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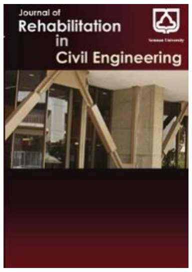

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Application of Nano Materials in Improving Geotechnical Properties of Soils: A Review Study

Foad Changizi [1,*]; **Abdolhosein Haddad** [2]

1. Department of Civil Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
2. Department of civil Engineering, Semnan University, Semnan, Iran
* Corresponding author: *st_f_changizi@azad.ac.ir*

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ABSTRACT

Today, with the application of nanomaterials in the various branches of science and engineering fields, some researches assessed how nanoparticles affected the geotechnical characteristics of soil. Based on the collection of information from the results of previous studies, the purpose of this review article is to introduce the nanomaterials used in the geotechnical engineering and their application in the problematic soils. In this paper, the modification of the engineering properties of the clay, the sand, the collapsible soil, the soil with liquefaction potential and the soil subjected to the freeze-thaw cycles by nano materials are evaluated. The results of previous researches have shown that the nano materials can increase the resistance properties of the problematic soils. The nano materials improve the soil behavior by two mechanisms such as filling the soil voids, which increases the soil density and improves the frictional resistance of the soil as well as the improvement in the soil particles bonds, which increase in the soil integrity. The results show that the addition of nano materials to clay can lead to an average increase in strength of more than 100% and in sandy soils less than 100%. Also, the optimum content of nanomaterials for decrease in the collapsible potential was approximately 0.1%.

1. Introduction

Currently, due to the expansion of construction activities, the use of the soils with the weak geotechnical properties is inevitable. Since the use of problematic soils in construction projects is associated with a lot of damage, the improvement of such soils should be a priority. In other words, the improve the soil with the goals of increasing bearing capacity, reducing compaction, and decreasing permeability. Among the various

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methods of the soil improvement, adding the additives materials to the soil is the most well-known method of soil modification. Among the additives, we can mention the polymeric materials like Persian gum [1,2], the chemical materials such as the cement and the lime, and the physical materials such as synthetic fibers, which have been used to improve soil behavior. The use of the natural and the synthetic fibers in the soil [3,4,5,6,7,8] the most widely are used in soil stabilization. Based on previous studies, the functional mechanisms of the fibers are similar to each other. Indeed, the fiber via absorption of the tensile stresses as well as increase in the frictional resistance leads to the improvement of strength properties of soil. Adding the additives materials like the cement and the lime to soil in order to the soil stabilization is a chemical methods. Depending on the type of the soil, the amount of cement required to achieve the maximum strength of soil is between 6% to 10% [9]. Also, the cement decreases the void ratio and the permeability of the soil [10]. On the other, the cement leads to increase in the water content, curing time, and compaction energy of the cement-treated soil [11–13]. The improvement of cement-treated soil was due to the hydration and the pozzolanic reaction [14–16]. Lime is one of the common additive materials in infrastructures such as roadways, railways and foundations [17–19]. The lime improves the soil resistance, but, decreases the ductility of the soil [20]. In general, additives such as fibers are used in order to improve the brittleness of the soil due to the cementitious additives.

In the nano materials industry, the structure and size of the grains are very small. The dimension particles of nano materials vary from 1 nano-meter to 100 nano-meters. The nano materials due to their small dimensions have unique properties and functions. Because nano-materials have a high surface area compared to their volume, a platform is provided for the high-level. In other words, the increase in the specific surface area of nano-materials can improve properties such as the shear and the compression resistances, the thermal resistance, the porosity reduction, the stiffness, etc [21,22]. These benefits lead to the reduction in the energy consumption and environmental effects, leading to reduction in the costs and increase in the safety of structures [23].

With the expansion of urbanization, the construction on the problematic soils is inevitable. Because using the conventional additions like the cement and the lime to improve the behavior of problematic soil presents concerns like the environmental pollution, it is essential to look into the new novel materials that will decrease these problems and enhance performance. With advances in nanotechnology and the application of nanomaterials in the geotechnical engineering, the soil stabilization with the nanomaterials has become possible as a physical-chemical method has attracted the attention of researchers [24,25]. Previous researchers have found that it is possible to increase the cementation reaction of soil by using nanomaterials with high specific surface area, and also by filling micro-voids of soil leads to increase in the soil density [26,27]. In general, depending on the soil only with nano materials or a combination of nano materials and additive materials is stabilized, the behavior of soil can be different. Table 1 describes some known nanomaterials in the soil improvement and also, the specifications of nano materials and their applications are listed in Table 1 and Table 2.

In this review paper, based on previous researches, the use of different nano materials to improve problematic soils is discussed. Indeed, the impact of the various nano-materials on the behaviour of the clay, the sand, the collapsible soil, the soil with the liquefaction potential and the soil subjected to freeze-thaw cycles are evaluated. The mechanism of action of nanomaterials in the problematic soils is different, which will be explained in the next section.

Table 1. Properties of nano materials used in the soil improvement.

	Nano materials									
Parameters	Silicon dioxide	Clay	Iron Oxide	zeolite	Alumina	Copper oxide	Carbon nanotubes	Calcium carbonate	Zinc oxide	Laponite
Formula	SiO_2	-	Cu	-	Al_2O_3	CuO	CNT	$CaCO_3$	ZnO	-
Particle density (g/cm^3)	2.4	5 - 7	5.24	2.3	3.6	6.4	2.1	1.4	5.6	2.57
Specific surface area (m^2/g)	170 - 200	500 - 750	40 - 60	200 - 220	≥15	20	600 – 700	30 - 60	50	370
Average particle size (nm)	20 - 30	1 - 2	20 - 40	50	80	40	10 - 15	15 - 80	<50	25
Color	White	Yellow	Red brown	White	White	Black	Black	White	White	White
Physical mechanism with soil	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Chemical mechanism with soil	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes

Table 2. Type of nano materials used for stabilization of problematic soils.

