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Effect of nano silica on swelling, compaction and strength properties of clayey soil stabilized with lime

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ABSTRACT

In soil site planning, soil layers, applied as foundations of buildings, installations and subgrade, should be able to withstand the loads within the range of allowable deformations and transfer them to the ground, hence soil properties such as strength and deformability are significant. Soil stabilization using additives in nanoscale can be applied as a method to improve soil engineering characteristics and strength. In recent years, nanotechnology has widely and rapidly been used in all science fields. Unfortunately, because of being a new science, inadequate research and lack of a comprehensive reference in geotechnical engineering, an understanding of nanotechnology applications and its particles' effects is required. Therefore in this study, the effects of adding nano-silica and lime with different percentages on clay are investigated. Results show that slight addition of nano-silica to clay mixed with lime results in a significant improvement in plastic properties, compaction, strength and swelling of the modified soil. The effects of curing time were also evaluated in this study and results showed that adding nano-silica causes strength of soil mixed with lime to increase more rapidly in a shorter time. The results of this study can be applied in all projects demanding to improve engineering properties of soils.
KEYWORDS: nano- silica, soil improvement, additives, curing time, uniaxial compressive strength, swelling.

1.INTRODUCTION

The idea of nanotechnology was first introduced by Richard Feynman in his lecture entitled "There's Plenty of Room at the Bottom" in 1959 [1]. Each field of science had a specific definition for nanotechnology, and the National Nanotechnology Initiative (NNI) provided a comprehensive definition of nanotechnology (NSTC, 2007). According to NNI, "nanotechnology" is the control, comprehension, and reformation of material based on the hierarchy of nanometers to develop matter with essentially new uses and a new constitution. This technology then progressed significantly in all sciences.

Unfortunately, for various reasons including complexity of geotechnical engineering and engineers' macroscopic view at soils, the impact of nanotechnology and its miraculous performance are still undiscovered in geotechnics area [2]. Nanotechnology can be applied in geotechnical engineering as a tool to improve soils' properties in order to provide a suitable soil for construction projects. The addition of some additives to soil is considered as one of the most effective improvement methods in enhancing soil's behavior such as stress-strain relation, permeability, and self-healing especially in some geotechnical structures such as earthen dams, embankments, synthetic slopes and landfills [3]. In this method, soils are mixed with additives to get their mechanical properties improved.

Many of soil and rock minerals are nano materials and their chemical reactions occur in nano scale. Zhang studied the effect of natural nanoparticles on engineering properties of soil. He found that the presence of only a small amount of nanoparticles in soil have significant effects on physical and chemical behavior and engineering properties of soil. He also concluded that soils including nanoparticles with intraparticles voids in nano scale usually demonstrated higher liquid and plastic limits and presence of fibrous nanoparticles [4]

Ghazi (zhang 2007) et al. performed a study on plastic and strength characteristics of a fine soil mixed with a nano material to enhance shearing strength of the soil. Then results of Atterberg limits and unconfined compressive strength tests were reported. The results showed that adding modified montmorillonitenano–clay to the soil increases liquid limit and plastic index, and unconfined compressive strength of the soil improves considerably. [5]

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Recently nano silica, because of its suitable performance compared with micro-silica, has frequently been used in soil improvement projects. This additive meets unique features which makes it suitable to be applied in soil improvement methods among the other additives. Moreover, research on pozzolanic activity of silica nanoparticles indicated a high pozzolanic activity of nano-silica compared to micro silica [6]. Since silica nanoparticles act as an accelerator, structure of cementitious materials becomes denser and more uniform even in a short time of curing [7].

The purpose of this study is to evaluate the effects of nano silica as a pozzolanic additive on engineering properties of clayey soil stabilized with lime. Results showed that after adding nano-silica to wet soil, Ca^{++} and hydroxide $2(OH)^-$ ions in lime decompose and soil PH level increases as much as $(OH)^-$ in lime increases. When soil PH is about 12.4, the dissolved silicate and Si ions in nano-silica are combined with $(OH)^-$ ions which produces $Si(OH)_3$. These hydroxiades are then combined with Ca^{++} ions to shape cementious gels called hydrated calcium silicate(CSH). Penetration of these cementious gels through voids and pores in soil texture causes soil strength to increase and soil swelling to reduce [8,9].

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^- \quad (1)$$

$$Ca^{2+} + 2(OH)^- + SiO_2 \rightarrow CaO.SiO_2 + H_2O \quad (CSH)\ (2)$$

2. Experimental Method

To investigate the effects of nano silica on clay stabilized with lime, Atterberg Limits, compaction and unconfined compressive strength tests on samples containing 0, 1, 3 and 5% weight of nano silica, as well as 0, 2 and 4% weight of lime were conducted, and effect of curing time on samples 7 and 28 days of age has been investigated. Therefore, three samples were made to conduct testing. The first set of soil samples without additives, second set contained 2 and 4% of lime, and the third samples set which soil was mixed with lime and 1, 3 and 5 percent of nano silica. First, soil is mixed with different percentages of additives, then Atterberg Limits and compaction tests were conducted according to ASTM D 4318-87 and ASTM D 698-78 standard. Samples mixtures are compressed up to 90 and 95% of compaction; then according to ASTM D 2166-87 standard, unconfined compressive strength tests were carried out on 7 and 28 days samples after curing time. In addition, to complete testing procedures and investigate the effects of nano silica and lime on soil swelling characteristics, swelling test of samples has been conducted according to ASTM D4546.

