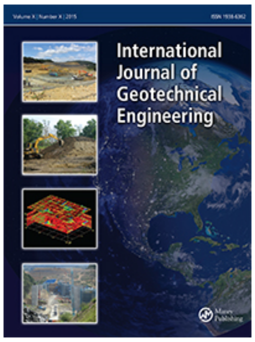

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Experimental study of the effect of nano-additives on the stiffness of cemented fine sand

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ABSTRACT

The stiffness of stabilized sand with powder nanomaterials (nano-SiO2, nano-Al2O3, and nano-MgO) in two cementation conditions is investigated in this study. The studies have been conducted using laboratory tests under unconfined, partly confined, and confined conditions. The nanomaterials in addition to filling the intergranular pore spaces have led to a better interlocking of the particles by improving the concentration on the surface roughness of them in an effective way. Therefore, they have increased the intergranular friction, resisted the movements of the particles, and reduced the deformation of the mass. In the cemented case, nanomaterials have generally participated in the hydrated medium of the cementitious matrix. In addition, pozzolanic materials have reduced the weak part of the hydration process and improved the strong part of it, by consuming calcium hydroxide and producing C-S-H. Subsequently, it has resulted in a reduction of axial and volumetric deformation of the specimens..

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Stabilized sand; nano-additive; confinement condition; stiffness; Pozzolanic materials; Hydration of cement; Ground improvement; SEM

1. Introduction

Uniform fine sands have some problems such as high settlements, liquefaction, bearing weakness as the subgrade of the roads, and instability in the excavation. So, stabilization of fine sands is common in construction projects. Loose saturated sands have the risk of liquefaction and uniform sands undergo significant settlements, especially under cyclic and dynamic loadings, thereby, stabilizing them is inevitable (Ahmadi, Eslami, and Arabani 2017). The main aim of reducing the significant settlements of the sandy soil is to decrease the porosity and increase the stiffness of the soil. Considering an elastic behaviour for deformation of the materials results in simple solutions, but for granular materials, the conditions would be different from reality (Davis and Poulos 1972). Porosity changes of sandy soils under completely confined conditions (one-dimensional settlement) depend on the applied stress level (Yoshimi, Kuwabara, and Tokimatsu 1975; Pestana and Whittle 1995). Any blockage in the wall or at the depth of the soil can affect the sandy layer's settlement conditions. The dependency of granular materials on confining stresses and confinement conditions are the main parameters of their deformation (Eid et al. 2009).

The stabilization by adding cement as a mixture or grouting is one of the most common methods to improve the weaknesses of uniform fine sand. Cementation of the sand and formation of intergranular adhesion increases the shear strength of the sand, stops the intergranular movement, and decreases the settlement of the soil. The ratio of cement to soil porosity determines how effective the cementation can be (Fonseca, Cruz, and Consoli 2009). On the other hand, the developments of nanotechnology in the recent decade, have provided the use of nanosized materials for soils stabilization. Although some limited studies have been conducted in order to investigate the effects of using nanomaterials on increasing the strength of cemented sands (Ghasabkolaei et al. 2017), most of the previous studies on usage of nanomaterial in soils improvement have focused on clays (Bahmani et al. 2014; Gao et al., 2015, 2018; García et al. 2017). Cement has been generally used in the improvement of sandy soils with the help of nanomaterials. The pore spaces existing in the coarse-grained soil (even in dense conditions) are not in the size of nano. In addition, the probability of formation of a chemical bond between the material and the sand, especially in silica ones, is low. Therefore, the nanomaterial acts as the filler of only some parts of the porosity. In the presence of the cement, by adding the nanomaterial, a chemical reaction between the nanomaterial and the cement is probable and can affect the performance and strength of the cement. A wide range of studies has been conducted on cement, in order to evaluate the performance of nanomaterials, especially those having pozzolanic properties. (Oltulu and Şahin 2014; Papatzani, Paine, and Calabria-Holley 2015). Qing et al. (2007) have shown that the pozzolanic activity of nano-SiO_2 is much more compared to silica fume. Therefore, if the adhesive material between the particles can be improved, it can be expected that the strength and stiffness of the stabilized mass will also increase (Constantinides and Ulm 2004). The characteristics of the cement paste having SiO_2 nanoparticles have been described by Jo et al. (2007). Investigating the performance of nanomaterials in cemented sand have often followed the effects on the shear strength and less attention has been paid to soil settlement and stiffness. By conducting unconfined compression tests, Kutanaei and Choobbasti (2016) have observed an increase in unconfined compressive

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strength due to the addition of 8% nanosilica. Choobbasti, Vafaei, and Kutanaei (2015) used 5, 10 and 20% nanosilica to better stabilize the cemented sand with 5, 9 and 14% cement. The results showed that adding up to 10% nanosilica increases UCS while adding more than 10% nanosilica acts reversely.

In this study, the effect of adding powder nanomaterials on the axial stiffness of fine sand and cement-treated sand has been investigated. Three nanomaterials including SiO_2, MgO and Al_2O_3 nanoparticles were used in preparing the test specimens. The effect of confinement has been considered in three conditions. Also, the microstructure specification of the specimens has been evaluated using any of the additives through SEM images.

2. Materials and experimental work

2.1. Experimental plan

The stiffness of sandy soil mixed with nanomaterial has been studied in three sections. In the first section, using the results of unconfined compression test, the changes of axial stiffness caused by the addition of nano-SiO_2 to the cemented sand have been obtained according to Young's modulus of the specimens. In this section, the sand mixed with 3 different cement contents (3, 6 and 9% of the weight of the sand) and 5 different nano-SiO_2 contents (0, 0.2, 0.4, 0.8 and 1% of the weight of the sand) has undergone the unconfined compression tests. In the second section, partly confined stiffness of the soil accompanied by stiffness of the sand mixed with nano-SiO_2 and also the one mixed with a combination of cement and nano-SiO_2 has been evaluated by stress-displacement measurements. The amounts of additives in this section is considered similar to the previous one. Finally, in the third section, the stiffness of the specimens in confined conditions has been studied by evaluating the one-dimensional settlement of the specimens in oedometer device. The sand mixed with 0, 3 and 6% cement has been considered as the basic condition and three types of nano-additives have been used in three variable contents of 0.4, 0.8 and 1.2%. The effects of nano-silica (NS), nano aluminium (NA), and nano magnesium (NM) on the unconfined stiffness have been studied in this section.

2.2. Materials

2.2.1. Soil

Anzali sand has been used in the tests of this study. The properties of this sand have been studied by Ahmadi, Eslami, and Arabani (2015). Anzali sand is fine-grained, clean and relatively uniform. The required soil has been taken from an area near the beach in the west of Bandar-e Anzali (Located in the south of the Caspian Sea). The gradation of the sand is shown in Figure 1. The physical properties of the used sand are presented in Table 1 based on the results of index standard tests. Also, the chemical elemental analysis of the used soil by conducting the XRF (X-Ray Fluorescence) is shown in Table 2. The soil specimen has more than 40% silica according to this analysis.

2.2.2. Additives

Three powder nanomaterials have been used in this study, including silicon oxide (SiO_2), aluminium oxide (Al_2O_3), and magnesium oxide (MgO) nanoparticles. The sizes of nano-SiO_2, nano-Al_2O_3, and nano-MgO have been 20–60 nm, 20–-50 nm, and up to 50 nm, respectively. All of the three nanomaterials are white and have a purity of 99%. Formula Weight of the NS, NA, and NM are 60.08, 101.96, and 40.30 g/mol, and their densities are 2.4, 2.9, and 3.58 g/mL, respectively. Ordinary Portland cement (PC) has been used in the tests of cemented sands. Chemical analysis of the used cement has been shown in Table 3.

