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Study of geotechnical properties of a gypsiferous soil treated with lime and silica fume

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Abstract. The gypsiferous soils are significantly sensitive to moisture and the water has a severe destructive effect on them. Therefore, the effect of lime and silica fume addition on their mechanical properties, when subjected to water, is investigated. Gypsiferous soil specimens were mixed with 1, 2 and 3% lime and 1, 3, 5 and 7% silica fume, in terms of the dry weight of soil. The specimens were mixed at optimum moisture content and cured for 24 hours, 7 and 28 days. 86 specimens in the sizes of unconfined compression strength test mold were prepared to perform unconfined compressive strength and durability tests. The results proved that adding even 1% of each of these additives can lead to a 15 times increase in unconfined compressive strength, compared with untreated specimen, and this increases as the curing time is prolonged. Also, after soaking, the compressive strength of the specimens stabilized with 2 and 3% lime plus different percentages of silica fume was considerably higher than before soaking. The durability of the treated specimens increased significantly after soaking. Direct shear tests showed that lime treatment is more efficient than silica fume treatment. Moreover, it is concluded that the initial tangent modulus and the strain at failure increased as the normal stress of the test was increased. Also, the higher lime contents, up to certain limits, increase the shear strength. Therefore, simultaneous use of lime and silica fume is recommended to improve the geotechnical properties of gypsiferous soils.

Keywords: gypsiferous soil; stabilization; lime; silica fume; unconfined compressive strength; durability

1. Introduction

Despite all the attention paid to the design of hydraulic structures, neglecting the destructive effects of problematic soils, results in irreparable consequences. Also, the high cost of construction of these structures and budget constraints persuades engineers to maximize the use of local material.

Gypsiferous soils are mostly found in arid and semi-arid regions of the world with an annual rainfall of less than 500 mm, such as Iran (FAO 1990). In arid and semi-arid parts of Iran, such as the south-west provinces, central deserts, and some north-east areas, large quantities of gypsum deposits exist in soils classified as Gypsiferous. The presence is reported in many places in the world, such as Algeria, Tunisia, and Central Australia (van Alphen and de Los Rios Romero 1971). Gypsiferous soils are classified as collapsible soils, too. Gypsum provides apparent cementation when the soil is dry, but the intrusion of water causes dissolution and softening of the soil that may lead to partial or complete failure of the soil and collapse of the structures (Jotisankasa 2005), (Ismael 1993).

Due to the vast extent of gypsiferous lands and increasing population growth, project construction in this type of soils is necessary. The study of the problems caused by these soils and the effect of gypsum on these projects is of particular importance.

Destruction of Zayandeh Rood irrigation network main canal, in Isfahan, the central part of Iran, is an example of this problem (Abbasi *et al.* 2011, Azinfar 1999). Another example is the damages of Maroon irrigation network main canal (canal A) in Behbahan city, located in Khuzestan Province SW of Iran, which is attributed to dissolution of gypsum in the subgrade of the canal and large holes formed, leading to differential settlements and final destruction of the canal lining (Abbaspoor *et al*. 2008). Fig. 1 shows the failure of Maroon irrigation network canal A concrete lining due to settlements caused by gypsum dissolution.

The soil stabilization method using additives such as silica fume, fly ash, and ground granulated blast-furnace slag, as the most common industrial by-product pozzolans, is used to modify the properties of soils. Pozzolans consist of aluminous and siliceous materials which, in very fine size, in the presence of water, react with calcium hydroxide and create cementitious materials (Mehta 1987).

The presence of sulfate in the soil stabilized with lime leads to the formation of colloidal products containing complex compounds of hydrous calcium aluminum sulfate on the surface of clay particles which, if some water is absorbed, a crystalline product called ettringite is produced from these materials. The amount of this product is controlled by the amounts of uncombined lime, gypsum and alumina available in the environment (Abdi and Wild 1992). Initially, this mineral increases the soil strength, since the formation of this material is associated with the absorption of environment water (Wild *et al.* 1996), but instead increases the soil swelling potential significantly

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Fig. 1 Failure of Maroon irrigation network canal A concrete lining

(Wild *et al.* 1999).

Comprehensive studies have shown that in soils containing sulfate stabilized with lime, silica fume prevents the formation of harmful products such as ettringite. On the other hand, carbonation occurs when there is not enough pozzolanic clay in the soil mixture. Calcium carbonate prevents pozzolanic reactions; therefore, silica fume addition prevents carbonation and increases the cementation reactions. Using silica fume increases soluble calcium content which enhances the pozzolanic activities (Leonards 1962). Adding silica fume also increases the *pH* significantly and by increasing this parameter, silicates and aluminates are released from its tetrahedral and octahedral sheet structures which accelerates the pozzolanic reactions. (Mckennon *et al.* 1994).

