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STABILIZATION OF PROBLEMATIC SILTY SANDS USING MICROSILICA AND LIME

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Abstract. In this study, to stabilize problematic silty sand soils, Microsilica-Lime admixture was used as an additive. Various samples containing 0, 1, 2, 5, 10 and 15% (by weight) Microsilica and 0, 1, 3 and 5% (by weight) Lime were prepared. To investigate the role of the studied additives on the stabilization of the sandy soils, unconfined compressive strength of the materials and their swelling potential, were considered. To do this, unconfined compressive strength test, California Bearing Ratio, also, swelling tests were carried out. As a result, the unconfined compressive strength of samples with 10% Microsilica and 3% Lime in curing time of 28 days was obtained about 50 times larger than the strength of the untreated samples. On the other hand, the samples stabilized only with 1% Lime showed considerable swelling potential while adding only 1% Microsilica caused a considerable reduce in the amount of swelling. Unconfined compressive strength of samples containing 1% Microsilica and 1% Lime was about 12 times larger than the strength of the untreated samples and these samples showed less swelling potential. Then, these amounts are considered as the optimal amounts, which are used in the road construction projects. Also, the results obtained from scanning the samples using electron microscope illustrated that the Microsilica causes to form crystalline micro-structures in the soil which is the main cause for increasing the strength of stabilized samples.

Keywords: soil stabilization, microsilica, lime, California Bearing Ratio (CBR), unconfined compressive strength, swelling potential.

1. Introduction

Geotechnical engineering comprises a variety of different fields (Baziar, Ghorbani 2005; Ghorbani *et al.* 2012; Ghorbani *et al.* 2014; Hasanzadehshooiili *et al.* 2012; Zavadskas *et al.* 2010). Stabilizing the base soil is one of the most important issues, which is common in all the projects located on the problematic or weak soils or in the projects that due to the heavy constructional devices or applying loads need higher strength parameters for the base material (Rafalski, Ćwiąkała 2014). Then, site characteristics play an important role in construction projects (Peldhus *et al.* 2010). In recent years, the use of industrial waste materials in stabilization of problematic soils has increased significantly. The use of these materials in construction projects is economic (Turskis *et al.* 2012) and also has positive effects on the environment conservation (Abd El-Aziz *et al.* 2004; Edincliler *et al.* 2004).

Fly ash, bottom ash, rice husk ash and steel furnace slag are some of the waste materials. The use of these materials alone or in combination with an activating material (such as cement or Lime) causes to form pozzolanic reactions and increase the resistance of the soil in the presence of water. Hydro aluminates calcium and hydro silicate are products of these reactions and lead to improve the mechanical specifications of the soil (Abd El-Aziz *et al.* 2004; Demir, Baspinar 2008; Edincliler *et al.* 2004). The extensive studies conducted on the mentioned materials introduced them as having very good artificial pozzolan affecting soil stabilization (Brooks 2009; Okonta, Govender 2011; Wang *et al.* 2003). Depending on the soil

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type, the optimal amount of fly ash for improving of engineering specifications of soil was reported between 15% to 30% (by dry weight of the soil) (Brooks 2009). The variations of Unconfined Compressive Strength (UCS) with percentage of fly ash mix revealed that UCS increases while adding the fly ash mix up to 30% and then it decreases (Chauhan *et al.* 2008).

Rice husk ash (RHA) as an agricultural waste material, which has high amounts of silica, is a way to reduce the amount of cement used in soil stabilization. Steel furnace slag which is waste material of industry is used with the cement to stabilize sulfate grained soils. Comparing to the case of using cement as the sole stabilizer of the soil material, adding steel furnace slag causes 2 times greater amount of increase in the unconfined compressive strength of the soil (Wang *et al.* 2003).

Microsilica is a very fine dust of silica from a blast furnace generated during silicon metal production and before the mid-1970s it was discharged into the atmosphere (Kalkan 2009). Microsilica, a carcinogenic material, is very dangerous for human health and environment. Hence, in the early seventies, the factories had to collect and landfill this dangerous material (Abd El-Aziz *et al.* 2004). Nowadays, this material is widely used in industry and is not a threat for the environment and is known as a suitable material for soil improving purposes.

Due to the extremely specific surface area, amorphous nature and high amounts of silica, the Microsilica is used for replacement of cement in binder systems (Demir, Baspinar 2008; Kaminskas 2008; Özkan, Sarıbıyık 2013).

The required condition for the presence of Microsilica in pozzolanic reactions is existence of an activator substance such as Lime. When Microsilica and Lime are mixed, pH value of the environment is increased in the presence of water and the active silica reacts with calcium hydroxide and forms calcium silicate hydrated gels (Demir, Baspinar 2008; Lin *et al.* 2003; Tastan *et al.* 2011). These chemical reactions are shown in Eqs (1)–(3) (Tastan *et al.* 2011).

$$CaO + H_2O = Ca(OH)_2, \tag{1}$$

$$Ca(OH)_2 = Ca^{2+} + 2(OH)^-, \tag{2}$$

$$Ca^{2+} + 2(OH)^- + SiO_2 = CaO.SiO_2 + H_2O. \tag{3}$$

Considerable number of researches has been conducted to study the effect of Microsilica on the stabilization of a broad range of geotechnical materials such as clay soils and grout materials. Also, effects of adding this efficient additive on a variety of material's mechanical properties have been studied. Research results have shown the positive effects of Microsilica on stabilization of problematic soils.