2.3. Preparing the specimens

The undercompaction technique has been used for preparing the specimens, based on the method described by

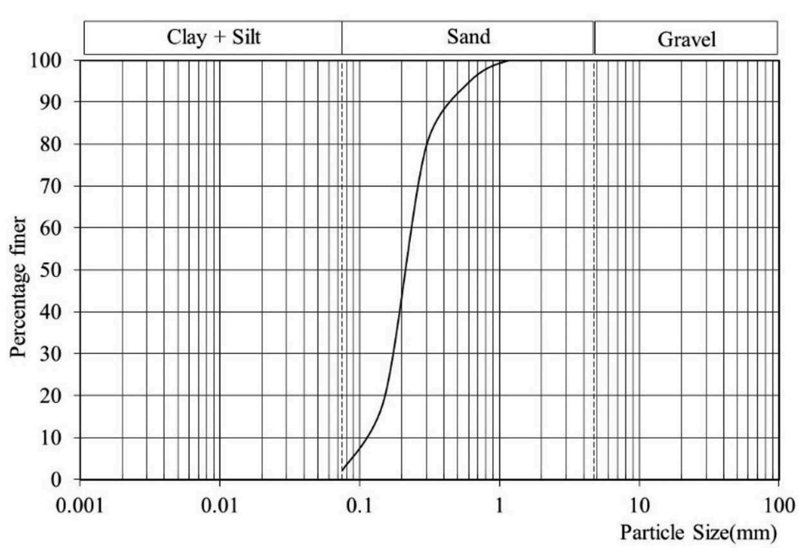

Figure 1. Particle size distribution of the soil.

Table 1. Physical properties of soil.

Soil properties	Values
Specific gravity	2.72
Maximum voids ratio (e_{max})	0.73
Minimum voids ratio (e_{min})	0.56
Maximum dry unit weight	16.9 kN/m^3
Optimum moisture content	19.3
Unified Soil Classification	SP
Grain size analysis:	
Effective diameter (D_{10})	0.109 mm
Median diameter (D_{50})	0.225 mm
Uniformity coefficient (c_u)	2.29

Table 2. Chemical analysis of fractions of sand by XRF.

Chemical composition	Weight (%)
SiO_2	40.41
CaO	18.6
Al_2O_3	11.63
Fe_2O_3	8.01
MgO	3.82
K_2O	2.08
Na_2O	1.28
TiO_2	0.9
P_2O_5	0.18
SrO	0.18
MnO	0.21
L.O.I (950ºC)	12.7

Table 3. Chemical properties of cement.

Chemical composition (wt %)		Mineralogical phase composition (wt %)	
SiO_2	21.36	C3S	51.69
Al_2O_3	4.95	C2S	22.33
Fe_2O_3	3.48	C3A	7.37
CaO	63.36	C4AF	10.58
MgO	2.95		
SO_3	1.85		
K_2O	0.65		
Na_2O	0.26		
Cl	0.01		
L.O.I	1.08		

Ladd (1978). At first, the required amount of sand in every one of the tests has been mixed uniformly (at least for 30 minutes) with the cement in dry conditions. Then, the nanomaterial has been added to the mixture, gradually and the mixed material has been prepared uniformly using a mechanical mixer. Finally, the water has been added gradually based on the optimum water content of each mixture and the mixing has been continued to reach a uniform mixture.

The optimum water content has been obtained by conducting the standard Proctor compaction test according to ASTM D698 standard (ASTM, 2012). The results of the conducted compaction tests on the specimens of the pure sand and the sands mixed with 3, 6, and 9% cement are shown in Figure 2. By adding the cement to the soil, the optimum water content of the specimen has decreased, while the maximum dry specific weight has increased. The studies of Kutanaei and Choobbasti (2017) have indicated that adding less than 2% nanomaterials have no sensible effect on the optimum water content of the sandy soil.

All of the specimens used in the stiffness determination tests have been kept in the laboratory with humidity insulation, at a temperature of 23 ± 2ºC, for 28 days. Conducting unconfined compression tests on the specimens with 6% cement and 1% nano-SiO_2 have shown that no significant change takes place in the unconfined compressive strength of the stabilized specimen after 28 days. The effect of curing time on the strength of stabilized specimens is shown in Figure 3. Therefore, during the curing time, the mixture incorporating nanoparticles and cement have exhibited mechanical behaviour similar to that of a pure cement paste.

3. Results and discussion

3.1. Unconfined conditions

Unconfined tests according to ASTM D2166 standard (ASTM, 2011) have been used in order to evaluate the effect of nano-additives on Young's modulus of the sand specimens stabilized with cement. Regarding the fact that the sand is

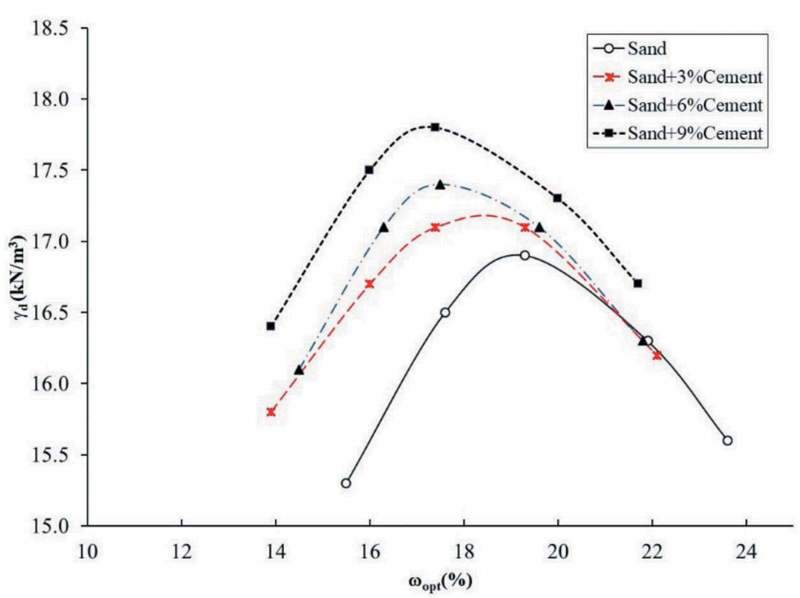

Figure 2. Variation in compaction parameters of sand mixed with cement.

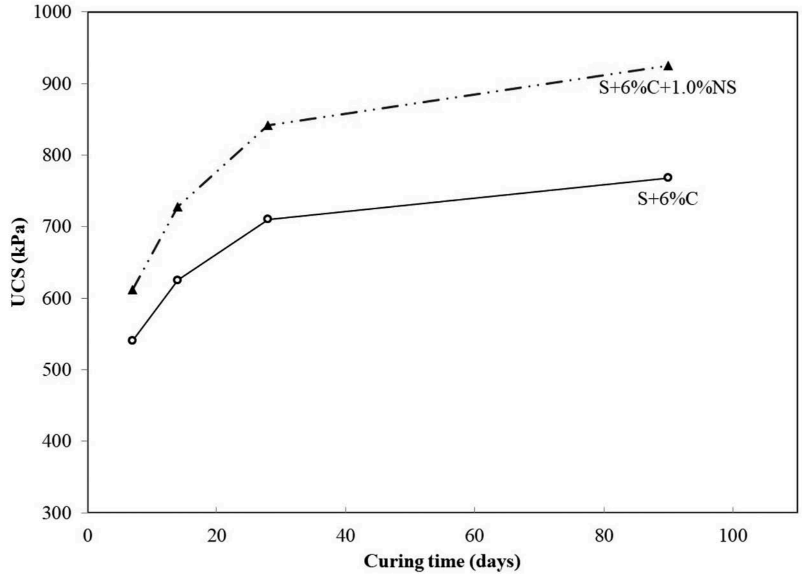

Figure 3. Effect of curing time on unconfined compressive strength of cemented samples.

unstable in unconfined conditions, 3, 6, and 9 percent of cement (relative to the weight of dry sand) were used for preparing the specimens according to section 2.3. In this phase, nano-SiO_2 has been used at 0, 0.2, 0.4, 0.8, and 1% of the weight of dry sand. The specimens were 38 mm in diameter and 76 mm in height. The specimens have been made in 5 layers in the mould. Each layer has been scratched after compaction at the optimum water content, in order to have the required connection. All of the specimens have been tested after the 28 days curing time. The stress-strain changes of the specimens having 3, 6 and 9 percent of the cement in the unconfined compression tests are shown in the charts of Figure 4. Analysing the stress-strain curves shows that the addition of nano-SiO_2 has increased the peak unconfined compression strength (UCS) of the specimens. Also, the peak strength of the specimens occurs in lower strains, as a result.

