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Evaluating the impact of nanomaterials on soil strength parameters

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Abstract

This study investigates the impact of nanomaterials on soil strength parameters. This project is carried out according to laboratory tests to determine the impact of nano-silica on the compressive strength and plasticity properties of soil. This project covers the operation of injecting nano-silica into the remoulded soil of Yazd University region, and performing the CPT test as the executive studies in addition to the analysis of nanoparticles by SEM (scanning electron microscope) and AFM (atomic force microscope) images of soil samples. These tests are done for two methods with and without nanomaterials, and then the results are compared. According to the results, nano-silica increases the Plastic Limit (PL) slightly and Liquid Limit (LL) considerably; hence, the addition of nano-silica will increase the Plasticity Index (PI) of soil. Following the increase in nano-silica, the soil compressive strength is also increased; the more the curing time increases, the more the compressive strength will be enhanced. The average rate of increase in compressive strength with time will be increased by increasing the percentage of nano-silica. Based on the results of field and laboratory tests for the injection of nanomaterials and according to silica cementation between soil particles, the nano-silica injection has resulted in the increased CPT strength of soil; hence it is offered as a suitable solution.

Keywords: Nano-silica, injection, SEM and AFM analyses, strength parameters
2020 MSC: 82D80, 97M50

1 Introduction

Understanding the nature of materials and their structures has always been significantly important. The materials play the main roles in the manufacture of human equipment and fulfilment of his needs as natural gifts. In proportion to the progress in recent years, science has been able to have a correct view of material and its ability, so it is now possible to build and establish newer models of molecules by examining the atomic and subatomic aspects of materials and elements. Nanotechnology is a new technology which has been developed around the world, and more precisely, “Nanotechnology is not a part of future, but it is the whole future” [6].

Nanotechnology is the ability to produce materials, tools and new systems by taking molecular and atomic control and utilizing the properties in which the scale appears. The main objective of the majority of nanotechnology studies is to form new compounds or create changes in the existing materials. The expansion of nanoscience and technology has led to the definition of vast applications in various scientific and industrial fields. Geotechnics and soil amendment are among these fields [3]. Meanwhile, soil behaviour modification with the help of additives has been one of the most

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effective methods in the improvement of soil behaviour parameters by researchers in geotechnical engineering. In this regard, nanomaterials which have unique properties and are used in other branches of engineering sciences have led to fundamental changes, and have been less into account in geotechnical engineering. Nanotechnology has created a new movement in material production systems. While the materials become very small, they will have significant new properties, but these properties are invisible at the micro-molecular or larger scales [15].

Mohr-Coulomb failure envelope is defined by two parameters: friction and adhesion. Normally, the intact soils containing the nanoparticles except for Smectite and Halosite have high adhesion and friction angle because of the bond created between nanoparticles and other soil matrix particles which substantially leads to larger and more powerful masses. Smectite has low direct contact with particles due to the formation of an electric double thick layer on the surface, and thus it has a lower friction angle than the other clays. Halosite has a significant impact on under-pressure soil failure due to the low bulk density and weak bonding between layers. In other words, the fiber nanoparticles improve the shear strength due to being woven such as the reinforced fibers. The combination of weaving effect and adsorption considerably increases the shear strength. There are numerous conducted studies on the use of fine materials for increasing soil strength parameters. However, nano-materials have been taken into account in geotechnical engineering in two recent decades. Yonekura and Miwa [14] used silica nanoparticles in order to increase the compressive strength of grout [14]. Noll et al [10] investigated silica nanoparticles in order to increase the soil resistance against the flow, fixation and permeability [10]. Furthermore, Butrón et al [2] performed the Odeometer, triaxial and pressure tests to investigate the effect of silica nanoparticles with the size range of 5 to 100 nm, and found that the soil strength was increased over time so that the soil containing the nanoparticles would become elastic at the early stages and then elastoplastic [2].

2 Different types of research tests

Chemical PH and XRF tests are performed on the studied soil since some of the chemical properties affect the type of stabilizer. Furthermore, the tests including the gradation, determination of plastic and liquid limits and unlimited compressive strength are done on the soil samples of Yazd University to find the type of soil and its physical and mechanical properties. The results of performed tests on the natural soil samples are as follows:

Fine-grained soil is selected from the remoulded soil of the Yazd University region (this type of soil is selected for performing the in situ test and injection in that area). The PH of this soil is equal to 7.5. Results of XRF soil are presented in Table 1.

