0.2C1.8Z	0.2	1.8	1.68	16.5
4C	4	0	1.85	14
2.8C1.2Z	2.8	1.2	1.77	15
1.6C2.4Z	1.6	2.4	1.74	15.5
0.4C3.6Z	0.4	3.6	1.70	16.2
6C	6	0	1.89	13.5
4.2C1.8Z	4.2	1.8	1.81	14.3
2.4C3.6Z	2.4	3.6	1.78	15
0.6C5.4Z	0.6	5.4	1.74	15.4
8C	8	0	1.93	12
5.6C2.4Z	5.6	2.4	1.85	13.1
3.2C4.8Z	3.2	4.8	1.80	14.2
0.8C7.2Z	0.8	7.2	1.76	15

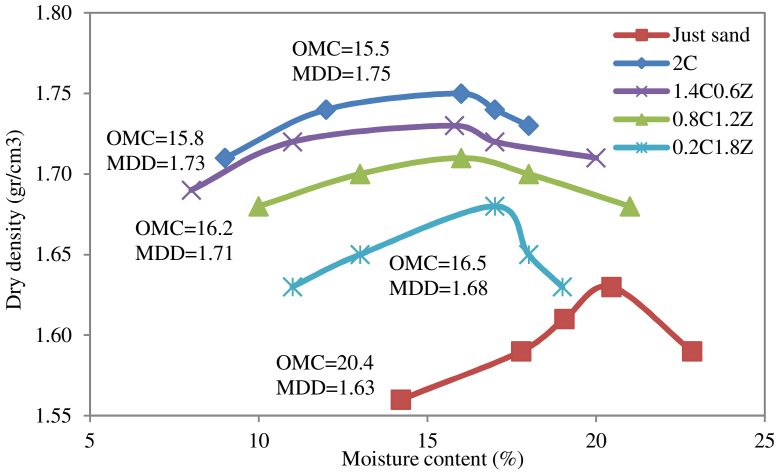

Fig. 5 The variation of dry density against moisture content for the sand-cement-zeolite mixture (2% cement)

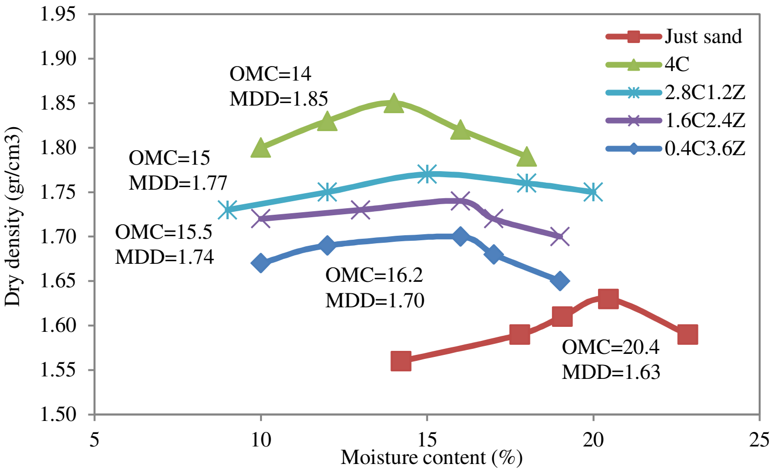

Fig. 6 The variation of dry density against moisture content for the sand-cement-zeolite mixture (4% cement)

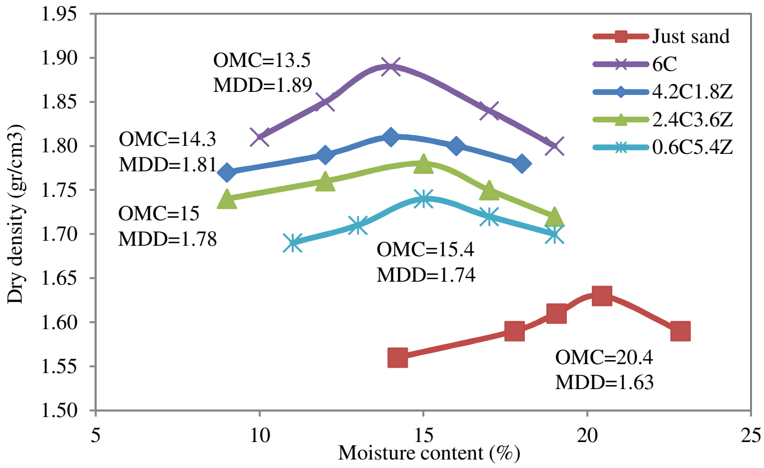

Fig. 7 The variation of dry density against moisture content for the sand-cement-zeolite mixture (6% cement)

