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STABILIZATION OF LIME STABILIZED CLAY REINFORCED WITH SYNTHETIC FIBERS AND SILICA FUME

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Meral DAYAN
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ABSTRACT

STABILIZATION OF LIME STABILIZED CLAY REINFORCED WITH SYNTHETIC FIBERS AND SILICA FUME

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Master of Science (M.Sc.)
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Several soil stabilization studies have been conducted in the literature with silica fume and fibers separately on coarse and fine grained soils. However, few studies have been conducted on freeze-thaw performance of soils modified with fibers or silica fume. This experimental study was conducted to investigate the effect of silica fume and polypropylene fiber modification on strength and freeze-thaw behavior of lime stabilized kaolinite clay. To observe the strength behavior, unconfined compressive strength tests were conducted. Strength losses were also measured after exposure to freeze-thaw cycles to investigate the durability of the modified samples. Control and modified samples were compacted at optimum moisture content and cured for 28 days. After curing, samples were inserted into the freeze-thaw chamber and after two, five and eight cycles samples were tested for compression. Synthetic polypropylene fiber content varied between 0.25 percent to 1 percent and silica fume content varied between 2.5 percent to 10 percent by dry weight of kaolinite in the prepared samples. Adding silica fume, fiber and mixtures having various silica fume-fiber ratios increased the compressive strength values and enhanced the freeze-thaw durability of the lime rich kaolinite specimens. Silica fume particles reacted with lime rich kaolinite as an extra silica source needed for hydration reactions. As a result, CSH gel products were formed, which surrounded the kaolinite particles. Fibers improved the friction resistance, interlock effect was created by cementation reactions between lime stabilized soil, fibers and silica fume. Silica fume and fiber modified lime rich clay reached the maximum strength at 0.25 percent fiber and 10 percent silica fume added specimens, strength values started to decrease with increasing fiber ratios. Silica fume, synthetic fiber and fiber-silica fume modified samples had an increase in compressive strength values with curing and modified samples exposed to freeze-thaw cycles had a lower strength loss compared to control specimens. Samples having higher strength values in unconfined compressive strength measurements were the most durable samples in the freeze-thaw tests with lower strength loss. The results indicated that fiber-silica fume modified kaolinite clay can be an economic and environmentally friendly alternative in soil stabilization projects by utilizing an industrial waste.

Keywords: Soil Stabilization, Silica Fume, Fiber Reinforcement, Freeze-thaw, Unconfined Compressive Strength.

ÖZET

SİLİS DUMANI VE SENTETİK FİBERLERLE MODİFİYE EDİLMİŞ KİLLERİN GEOTEKNİK ÖZELLİKLERİNİN ARAŞTIRILMASI

Meral DAYAN

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Literatürde, kaba ve ince taneli zeminlerde silis dumanı ve lifler ayrı ayrı kullanılarak çeşitli stabilizasyon çalışmaları yapılmıştır. Ancak, silis dumanı veya liflerle yapılan stabilizasyon çalışmalarında donma-çözünme etkisi üzerine az sayıda araştırma mevcuttur. Bu çalışmada kireç ile zenginleştirilmiş kaolin kiline silis dumanı ve polipropilen lif eklenmiştir, bu katkı maddelerinin kilin dayanımına ve donma-çözünme davranışlarına etkisi araştırılmıştır. Dayanımdaki değişimleri gözlemlemek için serbest basınç testi uygulanmıştır. Ayrıca modifiye edilmiş numunelerin donma-çözünme etkisi altındaki dayanım kaybı da ölçülmüştür. Optimum nem içeriğine sahip kontrol numuneleri ve modifiye edilmiş numuneler sıkıştırılarak, dayanım kazanmaları için 28 gün boyunca kür odasında bekletilmişlerdir. Kürlenme döneminden sonra numuneler donma-çözünme kabinine yerleştirilerek iki, beş ve sekiz döngüye tabi tutulmuşlardır ve numunelere basınç testi uygulanmıştır. Hazırlanan numunelerde sentetik polipropilen liflerin içeriği kaolin kilinin kuru ağırlığınca yüzde 0.25 ile yüzde 1 oranı arasında ve silis dumanı içeriği ise kaolin kilinin kuru ağırlığınca yüzde 2.5 ile yüzde 10 oranı arasında değişmektedir. Kireçle iyileştirilmiş kaolin kil numunelere silis dumanı, sentetik lif ve bu katkıların farklı oranlardaki kombinasyonlu karışımların eklenmesi numunelerin basınç dayanımını ve donma-çözünme döngülerine olan direncini artırmıştır. Hidratasyon reaksiyonlarında ihtiyaç duyulan ekstra silika kaynağı için silis dumanı partikülleri kireçle zenginleştirilmiş kaolin kiliyle reaksiyona girmiştir. Sonuç olarak, kaolin parçacıklarını çevreleyen CSH jel ürünleri oluşmuştur. Fiber katkısı karışımda sürtünme direncini artırmıştır, ayrıca kireçle zenginleştirilmiş kil, silis dumanı ve fiberler arasındaki çimentolaşma reaksiyonlarında kenetlenme etkisi oluşmuştur. Maksimum dayanıma yüzde 0.25 fiber ve yüzde 10 silis dumanı içeriğine sahip kireçle modifiye edilmiş kil numunelerde ulaşılmıştır ve fiber oranı arttıkça basınç dayanımlarında düşüş olduğu gözlemlenmiştir. Sentetik lif, silis dumanı ve sentetik lif-silis dumanı ile modifiye edilmiş numunelerin dayanımında kürlenme süresinden sonra artış gerçekleşmiştir ve donma-çözünme döngülerinden sonra katkılarla modifiye edilmiş numunelerde kontrol numunelerine göre daha düşük dayanım kaybı oluşmuştur. Serbest basınç dayanım testlerinde en yüksek dayanım değerlerine sahip numuneler, donma-çözünme döngülerinde de düşük dayanım kaybı ile en iyi performansı göstermiştir. Sonuçlar endüstriyel atık kullanılarak yapılan zemin iyileştirme projelerinde, silis dumanı ve sentetik lifler ile modifiye edilmiş kireç katkılı kil çalışmasının ekonomik ve çevre dostu bir alternatif olduğunu göstermiştir.

Anahtar Kelimeler: Zemin İyileştirme, Silis Dumanı, Çelik Donatı, Donma-Çözünme, Serbest Basınç Dayanımı

To my family and my future,

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVATIONS

E_{50}	Modulus of Deformation
CL	Clay
CSH	Calcium Silicate Hydrate
XRD	X-Ray Diffraction
UCS	Unconfined Compressive Strength
CBR	California Bearing Ratio
SEM	Scanning Electron Microscopy

1. INTRODUCTION

In the cold regions, soils are subjected to one or more freeze-thaw cycles each year. Freeze-thaw cycles affect the performance of soils and buildings, railroads, embankments, unpaved roads and pipelines constructed within or on the soils. Soils affected from freeze-thaw cycles show visual damages and change in strength, volume, bearing capacity and compressibility values (Porebska, 2002; Qi et al., 2006, 2008; Shibi and Kamei, 2014; Xu et al.,2017; Zhou et.al.,2018). During the freezing stage, pore volume increases due to the phase transformation of water into ice. The process changes the void ratio and alters the structural characteristic in macro and micro scales. Ice formation in frozen soils depend on soil type, moisture content and temperature (Roustaei et al., 2015). Therefore, type of soil and stabilization agent used in the construction activities in zones prone to freeze-thaw action must be chosen carefully. Durability of stabilized soils exposed to freeze-thaw cycles varies with the soil type and amount and type of additive used in stabilization (Khoury and Zaman, 2007; Yarbasi, 2007; Olgun, 2013; Yadav and Tiwari, 2017).

Improvement of engineering properties such as shear strength and compressibility characteristics of soft soils can be carried by several soil stabilization techniques (Yetimoglu *et.al.*2005; Tang *et.al.*, 2007; Saygılı, 2015; Jiang *et.al.*; 2015). Ground improvement methods include use of admixtures, soil replacement, compaction, preloading, and thermal methods (Nelson and Miller, 1992; Fu *et.al.*, 2015; Garcia *et.al.*, 2015; Anggraini *et.al.*, 2017; Muguda *et.al.*, 2018).

