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Research Article

The effect of curing time and freeze-thaw cycles on the undrained shear strength of lime-stabilized alluvial soils

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Abstract: This paper presents an experimental effort to elucidate the stabilization mechanism of alluvial soils with lime and check their durability against freeze and thaw (FT) cycles. The effect of stabilization-related parameters such as lime content and curing period were investigated. The lime content was changed as 0, 3, 6, 12 %, while curing periods were 7, 28, and 56 days. The mixtures were kept in a closed system cabinet at -24 and +24 Celsius degrees for 24 hours to expose the samples 0,1 and 2 FT cycles. To analyze and compare the effect of FT cycles, Unconsolidated-Undrained (UU) triaxial tests were performed under different cell pressures. In addition, SEM and EDAX analyses were conducted to evaluate the mechanism at the microstructural and compositional levels. It was determined that the highest strength could be obtained in the samples in which 6% lime content was kept in 28 days of cure. After this curing period, it has been determined that minerals that affect the mechanism between lime and soil adversely were formed. The fact that the development of chemical reactions stopped or did not progress in the 56-day curing period has confirmed the production of such minerals. However, these samples, whose strength did not increase as expected, were not affected much by FT cycles. It means, no significant difference was obtained from cycles 1 to 2, since a major part of the sample's integrity was affected from the first cycle. The deterioration of the soil integration and growth of needle-like harmful minerals in the long term were also verified with the SEM images and EDAX analyses.

Keywords: curing period, freeze-thaw cycle, lime stabilization, undrained shear strength.

1. Introduction

The demand for new constructions due to rapid population growth led engineers to use sites in which subgrade soil has inadequate strength (Jahandari et al., 2019). For decades, many researchers have come up with the idea of applying different soil stabilization techniques to enhance the fundamental properties of soft soils to prevent any possible damage to the structures supported by these soils (Cai et al., 2006; Tang et al., 2007; Jiang et al., 2015; Firoozfar and Khosroshiri, 2017; Wu et al., 2020). Among them, the application of chemical stabilizers is the most effective method for soils experiencing certain problems that lead them to exhibit serious loss of strength (Sharma et al., 2008).

To apply stabilization methods economically and quickly, many researchers have suggested using hydrated lime as a chemical stabilizer to improve strength (Bell, 1996; Boardman et al., 2001; Sharma et al., 2008; Mellas et al., 2012; Negi et al., 2013; Calik and Sadoglu, 2014; Phanikumar et al., 2015; Alrubaye et al., 2018). Soil stabilization with lime has mainly been categorized into two different stages regarding the time elapsed which is called as curing period. The stage at which ion exchange between lime and soil causes a more flocculated structure and increases workability, in turn, is defined as the immediate stage. The vast majority of this phase consists of interchanging divalent calcium ions (Ca^{+2}) in lime with monovalent cations (Na^{+1}) in fine-grained soils, particularly clayey soils. The further exchanges lead to a decrease in the number of negative charges in clay so that in repulsive forces. Less repulsion means closer particles, thereby, more flocculated material (Eades and Grim, 1960). This is the process that causes a reduction in the plasticity of the soil and results in the clayey soil behaving like granular soil. In general, this stage ends in hours and days. The other and main phase of the stabilization that is responsible for gaining strength includes pozzolanic reactions and is named the long-term stage since it lasts months or even years. As time passes, the pH of the water increases, and at a certain value of pH (12.4), free minerals in the soil react with the calcium in lime resulting in the formation of cementitious (CSH) gels. Based on these instructions, the stabilization of soil by lime has gained much more attention among researchers, especially regarding the possible parameters affecting the reactions (Osinubi, 1995). Cai et al. (2006) studied the most important influential factors of stabilization such as the curing period and the amount of lime. Based on experimental efforts, it was concluded that the shear strength of clayey soils can be enhanced by the addition of lime in the circumstances of longer periods and higher amounts. However, increase in strength was seen to be limited up to a point that can be defined as the optimum lime dosage or effective content at which maximum strength is achieved and further increment only results in reduction. The optimum lime dosage was found about 5% in terms of both Unconfined Compression Strength (UCS) and shear strength parameters (cohesion and internal friction angle). The same dosage of lime also found enough for stabilization by Mukhtar et al. (2010) for an expansive soil type. Factors other than the curing period and amount of lime that are found to be effective in the stabilization can be summarized as the Cation Exchange Capacity (CEC) of soil, which increases with clay content, the mineral amount in the soil, especially silica and alumina minerals, temperature, and pH value (Kassim et al., 2005). In addition to strength, it was also proved that lime addition poses some changes on the geotechnical properties of soil such as liquid limit, plastic limit, and accordingly plasticity index. Within the frame of research, a general conclusion that the soils exhibiting higher plasticity are much more susceptible to lime stabilization was proved (Mehta et al., 2014). Moreover, up to an optimum lime dosage plasticity index of the soil experiences a decline while lime content is increasing, yet no specific deductions have been made about how the liquid limit of soil changes for the lime content.

So far, the aforementioned studies investigated only the stabilization process not the influential factors of stabilization for the worst conditions such as undrained loading and freeze-thaw phenomena. To ensure a safe design, some circumstances such as loading conditions shall be taken seriously by considering soil type, magnitude, and rate of loading while determining soil strength. In case soil with low permeability experiences rapid loading, it gives a rise to a short-term or undrained loading condition in which water in the soil is not allowed to drain, thereby, the development of excess pore water pressure becomes unavoidable. If this is the case, the soil shows lower shear strength in terms of effective stresses which is expressed as undrained shear strength and taken as the lowest boundary of a design project (Sharma and Bora, 2003; O'Kelly, 2013). To measure it, many options were introduced in both field and laboratory. In the laboratory mostly suggested test is the Unconsolidated-Undrained (UU) triaxial compression test since the test allows soil specimens to have a confinement while it is axially loaded. Another adverse situation that makes the soft soil weaker can be considered as seasonal weather changes which lead the damages in the form of cracks in building walls or pavements etc. (Wang et al., 2015). The temperature fluctuations all year round or even all day long cause the water content of the soil to change phases and cause volumetric defects. The damages can be severe or limited which is affecting the structure's service life. Even though at the sites that are not located in the regions, where extreme temperatures are observed, the soil can exhibit physical changes due to the frequently occurring temperature fluctuations because of different reasons such as groundwater level, type of soil, capillary effect, etc. (Firoozfar and Khosroshiri, 2017). The main effects caused by the applied FT cycles may vary according to the mineralogic composition of the soil being used, the degree of saturation, and FT exposure time (Hotineanu et al., 2015). In the existence of some minerals, i.e., montmorillonite, the changed structure due to the freezing of soil can be reversed partially by thawing (Cui et al., 2014). Even so, a total restoration is not possible since every cycle leads to an increase in the size of pores, thereby, reducing particle-to-particle contacts (Li et al., 2017).

