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The effect of hydrated lime on the petrography and strength characteristics of Illite clay

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Abstract. In this research, soil samples of the Kerman sedimentary basin, Iran, were investigated through laboratory tests such as petrography (Scanning Electron Microscopy (SEM), X-Ray Fluorescence Spectroscopy (XRF) and X-Ray Diffraction (XRD)), physical and mechanical characteristics tests. The soil in this area is dominantly CL. The petrography results showed that the dominant clay mineral is Illite. This soil has made some problems in the earth dams due to the low shear strength. In this study, a set of samples were prepared by adding different amounts of lime. Next, the petrography and strength tests at the optimum moisture content were performed. The results of SEM analysis showed substantial changes in the soil structure after the addition of lime. The primary structure was porous and granular that was changed to a uniform and solid after the lime was added. According to XRD results, dominant mineral in none stabilized soil and stabilized soil are Illite and calcite, respectively. The pozzolanic reaction resulted in the reduction of clay minerals in the stabilized samples and calcite was known as the soil hardener material that led to an increase in soil strength. An increase in the hydrated lime leads to a decrease in their maximum dry unit weight and an increase in their optimum moisture content. Furthermore, increasing the hydrated lime content enhanced the Unconfined Compressive Strength (UCS) and soil's optimum moisture. An increase in the strength is significantly affected by the curing time and hydrated lime contents, as the maximum compressive strength is achieved at 7% hydrated lime. Moreover, the maximum increase in the California Bearing Ratio (CBR) achieved in clay soils mixed with 8% hydrated lime.

Keywords: petrography; illite clay; physical and mechanical properties; lime additive

1. Introduction

Soil stabilization improves geotechnical parameters of the soil in the project sites (Abbasi Dezfouli and Shakiba 2020, Hashemi *et al.* 2019, Kafashzadeh *et al.* 2018). Over the past century, several additives such as cement, fly ash, lime, waste materials, Pozzolan, and tar have been used as soil stabilizers (Aly 2015, Chenari *et al*. 2018, Kozakova *et al*. 2013, Oyelami and Van Rooy 2016, Sujatha *et al*. 2018). Adding these materials to sensitive soils can be useful in large scale projects such as road construction (particularly in a case that it will be required to replace the entire soil with poor physical and geotechnical properties, which involves huge soil volumes) and earth dams (Bagherzadeh Khalkhali *et al.* 2019, Mahboubi *et al.* 2019). In this regard, different researchers have studied the effect of lime on clayey soils (Aziz *et al.* 2015, Ismaiel 2013, Sahoo and Pradhan 2010, Sakr *et al.* 2009, Seco *et al.* 2011). El Shinawi (2017) studied the instability improvement of subgrade using lime additives. Moreover, Rangeard *et al*. (2016), Xu *et al.* (2019) and Mohamadabadi *et al.* (2019) studied the mechanical behavior of fine-grained soil. Yi *et al.* (2015) investigated the effects of the lime additive on the properties of marine clay. Fattah *et al.* (2010) studied the mechanical behavior of expansive soil using different additives.

Table 1 The effect of lime on clay engineering properties in previous studies

References	Effect of lime on clay engineering properties
Chen (2012)	The maximum increase in Unconfined Compressive Strength (UCS) reached by adding 8% of lime.
El Shinawi (2017)	The maximum increase in UCS and California Bearing Ratio (CBR) reached by adding 8% of lime.
Harichane *et al.* (2011)	The maximum increase in UCS reached by adding 8% of lime. The maximum of lime required to improve the plasticity index of a clayey soil is 4%.
Modarres and Nosoudy (2015)	The maximum increase in UCS and dry density reached by adding 9% of lime. By adding 6% of lime the maximum liquid limit is obtained.
Attoh-Okine (1995), Bagherpour and Choobbasti (2003), Okagbue and Yakubu (2000)	The maximum changes in the plasticity index reached before adding 10% of lime. Adding more than 10% of lime has no significant impact on the plasticity index.

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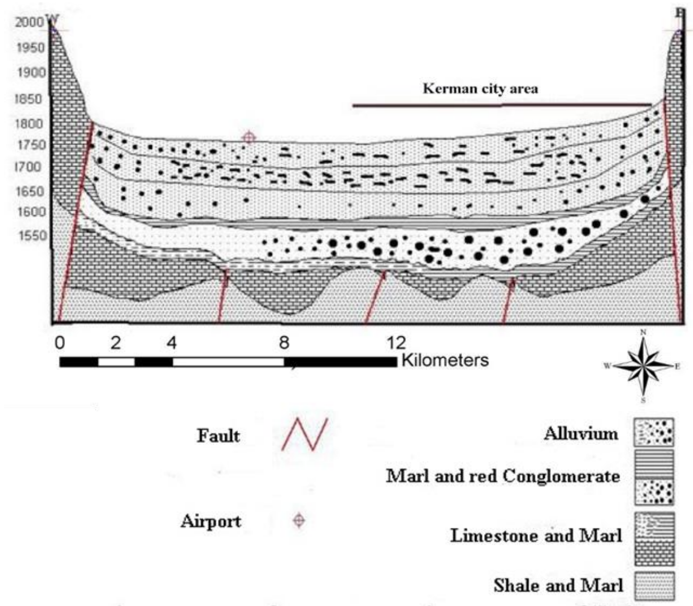