Utilizing existing clayey soil in subgrade or backfill applications after stabilization has become popular due to environmental and economic reasons (Consoliet *et.al.*, 2010). An increasing number of studies in recent years show that strength of clayey soils has been improved by mixing soils with cement and fly ash to improve the compressive strength (Kaniraj and Havanagi, 1999; Kolias *et.al.*, 2005; Porcino *et.al.*, 2012; Horpibulsuk *et.al.*, 2011, 2012; Disfani *et.al.*, 2014).

So far, many researchers investigated natural, manufactured materials and industrial wastes for stabilizing fine grained soils. These investigations showed that silica fume addition improved the hydraulic conductivity, compressive strength, and swelling properties of fine grained soils (Prabakar *et.al*, 2002; Kalkan, 2011).

1.1. Stabilization Studies with Lime, Silica Fume and Fibers

Cai *et.al*, (2006) investigated polypropylene fiber (0.05%, 0.15%, 0.25% by weight) and lime (2%, 5%, 8% by weight) modification on clayey soils. Results showed that lime, fiber amount and curing period increased compressive strength values. The optimum strength gain was achieved with 5 percent lime in this study. Fratalocchi *et.al*, (2009) conducted laboratory and test pad experiments on lime stabilization. Low compressibility and high shear strength was observed on laboratory work and tests pads. Mukhtar *et.al* (2010) worked with lime stabilization on highly expansive clays. Results indicated that 5 percent lime is the optimum amount for reactions in soil stabilization with lime on expansive soils.

Soil is capable of withstanding compressive and shear forces however it demonstrates low performance with tensile forces. Soils modified with randomly distributed fiber created attention in geotechnical engineering and many studies have been conducted with natural and synthetic fibers in soil reinforcement (Nataraj and McManis, 1997; Prabakar and Sridhar, 2002; Yetimoglu and Salbas, 2003; Tang *et.al.*, 2007, 2010; Edincliler *et.al.*, 2010). Results obtained from current studies indicated that the strength increase occurs because of fiber strength, fiber content and friction resistance within soil and fiber interface. Incorporation of fibers in geotechnical projects is a trending topic for researchers because natural and synthetic fibers are economic options to alternative construction materials (Puppala and Musenda, 1998). Additionally, synthetic fibers can also be produced from recycled materials which reduces environmental impacts.

Triaxial tests conducted on randomly distributed fibers added cemented soils demonstrated that fiber modified soils have higher residual and peak strength and transition of the brittle behavior to ductile (Consoli, 1998). Soft soil specimens tested after modification with lime and coir fiber showed that with increasing curing time, compressive and tensile strength values increased (Anggraini *et.al.*, 2015). Tests conducted on low plasticity soil stabilized with lime, steel and jute fiber showed up to 6 times increase in the compressive strength values (Güllü and Khudir, 2014). All these studies showed that lime, silica fume and randomly oriented fibers can increase the strength values and improve the fracture toughness and ductility of the soft soils.

Alrubaye et al. (2017) studied on soft kaolinite clay treatment with silica fume and lime. The researchers investigated the physical properties of kaolinite clay modified with 6 percent silica fume and lime percentages changing from 3 to 9 percent. The optimum percentage to improve the shear strength of the tested samples was found 5 percent for lime and 6 percent for silica fume. SEM studies conducted by the researchers showed that due to pozzolanic reactions within the modified clay, new cementation minerals were produced. Pozzolanic products helped in filling the voids of the clay specimens.

Güllü and Fedakar (2017) worked on the measurement of unconfined compressive strength of sand samples modified with polypropylene fibers and sludge ash. A series of unconfined compressive strength tests were applied to the control and stabilized test specimens. Stabilized samples contained from 10 percent to 30 percent sludge ash and 0 percent to 1 percent polypropylene fiber by weight. Samples were cured for 1 and 2 weeks. After the curing period, the samples modified with sludge ash showed increase in the unconfined compressive strength values up to 3 times. Addition of polypropylene fiber to the sludge ash modified samples improved the stress-strain characteristics and unconfined compressive strength values of the tested samples. Samples modified with 10 percent sludge ash and 1 percent polypropylene fiber performed best in the unconfined compressive strength tests.

Nagrale and Patıl (2017) investigated improvement of subgrade soils with class F fly ash, polypropylene fiber and hydrated lime. Soil samples were mixed with, 1.5 percent to 6 percent lime, 5 percent to 20 percent fly ash and 0.25 percent to 1 percent fiber to measure the improvement on the subgrade soil. CBR values of samples modified with lime, fly ash and fiber were increased up to 5, 2.5 and 3 times respectively. It is concluded that, pavement resting on modified subgrade soil is economic in terms of thickness reduction in lower layers of the pavement and also saving a considerable amount of construction material. Service life of the road section for the soils stabilized with lime, fly ash and fiber were calculated as 6.5, 4.4 and 3.3 times more as compared with the control test section.

Goodarzi et al. (2016) studied expansive clay stabilization with cement and silica fume-cement blend (CSF) additives. Cement and CSF addition were in the range of 2.5 percent to 20 percent to the expansive clay test specimens. Prepared samples were cured up to 28 days. Samples mixed with cement showed up to 2.5 times improvement in the unconfined compressive strength values compared to control specimens. Samples mixed with cement-silica fume blend showed more than 3 times performance gain in the unconfined compressive strength test results for the 28 days cured specimens. Researchers also investigated the effect of curing temperature and cured another set of specimens at 40°C. Unconfined compressive strength results nearly doubled with the effect of high temperature curing. Scanning electron microscopy studies revealed that silica fume addition caused densification of the soil matrix with new and additional cementing products compared to samples modified with cement only.

Chen et al. (2015) investigated the effectiveness of polypropylene fibers on cement stabilized and fiber reinforced soft clay. Researchers studied with monofilament polypropylene fibers and fibers obtained from waste polymer textile bags. Unconfined compressive strength tests were performed on fiber and cement modified clay samples after curing. Test results indicated that fiber and cement modification increased the unconfined compressive strength and improved the ductility of the clay samples. Polypropylene fibers performed a little better than the fiber bundles obtained from waste polymer textile bags in the test results. Fiber reinforced cement added clay specimens performed better in 7 days curing period compared to cement stabilized clay samples with no fiber.

Tang and Zhao (2010) worked on interfacial shear strength of soils modified with fiber. To observe the behaviour and strength properties of soils modified with fiber, specially designed apparatus is used for pull-out tests. Test results revealed that water content and dry density had a serious effect on interfacial strength. Also with the addition of cement to the matrix and with increasing curing time, interfacial peak strengths obtained from pull-out tests showed a dramatic increase. Scanning electron microscopy studies showed that after shearing, grooves and deformations were observed on the fiber which proves the interaction between soil and fiber.

Bakir et al. (2017) studied improvement of collapsible soils with glass fiber addition. Samples treated with glass fiber were compacted with different water contents and compaction energy. Soil samples having 20 percent clay and 80 percent sand were used for the testing. Consolidation setup is used in this study to observe the improvement with glass fiber addition. Glass fiber was added from 0 to 6 percent to the specimens with varying water contents from 2 to 6 percent. Samples were compacted at three different energy levels before testing. Oedometer results showed that glass fiber addition reduced the collapsibility of the tested soil specimens.

Fattah et al. (2015) investigated lime-silica fume mixture effect on bearing capacity of soft clays. Lime, silica fume and lime-silica fume mixtures were used for stabilizing soft clay specimens. Additives were prepared in slurry form and grouted into the specimens. 2 percent to 6 percent lime and 2.5 percent to 10 percent silica fume and their various mixtures (2% lime + 5% silica fume, 4% lime + 5% silica fume, 6%lime + 5% silica fume) were used for stabilization. Effectiveness of the grouting, effect of injection hole spacing and grouting depth were also investigated in the study. Bearing capacity of soft clay specimens were increased between 6.58 percent to 88 percent after stabilization with lime and silica fume. Unconfined compressive strength tests were also performed on soft clay samples mixed with different percentages of lime and silica fume mixtures. Test results revealed that mixtures having 4 percent lime and 5 percent silica fume had the highest strength values.