These temperature fluctuations and their effects on the soil can be simulated in laboratory conditions by applying FT cycles to the soil sample subsequently. This effect can be more pronounced in particularly frost-susceptible soils such as silty soils (Wang et al., 2014; Arasan and Nasirpur; 2015; Jumassultan et al., 2021). Researchers on lime stabilized soils have presented the soil-lime interaction in detail, yet few studies conducted to apply FT cycles on the stabilized soils and investigated undrained shear strength properties (Al-Mukhtar et al., 2012; Aldaood et al., 2014; Hotineanu et al., 2015; Gullu and Fedakar, 2017; Yılmaz and Fidan, 2018; Saygili and Dayan, 2019; Baldovino et al., 2021). Furthermore, instead of using a frost susceptible type of soil, the main focus was on the clayey soils so that the attention was again given to the stabilization, not the FT requirements (Yıldız and Soğancı, 2012; Güllü, 2015; Tebaldi et al., 2016; Boz and Sezer, 2018; Bozbey et al., 2018; Zhang et al., 2019; Ismeik and Shaqour, 2020). There are very few studies available in the literature concerning the freeze-thaw resistance of the lime stabilized silty soils and it is emerging as a newly research topic (Zhan et al., 2015; Nguyen et al., 2019; Baldovino et al., 2021). As a general perspective, in the studies conducted on the FT behavior of soils, main attention was given to the volumetric changes of the sample in the form of frost heave and thaw subsidence owing to the repeated cycles (Liang et al., 2006; Tanaka et al., 2009). Yıldız and Soğancı (2012) analyzed the effect of some influential parameters belonging to the FT phenomenon on the permeability of fine-grained soil. The number of cycles and overburden pressure were found to be highly effective on the permeability. Liu et al. (2010) investigated the behavior of expansive soil stabilized with cement and lime. The experimental efforts showed that stabilized soil samples exhibited more durable behavior than natural ones. Another important output of the study was that FT exposure led the reactions between soil and lime to take place more slowly but not ceased pozzolanic activity at all. Jafari and Esna-ashari (2012) investigated the influence of repeated FT cycles (3 cycles) on the strength of lime-stabilized clay. The samples were also mixed with waste tire cords in different proportions. According to the UCS tests, the inclusion of both tire cord and lime showed a remarkable performance on the strength against FT action. Yılmaz and Fidan (2018) have investigated the pozzolanic activity of lime and perlite-stabilized clayey soils under FT cycling. The most important output of the study, in which a closed-type FT system was used, was that the pozzolanic activity of perlite decreased less than that of lime. This may be because the mineralogy of clays is highly sensitive to pozzolanic activities. There are still gaps in how lime-stabilized silts will behave under these conditions. In this context, Nguyen et al. (2019) studied the comparison of unconfined compression strength of three distinct soils (low plastic clay, low and high plastic silts) under both FT and non-FT conditions. As a result of the study, it was determined that lime application was effective in low-plasticity soils with high lime content and a long curing period. Through the literature, it has been seen that the number of studies examining the behavior of lime-stabilized silty alluvial soils, which are the weak soil type that is the subject of this study and is frequently encountered in the field, are not discussed.

An attempt was made in this paper for investigating lime-stabilized alluvial silty soil (a frost susceptible soil type) behavior under undrained loading conditions and against repeated FT cycles (0, 1, and 2 cycles). The stabilization was made by increasing lime content (0, 3, 6, and 12%) and curing period (7, 28, and 56 days) to find the most effective dosage and time for stabilized samples together with FT action. The engineering characteristics of the soil that will likely change, especially undrained shear strength and Atterberg limits, were measured by laboratory experiments. A major part of the research in the literature consisted of the UCS test owing to its simplicity and quickness, however, it is quite obvious that UCS tests are not adequate to simulate site conditions since there is no application of confining stress, unlike the field conditions. To address it, in the current study, UU triaxial compression tests were performed to also find confinement effects such as 100, 200, and 300 kPa. Besides, to find out the mineralogic composition of both materials, soil, and lime, X-ray Diffraction (XRD) analyses were performed. The microstructural characterization of the stabilized samples was obtained by interpreting the images obtained by SEM analysis and by examining the elemental densities in EDAX analysis.

2. Materials and methods

2.1. *Materials*

2.1.1. Alluvial soil

The fine-grained soil used in the current study is an alluvial soil type sampled from Izmir (Turkey) which is a representative field for undrained loading conditions due to the rapid constructions. Alluvial soils possess a soft soil behavior with low shear strength, thereby, exhibiting large vertical deformations during construction. The construction site (Figure 1), according to a geotechnical characterization study conducted on the site by Semerci et al. (2018), consisted of a broad range of soil types from gravel to clay but mainly low plasticity clay or silt.

Figure 1. The construction site.

In the present research, silty soils taken from the site were selected based on their frost tendency (Wang et al., 2014). The geotechnical properties of the soil sample utilized in the study are demonstrated in Table 1. Owing to its plasticity index, the soil was classified as having low swelling potential.

Table 1. Characteristics of the soil sample.

Parameter	Value	Unit	Utilized standard
Liquid limit (LL)	36.5	%	ASTM D4318-10
Plastic limit (PL)	28.7	%	ASTM D4318-10
Plasticity index (PI)	7.8	%	ASTM D4318-10
Specific gravity (G_s)	2.7	-	ASTM D854-14
Optimum moisture content (OMC)	20	%	ASTM D698-12
Max. dry density (MDD)	16.3	kN/m^3	ASTM D698-12
Fine content (F_c)	67.0	%	ASTM D1140-17
pH	8.41	-	ASTM D4972-19
Soil class (USCS)	ML	-	ASTM D2487-11
Clay fraction (HT)	15	%	ASTM D7928-17
Clay fraction (LDM)	8.6	%	ISO 13320:2020

The properties indicating the soil's particle size distribution, particularly fine content, and clay fraction, were evaluated by using both the Laser Diffraction Method (LDM) and Hydrometer Test (HT). In recent, owing to its simplicity and providing a wide range of data, LDM has become one of the most suggested tools to assess particle size distribution of soils (Miller and Schaetzl, 2012; Yang et al., 2019). To obtain reliable results and make a comparison, a hydrometer test was also performed in addition to LDM. It was observed that the presence of higher clay contents was indicated by the hydrometer test.

One of the key effective parameters of stabilization is to better-understanding soil characteristics such as the mineral composition of the soil. The dominating minerals of the soil were detected by identifying peak conditions coming from the XRD analysis. The PANalytical brand Empyrean model XRD device was utilized for conducting the analysis. The Rietveld method was employed to calculate the quantitative ratios of minerals, enabling quantitative XRD analysis. XRD pattern of the soil has been shown in Figure 2. The most notable finding that may be detected from XRD analysis was the presence of sulfate-containing minerals such as melanterite, epsomite, polyhalite in the alluvial soil.