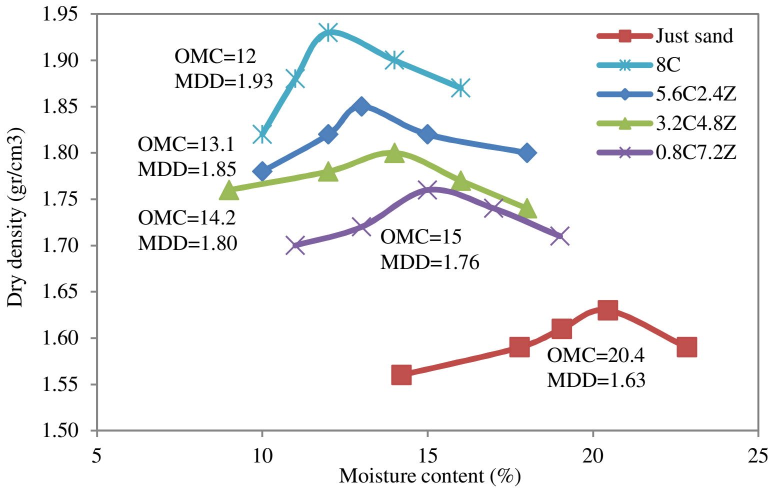

Fig. 8 The variation of dry density against moisture content for the sand-cement-zeolite mixture (8% cement)

4.2. *Results of CBR tests*

In Fig. 9, it is shown that the inclusion of zeolite (up to 30% of cement content, as a replacement material) to the sand containing 6% cement leads to a considerable rise in the value of CBR. In other words, 4.2C1.8Z has the highest CBR. It should be mentioned that one of the important reactions between zeolite and cement particles is the pozzolanic reaction. This time-dependent reaction involves interactions among sand, cement, and zeolite to create various kinds of cementitious products. Several researchers such as Mola-Abasi et al. [13] and Chenarboni et al. [22] have also expressed that with lengthening the curing time in soil stabilization with zeolite, the pozzolanic reactions occur. Thus, the soil gets stiff and the strength increases significantly.

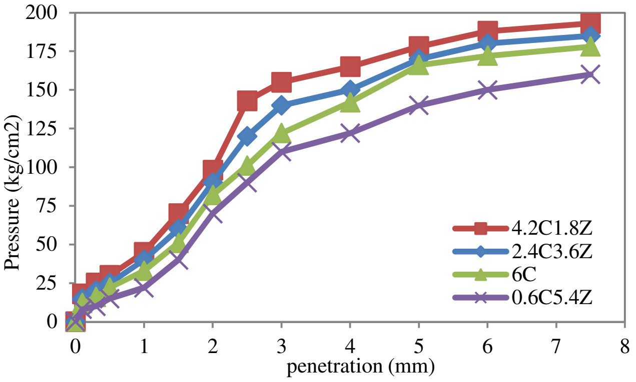

Fig. 9 The variation of pressure with penetration for sand-cement-zeolite mixture (6% cement)

The pozzolanic reaction is dependent on chemical and mineralogical compositions of cement and zeolite. It should be noted that both zeolite and cement contain large amounts of alumina and silica chemically. During pozzolanic reactions, the availability of silica and alumina from amorphous minerals increases. The alumina and silica inside the zeolite structure grow reactions with $Ca(OH)_2$ (calcium hydroxide) to generate CAH (calcium aluminate hydrate) and CSH (calcium silicate hydrate), which subsequently crystallize to bind the structure together [23]:

$$Ca(OH)_2 + SiO_2 \rightarrow C-S-H \tag{1}$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow C-A-H \tag{2}$$

Aluminum and silicon oxides' structure of the zeolite is depolymerized in the aqueous phase of the mixture, following the $Ca(OH)_2$ hydrolyzation. The Ca^{2+} ions react with monosilicates and aluminates and lead to the generation of CSH and CAH, which are analogous to those created during the hydration of cement. By performing X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) analyses, Rajabi and Ardakani [15] expressed that soil stabilization with zeolite leads to the occurrence of chemical reactions and creation of cement products including CSH and CAH gels, which are one of the principal reasons behind the increased strength of the hydrated cement paste. These gels fill the pores between sand and cement matrix in the Interfacial Transition Zone (ITZ), bind the structure together, and lead to an enhancement in the strength against the forces. Alongside this, the inclusion of zeolite in cemented sand increases the contact area between particles, reduces the porosity, and improves the interfacial microstructure characteristics between sand and cement. Hence, a dense network of interconnected particles is formed and CBR value improves. It can be observed from Fig. 9 that for zeolite contents more than 30% (2.4C3.6Z and 0.6C5.4Z samples), the CBR values begin to descend.