The aforementioned studies generally focused on the strength increase of soils stabilized with lime, silica fume and fiber. However, there is a limited number of work in the literature, which strictly focused on the freeze-thaw behavior of the soils stabilized with lime, silica fume and fibers.

Kalkan (2009) investigated freeze-thaw action on strength and permeability of fine grained soils. Silica fume was used as an additive to improve the freeze-thaw performance of clayey soils. Experimental results showed that stabilized soils containing silica fume are more durable to freezing-thaw action compared to natural soil samples.

Roustaei et al. (2013) studied the effect of polypropylene fibers in improvement of cohesive soils in terms of durability. 0.5, 1 and 1.5 percent polypropylene fibers were added by weight to natural soil for stabilization, and samples were exposed up to 9 freeze-thaw cycles. It has been found that compressive strength of modified samples showed less strength reduction with increasing number of freeze-thaw cycles. This performance gain was attributed to the polypropylene fibers acting as a tensile member in the soil matrix.

Jafari and Esna-ashari (2012) conducted unconfined compression tests to study the effect of waste tire cord on lime stabilized clayey soils subjected to freeze-thaw action. Prepared samples were subjected up to 3 freeze-thaw cycles and afterwards tested for compression. Test results showed that stress-strain behavior and strength depended on lime and tire cord content. For stabilized specimens, fiber added lime stabilized samples presented less strength loss with increasing freeze-thaw cycles.

Kravchenko et al. (2018) conducted unconsolidated undrained triaxial compression tests on the fiber reinforced fine grained soil samples subjected to freeze-thaw cycles. Polypropylene and basalt fibers were added into low plasticity clay soil to improve the engineering properties. Decrease in the strength of the tested samples were observed with increasing number of freeze-thaw cycles. Test results showed that, samples modified with polypropylene fiber presented higher performance in the test results. Samples modified with 0.5 percent polypropylene fiber had 10.7 percent higher internal friction angle than samples modified with 0.5 percent basalt fiber. Besides that, before freezing and after 15 freeze-thaw cycles, samples modified with polypropylene fiber showed the best results.

Li et al. (2018) investigated the tensile behavior of polypropylene fiber reinforced silty clay before and after various freeze-thaw cycles. Direct tensile tests were performed on test specimens. The test results indicated that, fiber addition to soil samples increased the stiffness, peak and residual strength and also failure behavior of test specimens changed from brittle to ductile after first freeze-thaw cycle. By increasing the number of freeze-thaw cycles, decrease in the tensile strength is observed up to 9 freeze-thaw cycles. It is reported that, most of the decrease in strength occurred at the first 5 freeze-thaw cycles.

The main objective of this study was to investigate the polypropylene fibers, silica fume and mixtures having various ratios of silica fume-fibers effect on freeze-thaw durability of lime rich kaolinite clay samples, for different silica fume and fiber contents and for varying numbers of freeze-thaw cycles.

2. MATERIALS AND METHODS

2.1. Materials

Kaolinite was supplied from Çanakkale region in Northwest Turkey. According to the Unified Soil Classification System, the soil is a low plasticity inorganic clay (CL). The grain size distribution of kaolinite is given in Figure 2.1 and the XRD pattern of kaolinite is given in Figure 2.2. The silica fume used in this research was obtained from Eti Electrometallurgy Inc. located in Antalya, Southwest Turkey. Slaked lime was supplied from Muğla, Turkey. Considering the compressive strength performances together with benefit-cost ratio, the optimum additive ratio of stabilizers was found as 5% for lime (Cai *et.al.*, 2006, Tang *et.al.*, 2007; Mukhtar *et.al.*, 2010)

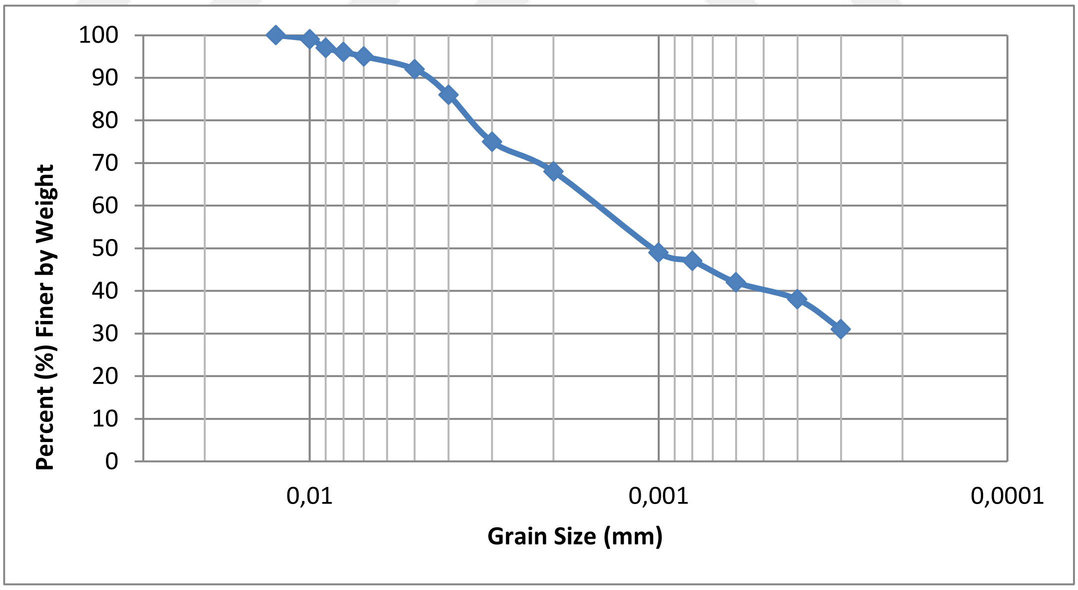


Figure 2.1. Grain size distribution of kaolinite clay

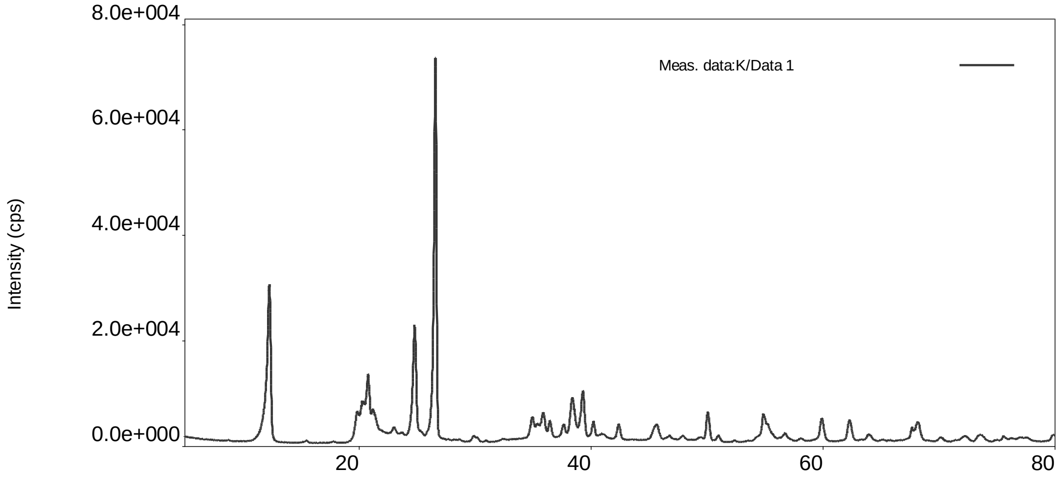


Figure 2.2. XRD pattern of kaolinite

Silica fume is a pozzolanic industrial by-product which is mostly effective in high performance concrete production having average grain diameter about 0.1 μm and unit weight 200-250 kg/cm^3. After high purity quartzite is reduced with coal and wood particles in electric arc furnaces, silica fume is obtained during the production of silicon metal and ferrosilicon alloys. The chemical compositions of kaolinite and silica fume are summarized in Table 2.1.