The increase in the strength of the specimens and the decrease in the strain corresponding to the peak UCS indicates an increase in the stiffness of the specimens having nanomaterials. The procedure of the changes in stiffness as a result of adding the materials can be understood better using the changes of Young's modulus. The elastic modulus in the form of a secant modulus can be determined as

$$E_{50} = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{1}$$

where E_{50} is the secant modulus, $\Delta\sigma$ is the change in axial stress up to reaching 50% of the peak strength, and $\Delta\varepsilon$ is the change in the corresponding strain. Therefore, based on the change in stress-strain of the specimens (Figure 4), Young's modulus for different specimens is obtained as shown in Figure 5. The change in secant modulus indicates that the stiffness of cemented specimens increases by adding the nano-SiO_2. By adding 1% NS to the specimens with 3, 6, and 9% cement, Young's modulus increases by 35, 36, and 24%, respectively. The rate of increase in E_{50} by increasing the amount of nano-SiO_2 available in the specimen, is more intense in lower percentages. By adding more than 0.8% NS to the specimens, Young's modulus has no significant change. The growth of unconfined stiffness due to the addition of nano-SiO_2, in the specimens with variable cement contents, is relatively similar.

3.2. Partly confined conditions

Specimens of stabilized sand with different percentages of cement (0, 3, 6, and 9% of the sand weight) and nano-SiO_2 (0, 0.2, 0.4, 0.8, and 1% of the sand weight) were prepared in cylindrical metal moulds with a diameter of 150 mm and a height of 300 mm. The displacement (settlement) of the specimen caused by the normal stress applied by a piston with a circular section and a diameter of 50 mm has been measured. The loading was applied by a constant rate of 0.1 mm/min and the change in load-displacement has been recorded. Regarding the dimensions of the specimens, the influence of effective depth has been considered, but the walls can affect the confinement of the specimens. The results of loading on different specimens are presented in Figure 6 as the change in relative settlement (S/B) to the change in normal pressure. The relative settlement is defined as the ratio of vertical deflection of the rigid foundation to the width of it, which is expressed as a percentage. The elastic settlement of the soil can be determined as (Bowles 1997)

$$S_i = \frac{qB(1-\nu^2)I_s}{E} \tag{2}$$

where S_i, B, I_s, ν, and E are the elastic settlement, width (diameter) of the foundation, shape factor of the load, Poisson's ratio, and elastic modulus of the soil, respectively. However, the confinement conditions affect the settlement and in partly confined condition, the settlement is expressed as

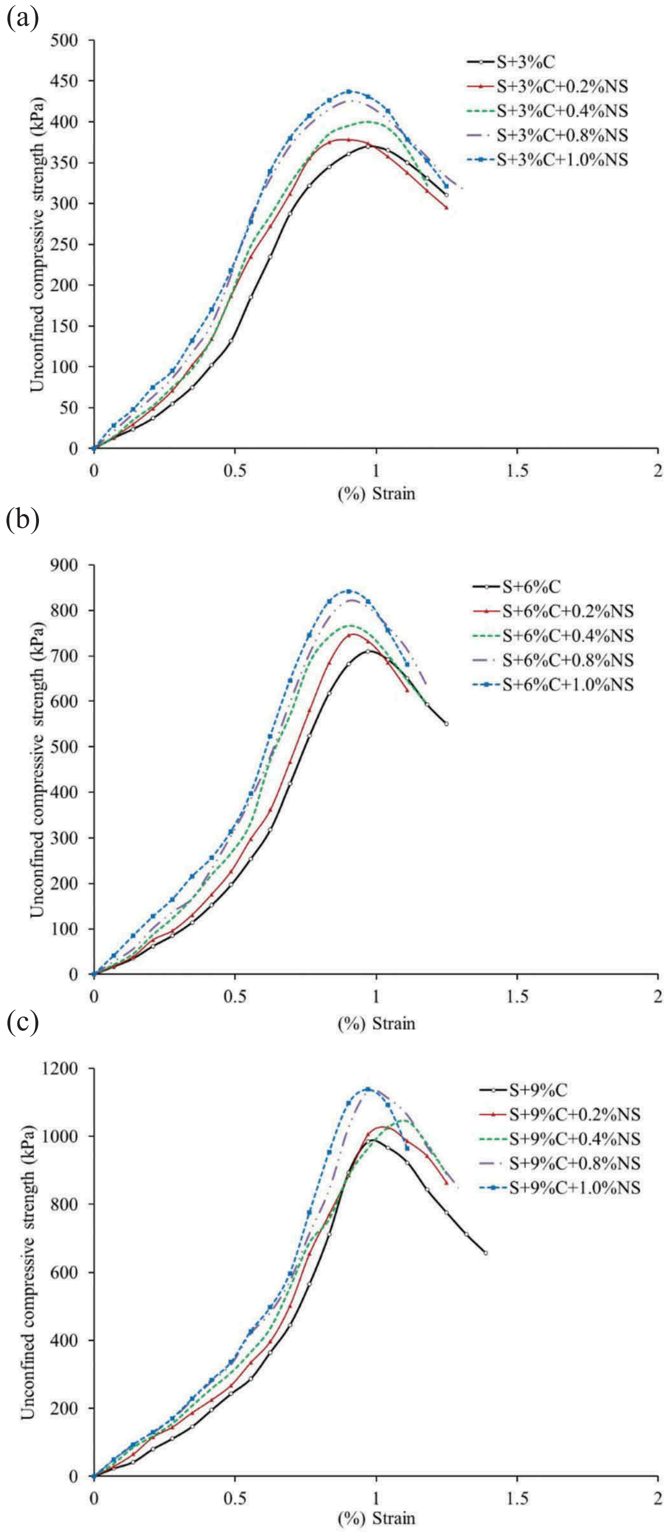

Figure 4. Variation of stress-strain curve for sand samples containing various amount of nano-SiO_2 with 3% (a), 6% (b), 9% (c) cement in unconfined condition.

$$S = S_i \times I_c \tag{3}$$

In which S is the settlement in partly confined condition and I_c is the confinement factor. Hence

$$\frac{q}{(S/B)} = \frac{E}{(1-\nu^2)I_s I_c} \tag{4}$$

The partly confined stiffness, E_{pc}, is defined as the ratio of the change in settlement to the relative settlement, which can be expressed by the following equation

$$E_{pc} = \frac{q}{(S/B)} \tag{5}$$

So

$$E_{pc} = \frac{E}{(1-\nu^2)I_s I_c} \tag{6}$$

Based on the slope of the curves in Figure 6, the change in partly confined stiffness due to the addition of nano-SiO_2 to the sand and cemented sand specimens is presented in Figure 7.

The change of E_{pc} in Figure 7 indicates that adding nano-SiO_2 to the cemented specimens, will have a significant effect on the unconfined stiffness of the specimens. The highest growth in E_{pc} has been observed for the specimen with 3% cement. E_{pc} has increased by almost 55% due to the addition of 0.8% NS to the specimen. Adding 0.4% nanomaterial to the specimens with 3 to 9% cement, has resulted in an increase in E_{pc} by 25 to 42%. However, the increase rate of E_{pc} has reduced by more addition of the nanomaterial. Also, E_{pc} has reduced slightly by increasing the nanomaterial from 0.8 to 1% in the specimens with 3 and 6% cement. Slight changes of E_{pc} in the specimens without cement, compared to those with cement, indicate that the nano has dominantly interfered in the properties of the cement paste. Due to the low doses of nano-SiO_2 used in experiments, no significant changes have taken place in the porosity. Therefore, the remarkable effect of nanomaterials on the increase of soil stiffness can be caused by the formation of chemical reactions in the cement paste.

