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APPLICATION OF NANOMATERIAL TO STABILIZE A WEAK SOIL

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ABSTRACT

There are little investigations in the literature on the nanotechnology's application in the geothecnical field. Since, lots of soil and rock minerals are nanomaterial and their chemical reactions are in the nano-scale, there is a great potential for the use of this technology in different fields of geothecnical engineering such as seepage, grouting, soil stabilization and etc. In this study the stabilization of a weak soil was investigated using nanomaterial. The weak soil was obtained from Boodian Road in North of Iran and classified as low plasticity clay. Fifty CBR tests were conducted in this study. At the first step the effect of lime on the stabilization of the weak soil was investigated. The results proved a little effect of lime in the soil improvement. At the second step, the effect of nano-silica on the stabilization of the soil-lime mixture was studied. The results illustrated the important effect of nano-silica in the soil-lime mixture, in which adding nano-silica increased the CBR strength of the soil and soil-lime mixture up to 21 and 7.5 times respectively. The effects of curing time were also evaluated in this study and the results showed that the CBR strength of the soil-lime mixture increases more rapidly with adding nano-material. In this research, the optimum mixture design for stabilization of the Boodian weak soil was selected as 5% lime and 3% nano-silica added to the soil.

1- INTRODUCTION

The nanotechnologies idea was suggested by Richard Feynman for the first time in 1959, with this sentence "There’s plenty of room at the bottom" (Feynman 1959). After that, this technology developed in all branch of sciences. Different descriptions of this technology exist in the literature. However national pioneers of nanotechnology in United States have presented a comprehensive definition of this technology (NNI 2007):

1. Research and technology development at the atomic, molecular, or macromolecular levels, at a length scale of approximately 1 to 100 nanometers (a nanometer is one-billionth of a meter, too small to be seen with a conventional laboratory microscope);

2. Creation and use of structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size, at the level of atoms and molecules;

3. Ability for atomic-scale control or manipulation.

The use of material characteristics in Nano scale, offers great advantages, in which fundamental evaluation occurs in human life, such as effective use of energy, economy and time increasing the quality of the products in which results the quality of life to increase, reducing economic dependencies and increasing national income.

The researchers in this field, need the especial knowledge of nanotechnology beyond their experts, and must learn the extensive requirements of nanotechnology. Due to a variety of subjects in geotechnics, and macroscopic view of researchers and engineers to the soil, very little investigation have been performed in the field of nanotechnology's applications in geotechnical engineering.

Many of soil and rock minerals are nanomaterial and their chemical reactions occur in nano scale. As a result of this fact, there is a great potential of nanotechnology's application in soil mechanics including seepage, grouting, soil stabilization and etc.

Mixture of soil with some special additive could improve the soil strength parameters, and this procedure has been performed in the past for stabilization and improvement of weak soils.

The main strategy of nanotechnology in geotechnical engineering is the improvement of soil parameters with application of nano materials. The presence of only small amount of nano material in the soil could influence significantly the physical and chemical behavior of soil due to a very high specific surface area of nano materials, surface charges and their morphologic properties.

In the limited investigation performed in this field, the effects of nano materials in engineering properties of soil have been considered mainly in two aspects including the effect of the presence of natural nanoparticles in the soil and the effect of adding nano materials in to the soil. In this way, Zhang studied the effect of natural nanoparticles in the engineering properties of soil. He found that the presence of only a small amount of nanoparticles in the soil have significant effect in the physical and chemical behavior and engineering properties of soil. He also concluded that the soils including nanoparticles with intraparticle voids in nano scale, usually demonstrated the higher liquid and plastic limits, and the presence of fibrous nanoparticles enhances the soil shear strength (Zhang 2007).

Ghazi et al (2011) performed a study on the plasticity and strength characteristic of a fine soil and its mixture with a nanomaterial. They reported the results of a series of Atterberg limits and unconfined compressive strength tests. The results showed that adding Modified Montmorillonite Nano clay into the soil increases the liquid limit and plasticity index and meaningfully improves the unconfined compressive strength of the soil.

