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IMPACTS OF FREEZING-THAWING AND WETTING-DRYING CYCLES ON A SILT STABILIZED BY LIME AND WASTE SILICA

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Abstract

The main objective of this research is to investigate the effects of lime and waste silica fume additive on a silt and its utilization on railway subgrades stabilization. For this purpose, lime and waste silica fume were added to the silty soil in different contents at the soil optimum moisture; then the California Bearing Ratio (CBR) tests were conducted on the soil samples to estimate the favorable mixture design. At the next step, a selected sample was chosen to be exposed to wetting–drying and freezing–thawing cycles. The results showed that the lime–silica fume additive increases the CBR values of the soil significantly. Furthermore, the first wetting–drying cycle enhances the samples' CBR value, but subsequent wetting–drying cycles decrease the sample's CBR value. Moreover, freezing–thawing cycles reduce the samples' CBR values.

Key words: freezing–thawing cycles, lime, silica fume, stabilization, wetting–drying cycles

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1. Introduction

Road construction is considered as one of the most important development indicators of a country. Therefore, in progress improvement of road, railway and airfield constructions is in developing countries. Having a satisfactory subgrade with appropriate strength and durability in different traffic conditions and weather is necessary for road construction (Nie et al., 2017; Ola, 1977).

Fine grained soils like silts in the subgrade of constructions make for some problems in achieving adequate road strength and consequently, reduce the pavement life. Hence, these soils need to be replaced with suitable soils, be compacted or stabilized. Replacement of soils is almost impossible for road subgrades due to their high costs and long distance from extraction site (Da Fonseca et al., 2009). The minerals in silts are predominantly quartz, feldspar, and mica. Consequently, silt has weak linkage among grains and low activity, which usually does not satisfy the requirements of road construction. Therefore, soil additives are commonly used to stabilize such silts (Zhu and Liu, 2008).

Application of stabilization agent on soils has a long history. Lime is a widely used traditional additive for chemically transforming weak subgrades into structurally strong road subgrades (Bell, 1996). Many other kinds of materials, such as cement (Aniculaesi et al., 2013; Jauberthie et al., 2010) and special additives such as pozzolanic materials like fly ash (Dermatas and Meng, 2003; Serbanoiu et al., 2017), silica fume (Abd El–Aziz, 2003), and rice husk ash (Choobbasti et al., 2010), which are as waste material, have been used for soil improvement. Most existing stabilizers like lime and cement are not very useful for silts, so the silts with such stabilizing agents usually cannot satisfy the requirements of road construction. The encountered problems mainly are lower early strength, greater shrinkage, easy cracking, and bad water stability (Mohamedzein et al., 2003; Sheng and Ma, 2001). Therefore, new methods are still being researched to increase the strength properties of silty soils.

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One of the stabilizer agents is waste silica fume, which is obtained from silicon material or silicon alloy metal factories. Nowadays, nearly 100,000 tons of silica fumes are produced on worldwide purposes each year. Although the silica fume is a waste material of industrial applications, it has become the most valuable by–product among the pozzolanic materials due to its very active, high pozzolanic property and very fine particles. These particles are approximately 100 times smaller than the average cement particle (Karimi et al., 2011).

When a pozzolanic material like silica fume is added to lime, calcium hydrate is analyzed and reacts with silica to form calcium–silicate cement with soil particles in presence of water that contributes the strength gain of the soil. This reaction is represented as (Eq. 1):

$$Ca(OH)_2 = Ca^{2+} + 2(OH)$$
$$Ca^{2+} + 2(OH)^{-} + SiO_2 = CaO.SiO_2 + H_2O \quad (1)$$

In previous studies, many researchers have investigated the effects of silica fume on the strength, geotechnical properties, swelling characteristics and desiccation cracks of clayey soils. It was seen that silica fume improved the properties of clayey soils (Abd El–Aziz et al., 2004; Kalkan and Akbulut, 2004; Kalkan, 2009; McKennon et al., 1994).