3.3. One-dimensional settlement (confined condition)

The confined stiffness of the sand stabilized with nanomaterials has been studied through measuring the one-dimensional settlement of different specimens using oedometer device. Regarding the mould of oedometer, the specimens have a diameter of 50 mm and a height of 20 mm. The variables of the experimental plan in this section include the amount of cement, the amount of nano-additive and type of nanomaterial. Three types of nanomaterials including SiO_2, MgO and Al_2O_3 nanoparticles have been added in the form of powder to the pure and cemented sands. 0.4, 0.8, and 1.2% nano additives have been used for the preparation of the treated sand. The loading has been applied vertically in 10 steps with a static pressure of 10 to 1600 kPa, and the vertical displacements of the specimens have been investigated. The results of pressure-settlement of the specimens are presented in Figures 8–10, for the specimens with 0, 3 and 6% cement, respectively.

Due to the confinement of the sidewalls and one-dimensional settlement of the specimens, the unconfined conditions are satisfied in the experiments. Based on

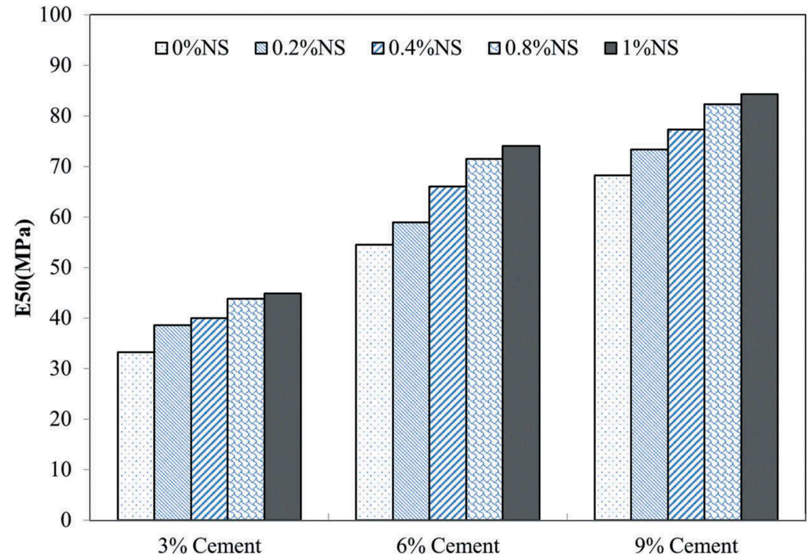

Figure 5. Effect of the addition of nano-Sio2 on the E_{50} of cemented sand.

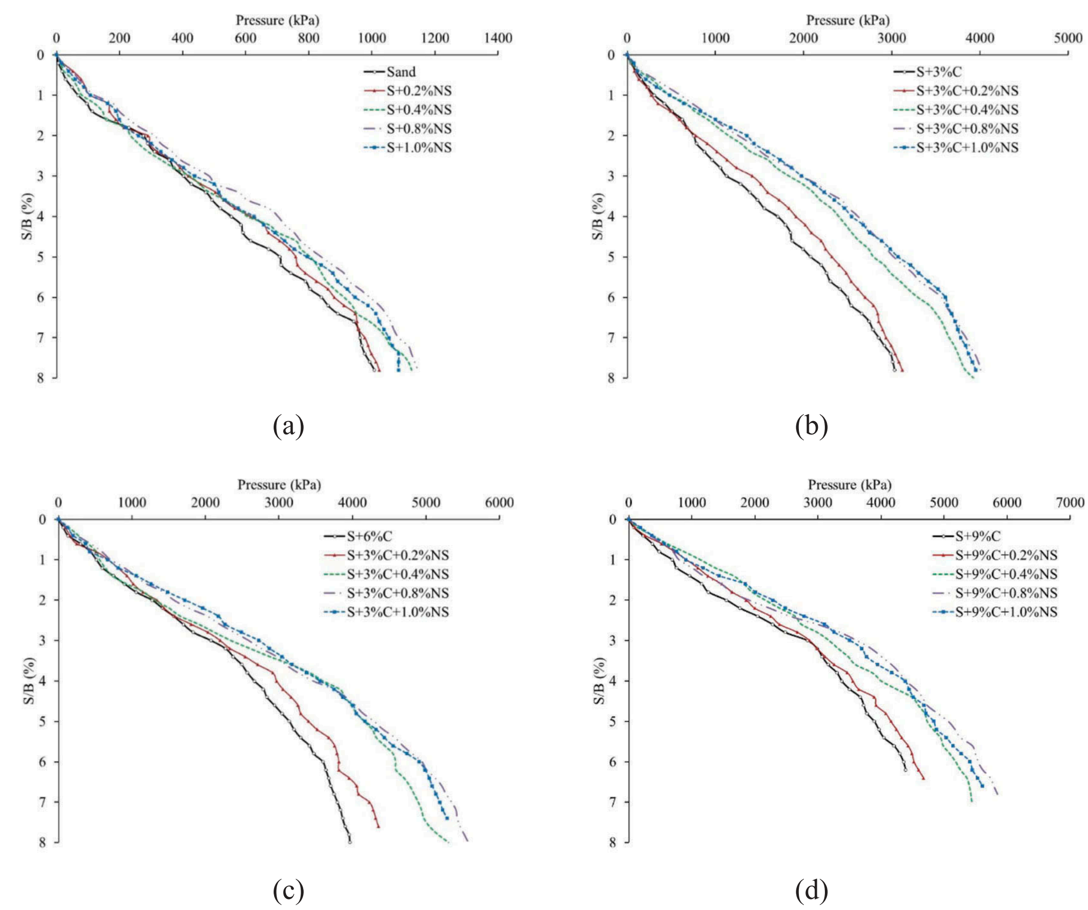

Figure 6. Variation of pressure-settlement curves for sand samples containing various amount of nano-SiO_2; (a) without cement, (b) with 3% cement, (c) with 6% cement, (d) 9% cement, in partly confined condition.

Hooke's law, the constrained Young's modulus is defined as (Budhu 2015)

$$E_c = \frac{\Delta\sigma_z}{\Delta\varepsilon_z} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \quad (7)$$

where the subscript c indicates the constrained conditions, E is the elastic modulus in effective stress conditions, and ν is Poisson's ratio. In a one-dimensional settlement test, the axial strain can be calculated by

$$\varepsilon_z = \frac{\Delta H}{H_\circ} = \frac{\Delta e}{1+e_\circ} \quad (8)$$

where H_o and e_o are the initial height and void ratio of the specimen, respectively. The results presented in Figures 8–10

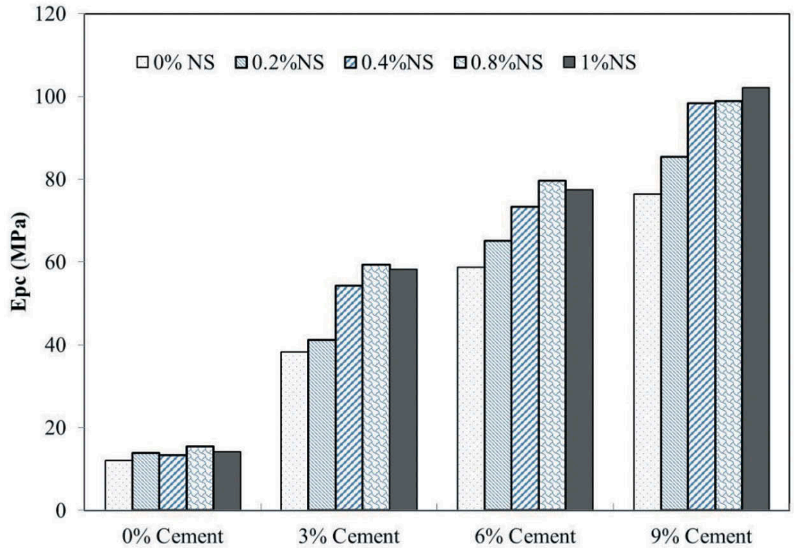

Figure 7. Effect of the addition of nano-Sio2 on the E_{pc} of sand with 0%, 3%, 6% and 9% cement.

