

# Laboratory Investigation on the Effect of Microsilica Additive on the Mechanical Behavior of Deep Soil Mixing Columns in Saline Dry Sand

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## Abstract

Since loose and salty subgrades consider as problematic barriers while constructing new transportation infrastructures such as railway tracks and roads are required, the current study aims to find a solution to stabilize these kinds of subgrades using the deep soil mixing (DSM) technique and micro silica additive. In the present study a series of experimental DSM columns were executed in a salty sand-filled chamber utilizing a laboratory scale DSM apparatuses. In the first step, by adding three salt percentages of 5, 10 and 20 into the original sand, four different sandy subgrades with a relative density of 70% were prepared. Considering three percentages of 10, 15 and 20 for micro silica additive, the water-to-cement ratio of 1, salt percentages of 0, 5, 10 and 20 totally 150 sand-cement columns were constructed in the lab environment. In continuation, unconfined compression strength (UCS) and elasticity modulus of all capped DSM columns have been determined and interpreted using scanning electron microscope (SEM) images at three ages of 7, 14 and 28 days. The results indicated that increasing the salinity of subgrade soil from 0 to 20% resulted in a falling UCS and Young module by 28 and 21% for 28-days specimens. Furthermore, as a solution, adding micro silica in cement-water grout up to 15% resulted in enhancing mechanical characteristics of the DSM columns. So that adding 15% microsilica caused a 21 and 42% increase in UCS and elasticity modulus of 28-days samples respectively, executed in subgrade with 20% salt.

## Keywords

deep soil mixing columns, loose salty-sand subgrades, microsilica additive, unconfined compression strength, elasticity modulus

## 1 Introduction

Salinity refers to presence of NaCl,  $\text{SO}_4^{2-}$  etc. ions in soil. Salts are crystalline compounds that convert to ion when dissolved in water. A large portion of the world including some parts of Iran, Australia, Saudi Arabia, Algeria, Morocco, China, the United State and South Africa has been covered by saline soils, which makes the importance of improving these soils twofold. From geotechnical engineering point of view, constructing new infrastructures on saline subgrades have been faced many difficulties. Stability and strength of structural elements contacted with saline soils can be rigorously affected. For instance, when superstructures are built on foundation with saline soils, their bearing capacity decreases while the foundation periodically is moistened [1]. Presence more than 5% salt in saline soils has a significant effect on their mechanical

properties [2]. In order to reclaim mechanical and chemical properties of salty soils a growing body of studies has been conducted using different techniques including electrochemical improvement and chemical improvement by adding cement, lime, fly ash and micro silica or adopting mechanical stabilization by insertion of geotextile material [3–10]. Effect of sodium chloride on the mechanical properties of cement-stabilized Lianyungang marine clay was investigated by Abduljawwad et al. [3]. In this laboratory research, a series of UCS tests were performed on the specimens, which were made by various sodium chloride and ordinary Portland cement. The result indicated that the presence of sodium chloride in soil had a negative effect and decreased both UCS and elasticity modulus of the cement-clay mixture. Jayasekera and Hall [11] examined an in-situ

soil treatment technique based on electro kinetics principles to improve mechanical properties of saline-sodic soil. The main results indicated that using electro kinetic treatment alone and with lime increased compressive strength of the soil by 100 and 200% respectively. Moreover, they found out that compressive strength of the soil was affected by soil type, clay content and different complex electro-chemical processes. An experimental study performed on mechanical behavior of sulphate saline soil as high-speed railway subgrade. In this study, effect of various salt contents without lime and different lime proportion for a fixed amount of salt on unconfined compressive strength of the sulphate saline soil was examined. The result showed that salt content of 5.5% and lime portion of 8.5% resulted in maximum unconfident compressive strength for unimproved an improved soil respectively. The effect of lime addition was so striking that the increase was 10 times more than the unimproved soil [12]. Another experimental study was carried out in scope of salty soil treatment to find out the effect of Metakaolin (MK) on the mechanical characteristic of cement-treated salty soft soil [13]. It was clarified that the strength of soil-cement samples increased by growing the amount of Metakaolin. The optimum amount of MK was found 3, 4 and 5% depended on ion content in each case. Besides, the strength of salt-rich soil-cement decreased while the ion content increased so that the MK couldn't eliminate the negative effect of ions.

On the other hand, ground improvement techniques such as stone columns, jet grouting and DSM are frequently used to improve problematic soils in depth. Among deep improvement methods, the DSM method with different slurry and additive like cement, microsilica, fly ash, lime and etc. has received much attention from geotechnics and geology researchers [14–23]. For instance, the effect of salt in loose soil was studied on soil improvement adopting deep soil mixing method with cement slurry. For this purpose, a series of laboratory and field tests were done to investigate UCS of soil-cement columns considering different content of  $\text{SO}_4^{2-}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ , water, cement and salt. It was found that increasing cement content led to gain in UCS and adding water had the reverse result. Furthermore, adding different amount of  $\text{SO}_4^{2-}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ , despite affecting the microstructure of the specimens, resulted in declined soil-cement UCS [24]. Al-Tabba et al. [14] studied the effectiveness of DSM method in layered sands by considering two different types of blade and different sand stratifications, two different grouts and different installation techniques. The UCS tests result indicated that the

optimum cement-pulverized fuel ash (PFA) soil-grout mix consisted 3.5 and 10% for cement and PFA respectively and this amount was 10 and 1% for cement and bentonite respectively for cement-bentonite soil-grout mixture. In another study, Esmaeili et al. [22] conducted a series of laboratory tests to find out the effect of microsilica additive on bearing capacity of DSM columns. To do this many experimental DSM columns installed in a loose sandy soil with different water to cement ratio (W/C) and microsilica percentages. The results indicated that cement slurry with W/C of 1 and 15% microsilica additive showed the maximum bearing capacity in terms of UCS.