The performed studies indicate that the application of nanomaterial in the field of chemical reactions produces more effective results compared with the physical presence of nanomaterial in the soil structure, and this is significant in stabilization of weak soils. In this way, the improvement and stabilization of the weak soil from Boodian road in north of Iran, as a case study, with the application of nanomaterial was investigated.

The aim of authors was to make a comparison between traditional stabilization methods of adding lime, and the new procedure of adding a suitable nanomaterial in the mixture of soil-lime. This study was performed based on the results of CBR tests which are more frequent applied in the practice.

2- EXPERIMENTAL PROGRAM

The experimental program was carried out in two parts: first, determination of geotechnical properties of soil, and soil-additive mixtures and second, mechanical behavior of soil-additive mixtures. A series of CBR tests were conducted to find optimum amounts of lime and nanomaterial in the mixture. The detailed descriptions of these two parts are discussed as below.

2.1- Materials

2.1.1- Soil The soil, used in this study, was obtained from Boodian road in north of Iran. The samples are collected in disturbed state and in sufficient quantity to perform all tests. The soil properties obtained from tests are illustrated in table 1, and the grain distribution cure is shown in the figure 1. According to the unified classification system this soil is classified as CL (low plasticity clay).

Fig. 1. Extracting the weak soil from Boodian road in North of Iran

Table 1. Properties of the soil

Properties	Value
Liquid limit	30
Plastic limit	21
Plasticity index	9
Specific gravity	2.65
Coefficient of uniformity (C_u)	100
Coefficient of curvature (C_c)	1
Effective of diameter (D_{10})	< 0.001 mm

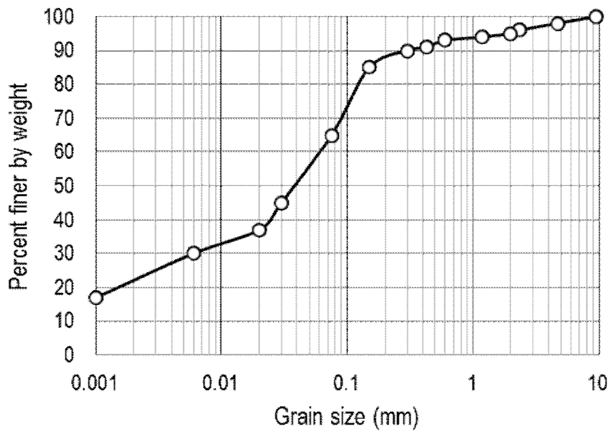

Fig. 2. Grain size distribution

2.1.2-Additives Hydrated lime ($Ca(OH)_2$) was used to improve the native weak CL soil from Boodian road. The physical and chemical specifications of the lime are shown in table 2.

Table 2. Lime characterization

Properties	Value
Cooler	white
Particle size	0.075 mm
Insolvable materials in acid	1.3%
$Ca(OH)_2$	92%
Fe2O3	0.3%
Al2O3	0.3%
MgO	0.85%
CaO	1.5%
Mn2O3	--
CO2	--

2.1.3- Nano-silica Nano-silica was used as nanomaterial additive on the soil-lime mixture. The selection of this additive was based on the results of XRD and XRF tests on the weak original soil, as illustrate in figure 2 and table 3.

Table 3. Results of XRF test for the soil

Properties	Value	Properties	Value
SiO2	66.8%	SO_3	0.003%
Al2O3	13.25%	L.O.I	5.79%
Fe2O3	7.11%	CL	85 ppm
CaO	0.52%	Ba	178 ppm
Na2O	0.89%	Sr	134 ppm
K2O	2.16%	Cu	42 ppm
MgO	1.56%	Zn	114 ppm
TiO2	1.094%	Pb	23 ppm
MnO	.0144%	Ni	83 ppm
P2O5	0.155%	Cr	120 ppm

