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# Influence of zeolite and cement additions on mechanical behavior of sandy soil

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ABSTRACT

It is well known that the cemented sand is one of economic and environmental topics in soil stabilization. In this instance, a blend of sand, cement and other materials such as fiber, glass, nanoparticle and zeolite can be commercially available and effectively used in soil stabilization in road construction. However, the influence and effectiveness of zeolite on the properties of cemented sand systems have not been completely explored. In this study, based on an experimental program, the effects of zeolite on the characteristics of cemented sands are investigated. Stabilizing agent includes Portland cement of type II and zeolite. Results show the improvements of unconfined compressive strength (UCS) and failure properties of cemented sand when the cement is replaced by zeolite at an optimum proportion of 30% after 28 days. The rate of strength improvement is approximately between 20% and 78%. The efficiency of using zeolite increases with the increases in cement amount and porosity. Finally, a power function of void-cement ratio and zeolite content is demonstrated to be an appropriate method to assess UCS of zeolite-cemented mixtures.


## 1. Introduction

Soil stabilization with cement has been a ground improvement method in geotechnical engineering for many years. Using cemented soil is a versatile and reliable technique among others to increase shear strength parameters. By borrowing materials from elsewhere, the cemented soils have advantages of economy, simple and rapid performances. The cemented technique is particularly suited for stabilization of problematic soils such as loose sand deposit. Cementation of sand can result in increasing brittle behavior of the material. The unconfined compression test is one of the major and rapid laboratory tests to evaluate the effectiveness of the stabilization with cement or other additives. The compressive strength of artificially cemented soils has been studied in the past by several investigators (e.g. Clough et al., 1981; Huang and Airey, 1998; Consoli et al., 2007, 2009a, 2013a; Dalla Rosa et al., 2008; Horpibulsuk et al., 2014; Yilmaz et al., 2015).

A number of studies have been done to assess the mechanical behavior and compressive strength increase of cemented sands using added fiber, glass, fly ash, silica fume and nanoparticle in the same manner (e.g. Consoli et al., 1998, 2009b, 2013b; Arabani et al., 2012; Choobbasti et al., 2015). However, there has been a little effort to the use of pozzolans such as natural zeolite. The natural zeolite, an extender, has been investigated for use as cement and concrete improver (Poon et al., 1999; Perraki et al., 2003). The natural zeolite contains large quantities of reactive $SiO_2$ and $Al_2O_3$ (Poon et al., 1999). Similar to other pozzolanic materials, zeolite substitution can improve the strength of cement by pozzolanic reaction with $Ca(OH)_2$, prevent undesirable expansion due to alkali–aggregate reaction, reduce the porosity of the blended cement paste, and improve the interfacial microstructure properties between the blended cement paste (Feng et al., 1990; Poon et al., 1999; Canpolat et al., 2004). Poon et al. (1999) observed that the pozzolanic activity of natural zeolite is higher than that of fly ash but lower than that of silica fume. Yılmaz et al. (2007) concluded that the clinoptilolite blend decreases the specific weight of cements.

This study aims to quantify the influence of the amount of zeolite and cement and relative density of artificially cemented sandy soils cured for 28 days on the strength parameters via unconfined compression tests, as well as to evaluate the power function fits to predict unconfined compressive strength (UCS) of the soils.

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## 2. Experimental program

### 2.1. Materials

The base sandy soil was obtained from Babolsar City located on the southern shorelines of the Caspian Sea. The soil is classified as poor-graded sand (SP) according to the Unified Soil Classification System (ASTM D422, 2003) with angular particle and specific weight ($G_s$) of 2.74. The soil is pure sand with a mean effective diameter ($D_{50}$) of 0.24 mm, and the uniformity and curvature coefficients are 1.75 and 0.89, respectively. The minimum and maximum unit weights are 14.9 kN/m$^2$ and 17.7 kN/m$^2$, respectively.

Portland cement of type II (ASTM C150, 2003) was applied in this research. The specific weight of the cement grains, specific surface and initial setting time are 3.11, >3000 cm$^2$/g, and >75 min, respectively.

The zeolite is of natural clinoptilolite kind and particles smaller than 75 μm (No. 200 sieve) are referred to as fine aggregates located near Aftar City in Semnan Province of Iran. The zeolite is non-plastic and classified as silt (ML) according to the Unified Soil Classification System (ASTM D422, 2003) with $G_s = 2.2$. The grain size distribution curves of the materials including sand, cement and zeolite are presented in Fig. 1.

