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Preposition of a Key Parameter to Estimate the Compressive Strength of the Sand stabilized with Cement-Zeolite and Reinforced by Polypropylene Fibers

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ABSTRACT: Nowadays, partial cement replacement with natural pozzolans like zeolite and the use of reinforcing agents such as fibers have been extensively used in the field of soil stabilization. In the current paper, the effects of the incorporation of polypropylene fibers and zeolite in a typical cemented sand have been examined. A set of unconfined compression strength (UCS) tests considering three distinct porosities (related to $D_r = 35$, 50, 70, and 85% sand), four cement contents (2, 4, 6, 8, and 10%), six different percentages of cement replacement with zeolite (0, 10, 30, 50, 70 and 90%) and the fiber content (0.5% by weight of cement in the mixture) has been performed. Then, the amounts of improved unconfined compressive strength (UCS) of the specimens as the result of zeolite and cement chemical properties have been estimated. Results indicate that the optimum amount of cement replacement by zeolite is 30%. Studies on zeolite-cement-sand mixtures reinforced by fibers have also shown that UCS improves in case cement content (C) and porosity (η) go up. Parameter $(SiO_2 + Al_2O_3)$ which are active particles (AP) participate in the chemical reaction introduced and UCS-AP diagrams have been drawn. Afterward, UCS was plotted against η / AP which is considered as a controlling parameter of UCS. This experimental research and the parameter $\eta^{-1.79} AP^{1.43}$ will introduce an acceptable description of mechanical properties. Finally, the effect of reinforcing agents in the mixture has been thoroughly studied through SEM analysis.

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1- Introduction

In recent years, the need for finding appropriate lands and treating problematic soils for building purposes has been developed due to the population growth and great competition among civil engineers has been generated for stabilizing and optimum use of available soils. Distribution of problematic soils especially loose sand poses a lot of difficulties to construction projects. The use of cement and fibers in ground improvement applications has shown excessive economic advantages. The mechanical behavior of cemented soils has been investigated by a lot of researchers [1-7]. Apart from the numerous advantages of using cement in sandy soils, brittleness is one of the major disadvantages which can be easily controlled with the aid of fibers. Fibers avoid tension crack formation and lead the resulting stresses to distribute in a wider area that reduces the brittleness of the cemented sand. Fibers act as plant roots and lead to the development of failure patterns. Moreover, the benefits of applying sand-cement fiber are the strength increment as well as the use of local soils in the field of stabilization. Plus, the use of fibers also improves the durability of samples in wet and dry cycles [8]. Recent research on the mechanical properties of fiber-reinforced cemented sands focused on the cement content added to sand or clay, the void ratio or porosity, various types of fibers with different lengths and content, molding water amount, and curing time [9-14].

Generally, several alternatives have been proposed to be applied instead of cement to reduce the pollution caused by cement factories, to save natural resource exploitation and energy utilization, and to use eco-friendly materials. Thus, cement substitution with pozzolans could be a suitable option to reduce the cement consumption in cemented mixtures [15]. They are broadly applied in cement and concrete production, which come up with less cement usage, supply higher strength during curing time, improve feasibility, enhance financial achievements, and increase the resistance of the mixture against acid and sulfate attacks [16, 17].

Pozzolans are produced (Man-made) as metakaolin, fly ash, micro silica, and silica fume by crushing pozzolanic rock such as zeolite, known as a common pozzolan. Due to the low production and high price of artificial pozzolans in Iran, the application of natural pozzolans as a part of cement is recommended [6]. As mineral pozzolans are effective in avoiding sulfate attacks, they are widely welcomed in concrete and soil stabilization. They can be categorized as artificial and natural ones. In Iran, the most renowned natural resources are Eskandan Pumice, Abyek Tuff, Jajrood Trass,

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Table 1. Results obtained from some previous research on the use of zeolite for geotechnical applications.

No.	Authors	Analyses	Summary of Results
1	Poon et al., [19]	Pozzolanic reactions	1) The curing period resulted in more pozzolanic reactions of zeolite. 2) Zeolite pozzolanic reactions were studied along with those of silica fume and fly ash reactions.
2	Oren et al., [20]	Hydraulic conductivity	1) Zeolite and bentonite caused a reduction in the hydraulic conductivity. 2) The lowest hydraulic conductivity coefficient was achieved by the optimum moisture content.
3	Joanna and Kazimierz, [21]	Absorbent layer	1) Substances that protect groundwater in landfills could be activated using zeolite and sand mixtures. 2) Absorption of ammonium and copper was observed in zeolite and sand mixture.
4	Ramezanpour, [22] and MolaAbasi et al., [23]	Scanning Electron Microscope (SEM)	1) Diminution of calcium hydroxide in the hydrated cement paste and increase of the calcium hydrate silicate production were observed because of the pozzolanic reactions. 2) Compaction of cement paste structure as filling the voids and inducing finer pores. 3) Improvement of the transitional area of the cement paste and materials because of the filling effects and pozzolanic reactions. 4) Ettringite crystals were shown to be formed due to the addition of the cement and zeolite, hence, the growth of the strength.
	MolaAbasi et al., [23]	XRD	The highest intensity of calcium silicate hydrate was represented in 30% cement replacement with zeolite in a stabilized sandy soil mixture.
5	MolaAbasi et al., [24]	Key parameters in predicting the strengths	1) The active particles parameter (AP) was presented as a key parameter to define the strength of zeolite-cement-treated sand. 2) It was concluded that the ratio of porosity/AP was one of the best fundamental parameters for approximation of the strength properties.

and Semnan Zeolite and the artificial ones include GBFS, BOFS, EAF, and LF.

Zeolite was considered to be a part of cement substitution in this study. There are large amounts of SiO_2 and Al_2O_3 particles (more than 50%) in zeolite whose reaction with $Ca(OH)_2$ in cement noticeably improves the cemented mixture strength during curing time. It also prevents undesirable expansions such as alkali-aggregate reactions [18]. Moreover, the addition of zeolite to the mixture modifies the characterization of interfacial microstructure and reduces the voids of the mixture [19]. There are numerous studies investigating the effect of zeolite and cement on sandy soils, some of which are listed in Table 1.

Unconfined Compression test is the frequently-applied method to measure the unconfined compressive strength (*UCS*) of the stabilized soils [25-27]. Given that this is a straightforward common test as well as being time-saving, it is widely used amongst researchers and practitioners. More than this, its required equipment is not much expensive and its results are both reliable and readily repeatable in comparison to other geotechnical tests such as triaxial tests. Besides, a number of dosage methodologies have been employed to assess *UCS*, which are presented in Table 2.