However wetting–drying activities in roadways may have significant influence on pavement performance but the effect of wetting and drying on the behavior of subgrade soil has received little attention especially for cohesionless soils. Due to the fact that the seasonal variation in moisture and temperature occurs in most areas, road beds are generally softer in the spring than they are at other times of the year (Rogers et al., 2006). Kalkan (2011) has investigated the influence of wetting and drying cycles on clays stabilized with lime and silica fume and found that silica fume decreases the progressive deformation of modified expansive clayey soils subjected to cyclic drying and wetting.

In cold regions, soils are exposed to at least one freezing and thawing cycle every year. The freezing and thawing of the soils can cause the considerable changes of the geotechnical properties (Eigenbrod et al., 1996; Viklander, 1998). Cracking is the ordinary results of freezing–thawing damage in stabilized soils. Yarbaşı et al. (2007) concluded that silica fume–lime additive enhances the freezing–thawing durability of granular soils. Generally, both natural and stabilized soils exhibit a brittle behavior after freezing–thawing cycles. Altun et al. (2009) demonstrated that Unconfined Compressive Strength (UCS) of silty soil stabilized with fly ash and cement subjected to freezing–thawing cycles was higher than natural soil specimens.

Although many studies have considered for effect of freezing–thawing and wetting–drying on stabilized soils, the impacts of stabilized pure silts have been lacking. Therefore, this research's aim is to investigate the feasibility of using silt stabilized with silica fume and lime for a railway subgrade and evaluating the effects of wetting–drying and freezing–thawing cycles on them.

2. Experimental procedure

2.1. Materials used

The silts used in this research were obtained from the Karaj railway project in Iran. Atterberg limits tests were carried out according to ASTM D 4318 (1999) and the Liquid Limit (LL) and Plastic limit (PL) of soil are determined to be 24 and 21 respectively. Therefore, the soil Plasticity Index (PI) equals 3.0 and the soil was classified as a silty soil with low plasticity (ML) according to the unified soil classification system ASTM D 422–87. The grain size distribution of the soil is shown in Fig. 1. The tested soil is consists of 16% sand, 64% silt and 20% clay. The optimum moisture content (ω_{opt})and the maximum unit weight (γ_{dmax}) of soil are determined 14.2% and 17.2 kN/m^3, respectively based on compaction test results (ASTM D1557, 1991).

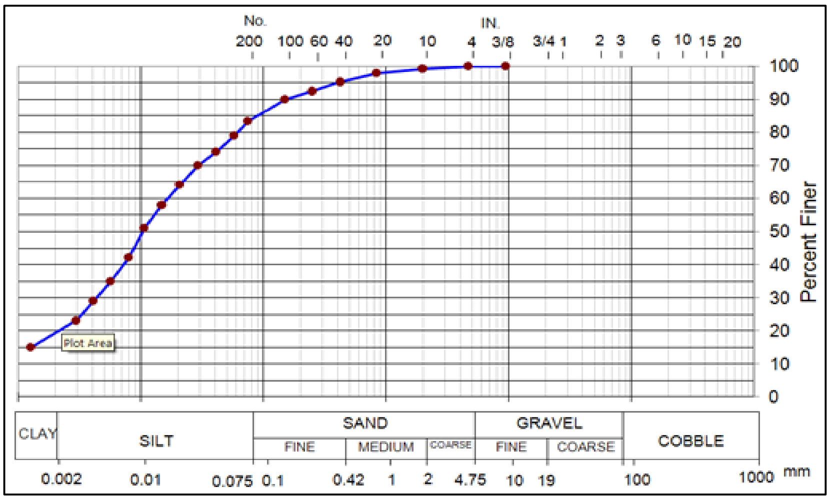


Fig. 1. Grain size distribution curve of the silty soil

The lime utilized in this study was an industrial hydrated lime. The chemical properties of lime and silica fume are presented in Table 1 and 2 respectively.