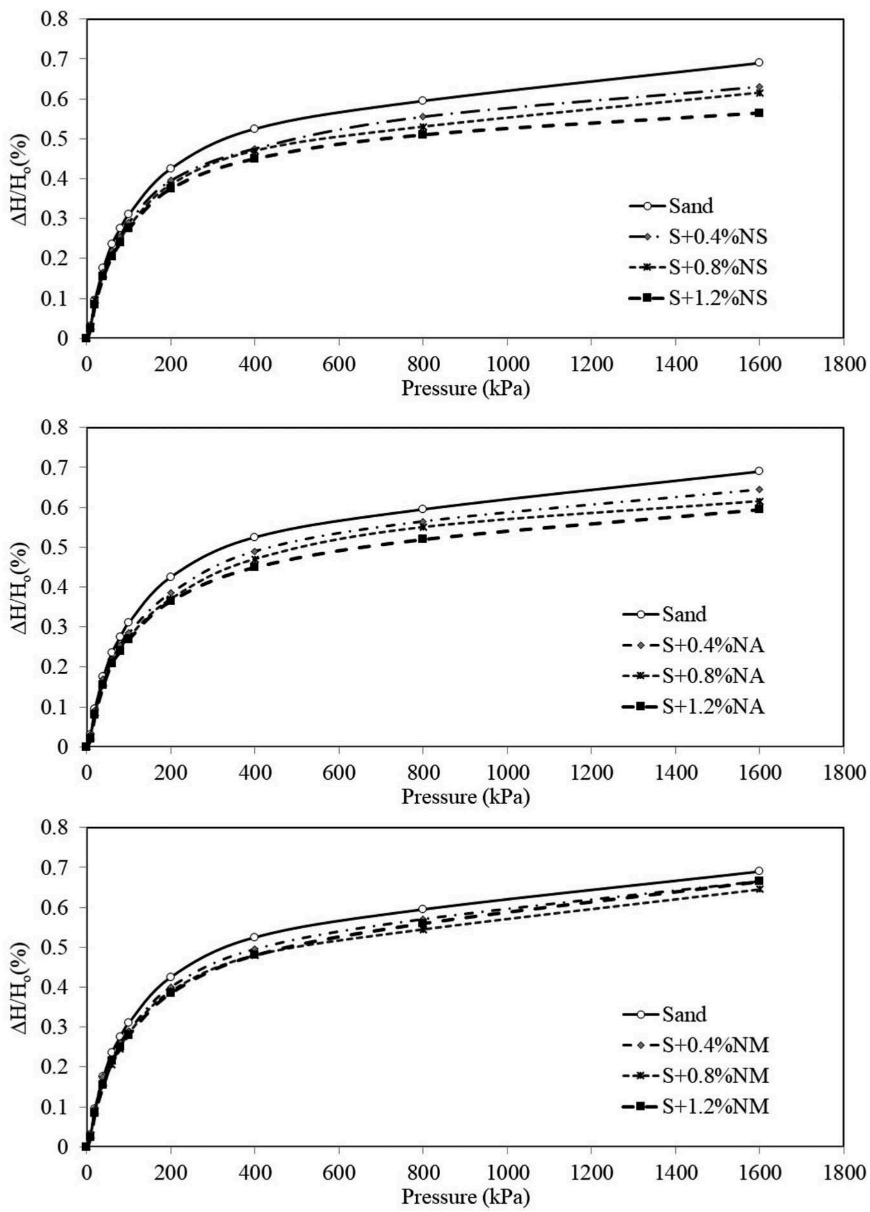

Figure 8. Variation of pressure-1d settlement curves for sand samples without cement and containing (a) nano-SiO_2, (b) nano-Al_2O_3, (c) nano-MgO.

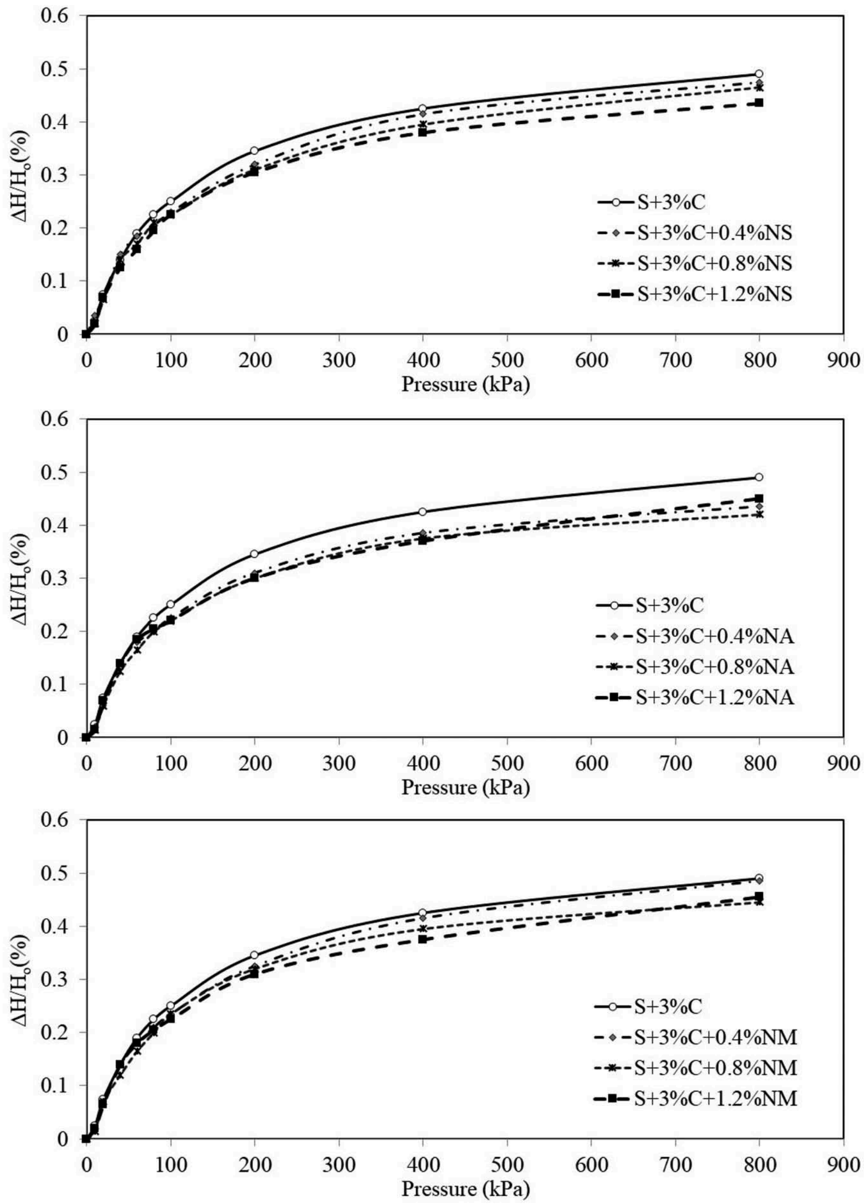

Figure 9. Variation of pressure-1d settlement curves for sand samples with 3% cement and containing (a) nano-SiO_2, (b) nano-Al_2O_3, (c) nano-MgO.

show that the amount of E_c is highly dependent on the stress level. By increasing the stress level, the stiffness of the specimens will increase strongly which is due to the compaction of specimens, in high stress levels, and high reduction of the void ratio of specimens. So, the change of confined stiffness of the specimens should take place at the same stress levels. Accordingly, by applying an axial stress of 200 kPa, E_c for different specimens are obtained as shown in Figure 11. The results show that adding each one of the three nanomaterials leads the constrained Young's modulus to increase. In the specimens containing cement, the effect of nanomaterials on the stiffness of the specimens is more intense, compared to those without cement. Adding 0.8% nano-Al_2O_3 to sand has increased E_c by 15%, while adding the same amount to the sand containing 6% cement has resulted in an increase in E_c by 23%. The effect of nanomaterials up to reaching a dose of 0.8% has a higher rate and by more increasing the nanomaterials, E_c increases less intensely. The comparison between the three nanomaterials indicates that nano-Al_2O_3 has the most effect and nano-MgO has the least effect on increasing the confined stiffness of the specimens.

