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Effects of Silica Fume and Lime Mixtures on the Some Geotechnical Properties of Clay Soils

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Abstract: In regions where cold climatic conditions prevail, freeze-thaw cycles cause various problems for clayey soils. In order to reduce or eliminate the effects of these problems, the resistance of the clayey soil to the freeze-thaw cycle should be increased. In this study, a clayey soil sample was improved by using a mixture of silica fume and lime to make it more resistant to the freeze-thaw cycle. Within the scope of the study, natural and stabilized clayey soil samples were subjected to freeze-thaw cycles at different curing periods. The results of the experimental study showed that the clayey soil samples stabilized with a mixture of silica fume and lime were more resistant to freeze-thaw cycles than the unstabilized clayey soil samples. As a result, it has been demonstrated that the mixture of silica fume and lime can be successfully used as an additive material to increase the freeze-thaw resistance of clayey soils for soil stabilization in geotechnical applications.

Keywords: clayey soil; soil improvement; silica fume; lime; freeze-thaw

1. INTRODUCTION

In regions dominated by cold climatic conditions, soils are exposed to freeze-thaw cycles at least once a year, resulting in significant changes in the geotechnical properties of soils (Eigenbrod et al., 1996, Viklander, 1998; Kalkan, 2009a). The volumes of clayey soils exposed to freezing and thawing cycles change, strength values decrease, bearing capacity decreases and microstructure changes occur (Zhang and Shijie, 2001; Hohmann-Porebska, 2002; Yarbasi et al., 2007; Yarbasi and Kalkan, 2020a). In regions with cold climatic conditions, freeze-thaw damage is one of the most important problems in road construction and excavation applications.

The design and construction of earth structures affected by freeze-thaw cycles requires a combination of appropriate thermal conditions and mechanical properties of qualified construction materials (Cruzda and Hohmann, 1997). It is important to analyze the strength properties of clayey soils subjected to freeze-thaw cycles under natural and laboratory conditions and to determine their strain rates (Andersland, 1989; Zaman et al., 1992; Cruzda and Hohmann, 1997; Ma et al., 2001; Kozlowski, 2003; Talmucci, 2003; Akbulut and Sağlamer, 2004, Hansson and Lundin 2006, Wang et al., 2006).

It has been noted in the literature that the expansive soils may cause severe damage to overlying structures, particularly to single-family residential buildings and buried pipelines and cables and consequent distress to people (Erguler and Ulusay, 2003; Sabtan, 2005). However, they are very important in geology, construction, and for environmental applications, due to their wide usage as impermeable and containment barriers in landfill areas and other environmentally related applications (Keith and Murray, 1994; Harvey and Murray, 1997; Murray, 2000; Kalkan, 2009a). Improvement of certain desired properties like bearing capacity, shear strength and permeability characteristics of soil can be undertaken by a variety of ground improvement techniques such as the use of soil stabilization (Abuel-Naga et al., 2006; Chu et al., 2006; Castro-Fresno et al., 2011).

Soil stabilization is a method of improving soil properties by mixing and blending other materials. Improvements include increasing dry unit weight, bearing capacity, volume change, performance of in situ subsoil's, sands and other waste materials to strengthen road surfaces and other geotechnical applications (Firoozi et al., 2017). The concept of stabilization is very old. Stabilized earth roads were used in ancient Egypt and Mesopotamia, and the Greeks and Romans used lime as a stabilizer (McDowell, 1959). However, recent heaving and premature pavement failure in sulphate containing lime and cement-treated subsoils has led to the validity of calcium based stabilization being questioned. When expansive soils containing sulphates are treated with calcium-based stabilizers, the calcium from the stabilizer calcium from the stabilizer reacts with soil sulphates and alumina to form the expansive mineral ettringite (Puppala et al., 1999; Kaminskas and Barauskas, 2014; Saussaye et al., 2015; Mohamedgread et al., 2019a).