Wild *et al.* (1996) examined the effect of ground granulated blast furnace slag addition on the geotechnical properties of lime-stabilized kaolinite subjected to the sulfates attack and concluded that this additive, by the reduction of the swelling potential, decreases the undesirable effects of sulfate presence in clayey soils stabilized with lime. Shihab *et al.* (2002) showed that adding fuel oil and bentonite to a gypsiferous soil decreases the solubility of gypsum due to reduction the gypsum dissolution coefficient rate via leaching the specimens treated with these two additives with river water. Ghiassian and Jahanshahi (2002) conducted tests of mixing lime with sulfate bearing soil in two steps. They concluded that, as some of the swelling reactions are completed between the two steps, the destructive effects of the ettringite formation are reduced, and the stabilized soil reaches a steady state earlier after adding lime at the second step. Zhang and Solis (2008) investigated physical and mechanical properties of a gypsiferous soil treated with fly ash. The results of the experiments carried out before and after adding this material showed that the engineering properties of these soils are improved to a satisfactory level by increasing the shear strength and maximum dry density and decreasing the swelling potential. Makarchian and Mirjafari (2009) explained that silica fume addition to the lime- stabilized sulfate-bearing soil reduces destructive effects of ettringite formation and its subsequent swelling. (Makarchian and Mirjafari Miandeh 2010). They, also, concluded that preparing specimens on the wet side of optimum reduces swelling potential significantly, although CBR of the soil may be reduced. Aziz and Ma (2011) showed that fuel oil addition to the gypsiferous soil decreases the permeability and the collapsibility and increases the durability of the treated specimens compared with untreated ones. Harichane *et al.* (2011) investigated the effect of a natural pozzolan, lime or a combination of both on compaction and strength of the treated cohesive soils cured for different periods. The results showed that the cohesive soils could be successfully stabilized by combining natural pozzolan and lime. Mishra (2012) attempted to improve the strength properties of clayey soil to be used as subgrade by using fly ash mixed with lime and observed that adding 3% lime along with 30% fly ash by weight of virgin soil improved the California bearing ratio (CBR) values remarkably. Also, the modulus of elasticity increased by ten times. Kadhim (2014) confirmed these results for cut-back asphalt treated gypseous soil. Moayed *et al.* (2012) studied the use of lime and mixture of lime and micro silica on stabilization of a saline soil. It was observed that a low percentage of lime is very effective. Adding micro silica to lime is useful up to some certain limit amount, and has a reverse effect if the amount is increased. Fattah *et al.* (2014) and Guleria *et al.* (2012) investigated the effect of acrylate liquid or treated tire chips addition to gypsiferous soils and reported reduced collapsibility and increased modulus and strength due to the isolation of gypsum particles from being exposed to the effect of water. Abedi Koupai *et al.* (2015) showed that silica fume is more effective than pumice and perlite on the strength and mechanical properties of gypsiferous soils. Ibrahim *et al.* (2015) studied the effect of adding hydrated lime, hydrated calcium chloride and kaolin on the collapse potential of a gypsiferous soil and concluded that all employed additives could be used to decrease the collapsibility of these soils, but lime decreases this property more significantly than the two other additives. Sivapullaiah and Jha (2014) examined the effect of fly ash blended with lime on physical properties and strength of gypsiferous soils. They concluded that the soil plasticity improvement and strength gain are accelerated due to the filling of voids with ettringite needles and formation of cementitious compounds, which enables interlocking of clay particles. Fattah *et al.* (2015) used lime and silica fume for grouting a soft clay underneath and around a footing. It was found that grouting of a slurry of lime-silica fume, increases the bearing capacity in a range of 7-88%. Mohammed and Vipulanandan (2015) stabilized a CL soil under sulfate attack with lime and fly ash. Calcium sulfate forms calcium silicate sulfate (Ternesite) and aluminum silicate sulfate. Therefore, treating soils with fly ash resulted in the formation of cementitious by-products, such as calcium or magnesium silicate hydrate, which reduce its swelling and increase its short-term compressive strength. Afsharian *et al.* (2016) indicated that the amount of gypsum in the soil had a direct effect on its rate of solubility. The statistical analysis showed gypsum percentage had the highest impact and hydraulic gradient had the lowest impact on gypsum solubility, while for clayey soils texture has no significant effect on solubility. Kilic *et al.* (2016) investigated the effect of lime, gypsum and lime- gypsum mixture on the swelling and compression strength of highly plastic clays compacted in an optimum condition. They indicated that adding gypsum is not effective but adding lime is very useful. Ibrahim and Schanz (2017) showed that silicone oil added to the gypsiferous soil increases the shear strength and reduces the dissolution of gypsum particles and collapse potential. Asghari *et al.* (2017) conducted a leaching process of a gypsiferous soil and found that the soil shear strength is decreased due to the cohesion reduction resulting from the removal of gypsum particles during leaching and the soil collapse is due to dissolution of gypsum. Alsafi *et al.* (2017) compared stabilization of gypsiferous soil with fly ash geopolymer binder and Portland cement and showed that fly ash is a better stabilizing agent than Portland cement due to its calcium-free structure which, compared to Portland cement, leads to a higher strength and sulfate resistance. Alrubaye *et al.* (2018) used lime and silica fume in the stabilization of a kaolin clay. A consolidation test was carried out on kaolin mixed with silica fume and different percentages of lime. Based on the results obtained, the coefficient of permeability decreases, which in turn reduces the compression index (C_c). The compression index and the average coefficient of volume compressibility decrease with increasing the stabilizer content due to a pozzolanic reaction happening within the soil which results in changes in the soil matrix.

The previous studies have well indicated the positive effects of the silica fume addition to sulfate bearing soils that have been stabilized with lime. Therefore, lime and silica fume were chosen as two additives used in this study.

Due to the limitation of studies conducted on the sensitivity of the gypsiferous soil structures in contact with water, one of the major aims of this research is to study the effect of lime and silica fume addition on the control of this feature. The most important objective of this research is the investigation of the impact of adding these materials on the strength properties of gypsiferous soil both before and after soaking the specimens.

2. Materials

The studied gypsiferous soil specimens were collected from the area of the main canal A of Maroon irrigation network in Behbahan city, located in Khuzestan Province, South West of Iran.