Whilst some research has been carried out on the treatment of saline soils, a limited studies have investigated the application of DSM columns using micro silica additive to improve the mechanical properties of the mentioned soils. The main objective of this experimental study is to find out the effect of salt amount on UCS and elastic modulus of soil-cement columns and investigate the application of microsilica additive on the mentioned parameters for saline soils. In this matter, in an experimental study by utilizing a DSM apparatus in laboratory scale with 6-blades hollow rod, totally 150 sand-cement columns were executed considering four salt percentages of 0, 5, 10 and 20, a water-cement ratio of 1, three micro silica percentages of 10, 15 and 20 and three curing ages of 7, 14 and 28 days to monitor the mechanical behavior of soil-cement columns with uniaxial loading device in conjunction with SEM images of columns' samples. The outcomes of the research are presented in the form of UCS and elasticity modulus of the columns.

## 2 Plan of experiments

### 2.1 Material properties

The material used in this study are sand, salt, cement and micro-silica which their properties will be presented in detail in the following. In order to install soil-cement columns in the lab environment, DSM machine developed and equipped in IUST was employed. Different elements of the machine and also the DSM columns execution process will be discussed in the next steps.

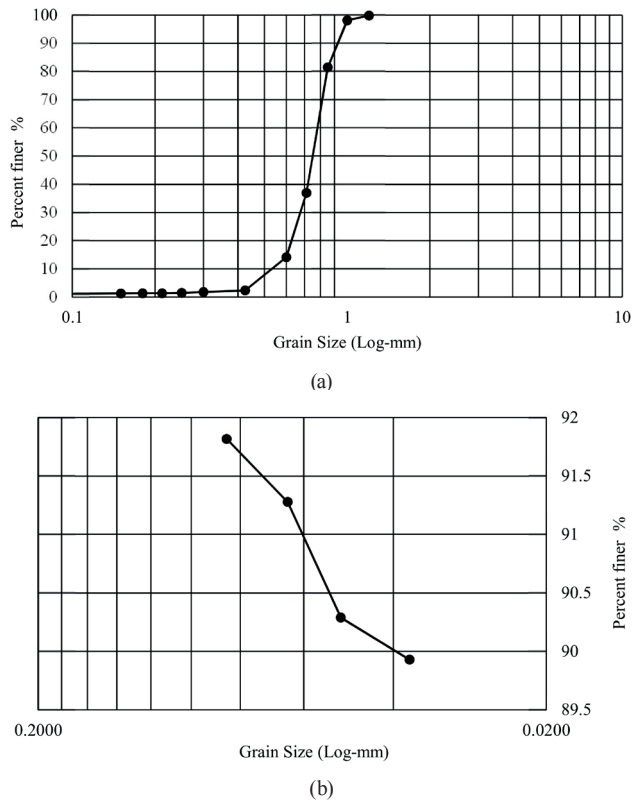
#### 2.1.1 Sand properties

In this study, poorly graded sand (SP) of Firoozkoh query in the vicinity of Tehran city with the particle size of 0.4–1 mm which showed improper engineering behavior in many geotechnical applications [25], was used for the preparation of loose sandy soil bed in the lab. Fig. 1(a) addresses the particle size distribution curve of used sand.

Table 1 likewise presents the mechanical and physical properties of the SP based on laboratory tests which have been carried out by authors [22].

**2.1.2 Salt, cement and micro silica properties**

In order to prepare saline soil subgrade, salt was taken from Qom lake with given chemical compositions in Table 2. It should be pointed out the presented properties of the salt have been extracted from X-ray Fluorescence (XRF) analysis. Type II Ordinary Portland cement (OPC) which is widely used for engineering purposes was selected as the main part of injecting slurry. Fig. 1(b) shows grain size distributed curve obtained accordance with ASTM D422-63 [30].



**Fig. 1** Particle size distribution curve of (a) the SP sand and (b) Portland cement type 2

**Table 1** Material properties of poorly graded sand (SP)

Parameter	Symbol	Unit	Value	Relavant Standard
Cohesion	$C$	$\text{kN/m}^2$	2.7	ASTM D3080-11 [26]
Friction angle	$\phi$	( $^\circ$ )	37	
Elasticity modulus	$E$	$\text{kN/m}^2$	14.9	ASTM D1194 [27]
Unit weight	$\gamma$	$\text{kN/m}^3$	16.3	ASTM D 4254 [28]
Relative density	$D_r$	%	70	ASTM D 4253 [29]
Maximum porosity	$e_{\max}$	%	84	ASTM D 4254 [28]
Minimum porosity	$e_{\min}$	%	56	ASTM D 4254 [28]

Moreover, in order to improve soil-cement columns compressive strength, microsilica additive with different proportions was added to the cement slurry. The properties of the cement and micro silica materials are summarized in Table 2.