Yamamuro, Bopp, and Lade (1996) and Nakata et al. (2001) have shown that for dense sands, the changes in the void ratio of the specimen in stress levels of less than 2 MPa, are linear in e-logσ plane. Although these changes become non-linear at higher pressures, after passing a non-linear amplitude, they again become linear with a steeper slope. Due to the high density of the sand in this study and also the stress level being limited to 1.6 MPa, the change in the porosity of Anzali sand versus the change in stress has become linear in the e-logσ plane. Figure 12 shows the linear changes of void ratio for dense Anzali sand. The change in void ratio has been obtained using the Equation (8) according to the change in settlement of the specimen. Therefore, due to

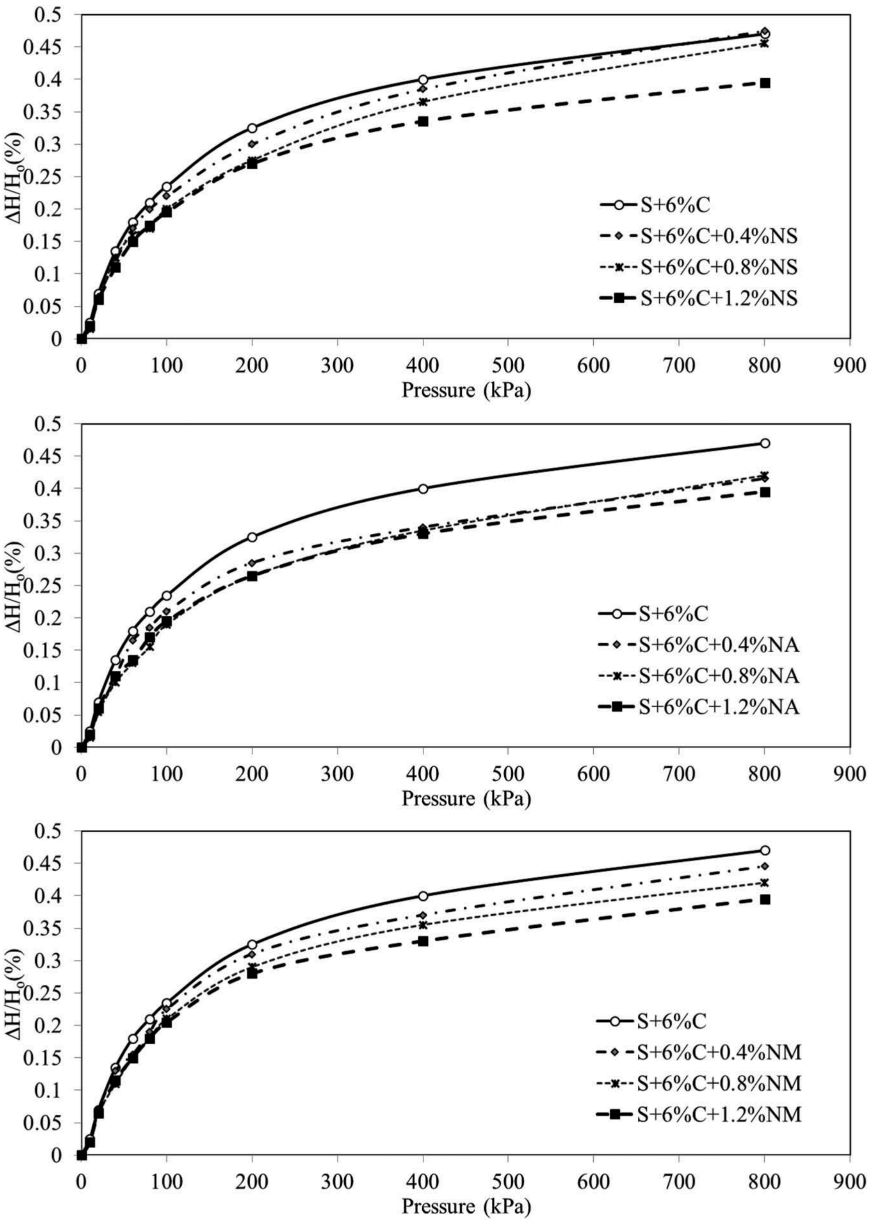

Figure 10. Variation of pressure-1d settlement curves for sand samples with 6% cement and containing (a) nano-SiO_2, (b) nano-Al_2O_3, (c) nano-MgO.

the linearity of the change in axial strain versus the change in the logarithm of the vertical stress, the confined stiffness factor (E'_c) can be defined as

$$E'_c = \frac{\log(\sigma'_{z_2}) - \log(\sigma'_{z_1})}{\varepsilon_{z_2} - \varepsilon_{z_1}} = \frac{\log(\sigma'_{z_2}/\sigma'_{z_1})}{((\Delta H)_2 - (\Delta H)_2)/H_\circ} \quad (no\ units) \tag{9}$$

The obtained values for the confined stiffness factor of different specimens are shown in Figure 13. Comparing the charts of Figure 13 with those of Figure 11 suggests proper conformity of adding nanomaterials at different stress levels. Nano-Al_2O_3 and nano-MgO have the most and the least effects among the tested materials, respectively. By adding 0.4, 0.8, and 1.2% NA to the sand specimen containing 6% cement, E'_c have increased by 11, 21, and 24%, respectively. The rate of increase in confined stiffness factor are more intense up to the addition of 0.8% nanomaterial and the changes in E'_c are not so significant by adding 50% more nanomaterial. The influence of cement on the effective conditions of nanomaterials can be observed obviously in the charts of Figure 13. By adding 1.2% NA to the specimens with no cement, a maximum increase of up to 16% has been observed in E'_c, which is limited to 10% for Nano-MgO. No significant effect has been observed in E'_c, by adding more than 0.8% nanomaterial of all three types.

3.4. Microstructural characterization

The images prepared by the scanning electron microscope (SEM) have been used for a microstructural characterization into the effect of nanomaterials on the mechanical performance of stabilized specimens. It is expected that no specific chemical reaction will take place and physical processes will dominate the changes in the stiffness if the specimen does not contain cement

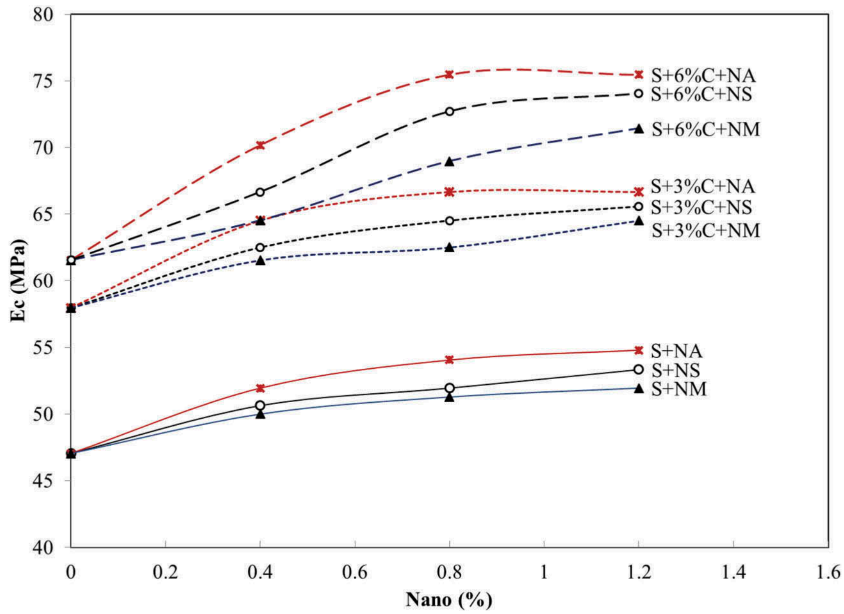

Figure 11. Effect of nano-additives on the E_c of sand and cemented sand under 200 kPa normal stress.