In one of these studies, by adding 25% Microsilica to the clay soil, unconfined compressive strength increased up to 138 kPa, and by increasing its amount up to 30%, there was not such a high increasing amount in the resistance of the soil. This matter represents the optimum value of Microsilica for the soil stabilization. Microsilica changes compaction parameters. Addition of Microsilica to fine-grain soils increases the optimum water content and decreases their max dry unit weight. The reason for increase in the optimum water content is changes in surface area of composite samples. Indeed, Microsilica changes the particle size distribution and surface area of the stabilized fine-grained samples (Kalkan 2009). In the same way, the main reason for experiencing a decrease in the max dry unit weight of the material is addition of higher amounts of Microsilica with low density, which fills the voids of the composite samples (Kalkan, Akbulut 2004). Addition of Microsilica to the fine-grain soil materials improves the freezing and thawing durability (Kalkan 2009) and decreases the vertical swelling of clay soil-Microsilica mixtures. The vertical swelling percentages of clay soil-Microsilica mixture samples decrease from 18.7% to 2.7% for the mixtures containing 30% and 50% Microsilica contents (Kalkan 2008). Microsilica decreases the permeability of the clay soils dramatically. Moreover, the investigations showed that the Microsilica is a valuable material to modify the properties of clay liners to be used in the landfill sites (Kalkan, Akbulut 2004). Also, Microsilica decreased the liquid limits and plasticity index and increased the plastic limits in all the clay samples. For this reason, the soil type of composite samples with high Microsilica contents changed from high-plastic clays (CH) to low-plastic clays (OH) (Kalkan, Akbulut 2004; Kalkan 2008).

Furthermore, in a different approach, mixture of Microsilica and cement was used in grout production to cause the resistance between sand grains. The results proved the positive role of Microsilica in making cemented grout. The max value for the unconfined compression strength of cement-Microsilica grouts is obtained when using 5% by weight of Microsilica in the mixture. Moreover, increasing the Microsilica percentage from 5% to 10% causes a fall in the value of unconfined compression strength (Moussa *et al.* 2007).

In addition, it is noteworthy to notice that the effect of this powerful and efficient additive on the mechanical properties of silty sand soil has not yet been studied.

As a matter of fact, road construction on desert sands has always had difficulties for civil engineers. These soils are usually fine-grain and contain few amounts of silt, which have not a significant strength and are not suitable for highway operations (Makarchian, Roshanomid 2007). Iran, with more than 30 million acres of desert and prairie dandruff always has been coping with this kind of problem. In central desert of Iran, a road construction with 230 km of length between two cities of Jandagh and Garmsar is being built. Since the resistive properties of silty sand soil of this area are low for road construction, improvement of its mechanical properties seems to be necessary. The soil contains 25% of sulfate gypsum ($CaSO_4 \cdot 2H_2O$). This soil is subject to swelling and losing of soil strength in saturated conditions. Finding a reliable and applicable solution for this case was the main aim of this research, which led to conducting a research to stabilize the silty sand soil using the mixture of Microsilica and Lime. Also, Lime is used as an activator for chemical reactions.

In this study, effects of adding Microsilica-Lime on the unconfined compressive strength, the California Bearing Ratio (CBR) and the swelling potential of sulfate silty soil were investigated and the optimal values for using in the Jandagh-Garmsar road project were determined. Then, by electron photographing, the structure of the minerals was studied to understand the main reason of changes in the material's behavior.

2. Materials

2.1. Soil

The soil which is used in this study is problematic soil of central desert of Iran. Soil aggregation curve is obtained according to *ASTM-D2487 Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).* According classification chart soil is attributed to the silty sand (SM) group.

The soil classification system is based on UNIFIED (USCS) standard. Over 70% of this soil grains have passed from sieve No. 40 (aperture size 425 μm). This type of soil contains 25% silt and 2% clay. The results gained from XRD test are presented in Table 1. According to Table 1, the soil contains 23% silica dioxide and 25% gypsum sulfate. Hence, the presence of sulfate in the soil with Lime and water often causes swelling problems.

2.2. Lime

The Lime used in this study is obtained from Qom limestone factory (near the project site) and is classified as hydrated Lime. This Lime consists of more than 51% quick Lime (CaO). Results of chemical analysis of the Lime are presented in Table 2.

2.3. Microsilica

Microsilica is non-crystalline silica and is a fine product of electric arc furnace in production of Frosilicium alloy factory. The physical shape of this product is like powder and the grains are spherical (Amorph). Spherical silica is much more active than the crystalline quartz and this matter makes Microsilica to have more company in pozzolanic reactions, and to have more advantageous in comparison to the other pozzolans (such as fly ash) (Lin *et al.* 2003; Xu, Chung 2000). Microsilica used in this study is produced by the Frosilicium factory of Iran, which is located in the Azna city. The particle diameter is between 0.1~0.2 microns. The amount of silicon dioxide (SiO_2) in the powder is about 90 to 95%. Table 3 shows some chemical and physical properties of used Microsilica.