Table 1: XRF analysis of soil sample

Compounds	Amount (%)
SiO_2 (silicon dioxide)	49.71
Al_2O_3 (aluminum oxide)	14.1
$L.O.l$	12.5
CaO (calcium oxide)	9.18
MgO (magnesium oxide)	4.13
Fe_2O_3 (iron III oxide - Hematite)	5.14
K_2O (potassium oxide)	2.94
Na_2O (sodium oxide)	1.18
MnO (manganese oxide)	0.096
SO_3 (sulfur trioxide)	1.024
Cu (copper)	
P_2O_5 (phosphorus oxide (V))	
TiO_2 (titanium dioxide)	
total	100

2.1 Test on the effect of nano-silica on plastic properties of soil

The soil of Yazd University region is used with gradation according to Table 2. This section evaluates the effect of adding nano-silica to clay through an unlimited compressive strength test (uniaxial). The results of tests and studies indicate the significant impact of nano silica on the resistance of clay which will be cost-effective in construction projects due to its low applied percentage. If the colloidal silica solutions are diluted to 5 weight percent, they will have a density and viscosity similar to water. This solution has 20 weight percent of silica and viscosity of 55, and PH 10; and the average particle size is 7 nm. Colloidal silica nanoparticles are created when H4SiO4 molecules react

Table 2: Soil gradation of region

Standard sieve number (BS)	Remaining weight on the sieve (Gr)	Percentage of soil remaining on the sieve	Percentage of passing soil from each sieve
#4	0	0%	100%
#8	59	3.97%	96.03%
#16	182	12.24%	83.79%
#30	314	21.12%	62.67%
#50	297	19.97%	42.7%
#100	359	24.14%	18.56%
#200	192	12.91%	5.65%
Under sieve	84	5.65%	0%
Total	1487	100%	-

with other molecules and build Siloxane chains (si-o-si). According to Iler [5], the surface of particles contains non-combined Silanol (SioH) groups. The inter-particle siloxane is created when the particles react with each other (Figure 1b). When the size of particles is sufficiently increased, their further growth can be prevented and the solution can be consolidated by an increase of PH. PH increase will ionize particles and thus they repel each other. The gelation time can be controlled and delayed by reducing the repulsive forces and this leads to clotted and coarse colloidal particles and eventually creation of a solid gel. The gelation rate is determined according to the rate of particle reaction with each other. The alkaline solutions like sodium hydroxide are used to stabilize and prevent the gelation of colloidal silica solution [5].

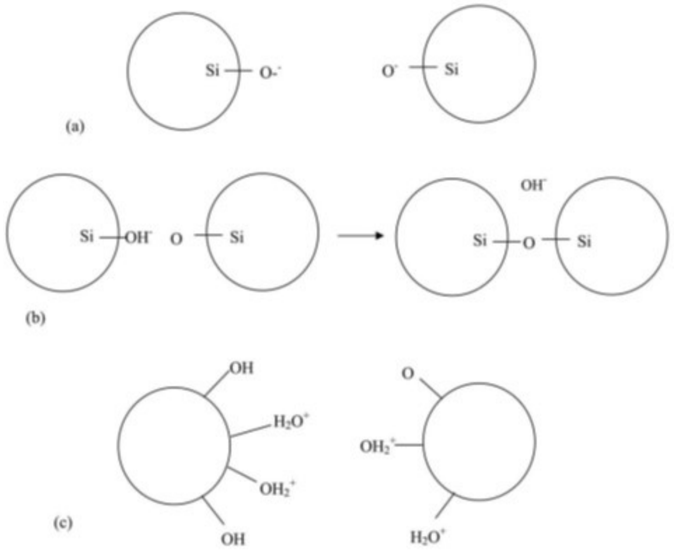


Figure 1: Behavior of colloidal silica particles in various rates of pH

A repulsive force is created between particles due to the $pH \geq 8$ of $-O$ on the surface. $8 > pH > 5$ for $-O$ on the surface of a particle will form the $Si - O - Si$ bond with H on the surface of another particle. $pH \leq 5$ of particles are neutral or repel each other [5]. Alkaline reactions with particle surfaces will create a negative charge in them, and thus the particles repel each other; this process is shown in Figure 1a. Hydroxide ions are added to alkaline solution and this operation strengthens the gelation process, but the colloidal silica has slow performance in high pH due to the high charge of particles. At low levels of PH, the charge of particles is reduced based on the concentration of hydroxyl ions in the solution. Therefore, the particles can also react with each other and form the Siloxane chains as shown in Figure 1b. According to Iler's results, the shortest gelation time occurs in PH of 5 to 6 [5], while the hydroxyl ions disappear and the particles become uncharged in PH of less than 5 (as shown in figure 1c). Therefore, the speed of forming the siloxane chains is reduced, and similarly the gelation period will be increased.

The sample gelation time diagrams for 5 weight percentages of solution in ionic strength and different PH values are shown in Figure 4. Generally, if the viscosity of colloidal silica is less than 100, it will penetrate into the loose sand under the injection with low head and extraction wells. The solid gel is formed if the viscosity is increased. Gelation time is measured from the end of the mixture operation to the formation of this gel. The duration from the formation of this solid gel to the time of the strength test is called the caring time. It is expected that the colloidal silica will be stable below the ground surface. According to Whang's estimation, the lifespan of colloidal silica is more than 25 years, while the lifespan of sodium silicate and Acrylate slurry is estimated from 10 to 20 years [13].