Table 2.1. Chemical composition of kaolinite and silica fume used

Element	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_4	P_2O_5	MnO	LOI
Kaolinite %	63.09	25.50	0.38	0.37	0.30	0.01	0.14	0.30	0.65	-	-	7.30
Silica Fume %	85-95	1-3	-	0.5-1.0	0.8-1.2	1-2	-	-	-	-	-	0.5-1

Synthetic polypropylene fibers were supplied from Polypropylene Fiber Inc. located in Istanbul, Turkey. The polypropylene fibers were 12 mm in length and 30 μm to 40 μm in diameter, having specific gravity 0.91 g/cm^3, with tensile strength of 600 MPa, elastic modulus of 3 GPa and linear strain at failure of 25 percent.

2.2. Sample Preparation

The required amounts of kaolinite, lime, silica fume and fibers for each sample were mixed in dry state. The kaolinite specimens were enriched with 5 percent by weight lime to provide extra calcium for the cementation reactions (Mukhtar *et.al.*, 2010; Cai *et.al.*,2006). The specimens were mixed with silica fume content changing from 0 to 10 percent and fiber content varying from 0 to 1 percent by weight. The standard proctor compaction test was conducted through ASTM D698-12e2 to determine maximum dry unit weight and optimum moisture content. The optimum moisture content of the samples with and without additives ranged from 18 percent to 23 percent, maximum dry unit weights ranged from 14.67 kN/m^3 to 15.58 kN/m^3. Samples were compacted at maximum dry density and optimum moisture content using Harvard mini compactor for unconfined compression testing in which the specimen size was 34 mm in diameter by 72 mm in height. After compaction, samples were wrapped with cling film and afterwards with aluminum foil to preserve the moisture, then stored in a humidity and temperature controlled curing room for 28 days (at 21°C and 90% relative humidity). Samples were named with clay (C), synthetic fiber (F), silica fume (S), respectively. Three samples were prepared for the same mixture types to provide reliability in the test results. The mixture ratios of the samples used in the experimental study are shown in Table 2.2.

Table 2.2. Kaolinite, lime, silica fume and synthetic fiber ratios of samples

		Materials %			
Samples	Kaolinite	Lime	Silica Fume	Synthetic Fiber	Total
CF0S0	95	5	-	-	100
CF0S2.5	92.5	5	2.5	-	100
CF0S5	90	5	5	-	100
CF0S10	85	5	10	-	100
CF0.25S0	94.75	5	-	0.25	100
CF0.25S2.5	92.25	5	2.5	0.25	100
CF0.25S5	89.75	5	5	0.25	100
CF0.25S10	84.75	5	10	0.25	100
CF0.5S0	94.5	5	-	0.5	100
CF0.5S2.5	92	5	2.5	0.5	100
CF0.5S5	89.5	5	5	0.5	100
CF0.5S10	84.5	5	10	0.5	100
CF1S0	94	5	-	1	100
CF1S0.25	91.5	5	2.5	1	100
CF1S0.5	89	5	5	1	100
CF1S10	84	5	10	1	100

C: Kaolinite, F: Fiber, S: Silica Fume

Unconfined compressive strength tests were conducted to observe the effect of silica fume working together with synthetic fibers on strength behavior of clayey soil samples. The unconfined compressive strength of the specimens is investigated by a universal compression loading machine with a maximum load capacity of 5kN. The unconfined compressive strength values of modified clay samples were determined using strain controlled application of the axial load to analyze the effects of freeze-thaw conditions on control and stabilized samples after 0, 2, 5 and 8 freeze-thaw cycles in accordance with the ASTM D2166M-16. Measurements are made of elapsed time, axial deformation and axial load. The loading rate was chosen as 1.0 mm per minute. Modulus of deformation was also calculated for samples modified with different silica fume percentages (E_{50}, strain at 50 percent of the unconfined compressive strength value).

To investigate interaction and cementitious bonds between lime rich clay, silica fume particles and synthetic fibers, modified samples were analyzed with scanning electron microscope (SEM). The test results were interpreted with JEOL JSM-7600F scanning electron microscope at Muğla Sıtkı Koçman University Central Research Laboratory.

Miniature Harvard compaction setup was preferred to prepare small samples for freeze-thaw cycles. Producing smaller samples made it easier to control the heat transfer within the specimens and minimized transient freezing (Konrad and Samson, 2000).

After 28 days of curing time completed, stabilized and control samples were subjected to freeze-thaw cycles in accordance with ASTM C666M-15 procedure A (freezing and thawing in water). Test specimens were subjected to freeze-thaw cycles by a programmable freezing-thawing device. Stabilized and control samples were placed in the computer controlled freeze-thaw chamber as seen in Figure 2.3. Test samples were conditioned at -18^{0}C and +20^{0}C for 5 hours intervals.

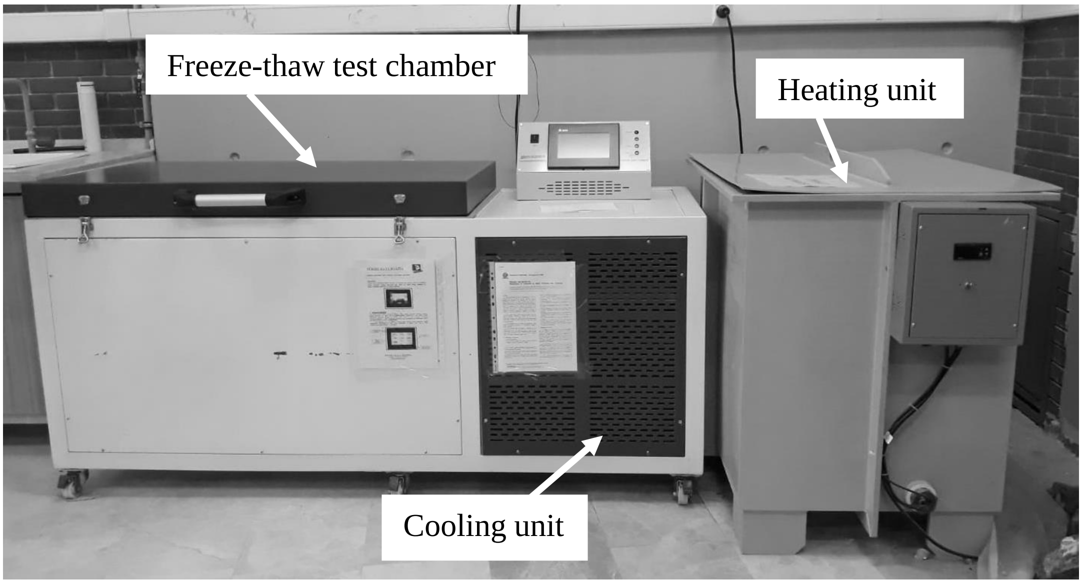


Figure 2.3. Computer controlled freeze-thaw chamber

Samples were exposed to 2, 5 and 8 freeze-thaw cycles to measure the change in durability. Using temperature and precipitation data Binal et al. (1997) generated a freeze-thaw severity index map for Turkey. For the Aegean region of Turkey, annual freeze-thaw cycles in the severity map lies between 2 to 8 cycles per year. These values were taken into account in the laboratory studies. After exposure, control and stabilized samples were tested in terms of strength to measure the change in durability.

3. RESULTS AND DISCUSSION

3.1. Stress-Strain Behavior

Figure 3.1 illustrates the stress-strain curves of the modified lime rich clay with fibers at various silica fume content. As shown in Figure 3.1, samples with 0 percent silica fume content showed ductile behavior while the other samples reached maximum strength values at lower strain, ranging from 1 percent to 2 percent, with the rise in silica fume content. Cementation reactions probably were the main factors on the change in the ductility of the modified lime rich clay as silica fume content increased (Chen *et.al*., 2015). Fiber modified samples with no silica fume content behaved in a ductile manner compared to silica fume added specimens. This can be correlated to the bonds between clay particles provided by fiber addition. Silica fume addition increased the cementation effect with the help of extra silicon dioxide insertion into the matrix. This extra silicon dioxide resulted in hydration reactions with lime which resulted in formation of additional cementation products (CSH). The cementation effect was a leading factor on the ductility behavior of the stabilized clay samples with the increase in the silica fume content in the matrix.