Table 1. Chemical properties of lime

Chemical names	***(%)***
$Ca(OH)_2$	82~93
$Mg(OH)_2$	0~5
SiO_2	0~9
Al_2O_3	0~1

Table 2. Chemical properties of silica fume

Chemical names	***(%)***
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
Water Content	0.01~0.04
pH	6.6~8.8

2.2. Test procedure

To evaluate the effects of lime–silica fume on the California Bearing Ratio (CBR) values of stabilized silty soils, oven–dried soil passing sieve #4 was treated with lime (1, 3, 5%) and silica fume (0, 2, 5, 8 and 12%) of dried soil weight, respectively. The required amount of water was added to the mixture to obtain soil optimum moisture as determined from standard compaction tests (ASTM D 1557-91, 1991). Three sets of samples were prepared for 1, 7 and 28 days curing time. Then CBR tests were carried out on the samples after soaking for 96 hours according to ASTM D 1883 (1999). At the end, several freezing–thawing and wetting–drying cycles (one, three and five) were conducted on the optimum additive content.

2.3. California Bearing Ratio (CBR) tests

To evaluate the potential strength regarding the time, CBR tests were conducted in three series of curing times (1, 7 and 28 days) according to ASTM D 1883-99. For this purpose, the samples were placed in 25ºC room temperature. To conduct the tests in soaked condition, the samples were submerged in water for 96 hours under the 4.5 kg overload according to the standard test method. In this procedure, a layer of water was also supplied at the base of the samples inside the container to maintain saturation and minimize water migration from the samples. Meanwhile, the variation of the samples unit weight and water content were determined after the samples soaking and swelling changes were measured during the soaking time. Thereafter, CBR tests were carried out according to ASTM D 1883–99 and the CBR value is determined based on the following equation: out according to ASTM D 1883–99 and the CBR value is determined based on the following equation:

$$CBR\ (\%) = (X/Y) \times 100 \quad (2)$$

where: X = Material resistance or the pressure on the piston for 2.54 mm of penetration, Y = Standard pressure for 2.54 mm of penetration = 6.9 MPa.

2.4. Freezing–Thawing cycles

Freeze–thaw tests are important for applications of fine–grained soils in cold regions. After performing the CBR tests, one mixture of lime and silica fume (3% lime, 2% silica fume) was chosen as a desired sample from both economic and resistance viewpoint (CBR>100 in minimum combination of lime and silica fume) to evaluate the effect of one, three and five freezing–thawing and wetting-drying cycles on the strength of the soil. To conduct freeze–thaw tests on the samples, complex field conditions are typically simplified into the one of the two commonly used testing systems: (1) an open system, where water at the bottom of the sample is made available during the freezing process; and (2) a closed system, where no source of water is available during the freezing process beyond that originally in the voids of the soil (Jones, 1987).

Freeze–thaw tests in present study were conducted in a closed system due to ASTM D5918 (2013) procedure for regions where there is little precipitation and deep water tables such as Karaj railway project. Freezing and thawing time and temperature are selected based on ASTM D5918 (2013) and also considering the existing environmental conditions in Karaj area and employer requirements. Three similar samples were rebuilt in the same above-mentioned condition on 6–inch CBR molds.

The molds were closed at the top and bottom, placed into a cold room after 28–day curing time, and required 96 hours for soaking. The samples were placed at –20ºC for 24 hours and after this time were transferred to the room temperature (25ºC) in a sealed plastic bag for the next 24 hours to expose to one freezing–thawing cycle. Samples were exposed to one, three and five freeze thaw cycles separately and then CBR tests were carried out on them.