3.Material

3.1. Clay

In this study, natural clay is used to conduct the desired testing. Soil grain curve is shown in figure1.

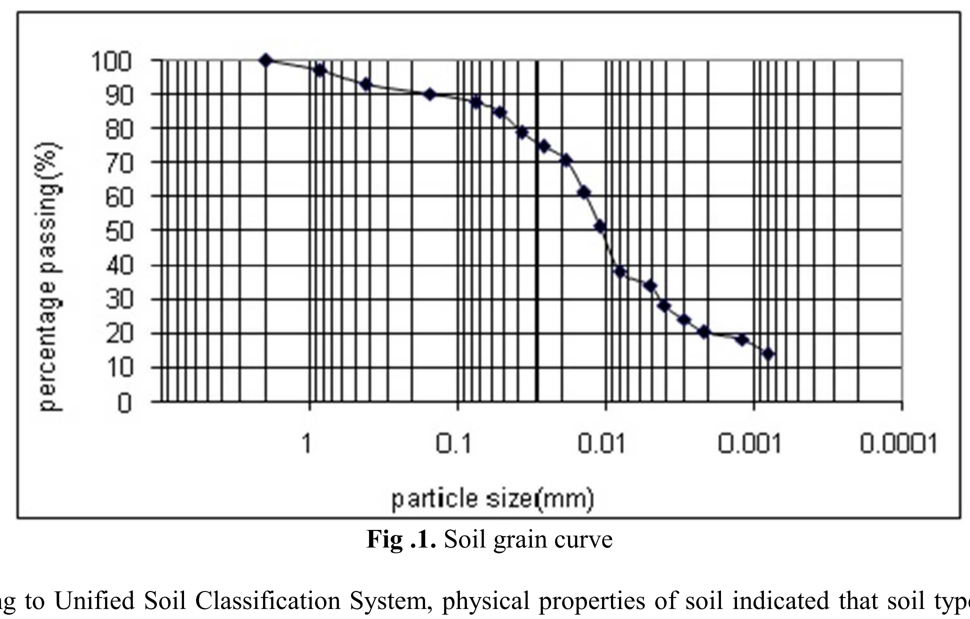

Fig .1. Soil grain curve

According to Unified Soil Classification System, physical properties of soil indicated that soil type is clay with high plastic properties (CH)Table 1. Results of standard compaction test showed that maximum dry density is 16.9 (kn/m^3) and its optimum moisture is 18.8 percent. Considering Table 1, soil plastic index and high activity of soil indicate a significant potential of soil swelling. X-ray mineralogical test results are given in Table 2.

Table .1. Soil characteristics

LL (%)	**61**
PL (%)	**30.1**
PI (%)	**30.9**
optimum moisture (%)	**18.8**
Maximum dry density(kN/m3)	**16.9**
density	**2.68**
soil type according Unified Soil Classification System	**CH**
passing percentage (sieve No. 200)	**68**
clay content (particles smaller than 0.002 mm)	**32.21**
activity index	**1.22**

Table .2. Soil mineralogical

Chlorite (%)	**3.9**
Montmorillonite (%)	**16.8**
Calcite (%)	**31**
Plagioclase (%)	**3**
Quartz (%)	**18.5**
Kaolinite (%)	**19.1**
Illite (%)	**1.5**
Dolomite (%)	**6.2**

3.2.Nano-silica

Silicon Oxide Nanoparticles are used in many cases as paint, plastic, color rubber, magnetic materials, in addition, nano-silica can be widely used in ceramics (sugar) porcelain, gypsum, batteries, paints, adhesives, cosmetics, glass, steel, fiber, glass, and many other fields. The purity of amorphous silica nanoparticles used in this study is 99% produced by US Nano Company. The dosage of using nano silica, recommended by the manufacturer, ranges from 0.5 to 5.5%. Considering economical issues of nano silica usage and the results of this research applied in soil stabilization projects, we decided to use 1, 3 and 5 percent of nano silica in the mixtures. Chemical analysis and characteristics are given in Table 3.

Table .3. Nano-silica characteristics

Silicon Oxide Nanoparticles (SiO2) Certificate of Analysis								
Sio2	**Ti**	**Ca**	**Na**	**Fe**	**SSA(m^2/gr)**	**PURITY %**	**SIZE (nm)**	**Color**
>99%	<120ppm	<70ppm	<50ppm	<20ppm	180-600	99	20 - 30	white

3.3. Lime

Lime with not vibrating specific weight of 550 kg /m^3has been used in testing procedures. Lime density is obtained 2.37 according to experimental tests.

4. Sample Making Method

First, soil is mixed with different percentages of nano silica and lime in a container. Then, this mixture is sufficiently mixed together for 45 minutes. Afterwards, small amount of distilled water is added to the mixture in several stages to produce homogeneous samples. After thorough mixing with water, samples are kept in an enclosed container for 16 hours. Samples with a diameter of 38 mm and 78 mm in height are provided by using static compaction method with 90% and 95% of compaction. Then, 7 and 28 days compressive strength tests are conducted for each sample with specific mixing percentage. Three cylindrical samples are provided to control tests on each of the mixing percentage. The samples used to carry out swelling tests were made in the consolidation test molding with 90% of compaction. Full description and results of the swelling test are presented as following.