Type of problematic soils	Nano materials
Clay	Silicon dioxide; Clay; Iron Oxide; zeolite; Alumina; Copper oxide; Carbon nanotubes; Calcium carbonate; Zinc oxide; Laponite
Sand	Calcium carbonate; Clay; Carbon nanotubes; Silicon dioxide; Alumina; Magnesium Oxide
Collapsible soil	Silicon dioxide; Clay; Alumina; Copper oxide; Calcium carbonate; Nano lime
Soil with liquefaction potential	Clay; Laponite
Soil subjected to freeze-thaw cycles	Silicon dioxide; zeolite

2. Behavior of nano-stabilized clay

The problems in the geotechnical properties of soft clay have caused researchers to look for the improvement of clay with different nano materials. Taha and Taha [28] reported that the maximum dry unit weight of soil (γ_{max}) is not affected by the nano-clay and the nano-alumina. But, the nano-copper increases the maximum dry unit weight of soil. The reason was that the density of nano-copper particle was greater than that of the nano-alumina particle. Pusadkar et al., [29] improved the engineering characteristics of soil such as the liquid limit, the unconfined compressive strength (UCS), the compaction characteristics via the nano-copper, and the optimum amount of nano was estimated to be about 1.5%. Luo et al. [30] reported that the combination of the nano-aluminum (nano-Al_2O_3) and the soil leads to an increase in optimal moisture as well as reduces the PI values of the soil. In accordance with the research of Majeed et al. [31], the nano magnesium (MgO) decreases the optimum moisture contents of clay. Also, with adding 0.3% nano-MgO to clay, the UCS of the clay increases 4.5 times compared to untreated soil. Among the other advantages of nano-MgO, it can mention that the problem of swelling pressure in the clay soils, which can be a problem under the certain conditions, was solved with the help of the nano magnesium [32]. Although nano-clay increases the shear strength of the soil, it also raises the plastic and the liquid limit of the clay [33]. Pham and Nguyen [34] observed that nano silica (nano-SiO_2) seemed to have a favorable impact on the soil swelling index. Changizi and Haddad [35] studied the resistance properties of clay stabilized with that nano-SiO_2. One of the significant results of this research was that the nano-SiO_2 improves the unconfined compression of clay by viscous gel leads to contact between clay particles (Fig. 1) and the optimum amount of nano-SiO_2 was estimated to be around 0.7%. Rajabi et al. [36] stated during a research that it is possible to control the consolidation parameters of the clay with the nano-iron oxide. Their results indicated that the optimum amount of nano was 2%. According to the research of Khodaparast et al. [37], the unconfined compressive strength increases by adding the zinc oxide nanoparticles up to 1.5%, and adding a more the amount of nano- ZnO decrease the resistance of the soil. Al Sharef et al. [38] believed that the effect of carbon nanotubes on the strength properties of clay with low liquid limit is more than that of clay with high liquid limit. Also, in the optimum amount of carbon nanotubes, which is equivalent to 0.1%, the unconfined compressive strength can increase by 100% for the clay with low liquid limit. According to the research of Kannan et al. [39], the optimum dosage of 0.4% nano-calcium carbonate improved the UCS by 1.94 times.

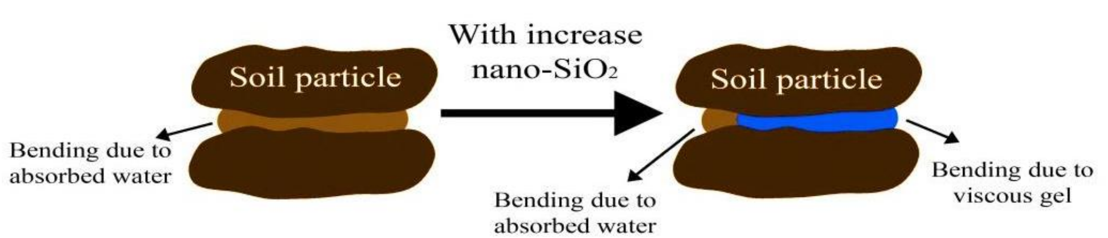

Fig. 1. Effect nano-SiO_2 on bonding between clay particles [35].

In many cases, the nano materials can be used with other additives. Indeed, due to the high specific surface of the nano materials and the ultra-fine particle size, the performance of other additives increases. Using the nano-SiO_2, Ghasabkolaei et al. [40] improved the functionality of clay treated with cement. According to their findings, the mixing clay with the cement enhances the unconfined compressive strength by 36% when 1.5% nano-SiO_2 is added. A similar outcome was also observed by Ghavami et al. [41]. According to Chen et al. [42], nano-$CaCO_3$ enhanced the cement soil's strength and the corrosion resistance. Kulanthaivel et al. [43] investigated in a lab how the mixture of white cement and the nano silica affected the geotechnical characteristics of the clay. Their findings showed that the clay mixed with 2% nano-SiO_2 and 3% white cement had an unconfined compressive strength (UCS) that was 185% higher than that of the soil mixed with 3% cement. Changizi and Haddad [44] examined the behavior of the samples modified with the nano-SiO_2 and the recycled polyester fiber. According to Fig. 2, the addition of nano-SiO_2 to the fiber-treated clay increases the UCS of the clay by 53%. In a laboratory study, Tomar et al. [45] acknowledged the positive effect of the synergy between the nano-SiO_2 and the polypropylene fiber. Changizi and Haddad [46] studied the shear strength of the clay treated with the nano-clay and the glass fiber. According to laboratory findings, in order to get the highest shear strength, 1% of nano-clay and 1% of fibers should be combined with each other, which under these conditions, the shear strength increases by 30% in comparison with the pure fiber. The change in the mechanical behavior of the soil treaded with the nano calcium carbonate - carpet waste fiber was evaluated by Janalizadeh Choobbasti et al. [47]. The research results showed the fact that increasing the amount of calcium carbonate content up to 0.8% increases the unconfined compressive strength by 57% more than that of pure fiber one.

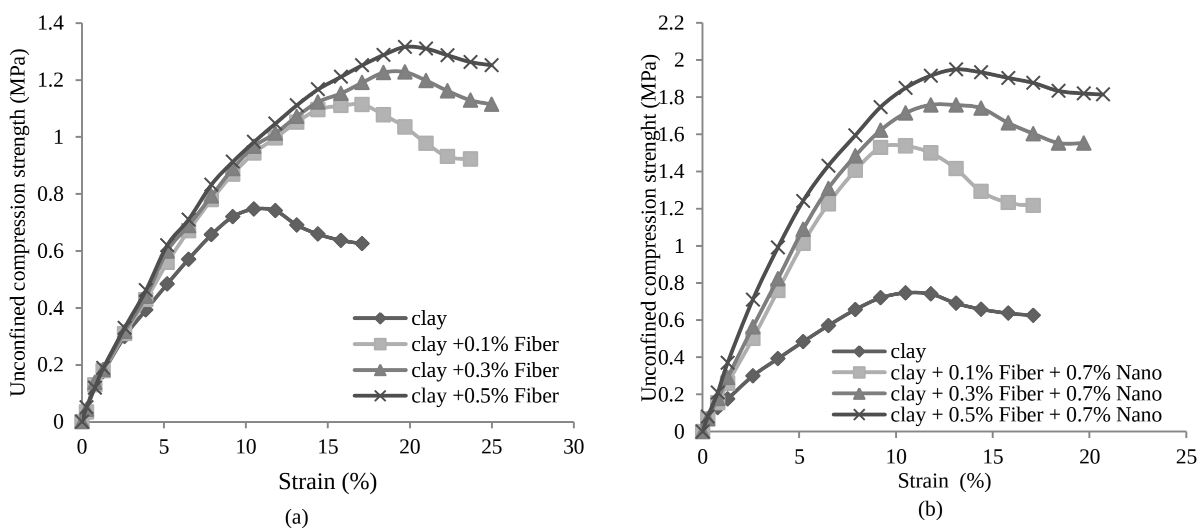

Fig. 2. Clay reinforced with fibers has increased unconfined compressive strength attributable to nano-SiO_2 [44].