3. Laboratory tests

3.1. Samples preparation

To prepare the samples, Microsilica and Lime were mixed in various ratios and were added to the soil. After thorough mixing, water was added to each of dry mixtures to reach the optimum moisture content of each mixture, gained from the proctor compaction tests. Then, they were mixed again. Soil samples used in this study are finer than No. 4 sieve (aperture size 4.75 mm). All samples were manually mixed and mixing in both dry and wet conditions was done homogeneously. For preparing different samples, various percents of Microsilica (0, 1, 2, 5, 10 and 15% by weight) and different percentages of Lime (0, 1, 3 and 5% by weight) were used. Thus, regarding the used additives percents, there were 23 different states for carrying out the required tests.

Table 1. Results of chemical analysis on the studied soil

Chemical names	Percentage
$(Mg, Fe)_6$, %	2
$KAl_2Si_3AlO_{10}(OH)_2$, %	4
$KAlSi_3O_8$, %	5
$NaAlSi_3O_8$, %	20
$CaSO_4$, $2H_2O$, %	25
$CaCO_3$, %	20
SiO_2, %	23

Table 2. Results of chemical analysis of the Lime

Chemical names	Percentage
K_2O, %	4
SO_3, %	0.8
MgO, %	2.65
CaO, %	51.64
$Fe_2 O_3$, %	0.13
Al_2O_3, %	0.24
SiO_2, %	1.36
L.O.I, %	39.18

Table 3. Results of chemical analysis of Microsilica

Chemical names	Percentage
MgO, %	0.5~2
CaO, %	0.5~1.5
Fe_2O_3, %	0.3~1.3
Al_2O_3, %	0.6~1.2
SiO_2, %	90~95
C, %	0.2~0.4
Na_2O_3, %	0.3~0.5
S, %	0.04~0.08
MnO, %	0.02~0.07
P_2O_5, %	0.04
L.O.I, %	0.4~3
PH	6.6~8.8
Moisture, %	0.01~0.4

3.2. pH tests

pH is a quick test to determine the required amount of Lime for stabilization of the soil and is performed according to *ASTM 6276-99a(2006)e1 Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization*. It is also called Eades and Grim test. Soil particles were passed through sieve No. 40 (aperture size 425 μm), and Silica powders and Lime were also passed through sieve No. 60 (aperture size 250 μm). After that, by adding 1 to 6 percent of Lime to the mixture containing 5, 10 and 15 percent of Microsilica pH values were measured.

The concentration of hydrogen ions in the solution is measured using pH test. In pozzolanic reactions, the pH of the environment must be approx about 12.6 (Sivapullaiah *et al.* 2006). In some other resources, it is recommended