The presence of gypsum minerals with special physical and chemical characteristics complicates the determination of properties such as moisture content, the grain size distribution and specific gravity of the particles. The studies conducted by Arakelyan (1986) showed that calcium hydrate is converted into semi-water gypsum at a temperature of 80-90°*C*, which, in turn, creates a significant error in the determination of moisture content of gypsiferous soils. Therefore, Arakelyan (1986) proposed Eqs. (1)-(2) for calculation of moisture content in the clayey

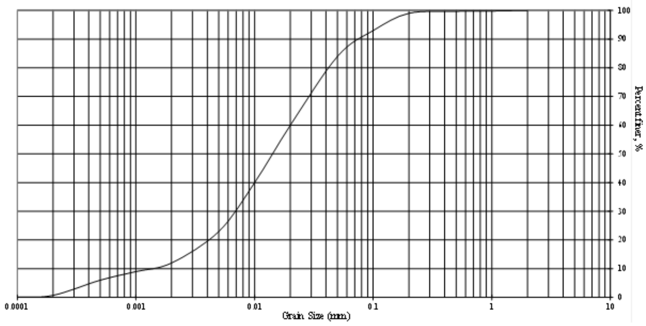


Fig. 2 Grain size distribution curve of the gypsiferous soil using a Master sizer laser machine

Table 1 Results of soil grain size analysis

Gravel (%)	Sand (%)	Silt (%)	Clay (%)
0	9.39	65.4	25.2

Table 2 Geotechnical properties of gypsiferous soil

Specific gravity of solids (G_S)	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Optimum moisture content (%)	Max dry density (kN/m^3)
2.56	21	32	11	16.3	17.7

Table 3 Chemical properties of soil

Gypsum (%)	Calcium (%)	Magnesium (%)	Chloride (%)	Sulfate (%)	*pH*
59	0.021	0.0036	0.0051	0.0558	7.73

and sandy soils containing gypsum, respectively, based on the data obtained from drying the soil at a temperature of 60 ± 2°C.

$$\omega_{clay}=1.007(\omega^{60})+0.007 \tag{1}$$

$$\omega_{sand}=1.003(\omega^{60})+0.003 \tag{2}$$

in which ω^{60} is the water content of the soil if tested at t=60 ± 2°C and ω is the corresponding value for testing the same specimen at $t=105 \pm 2°C$ when avoiding liberation of crystallized water.

The gradation curve of the specimen, measured using a Master sizer laser machine is presented in Fig. 2, and the grain size analysis is shown in Table 1. The geotechnical and chemical characteristics of the soil specimens are presented in Tables 2 and 3, respectively.

The Atterberg limits of the soil were determined in accordance with the ASTM procedure (ASTM D4318-17). According to the Unified Soil Classification System, the soil was classified as a clayey soil with low plasticity (CL).

The optimum moisture content (OMC) and maximum dry density (MDD) of each mixture were determined by conducting standard Proctor compaction test (ASTM D698-12) on that specific mixture. The data was used in specimen preparation process. The optimum moisture content was increased as the lime or silica fume content were increasd. However, the maximum dry density was decreased.The decrease is attributed to two main reasons: flocculation and aggregation of the soil grains, due to cation exchange reaction and coating and binding the clay particles by lime

Table 4 Chemical composition of hydrated lime

SiO_2 (%)	Al_2O_3+Fe_2O_3 (%)	L.O.I (%)	CaO (%)	MgO (%)
0.7	1.2	26.6	71.1	0.4

Table 5 Chemical composition of silica fume

H_2O (%)	SiC (%)	C (%)	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	SO_3 (%)	Cl (%)
0.08	0.05	0.3	94.52	0.78	1.32	0.45	0.92	0.31	1.01	0.12	0.1	0.04

and silica fume, which yields a coarser soil with larger pores and replacement of soil grains with lime and silica fume, which are much lighter than soil. The results were consistant with Harichane *et al.* (2011).

The chemical properties of hydrated lime and silica fume used in this research are also reported in Tables 4 and 5, respectively.

Various factors, such as the amount of available clay in the soil and its plasticity Index, affect the soil and lime reactions. Fine-grained clayey soils containing more than 25% finer than No. 200 sieve and a plasticity index greater than 10% are suitable for stabilization with lime (ARTBA 2004). Thus, considering the characteristics of the soil, it is a good candidate for stabilization with lime and silica fume.

Fig. 3 Some sealed specimens after curing

3. Specimen preparation

3.1 Specimen preparation for unconfined compressive strength and durability tests

Initially, 1, 2 and 3 percent lime were added to the gypsiferous soil specimens, and then silica fume was added to each of the soil-lime mixtures in the percentages of 1, 3, 5 and 7, regarding the soil dry weight. All specimens were prepared at the maximum dry density and optimum moisture content obtained from a standard Proctor compaction test (ASTM D698-12). The dry weight of the required soil for each mixture was determined based on the volume of the unconfined compression strength test mold and maximum dry density.

In order to minimize the specimen disturbance, the specimens were prepared inside an unconfined compression strength test mold with a diameter of 5 and a height of 10 cm. Before compaction, the interior wall of the mold was coated with a lubricant and a plastic cover to make it easy to extrude the specimen using a hydraulic jack. The prepared mixtures were divided into five equal volumes, and each part is so compacted that it occupies one-fifth of the mold volume. This issue was carefully controlled for each part by placing a caliper on the surface of the compacted part of the specimen. The specimens were extruded from the mold by a hydraulic jack and completely sealed after removing the plastic cover. The specimens were cured for 24 hours, 7 and 28 days. Fig. 3 shows some of the prepared specimens. A total of 86 specimens were prepared in the size of the unconfined compression strength test mold to conduct unconfined compressive strength and durability tests. For inspection of the reproducibility of data, two replicas of each specimen were prepared and tested and the results were averaged.