3. Effect of nano materials on the sand

The strength parameters of sand stabilized with the nano-$CaCO_3$ was examined for by Mohammadi et al. [48]. The outcomes showed that the nano-$CaCO_3$ causes a decrease in the deformation and an increase in the soil stiffness. Also, it was determined that 0.7% of nano-$CaCO_3$ was the ideal level. The impact of the nano clay and the recycled polyester fiber on the shear behavior of the sand was evaluated by Kholghifard and Amini Behbahani [49]. Sand treated with 1% nano-clay and 1% recycled polyester fiber has the cohesion and the angle of internal friction that are 174% and 41% higher than the untreated sand (Fig. 3). According to the report of Zhao and Xu [50], although the carbon nanotubes decrease the friction angle of soil, but on the other hand, it increases the cohesion of sand. Valizadeh and Janalizadeh Choobbasti [51] reported that the optimal amount of the nano-graphene is 0.06% and the soil resistance can increase by 73% in this nano amount compared to the untreated sand. Ahmadi [52] studied the effect of the some nano materials like nano-SiO_2, nano-Al_2O_3, and nano-MgO on the confined stiffness factor of the sand stabilized with cement. Based on the obtained results (Fig. 4), it is evident that nano-MgO has the least impact on the soil's restricted stiffness while nano-Al_2O_3 has the most impact.

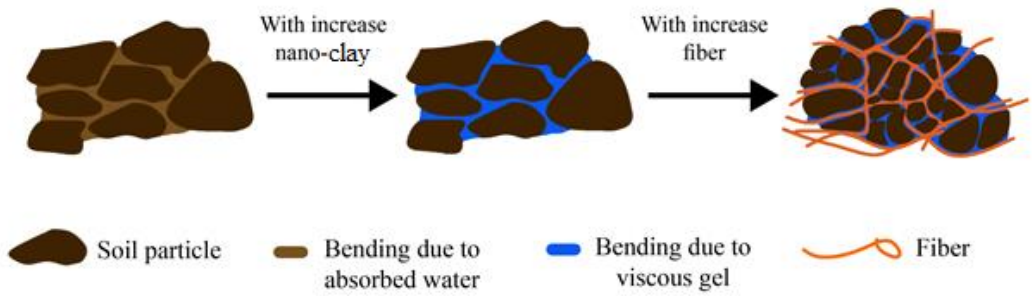

Fig. 3. Sketch drawing of interfacial mechanical behavior of soil reinforced and stabilized with nano-clay [44].

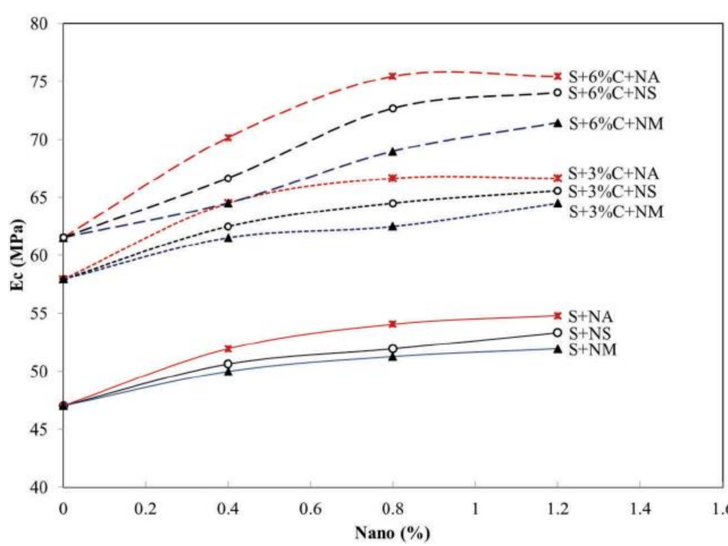

Fig. 4. Effect of nano-additives (NS = nano-SiO_2, NA = nano-Al_2O_3, NM = nano-MgO) on the confined stiffness of sand and cemented sand [52].

Based on the research of Babaei et al. [53], the shear characteristics of cement-stabilized sand improve as a result of adding the nano titanium dioxide. In fact, the nano titanium dioxide raises the C-S-H compounds, which causes a rise in the sand compaction. Another result of the research was that the maximum resistance of soil is obtained at 2% nano titanium dioxide. Babaei et al. [54] believed that the nano-ZnO increases the strength properties of cemented sand and also decreases the micro-cracks due to loading. Kulkarni and Mandal [55] used nano zinc oxide (ZnO) and cement as additives in order to improve the subbase soil of the road. Their report indicated that the combination of 1% nano zinc oxide and 6% cement can bring the best performance of the subbase soil. The effect of nano-clay on the permeability of silty sand was evaluated by Kamgar et al. [56] via the falling head tests. The findings demonstrated that 25% nano-clay significantly reduces the soil skeleton's porosity, leading to a remarkable reduction in the permeability of sand.

4. Effect of nano materials on the collapsible soil

The collapsible soil is an unsaturated soil that is the stiff under the normal conditions of loading, but when it is exposed to the moisture, it undergoes a significant reduction in the volume of the soil, leading to a lot of damage. Iranpour and haddad [57] improved the collapsible behavior of the soil by using the nano materials like the nano-clay, the nano copper, the nano alumina, and the nano-silica. The results showed that the optimum content of all mentioned nanomaterials is approximately 0.1%. Also, the nano clay has the greatest effect on reducing the collapsible potential and the nano copper has the least effect (Fig. 5). Haeri and Valishzadeh [58] reported a similar result that the optimum amount of nano-silica in order to reduce the collapsible potential is 0.1%. They also showed that by adding 0.2% of the nano-calcium carbonate to the collapsible soil, the collapsible potential decreases by 64%. Al-Murshedi et al. [59] believed that the nano silica fume can reduce the collapsible potential by 50%. Hosseini et al. [60] via the laboratory tests evaluated the collapsible potential of soil stabilized with nano-SiO_2 and the lime. They reported that the performance of nano-SiO_2 in decreasing the collapsible potential of soil is better than that of the lime. Kargar et al. [61] reported a similar result for the effect nano silica on the collapsible soil. Zimbardo et al. [62] used the nano-lime to increase in the strength of the bond between the soil particles to reduce the collapsible potential of soil. The change in the collapsible soil properties by adding the nano-clay was evaluated by Johari et al. [63]. The results indicated the fact that in order to reduce the collapsible index of soil from severe to slight, it is necessary to add 5% of nano-clay to the soil (Fig. 6a). Johari et al. [64] reported the positive effect of nano-SiO_2 on the behaviour of collapsible soil. They concluded that the nano-SiO_2 decreases the collapsible index of soil from severe to slight (Fig. 6b).