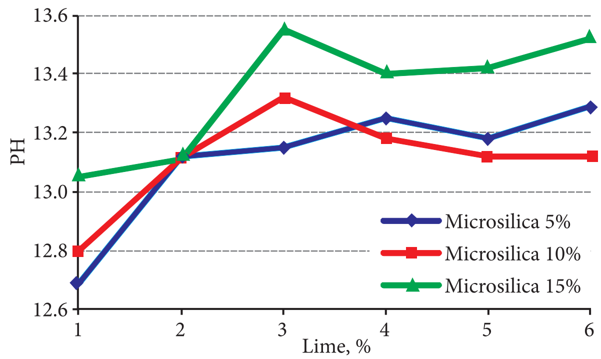

Fig. 1. Effect of adding Microsilica and Lime on the pH values

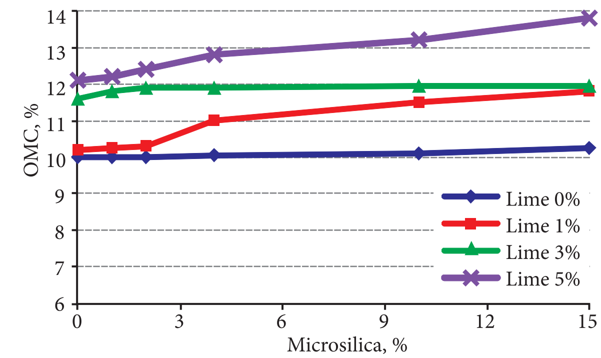

Fig. 2. Effect of adding Microsilica and Lime on the optimum moisture content

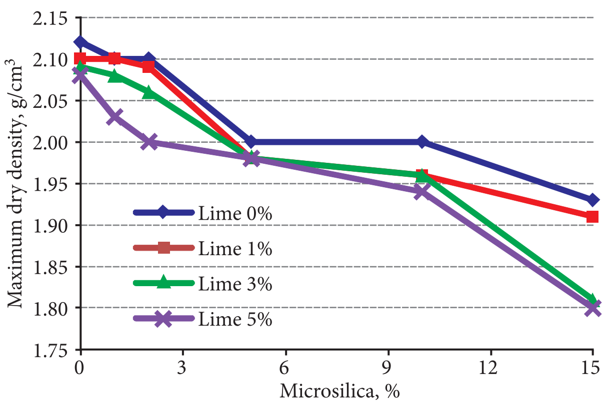

Fig. 3. Effect of adding Microsilica and Lime on max dry density of mixtures

that the min value of pH must be 12.4 (Kavak, Akyarh 2007). The value of pH affects on the swelling amounts and on the formation of Ettringite minerals. This mineral is formed in presence of Lime and in high pH levels in a thin rod figure. Increase in the amount of Lime causes an increase in its length and diameter. Also, Ettringite will disappear due to the lack of Lime and sodium sulfate, also, in the case of low environmental pH levels (William *et al.* 1999). It is noteworthy, that the pH values of 12.4 or 12.6 do not completely guarantee the pozzolanic reactions between soil and Lime. Hence, the results gained from this method must be verified using the other test results. Fig. 1 shows the variation of the environment's pH with Microsilica and Lime.

According to Fig. 1, the pH values are between 12.64 and 13.54. This means that the presence of Microsilica and Lime are efficient additives for a stable stabilization. Moreover, Microsilica and Lime compose a strong bases combination, which is ideal for formation of Calcium Hydro Silicate mineral (C-S-H).

The results showed that by adding 5% Microsilica and 1% Lime, the pH value increases to 12.7. Also, for 3% of Lime, the value of pH is independent of the amount of the Microsilica and all of them are acceptable. Since the pH values do not change in the range of 3 to 6% for Lime, the max strength will be achieved at 3% Lime. Although, according to the gained pH values for different percents of Lime and Microsilica, and comparing them, the optimum amount of Lime for pozzolanic reactions is 1%.

3.3. Compaction test

Compaction tests were conducted according to *ASTM D1557-02 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort*. Optimum moisture content and max dry density of all the mixtures were obtained.

Changes in the optimum water content are shown in Fig. 2 and changes in the max dry density of the proctor compaction test are shown in Fig. 3.

With increasing in the amount of Microsilica and Lime in silty sand soil, the optimum water content increases and max dry density decreases. According to Fig. 2, the lowest water content value of the soil belongs to untreated (natural) soil with 9.95% water content and the max amount of water content is shown in the sample, which contains 5% Lime and 15% Microsilica. According to Fig. 3, the highest max dry density is 2.12 gr/cm^3 and is related to untreated soil samples and the min dry density is 1.8 gr/cm^3, which are seen in the samples made of 15% Microsilica and 5% Lime. Optimum water content was increased because of the type of particles distribution, particle size reduction and increasing in the amount of surface area of stabilized samples (Kalkan 2009; Kalkan, Akbulut 2004; Pera *et al.* 1997; Yarbasi *et al.* 2007). On the other hand, due to the low density of Microsilica and Lime in comparison to the soil, adding of Lime and Microsilica leads to a reduce in the dry density of mixtures (Atom, Al-Sharif 1998; Kalkan, Akbulut 2004).

3.4. California Bearing Ratio and swelling tests

CBR tests were performed according to *ASTM D1883-14 Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils*. Diameter and height of the cylindrical mold used in this experiment were respectively 6 and 4.8 inches. Twelve samples were made for each of mixtures, six of them for dry curing and six of samples for curing in saturated conditions in both 7 and 28 days curing time.

288 samples were built for all different percentages of mixtures. Each of the prepared mixtures was divided to three different samples. And, each of these three samples was compacted separately. For this purpose, the samples were casted in 5 layers and then the casted layers were compacted separately. Three different compactions for each of samples were obtained by different hammer blows, 10, 30 and 65 hits. Then, to keep the samples' water content, the samples were brought out from the molds and were placed into two-layer plastic sheeting and were maintained in the laboratory temperature for curing time of 7 and 28 days.

For saturating the samples with different ages, the plastic covers were removed and the samples were soaked into the water containers for 96 h. A 2.5 kg overhead was placed on the saturated samples during this period. Also, strain gauges were installed on the samples during the saturation period and swelling of the samples was measured. Samples were placed into the California Bearing Ratio loading device in dry and saturated conditions. In this experiment the amount of the cylindrical rod penetration was 1.27 mm/min.

3.4.1. The effect of Microsilica-Lime on CBR test

CBR tests were conducted on 23 different types of mixtures and their results for 30 blows are shown in Figs 4–7. By adding Microsilica, CBR strength of the soil increases dramatically. The highest amount of CBR belongs to the sample, which contains about 10% Microsilica and 3% Lime with 28 days curing time (226% increase). Similar to unconfined compressive strength, the CBR number of mixtures increased by adding Microsilica to 10% and then by adding Microsilica to 15% and consequently decreasing the samples' dry density, the CBR number of samples was reduced. It is important to note that the CBR number of samples containing 1% Microsilica and 1% Lime is 80%. Since the soils which have the CBR numbers larger than 50% are suitable for using in road pavement, using Microsilica for stabilization of silty sand of desert areas in Iran is a good and economical solution.