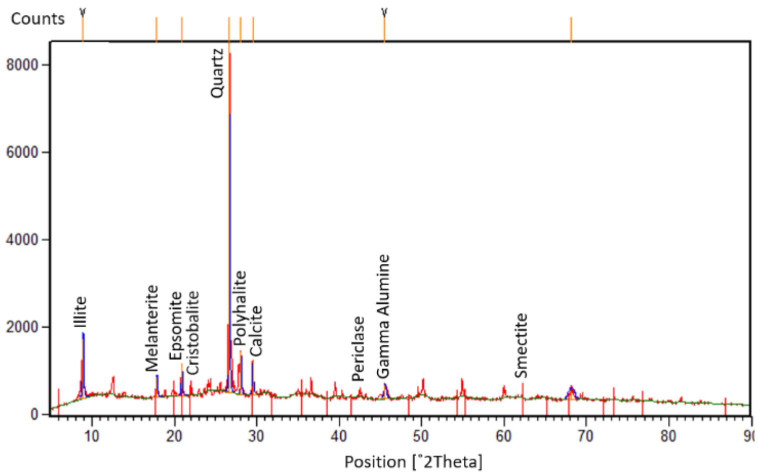

Figure 2. XRD pattern of the soil.

2.1.2. Hydrated lime

In the current study, hydrated lime with a specific gravity of 2.61 and a maximum particle size of 0.425 mm was utilized as the chemical material for the stabilization of the soil. The lime was chosen to be rich in calcium oxide to satisfy stabilization requirements. According to the XRD analysis results, it contains 67.3% of calcite and 32.7% of vaterite.

2.2. *Method*

In the experimental program of this paper, the mainly adopted procedures can be summarized as the preparation of natural and lime-stabilized samples, applying previously specified curing periods, determining consistency limit tests on some of the cured samples, freezing and thawing the samples repeatedly, and finally testing the samples by triaxial compression test (UU test). The samples were identified with codes as in Table 2 via corresponding variable parameters in the tests. Additionally, the testing process including each stage can also be seen in Figure 3.

Table 2. Sample codes for varying parameters.

Sample code	Lime (%)	Curing (days)	FT cycles
0L*1D*0C*			0
0L1D1C	0	1	1
0L1D2C			2
3L7D0C			0
3L7D1C	3		1
3L7D2C			2
6L7D0C			0
6L7D1C	6	7	1
6L7D2C			2
12L7D0C			0
12L7D1C	12		1
12L7D2C			2
3L28D0C			0
3L28D1C	3		1
3L28D2C			2
6L28D0C			0
6L28D1C	6	28	1
6L28D2C			2
12L28D0C			0
12L28D1C	12		1
12L28D2C			2
3L56D0C			0
3L56D1C	3		1
3L56D2C			2
6L56D0C			0
6L56D1C	6	56	1
6L56D2C			2
12L56D0C			0
12L56D1C	12		1
12L56D2C			2

*The letters L stand for lime content, D for days of curing, and C for cycle no.

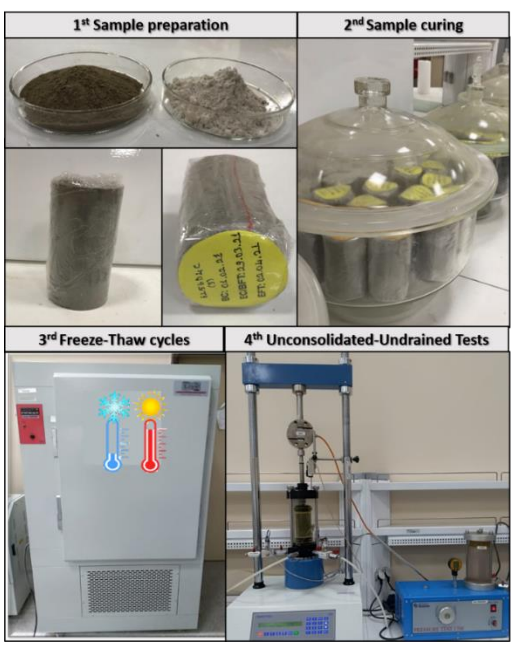

Figure 3. Procedures followed in the paper.

2.2.1. Sample preparation

The soil samples were divided into 4 different groups according to the lime content (Table 3) and an experimental schedule was arranged by considering their curing periods. The natural soil samples (first group) were prepared by mixing air-dried alluvial soil with water in their calculated amount according to the predefined optimum compaction properties such as maximum dry density and optimum moisture content. To satisfy homogeneity, the mixtures were prepared separately. In other words, the whole material weight was divided and mixed into 10 layers by considering the recommendation for compacted sample preparation given in ASTM D2850 standard for Unconsolidated-Undrained (UU) Triaxial Compression tests. Each layer was compacted in a split mold having dimensions of 5 cm diameter and 10 cm height by using a tamper to reach desired density. By considering the required energy of Standard Proctor, 20 blows of tamping, with a tamper of 11.8 N approximately, were found enough to obtain the samples.

After the compaction was completed, the samples were removed from the mold by a hydraulic extruder and immediately wrapped in two-layered stretch films and put into a locked bag to prevent moisture loss from the sample. The sealing process was selected through several trial tests, including different sealing materials such as aluminum foil, stretch film, and several types of locked bags. Among them, the most effective preservation method, to keep water content constant in the sample during curing time and FT process, was chosen. Additionally, to identify samples, they were labeled with the codes given in Table 2. Each group of samples having presented properties of lime contents in Table 3 was prepared in the same manner as the first group. For the tests, two identical samples with the same characteristics were prepared and the experiment was repeated in cases where the test results of those samples were inconsistent.

Table 3. Sample groups in the tests.

Group No	I	II	III	IV
Lime content, %	0	3	6	12
Degree of saturation, %	84.9 (average)			
Curing, days	1 – 7 – 28 – 56			
FT cycles	0 – 1 – 2			
Confinement, kPa	100 – 200 – 300			

As it is indicated in Table 3, the compacted specimens had a degree of saturation values between 84.6 - 85.2% according to the sample preparation stages. Since the samples with higher than 80% of saturation remain in the zone of partial saturation, the tested samples in the current study were considered partially saturated samples (Kamata et al., 2009). In the study, it was not aimed to reach full saturation in the samples in order not to change the characteristic properties of the soil (i.e. water content, void ratio) under its optimum conditions. Moreover, the testing procedures were arranged according to the given recommendations in the studies to avoid any possible effect of saturation (Vanapalli and Fredlund, 1997; Nishimura, 2006; Tsukamoto 2019).