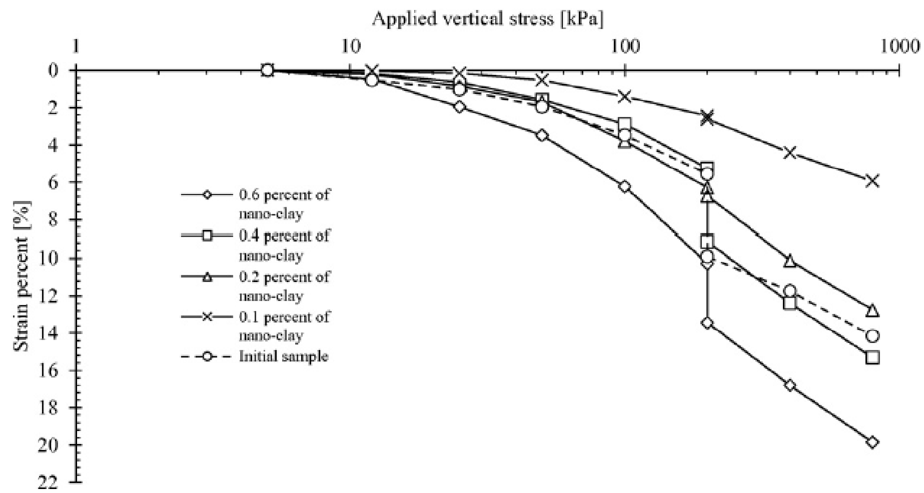

Fig. 5. The results of an experiment to determine the potential of sample collapse when mixed with nanoclay [57].

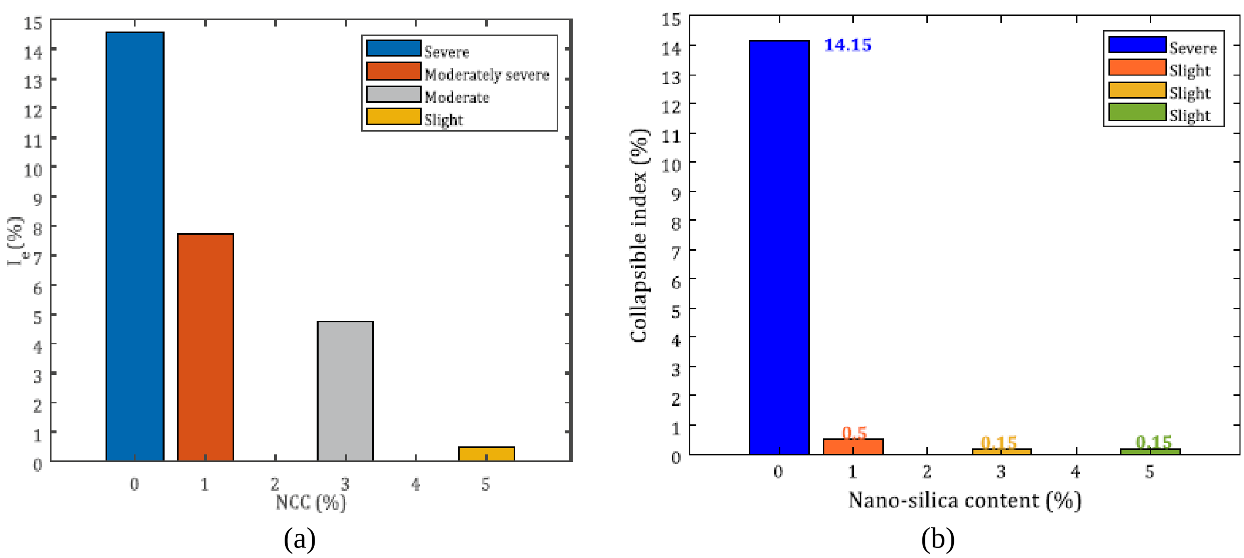

Fig. 6. The degree of collapse for samples that were rebuilt using a) nano-clay and b) nano-silica [63].

5. Effect of nano materials on the liquefaction

Among the risks of liquefaction, we can mention a significant reduction in the carrying capacity, increase in the settlement and the large movements. Using the technique of triaxial cyclic testing, Yazarloo et al. [65] investigated the impact of nano-kaolinite on the liquefaction resistance of sand. The claim was made that the liquefaction resistance of sand for the values less than 7% nano-kaolinite decreases and the positive effect of nano-kaolinite are observed in values higher than 7%. With adding 9% nano-kaolinite to soil, the number of cycle to the liquefaction increases about 65% (Fig. 7). But, the increase in the confining pressure decreases the positive effect of nano-kaolinite. Sandiani and Tanzadeh [66] with aim reduction in the liquefaction potential of sand adding the mixture of nano clay and glass fiber to the soil. They reported that with 0.5% glass fiber and 1% nano-clay can increases the liquefaction resistance. The number of cycle to the liquefaction depending on the cyclic stress ratio can increase from 100% to 490%. Cornejo [67] by using the nano laponite improved the liquefaction resistance of sand. The shape of laponite particles is usually disc shape, whose thickness and diameter are 1 nm and 25 nm, respectively (Fig. 8). Based on the results of the research (Fig. 9), the laponite can repair the sand skeleton with the low density and significantly increase the number of cycles required to reach 100% of the excess pore pressure. Huang et al. [68] studied the laponite particles on the liquefaction mitigation of the sand via the centrifuge tests. The results showed that the 3% laponite significantly reduces the soil settlement due to the seismic load. Also, due to the laponite's effect on the decrease in the permeability coefficient of sand, the amount of soil settlement under seismic load decreases in comparison with the natural sand. Based on the research done by Ochoa-Cornejo et al. [69], in a certain stress ratio, the laponite materials increase the number of cycles required to reach liquefaction.

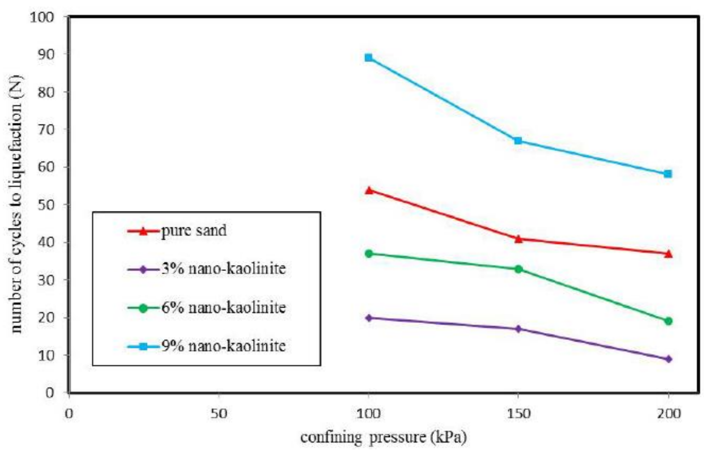

Fig. 7. The effect of nano-kaolinite on the liquefaction resistance of treated and untreated samples [65].