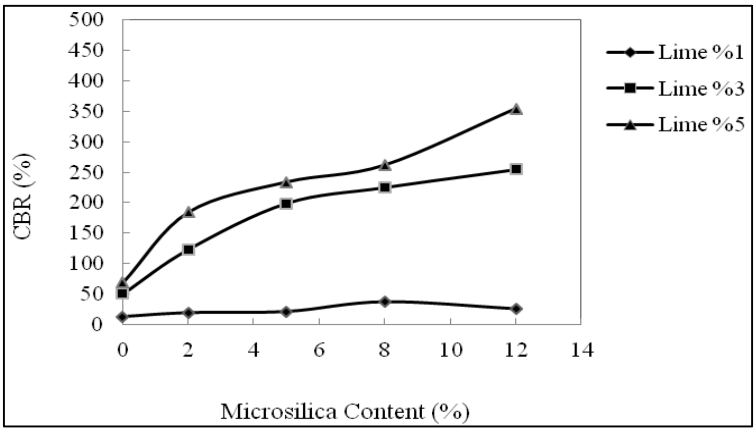
2.5. Wetting - drying cycles

The stabilized samples, which are cured for 28 days, are subjected to wetting–drying cycles. The wetted samples were placed in room to air–dry after soaking for 24 hours. Then they were again submerged in water for next 24 hours. A wetting–drying cycle was completed with the saturation of samples and their drying in an air–dry environment. Samples were exposed to one, three and five freeze wetting-drying cycles separately, and then CBR tests were carried out.

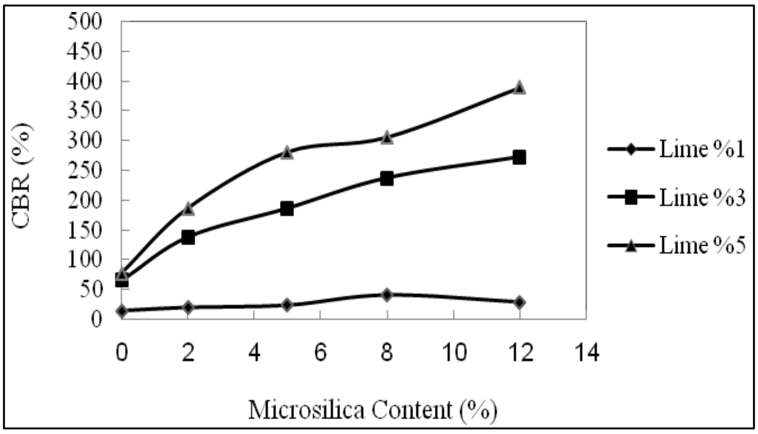
3. Results and discussion

3.1. Effect of additives on the CBR values

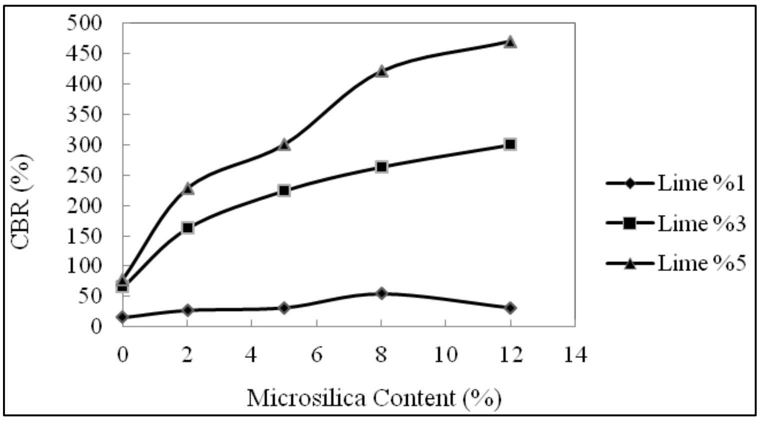
The CBR tests were conducted in both stabilized and unstabilized silty soils at the soil optimum moisture content with different amount of lime and silica fume and various curing time. The CBR value of unstabilized sample was 4.8%. The effects of additives on the CBR values of samples in 1, 7 and 28–day curing time are presented in Fig. 2. From Fig. 2, it can be observed that in the low amount of lime (1% of dry soil weight) an increase in silica fume amount up to 8% causes an increase in CBR values followed by a decrease. For 3% and 5% lime, increase in silica fume amount causes an increase in CBR values. The explanation of this behavior is probably related to pozzolanic reaction in lime-silica fume mixture.