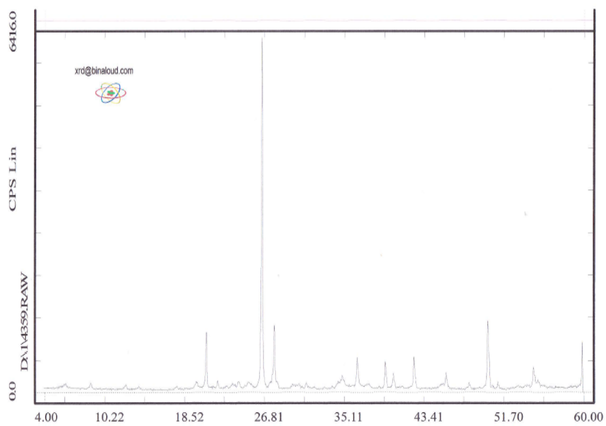

Fig. 3. Graph of XRD test for the soil

Table 4. Results of XRD test for the soil

Major Phase(s)	**Minor Phase(s)**
Quartz (33-1161) SiO2	Chlorite (29-0701) (Mg,Fe)6(Si,Al)4O10(OH)8
Albeit (09-0466) NaAlSi3O8	Muscovite - Illite (26-0911) KAl2Si3AlO10(OH)2
	Orthoclase (31-0966) KAlSi3O8
	Hematite (33-0664) Fe2O3

The physical and chemical properties of hydrophilic fumed silica are shown in table 5.

Table 5. Properties of Nano silica

Properties	Value
SiO_2	99.8 %
Cooler	white
Particle size	12 nm
Specific surface area (SSA)	200 m^2/gr
Tapped density	50 gr/lit
Bulk density	30 gr/lit
Ignition loss	1 %
PH	3.7-4.7

2.2- Method

3.2.1- Testing program   To evaluate the effect of Nano-silica additive on the improvement of the weak soil strength, a total of 50 CBR tests were conducted.

As first step, the effect of lime on the stabilization of soil was investigated. The trial-and-error approach was used to find optimum amount of lime in the mixture. The amount of lime for each mixture was calculated based on the dry soil mass, and selected as 0-1-3-5-7%. Curing time for these series of test was taken as 48 hours at 50^{o}c temperature, in which was equal to curing time of 28 days at 23^{o}c (Qubin et al 2000).

To evaluate the effect of curing time for the optimum amount of lime, the samples were tested immediately, and at 3-7-14-28 days after preparation. These series of tests were conducted with the optimum amount of lime in the mixture.

In the second step, effect of Nano-silica on the improvement of the soil-lime mixture strength was studied, based on the optimum amount of lime determined in the previous step. To reach to this aim, 0-1-3-5% of dry soil mass of nano-silica was added to the soil-lime mixture. Considering the effect of curing time, the samples were tested immediately and at 3-7-14-28 days after preparation. The total testing programs are declared in table 6.

2.2.2- Molding and curing of specimens   To perform the CBR tests, the soil, soil-lime and soil-lime-Nano-silica compacted specimens used in the tests were prepared by hand-mixing of dry soil, lime and Nano-silica. As mentioned in the previous part, the amounts of additive to the soil were based on the dry weight of soil. In each sample, the optimum amount of water was determined in standard compaction test and the CBR specimens were prepared base on desired moisture. After mixing the dry soil and additives, the water was added to the dry soil mixture by spraying into the samples.

After preparation of the mixture for one specimen, the mixture was stored in a covered container for 24 hours to primary curing (or the mellowing period). The same portion of specimens was selected for moisture content test, to ensure the amount of optimum moisture in the mixture. Then, the specimen was compacted in 3 layers, each layer with 65 blows of a (5.5ibf) hammer dropped from a distance 12-inch inside cylindrical mold of CBR.

The CBR specimen was placed into double plastic bugs to prevent loss of moisture before testing. These specimens were carried into the humid room at 23±2^{o}c until specified curing time.