To clarify in more depth, it can be stated that in the pozzolanic reactions, the amounts of SiO_2 and Al_2O_3 in reaction with CaO influence the strength significantly [24]. For the sufficient amount of CaO, growing SiO_2 and Al_2O_3 will result in a more active pozzolanic reaction that improves the strength. With the increase of cement percentage, the SiO_2 and Al_2O_3 values (reaction particles) increase while their total amount will be lower than CaO. Therefore, it is anticipated that if the values of these particles get more, CBR will be enhanced too. If zeolite percentage increases, the SiO_2 and Al_2O_3 will grow but CaO reduces. As particles of SiO_2 and Al_2O_3 become more than the particles of CaO (specimens with more than 30% replaced zeolite), the pozzolanic reactions and CBR consequently decrease due to the reduction of the CSH and CAH amounts. In addition, once the amount of CaO particles becomes more than the sum of SiO_2 and Al_2O_3, some of the $Ca(OH)_2$ resulted from the hydration of CaO stay unreacted, and vice versa. Table 6 presents that with replacing 30% cement by zeolite, the highest improvement of CBR occurs because the sum of Al_2O_3 and SiO_2 (35.5 + 6.7 = 42.2%) will come into a balanced condition with CaO (44.6%). This finding is the range of the optimum results found by previous investigators. Canpolat et al. [25] reported that the replacement of 20% cement with zeolite enhanced the strength of the cement paste. Moreover, MolaAbasi et al. [26] and Salamatpoor et al. [27] expressed that the UCS of the cemented sand increases when the cement is replaced by zeolite at an optimum proportion of 30 and 40%, respectively.

Table 6 Chemical characteristics of the cement replaced by 30% zeolite

Content	SiO_2 (%)	Al_2O_3 (%)	CaO (%)
0.7 cement	15.3	3.4	44.3
0.3 cement	20.2	3.2	0.3
Total	35.5	6.7	44.6

It can be concluded that by the cement substitution with 30% zeolite, the presence of $Ca(OH)_2$ as a product of hydration reaction comes into a balance with the silica and alumina available in zeolite enrolling in the pozzolanic reaction, and all these chemical constituents are entirely consumed to yield CSH and CAH gels, resulting in the maximum CBR. However, for samples with more than 30% zeolite, this balanced condition will not occur. For example, with replacing 60% cement by zeolite, the sum of Al_2O_3 and SiO_2 (49.1 + 8.3 = 57.4%) will be much higher than CaO content (26%). Therefore, appropriate pozzolanic reactions will not take place and CBR will be reduced. In other words, with increasing percentage of zeolite, although pozzolanic particles will grow, CaO content which is a key element for the reaction reduces and consequently the pozzolanic reaction will not accomplish. Further increment of the zeolite up to 90% will result in the decrease of the amount of CaO, which cannot provide enough $Ca(OH)_2$ for the increasing amount of SiO_2 and Al_2O_3 to be completely consumed during the pozzolanic reaction. In this state, as seen in Fig. 10, CBR reduces because a part of SiO_2 and Al_2O_3 remains unreacted and ineffective. The reaction continues until CaO exists and Al_2O_3 and SiO_2 are not much more than CaO, as once this happens there will not be any CaO to react with. Therefore, it is clear that Al_2O_3, SiO_2, and CaO significantly affect CBR value.