The main objective of the current paper is to assess the effect of a reinforcing agent (polypropylene fiber) on the *UCS* of the cement-zeolite stabilized sands. The other imperative goal of this study is to introduce a key parameter that can estimate the UCS of the mixture having some input variables (studied in this paper) such as relative density, cement, and zeolite contents. These

Table 2. Related dosage methodologies which have been presented before.

Researchers	Mixture type	Contributing parameter
Consoli et al., [27]	soil-cement	porosity/cement ratio
Consoli et al., [26]	Fiber-soil-cement	porosity/cement ratio
Mola-Abasi et al., [6]	zeolite-cemented sand	porosity/Active Particles ratio

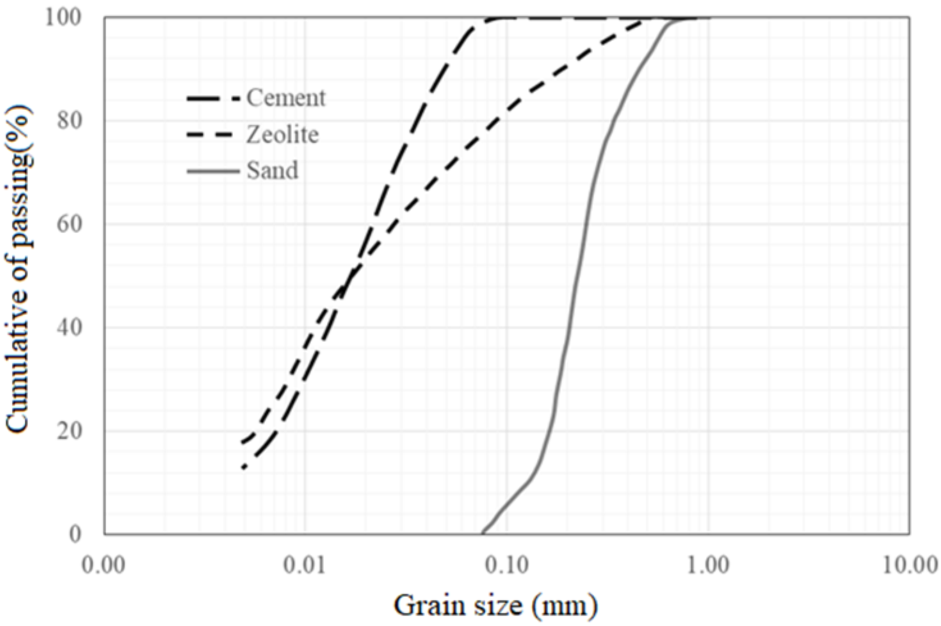


Fig. 1. Grain size distribution of the studied sand, cement and zeolite.

factors have not been studied before, hence, are regarded as an innovative idea for this paper. In this paper, the first experimental process is explained, and then the effects of controlling parameters on the *UCS* of the samples are analyzed. Ultimately, a simple new correlation formula for the studied fiber-reinforced zeolite-cement mixture is given.

2- Experimental Program

In this study, first, some tests were done to determine the geotechnical properties of the materials, and then, compression strength tests considering four distinct porosities, cement, and zeolite contents reinforced by polypropylene fibers were performed.

2- 1- Materials

the parent soil used in this study is poorly graded Babolsar sand, the stabilizers include Neka ordinary Portland cement type II and natural zeolite (clinoptilolite type) and the reinforcing agent is 12 mm-length polypropylene fibers (0.5% by weight of cement in the mixture). The grain size distributions of sand, cement, and zeolite are shown in Fig. 1. As presented in Fig. 1, the cement particles are smaller than zeolite. Also, given that the size of the studied materials was not similar, Scanning Electron Microscope (SEM) micrographs with different scales including 300 and 80 times more than real sizes of fiber and sand (coarser particles) as well as 3000 times more than cement and zeolite (finer grains), are presented in Fig. 2.