In order to investigate the significant sensitivity of strength of soils containing gypsum salts in the vicinity of water, unconfined compressive strength tests (ASTM D2166 -16) were conducted on treated and untreated specimens, both before and after exposure to water. According to this standard, loading speed should be 0.5 to 2 percent of the axial strain/min, hence, an axial deformation rate of 0.5 mm/min was applied to the specimens. Also, some specimens were exposed to water, in order to investigate the effect of these additives on the level of sensitivity of gypsiferous soil structure. In other words, the durability of the specimens in contact with moisture over time was studied through these experiments. The prepared specimens were placed in the visible vessels containing distilled water. To avoid reducing the rate of specimen deterioration, the water in the containers was replaced with fresh distilled water regularly. After two months of exposure to water, the specimens were removed from the water and their dry weight was measured. Since the specimens were initially prepared at optimum moisture content and saturated after exposure to water, the dry weight was used as a basis of the calculation of the durability of the specimens, Eq. (3)

$$durability = \frac{final\ dry\ weight}{initial\ dry\ weight} \tag{3}$$

Since in the UCS tests, the specimens cured for 7 or 28 days, did not undergo any significant damage after soaking, only 12 specimens, containing various percentages of lime and silica fume, and 1 untreated specimen, cured for 24 hours, were prepared to study the effect of these additive materials on the durability of the structure of gypsiferous soil in contact with water.

Fig. 4 Specimen extracted by surcharge from the mold

Fig. 5 Sealed specimen inside the shear box for curing

3.2 Specimen preparation for the direct shear test

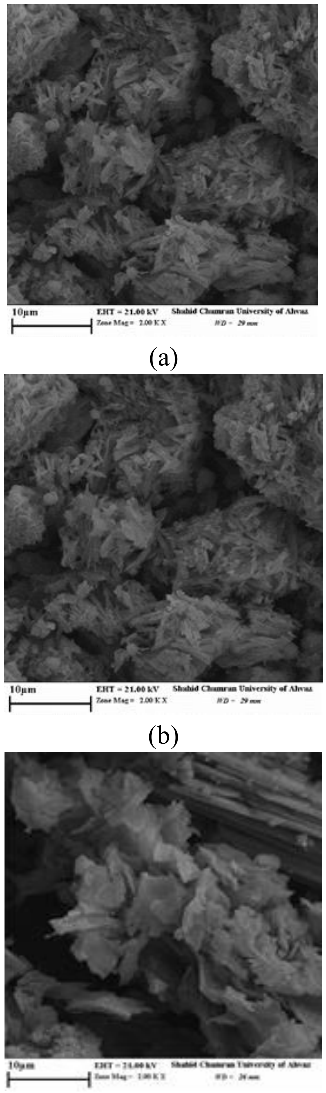
In order to minimize the specimen disturbance in the direct shear test, before compacting the soil mixture in the mold, its walls were pre-lubricated. Since the cured specimens showed a significant hardening and a very low strain rate under the application of the vertical load, the normal force was initially applied to the specimens, and the specimens were consolidated, then cured and finally loaded with the shear force.

After compacting the mixture in the special mold, with inside dimensions of 60 mm × 60 mm × 20 mm, the specimen was removed from the mold by the surcharge pressure, illustrated in Fig. 4. The specimen was put in the shear box, and a normal force was applied to the specimen. The shear box was removed from the machine and, keeping the specimen inside in order to minimize the specimen disturbance, fully sealed and cured for 24 hours (see Fig. 5). Finally, the direct shear test was conducted on the specimens at a rate of 0.5 mm/min (ASTM D3080-11).

4. Results and discussions

4.1 Mineralogical analysis

Fig. 6 presents SEM of untreated and treated specimens. The untreated soil includes big pores (Fig. 6(a)). The pores have reduced in size in the soil treated with 2% lime (Fig.6(b)) due to formation of calcium aluminate and silicate hydrates. These cementitious matters are the product of pozzolanic reaction and combine to form ettringite needles. The process continues when 5% silica fume is added, too (Fig. 6(c)). However, the ettringite needles react with silica fume and reduce in volume. Instead, calcium silicate plates form and grow in size.



(a)

(b)

(c)

Fig. 6 SEM of specimens after 7 days of curing: (a) untreated soil, (b) soil+2% lime and(c) soil+2% lime +5% silica fume

4.2 Results of unconfined compressive strength test

After curing, specimens were removed from the plastic covers, and an unconfined compressive strength test was performed on them at an axial deformation rate of 0.5 mm/min. Other specimens were tested after putting them in contact with water for two months to study the effect of moisture on their structure. Fig. 7 illustrates failure types of the some of the specimens, at the end of the unconfined compressive strength test.

The untreated specimen collapsed upon contact with water and practically no specimen was left to perform the unconfined compression strength test after a few minutes. However, adding even 1 percent lime and 1 percent silica fume increased the compressive strength significantly in

(a) (b) (c) (d)

Fig. 7 Failure types of some of the specimens tested by UCS before soaking: (a) untreated, (b) soil+1% lime, (c) soil+1% lime+ 1% silica fume and (d) soil+1% lime+ 3% silica fume

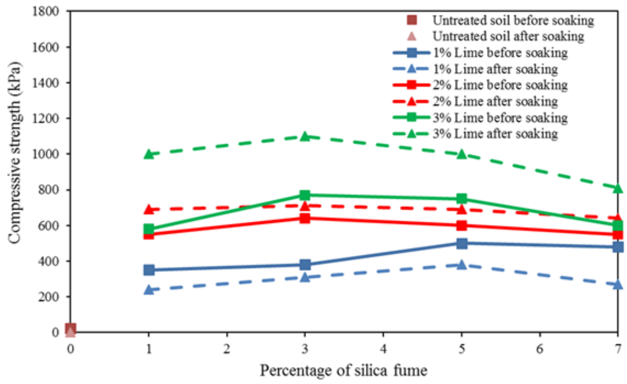


Fig. 8 Effect of lime and silica fume addition on the compressive strength of specimens cured for 24 hours before and after soaking of the specimens