2.2.3- CBR tests   California bearing ratio (CBR) is one of the useful and common methods in evaluating the strength of soil for the design of subgrade, sub base and base of roads. This test, which is simple, fast and reliable have been used to verify the stabilization of weak soils by adding physical and chemical additives (Raymond et al 2007 - Li Chena et al 2009 and Joel Beeghly et al 2010).

In order to measure the direct strength of mixture of soil and additives the CBR test was identified as suitable and reliable method. The cured specimens were subjected to the penetration by a cylindrical rod of CBR test apparatus.

The uniform rate of penetration piston, with diameter of 1.954 inch, into the specimen was 0.05 inch/mine (1.27 mm/min).

The load readings were recorded at penetration step of 0.5 mm, after each test, the penetration depth was measured manually by ruler and compared with the final gage reading to evaluate the accuracy of the test.

Table 6. Testing program

Samples	CBR tests				
	immed iately	3 days	7 days	14 days	28 days
Pure soil	2	-	-	-	2
Soil with 1% lime	-	-	-	-	2
Soil with 3% lime	-	-	-	-	2
Soil with 5% lime	2	2	2	2	2
Soil with 7% lime	-	-	-	-	2
Soil with 5% lime and 1% nano-SiO_2	2	2	2	2	2
Soil with 5% lime and 3% nano-SiO_2	2	2	2	2	2
Soil with 5% lime and 5% nano-SiO_2	2	2	2	2	2
SUM	50				

Fig. 4. Curing room for CBR samples

Fig. 5. CBR apparatus

3- RESULTS AND DISCUSSION

3.1- Effect of lime on stabilization of soil

<u>3.1.1- Compaction tests</u> The results of compaction test in the soil-lime mixture with 0-1-3-5-7% lime are illustrated in figure 3, and summarized in table 7.

As shown in figure 3, with increasing the amount of lime in the mixture, the maximum dry density of the mixture decreases and optimum moisture content increases. Decreasing the maximum dry density of the soil-lime mixture is significant in low percent of lime (1-3%) compared with high percent of lime (5-7%). This is mainly due to chemical reaction in the mixture which occurred rapidly between soil and lime particles and caused changes in the structure of soil (Sherwood 1995 – Osinubi et al 1998).

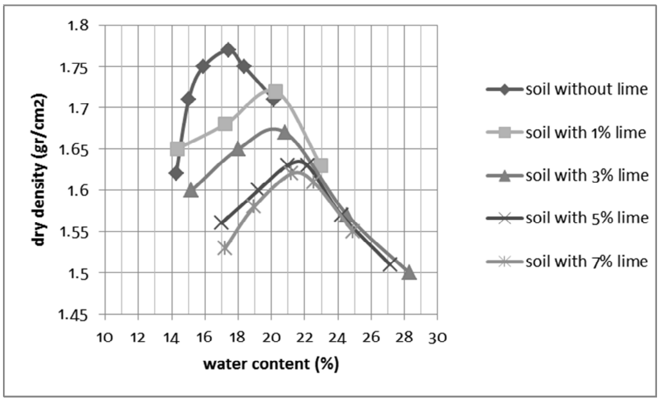

Fig. 6. Compaction characteristics curve for stabilized the soil with lime

Table 7. *Results of the compaction tests for soil-lime mixture*

Samples	γ (gr/cm^3)	ω (%)
Pure soil	1.77	17.5
Soil with 1% lime	1.73	20
Soil with 3% lime	1.67	20.3
Soil with 5% lime	1.65	20.5
Soil with 7% lime	1.64	21

These chemical reactions also increases the optimum moisture content of the mixture due to structural changes, in which the dispersed structure changes to flocculated structure and in result, mixture absorbs more moisture. Another reason for this occurrence is the hydration process of lime during pozzolanic reaction.

<u>3.1.2- California Bearing Ratio Test (CBR)</u> CBR tests in this part were conducted to find optimum amount of lime. Figures 7 and 8 show the CBR test results of the soil-lime mixtures with 0-1-3-5-7% of lime additive.