**2.2 Salt-sand samples preparation**

A box with dimensions of  $2 \times 1 \times 0.8$  m (see Fig. 2) was selected as a chamber for preparation and insertion of sandy soil bed in lab. In the beginning, the salt with specified weight ratios of 5, 10 and 20% were mixed with sand and afterwards, the sand-salt admixture was poured in 5 cm-layers thicknesses and each layer was compacted using a laboratory roller with 12 kg weight. After 9 times passing of roller a relative density of 70% was achieved to provide an acceptable subgrade soil for execution of DSM columns [16]. It should be pointed out that during the compaction process, the in situ dry density measurement was

**Table 2** Chemical and physical properties of microsilica, cement and salt

Compositions percentage	microsilica	cement	Salt
$\text{SiO}_2$	91.2	20.6	-
$\text{Al}_2\text{O}_3$	1.23	4.35	-
$\text{Fe}_2\text{O}_3$	0.76	4.20	<<
$\text{MgO}$	0.33	1.94	0.914
$\text{CaO}$	0.42	-	0.358
$\text{SO}_3$	0.32	2.78	1.016
$\text{Cl}$	-	-	41.841
$\text{K}_2\text{O}$	-	-	0.055
$\text{Na}_2\text{O}$	-	-	55.815
Physical properties			
Specific surface ( $\text{m}^2/\text{gr}$ )	20	1.3	-
Particle average diameter ( $\mu\text{m}$ )	0.15	35	800
Unit weight ( $\text{kg/m}^3$ )	200	1800	2170



**Fig. 2** Salty sand subgrade compaction in chamber using a 12 kg laboratory roller



regularly performed to assure the mentioned relative density had been achieved. Also according to ASTM D4254-00 [28] and ASTM D4253-00 [29].

### 2.3 DSM apparatus specifications

As Fig. 3 illustrates, the main parts of laboratory DSM machine are including rotary motor, a 6-blades drilling rod and slurry injection sealing system which are installed on a moving plate. The rotating blades which are coupled to the rotary motor is allowed by the moving plate to be moved vertically. The device's function is to initially rotate the blades clockwise at a speed of 58 rpm and penetrate with a speed of 6 mm/s into the soil up to the wanted depth. Then the blades start rotating counterclockwise upward and cement slurry outflows from the nozzle which is located at the end of the blades concurrently. Accordingly, the surrounded soil is mixed with the injected cement slurry using blades' penetration in the soil and consequently DSM columns are formed. It should also be noted that to supply slurry during the operation, a tank placed at the height of 2.5 m from the ground floor was used to inject the slurry gravitationally into the hollow tube. To prevent slurry leakage during the operation, a sealing system installed at the top of the rotary rod. It also should be added that during blades penetration process and before starting slurry injection, constant air pressure of 0.5 bar was injected in the rod through sealing system to prevent nozzles' blocking.

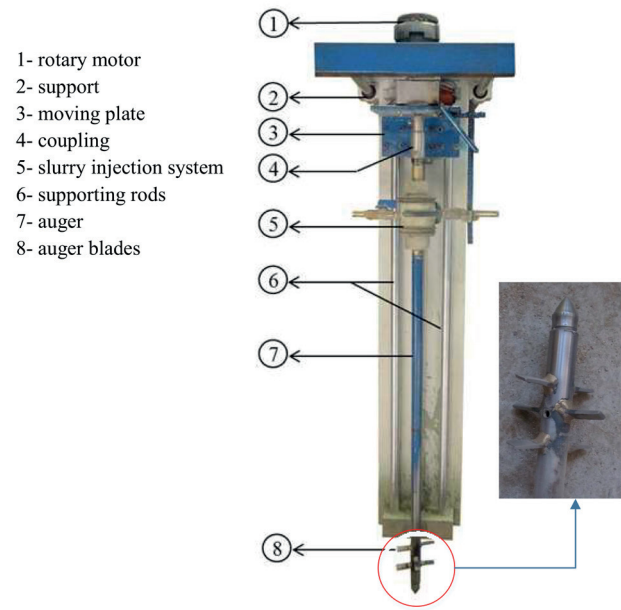


Fig. 3 Deep soil mixing device designed at Iran University of Science and Technology [22]

### 2.4 DSM columns execution

After preparing the subgrade with saline sand in the chamber, location of each column were marked as shown in Fig. 4(a) using chalk. After that, the DSM device was placed at the right positions and then the binder has been uniformly mixed with the salty sand and finally the cement-soil columns were formed with 9 cm diameter (D) and 40 cm length (L) (see Fig. 4(a) to (c)).