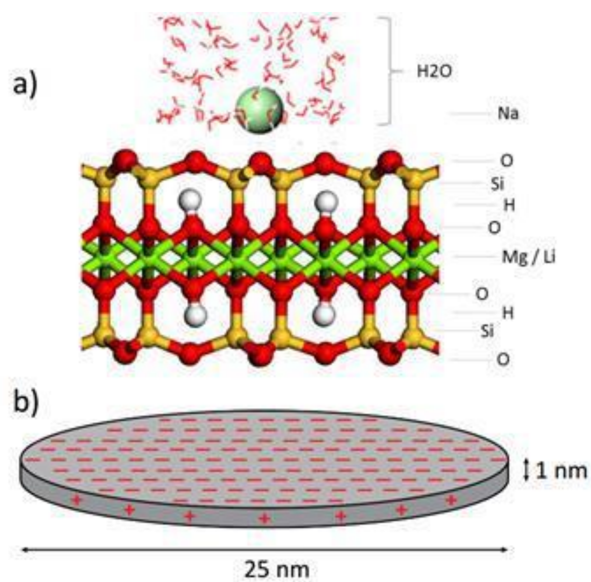

Fig. 8. Structure of laponite, and b) geometry of individual laponite particle [67].

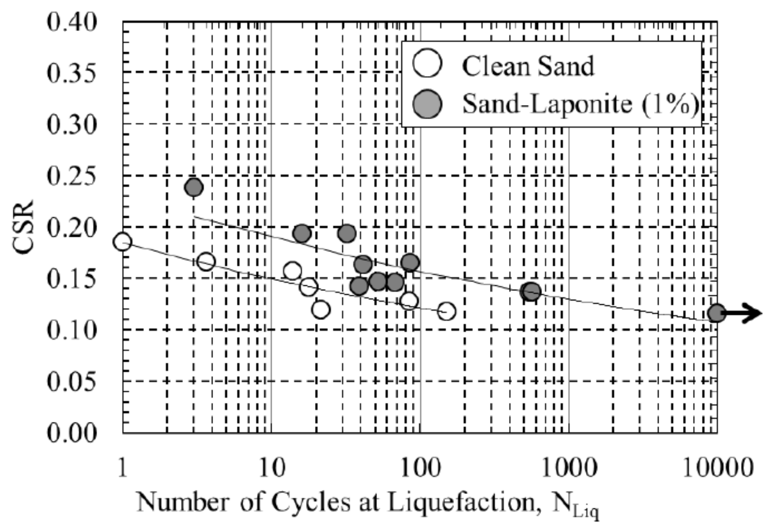

Fig. 9. Cyclic resistance of specimens made of clean sand and sand-laponite [67].

6. Effect of nano materials on the soil subjected to freeze-thaw cycles

Based on the previous research, the soil engineering properties can change under the effect of the freeze-thaw cycles. Further, the some researchers studied the effect additives materials such as the nano materials on the resistance properties of the soil subjected to the freeze-thaw cycles. Shahsavani et al. [70] assessed the strength properties of nano-SiO_2 stabilized clay under the freezing-thawing cycle condition. The results showed that the optimum content of nano-SiO_2 was 2%, and in this content of nano-SiO_2 after 9 cycles of freeze-thaw, the unconfined compressive strength of nano-SiO_2 stabilized clay was 50% more than that of untreated soil. Changizi et al. [71] assessment on the effects of additions such nano-SiO_2 to the soil exposed to the freezing and thawing cycles. According to the findings, even though more cycles cause reduction in the shear characteristics of clay, adding nano-SiO_2 up to 1% reduces the detrimental impact of thermal fluctuations on the shear strength of the improved soil. The loss in the cohesion after 12 freeze-thaw cycles is 18% for the soil treated with 1.0% nano-SiO_2, whereas it is 45.6% for the unimproved soil, according to Fig. 10.

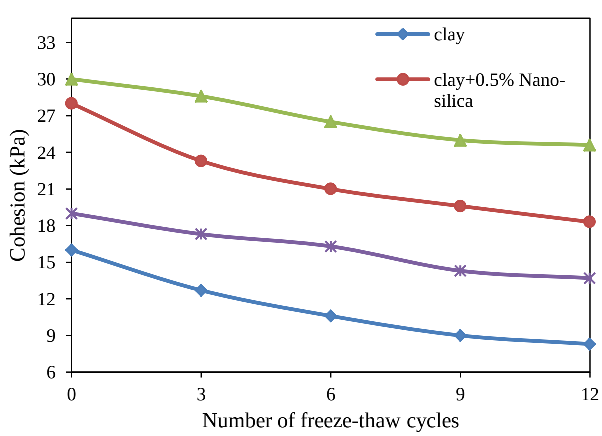

Fig. 10. Samples' cohesion changes as a result of various freeze-thaw cycles [71].

To lessen the detrimental impact of thermal cycles on the strength properties of clay, Ahmadi et al. [72] employed a blend of the nano-SiO_2 and the glass fibers. They demonstrated that the mixture of 2.5% glass fibers and 1% nano-SiO_2 results in the improvement in soil resistance properties. In fact, after 12 freeze-thaw cycles, this combination increases the soil's unconfined compressive strength by 93%. Another result of this research was that the internal friction angle of the soil can be increased more successfully by the glass fiber and nano-SiO_2 composite than through soil cohesion. Akbari et al. [73] were chosen the lime and the nano-zeolite as effective material in order to redaction in the negative effect of the freeze-thaw cycles on the soil. The results indicated the fact that after 7th cycle of wet-dry, The UCS of soil that has been stabilized with lime is increased by around 143% when nano-zeolite is added. In fact, the presence of nano-zeolite would enhance pozzolanic and cation exchange processes.

7. SEM imaging of nano materials

In the investigation of nano mechanisms in the soil, the scanning electron microscopy (SEM) and the field emission scanning electron microscopy (FESEM) pictures are frequently used. Instead of employing the more traditional tungsten hairpin or LaB6 filaments, the high-resolution field emission scanning electron microscopy (FESEM) is accomplished using a field emission gun (FEG). In ideal circumstances, a resolution of 0.5 nm has been attained, and conducting materials routinely enable 5 nm resolutions at 30 kV. SEM pictures of soil that has been combined with nanomaterials are frequently used to evaluate the mechanism of nanomaterials. Fig. 11 illustrates how the soil's structure changed as a result of interacting with the nano-SiO_2. Based on the mechanism described by Changizi and Haddad [74], the double layer water between soil particles is what gives clay particles their cohesiveness (Fig. 8a). When you add nano silica to the soil, the nano materials absorb the double layer water and produce a viscous gel (Fig. 11b), which connects the soil particles to one another. Since the viscous gel in comparison with the double layer water has a stronger cohesion, the resistance property of nano-improved clay is better than that of the natural clay. Moreover, the viscous gel fills in the spaces between the soil particles, increasing the contact surface of the soil particles and, in result, the effective interfacial contact area and the interlocking forces between the clay particles.