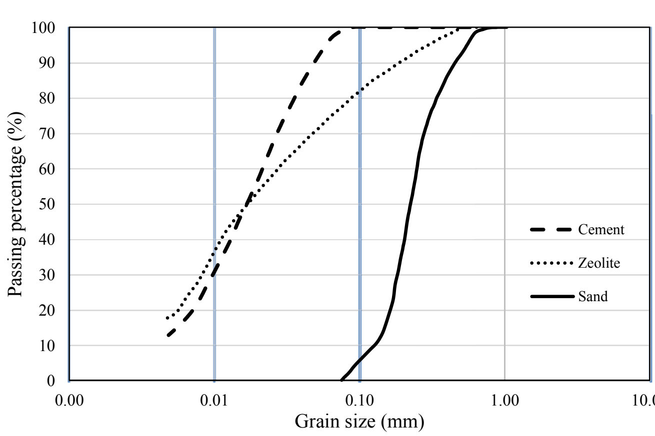


**Fig. 1.** Grain size distribution curves of sand, cement and zeolite.

### 2.2. Experimental program, sample preparation and test process

The positive effect of zeolite on cemented sand strength requires the curing time to be long enough due to pozzolanic reaction. The pozzolanic activity of zeolites with cement depends on their chemical and mineralogical compositions. In this study, the curing time of 28 days is selected.

Cement content ($C$), replacement of cement by zeolite ($Z$) and void ratio ($e$) are the variable parameters in the testing program to identify the effect of cement and zeolite additives on sand strength. The variables measured in sample preparation are presented in Table 1.

For unconfined compression tests, cylindrical specimens ($\phi$38 mm × 76 mm) were used. Given a void ratio $e$, the target dry unit weight $\gamma_d$ can be calculated according to the following equation:

$$\gamma_d = \frac{G_s \gamma_w}{1 + e} \tag{1}$$

**Table 1**
Description of parameters.

| Variable | Description of samples |
|---|---|
| Soil type | Poorly graded sand from Babolsar City (Shores of Caspian Sea) |
| Cement agent | Portland cement (type II) |
| Cement content | 2%, 4%, 6% and 8% dry unit weight of base soil |
| Type of zeolite | Natural clinoptilolite zeolite |
| Zeolite content (replacement by cement) | 0%, 10%, 30%, 50%, 70% and 90% of cement content |
| Void ratio | 0.648, 0.591 and 0.563 corresponding to $D_r$ = 50%, 70% and 85% sands, respectively, where $D_r$ is the relative density |
| Water content | 10% weight of base soil |
| Sample size | 38 mm in diameter and 76 mm in height, compacted in three layers |
| Curing condition | 28 d in humid room with the relative humidity greater than 90% |

where $G_s$ is a composite specific weight (due to the specific weight of cement grains (3.11) greater than that of sand and zeolite grains (2.74 and 2.2, respectively)) based on the zeolite, cement and sand percentages in the specimens. This equation is also used for precise calculation of void ratio and porosity. Sand, cement and zeolite (based on the mixture procedure shown in Table 1) were mixed uniformly, then tap water (10% of dry unit weight) was added continuously to the soil-cement mixture. The specimens were tamped into three identical layers to reach the specified dry unit weight considering the compaction method proposed by Ladd (1978). The top of each sample was slightly scarified. The time used to preparation, mixture, and compaction was always less than 1 h, although using zeolite increases the initial setting time of cement. A small portion of mixture was also taken for moisture content determination. Additionally, the specimens were wrapped in plastic bags and cured for 28 days in a humid room at 24 °C with the relative humidity greater than 90%.

The unconfined compression test is one of the major and rapid laboratory tests to evaluate the effects of zeolite quantity, cement content, porosity, and void-cement ratio on the mechanical strength of soil-zeolite-cement mixture. An automatic loading machine with a maximum capacity of 10 kN and proving rings with capacities of 2 kN ± 0.0014 kN and 10 kN ± 0.0061 kN, respectively, were used for the unconfined compression tests. Seventy two unconfined compression tests in total were performed (0.76 mm/min) according to ASTM D2166 (2000). Failure types of stabilized specimens are shown in Fig. 2. Because of the typical scatter of data obtained from unconfined compression tests, every three specimens were tested and the average was considered. The satisfactory number of tests per class of specimens is checked by the calculated value of standard deviation/mean of UCS obtained from the three samples, which was 4.