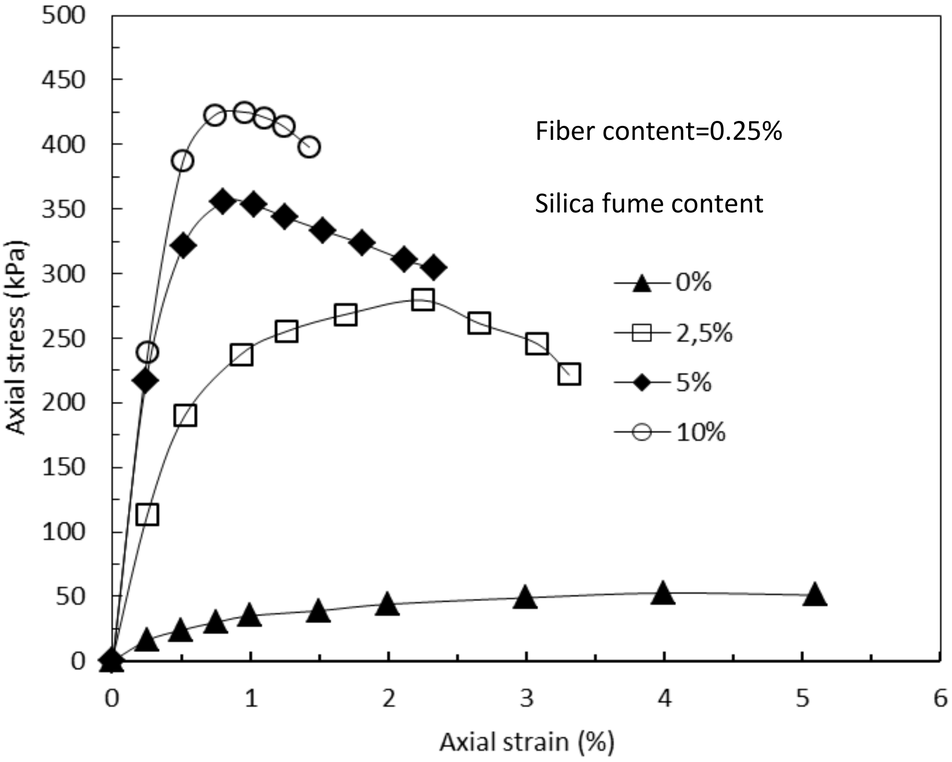


Figure 3.1. Stress-strain graph of samples modified with varying silica fume content

Figure 3.2 shows stress-strain curves of CF0S2.5 and CF0.25S2.5 samples. CF0S2.5 had no synthetic fiber whereas CF0.25S2.5 had a fiber content of 0.25 percent. Samples mixed with fibers performed better in unconfined compression testing. Peak compressive stress of the samples with no fiber is at 0.7 percent strain whereas the specimens with fibers had higher peak stress levels. Fiber addition improved not only the ductility of silica fume stabilized clay but also its bearing capacity (Chen *et.al.*, 2015; Anggraini *et.al.*, 2015). The cementation effect binded the fibers with lime rich kaolinite clay grains resulting in higher strength values (Horpibulsuk *et.al*, 2012). The cementation products attached on the fiber surface increased the friction between the fibers and the modified clay matrix. With increasing strain, fibers acted as tension members in the matrix and worked like a net inside, which increased the resistance in the soil particles resulting in higher axial peak stress levels (Ayeldeen and Kitazume, 2017).

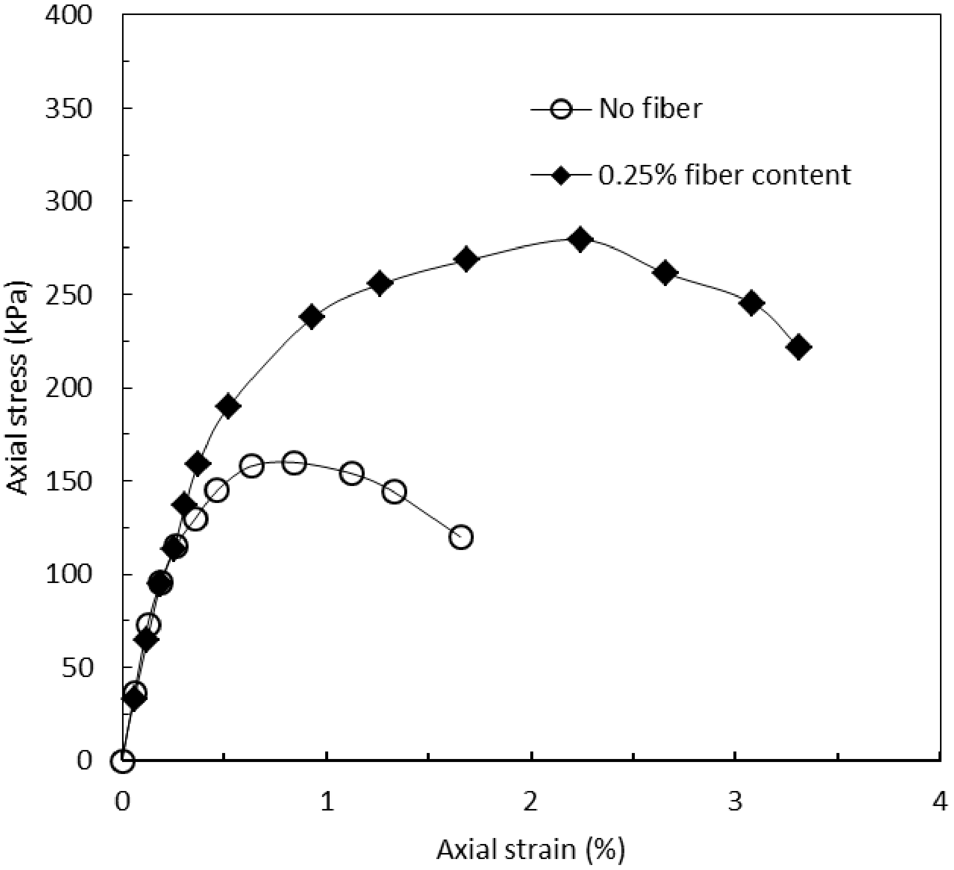


Figure 3.2. Stress-strain curves for specimens with 2.5% and without synthetic fibers.

Figure 3.3 illustrates the stress-strain curves of the modified lime rich clay with 2.5 percent silica fume at various fiber content. Samples reached their maximum axial stress around 2.5 percent strain level. Fiber bonds with clay grains helped the modified clay behave in a more ductile manner. Samples behaved more ductile with the increasing amount of fiber in the matrix. Axial strains at peak level increased from 2.2 percent to 3.0 percent with increase in fiber level from 0.25 percent to 1.0 percent. Meanwhile, with increasing amount of fiber, unconfined compressive strength values decreased up to 12 percent, keeping the silica fume level constant. The higher silica fume content led to higher compressive strength levels by increasing the matrix stiffness, the bonds between the fibers and mixture also increased thanks to the cementitious products formed, resulting in a considerable increase in compressive strength.