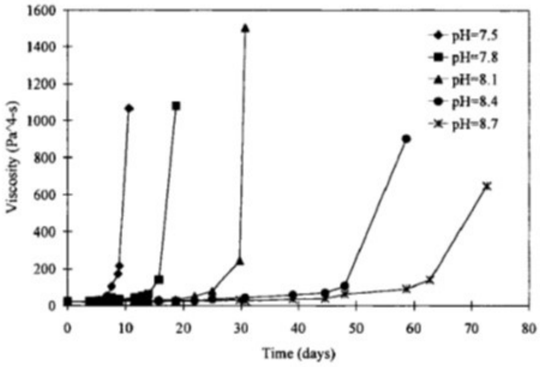


Figure 2: Diagrams of Colloidal silica gelation time

2.2 Soil injection test

In terms of engineering, all kinds of soils, in which the construction of structure is not safe and are under the impact of weather conditions, are basically called problematic soils. The problematic soils have different kinds including expansive, water absorbent, collapsible, and loose soils, etc; and our review is limited to remoulded soils. The existence of remolded soils is a fundamental problem in numerous regions of Yazd and this has led to the subsidence of buildings in most of the areas. Therefore, we started the field visit to find the perfect place, and finally, this visit ended with the selection of 5 separate regions where their names were sent in a letter to the Department of Construction at Yazd University to get the final licence. In response to this letter, the Department of Construction at Yazd University granted the licence for a field test in a region with remoulded soil. As there is the liquefaction problem only in a few areas of Yazd City, we changed the topic of problematic soils from liquefaction to remolded soils because the existence of remoulde soils was a fundamental problem in most of the regions in Yazd City and it had led to the subsidence of buildings in many areas. The target nano-materials should be injected into the soil in order to consolidate the soil. The injection of materials is divided into two types in terms of operation:

- Experimental
- Executive

2.2.1 Experimental injection

The experimental injection is an injection which is performed before the executive injection. This injection in fact leads to data for executive injection. To perform the experimental injection, the slurry was made and injected in different percentages. At this stage, we studied the infiltration rate of materials into the soil. According to the results of this study, the injection could not be done by gravity method in this type of soil, and thus we needed to apply the injection pump. Then we created a hole in the container and put it under the pressure of 3 bars. The operation of this operation indicated the adequacy of the pressure of 3 atmospheres for the type of soil.

2.2.2 Executive injection

Executive injection: It refers to the execution of an injection operation. For instance, we did a test at the beginning of place, and thus we designed a drill with a length of 1m and diameter of 10cm with holes which had diameters of 8mm, and then dipped this drill in a region of university with remoulded soil by the help of hammer; and finally, we filled it with water for observing the injection.

The implementation of this sample revealed the important issues such as the position of pipes in the ground or boring because it was hard to enter a one-meter pipe into the ground by a hammer blow. After boring and placing pipes, we should provide two types of packing: 1- the inside pipe packing, and 2- the outside packing. A type of fastener was used for providing the inside packing; and the outside packing was done by cement. The map of 10 implemented boreholes is presented as follows.

Figure 3: Sample injection in the beginning of region

Figure 4: Implemented boreholes

C1 and C2 and C3 boreholes were injected with cement grout and A2 and A3 and B2 and B3 boreholes with nano materials. The hand pump was used for injection.

2.3 Cone Penetration Test (CPT)

The CPT is performed by Mahan Zamin consulting engineering company in accordance with German standards with a tool shown in the figure below. The following results are obtained within 30 cm according to the sketch (5-7) by calculation and consideration of necessary correction.

Figure 5: Tool for land strength testing

The results of CPT indicate an increase of more than double strength by injecting the nano materials. The time consumption also has a significant impact on the process of strength increase.

3 Research results

3.1 Results of studies impact of nano-silica on the compressive strength of soil

Nanoparticles of silica are used in powder with an average size of 15 nm as shown in Figure 1. The amounts of 0.5, 1, 1.5, 2 and 3 weight percentages of nano-silica are added to soil passing through the 40-mesh sieve in order to prepare the sample. The mixture should be continued until homogeneous samples, and this needs the time of about 45 minutes. Afterwards, the plastic and liquid limit tests are done according to ASTM, D-4318 standard. The plastic limit test is done based on the 3-mm thread method, and the liquid limit is performed by Casgrande's tool.

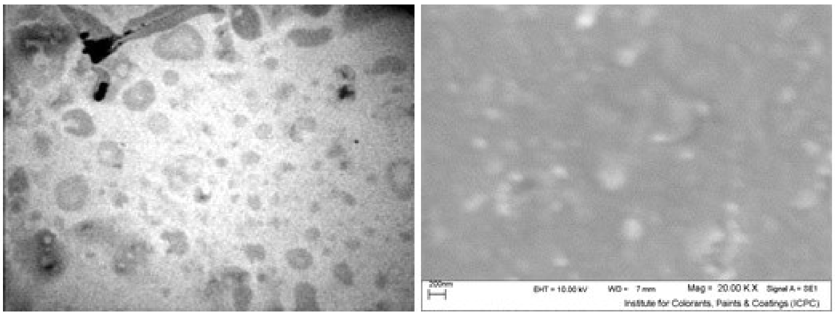


Figure 6: SEM image of nanoparticles (left), and TEM image of nanoparticles (right)

SEM and TEM images show the silica nanoparticles and their dimensions. However, the TEM image quality is much better than the SEM image. According to the results, nano-silica leads to a slight increase in the plastic limit (PL), but a significant increase in Liquid Limit (LL); hence, the addition of nano-silica will increase the Plasticity Index (PI).