## 3. Results

The stress–strain curves of specimens stabilized with 4% and 8% cement contents with respect to different zeolite substitutions, under the condition of constant void ratio ($e$ = 0.591), are illustrated in Fig. 3. It is shown that the maximum axial stress significantly increases due to cement stabilization, and the strain corresponding to the peak axial stress decreases. By increasing zeolite replacement of cement, the peak strain increases in comparison with cemented samples. In other words, utilizing zeolite in cemented sand increases the displacement at failure, and reduces the brittle behavior. Since the main objective of this paper is to estimate UCS, less attention is paid to the strain and failure types.

**Fig. 2.** Failure types of stabilized specimens.

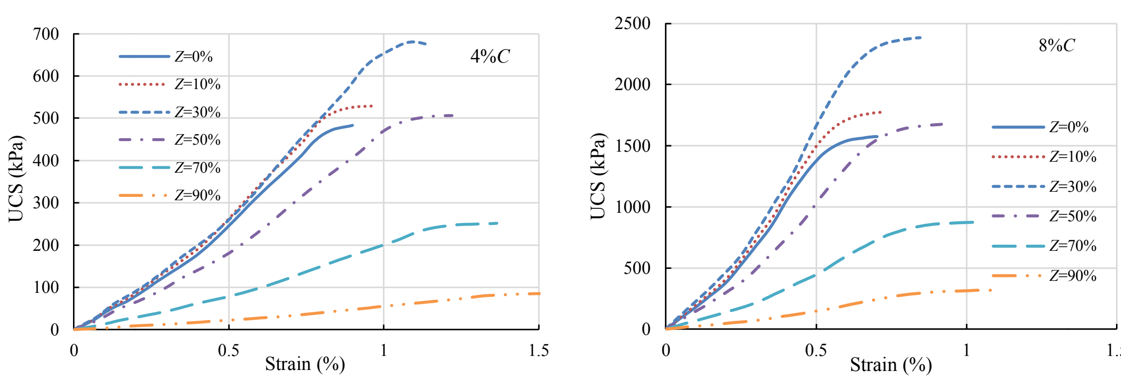


**Fig. 3.** Stress–strain curves of zeolite-cemented sand ($e$ = 0.591).

### 3.1. Effects of cement and zeolite contents

Results of unconfined compression tests for different cement contents (2%, 4%, 6% and 8%) and replacements of cement by zeolite (0%, 10%, 30%, 50%, 70% and 90%) are presented in Fig. 4.

The larger amount of cement causes the greater UCS for a given void ratio and zeolite content. Cement replacement by zeolite (for the whole range of cement studied) causes UCS to increase first and then decrease, and polynomial relationships can be observed for all the soil-cement-zeolite mixtures.

Fig. 4 shows that, at 30% replacement of cement by zeolite, the maximum UCS is obtained. The increasing rate of UCS of optimum zeolite-cemented sand samples in comparison with that of cemented samples $((UCS_{\text{zeolite cemented sand}} - UCS_{\text{cemented sand}})/UCS_{\text{cemented sand}})$ is validated in Fig. 5. It can be observed from this figure that, for mixtures with higher cement content and lower relative density, the increasing rate is greater due to higher amounts of zeolite-cement hydration products. Therefore, the zeolite has a major effect on the strength of zeolite-cemented sand. The 30% replacement of cement by zeolite is enough to generate a significant increase in strength.

### 3.2. Effects of porosity, void-cement ratio and zeolite content

Fig. 6 shows the effects of porosity, $n$, on the peak strength of zeolite-cemented sand (up to 50% replacement of cement). It is shown that UCS reduces with the increase in porosity of both zeolite and cement samples. The decreasing rate of strength for cemented mixtures is larger than that for zeolite-cemented samples. In other words, at the optimum cement replacement by zeolite (30%), the variation of UCS is approximately constant with increasing porosity. Therefore, zeolite is generally used in large porosity blends instead of cement.