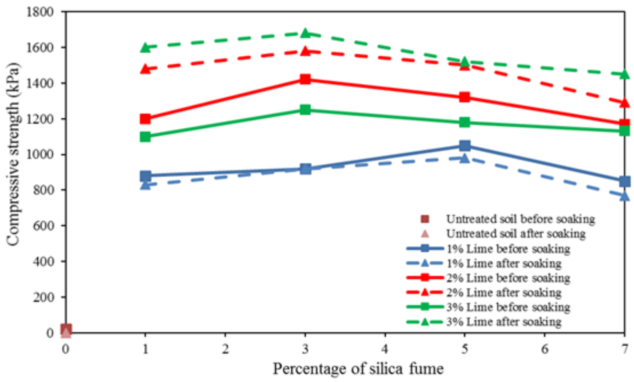


Fig. 10 Effect of lime and silica fume addition on the compressive strength of specimens cured for 28 days before and after soaking of the specimens

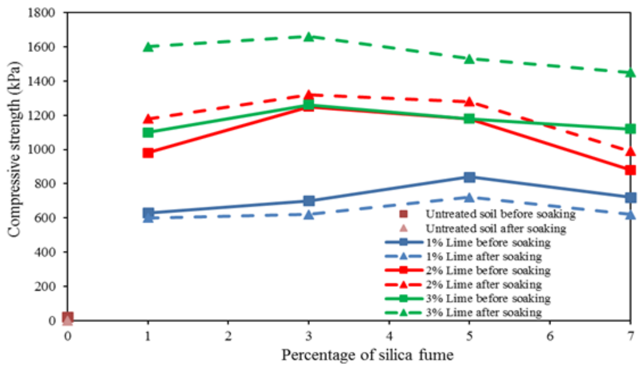


Fig. 9 Effect of lime and silica fume addition on the compressive strength of specimens cured for 7 days before and after soaking of the specimens

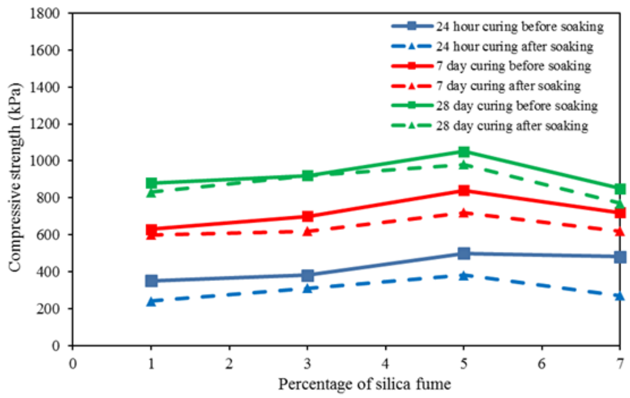


Fig. 11 Compressive strength of the specimens containing 1% lime before and after soaking with changing of curing time

comparison with the untreated specimen. The results of UCS tests before and after specimens were in contact with water are presented in Figs. 8-10.

After soaking, the compressive strength of the specimen containing even 1% of lime and 1% of silica fume, was ten times more than that of the untreated specimen before soaking. The compressive strength of specimens containing 2 and 3% of lime was increased considerably after soaking. The highest compressive strength was observed in the specimen containing 3% lime and 3% silica fume after soaking, which after 24 hours of curing, showed an increase of about 48 times compared with the untreated specimen even before soaking. This ratio is much higher, 73, for the specimens cured for 28 days.

Due to the completion of the cementation reactions over time, the compressive strength of the specimens is significantly increased as the curing time is prolonged. This

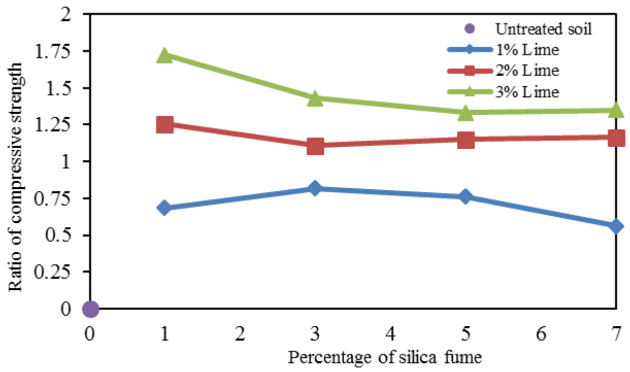


Fig. 12 Comparison of the compressive strength reduction ratios of untreated and stabilized specimens (24-hour curing)

Fig. 13 The complete collapse of the untreated specimen after 30 minutes from the beginning of exposure to water

is proven by the results of UCS tests of the specimens containing 1% lime as shown in Fig. 11.

In order to investigate the effect of soaking on the strength of specimens, the ratio of strength is introduced as in Eq. (4)

$$ratio\ of\ strength = \frac{compressive\ strength\ after\ soaking}{compressive\ strength\ before\ soaking} \quad (4)$$

Fig. 12 presents the changes of the ratio of the compressive strength of the specimens with different silica fume contents cured for 24 hours. It clearly illustrates a significant increase in this ratio for all stabilized specimens compared to untreated specimen.

4.3 Results of durability test

As shown in Fig. 13, the untreated specimen collapsed immediately after contact with water, indicating a high sensitivity of the gypsiferous soil structure adjacent to water.

Also, Figs. 14(a)-14(l) show the condition of stabilized specimens after two months of exposure to water. In Fig. 14, the letters L and S stand for lime and silica fume, respectively. The stabilized specimens were subjected to water for two months, and their durability was calculated using Eq. (3). The results of the durability test and calculated ratios are reported in Table 6.

Figs. 14(a)-14(l) and the data of Table 6 clearly show very slight or no damages of the stabilized specimens.