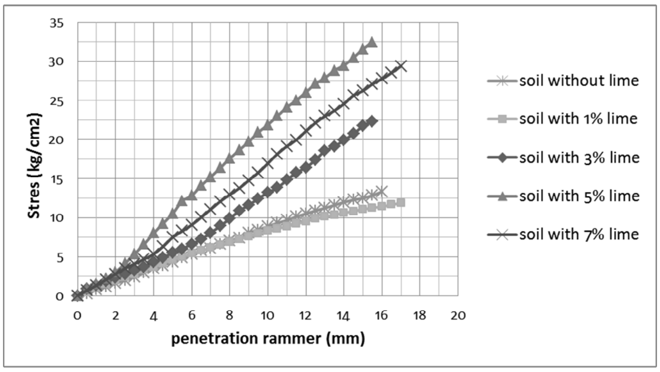

Fig. 7. CBR test's result for different amount of lime in the soil

As mentioned previously, the specimens were cured during 48 hours at 50^{o}c which is equal to 28 days curing at 23^{o}c. These results are reported in figure 8.

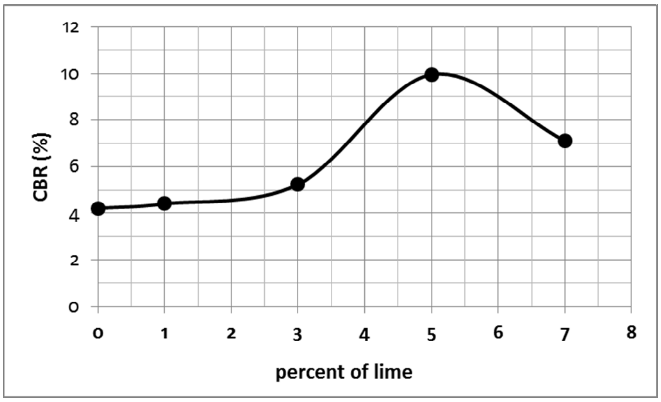

Fig. 8. Behavior of CBR strength of the soil with adding different presents of lime

The figure 8 shows the CBR strength of the mixture increases until adding 5% of lime, and then decreases. This phenomenon is due to the saturation state in chemical reactions between soil, lime and water.

3.2- The effect of Nano-silica in the improvement of the soil-lime mixture

The results in the previous part showed that adding lime in the soil, could not improve the soil strength sufficiently, which is needed in the practice. After proper studies on the nanomaterial in one side and evaluation of the results of XRD and XRF tests on the original soil of Boodian road on the other side, the use of Nano-silica for stabilizing the weak soil and improving the shear strength parameters was suggested.

Silica is known as a pozzolanic material and has been used to stabilize and improve soil strength (McKennon 1994 – Rodriguez 2004). The chemical pozzolanic reactions between silica and lime particles cause the improvement of mixture.

In this part, the effects of Nano-silica in the improvement of soil-lime mixture were studied. It is noteworthy that the amount of lime in all specimens in this part was 5%, in which it was determined as optimum amount in previous step.

<u>3.2.1- Compaction test</u> The results of compaction tests on the soil-lime-nano-silica mixture with 0-1-3-5% of nano-silica, based on the dry soil mass, are illustrated in figure 9 and table 9.

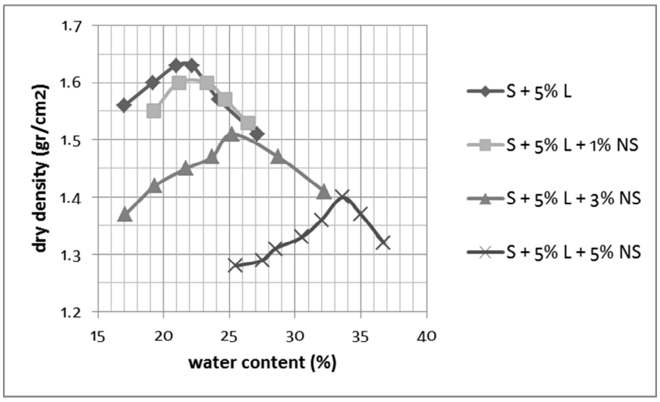

Fig. 9. Compaction characteristics curve for stabilized the soil-lime mixture with nano-silica