4. Experimental Results

4.1.Atterberg Limits Tests

Plastic limit tests are performed according to ASTM D-4318-87 standard. Results of which are shown in Figure2.

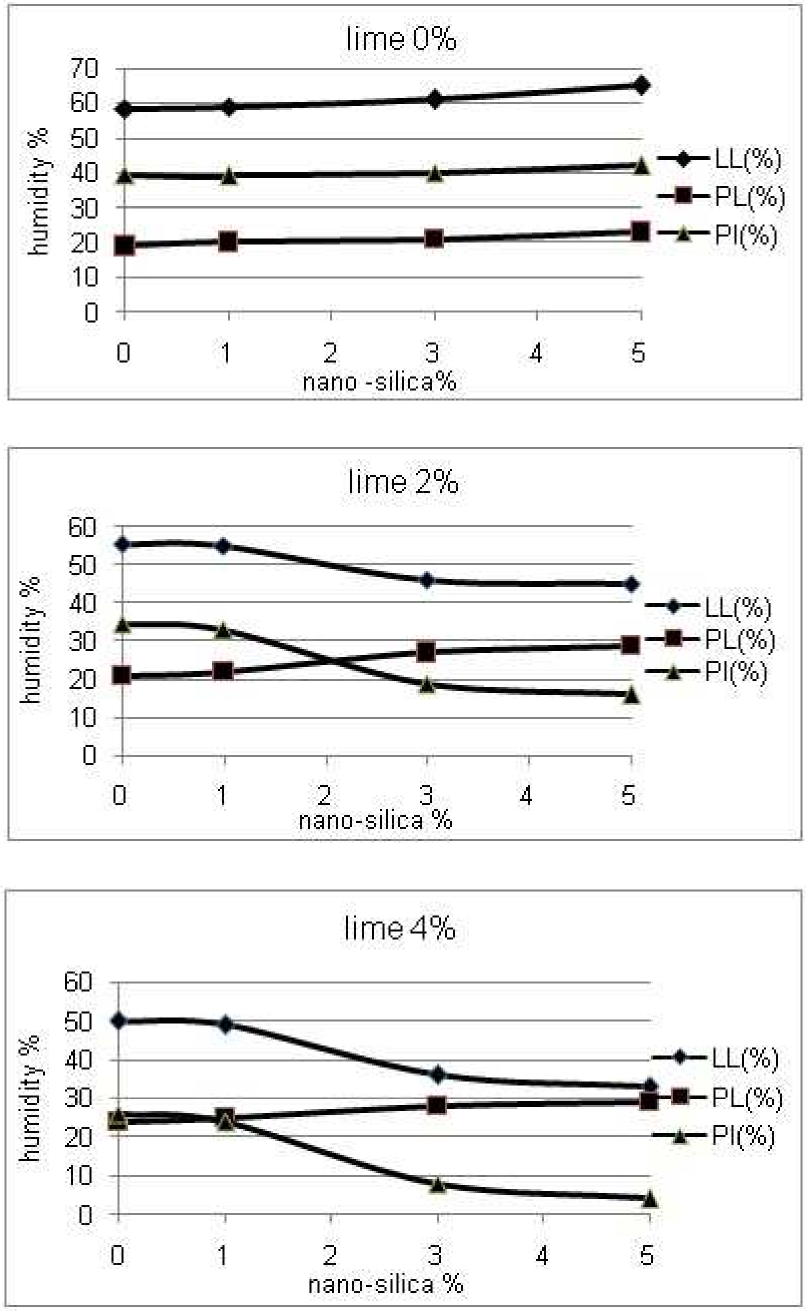

Fig. 2. Changes of Atterberg Limits graphs of clay with different percentage of lime and nano-silica

Experimental tests on samples without lime confirmed that mixing nano silica with clay causes Atterberg limits to increase slightly since silica nanoparticles have high specific surface due to their very small size. When the plasticity of clay is increasing, it is expected that permeability of samples reduces. Hence, the amount of water surrounded by mixture particles increases which results in increasing plasticity parameters of soil mixed with nano silica.

As can be seen in figures, adding lime to soil causes cation exchange reaction between CaO in limestone and Sio_2innano silica to start; consequently clay particles come closer together. As a result of these interactions, soil physical properties are changed and soil acts as a coarse-grain texture, therefore soil plastic properties are improved.

Considering the obtained graphs, adding nano silica up to 3% can cause dramatic changes in improving soil plastic characteristics. But by adding nano silica in the range of 3 to 5 percent no dramatic changes are observed. This may indicate that addition of nano silica up to a certain amount will improve soil performance in short term. In fact, adding high amount of nano silica causes specific surface of particles to increase, therefore soil plasticity is increased. This can overcome the improvement effects created by immediate reactions in short term.

Highpercentage of nano silica particles will notsignificantly affect soil plasticity improvement in short term, however it could have an impact on the process of cementation and soil strengthen long term.

4.2.Compression Tests Results

Figure 3.shows the results of compression tests on samples mixed with different percentages of clay, lime and nano silica.