2.2.2. Sample curing

After samples were prepared and preserved conveniently, several curing periods were provided to allow the reactions between soil and lime. In general, 7 days of curing was found to be enough to start immediate reactions by the researchers (Boardman et al., 2001). It was also noted that increasing the curing period is a way to obtain stabilized samples with higher shear strength. In addition to these studies, to make more detailed conclusions about how the curing period is effective on the undrained shear strength of stabilized soils, each group of lime stabilized samples (II, III, and IV) was cured for 7, 28, and 56 days in a desiccator, in which, samples were protected from undesirable room conditions. In case natural samples were being tested, to guarantee sufficient time for moisture distribution through the sample, one-day curing was applied. Each sample was weighed before and after curing, to be sure whether the loss of water occurred beyond the allowable limits or not. The main interest in specifying several periods was for a better understanding of the most effective curing time for the soil type tested against FT exposure.

2.2.3. Geotechnical index tests

Before conducting the strength tests, basic geotechnical parameters were specified for the samples with or without lime to determine how the compaction properties or plasticity index of the soil responded to the stabilization. As given in Table 1, optimum moisture content, maximum dry density, plastic limit, liquid limit, and plasticity index were determined by using relevant standards. The primary objective of this section was to establish compaction and phase changes in the soil due to the lime addition and make relations with the strength mechanism of stabilized soils. Therefore, it is significant to determine limit values after lime stabilization and curing.

2.2.4. Freeze-Thaw (FT) cycles

Before conducting triaxial tests on the natural and lime-stabilized soils, the samples were exposed to seasonal temperature change effects by using a freeze-thaw chamber. The manually operated equipment has the capacity of applying temperatures from -30°C to +30°C with 0.1°C sensitivity. A closed-type apparatus is used without a water supply unit, thereby, only water exists in the soil (Qu et al., 2019). For fine soils, low permeability is achieved so that behavior corresponds to a closed system. The requirements introduced by ASTM D560 were satisfied. Taking into account the characteristics of the sampling area, the samples were frozen at -24°C and thawed at +24°C. When the average annual temperatures of the region are examined, it has been determined that it varies between 20°C degrees in summer and -8°C in winter. FT temperatures have been determined in this way to consider these two values and regulate the temperatures in a way that covers the whole world. Each action, freeze, and thaw were applied to the samples for 24 hours which means that the FT cycle was completed within 48 hours. The specimens were undergone 2 cycles in total by following freezing and thawing processes one after another. The internal temperature in the chamber was controlled by maintaining a thermometer during the cycles, in some cases, ∓2°C oscillations were tolerated. The main parameter aimed to consider during this part of the experiments was measuring the freeze and thaw performance of stabilized soils. The main question was, how is the effect of lime stabilization on the ductility of the silty soils after exposure to repeated FT cycles. Employing both improvement and destroying effects together, the soil response shall be understood.

2.2.5. Unconsolidated-Undrained (UU) triaxial tests

To find undrained shear strength, UU triaxial compression tests were performed on the samples (listed in Table 2) which had completed the first three steps of the testing program. In the UU testing procedure, while the samples were under the influence of confining pressures by the surrounding water, they were also subjected to shear in the axial direction without allowing drainage.

The load rate shall be determined according to the sample characteristics, but to avoid the influence of strain rate on the tests, rates between 0.05 - 1 %/min proved to be enough (Nishimura, 2006). In the current study, a rate of 0.1mm/min was selected to ignore the shearing rate, but at the same time satisfy a quick test. The loading was continued until reached 15% strain and then the test was stopped as suggested by ASTM D2850. In other words, the failure time was defined as the time at which a 15% strain rate was achieved, in this case, it corresponded to 15 mm axial deformation. Samples were weighed before and after the experiment to check whether any volume changes were encountered during the experiment.

The samples in the current study were called partially saturated since the initial degree of saturation values, presented in Table 3, didn't meet the requirements of full saturation. To maintain the basic characteristics and moisture content of the samples, no saturation was applied to the samples before the triaxial compression tests. Thereby, even if drainage was not allowed during the test, volume, and degree of saturation possibly changed due to the consolidation or compression of air in the soil under confinement (ASTM D2850). Thus, depending on the magnitude of applied confining stress, the samples of the same physical properties respond differently which is not usually the case encountered for fully saturated samples tested in UU. When fully saturated samples are being tested, the identical specimens should pose the same undrained shear strength independent from the confining pressure value. In the present study, except for stabilization and FT effect, the confinement effect on the samples' degree of saturation was also investigated after applying three different cell pressures such as 100, 200, and 300 kPa. The choice of pressure values was based on several kinds of research conducted. Tsukamoto (2019) offered low confinement effects in the case of partially saturated samples to be tested since the soils in the vadose zone are considered partially saturated and under the low confining. However, the main problem that may arise in UU tests due to these types of specimens is the potential development of matric suction. The contribution to the undrained shear strength due to the matric suction can be positive, negative, or constant based on the pore pressure parameters (A and B) of the soil (Vanapalli and Fredlund, 1997). This situation causes variations in shear strength even for identical samples due to the change in the applied confining stress, so that, no horizontal failure envelope is obtained from these tests. Vanapalli and Fredlund (1997) proved that the contribution of suction can be relatively smaller for the samples prepared in OMC than wet of optimum or dry of optimum. In addition to this, Fredlund and Rahardjo (1993) found the suction can be neglected in samples are loaded at higher confining pressures and a slight horizontal envelope is achieved due to the saturation closing 100%. Based on these concluding remarks, by considering both the partially saturated soil environment and the possibility of significant changes in the results due to matric suction, each sample with the given codes in Table 2 was axially loaded under 100, 200, and 300 kPa confining pressures, successively. In Figure 4, a total of 110 tested samples including the repeated ones can be seen.

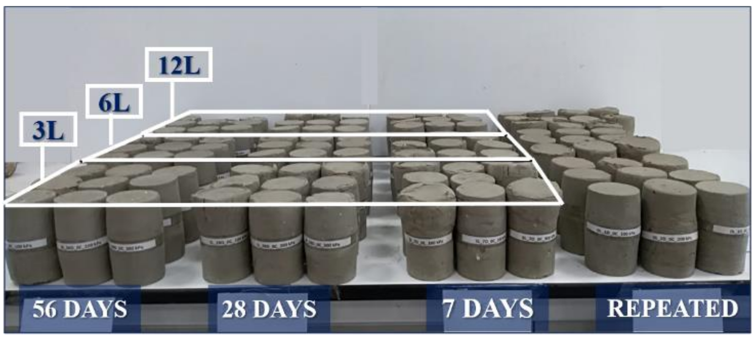

Figure 4. Tested samples after UU.

3. Results and Discussion

3.1. Geotechnical index tests

The consistency limits tests and Standard Proctor tests were performed to find the influence of lime stabilization on the physical properties. Atterberg limit tests were performed on natural and stabilized soil samples under circumstances of several lime contents (0, 3, 6, and 12%) and curing periods (1, 28, and 56 days) and the test results were presented in Table 4.