A relation between UCS and void-cement ratio ($n/C$), defined as porosity/cement mass ratio, is shown in Fig. 7. It should be noted that UCS values of the samples with the 2% replacement of cement by 90% zeolite were very low and omitted in Fig. 7. For each mixture studied, the specimens have different cement contents and porosities. In this study, there is not a unique relation between UCS and the ratio $n/C$. Moreover, a power function (Eq. (2)) can be applied for the ratio $n/C$ to make compatible the effect of its variation on UCS (Fig. 8). It was found that applying a power of 0.9 to $C$ and −1.7 to $n$ for all mixtures studied, a better adjustment of the data for the UCS was reached, as presented in Fig. 8 and Eq. (3).

$$UCS = 10048\left(\frac{n}{C}\right)^{-1.069} \quad (2)$$

$$UCS = 160543n^{-1.7}C^{0.9} \quad (3)$$

As shown in Fig. 4, UCS increases first and then decreases with cement replacement by zeolite. A unique relationship can be achieved to correlate UCS with zeolite and cement contents and porosity, considering 28 days curing time, which can be presented as follows:

$$UCS = 13156n^{-1.5}C^{1.32}\left(1.63 + Z^{1.44-0.152Z}\right) \quad (4)$$

The performance of this correlation has been shown in Fig. 9. From Figs. 8 and 9, it also can be concluded that correlation coefficient, $R$, is not a proper parameter for evaluating the performance of power models prediction since a small variation in input causes large variations in output. Therefore, root mean squared error (RMSE), mean absolute percent error (MAPE) and mean absolute