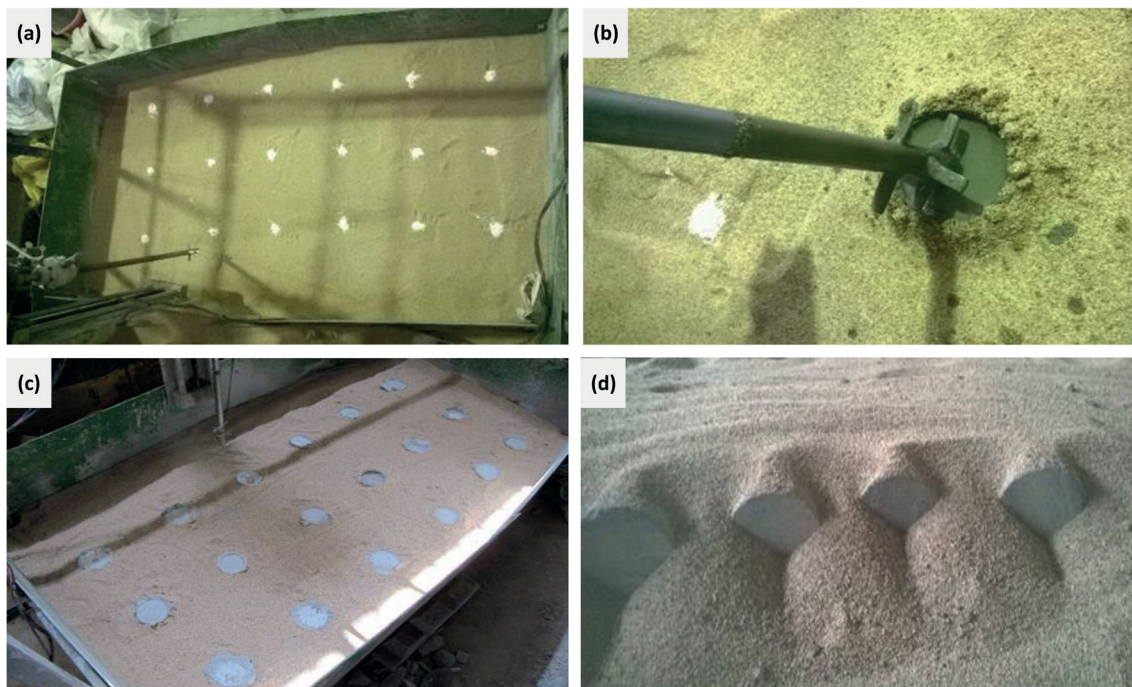


Fig. 4 Different steps for executing DSM columns in the lab: (a) mark the exact location of the columns; (b) Executing the columns; (c) 18 executed columns in the box; (d) samples curing

It is worthy to be mentioned that in this study, a cement slurry with water to cement ratio of  $1(w/c = 1)$  and cement dosage of  $200 \text{ kg/m}^3$  is agreed for DSM column execution on the basis of reported results in the previous study of the authors [22]. Although the best microsilica additive percentage in absence of the salt has been reported as 15% of the cement weight for achieving the best strength in deep mixed columns in SP sand, in presence of the salt this parameter is considered to vary as 5, 10 and 20% values.

Moreover, it should be pointed out that the DSM columns were executed 30 cm apart (center to center distance) to prevent interaction and disturbance of the columns. Considering various salt percentages, specimens' ages and micro silica percentages, three DSM columns were executed to ensure the results of experiments. Eventually, 150 DSM columns were constructed and prepared to perform UCS tests. Since the number of specimens was large and also the chamber's space was limited, the columns were removed from the box after 7 days and transferred to

a curing place in the lab, where the temperature was constant ( $25^\circ\text{C}$ ), until the right time (7, 14 and 28 days) of UCS tests (see Fig. 4(d)). As the humidity and salinity affected the results, the samples were surrounded with the same subgrade soil to simulate in situ conditions.

### 2.5 Sample preparation and UCS tests

In order to prepare the samples for UCS test, all columns were cut and prepared in 9 cm diameter and 20.25 cm in length ( $L/D=2.25$ ) to satisfy the criterion of length-to-diameter ratio  $2 \ll L/D \ll 3$  in accordance with ASTM D2166-00 standard [31] (Fig. 5(a) to (d)). Afterwards, the samples were subjected to uniaxial compression loading and accordingly, their compressive strength and modulus of elasticity were evaluated. The machine adopted for carrying out uniaxial compression tests was fully automatic which presented a stress-strain diagram for each specimen. It also should be noted that axial load was applied to samples at a constant loading rate of  $0.15 \text{ MPa/sec}$  (Fig. 5(e)).



**Fig. 5** Different steps of carrying out the uniaxial compressive test: (a) original DSM columns; (b) cutting and capping the samples; (c) prepared samples; (d) automatic loading device; (e) failure mechanism of the DSM specimens

Fig. 5(e) shows the failure mechanism of cement-soil columns under uniaxial load. This failure mechanism is so close to what happened to rocks samples under axial loading. When a DSM column is subjected to axial load as the sample is compressed axially, transverse expansion occurs simultaneously. Consequently, existing friction between loading jack jaws and two ends of columns causes a restriction for lateral expansion (Poisson's effect) which leads to a wedge type failure for columns [32]. Fig. 6 shows the strain-stress curve for a 28-days DSM sample.

### 3 Result and discussion

In this section, firstly, the impact of salt on the mechanical behavior of DSM columns is discussed. Then, The influence of micro silica additive on both UCS and elasticity modulus of cement-soil columns executed in the saline subgrade will be described. Next, curing time effect on mechanical properties of DSM is presented and finally, the relation between UCS and elasticity modulus of the columns with curing time and amounts of salt and microsilica is determined.

#### 3.1 The effect of salt on DSM columns behavior

Fig. 7 illustrates the effect of soil salinity on the mechanical behavior of DSM columns in terms of UCS for three different ages of 7, 14 and 28 days. From the figure it can be seen that for all ages, increasing the amount of salt in the subgrade resulted in decreasing UCS of the columns. The most decline observes for 14 days specimens is about 37% when 20% salt in the sand subgrade is included while this value is also about 28% and 33% for 28 and 7 days samples. From the chart it can be concluded that except for 14 days samples, by adding salt in the sandy subgrade up

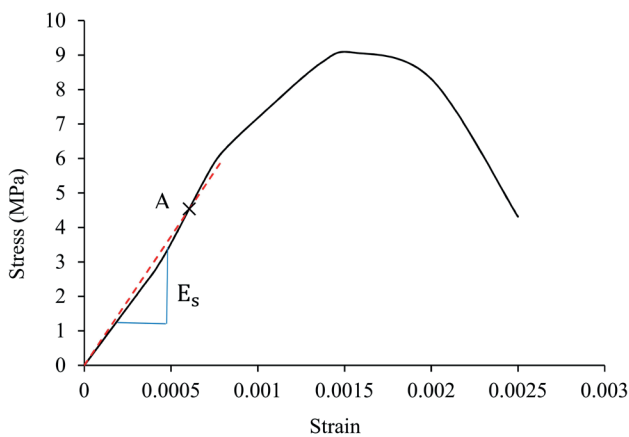


Fig. 6 Stress-strain curve of a 28-day DSM column with W/C of 1, salt and microsilica percentages of 0

to 10% the UCSs of the columns are smoothly fallen and for more salt percentages, the UCSs values have been significantly affected.