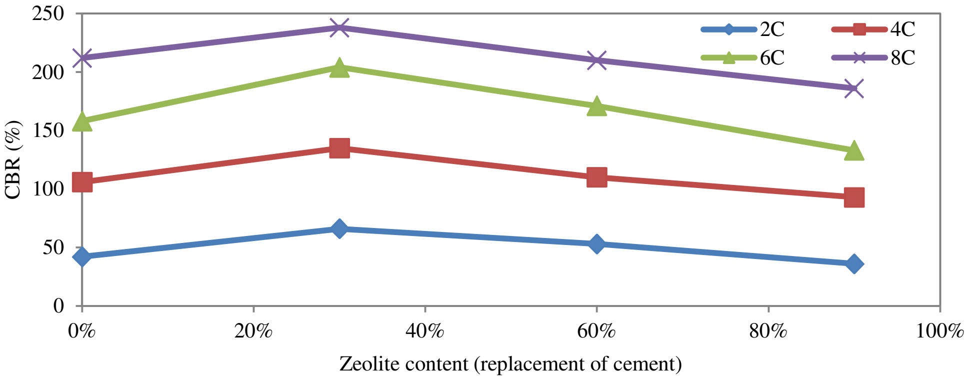

Fig. 10 The CBR values for different samples after 28 days of curing

Since the CBR test is complex and time-consuming, some correlations between CBR and MDD are proposed. These correlations can be used for evaluation of the subgrade or sub-base strength, as well as the prediction of resistance to failure and load-bearing capacity using MDD. The correlation coefficient (R^2) is usually defined as a single summary number that presents a good idea about how closely one variable is related to another variable. It should be noted that the strength of the relationship varies in degree according to the value of the R^2. Fig. 11 depicts the CBR-MDD relationship for zeolite-cemented sand in this study. Although several researchers such as Bassey et al. [28] and Katte et al. [29] proposed the correlations between CBR and MDD, the high R^2 value ($R^2 \geq 0.80$) in this investigation is indicative of a strong relationship between these parameters. In addition, the error between the predicted and experimental data is less than 15%.

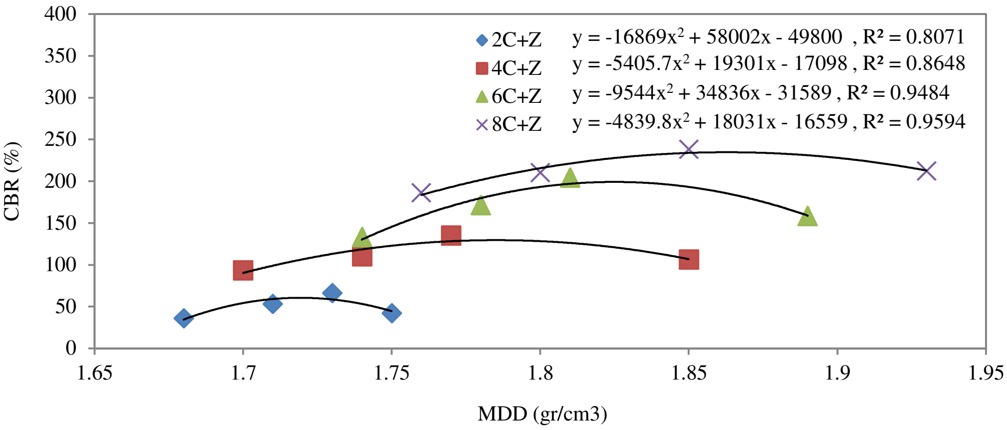

Fig. 11 The correlations between CBR and MDD

5. Conclusions

Importance of protecting the environment and decreasing pollution induced by cement production process has led to the search for alternatives that can be used instead of cement. This optimization directly minimizes the exploitation of natural resources, reduces consumption of energy, conserves the environment, and reuses industrial wastes. Thus, in this study, zeolite was applied as a partial replacement of cement in cement-stabilized samples, and the compaction characteristics and CBR values were estimated. CBR values are closely connected with the properties of compaction. Therefore, CBR test can be utilized as an approach of earthwork evaluation. The major conclusions of this study are as follows:

(1) The inclusion of cement into the sand increased MDD through filling the spaces between sand particles and its greater specific gravity than sand, while with the incorporation of zeolite into the cemented sand, MDD decreased due to its lower density than that of the cement. Moreover, due to the great specific surface area of zeolites, the moisture absorption in them will be higher. Hence, OMC increased with the incorporation of zeolite to the cemented sand.

(2) Zeolites are made up of high amounts of alumina and silica, naturally. As zeolite particles are added to cemented sand (up to 30% of cement content), they prefer to experience considerable pozzolanic reactions with Ca(OH)2 to generate cementitious products, thus enhancing CBR. Moreover, inter-particle filling properties of zeolite contribute to the CBR increase. However, for more than 30% zeolite, appropriate pozzolanic reaction will not occur and will not lead to the reduction of CBR.

(3) The proposed CBR-MDD correlations can be utilized for estimation of the subgrade or sub-base strength, as well as the prediction of resistance to failure and load-bearing capacity by MDD.

(4) Million tons of zeolite tuff can be found in Iran, particularly clinoptilolite tuffs, which are easily accessible. In addition, this material is environmentally friendly and has high contamination absorptivity. Therefore, using zeolite as a natural and inexpensive pozzolan can be a suitable material for improving the mechanical properties of cemented sand.

Conflicts of Interest

The authors declare no conflict of interest.

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