Table 9. *Results of the compaction tests for soil-lime and nano-silica mixture*

Samples	γ (gr/cm3)	ω (%)
Pure soil	1.77	17.5
Soil with 5% lime	1.65	20.5
Soil with 5% lime and 1% nano-SiO_2	1.61	22.3
Soil with 5% lime and 3% nano-SiO_2	1.51	25.3
Soil with 5% lime and 5% nano-SiO_2	1.4	33.3

As shown in figure 9, adding a small amount of nano-silica in the mixture of soil-lime (5% lime), causes that the maximum dry density of soil-lime mixture to decrease, whereas the optimum moisture content of the mixture increases.

The chemical reaction between lime and nano-silica plays a main role in these phenomena, such that the dispersed structure of the soil changes to flocculated structure. It is noteworthy that the presence of nano-silica in the mixture increases chemical pozzolanic reaction, and speeds up their processes. With increasing the pozzolanic reaction, a large amount of water in the mixture participates in chemical reaction and as a result the more amount of water is required. The low density of nano-silica (30-50 gr/lit) also results in decreasing the maximum dry density of the mixture.

<u>3.2.2- California Bearing Ratio Test (CBR) of soil-lime-nano-silica mixture</u> To evaluate the effect of nano-silica in improvement of the strength of soil-lime mixture (5% lime), a series of CBR tests were performed.

Figure 10, shows the CBR results of the mixture with 0-1-3-5% of nano-silica, when the specimens were cured at 25^{0}c during 28 days.

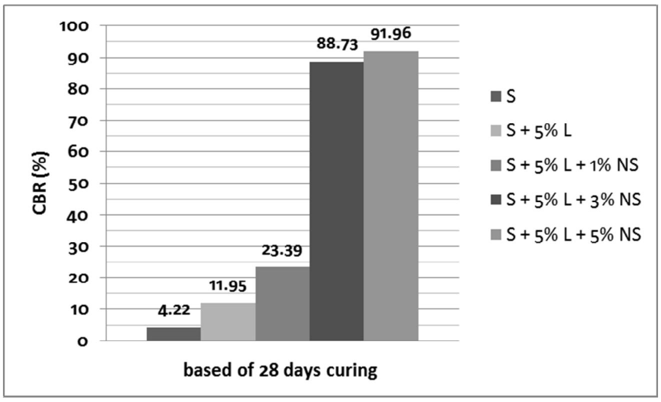

Fig. 10. The significant effects of nano-silica in the CBR strength of soil-lime mixture

Figure 10 indicates that the application of nano-silica is very effective and significant for the improvement of the CBR strength of soil-lime mixture, and the mixture with 1-3-5% of nano-silica increases the CBR strength of soil-lime mixture up to 2, 7.5, 8 times respectively. In addition, the presence of 1-3-5% of nano-silica in the mixture of soil-lime, compared with pure soil samples, produces the CBR strength up to 5.5, 21, 22 times respectively.

The effects of curing time in the experiments were investigated regarding the different amount of nano-silica in the mixture, and considered immediately, 3, 7, 14 and 28 days after molding. The results are shown in figure 11.