Fig. 1 The geological profile of the Karman sedimentary basin

Based on the technical literature, stabilization of clayey soils using common stabilizers such as cement and lime improves their strength and durability in freezing and thawing conditions and facing water (Chandrasekaran 2018, Cruz *et al*. 2017, Lu *et al.* 2014, Modarres and Nosoudy 2015, Obuzor *et al.* 2012, Sekhavati and Jafarkazemi 2019).

Table 1 shows previous studies about the effect of lime additive on clay engineering properties.

The present study was conducted to investigate the lime impact on improving the petrography characteristics, compaction, CBR, Atterberg limits, and unconfined compressive strength properties of the soils in the Kerman sedimentary basin. The soil samples were subjected to sieve analysis, unit weight, unconfined compressive strength, gradation, Atterberg limits, CBR, compaction, X-Ray Fluorescence Spectroscopy (XRF), Scanning Electron Micrograph (SEM) and X-Ray Diffraction (XRD) tests. The soil samples were prepared by adding different contents of hydrated lime to the clayey soils. Then, to study the effect of lime additives on compressive strength, the soil mixtures were tested at curing times of 7, 14, 28, and 90 days.

2. Study area

The study area is Kerman sedimentary basin located in southern Iran with geographical coordinates of X: 505624 and Y: 3351027. Fig. 1 presents the geological profile of this basin, which is a Graben generated by the movements of normal faults existing in the mountain-plain boundary and the uplift of the mountains. Considering the sedimentary model of this basin, it can be stated that it has been formed in the late Quaternary. Also, it is seen that the basin is partially covered with salt patches and silt-clay playas.

The geological units of this basin consist of Cambrian and Precambrian rocks (Dezu series), Permian and Tertiary rocks (Jamal and Shotori carbonates), and Jurassic rocks (a set of detrital rocks including sandstone and shale making Nayband, Shemshak, and Badamou formations). The dominant rocks of the basin are Cretaceous shales, sandstone, and limestones, which make three separate heights in the eastern part of the city.

The Paleogene rocks in the study area include andesite-tuffite units and the Kerman (base) conglomerate formation. Also, the Neogene rocks (young Neogene-Quaternary conglomerates) as the oldest Quaternary sedimentary rocks in the study area cover a wide range of the northeastern part of the city. These detrital sediments including breccia, conglomerate, marl, sandstone, and thin layers of gypsum.

The abundance of clayey soils with low plasticity (CL) in the Kerman city and its application in the core of Gishigan-e Rayen dam makes it necessary to study the properties of these soils and find a method for enhancing their properties. The Gishigan-e Rayen dam is an embankment dam with clayey core. The dam has been constructed to supply agricultural water in 1988. In April 2012, the dam collapsed, and the stored water caused flooding and financial damages.

3. Materials and methods

Since the soil in the study area, based on geotechnical investigations and in accordance with the Unified Soil Classification System (USCS) (ASTM D2487), is mainly CL (a clay with low plasticity), the effect of lime additive was investigated on its properties. The stages performed for this purpose are including the preparation of clay soil samples, performing index soil tests (determining physical and strength properties, SEM, XRF, and XRD). Then new soil samples by adding various lime amounts were prepared, and compaction and UCS tests were performed. The Atterberg limits were determined according to the ASTM D4318 (ASTM 2010), (Table 4). Moreover, the optimum moisture content and the maximum dry density of the soils during the Proctor test were determined according to the ASTM D854. Finally, the UCS and CBR of the soil samples were determined according to the ASTM 2166 (ASTM 1998) and ASTM D1883 (2007), respectively.

To prepare soil samples consisting of hydrated lime and clay soil, first the hydrated lime was mixed with clay and then water was gradually added to the mixture until the optimum moisture content (20%) is reached through the compaction test. Then, the mixed materials were placed in plastic bags and sealed to avoid losing their moisture. The ratio of lime in the soil mixture was defined as its dry weight to the soil dry weight. For conducting the compaction test, 8 contents of hydrated lime were considered and thus 8 mixture types were prepared (Table 7). The required samples for studying the effect of curing time on UCS and CBR were then prepared by adding five different lime amounts.