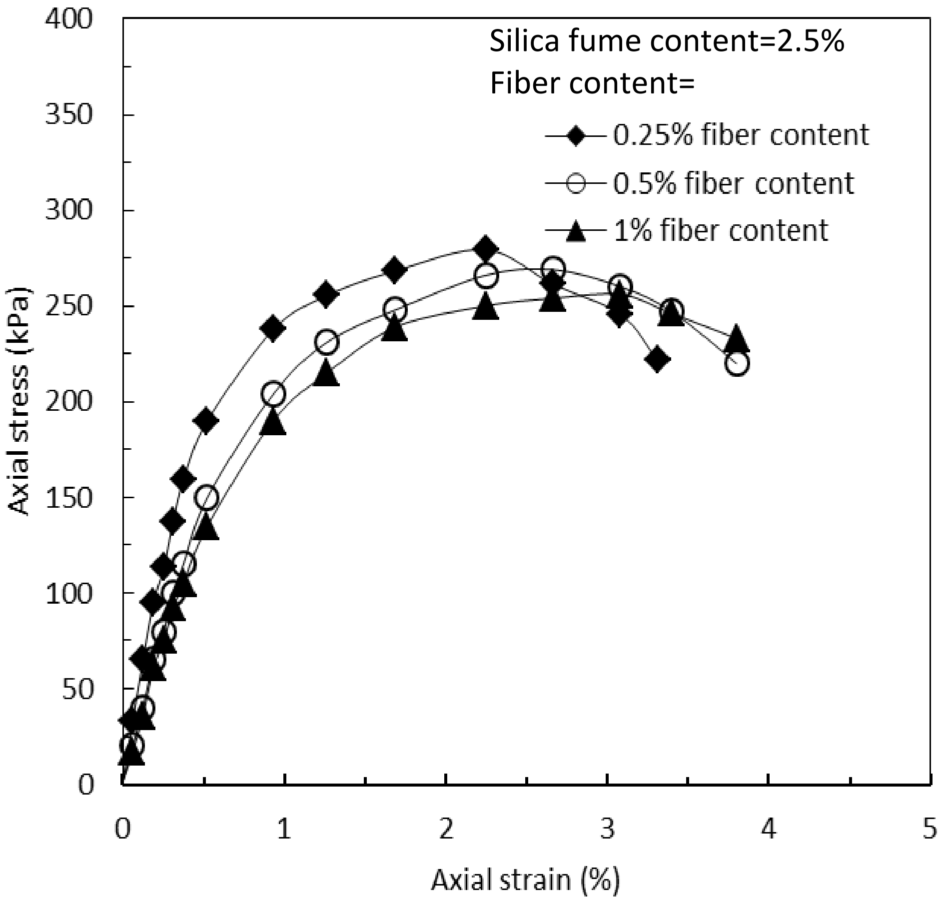


Figure 3.3. Stress-strain graph of samples modified with varying fiber content.

3.2. Modulus of Deformation

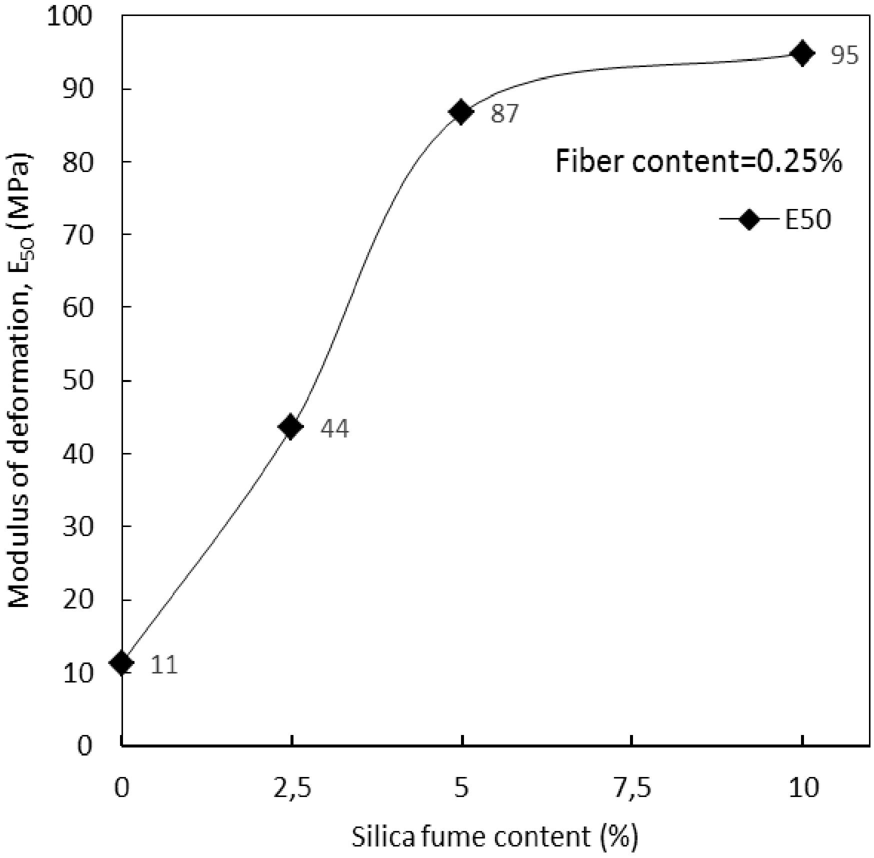


Figure 3.4. Modulus of deformation of samples modified with varying silica fume content.

Figure 3.4 shows variation of deformation modulus (E_{50}) with different silica fume content after curing. It is clear that modulus of deformation is increasing within same trend as in unconfined compressive strength values. Unconfined compressive strength increased 300 percent with increasing silica fume content from 0 percent to 10 percent. Modulus of deformation increased 860 percent for the same silica fume content variation. Due to the change in the stress-strain curves, modified clay soils translated from ductile to brittle characteristics. As seen in Figure 3.3, within same silica fume content with varying fiber ratios, modulus of deformation is very similar. With increasing the silica fume content to 10 percent, modulus of deformation reached up to the highest value obtained (95MPa). Variation in silica fume content affected the modulus of deformation, however variation in fiber content did not make a considerable change in modulus of deformation for constant silica fume levels in the mixtures.

Unconfined compressive strength values of silica fume, synthetic fiber and mixtures having various ratios of silica fume-fiber added clayey soil samples are illustrated in Figure 3.5. Compared to control samples (CF0S0), the strength values of the stabilized samples containing 0.25 percent fiber and 10 percent silica fume (CF0.25S10) increased 8 times (Figure 3.5.). Performance gain in the stabilized samples is based on the internal friction of silica fume grains and cementation reactions within clay, lime and silica fume (Gillot, 1968; Ola, 1978, Harianto *et.al*, 2009). Kaolinite enriched with 5 percent lime helped to produce calcium and hydroxide ions (Saride *et.al*, 2013; Khemissa and Mahamedi., 2014).

3.3. Unconfined Compression Test Results

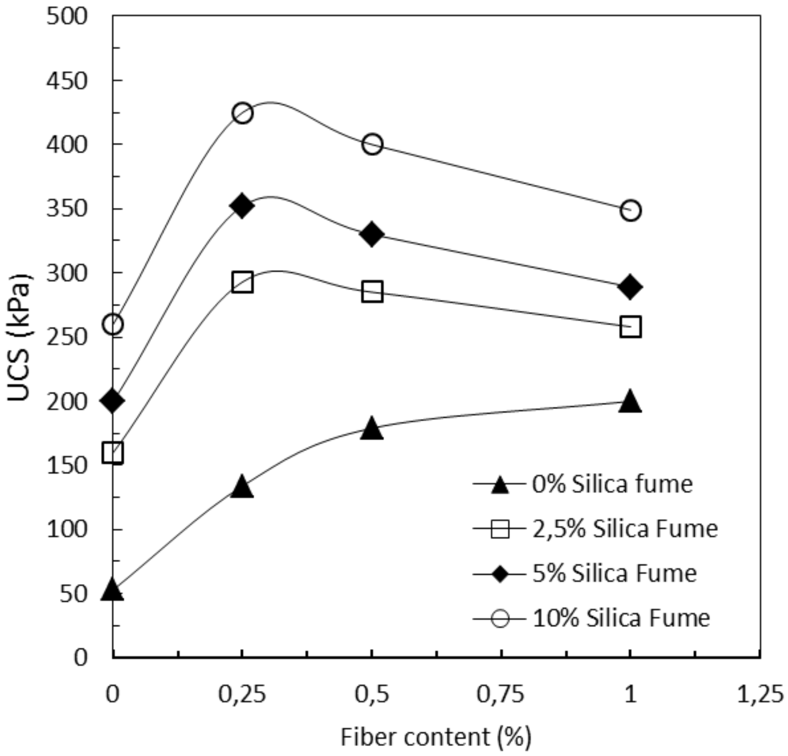


Figure 3.5. Effect of polypropylene fiber on the unconfined compressive strength with varying silica fume contents.