Several soil stabilisation methods are available for the stabilization of expansive clayey soils. These methods include the use of chemical additives, rewetting, soil replacement, compaction control, and moisture control, surcharge loading and thermal methods (Chen, 1988; Nelson and Miller, 1992; Yong and Ouhadi, 2007). Many researchers have investigated natural, manufactured and by-product materials and their use as additives to stabilize clayey soils. All these methods can have the disadvantages of being ineffective and expensive. Therefore, new methods are still being researched to increase the strength properties and reduce the swelling potential of expansive soils (Akbulut et al., 2007; Al-Rawas et al., 2005; Asavasipit et al., 2001; Bell, 1996; Cetin et al., 2006; Guney et al., 2007; Kalkan and Akbulut, 2004; Kolias et al, 2005; Miller and Azad, 2000; Moavenian and Yasrobi, 2008; Prabakar et al., 2003; Puppala and Musenda, 2002; Senol et al., 2006; Kalkan, 2006;Sezer et al., 2006; Kalkan and Yarbasi, 2013; Kalkan et al., 2019; Mohamedgread et al., 2019; Yarbaşı and Kalkan, 2019b; Kalkan, 2020; Kalkan et al., 2020; Kalkan et al., 2022).

Silica fume (SF), which has high reactive pozzolanic properties, is an important industrial by-product material with its fine-grained structure, large surface area and high SiO2 content. SF, which is very fine-grained separated silica, is generally used as an admixture in concrete mix (Panjehpour et al., 2011; Singh et al., 2016; Imam et al., 2018). Although silica fume is a waste material of industrial applications, it has become the most valuable by-product among pozzolanic materials due to its very active and high pozzolanic properties (Atis et al., 2005). Previous studies have investigated the effects of SF on the strength, permeability and swelling properties of clay soils. SF was found to improve these properties of clay soils (Kalkan, 2009a; Kalkan, 2009b; Kalkan and Akbulut, 2004; Kalkan, 2012; Kalkan, 2013).

Lime (LM), a very cheap material, is widely used to stabilize loess. Recently, many scientists have investigated the mechanism of soil stabilization and the micro-reaction mechanism between LM and soil and some important achievements have been made. Fly ash is the combustion residues of finely ground coal in electricity generation. It is a potentially active volcanic ash material. LM-fly ash loam can be used in road engineering; it is a kind of backfilled soil mixed with fly ash, lime and loess. There is some research on the strength increasing process and discipline of LM-fly ash loess (Yang et al., 2001; Zhang et al., 2004; Li et al., 2005; Zhang et al., 2013; Tozsin et al., 2014a; Tozsin et al., 2014b; Tozsin et al., 2015).

This study was carried out to investigate the effects of SF and LM mixtures on some geotechnical properties of CS. In this context, improved CS samples were obtained by adding SF and LM mixtures to CS and these samples were subjected to free pressure and freeze-thaw tests. The results obtained from the experimental work carried out under laboratory conditions were evaluated.

2. MATERIAL AND METHOD

2.1. CS

CS used in this study was supplied from the outcrop of sedimentary sequence at the western side of Oltu District (Erzurum, ND Turkey). The CS material is defined as a high plasticity soil (Kalkan, 2003; Kalkan, E., Bayraktutan, M.S., 2008; Kalkan, 2009). Some properties of CS were given in Table 1.

Table 1. Some properties of materials used in this study (Akbulut et al., 2007; Harichane et al., 2011; Yarbasi and Kalkan, 2020)

Properties	CS	SF	LM
Density, g/cm^3	2,63	2,2.5	3,4
Sand, %	2	-	-
Silty, %	66	20	-
Clay, %	32	80	-
Liquid limit, %	72	-	-
Plastic limit, %	35	-	-
Unit volume weight, g/cm^3	37	-	-
Specific surface area, m^2/kg	243,6	20,12	-

2.1. SF

SF is a byproduct of the reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys. SF used in this study was obtained from Ferro-Chromate Factory in Antalya (Turkey). The density of silica fume is 2.0–2.5 Mg/m^3, and itsbulk density is 0.3–0.5 Mg/m^3. Some properties of SF are summarized in Tables 1.