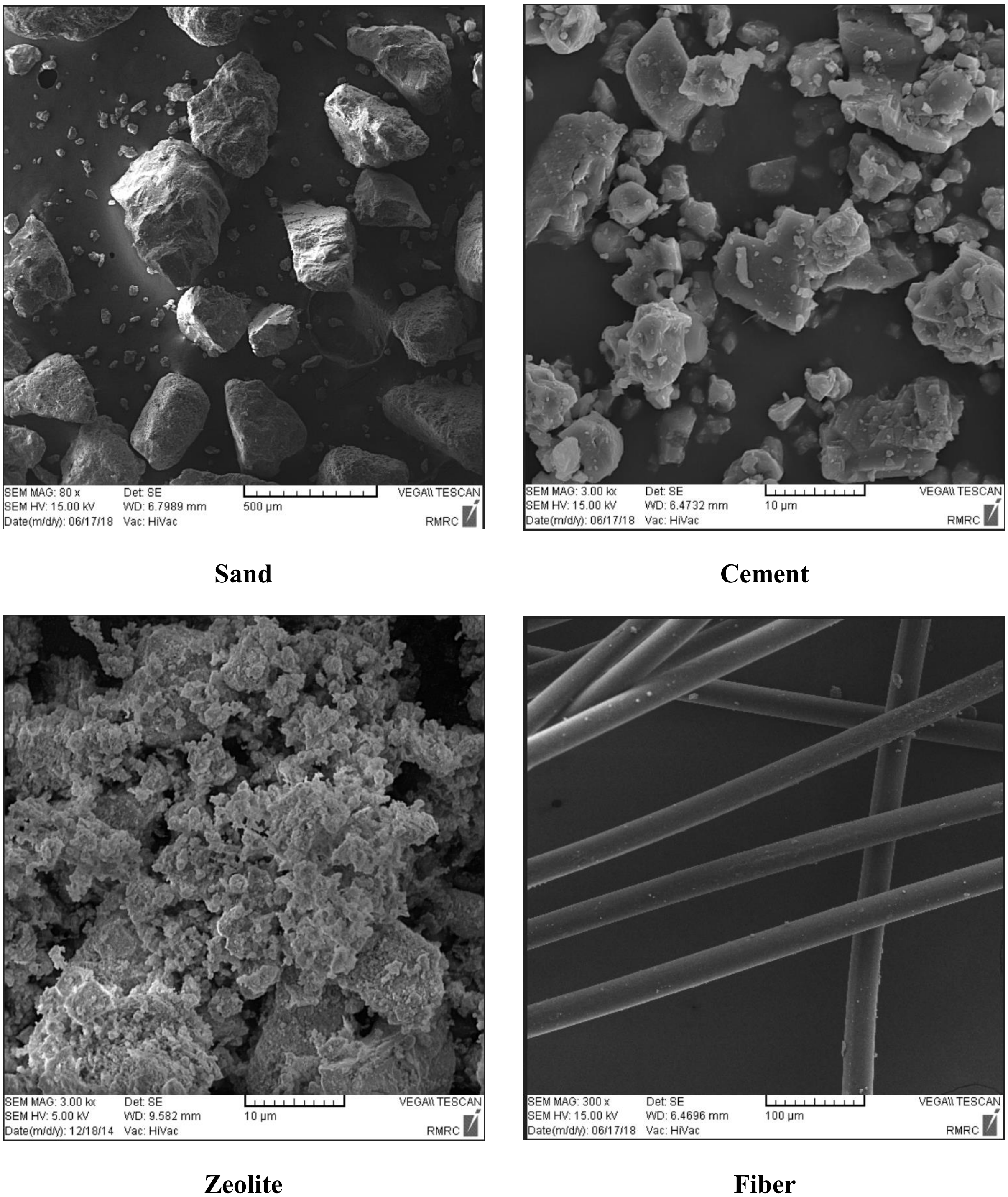


Fig. 2. SEM images of sand, cement, zeolite, and polypropylene fibers.

Table 3. Physical properties of polypropylene fibers.

Features	Adoption to cement	Cross section	Thickness (μm)	Tensile strength (kPa)	$\gamma_d (kN/m^3)$	Length (mm)
	Excellent	Circular	23	400	0.91	12

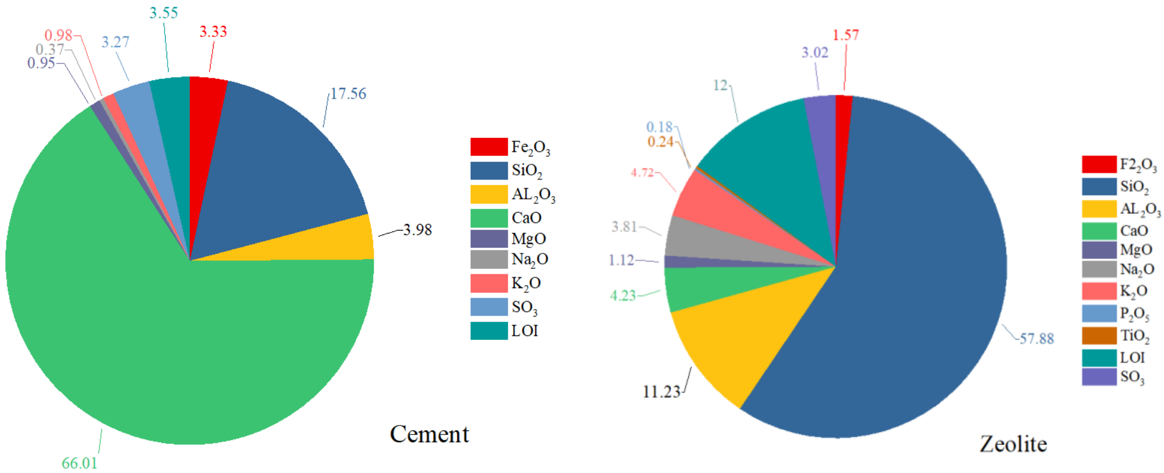


Fig. 3. Chemical constituents of the cement and natural zeolite

It should be noted that G_S, $\gamma_{d\max}$ and $\gamma_{d\min}$ of sand is 2.74, 17.7, 14.9, and 0.24, based on ASTM D854 [28], ASTM D698 [29], and ASTM D422 [30], respectively. Moreover, (ASTM D854 [28]), D_{50} (mm) (ASTM D422 [30]), LL (%), and PL (%) (ASTM D4318 [31]) of zeolite are 2.22, 0.0013, 23, and NP, respectively. Moreover, Fig. 3 presents chemical features of cement and zeolite whereas Table 3 highlights the physical properties of polypropylene fibers.

2- 2- Sample Preparation

In general, cement substitution with zeolite causes the pozzolanic reaction to be commenced and it would not be influential enough unless curing time is considered. Cement and zeolite mineralogical and chemical structures are the reason for developing such a pozzolanic activity. Besides, Molaabasi et al., [32] indicated that *pH* changes of zeolite mixtures will stop in 42 days of curing time. Thus, 42-day is the time that the maximum hydration reaction differences between cemented and zeolite-cemented sand happen, so it is a viable option for subsoil treatment. All of the other considered parameters in the experimental program are enlisted in Table 4. Furthermore, to prepare the specimens, dry unit weight is required for the determination of which two different approaches can be adopted including the use of the maximum dry density obtained from the compaction curves and also the use of maximum and minimum void ratio test results. The former approach is usually used for fine soils whereas the latter one is normally employed for coarse-grained soils. Based on the minimum void ratio standard, for the soils having less than 15% fine grains, the latter approach is more valid. Hence, in this paper, as the content of fine grains (stabilizers contents) is less than 15%, densities were obtained from the maximum and minimum void ratio tests. The following steps were done to determine the dry weights of the materials:

The values of void ratios with respect to relative densities of 35, 50, 70, and 85% were obtained 0.315, 0.282, 0.238, and 0.205, respectively. In the next step, the dry unit weight of the mixtures related to the inclusion of stabilizers was computed and variations of the sample unit weight were considered as Eq. (1).

Table 4. Description of the considered parameters

Variables	Description of samples
Soil type	Babolsar Sand, SP
Cement type	Neka Cement, type II
Cement content	2, 4, 6, 8, and 10% dry unit weight of the parent soil
Type of zeolite	Clinoptilolite
Zeolite content	0, 10, 30, 50, 70 and 90% of cement
Type of fiber	Polypropylene
Fiber content	0.5%
Fiber	Diameter=2 mm, length=12 mm
Porosity	Corresponding to Dr=35, 50, 70 and 85% sand
Water content	10% weight of the parent soil
Sample size	Diameter=38 mm, Height=76 mm
Curing time	42 days

$$\gamma_d = \frac{G_{s\,mix}\gamma_w}{1+e} \quad (1)$$

Where $G_{s\,mix}$ is the average weight of the materials.

The third step is related to the weights of the materials and water as Eq. (2).