Fig. 8 shows the elasticity modulus, E, of DSM columns versus the amount of salinity of subgrade soil for 7 and 14 and 28 days curing period. According to the graph, although the elasticity modulus of samples has been negligibly decreased by adding 5% salt, this parameter has declined remarkably by adding 10% and 20% salt into the sandy bed. The most drop for the elasticity modulus occurred for 28 days specimens by a 21% decrease. It also should be pointed out that this value is almost 17% for both 7 and 14 days samples.

The mechanism of decrease in UCS and elasticity modulus of DSM columns in presence of salt is related to sand replacement by salt which has the lesser mechanical properties in comparison to the sand. It can be understood that as the columns are executed, the salt particles in sand dissolve by the slurry and after drying, they become salt crystal again and place between cement bonds and sand particles. To be more specific and investigate the reason, the SEM image of a sample with 20% salt was prepared (Fig. 9).

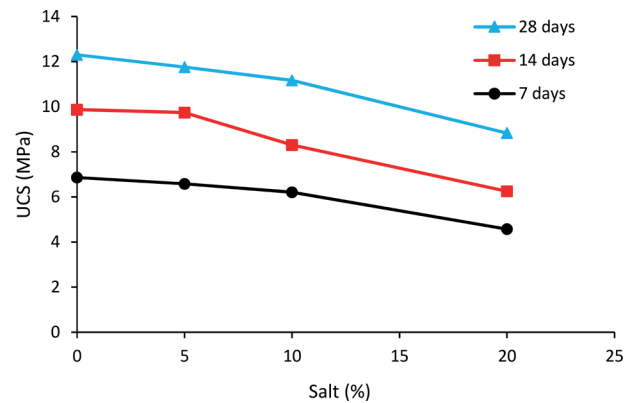


Fig. 7 The effect of salinity on UCS of DSM columns at various ages

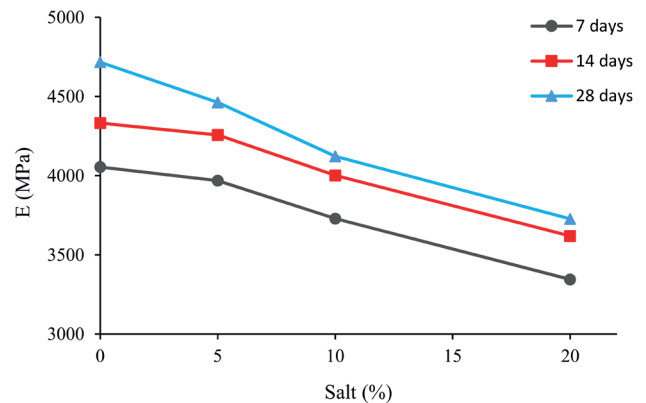


Fig. 8 Elasticity modulus of DSM columns versus amount of salinity



In addition to having weaker mechanical properties than cement and sand particles, these salt crystals with cubic microstructure cannot form an integrated bond with needle-shaped structures of cement particles which result in weakening of the specimen's UCS and elasticity modulus. From a chemical point of view and based upon what investigated by Xing et al. [24]  $Cl^-$  has a negative effect on the strength of saline soil-cement in short, intermediate and long-terms. According to this study, soft  $Ca_2Al(OH)_6Cl(H_2O)$ , as result of interaction between  $Cl^-$  and  $Ca^{+2}$  and  $Al^{+3}$ , has no coherence function and the deposits on the soil grains prevent them to being combined with  $Ca(OH)_2$  to increase the strength of soil-cement-soil.

**3.2 Effect of microsilica on UCS of DSM columns**

As mentioned before the soil salinity had an inverse relationship with mechanical properties of cement-soil columns. In this study, microsilica additive has been added in cement slurry by 10, 15 and 20% (by weight of cement) as a treatment to improve the mechanical properties of executed DSM columns in the saline subgrade.

Fig. 10(a) demonstrations the effect of microsilica on UCS of DSM columns with different amount of salt for 28 days samples. The maximum enhancement in the UCS can be assigned to 15% microsilica additive by 24, 19, 18 and 21% compared to original samples related to DSM columns with 0, 5, 10 and 20% amount of salt respectively. It should be noted that the pervious study carried out by the authors also showed this trend for experimental cement-soil columns [22]. As can be seen from the graph, using microsilica up to 10% shows insignificant improvement of DSM columns in terms of UCS and also the UCS has slightly declined by adding 20% microsilica compared to 15%.

Fig. 10(b) depicts microsilica percentage versus elasticity modulus of DSM columns for 0, 5, 10 and 20% amount of salt. As it can be seen, such as UCS, the most improvement in terms of elasticity modulus has been gained at 15% microsilica by 34, 36, 38 and 42% for the executed columns in subgrade with 0, 5, 10 and 20% salt respectively. Furthermore, like the UCS trend, the elasticity modulus of the columns has fallen by increasing microsilica from 15 to 20%. Regarding interpretation of the effect of microsilica additive on mechanical properties of DSM columns, SEM images of the soil-cement samples were prepared. Fig. 11 shows two examples of SEM images related to DSM columns without salt at age 28 days with 15 and 20% microsilica. According to the physical properties of utilized microsilica and cement, the particles of microsilica are

approximately 230 times finer than cement ones. As previously investigated by the authors [22], improvement of mechanical properties of DSM columns is vastly dependent on uniform distribution of microsilica particles in empty space between cement particles as fillers. From the