2.1. LM

LM as an additive acquires various important changes the designing properties of soil. At the point when LM included soil as an added substance, it diminishes soil pliancy and swell therapist potential separated from improving quality properties (Tangri, 2021). LM used in tests was supplied from Kayseri Lime Factory in Kayseri, Turkey. Some properties of LM was summarized in Table 1.

2.1. Preparation of Mixtures

The CS, SF and LM were weighted in the required proportions and then blended together under dry conditions. The weights of the mixtures were determined according to the formula below;

$W_{MIX} = W_{CS} + W_{SF} + W_{LM}$(1)

where W_{MIX}, W_{CS}, W_{SF}, W_{LM} are the total dry weights of sample mixtures, CS, SF and LM, respectively. Combination of mixtures used in this study was given in Table 2.

Table 2. Combination of mixtures used in this study

No	Sample	Materials (%)			Total (%)
		CS	SF	LM	
1	MIX0	100	-	-	100
2	MIX2	80	15	5	100

2.5. Compaction Test

In this study, Standard Proctor test was carried out in accordance with ASTM D 698 to determine the optimum moisture content (OMC) and maximum dry unit weight (MDUW) of samples and to yield sample for the unconfined compression tests.

2.6. Unconfined Compression Test

Unconfined compression test is widely used as a quick and economical method of obtaining the approximate compressive strength of the cohesive soils. In this study, the UCS values of samples were determined from the unconfined compressive tests in accordance with ASTM D 2166.

3.4. Freeze-Thaw (F-T) Tests

All samples were subjected to F-T tests in accordance with ASTM C 666. The samples were placed in the freezing apparatus and conditioned at −18 °C for 2.30 h. After the freezing was completed, the samples were transferred from the freezing apparatus into a test room at +20 °C for 2.30 h. This F-T cycle was repeated 20 times and then these samples were subjected to the unconfined compression tests.

3. RESULTS AND DISCUSSION

3.1. Effect of SF and LM Mixtures on UCS

The effect of SF and LM mixtures on UCS values of CS was obtained by carrying out unconfined compression tests at the laboratory condition. It is known that curing period is effective on chemical soil stabilization. To see this effect, all samples were subjected to curing periods of 1, 7 and 28 days. At the end of the curing periods, free pressure tests were performed on the samples and the experimental results are illustrated in Figure 1.

As shown Figure 1, in parallel with the increase in the addition of SF and LM mixture to CS (MIX2), the UCS values of stabilized CS (MIX2) also increased. Similar increase was observed in the curing cycle and all samples gained more strength at 28th day. Similar trends were obtained with the addition of additives to clayey soils (Ranjan et. al., 1996; Prabakar and Sridhar, 2002; Akbulut et al., 2007; Zaimoğlu, 2010; Hejazi et al., 2012; Kalkan, 2013; Muntohar et al., 2013; Lv and Zhou, 2019; Benziane et al., 2019; Yarbaşı and Kalkan, 2020b).

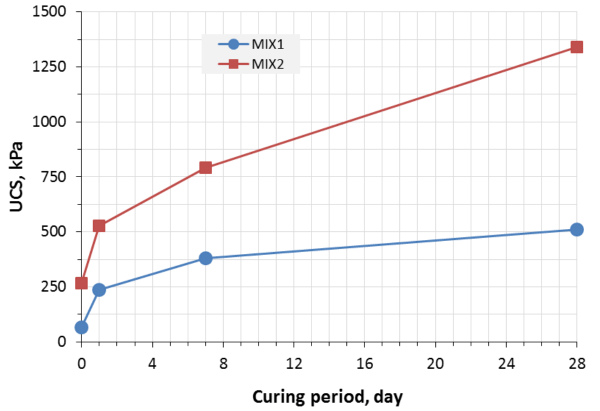

Figure. 1. Effect of NP and STR on the UCS of unexposed samples

The addition of NP and STR mixtures to the CS material caused a change in the composition of the stabilized CS. It is reported in the literature that the addition of additives changes the composition, mineralogy and grain size distribution of clayey soil (Gillot, 1968; Ola, 1978; Kalkan and Akbulut, 2004; Yarbasi and Kalkan, 2020; Yarbasi et al., 2023).