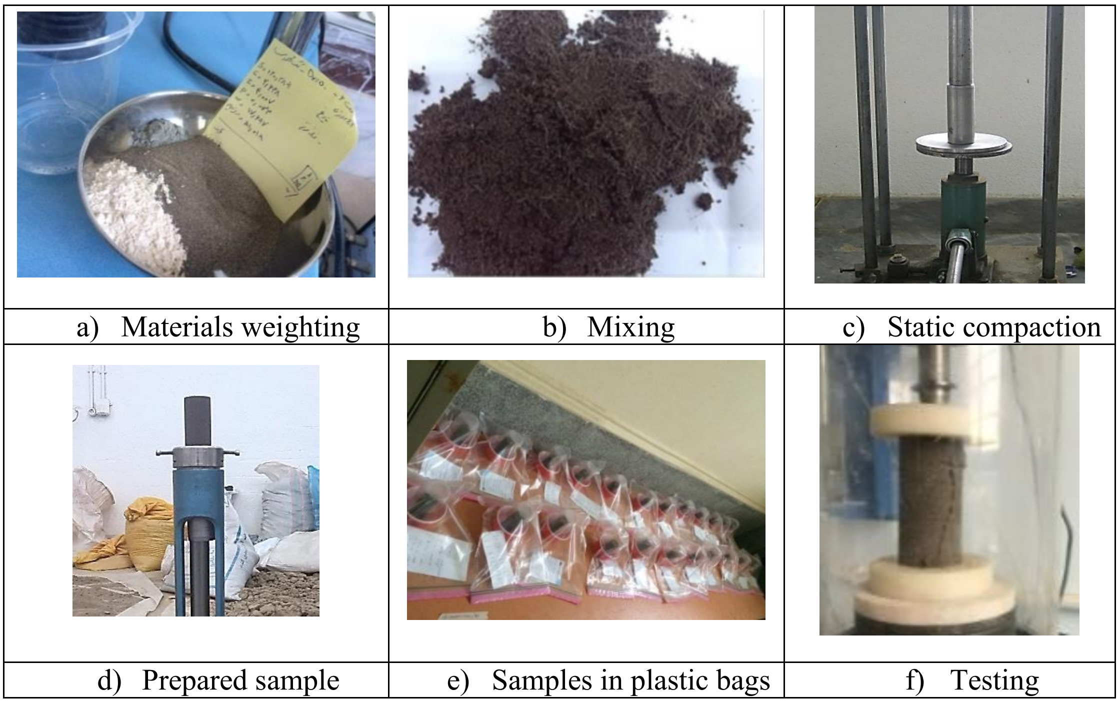
$$w_s = \gamma_d V \quad (2)$$

γ_d is the unit weight of each mix design which was computed from the previous step and V is the sample volume. Regarding each specific mix design, the weight of sand, cement, zeolite, and fibers were weighed. Then, based on Molaabasi et al., [5], the required moisture content was obtained for any mixture by multiplying to 10% (the optimum value corresponding to the highest unconfined compression strength).

Noteworthily, moist tamping and under compaction approaches were used for preparing the samples and 1 gram extra water was added to ignore evaporation during the sample preparation process [33]. Cement, zeolite, and sand were mixed for 3 min and then fibers were randomly added and mixed for another 3min and finally, they were all mixed with water for 5min [34]. Samples were statically compacted by hand-mixing and were kept in plastic bags after measuring their weights and dimensions with 0.01gr and 0.02 mm accuracies to avoid moisture losses up to the end of the curing period. The process of preparing a specimen is presented in Fig. 4.

2- 3- Test Procedure

Generally, unconfined compression is regarded as the most convenient, straightforward, and economical test to be conducted measuring the strength of the stabilized samples to achieve the most accurate engineering judgment, hence, it would be beneficial to provide the possibility to estimate the strength value even without performing any experimental tests. In the current paper, the unconfined compression tests were carried out based on ASTM D-2166 [35]. In terms of the compression test, the load was applied to the specimen up to when failure happened then the maximum load was recorded and *UCS* was calculated, accordingly. The loading system of the unconfined compression test is illustrated in Fig. 5 where loading is applied mechanically. It should be noted that the capacity of the loading ring is 10 kN and the accuracy of the displacement gage is 0.01 mm. The loading rate, also, is 0.1%/min which is consistent with the previous study performed by Molaabasi et al., [23].



a) Materials weighting
b) Mixing
c) Static compaction
d) Prepared sample
e) Samples in plastic bags
f) Testing

Fig. 4. The process of sample preparation.

Fig. 5. The employed UCS apparatus in this study.

Table 5. Chemical components of the optimum mix design (30% cement replacement with zeolite)

Chemical name		SiO_2	Al_2O_3	CaO
Percent (%)	0.7cement	15.33	3.402	44.324
	0.3zeolite	20.232	3.24	0.372
	Sum	35.562	6.642	44.696
		42.204		44.696

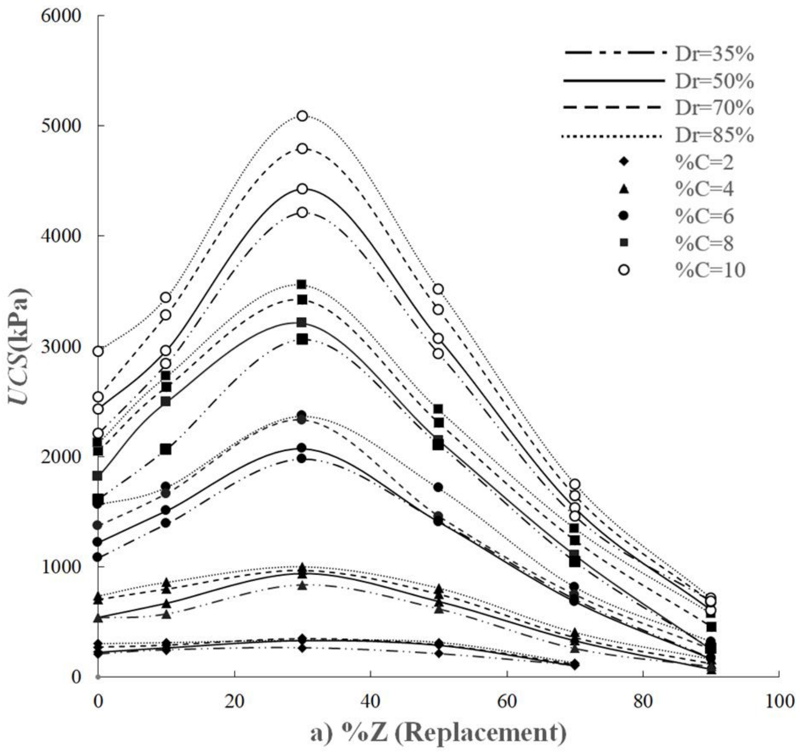


Fig. 6. Effect of zeolite addition into the sand on reinforced zeolite-cemented sand

3- Results and Discussion

3- 1- Effect of Zeolite and Cement Contents on the UCS

UCS of the zeolite-cemented sand and the fiber-reinforced zeolite-cemented sand are plotted against the zeolite content (Z%) in Fig. 6. In all none- and fiber-reinforced samples with cement contents ranging from 2 to 10%, *UCS* has grown. The optimum value of the *UCS* happened at cement replacement with 30% zeolite (peak of the curve). For higher zeolite contents (>30%), however, a decreasing trend is observed. In case cement is replaced with 30% zeolite, the amount of ($SiO_2 + Al_2O_3$) is almost equal to Cao (Table 5). Hence, in case a high strength is required, 30% cement replacement with zeolite will suffice.