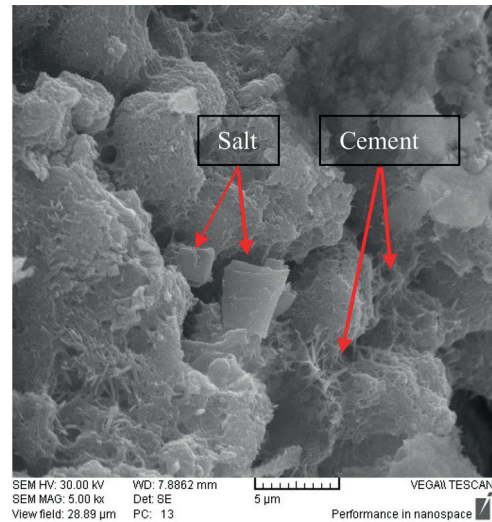


Fig. 9 A SEM image of a 28-day specimen with 20% salt

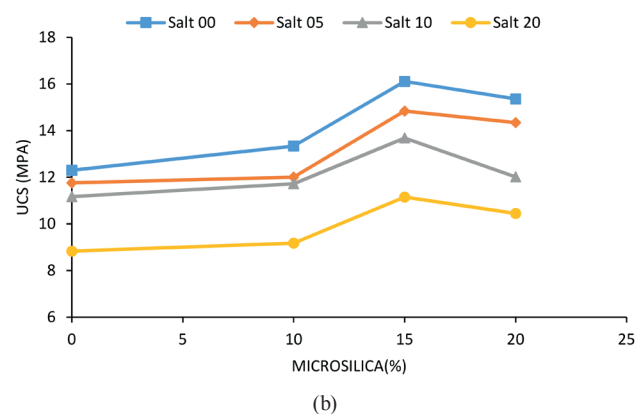
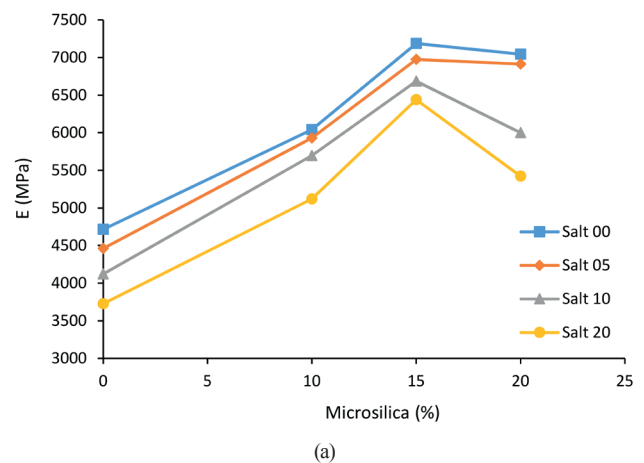
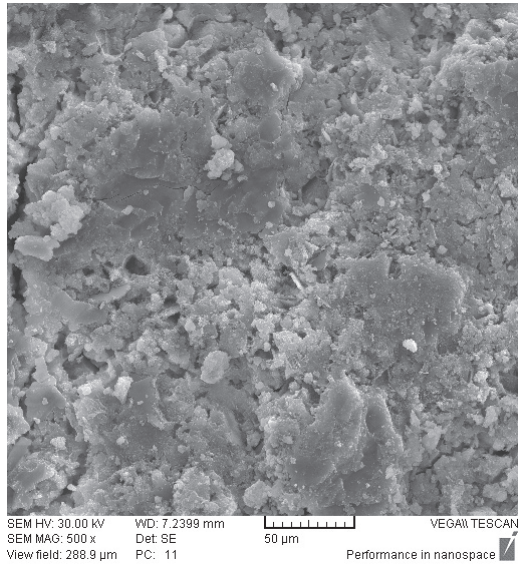
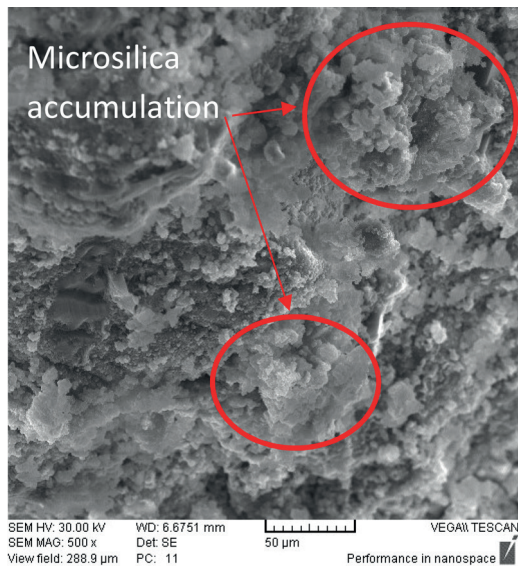


Fig. 10 The effect of microsilica additive on 28 days cement-soil columns: (a) UCS; (b) elasticity modulus



(a)



(b)