Table 6 Results of durability test

Percentage of silica fume	Percentage of lime		
	1	2	3
1	99	100	99.9
3	99.8	99.9	100
5	99.9	100	99.9
7	100	100	100

4.4 Results of the direct shear test

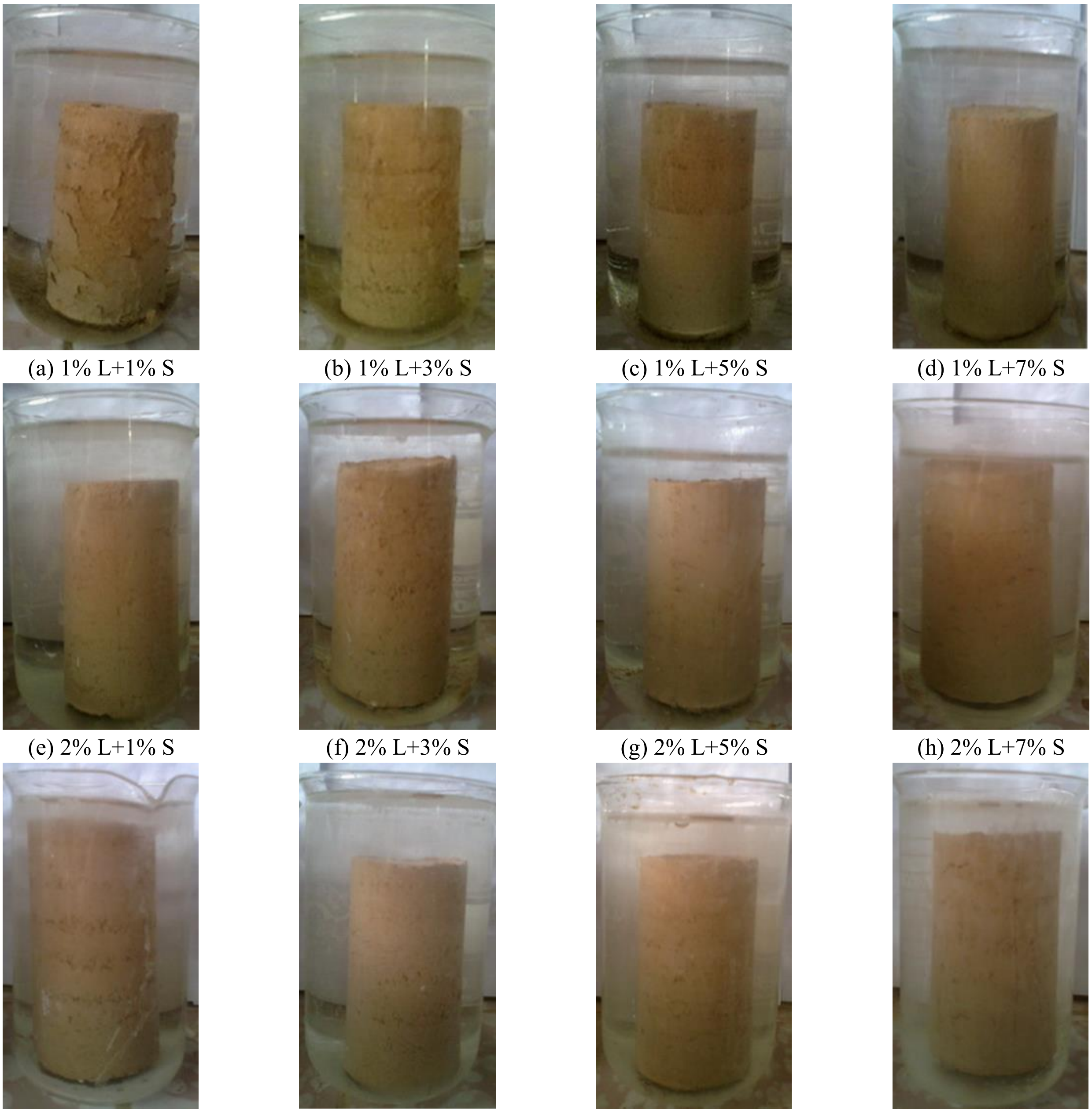
Direct shear tests were performed to evaluate the effect of adding lime and silica fume on the behavior of soil under shear loading. The direct shear tests were conducted on 39 specimens prepared from both untreated and treated soil specimens and their shear strength parameters were measured and compared. Figs. 15-17 show the Mohr-Coulomb failure envelope for untreated and treated specimens. The shear strength parameters of the specimens are, also, reported in Tables 7 and 8. It is evident that lime treatment is more efficient than silica fume treatment. Similar results were reported by Mohammad *et al.* (2015).

A three-dimensional plot of the data is presented in Fig. 18, for both the internal friction angle and cohesion of treated specimens. As it is depicted, lime addition is more effective than silica fume since in both plots the changes along the silica fume axis are much narrower than those along the lime content axis. Also, the cohesion and internal friction angle show an inverse correlation. It seems that higher lime content increases the specimen cohesion. While increasing the silica fume content does not show a consistent trend, generally, it reduces both of the shear strength parameters.

Figs. 19-21 show the variation of the shear strength of the specimens due to the increase in the percentage of silica fume compared to those of untreated specimen.

In specimens containing 1% lime, the shear strength and its parameters, cohesion and internal friction angle, were decreased as the percentage of silica fume was increased, while in the specimens containing 2% lime, the shear strength and the internal friction angle increased slightly, but the soil cohesion changes did not show a consistent trend. Also, in specimens containing 3% lime, no optimum percentage of silica fume was observed from the results of these tests.

The results show that the shear strength and its parameters depend on the proportionality of different influential factors, such as fraction of lime and silica fume relative to clay and gypsum contents. A suitable amount of silica fume will be combined with lime and gypsum, and develop the cementation process, yielding a significant increase in shear strength. However, higher or lower contents of the components, such as lime or gypsum, or even clay fraction of the soil, will degrade the cementation process and lead to a reduction of the shear strength. Therefore, the variations of shear strength parameters do not follow a monotonic trend. Similar results were reported by Alrubye (2018) for non-gypsiferous soil, too.