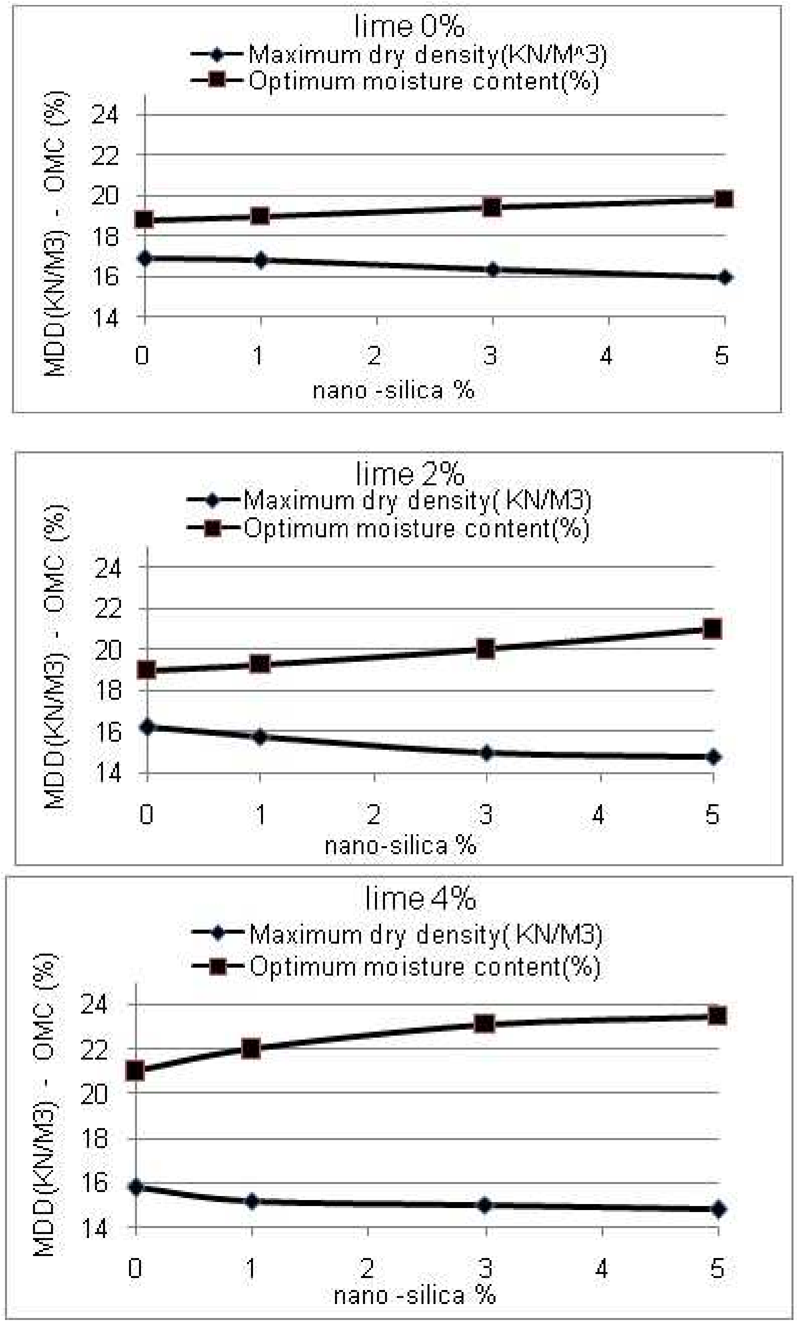

Fig. 3. Changes of maximum dry density weight and optimum moisture content of samples with different content of lime and nano silica.

As can be seen in samples with 0% of lime, addition of nano-silica to the soil causes maximum dry density (MDD) to decrease and optimum moisture content (OMC) to increase. In fact, by adding nano-silica to the soil, surface water absorption of particles increases due to nano silica' softness, hence it can cause a minor increase in the optimum moisture content, and dry density weight is decreased.

In samples where lime is mixed due to the rapid reactivity properties of silica nanoparticles with lime, soil particles are flocculated in immediate reactions. This can make compaction process difficult and cause soil particles to need more water to move on each other. Thus, optimum moisture content of the mixture increases. Although the addition of nano silica up to 3% causes significant changes in compaction parameters, there is not considerable variation on compaction characteristics between 3 to 5 percent of nano silica. Hence, small percentage of nano silica can make the soil more workable.

4.3. Compressive Strength Tests Results

Unconfined compressive strength tests were conducted on 7 and 28-day samples of age with 90 and 95 percentage of compaction according to ASTM-D-2166-87 standard. Results are presented as following.

4.3.1. 7-day samples

Figure 4.shows unconfined compressive strength (UCS) test results for 7- day samples.