Table 4. Atterberg limit results.

Lime (%)	Curing (day)	LL (%)	PL (%)	PI (%)	MDD (kN/m^3)	OMC (%)
0	1	36.5	28.7	7.8	16.3	20.0
3	1	31.2	21.5	9.7	16.6	19.1
	28	36.3	26.9	9.4		
	56	37.6	29.1	8.5		
6	1	32.3	20.8	11.5	16.8	18.0
	28	36.5	27.6	8.9		
	56	38.4	30	8.4		
12	1	32	22.3	9.7	16.8	17.2
	28	34.6	28.9	5.7		
	56	35.3	29.8	5.6		

According to the liquid and plastic limit results, a general decreasing trend in the values for the samples cured for 1 day was obtained. Further increase in lime addition resulted in higher values yet no remarkable change was observed. This pattern shifted when longer curing periods were applied. The general trend was having an increase at first, then a decrease after a certain limit which can be called optimum lime dosage. Especially, for the samples cured for 56 days, this orientation was more obvious even for the plasticity index. In a short time, the plasticity index tended to show slight increase, but this progress reversed for the samples with high lime addition and curing periods. When the results for 28 and 56 days were evaluated, plastic limit values increased with the lime content, whereas the liquid limit and plasticity index values decreased. Additionally, optimum lime dosage in terms of liquid limit and plasticity index was found about 6% after which both tend to reduce. In Figure 5, the lower and upper limits of the plastic limit values were determined, and it was clearly seen that the values peaked at 6% lime and then showed a decreasing trend with a larger scatter due to the curing. This is the minimum amount of lime that is required to start reactions for the type of soil being tested. Similar findings were also reported by various researchers. Ünver et al. (2021) reported this value between 4 and 5% for liquid limit and plasticity index.

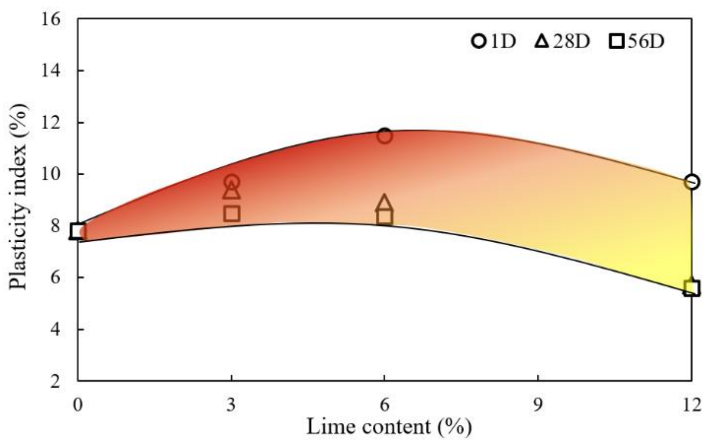

Figure 5. Variation in the plasticity index with lime.

The creation of cementitious gels, which requires sufficient time to take place, is mainly responsible for the reduction in the plasticity of the soil with curing. In the present study, the amount of decrement is limited since fewer clayey minerals are presented in the soil. Similarly, applying the curing period was highly affected to obtain a definitive reduction in plasticity.

In addition to the Atterberg limits, Standard compaction tests were applied to the natural and stabilized samples. From the compaction curves, with the increase of lime ratio, a decrease in optimum water content and an increasing trend in maximum dry unit weight has come to the fore. However, when the values were examined, it was determined that the difference between them remained at a tolerable level and therefore there would be no harm in preparing the samples at optimum compaction values in their natural state.

3.2. Undrained shear strength

3.2.1. Lime content

Figure 6 illustrates the curves plotted between undrained shear strength and lime content under the exposure of 0, 1, and 2 FT cycles (according to the averages of the three confining stresses). Herein, linear lines drawn for different curing times were drawn by averaging the values obtained from each confining pressure. Then, the average resistance line, named AVG in curves, was formed by taking the average of the values over the 3 curing periods to better interpret the relation in terms of lime amount.

The most apparent behavior, in all curves given in Figure 6 is that the undrained shear strength of the soil is enhanced by increasing lime content up to a certain point (about 6% in the current study) which was previously mentioned as optimum lime dosage. At this dosage, maximum values for strength were measured, however, beyond that point the stabilization affected strength negatively. The main factor responsible for this behavior is the fixation of lime in the soil (Hilt and Davidson, 1960). In other words, no material remains available for the pozzolanic activity, therefore, additional increments affect the structural integrity adversely. In addition to strength, by comparing the three graphs presented in Figure 6, it is seen that the FT exposure leads to no change in the optimum dosage. This means the fixation will take place at about the same content of lime even under temperature changes due to the cycles. Because during freezing and thawing, the structure of soil was destroyed, the activity of the materials for further reactions also declined. In a study conducted on the FT behavior of lime-stabilized soils, through microstructural analysis it was proven that freezing and then thawing the samples leads to structural deterioration in form of cracks, thereby, soil particles lose contact with the produced materials during pozzolanic reactions (Zheng et al., 2015; Saygili and Dayan, 2019). Despite the negative impacts raised from FT exposure, lime was found to be still effective on the undrained shear strength up to the optimum value. Another noteworthy issue is that the strength values obtained at different curing times are closer to each other at the optimum dosage.

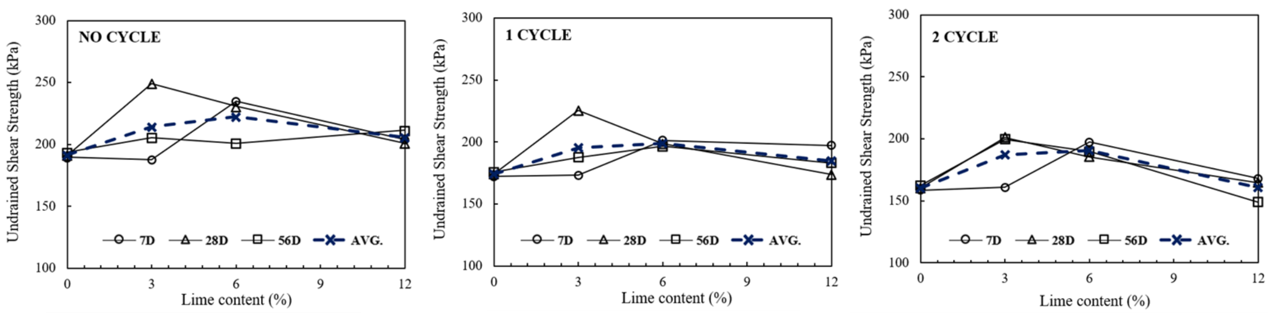

Figure 6. Variation in the c_u concerning lime content.

The stabilization effect on the durability of the samples also was checked by comparing the ratio of the stabilization (Table 5) in which the natural values were assumed to have 100% of stabilization.