(a) 1% L+1% S (b) 1% L+3% S (c) 1% L+5% S (d) 1% L+7% S

(e) 2% L+1% S (f) 2% L+3% S (g) 2% L+5% S (h) 2% L+7% S

(i) 3% L+1% S (j) 3% L+3% S (k) 3% L+5% S (l) 3% L+7% S

Fig. 14 Condition of stabilized specimens after two months of exposure to water

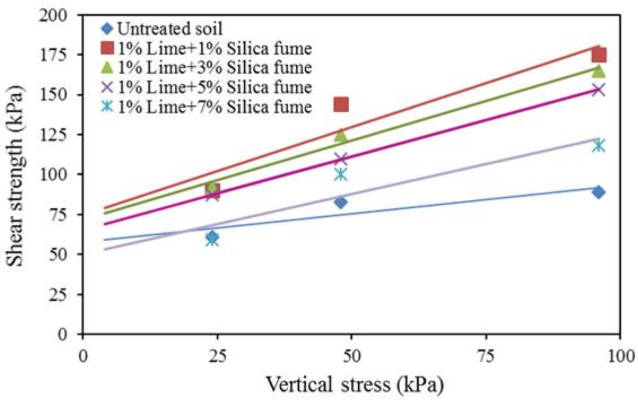


Fig. 15 Comparison of Mohr-Coulomb failure envelope of specimens treated with 1% lime and the untreated specimen

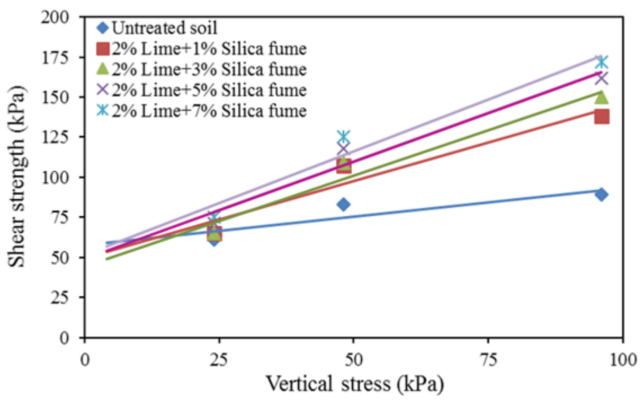


Fig. 16 Comparison of Mohr-Coulomb failure envelope of specimens treated with 2% lime and the untreated specimen

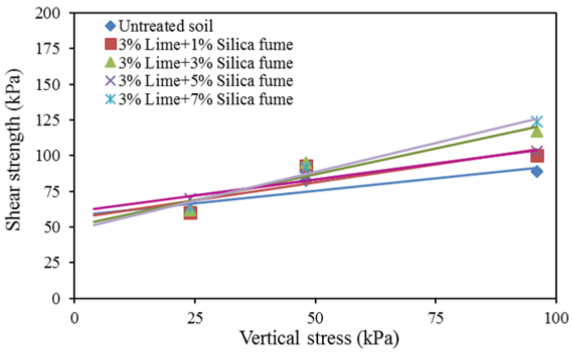


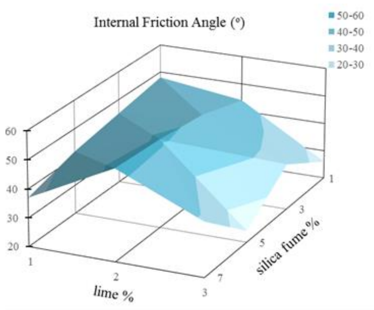
Fig. 17 Comparison of Mohr-Coulomb failure envelope of specimens treated with 3% lime and the untreated specimen

Table 7 Results of direct shear tests cohesion (kPa)

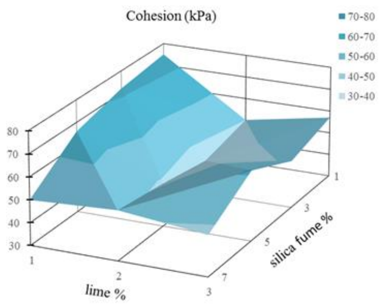
Silica fume content(%)	Lime content(%)			Untreated specimen
	1	2	3	
1	75	50	57	58
3	72	45	51	
5	66	49	61	
7	50	52	48	

Table 8 Results of direct shear tests-Internal friction angle (°)

Silica fume content(%)	Lime content(%)			Untreated specimen
	1	2	3	
1	48	44	26	19
3	45	49	36	
5	42	51	24	
7	37	52	39	



(a)



(b)

Fig. 18 Shear strength parameters vs. additives contents: (a) Internal friction angle (°) and (b) Cohesion (kPa)

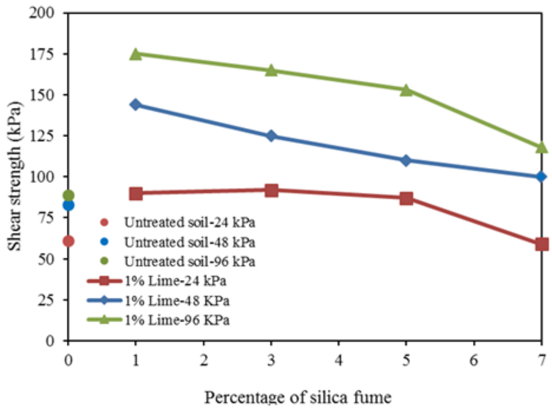


Fig. 19 Effect of silica fume on the shear strength of the specimens stabilized with 1% lime