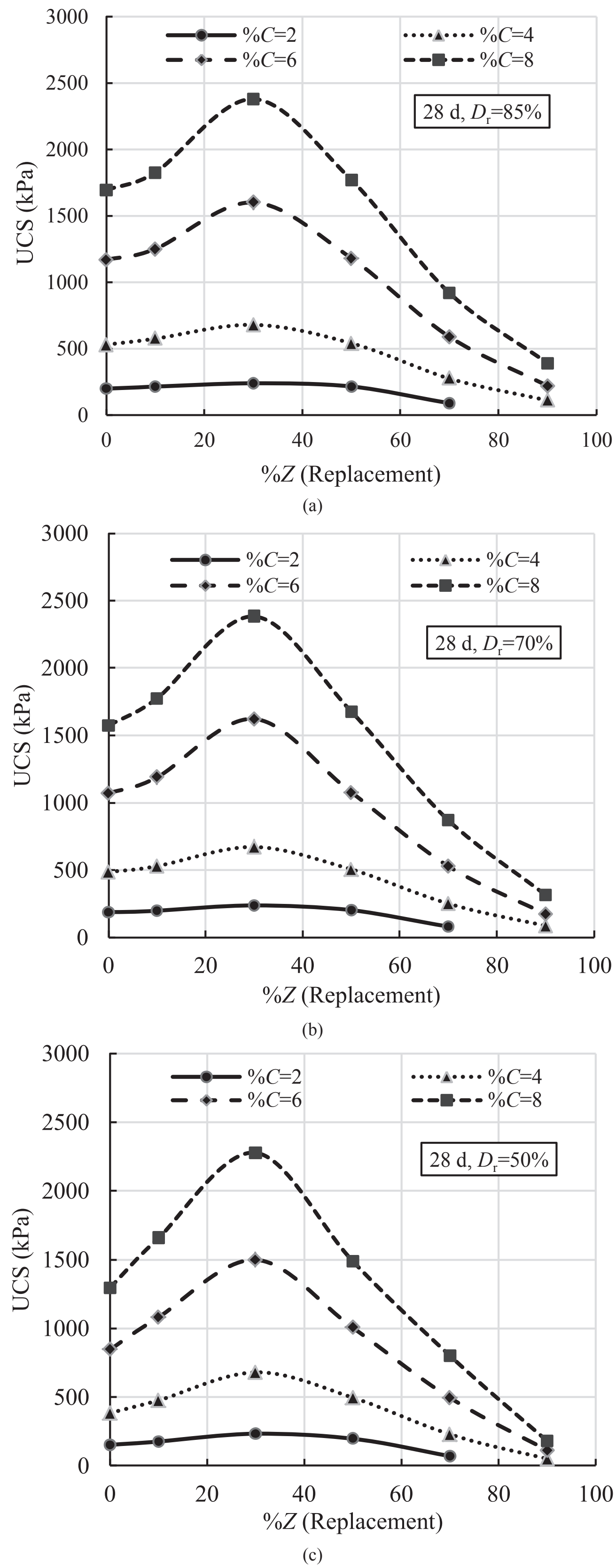


**Fig. 4.** Effects of additive materials on UCS of cemented sand.

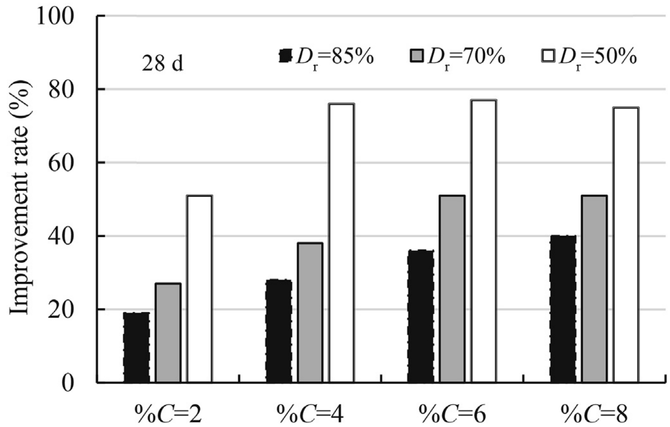


**Fig. 5.** UCS improvement of cemented sand at the optimum cement replacement of zeolite.

deviation (MAD) are used to evaluate the performance of the proposed equation, which are defined as follows:

$$RMSE = \sqrt{\frac{1}{M}\sum_1^M (C_{mi} - C_{pi})^2} \tag{5}$$

$$MAPE = \frac{\sum_1^M |C_{mi} - C_{pi}|}{\sum_1^M C_{mi}} \times 100\% \tag{6}$$

$$MAD = \frac{\sum_1^M |C_{mi} - C_{pi}|}{M} \tag{7}$$

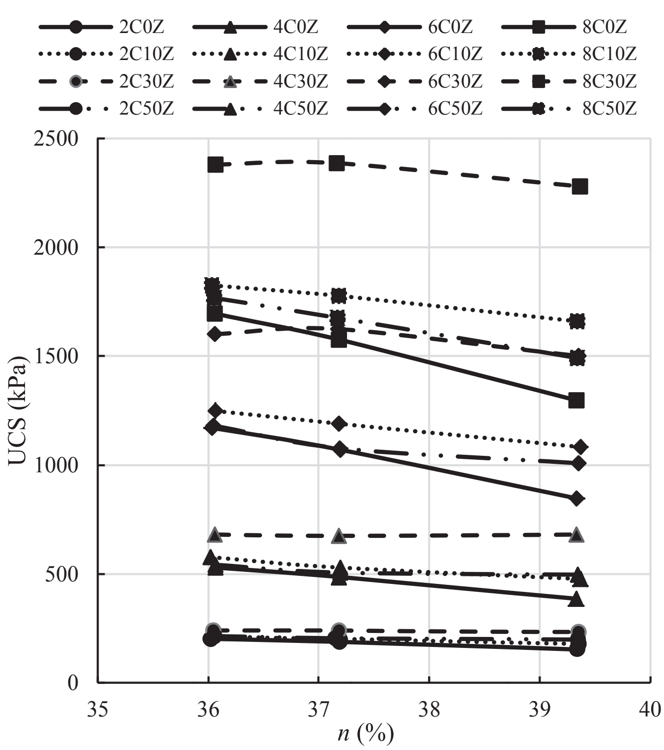


**Fig. 6.** UCS variations with porosity for cement-zeolite samples. The first datum in the legend represents the cement content (%), and the second indicates the zeolite content (%).