(a)



(b)



(c)

Fig. 2. Effect of the various amount of lime– silica fume additive on the CBR values of stabilized soil
(a) 1–day curing time; (b) 7–day curing time; (c) 28–day curing time

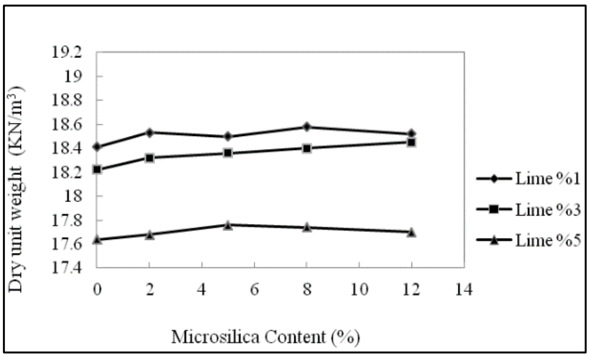
Generally, when a pozzolanic material like silica fume is added to lime, calcium hydrate is analyzed and reacts with silica to form calcium–silicate cement with soil particles in presence of water that contributes the strength gain of the soil. In low percent of lime (1% of dry soil weight) the amount of lime to achieve the calcium-silicate is not enough for more than 8% silica fume. Therefore, the pozzolanic reaction is not completed and the CBR values are reduced. But as the lime increases (3% and 5% of dry soil weight) the pozzolanic reaction are completed and the CBR values are also increased. In general, the CBR values of treated soil increases with increasing curing age due to completion of puzzulanic reaction. This behavior is in agreement with earlier findings (Abd El–Aziz et al. 2004; Karimi et al., 2011; Yarbaşı et al. 2007), were also reported soil CBR test results in sandy soils stabilized with lime and silica fume.

Fig. 2 is also show that the maximum CBR value of cured samples was obtained at 5% lime and 12% silica fume on 28–day after curing. The CBR value in this mixture was increased from 4.8% for unstablized soil to 470.8% for the stabilized soil. Therefore, it is resulted that up to 466% increase in CBR value of stabilized soil as compared to unstabilized silty soil.

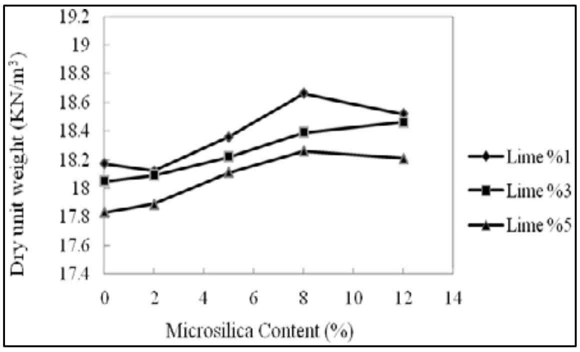
The sample moistures are determined after soaking by producing water content test on witness sample. After that, the dry unit weight is determined by measuring total weight of soil sample. The obtained results in different curing times are shown in Figs. 3 and 4, respectively. It is observed that the addition of lime reduces the maximum compacted dry unit weight and increase the optimum moisture content (OMC) in accordance to past studies such as Neubauer and Thompson (1972), Harichane et al. (2011), Amiralian et al. (2012) and Zoubir et al. (2013). The explanation of this behavior is probably a consequence of the following reasons: (1) the lime causes aggregation of the particles to occupy larger spaces and hence alters the effective grading of the soils; (2) the specific gravity of lime generally is lower than the soils tested. Furthermore, the increase in optimum water content (OMC) is due to the high surface area of lime, and the decrease in maximum dry density (MDD) is due to the low specific gravity of lime (Harichane et al., 2011).

Variations in MDD and OMC with the increase in silica fume for lime-stabilized soils are also presented in Figs. 3 and 4 respectively. It has been shown that the addition of a combination of lime and silica fume to the soil increase the MDD as the percentage of silica fume increases to a threshold content, after which a decrease in MDD is noted. This threshold is reached at about 8% silica fume.