Table 5. Stabilization ratios based on undrained strength.

Sample No	Stabilization ratio, r_s (%)		
	0C	1C	2C
0L1D	100.0	100.0	100.0
3L7D	99.0	100.7	101.6
6L7D	123.9	116.9	124.5
12L7D	107.7	114.6	106.0
3L28D	131.4	130.9	126.9
6L28D	121.7	115.2	117.0
12L28D	106.0	100.8	103.9
3L56D	108.4	109.0	125.9
6L56D	106.0	114.1	119.8
12L56D	111.5	106.3	93.6

The rates were calculated by using the average of the strengths corresponding to the three confining pressures and separately for each cycle. For instance, the undrained shear strength of 6L7D1C was determined by taking the average of the strengths obtained under 100, 200, and 300 kPa cell pressures, and its stabilization ratio was calculated by dividing the average strength of 6L7D1C by that of 0L1D1C. In the case of a 2 cycled sample was considered, the avg. strength of 2 cycled ones was rated.

The rates between average strength values have proven that at the contents closer to optimum dosage maximum stabilization was obtained. Especially for the samples cured in 28 days, the stabilization amount was highly effective in producing more durable samples to FT exposure. In a study conducted by Little (1998) several aggregates were stabilized with lime using the Texas triaxial method and an overall 50 to 150% stabilization was achieved depending on the soils' mineralogy. Since lime stabilization requires the main focus on reactive soils, the subject was widely investigated for plastic and expansive soils. In other words, the lime-soil strength-gaining mechanism over time or percentage being effective for low plastic soils, as in the current one, remained unexamined. The soil in the current study poses a low plastic behavior with low activity, thereby, strength increase stayed in a limited range when compared with the clayey soils. However, it is a convenient type of soil to investigate FT performance. The understanding of lime stabilization with these types of soils may give new perspectives to make the right stabilization method against FT action.

3.2.2. Curing period

To investigate the time dependency of the stabilization process, for the soil type tested in the present study, several periods from 7 to 56 days were applied based on the previously reported studies. In Figure 7, the relation can be better represented for non-FT cycled samples.

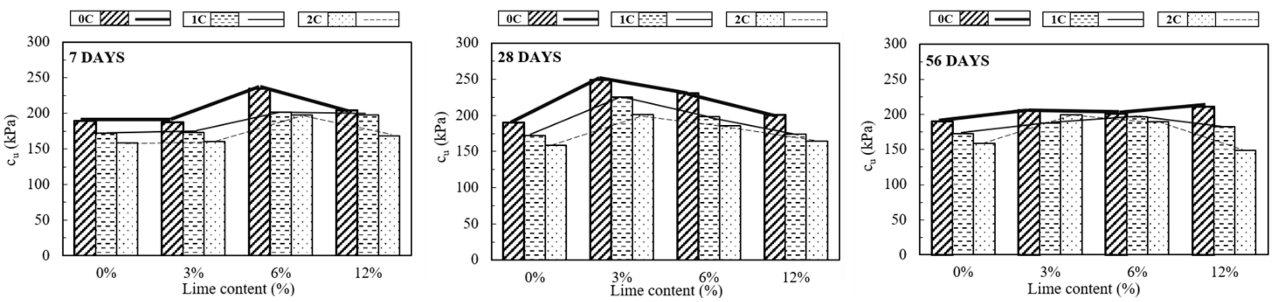

Figure 7. C_u vs. lime content for distinctly cured samples.

As seen from Figure 7, although in all periods average undrained shear strength was increased, the soil samples cured for 28 days showed a much more strength increase, up to the optimum dosage, than the others. It is seen that the increase in strength starts to decrease especially after 28 days, in other words, the positive effect of the period after 28 days on strength decreases. This tendency is probably related to the formation of detrimental minerals, such as ettringite, in environments with a considerable sulfate concentration in the lime-stabilized soils over time, after which, micro-level cracks developed and structural distress occurred (Little et al., 2005). For the formation of the ettringite mineral, the pH and sulfate density of the environment must be high.

The presence of alumina in the soil being tested in this paper induces a high rate of pH environment which was also increased by lime, the use of sulfate-containing soil and undistilled pore water may have increased the sulfate density and provided an environment for the formation of this mineral (Dermatas, 1995). Another serious factor that may contribute to the formation process is the temperature change. In addition to the fact that temperature changes increase the solubility of minerals in the environment and thus the rate of occurrence of reactions, when the temperature drops below 15°C, the conversion of ettringite to thaumasite may also cause significant decreases in strength (Dermatas, 1995; Arnett et al., 2001; Crammond, 2002; Jallad et al., 2003). The extreme temperature changes during the FT cycles may have even caused the formation of this mineral, especially in the 56-days cured samples in which the time required for the ettringite to transform into thaumasite was more sufficient than the others. This formation may stay at a limited level, yet accumulation affected the rise in the strength negatively. This situation proves that, depending on the soil and stabilizer characteristics, long-term periods may not always result in a significant increase in strength. For some soils, as in the current one, immediate impacts can show many visible effects, in the meantime, have the opportunity of timesaving.

3.2.3. FT cycles

From measured strength properties, exposing the natural and stabilized samples to FT cycles highly affected the data, especially in 7- and 28-days curing periods. In Figure 8, the average values of strength were given for each cycle.

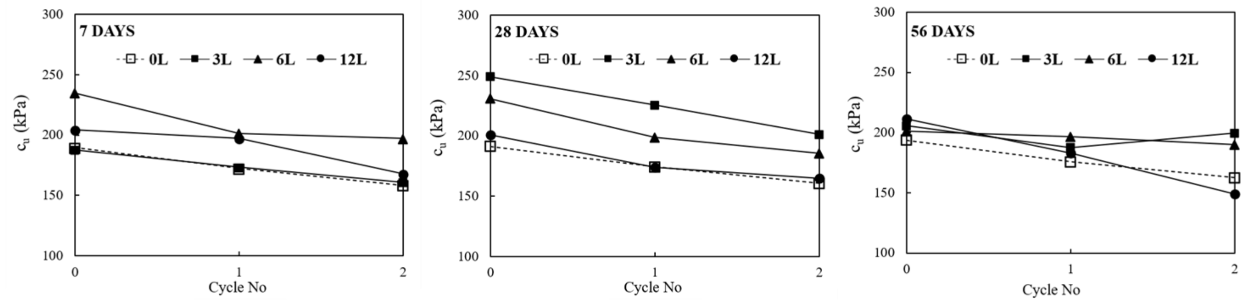

Figure 8. C_u vs. lime content under different cycle effects.