A typical stress-strain curve for the samples containing 4% cement and having a relative density of 50% is presented in Fig. 7. As shown in the figure, with increasing the amount of zeolite, the failure strain increases. It can be also mentioned that it reduces the wet properties of cementitious materials.

One of the most common parameters to evaluate the ductility of the specimens is the brittle index which is defined as follows:

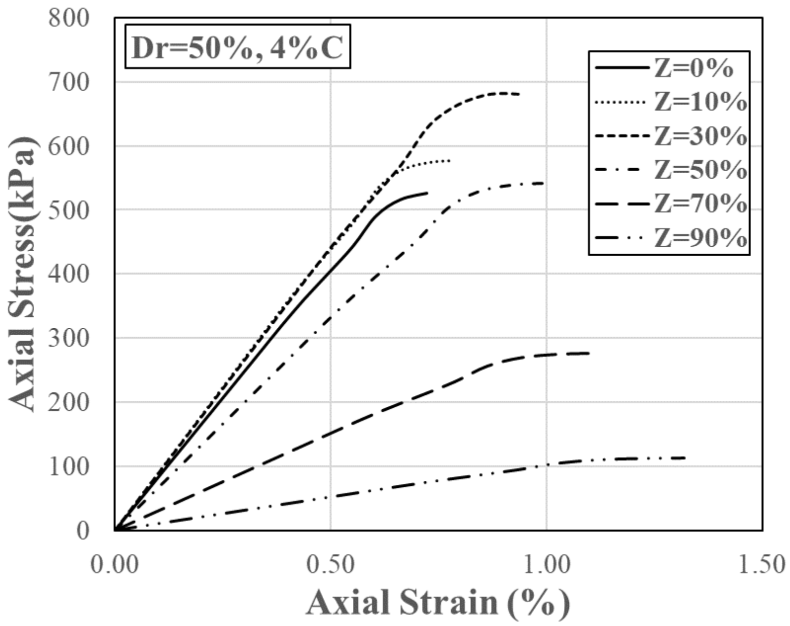


Fig. 7. The stress-strain curve corresponds to the samples containing 4% cement content and having 50% relative density.

$$B_i = \frac{q_{\max} - q_{res}}{q_{res}} \tag{3}$$

Where q_{max} and q_{res} are maximum and residual strengths that are normally investigated through triaxial apparatus which considers the confining pressure. Yet, in the unconfined compression test, as the confining pressures are not available, the stress in the sample reaches to zero after being exposed to the maximum stress where the brittle index cannot be measured. Hence, the brittle index corresponding to 56-day cement-treated sands containing fibers cannot be measured through the unconfined compression test. Consequently, other criteria like failure strain are assessed. It can be indirectly mentioned that the increase of the brittle index considerably decreases the failure strain. Use of polypropylene fibers, it was concluded that the failure strain increased. The failure strains and strength values corresponding to the fiber-reinforced samples are more than those without fibers. Moreover, the efficacy of fibers on the reduction of brittle behavior of the samples is totally observed from *SEM* micrographs which is further explained in the following parts.

The strength improvement rates of the optimum fiber-reinforced zeolite-cemented sand (*FZC*) specimens compared to fiber-reinforced cemented (*FC*) ones as ration increase parameter (R_i) in percentage is demonstrated in Fig. 8 for the samples whose relative densities are 50%.

$$R_i = \left[\frac{\left(UCS_{FZC} - UCS_{FC}\right)}{UCS_{FC}}\right] \times 100 \tag{4}$$

When samples were prepared with a lower degree of compaction and higher cement contents, the strength improvement rate was higher. In other words, although looser samples have lower strength when Z=30% replaces cement, the strength improvement percentage grows much more than that of the dense ones. For instance, as it can be clearly observed in Figs. 6 and 8, with cement content of 10% in relative densities of 35% and 85%, *UCSs* of cemented samples were 2433 and 2651 kPa, respectively. Whereas, at 30% cement replacement with zeolite, strengths reached to 4210 and 5086 kPa. Hence, strength improvement rates are 91% and 73% according to Eq. (3). That is, the less compacted the mixtures were, the more applicable zeolite was; therefore, researchers and users can opt the fewer amounts of cementitious materials with optimum content of zeolite and the energy for compacting layers in order to provide a blend that gains the highest strength which is essential in the future prospects.

Moreover, it should be noted that based on what has been shown in this paper and some previous related ones [5, 32, 36, 37], *UCS* shows the same trend, and when Z=50%, roughly

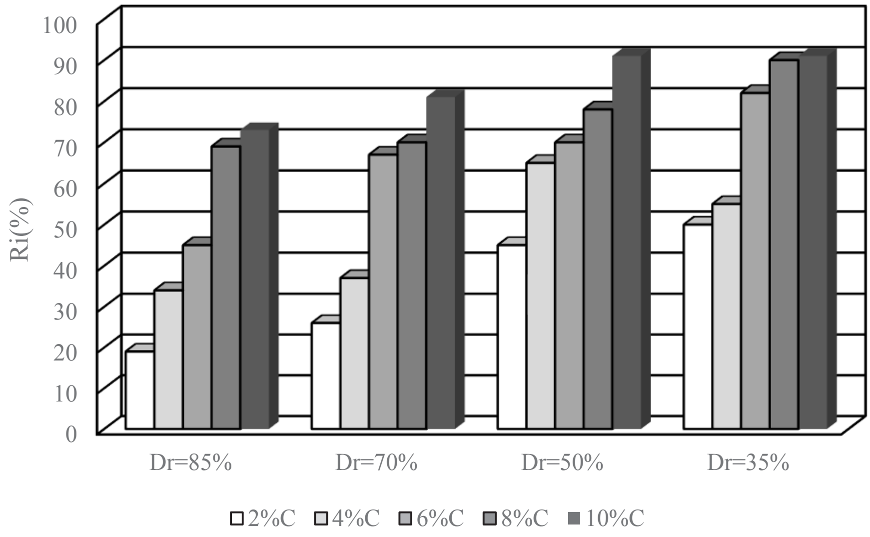


Fig. 8. Strength improvement rate (Ri%) when Z=30%

reaches to the primary compressive and tensile strength that cemented sands provide and hence, use of zeolite instead of cement has been justified and strongly recommended.