Several researchers (Ola, 1977; Rahman, 1986; Amiralian, 2012; Basha et al., 2003; Harichane et al., 2011) revealed that the change in dry density occurs because of both particles size and specific gravity of the soil and the stabilizer used. Principally, the increase in MDD is an indicator of improvement. The decrease of moisture content is also effective in the improvement of soil resistance and decrease of swelling potential especially in freezing–thawing cycles.



(a)



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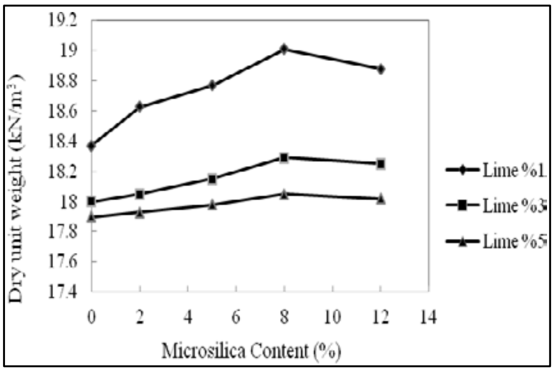

(c)

Fig. 3. Effect of lime–silica fume additive on dry unit weight in (a) 1 curing day (b) 7 curing days (c) 28 curing days

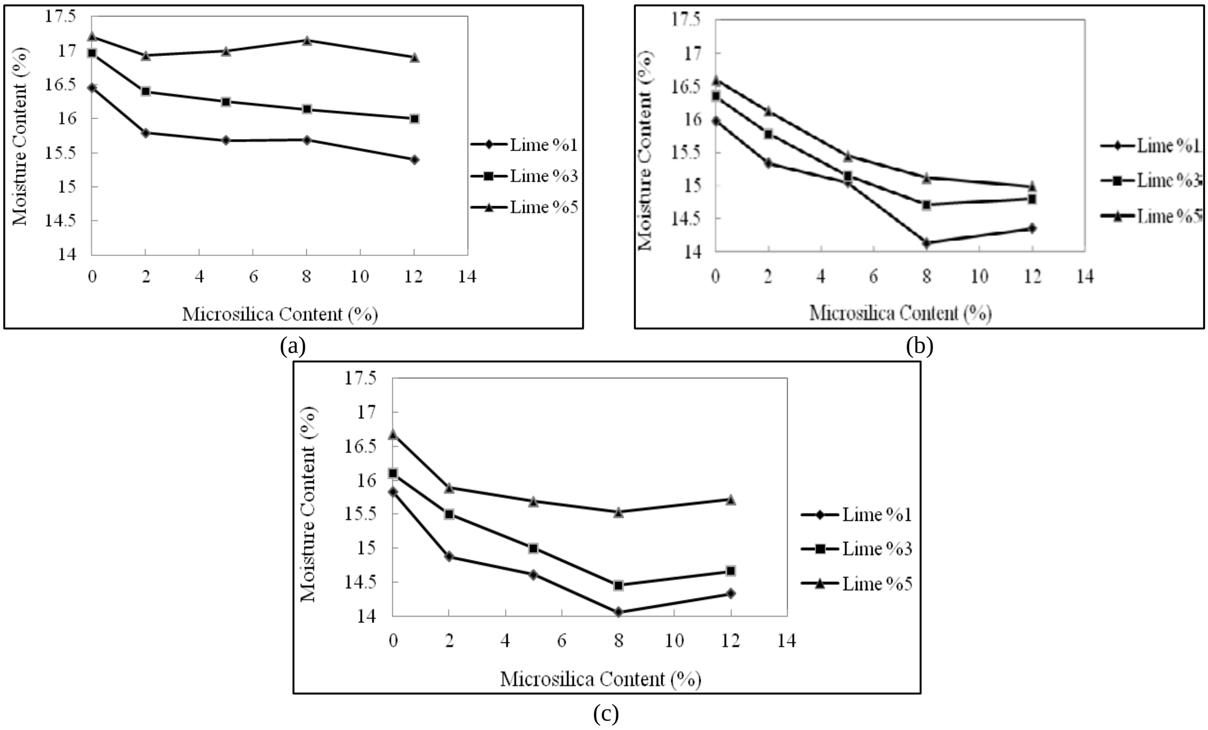

Fig. 4. Effect of lime–silica fume additive on moisture after soaking in (a) 1 curing day (b) 7 curing days (c) 28 curing days