Table 3: Atterberg smoke of soil by addition of nano-silica

Nano-silica percentage	**PL (%)**	**LL (%)**	**PI (%)**
0	19.1	31	11.9
0.5	19.3	34	14.7
1	19.5	37	17.5
1.5	20.02	39.3	19.28
2	20	40.2	20.2
3	21.8	41.9	20.1

Therefore, nano-silica can be a perfect candidate to improve the soils which need higher plastic properties. The clay core of earth dams is among these cases when the access to appropriate credit sources needs consumption of much time and cost.

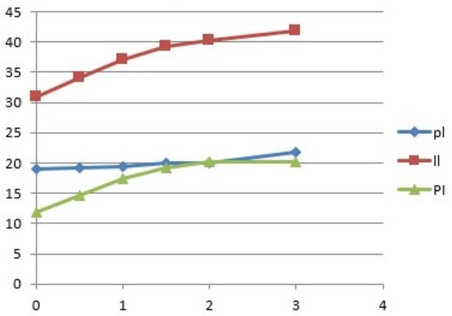


Figure 7: Changes in Atterberg's limit of soil by addition of nano-silica

3.2 Results of consumed nano-silica in compressive strength of soil

According to the results of uniaxial compressive strength under a variety of curing times with different percentages of nano-silica in Table 4 and based on the provided diagrams, the compressive strength of samples has been significantly increased until an increase of 3% in nano-silica after 28 days. This increase is caused by reactions between nano-silica and clay and the particles' binding and silica gel setting.

Table 4: Results of compressive strength test (kg/cm2)

Sample	Strength in 7 days	Strength in 14 days	Strength in 28 days
C_0	5.3	5.9	6
Cn0/5	8.1	13.7	19.2
Cn1	10.8	17.4	22.96
Cn1/5	11.5	31	38.5
Cn2	12.4	33.2	41.7
Cn3	14.9	26.9	47.23

In Table 4, C0 refers to the typical sample with zero percent of nano-silica, and similarly, the Cn0 /5, Cn1, Cn1/5, Cn2 and Cn3 samples have 0.5%, 1%, 1.5%, 2% and 3% of nano-silica respectively. In the C0 sample, it is expected that there is not any difference between the 7-day, 14-day and 28-day strength, but Table 4 indicates a small percentage of the difference between these values, and this phenomenon can be explained by the following reasons:

- A small percentage of organic matter in the soil may cause changes in the strength over time.
- The test error test and not-calibrated device.

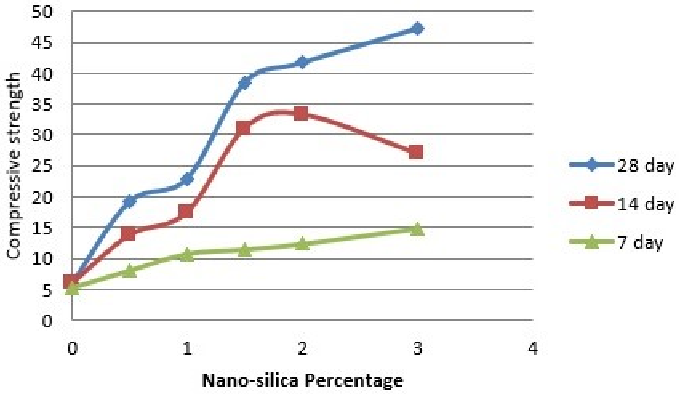


Figure 8: Diagram of changes in compressive strength by increasing the nanoparticles

Figure 5 shows the increase in unlimited compressive strength by increasing the percentage of nano-materials. The curing time is among the main factors in increasing the strength of samples, and it completes the Pozzolanic reaction and chemical interactions between nano-silica and clay. Figure 6 shows the diagrams (A) to (F) for the effect of curing time on the uniaxial compressive strength. According to the diagrams, the more the curing time is increased, the more the compressive strength is enhanced. The average rate of increase in compressive strength with time is enhanced by an increase in the percentage of nano-silica.

Figure 9 from A to F are respectively the diagrams of compression strength changes with time for samples with 0 percent, 5.0 percent, 1 percent, 1.5 percent, 2 percent, and 3 percent of nano-silica.

3.3 Study on the microscopic structure of improved soil by nano-materials

Natural soil structure is tested by numerous researchers [4, 8, 9]. However, the natural soil structure is often caused by deposition of solution in contact with internal particles, the lack of electric charge, and Van der Waals force in order not to be applicable compared to hydration and Pozzolanic reactions, and thus perhaps for improved soil by additives.

The tools and equipment play key roles at the nano-scale because the work on nanotechnology will be certainly impossible without tools. In the past, most of the researchers even did not know that their research was on nanotechnology due to the lack of technology and measurement and analysis tools. As described above, the base elements have different characteristics each of which needs exact tools for determination. In this regard, the applied analyses include microscopic analysis, structural analysis, elemental analysis, bonding analysis, characterization, surfaces, and so on. Microscopic analysis has received greater attention. The SEM and AFM are used to investigate the fine soil particles.