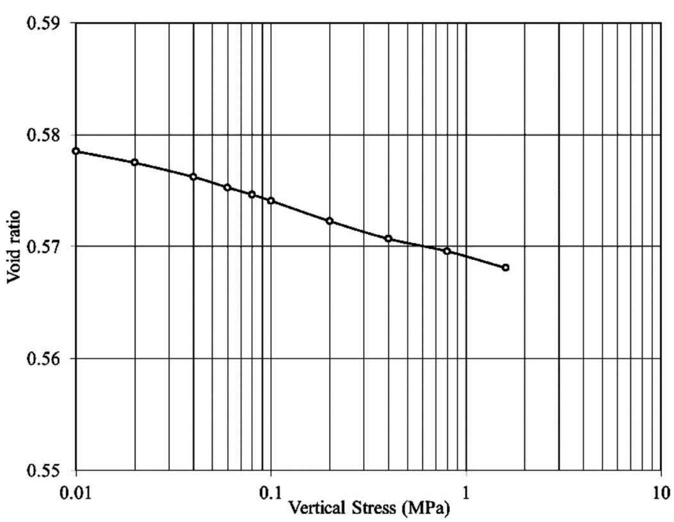

Figure 12. Variation of e-log σ for Anzali sand.

particles. A SEM micrograph of a sand specimen containing 1% NS is shown in Figure 14. As can be observed, nano-SiO_2 completely interacts with sand surface, due to its small size. The concentration of nanoparticles on the sand particles' surface can be seen in Figure 14(b).

Accumulation of the particles and surface roughness of the sand result in a suitable continuity between the sand and nano-SiO_2 which can increase the interlocking between the grains and shear strength of the mixture, due to the high stiffness of the silica. This process can be totally effective in the movement of the particles and subsequent settlement of the specimens, especially in partly confined conditions. However, by increasing the nanomaterials and covering the side surface of the sand grains, the concentration of the nanomaterials can increase the intergranular space which may facilitate the movement of sand grains under vertical overload. The case may be different for the confined conditions in which increasing the nanomaterial results in the filling of void spaces and accordingly resist the volumetric strain under compressive loading. This process will depend on the stiffness of nanomaterials and its proper mixing in the soil. The specimens containing nano-Al_2O_3 and nano-SiO_2 have shown less volumetric strain in the confined tests, due to the high stiffness of aluminium and silica.

On the other hand, the treatment process during the curing time will be accompanied by chemical reactions, due to the presence of the cement and use of water in mixing. We know that Portland cement has four major components including silicate phases; C_3S and β-C_2S, and aluminate phases; C3A and C_4AF. Generally, in the cement references, the ingredients of cement including CaO, SiO_2, Al_2O_3, Fe_2O_3, and H_2O are shown by the letters of C, S, A, F, and H, respectively. The chemical reaction between calcium silicate of the Portland cement and water produces two important components; crystalline calcium hydroxide and an approximately amorphous calcium silicate hydrate named C-S-H (Taylor 1997). The hydration reaction of the cement can be expressed as (Neville 2011)

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2 \tag{10}$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2 \tag{11}$$

Generally, the strength and durability of hardened cement paste can be attributed to C-S-H. However, the chemical formula for the production of C-S-H in the above equations depends on the C/S ratio. The molar ratio of calcium to silicon is one of the most important parameters determining the structure of C-S-H. This ratio varies from 0.7 to 2.1. High values of C/S can occur under curing or intense hydration conditions, while the low ratios can take place in the presence of the cement additive (Lothenbach, Scrivener, and Hooton 2011). The reduction of C/S results in an increase in the mean length of the silicate chains and the interlayer distance which affect the structural morphology. The SEM micrograph of the

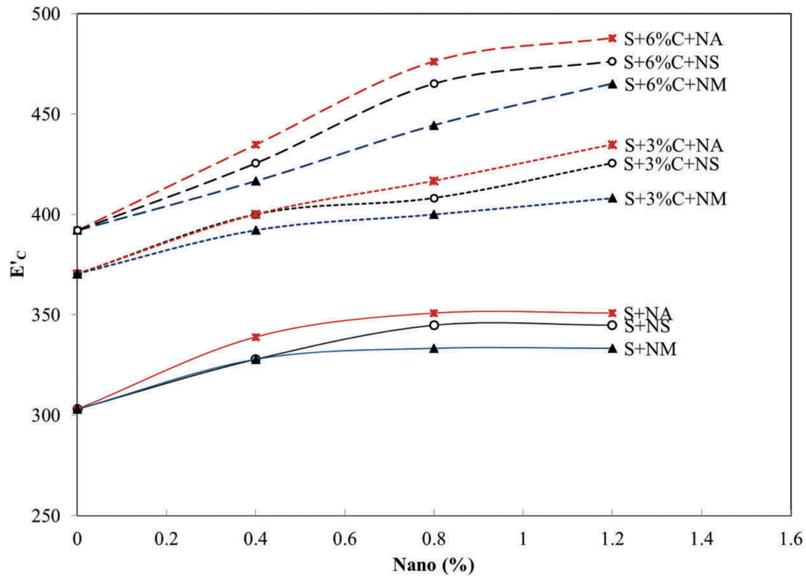

Figure 13. Effect of nano-additives on the $E_c^{'}$ of sand and cemented sand.

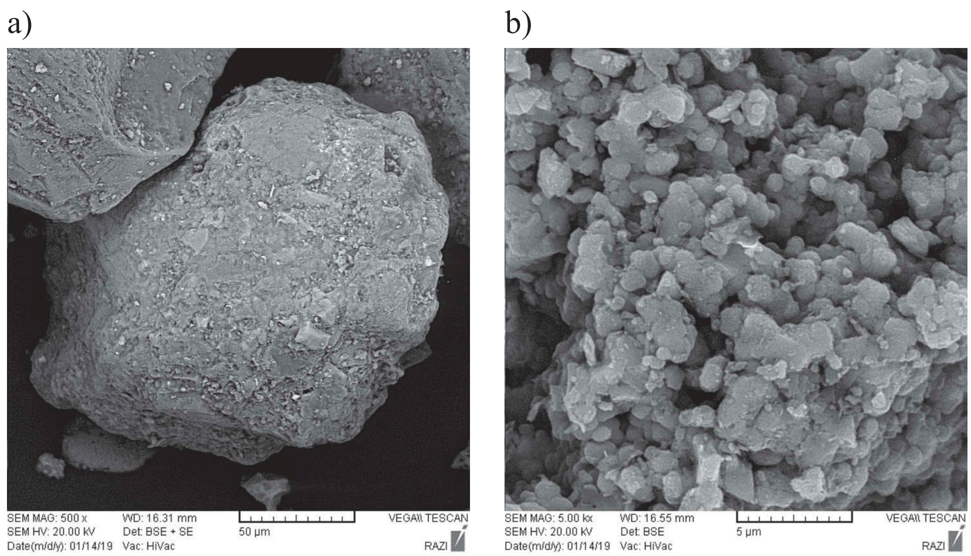

Figure 14. SEM micrographs of sand with 1% nano-SiO_2; a) 500X magnification, b) 5kX magnification.

sand specimen containing 6% cement and 1% nano-SiO_2 is shown in Figure 15. The size of both products of hydration (C-S-H and CH) is recognizable in the Figure.

The structure of C-S-H gel is in the nanoscale (Selvam et al. 2009) and modifying it can increase the stiffness and mechanical properties of cement paste. As a result, the addition of proper nanoparticles can affect the strength and stiffness of the mortar, fundamentally, by changing the nanostructure of hydration. Also, in the hydrated cement paste, there are nanosized void spaces in addition to nanostructure solid materials, which are filled with water or air. Therefore, adding the right amount of nanosized materials can be effective in the filling of the void spaces, in addition to the formation of a better chemical reaction. So, two main roles of using nanomaterials are notable in improving the strength and stiffness of cemented sand: first, its usage as a filler of nanosized pores, and second, involving in the reaction for the production of C-S-H, which is more important. The pozzolans are often effective in this important role. They are siliceous or siliceous and aluminous materials which react chemically with calcium hydroxide (the second product of Portland cement hydration based on the Equations (10) and (11)) in the presence of water, at the normal temperature and produce calcium silicate hydrate and some other cement compounds.