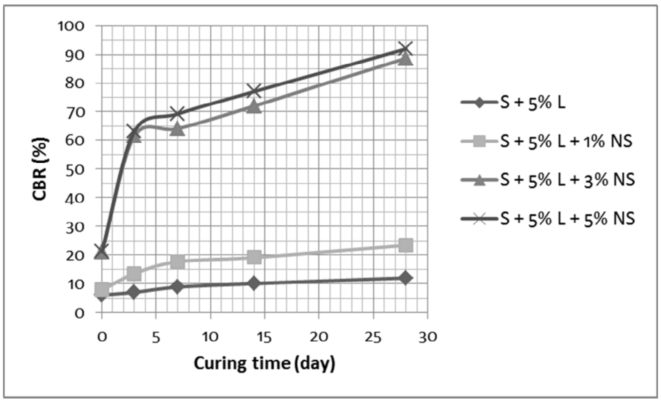

Fig. 11. The effects of curing time in CBR strength for different amounts of nano-silica

As illustrated in figure 11, the rate of CBR strength growing in first days with the mixtures containing nano-silica is very high which are very effective especially in the projects with time limitations. For example the CBR strength of the mixture with only 1% of nano-silica after 3 days curing is greater than the CBR strength of the soil-lime mixture after 28 days curing whereas the presence of 3% nano-silica in the mixture produces more strength after only a few hours.

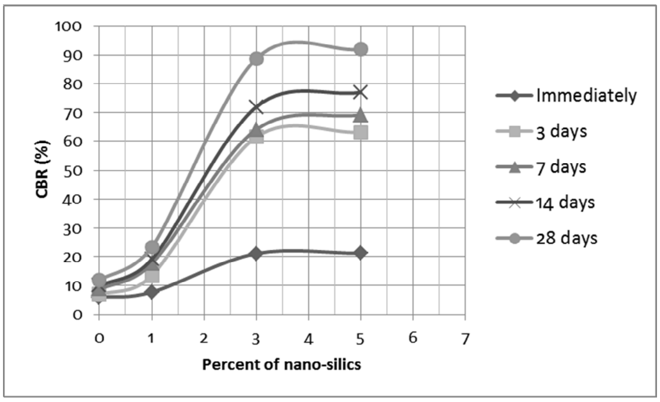

Fig. 12. The effects of different amount of nano-silica in the CBR strength of the mixture

Considering the results in figure 12, the optimum amount of nano-silica were selected as 3%, which has the maximum rate of CBR strength increase. The results suggest that the 3% of nano-silica and 5% of lime improves the CBR strength of weak soil more effectively.

4- CONCLUSION

In this study the application of nanomaterial in the stabilization of low plasticity clay of Boodian road was investigated. The nano-silica was selected as one active pozzolanic material and added to the soil-lime mixture with optimum amount of lime.

The results of this study can be drawn as follow:

- The optimum amount of lime in the mixture of soil-lime was 5% in which the highest amount of CBR strength was achieved.
- Adding nano-silica in the mixture of soil-lime (5% lime) caused decreasing the maximum dry density of the mixture and increasing the optimum moisture content.

- The CBR strength of the soil-lime mixture (5% lime) with adding 1% of nano-silica, increased up to 2 times, after 28 days curing. This increase was 7.5 and 8 times for 3% and 5% of nano-silica respectively.
- The same comparison made for CBR strength of soil and soil-lime-nano-silica mixture and results showed an increase of 5.5 times in CBR strength of soil for 1% nano-silica after 28 days curing. This increase was 21 and 22 times for 3% and 5% of nano-silica respectively.
- The CBR strength of soil-lime mixture and soil-lime-nano-silica mixture increased with increasing curing time.
- The rate of CBR strength growing in mixtures containing nano-silica is very high which can be significant and more useful in practice. For example the CBR strength of mixture with only 1% nano-silica, cured in 3 days, was more than the CBR strength of soil-lime mixture cured in 28 days. Whereas the mixture with 3% nano-silica, cured in only a few hours, produced the strength more than the mixture of soil-lime, cured in 28 days.
- Based on the results presented here, the optimum mixture design for stabilization of the Boodian weak soil was selected as 5% lime and 3% nano-silica.
- The CBR strength of weak soil with 5% lime and 3% nano-silica (which is optimum mixture design) is perfectly sufficient for utilization as subgrade, sub-base and base materials in the road construction.

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