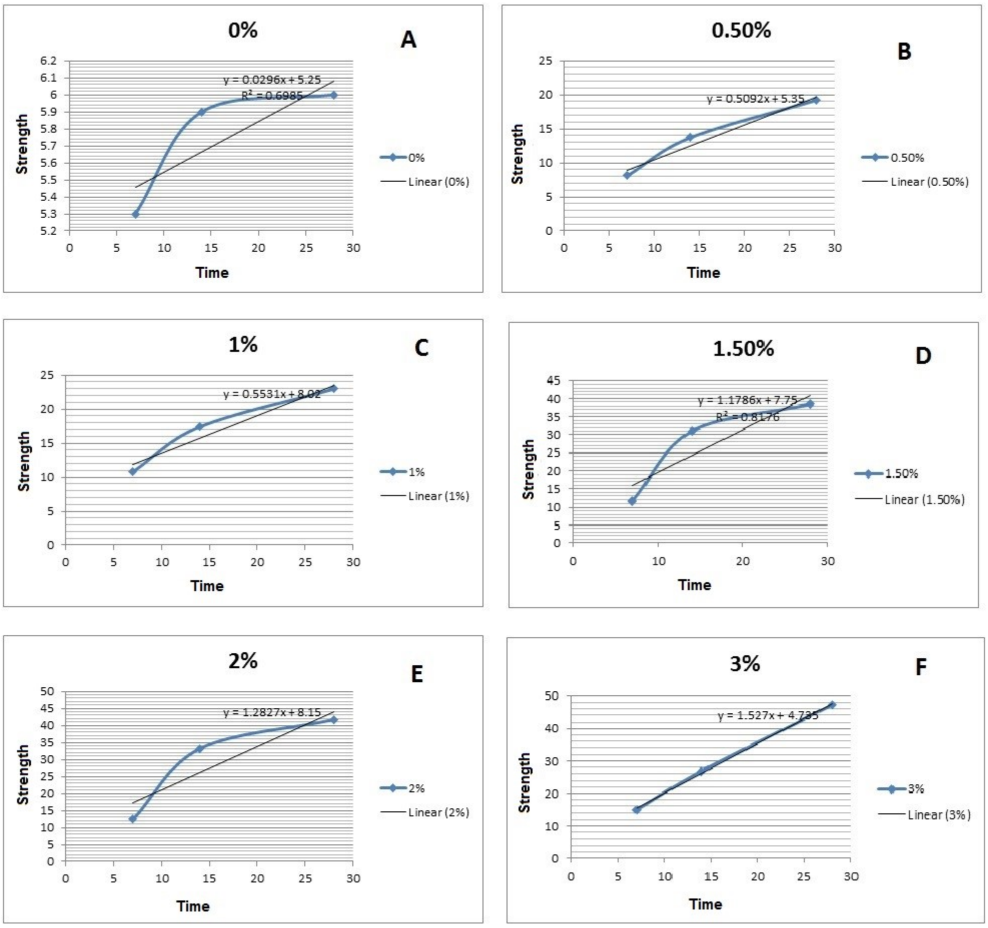


Figure 9: Diagrams of compressive strength changes with time

3.4 Analysis of scanning electron microscope (SEM)

For preparing the sample for SEM imaging, first, we should separate water from the sample because water is vaporized in the vacuum. All metals are conductive, so there is no need to prepare them for imaging by SEM. Materials, which are not among the metals, should be covered by a thin conductive layer. This is done by a tool called the cover and through the electric field and argon. Therefore, the sample is placed in a chamber of vacuum; and the electron is separated from argon due to the presence of argon and magnetic field, and thus the atoms will gain the positive charges. The argon ions are absorbed by gold foil with a negative charge. The argon ions collided with gold atoms of gold foil surface. These gold atoms are put on the surface of the sample and create a conductive gold coating on the surface of the sample.

3.4.1 SEM images of soil samples

The following images are prepared from soil samples of the studied region by SEM machine of Razi Research Institute.

SEM images show the nano-sheet structure of sand. These are the nano-sheets with a thickness of about 10 nm. The A, B, C and D images are respectively taken from samples with 0, 1, 2, and 3% of nano-silica. Sample D shows higher density than the other samples, and this can be due to the adhesion of silica nanomaterials.

3.4.2 Soil analysis by atomic force microscope (AFM)

Sub-nanometer resolution of atomic force microscope has created a new path for study on the appearance of particles, and it has been recently proven by researchers in investigating the mineral particles [1, 7, 11]. Mahar Fan

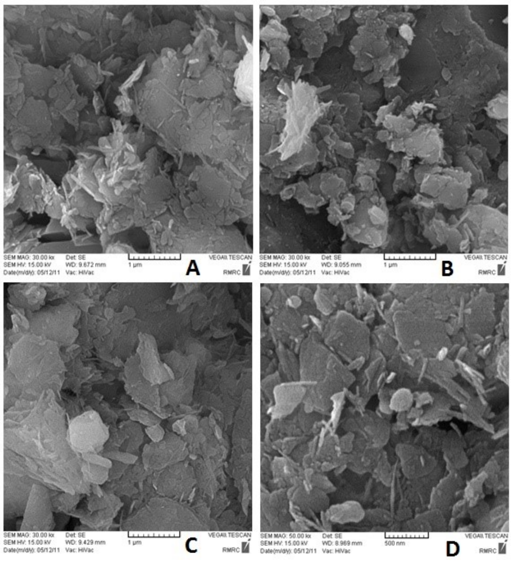


Figure 10: SEM images taken from soil samples with different percentages of nano-silica

Abzar Company tool is used for AFM analysis. AFM images of samples by adding nano silica are shown in Figures 11 to 14. The AFM images are analyzed by SPM software.