Effect of number of blows on the CBR value of stabilized soils

To investigate the role of number of blows on the CBR of stabilized soils, the CBR numbers of samples stabilized with different percents of Lime and Microsilica were gained for three different blows, 10, 30 and 65 in both dry and saturated conditions. Also, all the samples were cured in 7 days and 28 days and results were reported for all these conditions. After sorting and comparing the results,

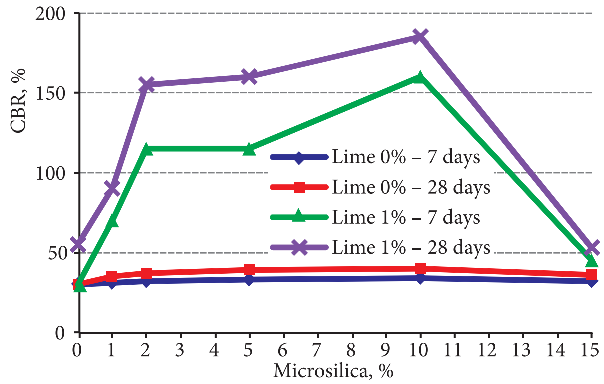

Fig. 4. Effect of adding Microsilica-Lime on CBR with 30 blows for 0% and 1% Lime in dry conditions

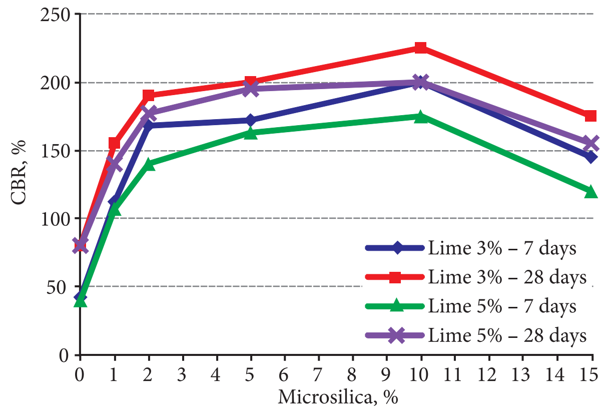

Fig. 5. Effect of adding Microsilica-Lime on CBR with 30 blows for 3% and 5% Lime in dry conditions

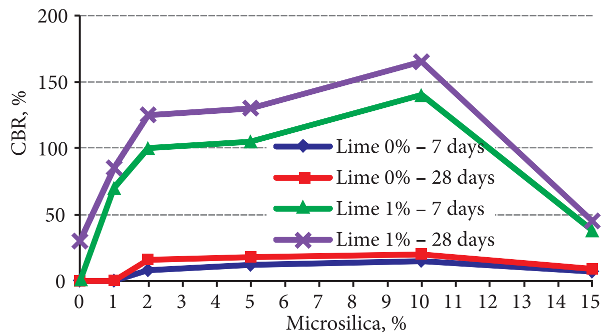

Fig. 6. Effect of adding Microsilica-Lime on CBR with 30 blows for 0% and 1% Lime in saturated conditions

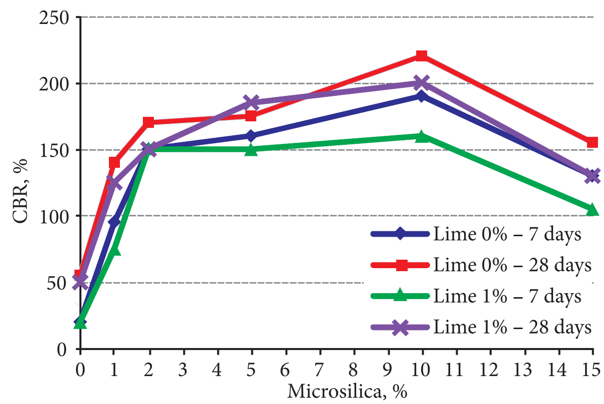

Fig. 7. Effect of adding Microsilica-Lime on CBR with 30 blows for 3% and 5% Lime in saturated conditions

it was achieved that for samples that were cured in 7 and 28 days in both dry and saturated curing conditions, the CBR number of samples experiences a significant rise with increasing the number of blows from 10 hammer hits to 30. But, increasing the number of blows from 30 to 65 does not lead to a considerable change in the CBR value. To better understand the effect of number of blows on the CBR values, Figs 8–9 as sample figures are presented (related to the samples stabilized with 1% and 3% Lime for different values of Microsilica and cured in 7 days).