As seen, in all circumstances the reduction in strength is clear, yet the amount of decrease differs from the first cycle to the second. In the first cycle, the structural integrity of the specimens was highly influenced, and thereafter, a limited additional effect was produced in the second one. This approves that the most apparent reductions in strength are generally generated in the first ones (Walker and Karabulut, 1965). After a rapid decline from 0 to 1 cycle, less difference was obtained in the transition from the first to the second one. For 56 days of curing, the propensity of less reduction in strength was observed almost in all cycle transitions. With an increase in the curing period, the disruptive effect of the 1 and 2 FT cycles on the strength began to remain at lower degrees. From there, it can be reported that the samples cured for 56 days exhibited more durable behavior against FT when the lower number of cycles was applied.

The damage resulting from FT cycles can be in the form of micro-cracks, but the production of cementitious gels through pozzolanic reactions helps to fill these pores, hence, reducing loss of strength by producing interlocking. As the behavior can also be concluded from the graphs in Figure 8, even if the cycles are applied, strength increased in most of the percentages of lime compared to that of natural ones. This is seen from the lines in the graphs with other lime contents being above the zero line at all curing times. Especially, the samples stabilized with lime contents up to the optimum dosage behave more durable to the FT cycles.

After then, cycles were found to reduce the strength considerably. Besides, more cycle application may cause the connections to reduce and result in a segmented structure of soil due to the microcracks (Viklander and Eigenbrod, 2000; Han et al., 2018).

In a study conducted by Gullu and Khudir (2014), again a low plastic silty soil was tried to stabilize against FT to improve its service life. Under the repeated FT cycles, a reduction in UCS values was obtained in case both lime and steel fiber was used, however, a good performance was achieved by using jute fiber instead of steel. Besides a separate improvement, stabilization by using the three of them together in their optimum dosage was found to be preferable for repeated cycles. The utilization of fiber in addition to the lime was found to be responsible for the change in the post-peak behavior and ductility so that the extra strength exhibited.

3.2.4. Confining stress

The role of confining stress in the UU tests conducted on partially saturated soil samples shall be considered to get a general overview of its effect on the results. The Mohr circles for the 28-days samples, where the best stabilization was obtained, are given in Figure 9 to get an overview.

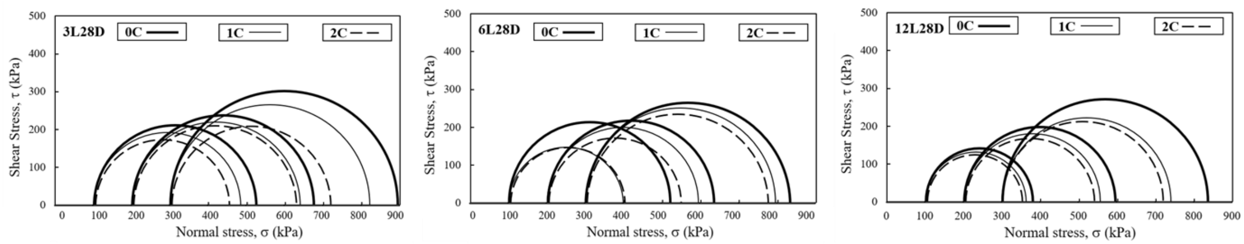

Figure 9. Mohr Circles of the samples in different lime amounts and FT cycles.

It can be seen from Figure 9, with increasing the confining, the undrained shear strength of the samples has slightly enhanced even in undrained conditions, especially for 12% of lime being used. This was because the samples did not have full saturation based on the initially defined distinctive preparation conditions such as dry density, water content, etc. The undrained response to different confining stresses could be explained by the volume changes in UU tests. This change is mainly caused by compressive effects and the presence of soluble gasses in the pores (Liu et al., 2012). In cases where the cycles were applied, it was observed that the slope changed slightly, but no radical changes were experienced. It was also a remarkable finding that the least slope, and therefore the most suitable results, were obtained in the samples with 6% lime content, where the maximum stabilization rate was achieved. Almost similar results were obtained in other curing times. Since the effect of the cycle is less in the 56-days samples, the Mohr circles of the different cycles overlapped at almost every confining pressure value.

In the current paper, since confining stresses were selected as high as possible and changes in the values remained in a limited range, the differences in shear strength values have been neglected and therefore the suction effect was not taken into account. However, it could be attributed to the strength together with the compression effect at low rates. It has also been confirmed by Kamata et al. (2009) for Toyoura sands that the strength increases as the B value decreases (as the saturation decreases) in the UU triaxial tests.

3.2.5. Microstructural analysis

To investigate the microstructural characteristic of the tested soil samples, a series of Scanning Electron Microscope (SEM) analyses were conducted using Zeiss Sigma 300 VP equipment. The analysis was mainly adopted for the samples with the highest stabilization ratio and the samples most affected by FT cycles. From the SEM images, illustrated in Figure 10, the aggregated-flocculated mechanism due to the lime stabilization can be inspected for the samples with 3L28D0C, 6L28D0C, and 6L7D0C codes. Moreover, some carbonate crystallization zones were detected for the mentioned samples that are mainly responsible for the increase in the undrained shear strength. In the case of non-cycled and 2 cycled sample groups (6L7D0C-6L7D2C and 12L56D0C-12L56D2C) were compared, it was clear that loss of contacts in the agglomerated particles caused the development of large pores and microcracks which are the main reasons for the reduction in the strength.

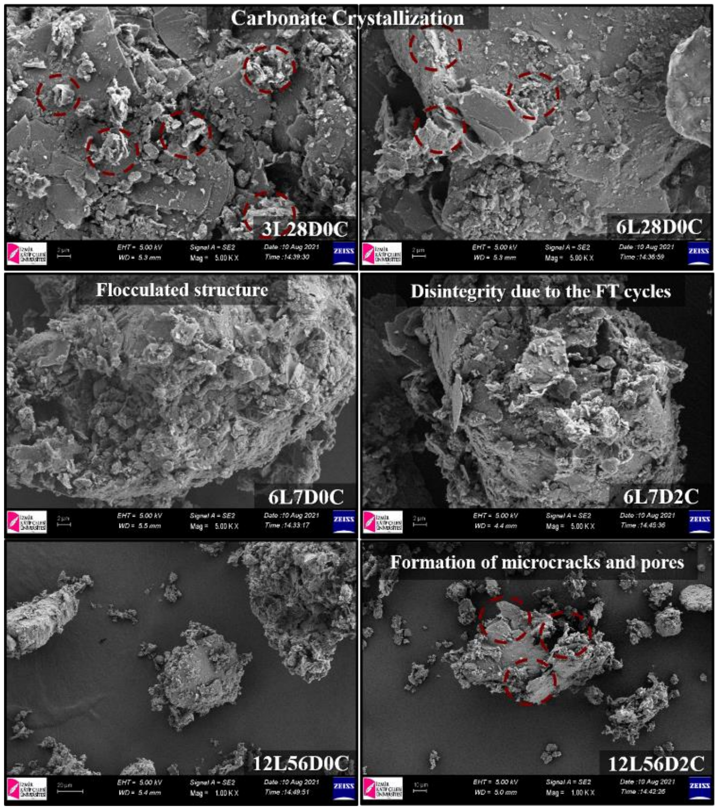

Figure 10. SEM images were taken from the samples.