4. Results and discussion

4.1 Experimental studies of the Kerman sedimentary basin

Geotechnical properties of the Kerman sedimentary basin were investigated using the laboratory tests including soil gradation, Atterberg limits, XRD, SEM, direct shear, triaxial, and standard proctor test. The results of physical and mechanical tests conducted on soil samples are presented in Table 2. Soil cohesion (C) values were measured using a triaxial test and are three times higher than those measured using the direct shear test. Also, the average internal friction angle (ϕ) values of soil samples in triaxial and direct shear tests are 20.9 and 4.5°, respectively (Table 2).

Investigating the results of tests conducted on soil samples revealed that they are mainly CL (Table 3).

Table 2 Description of the indexes and distribution of geotechnical parameters in the Kerman sedimentary basin

Variable	Mean	Median	Mode	Standard Deviation	Min.	Max.
LL (%)	38.28	34	31	7.58	15	68
PI (%)	14.66	14	12	5.91	2	40
Passing Mesh 200 (%)	89.19	94	99	13.43	12	10
ω (%)	20.08	2.50	24	6.36	3	39.5
γ_b (g/cm^3)	1.84	1.85	1.91	0.14	1.33	2.34
γ_d (g/cm^3)	1.54	1.54	1.49	0.103	1.21	1.88
Φ_D (degree)	20.86	23.20	28	0.807	0	34
C_D (kg/cm^2)	0.20	0.05	0.02	0.2	0	0.66
Φ_T (degree)	4.5	3.6	2	3.3	0	16
C_T (kg/cm^2)	0.48	0.42	0.40	0.194	0.13	0.98

ω is water content, γ_b is bulk density, γ_d is dry density, Φ_D and C_D are friction angle and cohesion in direct shear test, respectively, Φ_T and C_T are friction angle and cohesion in triaxial compressive test, respectively

Table 3 Frequency and the percentage distribution of the studied soils according to the USCS

USCS	Frequency	Frequency percentage	Percentage of valid frequency
CH	146	4.5	4.9
CL	2500	77.1	84.5
CL-ML	144	4.4	4.9
GC	5	0.2	0.2
GC-GM	1	0	0
GM	4	0.1	0.1
MH	12	0.4	0.4
ML	77	2.4	2.6
SC	21	0.6	0.7
SC-SM	12	0.4	0.4
SM	33	1	1.1
SP	2	0.1	0.1
SP-SM	2	0.1	0.1
SW-SM	1	0	0
Total	2960	91	100

Based on the obtained results, it can be stated that the sedimentary basin is mainly covered with fine-grained clay and silt sediments from the surface to a large depth. The XRD analysis revealed that Illite is the main clay mineral of the studied soils (Fig. 2).

4.2 Effect of hydrated lime on CL soil

Results showed that the study area is mainly (77.1%) covered with CL soil. Poor mechanical properties of this type of soil resulted in cracking in the clayey core and destruction of the Gishigan-e Rayen dam. The clay soil with low plasticity usually has low resistivity and bearing capacity. One way to deal with the problems of this type of soils is to stabilize them with lime additive. In addition to the effect of forces, type of soil, moisture, and density of compacted soil, even the minerals of the soil can play a major role. However, dry soils with low plasticity are more likely to crack. Because the tensile strength is insignificant, the small tensile strains lead to cracking. Muhunthan (2000) assessed the cracking of the Teton dam which was caused by the internal instability of the core and stated that clay with low plasticity has resulted in dam destruction. Also, clayey soils with low plasticity and low shear strength caused problems during drilling of boreholes at the dam sites (Ghafoori *et al.* 2018, Lashkaripour *et al.* 2018, Rastegarnia *et al.* 2017, 2019, Rahimi *et al.* 2019). Thus, it is necessary to assess the geomechanical characteristics of the dam sites in the site selection stage (Khaleghi Esfahani *et al.* 2018, Motaharitabari Shooshpasha 2018, Rastegarnia *et al*. 2018, Sohrabi-Bidar *et al.* 2016).

The effect of hydrated lime on CL properties is described in the following.

4.2.1 Laboratory tests of the clay soil

The particle size distribution of studied clay using the ASTM D-422 standard (ASTM 2007) is shown in Fig. 4.