The silica fume in the soil matrix was an additional source to siliceous compound of kaolinite clay and reacted with calcium and hydroxide and formed calcium silicate hydrate gels (CSH). CSH gel structure formed after curing contributed to the development of a strong and brittle matrix (Bell, 1993; Kalkan, 2011). Figure 3.5 shows that the unconfined compressive strength values of fiber mixed samples without silica fume had a tendency to increase with increasing fiber content. However, UCS values of silica fume and synthetic fiber stabilized clay samples had a trend to increase up to a peak stress level. According to the measured data, the optimum synthetic fiber content additive was 0.25 percent by weight for the samples studied.

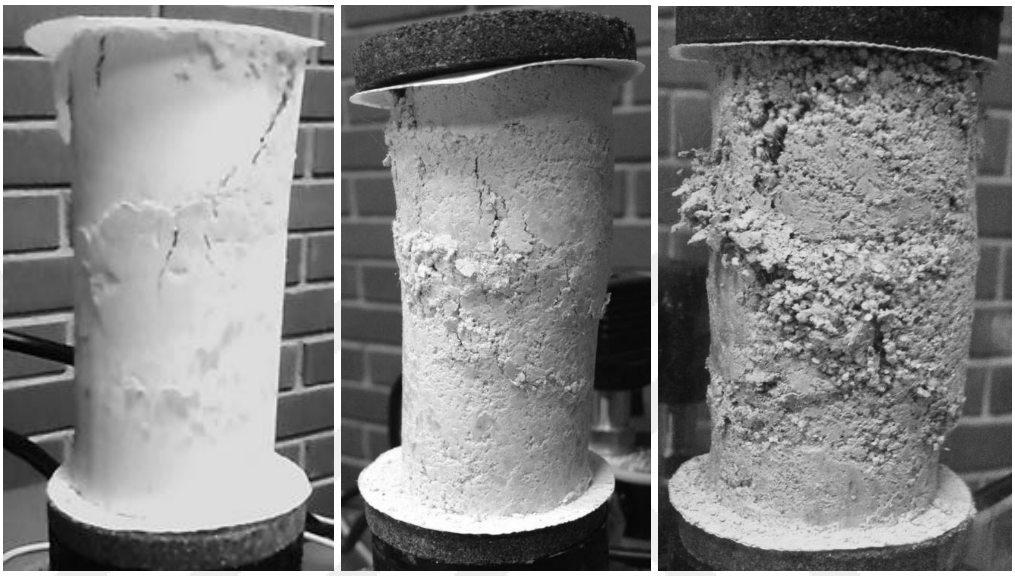
Both synthetic fibers and silica fume played an important role in the strength gain of the modified clay specimens (Cai *et.al*., 2006; Anggraini *et.al*., 2015; Chen *et.al*., 2015). The test results showed that usage of fiber and silica fume mixtures together had higher performance than only modifying lime rich kaolinite clay with one additive (silica fume or fiber). Fibers probably improved the friction resistance and interlock effect was created by cementation reactions between lime stabilized soil, fibers and silica fume (Harianto *et.al*., 2009).

Fiber and soil interface produces a complex mechanism. In the literature, researchers found that pullout performance is affected by several factors such as, surface roughness, dry density, confinement stress, displacement rate and embedded fiber length (Brandstetter *et.al*., 2005). In this study after compacting and curing the samples, synthetic fibers were covered with cementitious products and kaolinite. After testing the modified samples in compression, soil particles and cementitious products were observed in SEM analysis on the fiber strips (Anggraini *et.al*., 2015).

3.4. Failure Modes of Samples

The failure modes of control and modified samples (with silica fume and fiber) are displayed in Figure 3.6. As seen from the images, silica fume and fiber addition changed the failure modes of modified clay samples. Cementation minerals formed after curing also strengthened the randomly distributed fibers in the soil matrix with

CSH gel, which performed like tree roots spreading the stresses into wider zones (Figure 3.6 (c)). As seen in Figure 3.6 the observed crack sizes are different on the surface of the three samples after compression testing. A similar behavior was observed from experimental measurements by cement-fiber modified soils (Tang *et.al*., 2007,2010) and lime-fiber modified soils (Cai *et.al*., 2006).



(a) CF0S0 (b) CF1S0 (c) CF1S2.5

Figure 3.6. Effects of fiber and silica fume addition on the failure modes; (a) control sample, (b) 1% fiber modified clay; (c) 1% fiber and 2.5% silica fume modified clay.

3.5. Freeze-Thaw Behavior and Scanning Electron Microscopy

Figure 3.7 and Figure 3.8 show the scanning electron microscope images of the modified kaolinite clay samples after 1 year curing. CSH gel and lime rich kaolinite remaining on the sheared sample’s synthetic polypropylene fiber strip are visible in the image. The plant root effect distributed stresses in a wider area and fiber strip pulled off cemented soil material while shearing, however the fiber itself was not ruptured (Anggraini *et.al*., 2015).

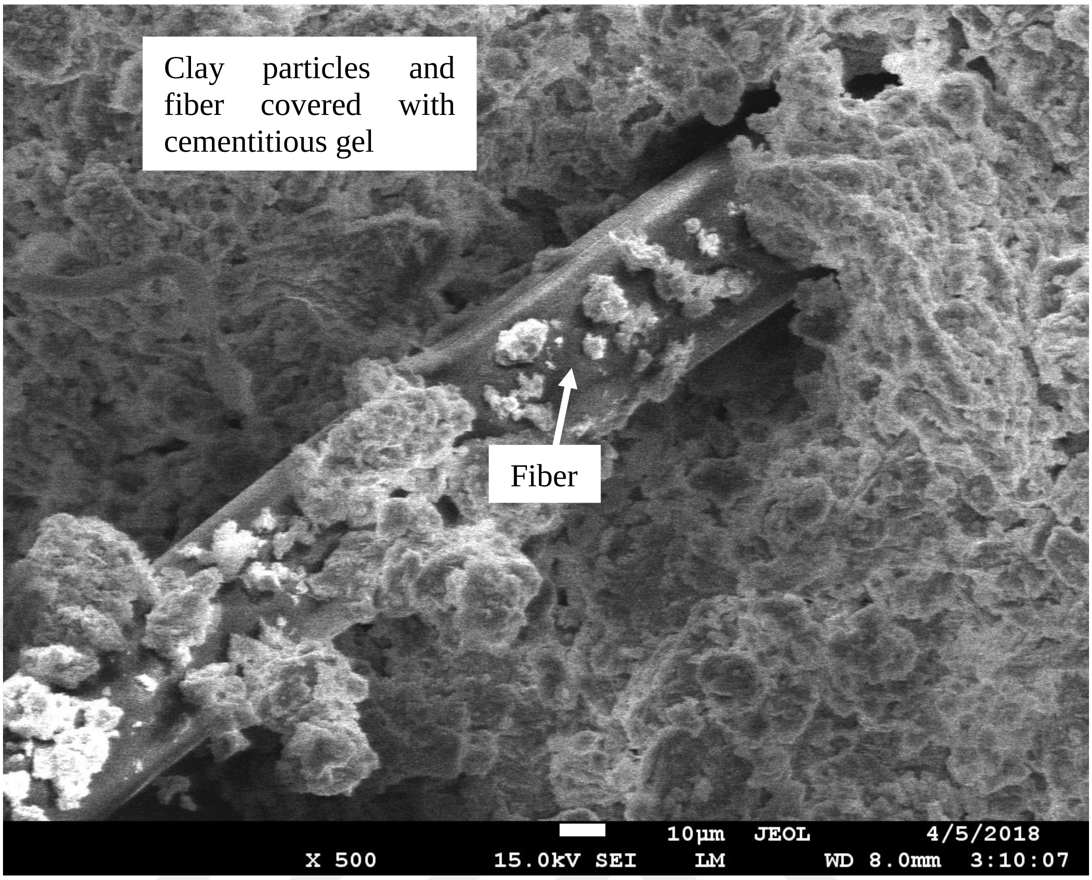


Figure 3.7. Image of fiber and silica fume modified clay with 0.25% fiber and 10% silica fume after 1 year curing (CF0.25S10-magnification 500x)

Silica fume particles reacted with lime rich kaolinite and through hydration reactions CSH gel products were formed, which surrounded the kaolinite particles as seen in Figure 3.8. Voids of the modified samples were filled with the CSH gel (Goodarzi *et.al.*, 2016).