To verify the possible formation of the minerals that caused the reduction in the pozzolanic activity at 56 days of curing, a quantitative analysis method Energy-Dispersive X-ray (EDAX) was performed with Malvern Panalytical device together with the SEM. The analysis was mainly employed to search for the chemical concentrations and available elements in the samples. In Figure 11, EDAX analysis of the samples prepared in the same stabilization amount, cured in different periods, as illustrated. From the given concentrations, it was mainly observed that the increased Ca content (17.5%) through stabilization was reduced with curing to 4%. This means that, in the long period, the available Ca^{2+} ions became ready to react with the sulfate in the solution and lead to the formation of the contaminated minerals (i.e., ettringite) which is also case confirmed in the study conducted by Raja and Thyagaraj (2019).

In long term, the presence of aluminum, sulfate, and calcium in the region, where ettringite is formed, allows the formation of ettringite crystals. Therefore, the longer curing periods showed a decreasing effect on the undrained shear strength gained in the short time. Furthermore, it appears that there may be needle-like ettringite minerals in the image taken from the region where the elemental analysis was performed in the 56-days-old sample.

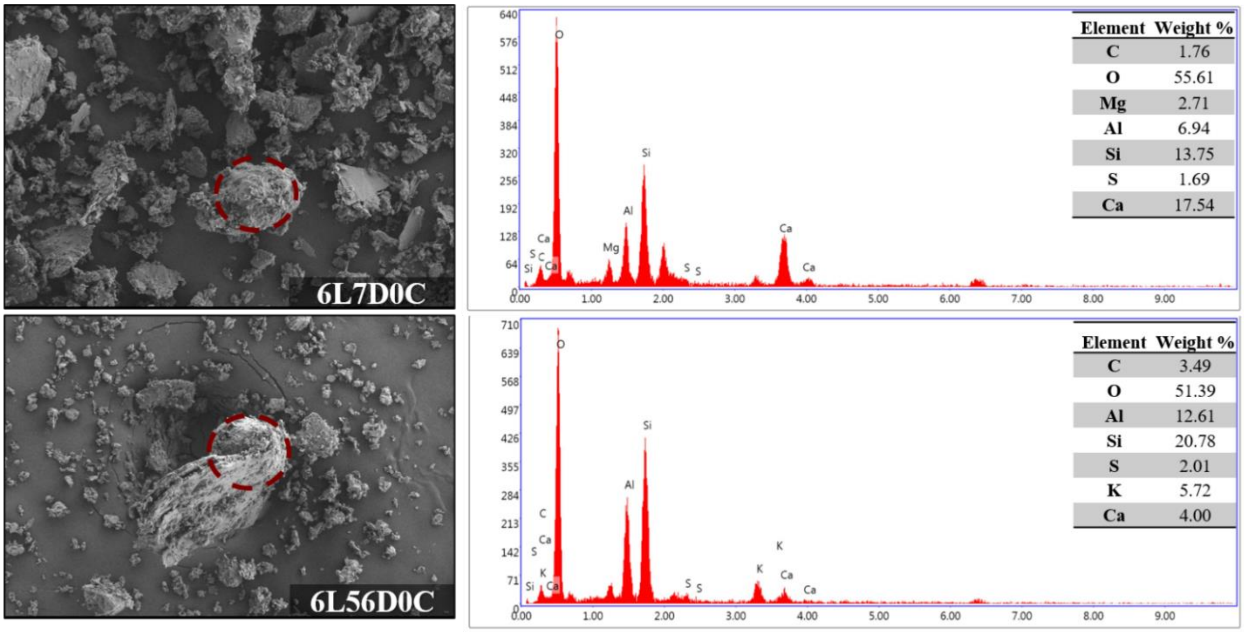

Figure 11. EDAX results of the samples with 6L7D0C and 6L56D0C sample codes.

4. Conclusions

The role of lime as a stabilizer in silty alluvial soils subjected to non, 1, and 2 FT cycles was investigated in the present study under several circumstances such as stabilizer amount, curing time, and confining stress. Through numerous UU triaxial compression tests conducted, the following conclusions were mainly highlighted.

1. While the data for undrained shear strength values were graphed, the optimum dosage of lime seemed to be around 6% and remained about the same levels for the cycled ones. Moreover, the stabilization at optimum dosage was found to have a significant impact, particularly in 28 days, on the durability of samples to the FT cycles. However, when the effect was compared with the previous studies, it seemed the strength achieved remained at lower degrees than in high plastic soils. Therefore, when this soil type is met, other stabilization materials may be more effective in gaining strength and cost.
2. The time-dependent behavior of pozzolanic reactions was investigated through the variation in curing periods. It has been proven that the use of longer curing periods doesn't always mean the generation of more strength. One should remember that there are some cases, in which, the characteristics of materials can take more control in the stabilization with calcium-based stabilizers. As a result of the increasing pH value and temperature changes in the environment, long-term reactions may allow the formation of harmful minerals. This situation has come to the fore as an issue that requires special attention when calcium-based stabilizers are used. From the cycled ones, it was also reported that less change in strength thereby more durable samples against FT was obtained in case samples were cured in longer times.
3. The specimens with increasing lime contents successfully stabilized against FT cycles by showing more strength degrees compared to the cycled ones in the natural form. Repeated cycles also tended to give less reduction in strength compared to the effect of the first cycle. To point out the FT effect at most, the study was conducted on a frost susceptible soil type, silty soil, even if it has low activity against reactions. It seemed that, even in the case of inactive soil being used, lime stabilization could be effective in reducing the adverse impacts caused by FT cycles. However, the utilization of additional materials together with lime such as fibers may be much more effective for these types of soils when faced with a frost susceptible condition.
4. To indicate the effect of confinement in partial saturation conditions, Mohr Circles of the samples were evaluated at different lime contents and cycles. Mostly affected content was detected as the highest one, whereas the most

convenient envelopes were formed in case of optimum lime content being used. Similar conclusions were made also for the cycled envelopes except for 56-days samples, in which, the Mohr circles of the different cycles coincide at nearly all confinements. As a result, it was determined from the Mohr circles that the strength remained at limited rates, and it was found adequate to make the calculations neglecting the matric suction.

5. By performing SEM analysis, the regions of carbonation were observed visually in the stabilized samples. The presence of cracks and large pores due to the FT cycles was also detected through microstructural analysis. Both SEM and EDAX analysis also verified the possible formation of contamination minerals in the long-term curing periods in which lower stabilization ratios were obtained. Further studies, including XRD analyzes, may be needed to confirm the mineralogical contents of the final soil.

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