Calcium hydroxide is a by-product of hydration of cement and a part of paste which binds the aggregates. However, calcium hydroxide is soluble in water. Therefore, it reduces the amount of paste and subsequently its density, by making porosity. The reduction in paste density leads to a decrease in strength and stiffness. Also, the created porosity makes the paste vulnerable to chemical elements and materials. On the other hand, calcium hydroxide results in the alkaline-siliceous reactivity and weakens the cement-based system. Therefore, it can be said that calcium hydroxide is a weak bond in the cement-based system. Pozzolanic materials can be used to reduce the negative effect of calcium hydroxide. By adding SiO_2 to the paste

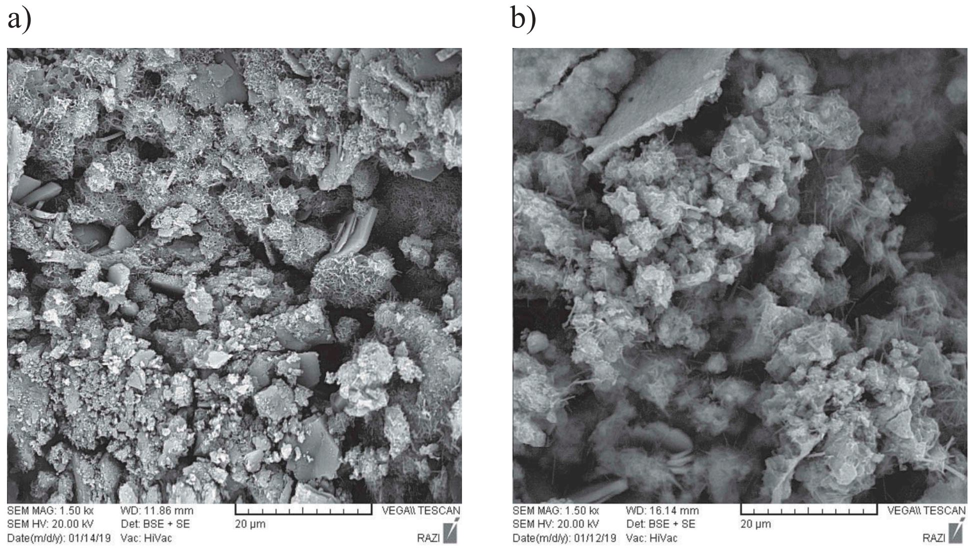

Figure 16. SEM micrographs of sand with 6% cement and (a) 1% nano-Al_2O_3, (b) 1% nano-MgO.

$$2Ca(OH)_2 + SiO_2 + H_2O \rightarrow C - S - H \tag{12}$$

Analysing Figure 15 shows that the usage of nano-SiO_2 has effectively consumed calcium hydroxide and reduced it compared to C-S-H. Alkalies and using calcium hydroxide decreas the pH of paste. Therefore, it can be said as a summary that pozzolanic materials change calcium hydroxide into cement materials and lead to higher strength and durability of the cement-based system, as a result. The reactivity of the pozzolans with calcium hydroxide depends on their basic properties such as chemical composition, crystallography, structural deformation, amorphous phase content, and size of the particles. By decreasing the size of materials to nanosize, their specific surface area multiplies. Therefore, nanomaterials provide a larger area for the reaction (Oltulu and Şahin 2011) and subsequently the addition of nanomaterials to the cement increases the chemical reaction. This is the most important reason for using nanomaterials. On the other hand, the nanosized materials, improve the nanostructure of hydrated cement by minimizing the nanosized pores in C-S-H. So, a denser matrix is created. In the confined tests, nano-Al_2O_3 and nano-MgO are also used in addition to nano-SiO_2, for stabilization of the specimens. The images of specimens containing 6% cement and stabilized with 1% NA and 1% NM, made by SEM are shown in Figure 16(a,b), respectively. Nano-Al_2O_3 can consume portlandite (CH) during the hydration process and produce calcium alumina silicate hydrate (C-A-H) as a supplement. Therefore, it has shown similar behaviour to those of stabilized specimens with nano-SiO_2. In addition, parts of nano-Al_2O_3 which have occupied the void space of the medium, have had higher strengths in volume change caused by applying the axial overload, due to the high stiffness of this nanomaterial. The comparison of SEM images shows that CH masses have more thickness and also larger void spaces have been formed between the sand grains, in the specimens containing nano-MgO. It seems that a major part of nanomaterial has filled the nanosized void spaces in the hydrated space. As a result, the deformation of specimens

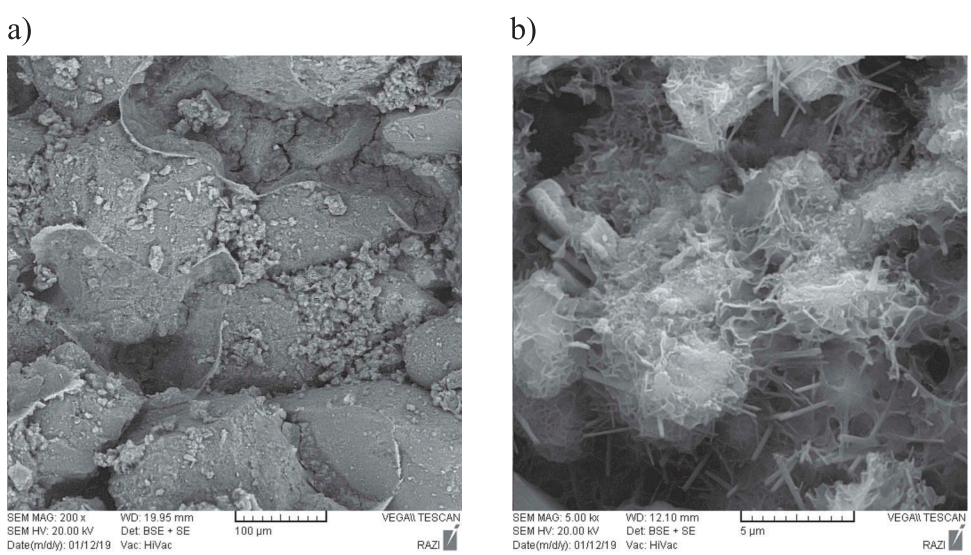

Figure 15. SEM micrographs of sand with 6% cement and 1% nano-SiO_2; (a) 200X magnification, (b) 5kX magnification.

containing nano-MgO is more, compared to those containing the same amount of Al_2O_3 and SiO_2.

4. Conclusions

The effects of adding nanosized materials on the stiffness and compressibility of fine sands for different confining conditions is investigated in this study. After preparing the specimens with different amounts of cement and nanomaterials, analysing their situation has shown that the existence of a little nanomaterial can increase the stiffness of soil, significantly. Although the nanomaterials were added up to 1% of sand weight, at most, Young's modulus has increased up to 36, 55, and 24% in the unconfined, partly confined and confined stiffness conditions, respectively, based on the conducted experiments. However, the performance of nanomaterials has been different, under cemented and uncemented conditions of sand. The interaction between nanomaterial and sand grains is physical in the specimens with no cement. Due to their fine size and high specific surface area, Nanoparticles have covered the surface of sand grains and form an effective interlocking at the contact surface, by making a local concentration. In the nanomaterials with higher stiffness, fewer deflections occur and the soil stiffness increases more. In the compounds containing cement, the interaction of nanomaterial in the stabilized mixture is a physical-chemical reaction. Major activities are related to the changes in cement paste and hydration reaction. Pozzolanic nanomaterials can produce additional C-S-H by using $Ca(OH)_2$ which increases the paste stiffness. In addition, nanomaterial results in a reduction in porosity and an increase in paste stiffness, by being positioned in the nanopores existing in the cement paste and improving the particle packing. The results of oedometer tests have shown that nanomaterial type, pozzolanic ability, and particles stiffness are effective in increasing the stiffness of paste and subsequently the cemented sand.

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