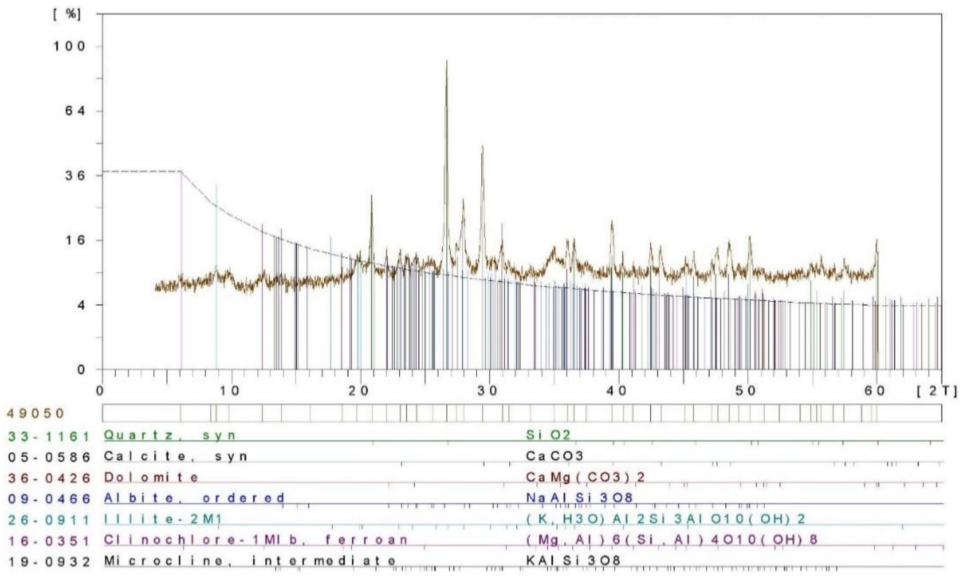

Fig. 2 The XRD test results of clay soil

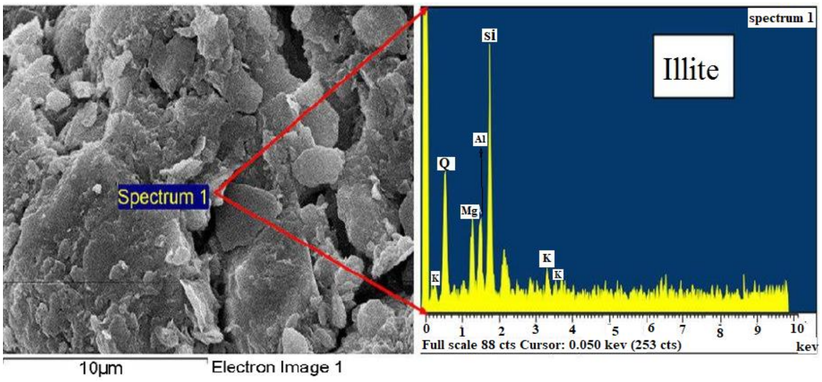

Fig. 3 SEM image of Illite

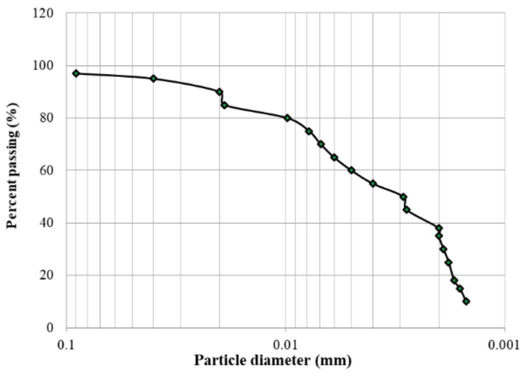

Fig. 4 The particle size distribution of clay soil

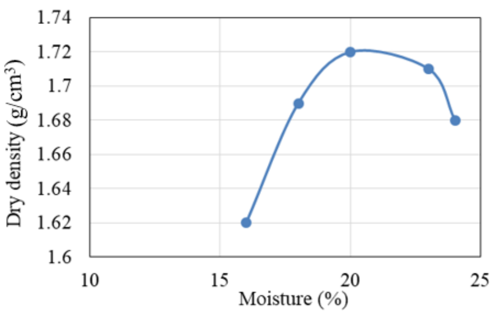

Fig. 5 The clay soil compaction curve

The results of unconfined compressive strength, compaction, CBR, and Atterberg limits tests are presented in Table 4. Based on the obtained results, the optimum moisture content and the maximum dry density of the studied soils are 20% and 1.72 g/cm^3, respectively (Fig. 5). The specific gravity (Gs) of clay soil according to the ASTM D854 was measured as 2.69 g/cm^3 (ASTM 2014), (Table 4).

The XRF results of clay and lime samples are presented in Table 5.

As presented in Table 5, the chemical composition of the clay studied in this research is CaO, SiO_2, Al_2O_3, and Fe_2O_3. The presence of Pozzolanic components (SiO_2 and Al_2O_3) along with CaO in the soil plays a key role in the components' cementation. The cations and anions of the studied soils are presented in Table 6. As the results show, $H_2CO_3^-$ and Cl^- are the most abundant ions in these soils.

By comparing the SEM images, it is observed that the addition of lime to clay soil causes the grains to attach to each other. As a result, the porosity of the specimens decreases and their strength increases (Figs. 3 and 6).