**Fig. 11** SEM images of 28-day DSM columns with 0% salt for (a) 15% microsilica; (b) 20%

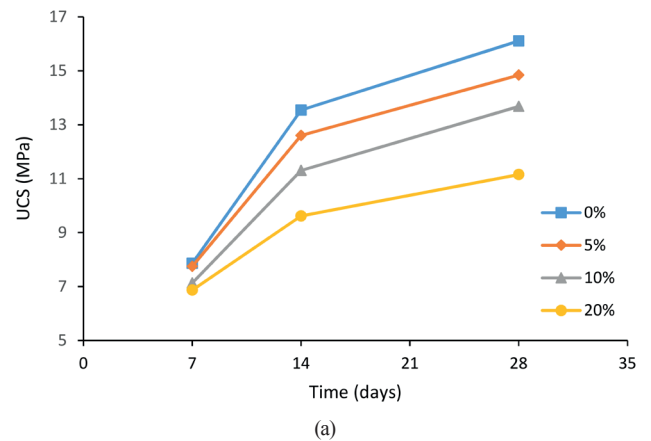
SEM images it can be seen that adding 15% microsilica in cement slurry has created a more uniform and integrated structure compared to 20%. The reason is that when the amount of microsilica increases from 15 to 20%, the extra particles which are more than adequate value for filling the empty space between particles, cause inappropriate distribution in particles which resulting in agglomeration of the particles. These agglomerations created in different parts of DSM columns causes weak and susceptible zones to failure. Likewise, these vulnerable zones leads to stress concentration and small cracks during loading process which result in decreasing compressive strength of the samples.

### 3.3 The effect of age on UCS and elasticity modulus

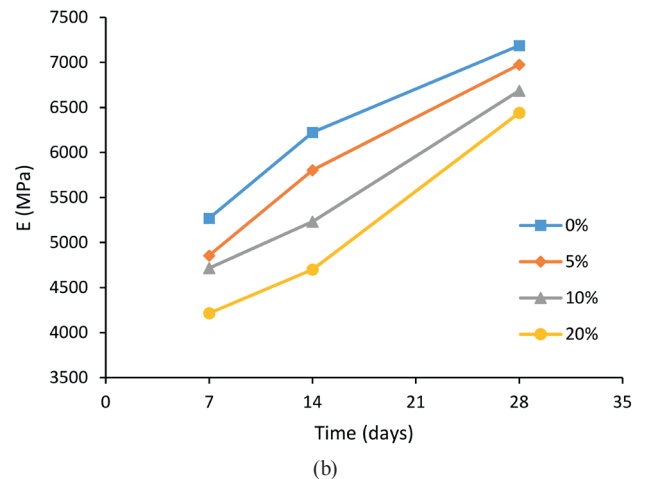
Fig. 12(a) shows the effect of samples' age on compressive strength and elasticity modulus of DSM columns with 15% micro silica executed in subgrade with 0, 5, 10 and 20% salt. As shown in the figures, mechanical parameters of the specimens i.e. UCS and elasticity modulus has raised due to increase in curing time. The highest values for UCS and elasticity modulus observed at the age of 28 days for samples with 0% salt. Regarding the UCS parameter, the most increase witnessed by 51, 54, 48 and 40% for different amounts of 0, 5, 10 and 20% salt respectively with increasing the samples' age from 7 to 28 days. The same enhancement occurred for the elasticity modulus by 27, 31, 29 and 35% respectively for executed DSM columns in sand subgrade with 0, 5, 10 and 20% salt content (see Fig. 12(b)).

### 3.4 Regression equations

Finding equations for predicting mechanical properties of DSM columns is one of the important issues which have received much attention by geotechnics researchers.



(a)



(b)

**Fig. 12** The effect of age on mechanical parameters of DSM columns contained 15% microsilica: (a) UCS; (b) elasticity modulus



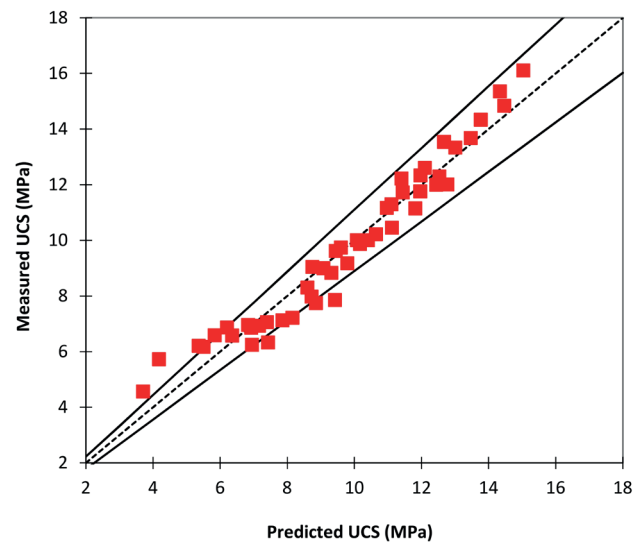
A number of researchers have reported the relation between compressive strength and elasticity modulus of cement-soil columns with water to cement ration, curing time, cement dosage, and soil dry density [33–37, 16, 21]. As a result of an experimental study carried out by the authors [22], two polynomial functions were proposed for compressive strength and elasticity modulus of DSM columns in terms of water to cement ratio, time and microsilica additive. Recently, a series of UCS and California bearing ratio (CBR) tests were carried out on stablized sulfate silty sand with microsilica and lime. According to obtained results, Ghorbani and Hasanzadehshooiili [38] were developed Back Propagation Articial Neural Network (BP-ANN) and Evolutionary Polynomial Regression (EPR) models to predict the UCS values for sulfate silty sand stabilized with different lime and microsilica. Since no study has yet been found to determine the relationship between the mechanical properties of deep mixing columns implemented in salty beds, this study attempts to find out and appropriate equations for compressive strength and elasticity of DSM columns involving salt percentage, age and micro-silica additive percentage. To this end, the laboratory test results were imported to SPSS software to establish equations for UCS and elasticity modulus of DSM columns. Afterwards, many regression equations with various were acquired for both UCS and elasticity modulus of the columns based on time, salt and microsilica amount. It should be pointed out that to find out the best predicting equation two factors were considered,  $R^2$  close to 1 and a low discrepancy between equation and laboratory outcomes. Finally, two Eqs. (1) and (2), were proposed for UCS and elasticity modulus of DSM columns in terms of time ( $t$ ), salt value ( $s$ ) and microsilica content ( $m$ ) for water to the cement of 1 and relative density of 70%. From the values, 0.947 and 0.901 for Eqs. (1) and (2) respectively, it can be claimed that the equations have sufficient confirmations with the obtained lab data.