The increase in the UCS values of stabilized CS (MIX2) can be attributed to chemical reaction between CS and LM particles. Because LM has significant amounts of calcium containing compounds, chemical reaction between CS and LM particles can produce Ca^{2+} and OH^{-1} ions. The active silica reacts with calcium and hydroxide forming calcium silicate hydrate gels. This chemical modification likely causes stronger and more brittle forms of material composing the clayey soil–silica fume mixture and decreases their volumetric shrinkage strain (Bell, 1993; Sherwood, 1993; Kalkan and Akbulut, 2004; Kalkan, 2009a; Kalkan, 2011).

3.2. Effect of NP and STR Mixtures on F-T Resistance of CS

The mixture of NP and STR played an important role on the F-T resistance of CS.Also, the samples of MIX1 and MIX2 were cured for 0, 1, 7 and 28 days. The end of curing period all samples were exposed to F-T cycles and then subjected to unconfined compressive strength and determined UCS values. The UCS values determined for MIX2 exposed to F-T cycles showed that the samples of MIX2 more resistance against to F-T cycles from that of samples of MIX1. The test results were illustrated in Figure 2.

In regions with cold climatic conditions, the F-T cycle causes the development of negative behaviour on natural and compacted soils. It is of great importance to increase the resistance of compacted clay soils, which are widely used in geotechnical applications, against F-T cycles. In this study, a significant improvement in resistance to F-T cycles was found in MIX2 samples treated with SF and LM mixtures. MIX2 samples improved by using SF and LM mixtures were more resistant to F-T cycles.

The main mechanism governing the alteration of soil behavior caused by the freezing and thawing cycles appears to be changes in the soil structures. The decrease in the unconfined compressive strength of natural fine-grained soil samples is attributed to the changes in soil sample structure due to particle rearrangements and the initiation of cracks (Cruzda and Hohmann, 1997; Viklander, 1997; Viklander and Eigenbrod, 2000). It is observed that micro cracks grow with increasing number of freezing and thawing cycles. These micro cracks cause the loss of stiffness and deformations on the stabilized samples and thus the unconfined compressive strength of stabilized fine-grained soil samples decrease with increasing freezing and thawing cycles (Hori and Morihiro, 1998; Yarbasi et al., 2007).

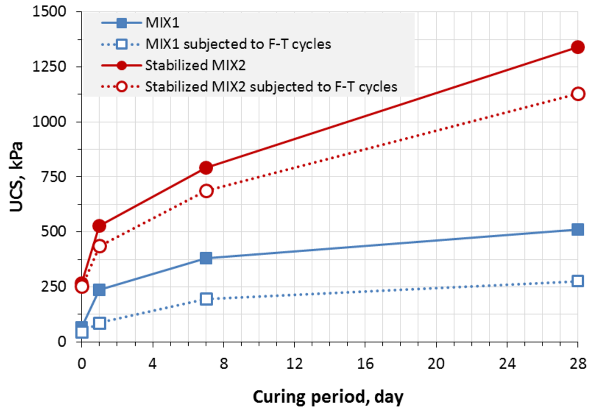

Figure. 2. Effect of NP and STR on the UCS of exposed samples

3. CONCLUSION

In this study, the effects of SF and LM mixtures on the UCS values of CS were investigated. At the same time, the resistance of CS (MIX2) improved with mixtures of SF and LM to F-T cycles was examined. According to the results, SF and LM mixtures significantly increased the UCS values of CS. At the same time, freeze-thaw test results showed that CS cured with SF and LM mixtures were more resistant to F-T cycles. As a result, it was concluded that the mixture of SF and LM can be used to improve the strength of CS. The results also showed that the use of such blends can reduce the stabilization costs.

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