In order to compare the samples minerals, XRD experiment was performed for different mixing ratios. Fig. 7 shows the XRD pattern obtained for stabilized clay with

Table 4 Clay soils characteristics

Parameters	Specific gravity (Gs)	Maximum dry density (g/cm^3)	Optimum moisture content (%)	Unconfined compressive strength (kPa)	CBR (%)	Shrinkage limit (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
Values	2.69	1.72	20	352	8	19	45	25	20

Table 5 Chemical analysis results of lime and clay sample (chemical compositions are in percent)

P_2O_5	SO_3	TiO_2	MgO	K_2O	Na_2O	CaO	Fe_2O_3	Al_2O_3	SiO_2	Sample
0.02	0.6	0.09	4	0.24	0.05	62	0.43	0.65	2.55	Lime
0.2	0.01	0.9	6.26	2.3	0.6	4.34	7.4	11	67	Clay

Table 6 Chemical analysis results of the studied soil

Cations and anions	SO_4^{2-}	CO_3^{2-}	HCO_3^-	Cl^-	Mg^{2+}	Ca^{2+}	Na^+	K^+
Concentration (mg/l)	7.5	2.3	10.2	10.2	6.6	4.2	6.16	0.93

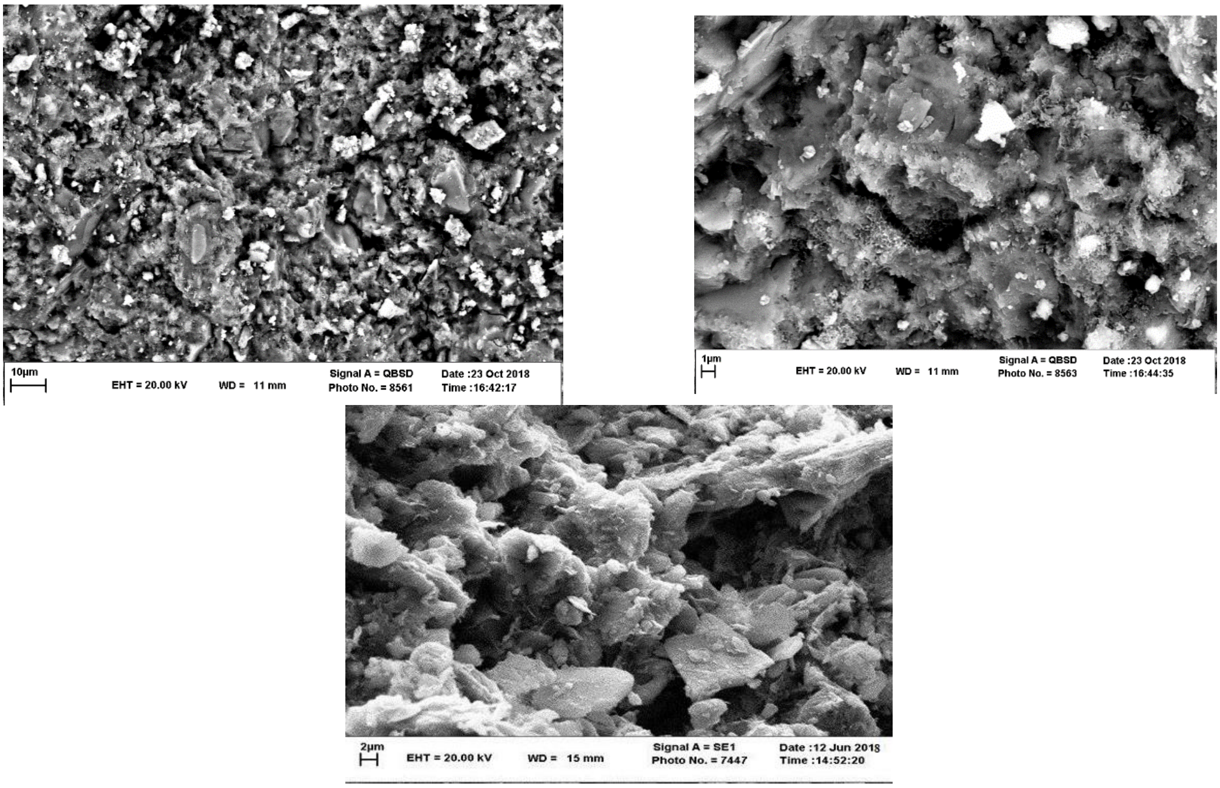

Fig. 6 SEM image of lime with the magnification of 100 (upper image) and stabilized clay with a magnification of 1000 (middle and lower images)

lime after 28 days of curing. According to Bragg's theory, the material with a microcrystal conformation, if the microcrystal material analyzed by XRD it produces special diffraction peaks that are not visible in the XRD pattern of the amorphous materials (Consoli *et al.* 2009). According to XRD results, none stabilized soil contains minerals such as Illite, Quartz, Calcite, Dolomite, Clinochlore, and Microcline. On the other hand, in the stabilized soil with lime the dominant minerals are calcite, silicon oxide quartz, calcium aluminate hydrates were observed. The pozzolanic reaction resulted in the reduction of clay minerals in the stabilized samples and calcite was known as the soil hardener material that led to an increase in soil strength (Ahmed 2015).