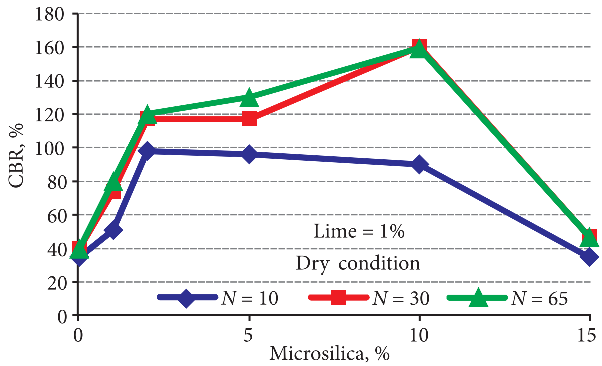

Fig. 8. CBR number of samples stabilized with 1% Lime and different values of Microsilica in dry condition (10, 30 and 65 blows)

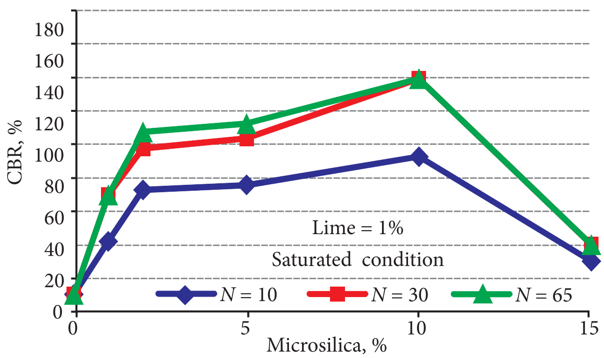

Fig. 9. CBR number of samples stabilized with 1% Lime and different values of Microsilica in saturated condition (10, 30 and 65 blows)

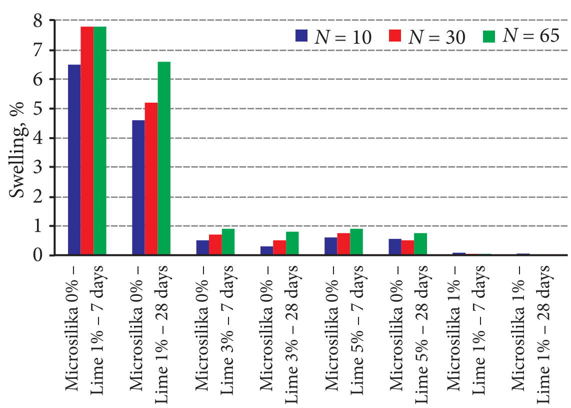

Fig. 10. Swelling potential of the samples stabilized with different percentages of Lime-Microsilica

3.4.2. The effect of Microsilica on the swelling potential

Only 23 samples out of 144 samples were swollen and almost all of the swollen mixtures had no Microsilica. Results obtained for the swollen samples are shown in Fig. 10. The swelling amount of the samples stabilized with the Lime in the lack of Microsilica was between 1% and 7%. But, the use of Microsilica stopped swelling of the material. Thus, by adding only 1% Microsilica, the amount of samples' swelling became zero. In general, by adding Lime to the soil, the value of pH in the environment increases. This phenomenon cause alumina and silica release in the soil. Also, increasing the amount of pH in the soil, the clay particles dissolve and alumina and silica release. Because of existence of considerable amount of sulfates in the soil, the free alumina reacts with the soil's sulfates. This leads to formation of Ettringait minerals. Ettringait is a swelling mineral and has high water absorbency and increases the swelling potential of the soil.

Using the Lime as the sole soil stabilizer in the lack of silica in the environment leads to producing of Ettringait mineral. The graphics in Fig. 10 show that the highest rate of the swelling belongs to the condition when just 1% Lime is used as the stabilizer. But, after adding 1% Microsilica to the sample, the swelling potential disappeared. To conclude, the Microsilica increases the strength of Sulfate silty sand, also, decreases its swelling potential. The results of swelling and the CBR tests show that there is an inverse relationship between the swelling potential and the strength of the samples. And, samples with less resistance have higher swelling potential.

3.5. Unconfined compression strength tests

Unconfined compressive strength (strain-controlled) tests were conducted in both dry and wet conditions with a penetration speed of 1 millimeter per minute according to *ASTM 2166 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. The samples preparation method was similar to CBR and the samples were compacted using Harvard compaction device. Despite of the CBR test, there were no variation in the compaction values and all mixtures were compacted in 5 layers and using 25 hammer hits. After samples compaction, they were kept in a plastic shelf at a constant temperature for the curing times of 7 and 28 days. In the wet samples preparation, according to the American Lime Association, at first, a round of the samples was covered with a cloth, which has the ability to absorb the water and a porous stone was placed at the bottom of the sample. Then, the sample was put in a plastic bag and enclosed tightly using an elastic web. The samples were placed in a tray filled with water in a way that just the porous stone was in contact with the water. For wet samples, the curing time is 24 h. Also, to decrease the experimental errors, for each experiment, three samples were prepared and the averages of the results for these three tests were reported as test results.

Effects of adding Microsilica and Lime on the unconfined compressive strength of silty sand soils in both dry and wet conditions for 7 and 28 curing samples are shown in Figs 11–12. By adding Microsilica to the silty sand soil, its strength has been increased. In comparison to the other researches, results gained from the experiments are in a good agreement with other research results conducted on clay soils. Indeed, in the previous researches carried out on clays, adding Microsilica to the soil caused an increase in the clay's resistance (Ola 1987; Kalkan 2009). Similarly, here, the resistances of silty sands are increased with Microsilica.