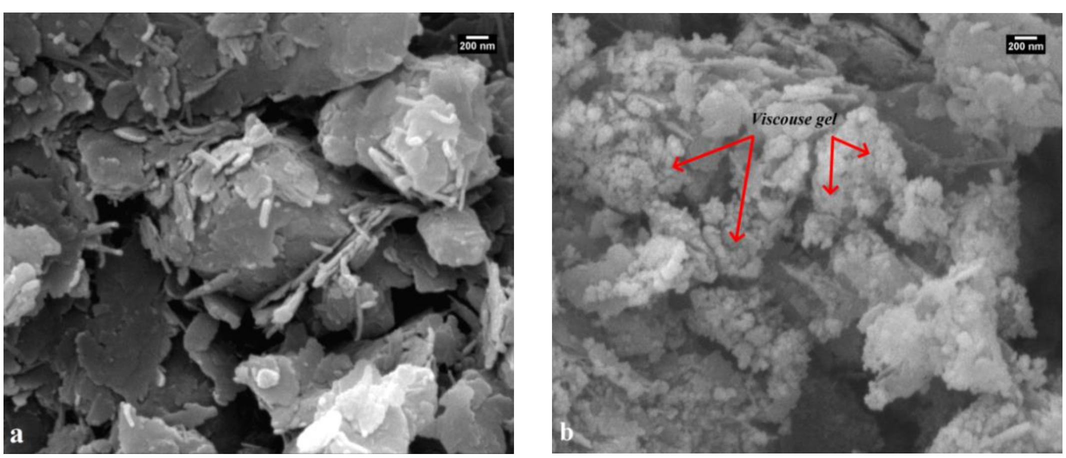

Fig. 11. Samples: (a) clay that hasn't been treated; (b) clay that has been stabilized with nano-SiO_2 [72].

Fig. 12 show the SEM image of soil stabilized with nano-iron oxide. As shown in Fig. 12, the number and volume of pores in the soil stabilized with 2% nano-iron oxide (Fig. 12b) are less than that of untreated soil (Fig. 12a). Indeed, by filling the soil cavities with nano particles, the continuity of the soil increases, leading to reduction in the porosity and improvement in the coefficients of compressibility and the shear parameters. It is worth noting that in high amounts of nano-iron oxide, for example, more than 2% (Fig. 12c), we see the accumulation of nano-materials in the form of clumps. This enhances soil porosity, which in causes the soil cohesion to increase and the soil friction angle to decrease [36]. The mechanism of mixture of the nano-zeolite or the nano zinc oxide with soil was similar to that of the nano-iron oxide. In other word, the nano-zeolite and the nano zinc oxide via decrease in the soil cavities leads to increase in the strength properties of soil. Also, adding the nano-zeolite or the nano zinc oxide to lime-stabilized soil by increasing the pozzolanic reactions, the system's compaction and the solid phase bonding are improved [37,73]. Ahmadi [52] believed that as the nano-Al_2O_3 fills the spaces between the soil particles, the soil's resistance to the volume change is increased. In other words, the stiffness of the soil increases significantly (Fig. 13).

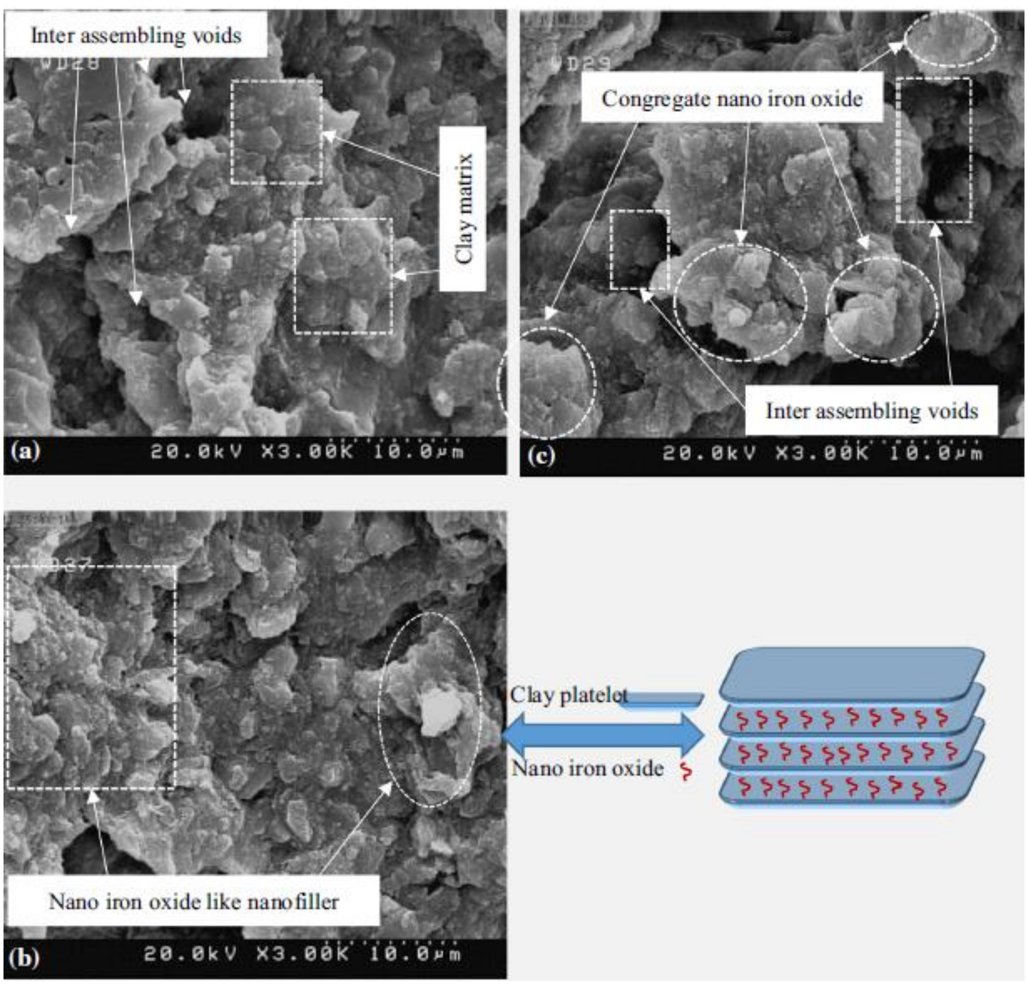

Fig. 12. SEM images for: (a) natural soil, (b) soil stabilized with 2% nano-iron oxide, (c) soil stabilized with 5% nano-iron oxide [36].