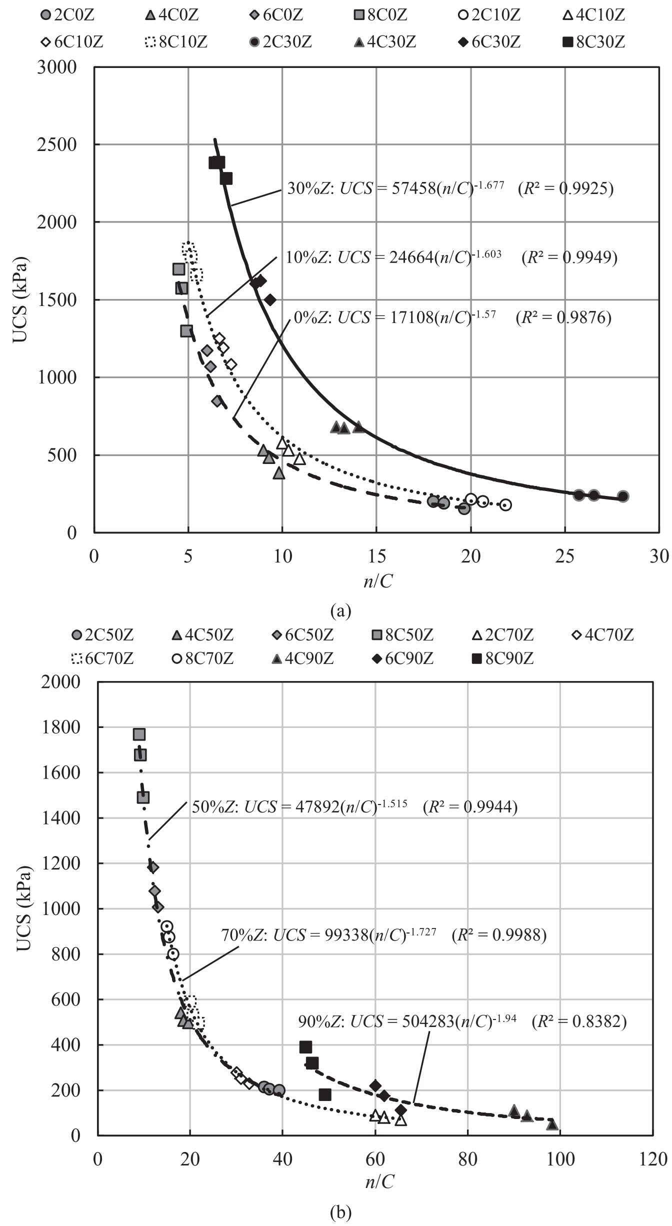


**Fig. 7.** Variation of UCS with $n/C$: (a) (0–30%)$Z$, and (b) (50–90%)$Z$.

where $C_{mi}$ and $C_{pi}$ are the measured and predicted UCSs, respectively; and $M$ is the total number of tests.

The lower the RMSE, MAPE and MAD values are, the better the model performance is. Under ideal conditions, an accurate and precise method gives RMSE, MAPE and MAD values of 0. Table 2 shows the values of RMSE, MAPE and MAD calculated by Eqs. (2)–(4), respectively. It can be seen that the best fit is achieved by Eq. (4).

## 4. Conclusions

(1) Using zeolite instead of cement causes an increase in UCS of cemented soil (for the whole range of cement studied).

(2) The addition of cement, even in small amounts, greatly improves the soil strength of zeolite cement and cemented soils. For samples with cement replaced by zeolite, UCS increases first and then decreases with zeolite replacement percentage.