Moreover, in order to be more precise and judge the equation, the predicted values of UCS and elasticity modulus were drawn versus the measured values in Fig. 13. The closer the data is to the line with a 45-degree slope, the higher the accuracy of the equations. In addition, good visual judgment can be made through two solid lines with  $\pm 5^\circ$  from the perfect agreement, dashed line [39]. As demonstrated in the figure, most of the points are scattered between two solid lines which indicate high precision of the equations.

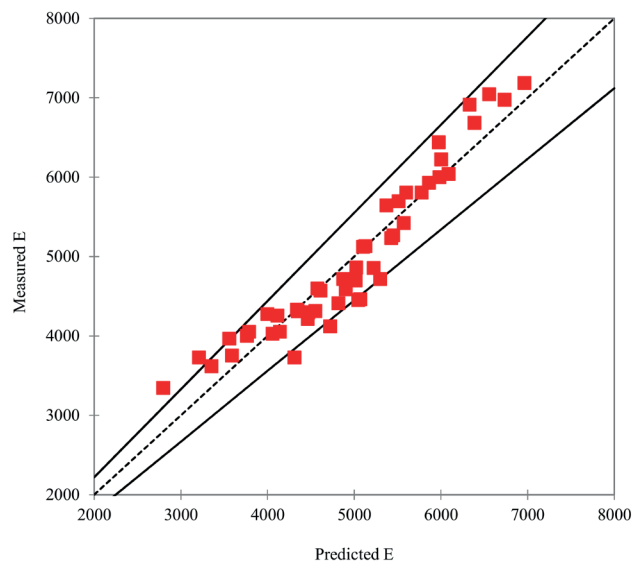
$$\begin{aligned}
 UCS = & 3.214 + 0.531t + 0.002t^2 \\
 & - 0.043s - 0.017s^2 + 0.001s^3 + 0.778m \\
 & + 0.122m^2 + 0.004m^3 \quad (R^2 = 0.947)
 \end{aligned}
 \tag{1}$$

$$\begin{aligned}
 E = & 3829.7 - 71.72t + 11.02t^2 \\
 & - 0.235t^3 - 22.66s - 5.67s^2 + 0.21s^3 \\
 & - 224.54m + 46.33m^2 - 1.59m^3 \quad (R^2 = 0.901)
 \end{aligned}
 \tag{2}$$

Where  $UCS$ ,  $E$ ,  $t$ ,  $s$  and  $m$  are unconfined compression strength (MPa), secant elasticity modulus (MPa) time (day), salt (%) and micro-silica (%), respectively.



(a)



(b)

**Fig. 13** Predicted values versus obtained values for DSM columns (a) compressive strength; (b) elasticity modulus

#### 4 Conclusions

The current paper aims to investigate the effect of salinity on the mechanical properties of DSM columns. For this, first of all, four sandy subgrades contain 0, 5, 10 and 20% salt were prepared at a relative density of 70%. The columns were executed using developed DSM device in the lab environment. It should be noted that the water to cement ratio of 1 was chose for cement slurry as well as 6-blade hollow rod. After capping and preparation of the experimental DSM columns, they were subjected to uniaxial load at three ages of 7, 14 and 28 days to evaluate their compressive strength and elasticity modulus. Microsilica additive also added at percentages of 10, 15 and 20 % in cement slurry to improve mechanical properties of executed DSM columns in the saline subgrades. Following results can be considered as the main achievement of this study:

1. By increasing the amount of salt in sandy subgrade the mechanical parameters of DSM columns have been decreased significantly. The result indicated that most decreases in terms of and elasticity modulus occurred for executed samples in the subgrade with 20% salt for all ages. These reduction values reported 33, 37 and 28% in terms of UCS and 21, 17 and 17% for elasticity modulus corresponding 7, 14 and 28 days specimens, respectively.
2. Analysis of SEM images showed that cubic-shape particles of salt caused discontinuity in cement connections and make them weaker which results in

deteriorating mechanical properties of cement-soil columns. The results also indicated that although adding microsilica up to 15% acted as a filler, and make a uniform particle distribution which led to improving mechanical properties of executed DSM columns in the salty subgrade, 20% micro silica additive resulted in falling both UCS and elasticity modulus because of unsuitable distribution of particles.

3. Adding microsilica in cement slurry led to raising both UCS and elasticity modulus of installed DSM columns in saline soil. It was also understood that using 15% microsilica (replacement of cement by weight) resulted in the maximum enhancement of 28-day DSM columns in terms of UCS and Young's modulus. These enhancements were 24, 19, 18 and 21% for UCS and 34, 36, 38 and 42% for elasticity modulus corresponding executed DSM columns in the subgrade with 0, 5, 10 and 20% salt, respectively.
4. According to statistical analysis, two polynomial equations were proposed to predict the UCS and elasticity modulus of DSM columns in terms of salt content, curing time and micro-silica percentage. It should be emphasized that the accuracy of the equations was high enough with values of 0.947 and 0.901 for UCS and elasticity modulus, respectively.

#### 5 Conflict of interest

The authors declare that they have no conflict of interest.

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