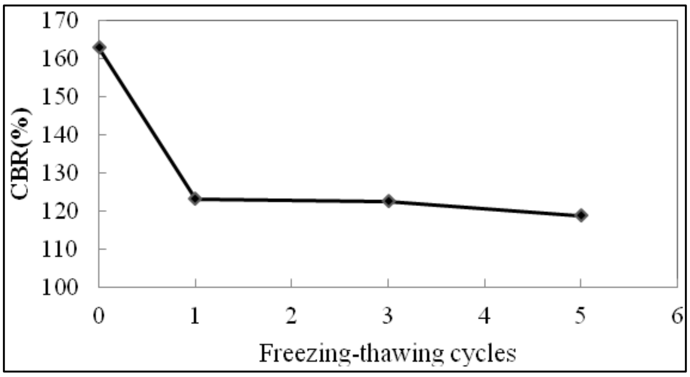

Fig. 5. Effect of freezing–thawing cycles on CBR values of the 28–day sample stabilized with 3% lime and 2% silica fume.

3.2. Effect of freezing–thawing cycles on samples CBR values

The sample stabilized with 3% lime, 2% silica fume was chosen as desirable sample in the terms of resistance (CBR>100 in minimum combination of lime and silica fume), and freezing–thawing cycles were conducted on it. It is generally agreed that the phase change from water to ice upon freezing causes a decrease in strength (Martin et al., 2009). The result of freezing–thawing cycles on CBR values of the sample are given in Fig. 5. It is observed that a sudden decrease was occurred in the CBR value of stabilized samples after the first cycle, but decreasing CBR values occurred very slightly during the third and fifth cycles. In spite of freezing–thawing effect on CBR values decreasing, CBR value of treated soil by lime and silica fume is more than 120%, even after 5 cycles which is appropriate for road construction projects. Mosta'r et al. (2011) reported the similar results in clayey soil stabilization with lime and silica fume. They reported that the soil strength stabilized with lime and silica fume after 12 freezing–thawing cycles are 32% more than the soil strength stabilized with lime alone.

Kalkan (2009) used a fine-grained soil stabilized by adding silica fume which was generated during silicon metal production. The test results show that the stabilized fine-grained soil samples containing silica fume exhibit high resistance to the freezing and thawing effects as compared to natural fine-grained soil samples. The silica fume decreases the effects of freeze–thaw cycles on soil strength and permeability due to decrease of void ratio.

3.3. Effect of wetting– drying cycles on CBR values

Fig. 6 presents the effect of wetting– drying cycles on the CBR values of samples. It is observed that the CBR value increased after the first wetting–drying cycle. Thereafter the sample CBR starts to decrease gradually. The reason for increasing CBR at the first cycle is assessed by decreasing in permeation due to lime–silica fume stabilizer that 96 hours submerging was not enough for required moisture penetration. It is notable that the CBR value rate after the fifth cycle is still more than initial amount.

Harichane et al. (2010) studied the impact of cyclic wetting and drying on compressive strength behavior of lime-natural pozzolana stabilized clayey soils. Based on the durability results obtained, they found that the clayey soils stabilized by the combined action of lime and natural pozzolana exhibits high performance and survive a full 12 cycles of wet-dry testing. Also, the residual compressive strength increases significantly compared to initial compressive strength. It seems that it might be the consequence of the continuing pozzolanic reaction and of extended curing during wet-dry cycles.