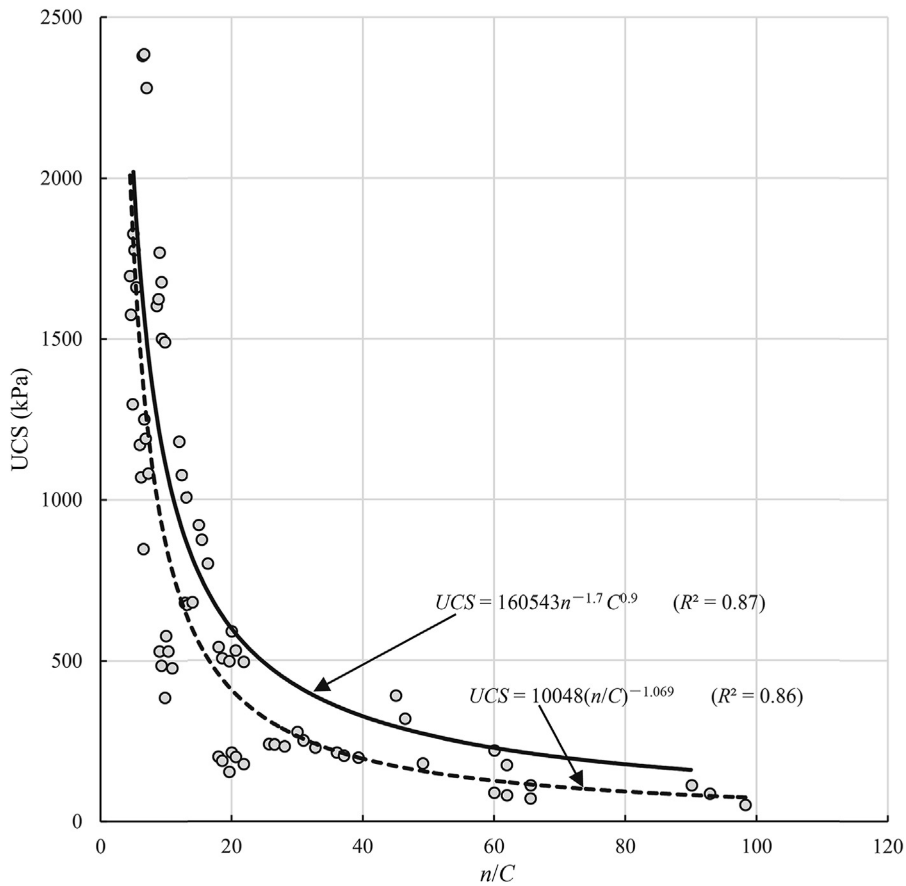


**Fig. 8.** Variation of UCS with adjusted $n/C$ and a power function with $n$ and $C$ values of 0.9 and −1.7, respectively, for all mixtures.

(3) The optimum zeolite content is 30% which can improve UCS from 20% to 78%.
(4) The rate of strength improvement, represented by Fig. 4, increases with the decrease in relative density and increase in cement content. It indicates that the effect of zeolite is larger for highly cemented and less for compacted mixtures.
(5) Decrease in the porosity of compacted mixture greatly improves the strength of cemented soils and slightly improves the strength of zeolite-cemented mixtures.
(6) The porosity/cement content ratio, represented by power functions (Eqs. (2) and (3)) for each of the six zeolite amounts is shown to be an acceptable parameter in the evaluation of UCS for the zeolite-cemented sand studied.
(7) For the studied soil, zeolite, and cement (considering 28 days curing time), a unique relationship (Eq. (4)) was achieved to correlate the UCS with porosity and zeolite and cement contents.
(8) Amongst the previously proposed equations, Eq. (4) gives the lowest values of RMSE, MAPE, and MAD and the highest $R^2$ value, and is proven to be more efficient than other power correlations.

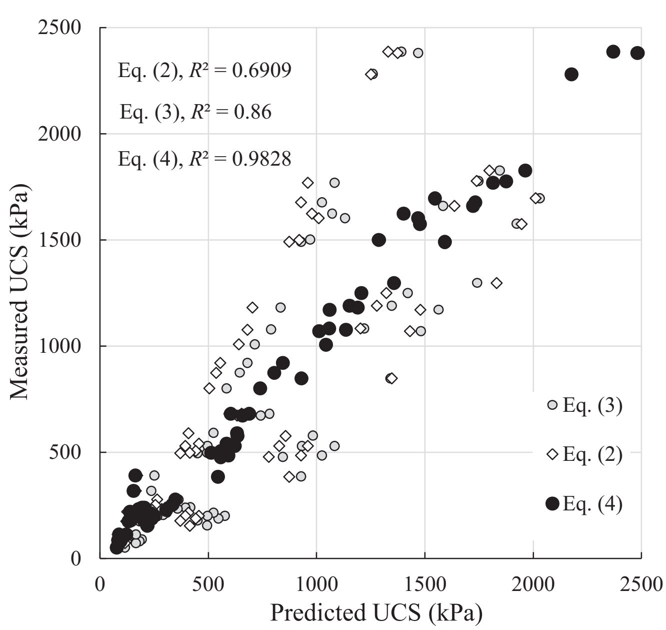


**Fig. 9.** Measured UCS versus UCS predicted by Eqs. (2)–(4).

**Table 2**
Statistical results for this study equations.

| Equation no. | MAPE | RMSE | MAD |
|---|---|---|---|
| (2) | 4.47 | 34.34 | 259.59 |
| (3) | 4.29 | 33.45 | 252.83 |
| (4) | 2.86 | 8.87 | 67.08 |

## Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no

significant financial support for this work that could have influenced its outcome.

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