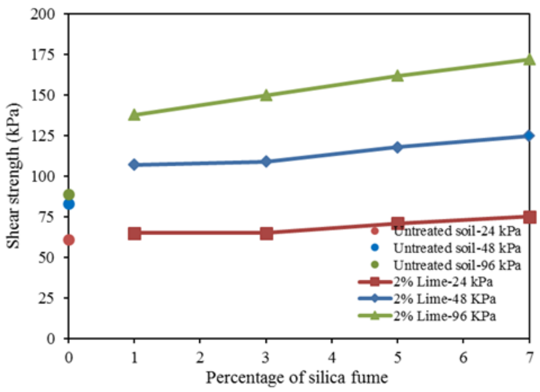


Fig. 20 Effect of silica fume on the shear strength of the specimens stabilized with 2% lime

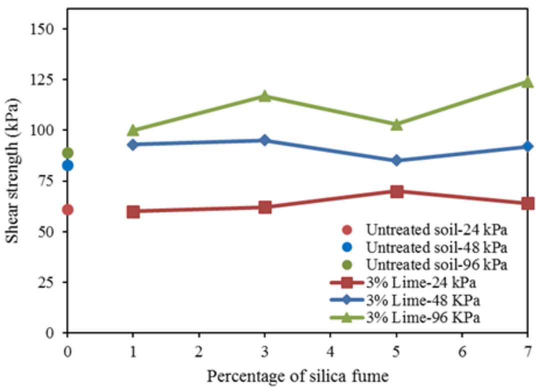
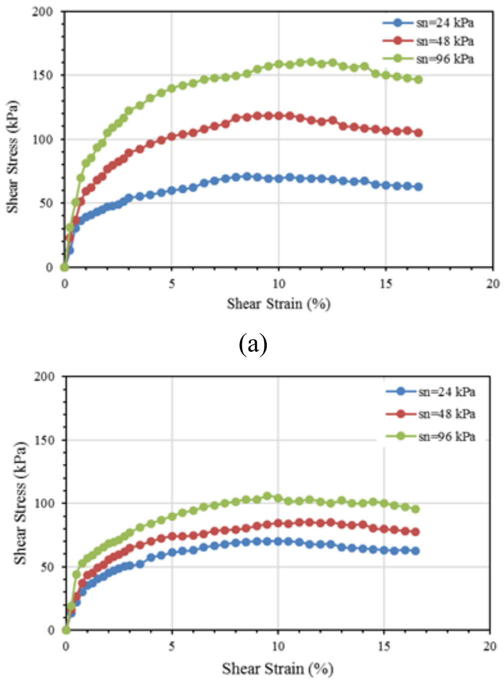


Fig. 21 Effect of silica fume on the shear strength of the specimens stabilized with 3% lime

4.4.1 Stress-Strain curves of the direct shear test

A total of 39 specimens were tested. There are too many stress-strain curves to be presented here, therefore, only the results of tests conducted on specimens treated with 5% silica fume and 2 and 3% lime are presented in Fig. 22. Comparing the curves for different lime and silica fume contents, it is concluded that the initial tangent elastic modulus of the specimens and the strain at failure increased as the normal stress of the test was increased. Also, the higher lime contents, up to certain limits, increase the shear strength. This is due to reactions between alumina and silica of silica fume and calcium contents of lime, resulting



(a)

(b)

Fig. 22 Stress-strain curves for gypsiferous soil specimens consisting 5% silica fume: (a) 2% lime and (b) 3% lime

in the cementitious materials. But, beyond a certain limit, the strength reduces due to the lack of proportional silica fume. This can be attributed to formation of ettringite needles. If the necessary conditions of developing of these needles is provided, larger needles form and weaken the soil structure, after initial improvement of the strength and deformability due to filling of the pores, in accordance with Harichane *et al.* 2011 and Lin *et al.* 2007.

5. Conclusions

The objective of this study was to investigate the effects of lime and silica fume on improvement of soils containing high gypsum content before and after soaking. The experiments were conducted on a gypsiferous soil taken from the body of the main canal of Maroon irrigation network, located in Behbahan city, South-West of Iran. The unconfined compressive strength and durability tests were performed on specimens cured for different periods to examine mechanical properties and their changes due to soaking. The results showed considerable increases in strength parameters due to the addition of lime and silica fume, and notable durability, too. It means very slight or no damage due to soaking in the long run, which is the condition of the soils used in the construction of canals in gypsiferous lands. The main conclusions of this study include:

• Untreated soil exhibited no stability against soaking and failed rapidly in contact with water.

• Lime and silica fume addition increased the stability of gypsiferous soil against soaking considerably, so that by adding even 1 percent of each additive, the durability of the soil was increased up to 99%.

• The compressive strength of the specimen containing even 1 percent lime and 1 percent silica fume, after soaking, was ten times more than the value of this parameter in the untreated specimen before soaking.

• The compressive strength of specimens containing 2 and 3 percent lime was increased considerably after soaking compared to before.

• The highest value of the compressive strength, after soaking, was observed in the specimen containing 3% lime and 3% silica fume, which after 24 hours of curing, showed an increase of about 48 times compared with untreated specimen even before soaking. This ratio was increased up to 73 times as the curing time is increased to 28 days.

• In the case of specimens containing 1% lime, the shear strength, cohesion and internal friction angle showed a reducing trend as the silica fume content is increased. In other words, the maximum increase in shear strength of the specimens stabilized with 1 percent lime was obtained by adding 1 percent silica fume. However, it was decreased with higher silica fume contents.

• As the compressive strength of the specimen containing 3 percent lime and 3 percent silica fume before soaking is about 770 kPa, the maximum verti cal stress applied on the specimen in the direct shear test (96 kPa) is not enough to compress the specimen and activate the friction of mixed particles. Therefore, the optimum contents of the additives are different in unconfined compressive strength and direct shear tests.

• The results of the tests carried out indicates that lime and silica fume have significant effects on the geotechnical properties of gypsiferous soil by increasing the strength and decreasing the collapse potential.

• According to the results obtained by this research, application of lime and silica fume, to improve the gypsiferous soil properties of the foundations of the structures subjected to the water is recommended.

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