4.2.2 Impact of lime on plasticity properties of clay soil

The effect of lime percentage on the Illite plasticity properties with a moisture of 20% is illustrated in Fig. 8. Generally, the clay plastic limit increased, and the liquid limit decreased (Fig. 8). The results of previous studies show that by increasing the lime percentage the liquid limit decreases (Bell 1988, Wang *et al.* 1963) and the plastic limit increases (Barker *et al*. 2006, Herrin and Mitchell 1961). In this research, plastic limit and liquid limit increased with increasing the curing time (Fig. 8). At a curing time of 28 days, the liquid limit is first increased and then decreased.

By increasing the lime percentage, the plasticity index is reduced due to the cation exchange process (Fig. 9). In most cases, because of cationic exchange, the effect of lime

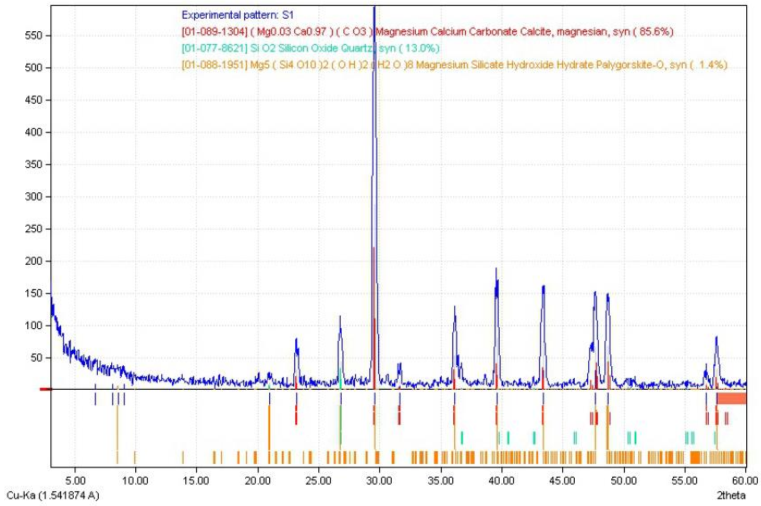

Fig. 7 The XRD test results of stabilized soil

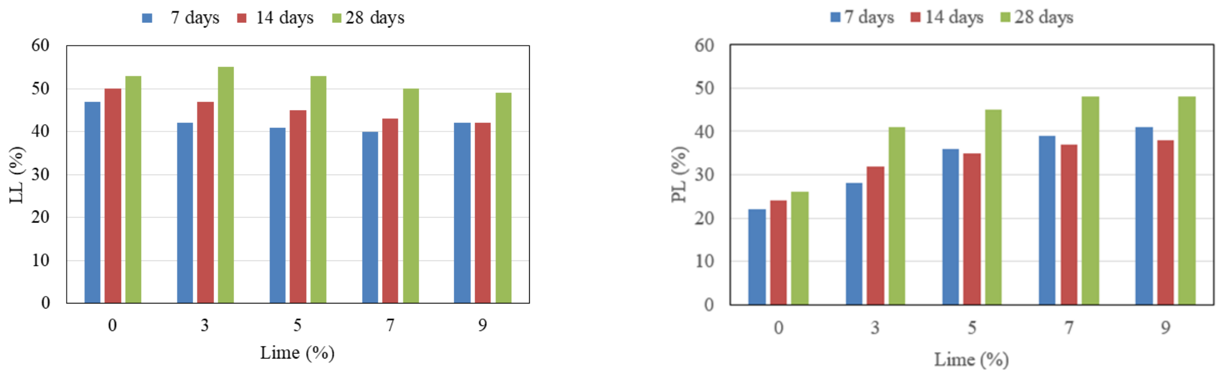

Fig. 8 Effect of lime percentage on the liquid and plastic limits

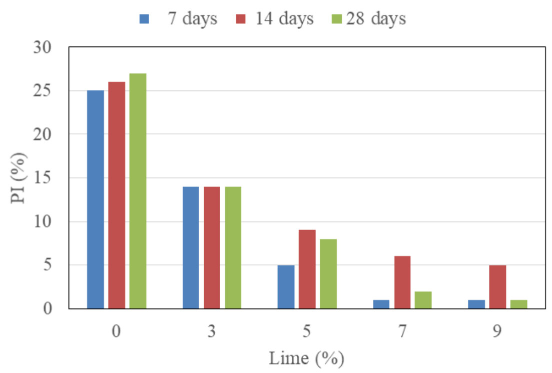

Fig. 9 The effect of lime percentage on the plasticity index

Table 7 The results of the standard proctor test on samples with different lime amounts