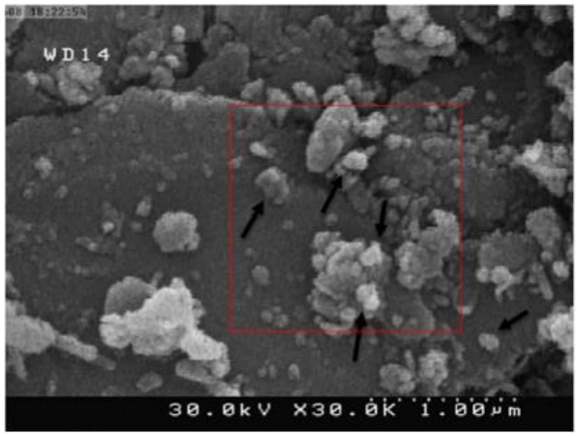

Fig. 13. Particle size distribution of nanomaterials in soil sample containing 0.4% nano-alumina [57].

The nano-clay via the bonding materials (Fig. 14) results in the soil structure strengthening. Nano copper fills the holes in the soil, increasing its density without causing any chemical reactions (Fig. 15). As seen in Fig. 16, the nano-ZnO has created a uniform surface for the soil. In fact, the void between the particles is filled by the nano-ZnO, and thus reduces the number of pores.

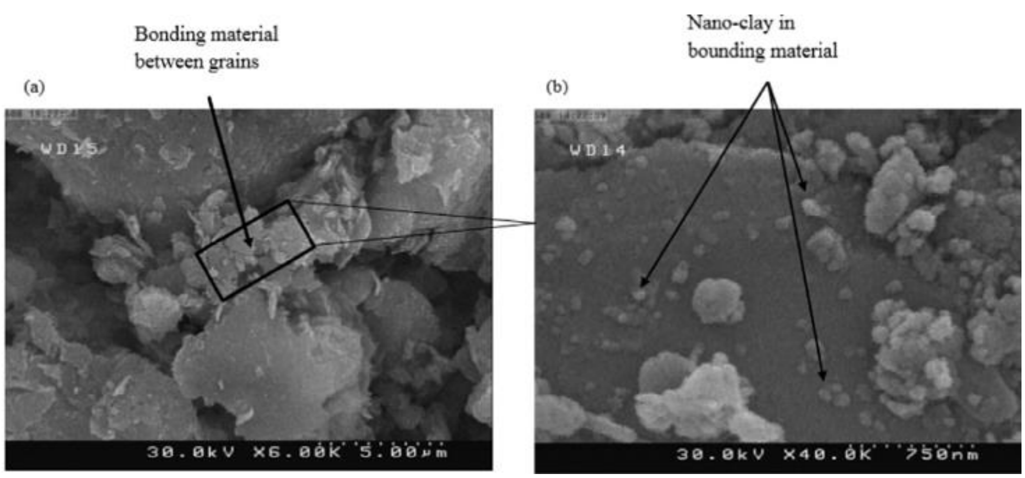

Fig. 14. Nanomaterials were found on the bonding substance in the soil that contained 0.6% nano-clay [57].

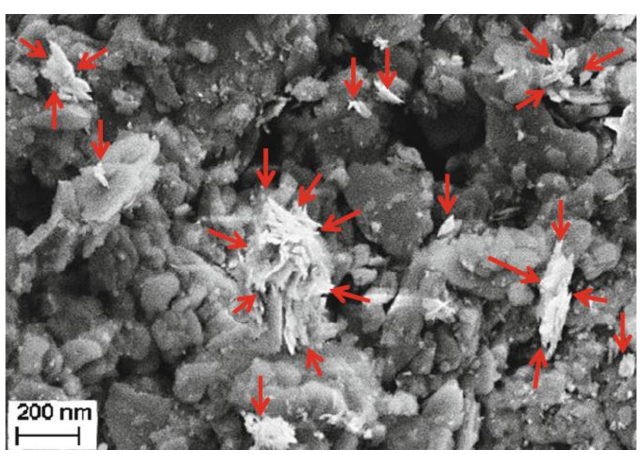

Fig. 15. Particle distribution of nanomaterials in soil containing 0.7% nano-copper [28].

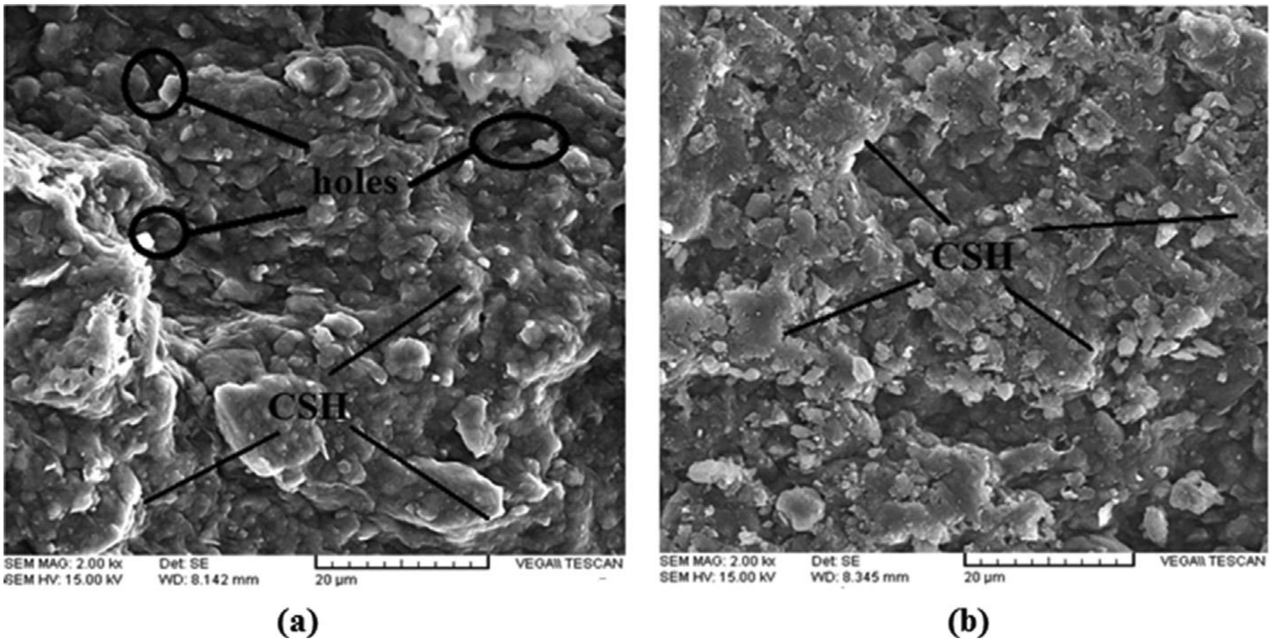

Fig. 16. SEM images of soil samples that had been lime-stabilized and included 1.5% nano-ZnO [37].