The most resistances in dry and saturated conditions were obtained in 10% of Microsilica. But, by adding the amount of Microsilica to 15%, the samples resistance was reduced. As it is shown in Figs 11–12, resistance of samples containing of 15% Microsilica at both curing ages of 7 and 28 days was significantly reduced in comparison to the samples with 10% Microsilica.

Previously, some researches were done on the effect of Microsilica, which leaded to presenting an optimum amount for Microsilica for mixing with the different soils (Kalkan, Akbulut 2004; Moussa *et al.* 2007). This phenomenon occurred because of reducing the dry density of the soil as a consequence of adding Microsilica. The current research results showed that the optimum amount of Microsilica for silty sand soil is 10%.

The main purpose of using Lime is creating pozzolanic reactions between Calcium Hydroxide and Microsilica. This leads to the formation of Calcium Hydroxide Silicate which is a cohesive material.

Moreover, Fig. 6 shows that the CBR number of saturated samples containing 1% Microsilica (without Lime) is very low. By adding only 1% of Lime, CBR number of saturated samples increased about 80 times in comparison to the untreated soil sample. According to Figs 4–7, the most strength of the samples was obtained from mixtures containing 3% Lime. The strength of sample containing 5% Lime showed negligible difference and samples containing 1% Lime had reasonable strength. This fact was obtained for both unconfined compressive strength test and CBR test. Earlier, pH tests showed that adding 3% of Lime to the mixture makes a suitable condition for pozzolanic reactions.

The results of CBR tests and UCS tests in combination with the pH values show that the optimum percentage of Lime for the stabilization of silty sand soil is about 1%, but by adding 3% Lime, the highest strength is obtained.

3.6. Scanning electron microscopy

To accurately study and understand the nature of changes as a consequence of stabilization in the material, also, to investigate the structure and porosity of the soil, a number of samples were scanned by electron microscope (SEM). In addition, the effect of increasing Microsilica, also, curing time was studied. The samples were made using a fixed percentage of 5% for Lime and different Microsilica percentages (0%, 1% and 10%) in both 7 and 28 days curing time. The taken images are shown in Figs 13–17.

Figs 14–15 show the images of samples made from 1% Microsilica and 5% Lime. These figures show that Calcium

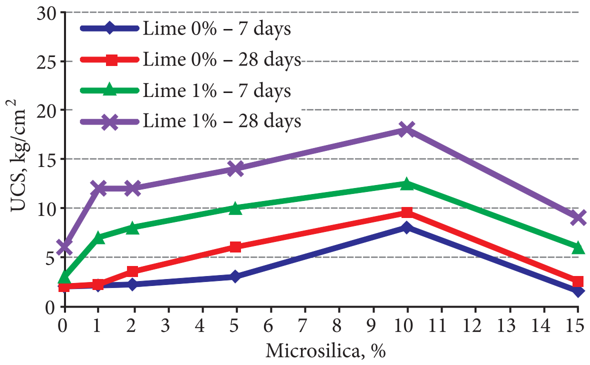

Fig. 11. Changes in unconfined compressive strength of dry samples containing 1% of lime with different percentages of Microsilica

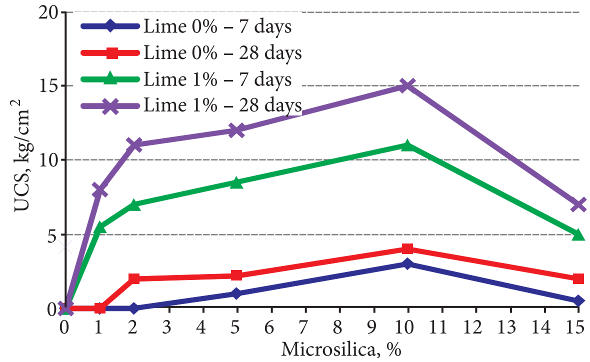

Fig. 12. Changes in unconfined compressive strength of wet samples containing 0 and 1 % of lime with different percentages of Microsilica

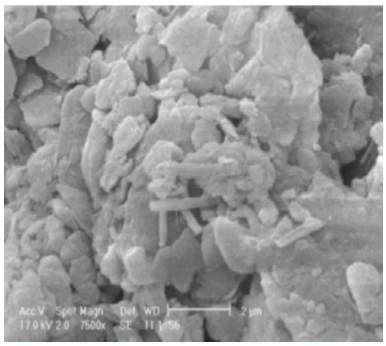

Fig. 13. Electron microscope image of the 7 day curing samples with 5% Lime and 0 % Microsilica

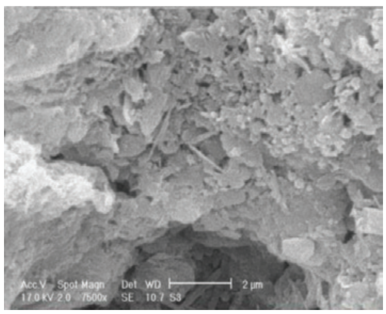

Fig. 14. Electron microscope image of the 7 day curing samples with 5% Lime and 1 % Microsilica

Hydro Silicate gel surrounds the sand and silt particles and the partly eroded pores of the soil. Also, in comparison to Fig. 13 and the amorphous structure of the sample, formation of crystalline structure is obviously shown in Figs 14–15, where 1% Microsilica is added to the samples. It is seen that quartz crystals are created in these samples. The crystalline structures show a higher strength in comparison to the structures composed of spherical minerals. The images gained allow a proper interpretation of previously obtained behaviors for the silty sand soil.