3- 2- Stiffness (E_{50})

Fig. 9. depicts the variations of cement content against the values of E_u for fiber-reinforced samples containing 0 and 30% zeolite contents. Here, the stiffness is obtained from the slope of the stress-strain curves of the samples having 50% relative density. As it can be seen, the stiffness results are in good agreement with the compressive strength values presented in Fig. 6. For both states including cement and zeolite-cement treated fiber-reinforced samples, an increase of cement content improves the stiffness.

3- 3- Effect of Porosity/ SiO_2 and Al_2O_3 Particles on the UCS

Based on the chemical reaction of cement including cement hydration and pozzolanic reaction, Al_2O_3 and SiO_2 values reacting with CaO have a great influence on *UCS*. If CaO is adequate in the mixture, growth of Al_2O_3 and SiO_2 will result in a more operative pozzolanic reaction which enhances *UCS*. Al_2O_3, SiO_2 and CaO has shown to have a substantial impact on *UCS* growth. *AP* is defined as:

$$\begin{aligned}&\text{If } CaO > Al_2o_3 + SiO_2 \rightarrow \\ &AP = Al_2O_3 \text{ and } SiO_2 \text{ Particles}\end{aligned} \tag{5}$$

$$\begin{aligned}&\text{If } CaO < Al_2O_3 + SiO_2 \rightarrow \\ &AP = CaO \text{ Particle}\end{aligned} \tag{6}$$

AP is the weight percent of either Al_2O_3 and SiO_2 or CaO (their minimum value). Considering cement and zeolite contents and weight percentages of Al_2O_3, SiO_2 and CaO of zeolite and cement (Fig. 3), *AP* can be easily computed. *AP* calculation process for the case with 4% cement content is presented in Table 6 as an illustration.

To clarify the influence of *AP*, Fig. 10 is presented which shows the variation of particles namely CaO, $A_2O_3 + SiO_2$ and *AP* particles. As it is obvious from Fig. 10, increasing zeolite content, CaO will decrease and sum of SiO_2 and Al_2O_3 will increase. Whereas, regarding to *AP* definition, *AP* will increase up to 30% cement replacement with zeolite and decrease in higher percentages. These changes totally fit the compressive strength variations.

To examine the capability of *AP* in predicting *UCS*, *UCS* is plotted against *AP* in Fig. 11 which corroborates the satisfactory correlation between *UCS* and *AP*. Hence, the use of *AP* can noticeably facilitate estimating the mixture strength and help engineers for more rational decisions in their designs.

Similar to Consoli et al., [27]research, η / AP was concluded to have a superior correlation with *UCS* which is thoroughly demonstrated in Fig. 12. It is plainly visible that

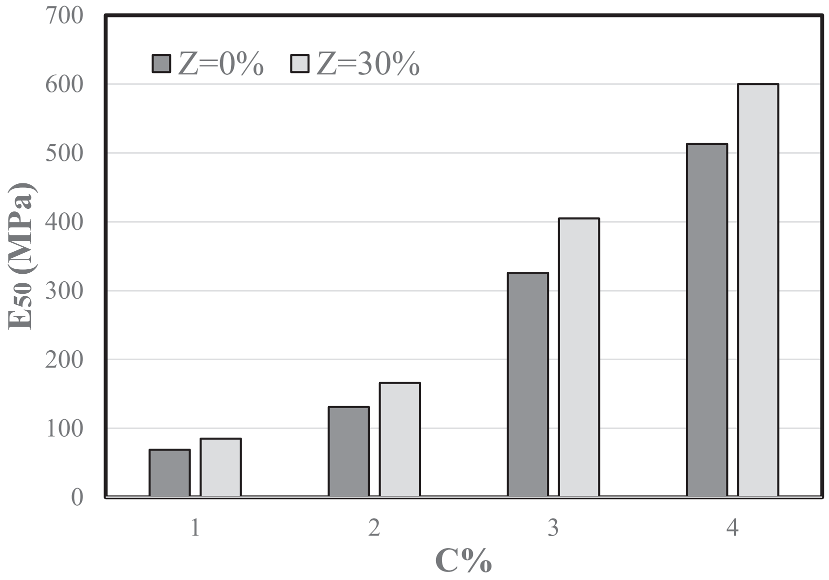


Fig. 9. Variations of stiffness against cement content for Z=0 and Z=30%.

Table 6. AP calculations related to samples with %4 cement

	%Cement	%Zeolite replacement	%Cement (in Sample)	%Zeolite (in Sample)	SiO_2 (Cement)	SiO_2 (Zeolite)	Al_2O_3 (cement)	Al_2O_3(Zeolite)	Sum of SiO_2 and Al_2O_3	Cao (Zeolite + Cement)	AP
	A	B	C=A-D	D=A*B/100	E=C*21.9/100	F=D*67.4/100	G=C*4.86/100	H=D*10.8/100	I=E+F+G+H	H=(C*63.32+1.24*D)/10000	AP=IF(I<H,I,H)
1	4	0	4	0	0.876	0	0.1944	0	1.0704	253.28	1.0704
2	4	10	3.6	0.4	0.7884	0.2696	0.17496	0.0432	1.27616	227.9520496	1.27616
3	4	30	2.8	1.2	0.6132	0.8088	0.13608	0.1296	1.68768	177.2961488	1.68768
4	4	50	2	2	0.438	1.348	0.0972	0.216	2.0992	126.640248	2.0992
5	4	70	1.2	2.8	0.2628	1.8872	0.05832	0.3024	2.51072	75.9843472	2.51072
6	4	90	0.4	3.6	0.0876	2.4264	0.01944	0.3888	2.92224	25.3284464	2.92224