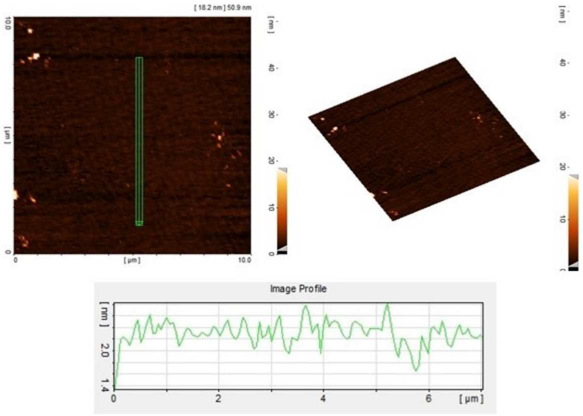


Figure 11: AFM image of a typical soil sample without nano-silica

3.4.3 Surface parameters obtained from SPM Software

S_a is the average roughness which is calculated according to the following equation:
$S_a = \int\int_a |Z(x,y)|\, dxdy$
S_{ds} is the density of summits [12].
$S_{ds} = \frac{\text{Number of summits}-\text{intersection}-\text{Number of summits}}{\text{Area}}$

According to the results, samples with 0% and 0.5% have the minimum number of summits. This result can be seen according to the AFM image.

3.4.4 S_{sk} (Skewness of assessed profile)

Asymmetric distribution function of range measures the ADF around the reference line. The distribution function of range is the density function of sample probability for $Z(x)$ during evaluation [12].

A porous surface has a high S_{sk}. $S_{sk} < 0$ is suitable for wear applications.

According to the diagram, the porosity is reduced by increasing the nono-particles.

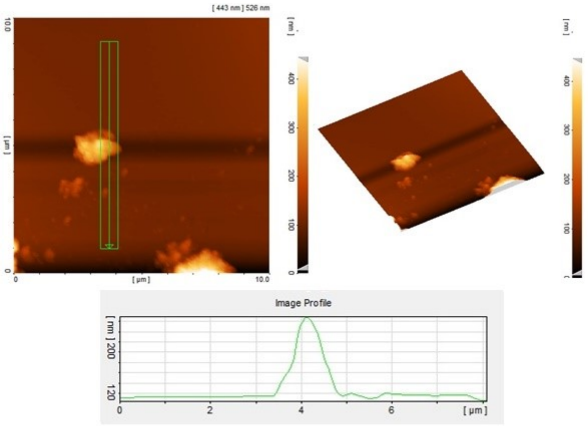


Figure 12: AFM image of soil samples with 0.5% of nano-silica

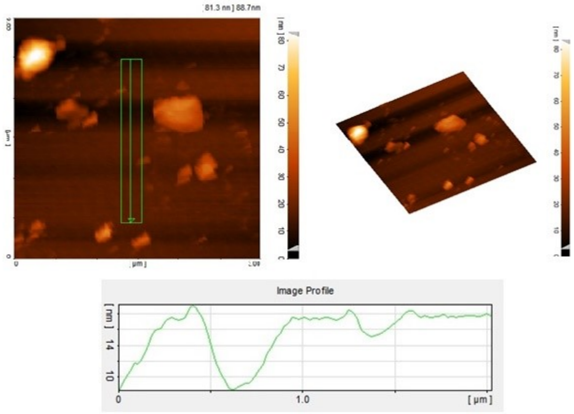


Figure 13: AFM image of soil samples with 1% of nano-silica

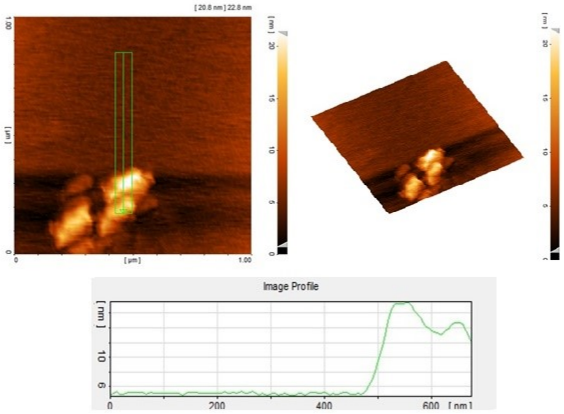


Figure 14: AFM image of soil samples with 2% of nano-silica

R_{ku} (kurtosis of evaluated profile [12]:

$R_{ku} = \frac{1}{S_q^4} \int \int_a Z(x,y)^4 dxdy$

This amount is smaller than 3 in a sample with 3% of nano-silica. This parameter is much larger than other samples in a typical sample, and it indicates the numerous surface holes. S_{td} measures the angle between the stratification line and the y-axis [12].