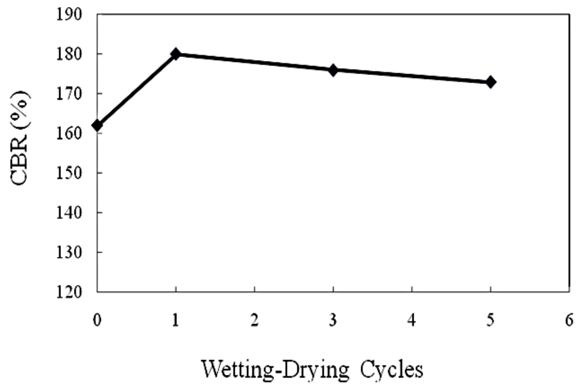

Fig. 6. Effect of wetting– drying cycles on CBR values of 28–day sample stabilized with 3% lime and 2% silica fume

4. Conclusions

The influences of lime–silica fume additive on silty soils and the freezing–thawing and wetting–drying and cycles were investigated in this study and the following conclusions were drawn:

- Lime–silica fume additive played an important role in the increase of the CBR values of the silty soil. The CBR value of the unstabilized soil increased from 4.8% up to 470.8% by adding 5% lime and 12% silica fume.
- In the low amount of lime (1% of dry soil weight) an increase in silica fume amount up to 8% causes an increase in CBR values followed by a decrease. For 3% and 5% lime, increase in silica fume amount causes an increase in CBR values. The explanation of this behavior is probably related to pozzolanic reaction in lime-silica fume mixture. Generally, when a pozzolanic material like silica fume is added to lime, calcium hydrate is analyzed and reacts with silica to form calcium–silicate cement with soil particles in presence of water that contributes the strength gain of the soil. In low percent of lime (1% of dry soil weight) the amount of lime to achieve the calcium-silicate is not enough for more than 8% silica fume. Therefore, the pozzolanic reaction is not completed and the CBR values are reduced. But as the lime increases (3% and 5% of dry soil weight) the pozzolanic reaction are completed and the CBR values are also increased. In general, the CBR values of treated soil increases with increasing curing age due to completion of puzzulanic reaction.
- Addition of lime reduce the maximum compacted dry unit weight and increase the optimum moisture content (OMC) of silty soils in accordance to past studies such as: Amiralian et al. (2012), Harichane et al. (2011), Neubauer and Thompson (1972), Zoubir et al. (2013). The explanation of this behavior is probably a consequence of the following reasons: (1) the lime causes aggregation of the particles to occupy larger spaces and hence alters the effective grading of the soils; (2) the specific gravity of lime generally is lower than the soils tested. Furthermore, the increase in OMC is due to the high surface area of lime, and the decrease in MDD is due to the low specific gravity of lime (Harichane et al., 2011).
- Addition of a combination of lime and silica fume to the soil increase the MDD as the percentage of silica fume increases to a threshold content, after which an decrease in MDD is noted. This threshold is reached at about 8% silica fume. Several researchers (Amiralian, 2012; Basha et al., 2003; Harichane et al., 2011; Ola, 1977; Rahman, 1986;) revealed that the change in dry density occurs because of both particles size and specific gravity of the soil and the stabilizer used.
- Principally, the increase in MDD is an indicator of improvement. The decrease of moisture content is also effective in the improvement of soil resistance and decrease of swelling potential especially in freezing–thawing cycles.
- Freezing–thawing cycles caused reduction in the CBR values of treated silty sample. Almost 90 percent of the reductions occurred at the first cycle and there was no significant reduction with subsequent cycles. In spite of the freezing–thawing effect on the CBR values decreasing, the CBR value of treated soil by lime and silica fume is more than 120%, even after 5 cycles which is appropriate for road construction projects.
- The CBR value of treated silty soil after the fifth wetting-drying cycle is still more than initial amount. It seems that it might be the consequence of the continuing pozzolanic reaction and of extended curing during wet-dry cycles. This behavior is in agreement with Harichane et al. (2010) studies on the impact of cyclic wetting and drying on compressive strength behavior of lime-natural pozzolana stabilized clayey soils
- Lime–silica fume additive mixtures can be used to improve the strength of silts for the road construction. In addition, stabilized soil has adequate durability versus wetting–drying and freezing–thawing cycles.

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