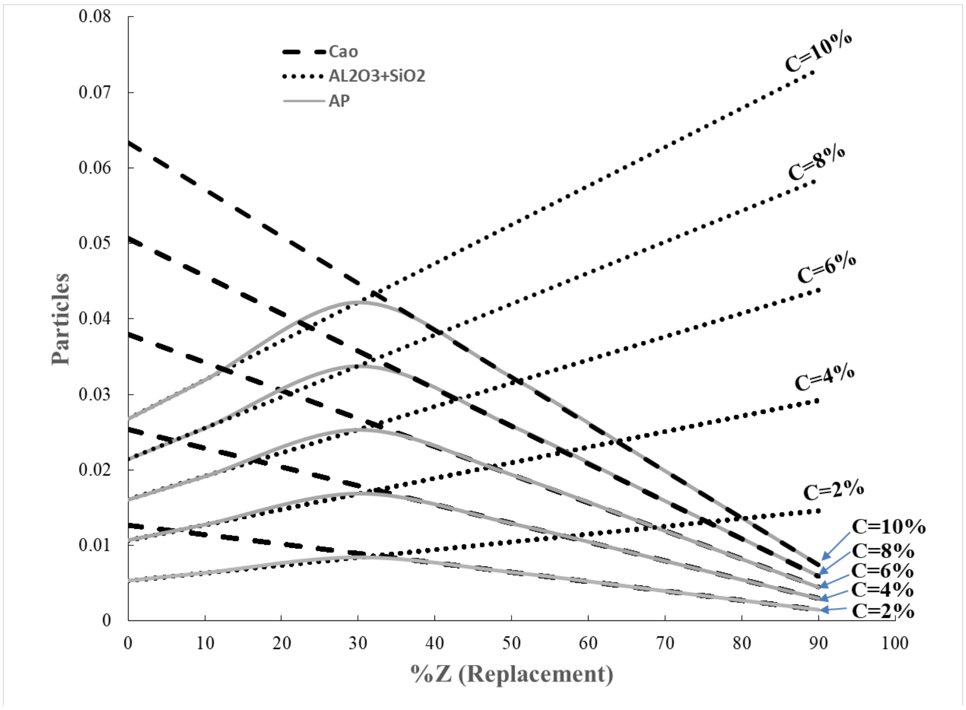


Fig. 10. Variations of CaO , $Al_2O_3 + SiO_2$ and AP particles against zeolite content

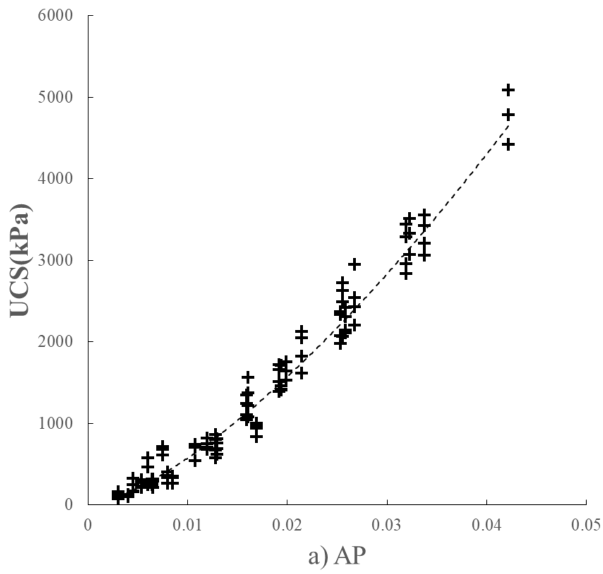


Fig. 11. Variations of *UCS* against AP.

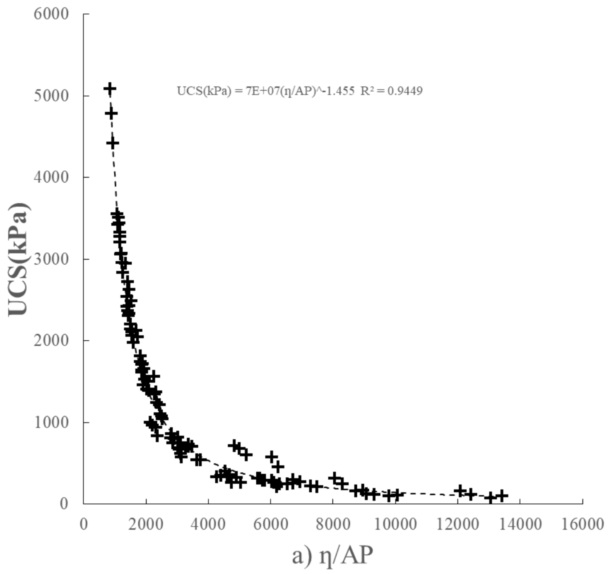


Fig. 12. Variation of compressive strength against η / AP

η / AP can be assumed as a vital parameter to successfully assess the compressive strength.

The current paper intends to assess the *UCS*s of the fiber-reinforced zeolite-cemented sands and to propose a key parameter that can correlate the relation between the mechanical properties using the findings of the unconfined compression tests. The proposed key parameter is the porosity/Active Particles ratio which was defined precisely in the previous sections. Such an idea originated from Consoli et al., [27] who used the porosity/cement ratio in their study. In this paper, a new variable is proposed instead of cement content which is capable of being the fundamental parameter for fiber-reinforced cemented sands. Generally, influential parameters in the estimation of the *UCS*s of the fiber-reinforced zeolite-cemented sands are porosity, cement, and zeolite contents. However, as the effect of zeolite on cemented sands is analyzed, fiber content, curing time and the base soil are considered the same and are not included as effectual parameters. It is plainly obvious that the proposed key parameter should cover the three aforementioned variables (porosity, cement, and zeolite contents).

Consoli et al., [27] indicated that η^{a_1} (*ai* is a constant) can be a suitable parameter that exponentially multiplies with another parameter and can be the other parameter. As a consequent, η / AP proposed as a key parameter. Finally, it can be clearly concluded that $UCS = a_1 \left(\eta / AP\right)^{a_2}$ is accurate and (η / AP) is a useful parameter. To have a clearer assessment, η and AP parameters can be used with different exponents ($UCS = a_1 \eta^{a_2} AP^{a_3}$) which result is presented in Eq. (4) that is more accurate.

$$UCS = 4.1 \times 10^{8} \eta^{-1.79} AP^{1.43} \quad \left(R^2 = 0.965\right) \tag{7}$$

As can be interpreted from Eq. (4), *AP* just encapsulates cement and zeolite contents (not the parent soil). Noteworthily, the use of this equation can be expanded for similar sands from the Caspian Sea coastal zone whose particles have semi-round and round shapes. Moreover, a highly accurate exponential relation can be proposed with the aid of Eq. (4) and some series of experimental analyses for the sands stabilized with cement and other pozzolanic materials (herein, zeolite has been studied).