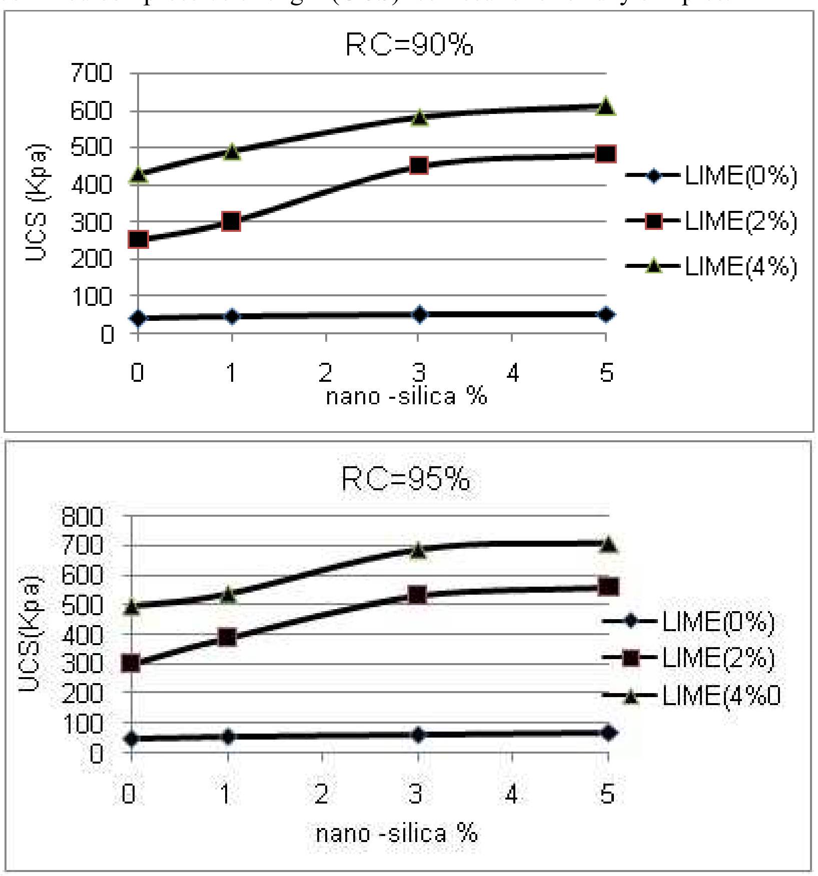

Fig. 4. Unconfined compressive strength tests on 7-day samples.

As can been seen in Figure4, 7-day compressive strength is not greatly impacted by adding nano-silica in samples without lime content. In addition, high percentage of nano silica (5%) resulted in a slight decrease in soil strength. This could be due to the increased moisture of samples and thus compressive strength is reduced. In samples where lime is used, compressive strength also increases. This could be due to lime that acts as an activator in immediate reactions with nano silica to produce cementitious materials. Since lime acts as an activator in reaction with nano silica to form immediate formation of cementitious materials, compressive strength of samples containing lime content is increased. As can be seen in Figure 4, the addition of nano-silica up to 3% showed considerable increase in compressive strength. However, in 7- day samples mixed with 3 to 5 percent of nano silica no significant changes are observed. This indicates that high percentage of nano silica (5%) has no significant effect on compressive strength in short term, and the optimal amount of nano-silica for 7- day samples is 3%.

4.3.2. 28-day samples

Figure 5.shows unconfined compressive strength test results for 28- day samples.

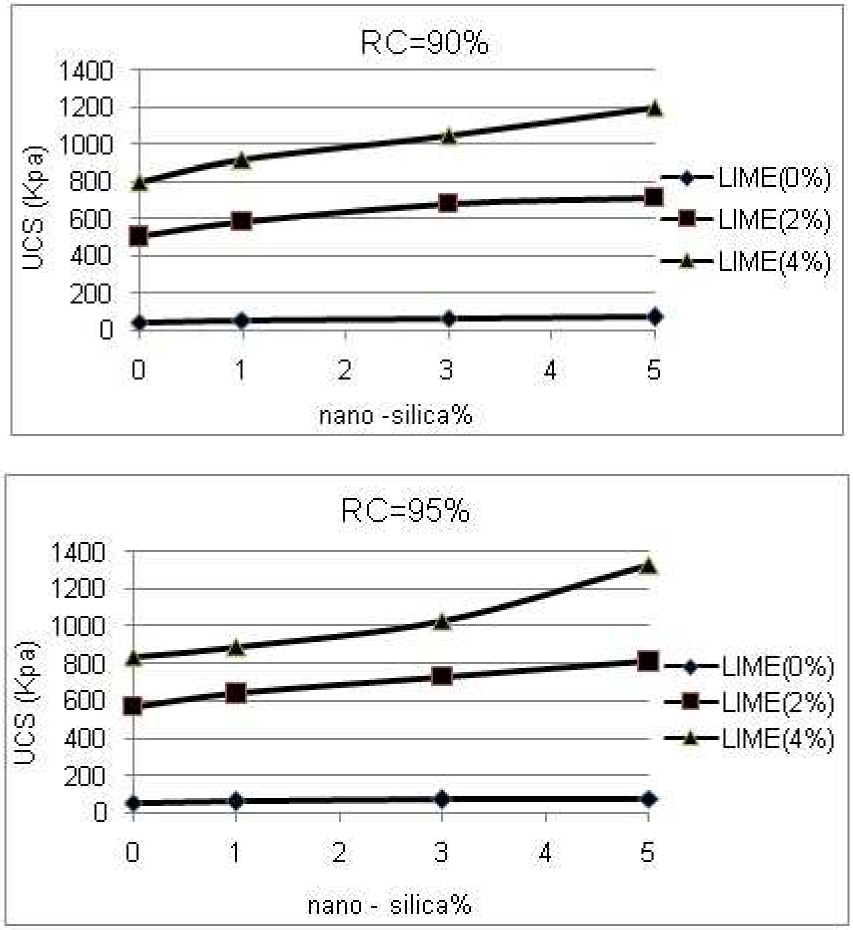

Fig. 5. Unconfined compressive strength tests on 28-day samples.