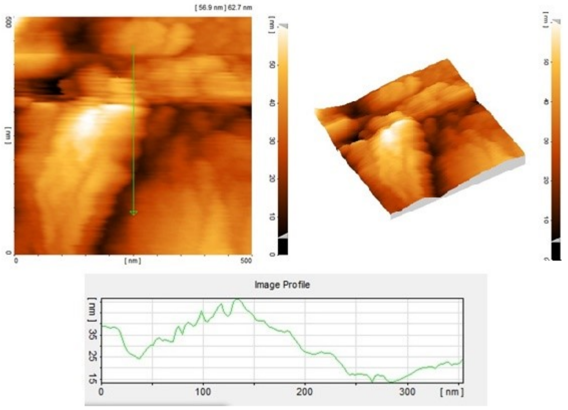
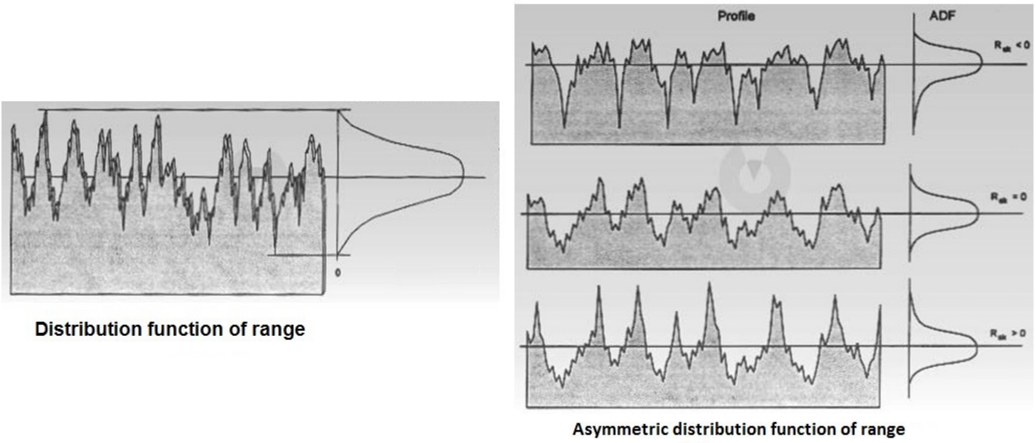


Figure 15: AFM image of soil samples with 3% of nano-silica

Table 5: Parameters obtained from software

Parameter	0%	0.5%	1%	2%	3%
S_y	18.9 nm	389 nm	50.2 nm	22.2 nm	39.1 nm
S_z	9.20 nm	294 nm	44.9 nm	21.0 nm	31.6 nm
S_a	369 pm	19.4 nm	4.40 nm	1.97 nm	6.11 nm
S_{sk}	8.38	3.66	2.22	2.65	-0.17
R_{ku}	213	19.6	9.03	10.2	2.58
S_{dq}	0.012	0.20	0.12	0.16	0.55
S_{sc}	203 mm^{-1}	1.13 μm^{-1}	2.91 μm^{-1}	23.0 μm^{-1}	130 μm^{-1}
S_{dr}	0.008%	1.76%	0.74%	1.33%	12.5%
S_{ds}	4.70 μm^{-2}	2.31 μm^{-2}	38.4 μm^{-2}	399 μm^{-2}	312 μm^{-2}
S_{td}	0	0	0	0	0
S_{ci}	0.028	0.042	0.009	0.006	0.001
S_{vi}	8.37	2.02	2.16	1.49	0.30
S_m	5.31 pm	214 pm	11.7 pm	6.25 pm	4.49 pm
S_c	15.7 pm	1.75 nm	58.8 pm	18.5 pm	5.12 pm
S_v	4.99 nm	87.0 nm	15.1 nm	4.97 nm	2.30 pm


Distribution function of range

Asymmetric distribution function of range

Figure 16: symmetry and asymmetry of distribution function of range [12]

3.4.5 Stratification line: Basic line and direction of surface model

S_{sc} is the total curvature of every point of surface in two perpendicular directions. S_{dq} is the gradient of root mean square in evaluated profile. Surface profile gradient: It is an angle of parallel line to profile with parallel line to reference line. Average gradient: Average gradient of all profile points during sampling [12].

It is applied to distinguish between the surfaces with the same Sa. S_{dr} is the growth rate of cleavages on the surface and it is 0% for a perfectly smooth surface [12].