(%) Lime	Optimum moisture content (%)	Maximum dry density (g/cm^3)
0	20	17
1	23	16
3	24	14
5	27	13.4
7	28	12.5
9	28.2	12
10	29	12
12	29.2	11.8

Table 8 The results of the compressive strength and the CBR tests for soils with various lime content cured for different periods

Samples	Unconfined compressive strength (kPa)				CBR (%)		
	7 days	14 days	28 days	90 days	7 days	14 days	28 days
1(0% lime)	310	307	335	340	10	15	30
2 (3% lime)	401	416	430	433	24	32.5	24
3 (5% lime)	750	760	772	784	43	49.6	68
4 (7% lime)	820	860	895	902	64	86.3	110
5 (9% lime)	850	870	865	842	65	84.2	105

percentage on clay soil plasticity is immediate. The variations of plasticity depend on the clay type and their specific surface. Swelling clay like Montmorillonite, has a high specific surface, while Kaolinite and Illite have a low and moderate specific surface, respectively (Bell 1996).

4.2.3 Compaction test of the mixed samples

Table 7 presents the optimum moisture and maximum dry density of mixed samples in the modified proctor test (ASTM 2012).

The effect of lime percentage on the optimum moisture and dry density of the samples are presented in Fig. 10. As

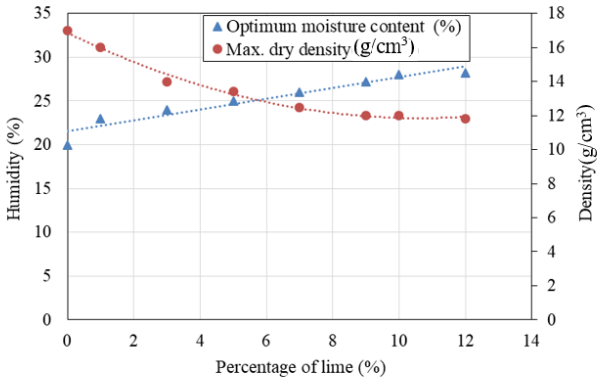

Fig. 10 The effect of lime percentage on optimum moisture content and maximum dry unit weight

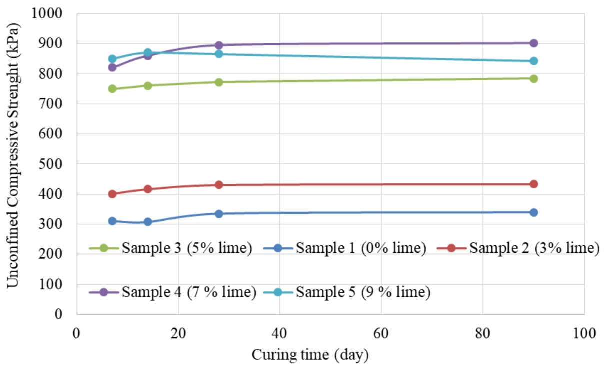

Fig. 11 The effect of curing time on the compressive strength of the soil samples

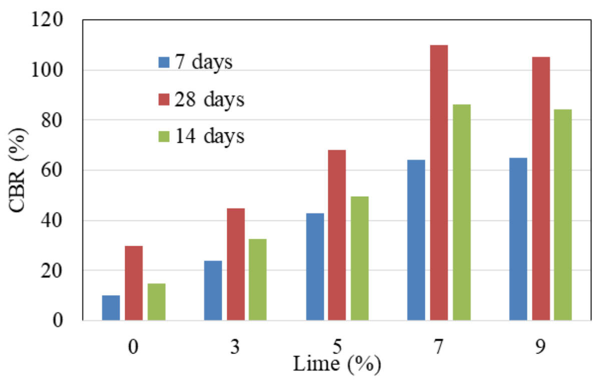

Fig. 12 Effect of lime content and curing time on CBR value

can be seen, increase in hydrated lime leads to a rise in the optimum moisture content and a drop in the maximum dry unit weight. Similar results were found by other researchers in terms of clayey soils stabilized by lime (Harichane *et al.* 2011, Manasseh and Olufemi 2008). The decrease in the maximum unit weight continues before adding 10% of hydrated lime and, then a constant trend is reached. In addition, the maximum increase in the optimum moisture content (28%) was achieved in clay soils mixed with 10% hydrated lime. Cation exchange immediately occurred and clay soil particles were coagulated by adding lime to the soil. This process led to the formation of air pores among the particles and the creation of a porous media with the lowest maximum dry unit weight. Besides, since further water is required to fill these pores, the optimum moisture content also increased (Foroutan *et al.* 2018, Modarres and Nosoudy 2015, Saghi *et al.* 2019, Shahrokhabadi *et al.* 2019, Yi *et al.* 2015).