Compressive strength results of 28-day samples show that the addition of nano silica to samples without lime content has little effect on compressive strength. This is because nano silica alone does not react significantly with soil, so an activator such as lime is needed, which this is clearly observed in samples mixed with lime. In these samples, the addition of lime to the wet soil causes Ca^{++} and hydroxide2 $(OH)^-$ ions to decompose and soil PH level is increased. This increase causes Ca^{++} and Sio2 ions to combine together, thus hydrated silicatecementitiousgels (CSH) are formed. This type of cement gels fills holes and pores in soil and increases soil strength. Unlike7-day samples, more addition of nano silica up to 5% causes strength of 28-day samples to continue to increase, as can be observed in figures.

4.4. Effects of curing

Effect of curing time on samples are given in Figure 6.It is obvious that addition of nano-silica has little impact on compressive strength of 7 and 28-day samples without lime content. This indicates that nano-silica requires an activator to enable its strength reactions.

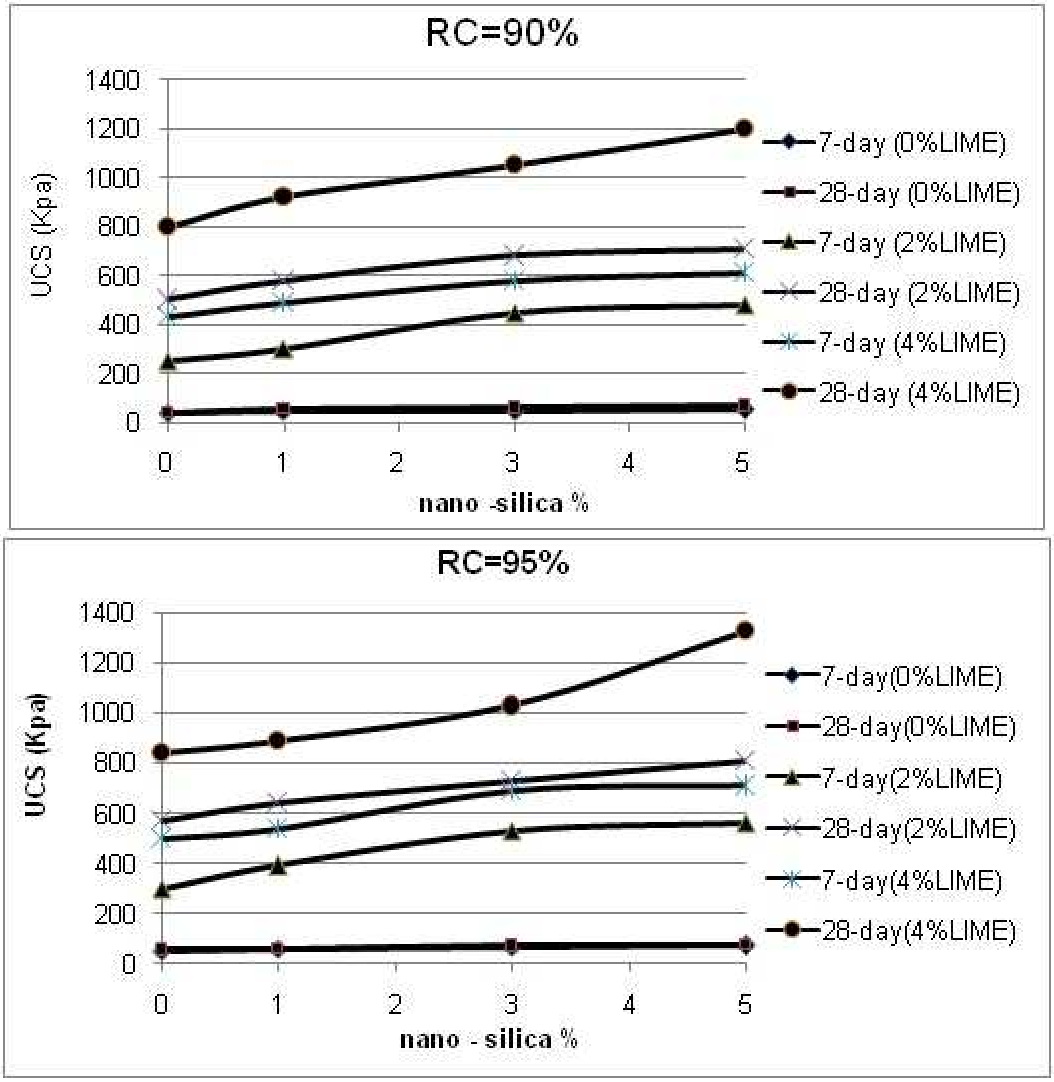

Fig. 6.Effects of curing time on compressive strength of samples.

As can be seen in other diagrams, the addition of lime to samples results in increasing compressive strength considerably. Diagrams clearly show the effects of curing time of samples. Curing time is obviously an important factor in determining and increase of compressive strength, since in samples mixed with lime and nano silica compressive strength reaches about 13 times after 28 days.

4.5.Free Swelling Test Results

Many types of plastic clays swell when absorbing water. Foundations built on such expansive soils are under considerable uplift forces due to swelling. These uplift forces will cause uplifting, cracking and foundation failure.