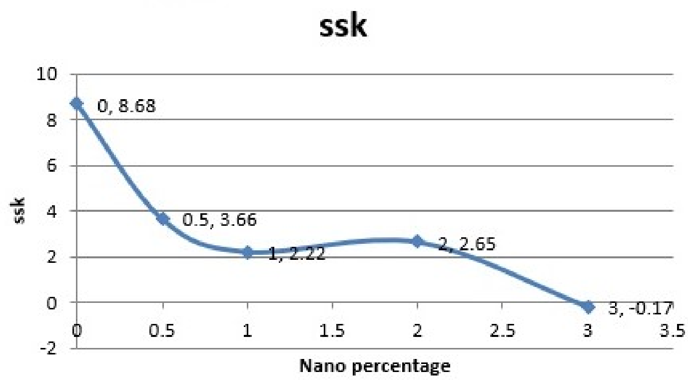


Figure 17: S_{sk} diagram in terms of nano-silica increase percentage

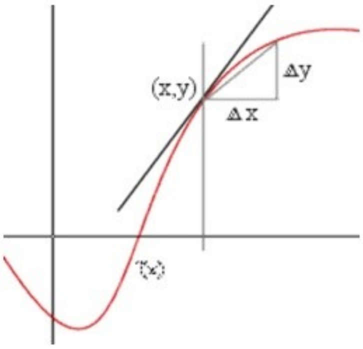


Figure 18: Average gradient

3.4.6 Matter ratio diagram

This curve shows the material ratio of profile as a function of surface height [12]. S_c is the profile height regardless of summits and deep valleys (core roughness profile).

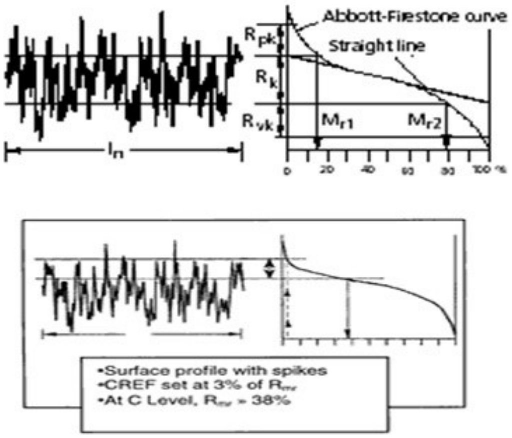


Figure 19: (S_c)

S_m: Average height of summits above the core roughness profile

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core void volume

peak material volume

The average depth of valleys below the core roughness profile (S_v), Sci and Svi are defined as follows:

Sci = Sc / Sq

Svi = Sv / Sq

The high Sci and Svi indicate that the holder is good for liquid [12]. According to table data, the typical sample has higher absorption than the sample with nano-silica percentage; therefore, nano-silica reduces the water absorption. The following graph shows the changes in these parameters according to nano-silica percentage.

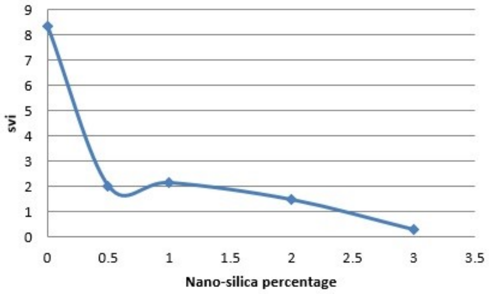

Figure 20: Changes in svi by increasing the percentage of nano-silica

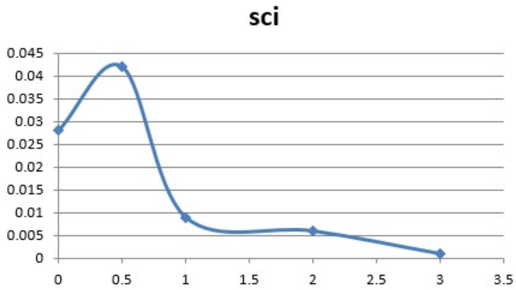

Figure 21: Changes in Sci by increasing the percentage of nano-silica

4 Summary and conclusion

1. Nano-silica slightly increases the plastic limit (PL), but significantly increases the liquid limit (LL), so the addition of nano-silica will increase the Plasticity Index (PI) of soil.

2. The compressive strength of soil is enhanced by increasing nano-silica.

3. The more the curing time is increased, the more the compressive strength is enhanced. The average rate of increase in compressive strength with time is increased in a higher percentage of nano-silica.

4. According to theories, the use of solid particles as the liquid solution will be successful for injection at the nano-scale.

5. According to the field and experimental tests, the injection of nano-silica will lead to an increase in the load-bearing capacity of soil according to the silica c available between the soil particles, and thus it is offered as an appropriate strategy.

6. The scanning electron microscope (SEM) is an exact method for investigating soil appearance, but it is very difficult to prepare the soil sample for this device.

7. Atomic force microscope (AFM) device provides the geometric morphology and surface properties with significant precision.

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valley void volume

8. The increase in nanoparticles will lead to a decrease in the surface porosity of soil particles.
9. Nano-silica reduces the water absorption, and this phenomenon is visible in AFM images.

4.1 Suggestions

1. The achievement of friction and adhesion values from continuous methods such as direct shear and triaxial tests and the comparison of values obtained from this test with values of microscopic images will lead to interesting results.
2. It is suggested to perform dynamic tests both in the laboratory and on-site.
3. It is not cost-effective to use pure nano-materials for improving the problematic soils; hence, it is suggested to perform the chemical and mechanical evaluation on the combination of these materials with other additives which have been already used for this purpose.

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