Moreover, the role of curing time on the samples' strength is obviously understood from Figs 14–17. As an example, Figs 14–15 are both captured from one specimen. The only difference between these two figures is in their process time, curing time. Indeed, in the specimen with more processing time, Fig. 15, the minerals have had enough time to form the crystalline structure and thus reveal more strength.

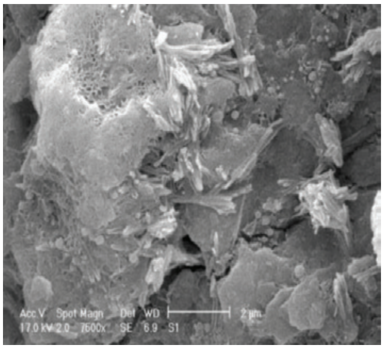

Fig. 15. Electron microscope image of the 28 day curing samples with 5% Lime and 1 % Microsilica

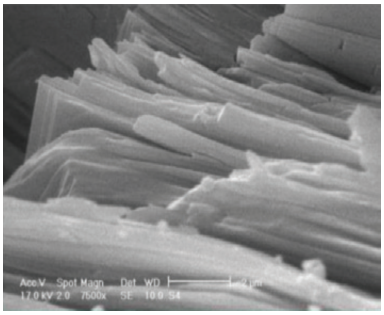

Fig. 16. Electron microscope image of the 7 day curing samples with 5% Lime and 10% Microsilica

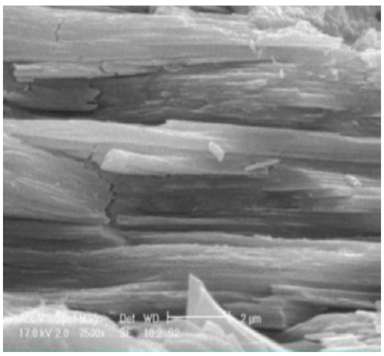

Fig. 17. Electron microscope image of 28 day curing samples with 5% Lime and 10% Microsilica

Forming crystalline mineral structures from their previous spherical shapes and decreasing the existent pores between minerals are two obvious reasons, which efficiently prove the accuracy of gained results for unconfined compressive strength and the CBR number.

4. Conclusions

1. In this study, a significant number of soil specimens (Sulfate silty sand) from the central desert of Iran was prepared and was stabilized using Microsilica and Lime. In order to evaluate the strength of the stabilized specimens and to solve the main problem of Jandagh- Garmsar road construction project, a 230 km road project in central desert of Iran, different tests such as unconfined compressive strength, California Bearing Ratio, swelling and electron microscopy imaging on different samples were conducted considering different percentages of the additives. To sum up the gained results:

2. Lime and Microsilica added to the silty sand soil cause an increase in the optimum water content and a decrease in the maximum dry density of the soil. Lime has more significant effect on increasing optimum water content and maximum dry density than Microsilica.

3. Adding Microsilica and Lime to the soil causes an increase of pH values (>12.6). Increase in pH values causes acceleration of pozzolanic reactions and hence, strength of most of 7 days curing samples is close to their final strength.

4. Increase in the amount of Microsilica has influence on the unconfined compressive strength and California Bearing Ratio test of silty sand soil. 1% Microsilica added to the untreated specimens, considerably increases their unconfined compressive strength and California Bearing Ratio. Moreover 1% of Microsilica prevents the swelling of silty sand soil.

5. Adding up to 10% Microsilica to the soil increases their strength. However, by increasing its amount to 15%, the sample's resistance decreases, due to decrease in their specific density when adding Microsilica.

6. All the samples containing Microsilica and Lime reached 70 or 80 percents of their final strength, during the 7 days curing. This demonstrates the advantage of Microsilica in stabilization of silty sand soils. Furthermore, saturation did not cause a dramatic reduction in the specimens' resistance. There was not a considerable difference between dry and saturated resistance of specimens stabilized with Microsilica and Lime. A possible reason for this is the formation of crystalline structures, which decrease the porosity of the samples. Then, the specimen's permeability decreases and saturation cannot significantly decrease the samples' resistance.

7. For the samples containing Microsilica, highest California Bearing Ratio numbers obtained with the compaction hit numbers of 30 and 65, whereas the highest California Bearing Ratio number of samples containing Lime was gained in low compaction hit number, 10.

8. To improve the problematic soil of Jandagh- Garmsar road construction project, the best stabilizing solution was gained when using a 1% Microsilica and 1% Lime as additives.

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