It is well known that swell-shrinkage characteristics of expansive soils are closely related to soil plasticity index and other parameters. Several investigators have studied empirical relations to estimate swelling characteristics of expansive soils based on Atterberg limits and index properties. [10, 11]

Swelling rate test can be used to determine the rate of swelling. This test is performed in consolidation test equipment so that samples absorb water freely. Sample's overload is almost zero and equal to the weight of the components of consolidation test equipment such as porous rocks, etc. Free swelling rate is defined as the ratio change of the total volume of soil to initial volume:

$$freeswellingra = \left[\frac{v2 - v1}{v1}\right] x100 \quad (3)$$

V_1=Initial volume
V_2=The secondary volume

Nano-silica and lime were added with different percentages to dry soil. Then water was added to each mixture considering the optimum moisture content obtained from compaction test for each specific mixture until a homogeneous mixture is formed. Ultimately, samples were compacted in consolidation test ring. This test was conducted according ASTM-D-4546 standard. Figure 7.illustrates the effects of nano silica and lime on free swelling rate of clay.

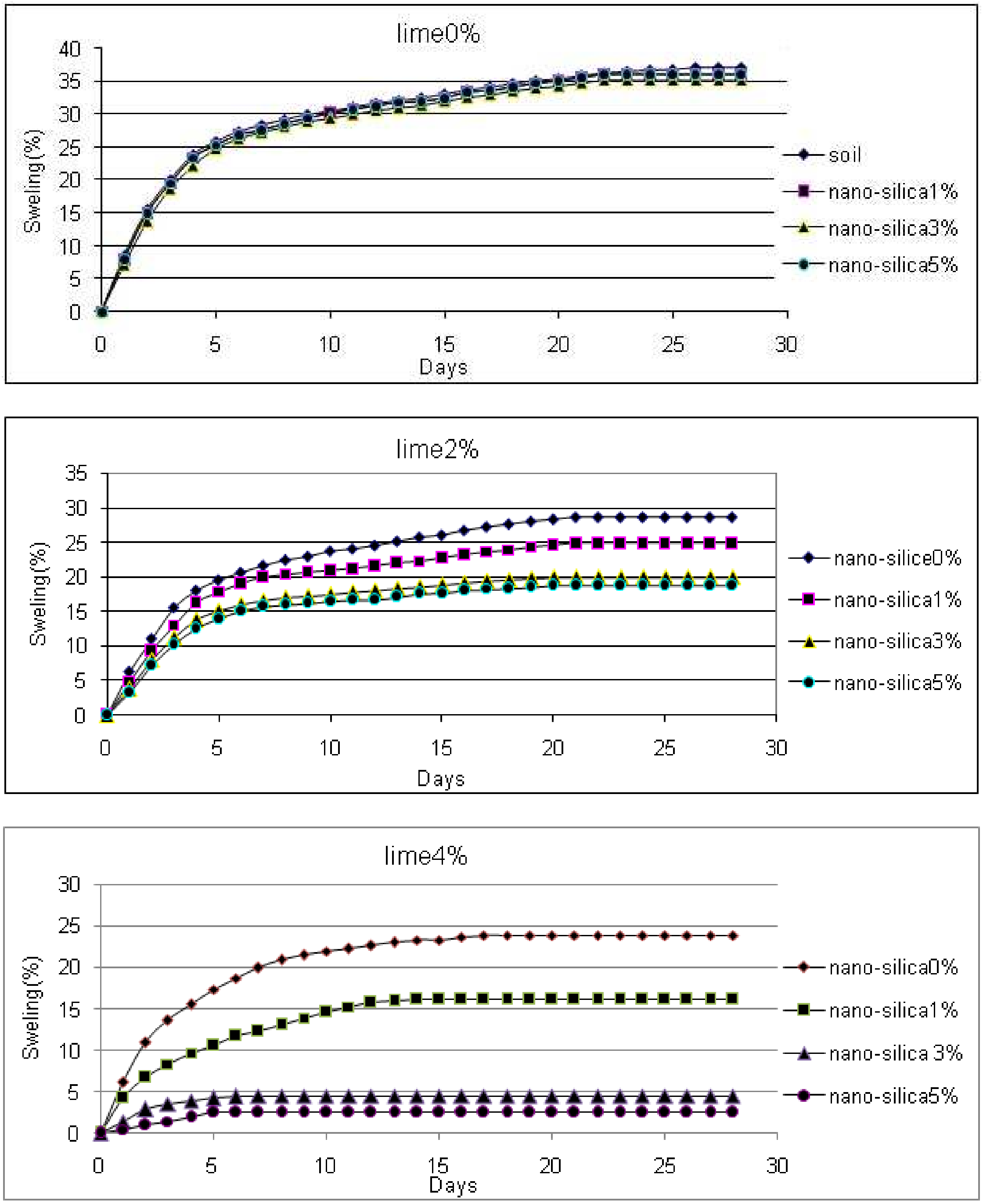

Fig.7. Results of free swelling test along with changes of nano silica and lime.

This experiment has been done within 28 day with different percentages of silica nanoparticles. Samples have been dipped in water during experiment to be provided with sufficient water to swell.

Results show that soil alone swelled up to 37% after 28days. But according to Figure 7, the addition of nano silica to samples without the presence of lime has little impact on soil swelling and it slightly reduces soil swelling. These minor changes are because of the reactions caused by slight amount of lime in the soil with nano silica. This could be due to lack of lime or an activating agent for cementitious reactions of nano silica in samples. However by adding 5% nano silica, due to small size of the particles and their high specific surface, water absorption and swelling of the samples slightly increased again.