4.2.4 Compressive strength test on the soil mixtures

The UCS test was performed according to the standard of ASTM (2005) on five samples after curing them for 7, 14, 28, and 90 days at the optimum moisture content (the samples for UCS test were compacted at optimum moisture content). After compaction, the samples were kept in the mold for 24 hours. Then samples were picked up from the mold, and the curing process at 25 °C was continued. Tests were carried out on the samples for curing times of 7, 14, 28, and 90 days. During the curing process, the samples were sealed with a rubber cover to preserve their moisture. The results of the UCS and the CBR tests are presented in Table 8.

The variations in the sample's compressive strength (with different lime contents) versus curing time are presented in Fig. 11. As shown, generally an increase in lime content and curing period of the samples results in a higher UCS. Also, it is observed that the optimum lime content is 7% and the maximum UCS is obtained after curing the samples for 28 days. In longer periods the strength reaches a constant value. This is in line with the results of other researchers. In this regard, Chen (2012) investigated the lime content required for clay soil stabilization and concluded that suitable lime content is ranged between 2% to 8%. Also, El Shinawi (2017) reported that the optimum lime content for improving the clayey sand in the road subgrade is 6%.

The main reason for increasing compressive strength might be the increase in Pozzolanic reactions occurring between the silicon (or aluminate silicon) components of a Pozzolan and calcium hydroxide. Moisture also increases cohesion and cementation properties. By adding lime to the clay, various reactions may occur (Bayrami and Dudran 2016, Mollaqasem *et al.* 2013, Houben and Guillaud 1994):

Cation exchange reaction: Almost all fine-grained soils indicate a cation exchange reaction in a short time when mixed with lime and water. In this reaction, the exchangeable clay cations are replaced with lime cations.

Pozzolanic reaction: This time-dependent reaction results in a considerable increase in the strength of clay soil and lime components. The Ca/Si ratio is an important representative of the strength properties of Pozzolan-lime mixes. A higher ratio of lime compared to Pozzolan results in an increased calcium silicate hydrate (CSH) ratio as the main product of Pozzolanic reaction with a high Ca/Si ratio. According to Aydin and Baradan (2012), the capability of producing CSH bonds decreases in the soil with an increase in the Ca/Si ratio.

Carbonation reaction: In this reaction, lime is mixed with the carbonic gas and then the lime is converted to an inactive limestone. The time required for these reactions is 14, 28, and 60 days and more.

4.2.5 The CBR test on the soil mixtures

The CBR test was performed according to the ASTM

D1883-14 (2014) on five samples after curing them for 7, 14 and 28 days at the optimum moisture content (CBR samples were prepared at optimum moisture content). In Fig. 12 it is generally seen that an increase in lime content and curing period of the samples results in a higher CBR. In this regard, the CBR value increases due to the bonding between clay and lime particles.

5. Conclusions

Soil stabilization is among the common methods applied in civil engineering projects for improving soil engineering properties. The effects of different materials such as lime and Pozzolans in soil improvement have been widely investigated. It is seen that these materials are sometimes used improperly in construction projects such as roads, airport lanes, and foundations. Since clay soils are abundant around the world and also in Iran, they may induce several problems in civil engineering projects.

Based on the geotechnical investigations conducted on the Kerman sedimentary basin, the study area is mainly covered with fine-grained CL soils. The average internal friction angle and cohesion obtained from direct shear tests are 20.9° and 0.2 MPa, respectively. The petrography results showed that the dominant mineral is Illite.

According to the XRD results, none stabilized soil contains minerals such as Illite, quartz, calcite, dolomite, clinochlore, and microcline. In contrast, in the stabilized soil with lime, the dominant mineral are including calcite, silicon oxide quartz, and calcium aluminate hydrates. The pozzolanic reaction resulted in the reduction of clay minerals in the stabilized samples and calcite led to an increase in soil strength. The results of the SEM analysis showed substantial changes in the soil structure after the addition of additives. The primary structure was porous and granular that was changed to a uniform and solid structure after adding lime.

The results of the standard Proctor test revealed that adding lime to clay soil results in an increase in the optimum moisture content and a decrease in the maximum dry unit weight. By performing the UCS test at the optimum moisture, it was found that after 7, 14, 28, and 90 days of curing, the maximum compressive strength is achieved in the soil with 7% lime and the optimum moisture content. Moreover, the highest UCS was obtained on day 28 days and then remained constant. Adding lime to the CL increased its CBR at optimum moisture content. Finally, the maximum increase in the CBR occurred in clay soils mixed with 8% hydrated lime.

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