3- 4- SEM analysis

The increase of the strength rate of cement- and cement-zeolite-treated sands is due to the addition of cement and zeolite and consequently, the occurrence of the chemical reactions in the mixture. *SEM* and *XRD* analysis related to the addition of cement and zeolite were thoroughly discussed by Molaabasi et al., [32]. In this section, *SEM* micrographs of the studied fiber-reinforced cemented and zeolite-cemented sands corresponding to the samples having 50% relative density are presented in Figs. 13a and 13b, respectively. As can be seen, fibers were resistant subjected to tension and were also coated by the stabilizers, decreasing inter-pore spaces and embedding between the particles which subsequently, enhanced the strength and strain energy. In cemented sands, due to its more brittle behavior, fibers were stretched more, hence, the cross-sectional area of the fibers was reduced. On the other hand, as zeolite incorporation changed the brittle behavior to the ductile one, less stretch was observed in the

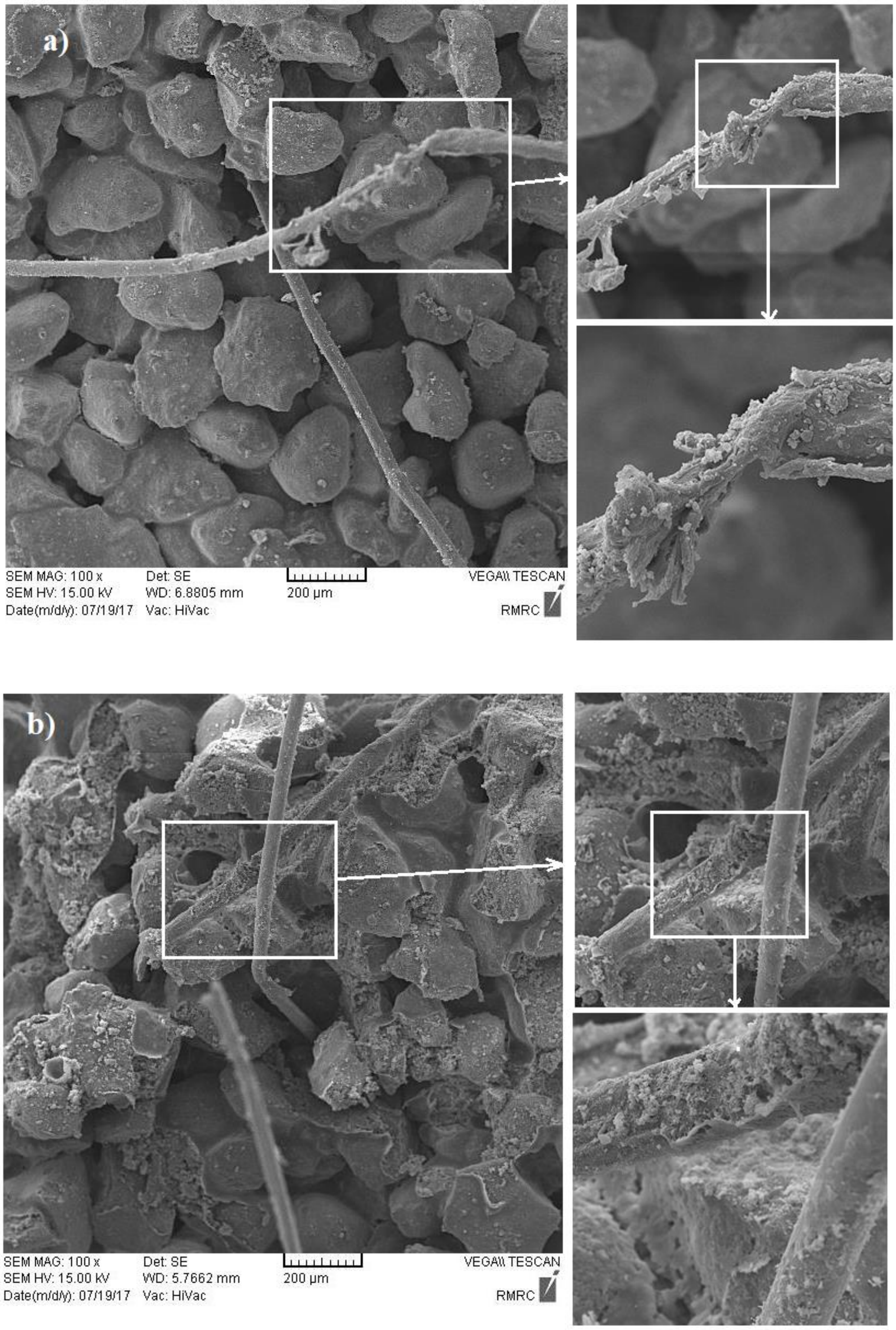


Fig. 13. ***SEM*** **micrographes of reinforced a) cemented and b) zeolite-cemented sands**

fibers. In other words, As shown in the figures, in fiber-reinforced cement-treated samples, the stress is applied to the fibers which consequently results in the reduction of cross-sectional area and increase of tensile characteristics, which is much less observed in cement-zeolite-treated samples.

4- Conclusions

In the field of cemented sand stabilization, the current paper and some other recent ones came to the conclusion that partial cement replacement with zeolite increases the *UCS*s of the samples. Other major results for fiber-reinforced zeolite-cemented sands include:

- The rise of cement content, whether zeolite and fiber exist in the mixture, improves the soil strength and failure strain significantly.
- An increase of the zeolite content by up to 30% increased the *UCS*s of the fiber-reinforced samples as the pozzolanic reactions were effectually accomplished in 42 days of curing. However, higher contents of zeolite decreased the *UCS* values, hence, 30% cement replacement proved to be the optimum state.
- When 30% zeolite content replaces cement, the amounts of SiO_2 and Al_2O_3 are close to CaO which is the optimum state for the applicable pozzolanic reaction contributing to the maximum strength.
- The efficiency of 30% cement replacement by zeolite on the strength increment was more significant by the reduction of the relative density from 85 to 35%.
- The key parameter, active particles (*AP*), which is defined as the minimum amount of CaO or $SiO_2 + Al_2O_3$, was shown to successfully predict the *UCS* of the fiber-reinforced samples. In the samples, *AP* and *UCS* have shown upward trends up to 30% zeolite substitution. However, passing this specific amount, a decreasing trend will be observed.
- It is verified that the proposed approach for the fiber-reinforced zeolite-cemented sands and the key parameter method is matching.
- As per the microstructural analysis, less stretch was observed in the fibers in the samples containing zeolite which indicates that zeolite makes the cementitious matrix more flexible.

In general, based on the process proved in the current study, the use of η / AP as a key parameter is strongly suggested with the aid of which *UCS* of fiber-reinforced zeolite-cemented sands can be predicted to achieve a highly accurate result. Moreover, additional experimental analysis including performing direct shear or triaxial tests are recommended for future research on the proposed materials.

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