Only addition of lime with 2 and 4% causes samples swelling to decrease. Although a lot of research, related to reduction of swelling in expansive soils using lime has been done, in this study lime with nano silica are added to soil samples in order to complete the soil swelling investigation done previously.

Results show addition of nano silica decreases swelling in samples containing 2% of lime so that swelling reaches 18.83% in samples containing with2% of lime and 5% of nano silica. But swelling is significantly decreased with the addition of nano silica in samples with 4% of lime so that in samples containing 4% of lime and 5% of nano-silica, swelling reduces to 2.5% as soil swelling becomes almost impossible. Considering figures illustrated above, the following conclusions are drawn for samples containing nano silica and lime:

1- In the early days of testing, swelling has been substantially reduced in samples mixed with lime and silica nanoparticles because of the small size of nano silica particles and immediate reactions with lime and nano silica, thus producing cementitious materials.
2- Swelling has reduced in all samples mixed with nano-silica and lime, but by the addition of nano silica more than 3 percent not much change was observed in swelling rate. This may indicate that the optimum percentage of nano silica is 3%.
3- In all samples, the addition of nano-silica and lime causes swelling of the samples to reach a constant rate in a shorter period of time, while swelling of clay continues after 28 days without any additives. This reflects the rapid pozzolanic reaction between nano-silica and lime. Because of the very fine particles of nano silica, pozzolanic reactions between lime and nano silica are done quickly and cause cementitius materials to form when absorbing moisture. As a result of these reactions, soil structure is changed to a cementitius structure which prevents soil volume changes.
4- The ions in the surface of clay particles causecations in pore water to be absorbed. These cations are called exchangeable cations and the number of them is CEC or the proportion of the negative charge to the surface of clay. CEC are typically higher in clay with higher specific surface which results in a higher level of activity and subsequently clay will also absorb more water [10]. In fact, CEC is reduced with increasing percentage of nano silica in the presence of lime in the soil. Consequently, water absorption and swelling will also decrease due to a decrease in CEC and forming larger particles.

5. Conclusions

- Soil improvement using additives is the most common method for soil stabilization. Improving soil properties using nano-material can be applied to solve geotechnical problems.
- This study found that the high reactivity of nano silica particles with lime is because of small size of particles which leads to improve properties of soil such as plasticity, compression, swelling and increasing strength in the shortest time.
- Due to small size of nano-silica, the addition of these nanoparticles will increase samples' reactivity even at an early age, subsequently compressive strength is increased. This can be very effective in projects which soil strength needs to be increased and its engineering properties to be improved in short term.
- Addition of silica nanoparticles alone to the soil does not have much impact on soil strength and another activator substance such as lime is needed.
- Soil plasticity is not improved with the addition of nano silica particles alone; moreover because of high softness of nano silica particles, addition of nano silica up to high percentages can increase soil plasticity. However, soil plasticity properties have been improved considerably in samples in which nano-silica and lime are used, so that in samples containing 4% and 5% of nano silica lime in respect, soil plasticity index value decreases as much as pi = 6, hence soil plasticity is lost and soil becomes more workable. Of course, results indicate that no significant changes are observed from 3 to 5% of nano silica addition.
- Addition of nano-silica alone caused a slight increase in soil optimum moisture content and a slight decrease in specific weight of samples. But because of rapid reactions and forming coarse particles as a result of adding nano silica and lime, optimum moisture content and maximum dry density of samples substantially increased

and decreased respectively; so that by adding 4% of lime and 5% of nano silica optimum moisture content and maximum dry density change from 18.8% and 16.9(kn/m^3) to 23.5% and 14.8(kn/m^3) in respect.

- Addition of nano-silica alone did not increase strength of the samples and samples' strength was reduced due to more water absorption. But addition of lime with silica nanoparticles, due to pozzolanic reactions between ca^{++} and sio$_2$ which formed CSH, caused strength of samples to increase dramatically; so that soil strength was initially 45 Kpa without any additives, but it reaches 1330 Kpa in 28-day samples containing 4% of lime and 5% of nano silica.
- Curing time diagrams indicated that because of small size of particles, addition of nano silica to samples mixed with lime has increased reactivity rate and hydration process with lime and produced cementitious materials even at an early age(7 days); consequently strength is increased because addition of 4% of lime and 5% of the nano silica caused samples` strength to change from 45kpa to 610kpa which can be very helpful in projects that soil strength should be increased and engineering properties of soil need to be improved in short term. It is evident that using high percentages of nano silica has little impact on strength of early age samples; approximately addition of 3 to 5% of silica nanoparticles has practically the same results.
- Addition of nano-silica without lime to clay not only has little impact on soil swelling but also high percentage of nano silica can increase swelling due to particles` softness and more water absorption. Addition of nano silica in presence of lime makes a significant decrease in the percentage of swelling of clays with high plasticity so that swelling of the soil after addition of 5% of nano silica and 4% of lime decreases from 37.5 to 2.5 percent within 28 days and practically soil swelling becomes impossible. This could be applied in areas where expansive soils put lots of pressure to foundations of structures and roads. Due to immediate reactions, production of cementitious and strengthening of soil texture, addition of nano silica to soils stabilized with lime makes swelling to decrease in the early days of testing. This advantage can be used in projects that need to control swelling in the early days.

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