X-ray diffraction analysis is another technique for analyzing the soil stabilized with nanomaterials (XRD). In the materials science, XRD analysis is a method for identifying a material's crystallographic structure. In order to measure the intensities and the scattering angles of the X-rays that leave a material, XRD first bombards it with incident X-rays. The following are some benefits of the employing numerical analysis: Determine structural qualities, measure the thickness of thin films and multi-layers, the identify crystalline phases and orientation, and the determine atomic arrangement. In fact, the most important application of the XRD analysis for geotechnical engineers is to detect the possible chemical reactions of nano-materials in the soil. For example, Ghavami et al. [41] determined the changes in the soil stabilization properties of nano-SiO_2 and silica fume on cement kiln dust compared to untreated soil via of the XRD analysis (Fig. 17). A helpful method for the characterizing nanomaterials is the transmission electron microscopy (TEM). It is a quantitative technique for figuring out the distribution, the size, and form of the particles. The SEM and TEM are both the electronic spectroscopic imaging methods, although TEM has a better resolution. Better spatial resolution and the added capability of analytical measurements are TEM's advantages over SEM. This method has a few restrictions, including the need for a high vacuum, thin sample sections, and the time-consuming sample preparation. For sample information to be represented by a high-quality image, the sample preparation is crucial [75]. Indeed, the purpose of this analysis is to investigate the structure of nanomaterials.

The choice of the type of microscopic images for the analysis of the nano mechanism depends on the size of the nano particles, so that the FESEM images can be used for nano particles with large dimensions and the TEM images can be used for nano materials with very small particle dimensions. In general, the SEM images and XRD analysis have most useful in investigating the mechanism of nanomaterials in the behaviour of soil.

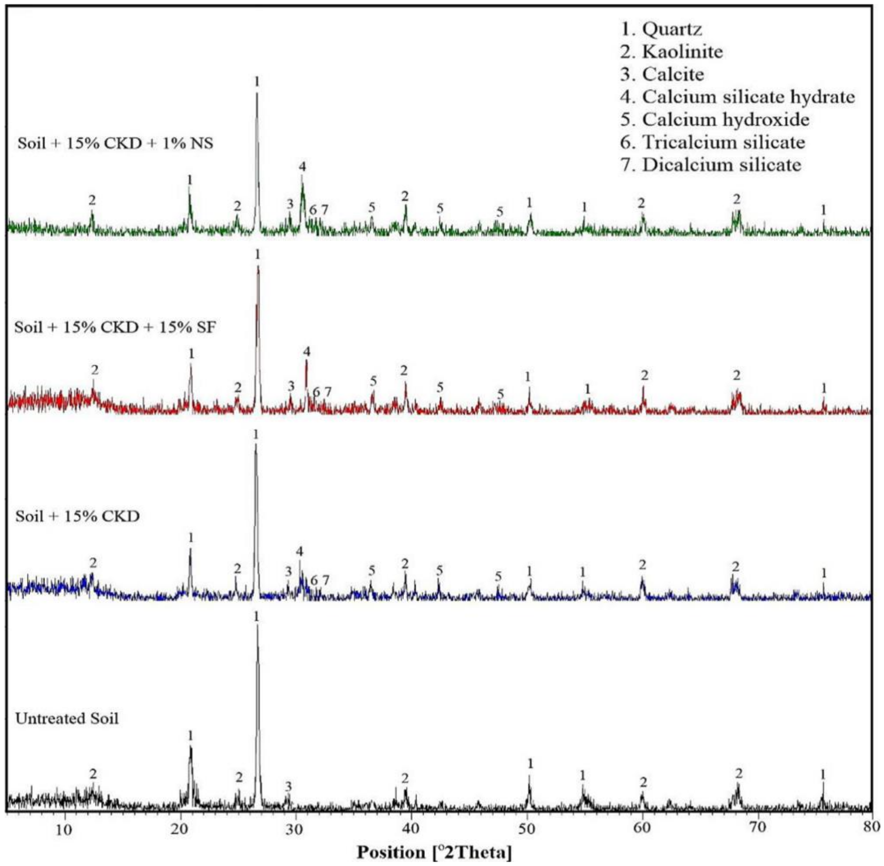

Fig. 17. Specimens' X-ray diffraction patterns: untreated soil; soil plus 15% CKD; soil plus 15% CKD plus 15% SF; soil plus 15% CKD plus 1% NS [41].

7. Conclusions

In this research, by reviewing previous studies, the impact of various nanomaterials on the geotechnical characteristics of the soil have been made. In general, the following results can be stated as the output of this research:

1- In general, nanomaterials improve soil behavior by two mechanisms: (1), filling the soil voids, which increases the soil density and improves the frictional resistance of the soil, (2), improvement in the soil particles bonds, which increase in the soil integrity.

2- A wide range of nano materials like nano-SiO_2, nano-Al_2O_3, nano-copper, nano clay and nano-MgO can be used to improve the resistance properties of clay. But the most widely used of them was the nano-silica, which suited to the soil conditions the optimum content of nano-SiO_2 was between 0.7% - 1.5% to improve the behavior of clay. It is necessary to mention that nano materials causes creation the brittle behavior in clay.

3- The results of previous research showed that the use of nano materials to improve the properties of sand requires the use of a much amount of the nano materials, which is not economical. For this reason, it is recommended to use nano materials together with other additives such as the cement or the lime to stabilize the sand.

4- In order to increase in the soil liquefaction resistance, it is recommended to use nano materials that reduces the soil pores and increases the cohesion of soil; the nano materials such as nano clay and nano laponite. Indeed, with increase in the cohesion of soil increases significantly the number of cycles required to start liquefaction.

5- In the conditions of freezing and thawing cycle, since the bonds between the soils particles are subjected to thermal stress, the use of nano-silica or the combination of nano-silica and the cement and the lime is recommended. Indeed, with the increase in the cementation of bonds between the soil particles, the strength of the soil skeleton is improved.

Although the use of nano materials in the soil improvement has advantages, but, the use of that is accompanied by challenges. For example, the method of mixing nanoparticles with soil in the high volumes of soil should be investigated. It seems that one of the main challenges in the use of nano materials in soil improvement is to use the proper mixing method in making a homogeneous mixture in workshop conditions and as well as and providing the suitable conditions for mixture curing. Also, the use of some nano materials like the nano-copper and the nano-alumina has no economic justification. Therefore, it is recommended that issues such as how to mix the nano materials and the soil as well as economic justification should be considered in the future research.

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Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Writing – original draft; Writing – review & editing were done by Foad Changizi and Abdolhosein Haddad.

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