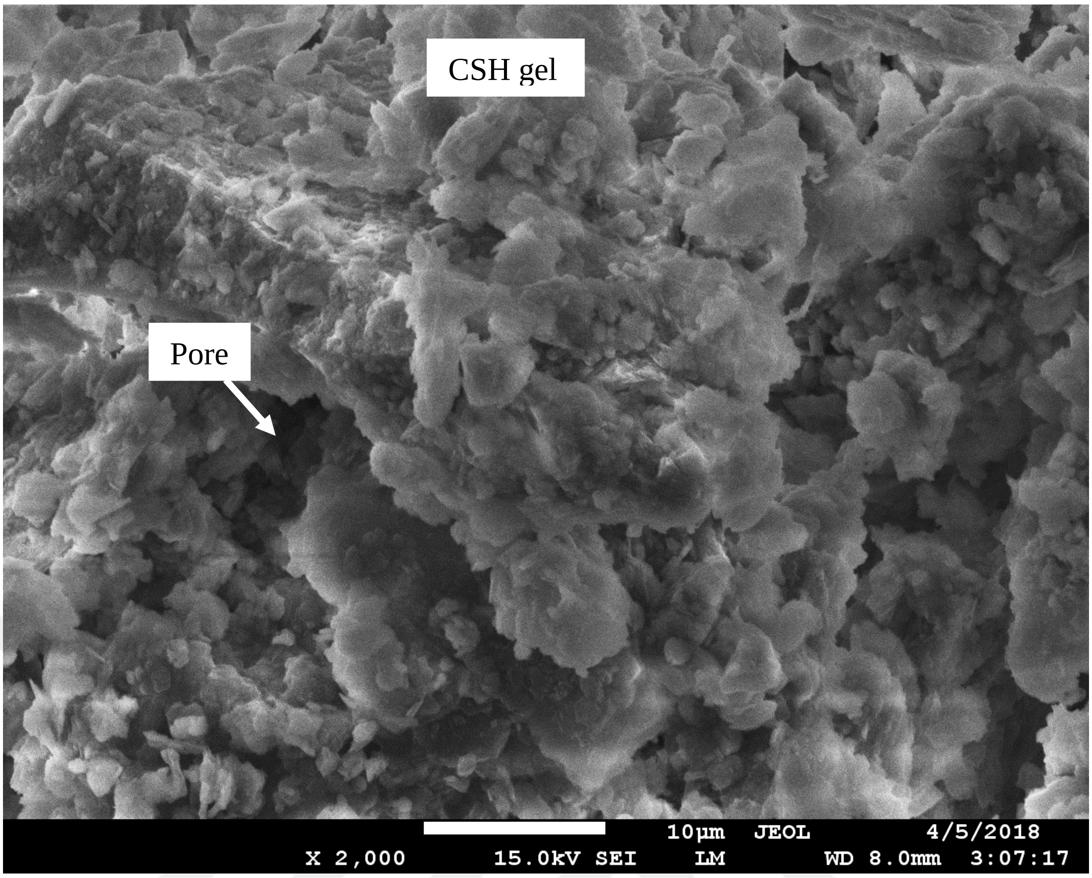


Figure 3.8. Silica fume and lime modified kaolinite covered with cementitious products after 1 years of curing (CF0.25S10- magnification 2000x)

During the freezing process, water in the pores expanded, which led to the formation of cracks and fissures in the matrix (Figure 3.9 and Figure 3.10). When compared to unfrozen samples in Figure 3.7 and Figure 3.8, fissures became visible and clay grains with cementation products lost much of their contact.

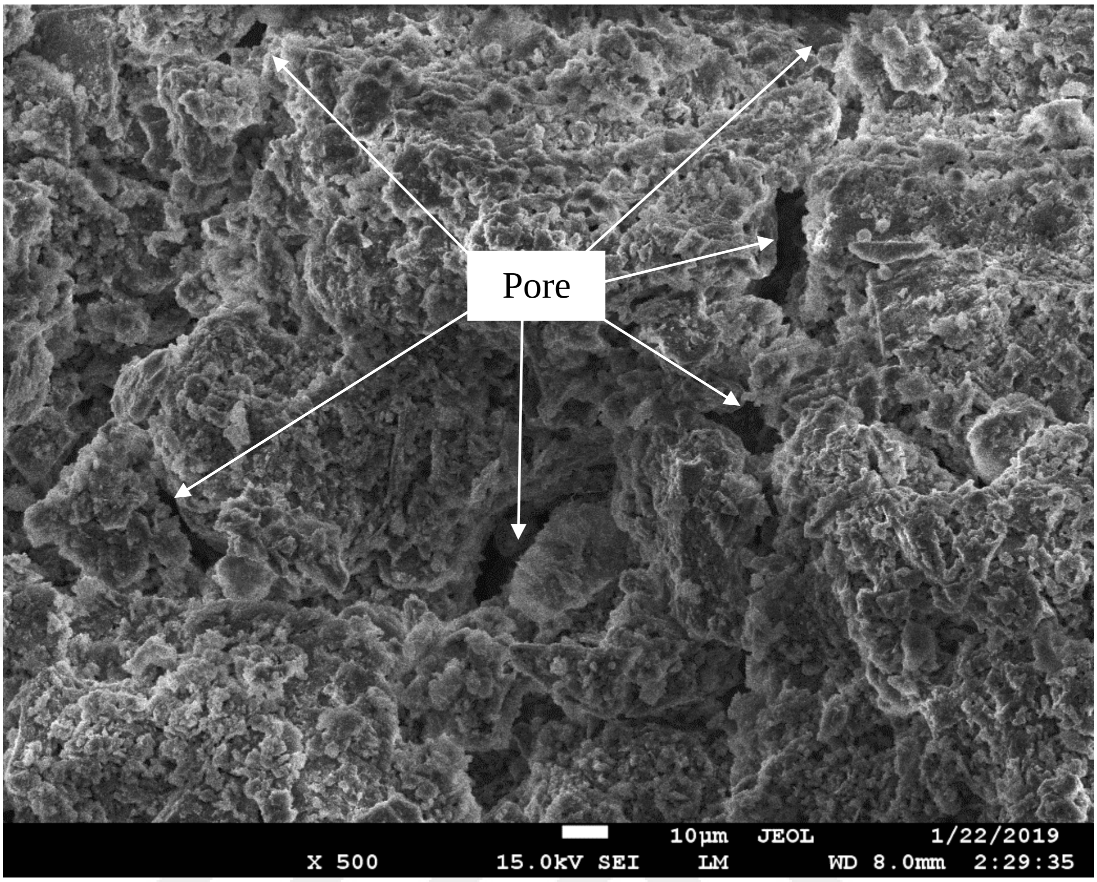


Figure 3.9. Image of fiber and silica fume modified clay with 0.25% fiber and 10% silica fume subjected to 8 freeze-thaw cycle (CF0.25S10 – magnification 500x)

As seen from Figure 3.7 to Figure 3.11, soil in the unfrozen state is denser. Freeze-thaw cycles increased the void volume by freezing and thawing, creating new fissures and cracks. As a result, unconfined compressive strength values decreased due to the loss of contact with increasing number of cycles as seen in Table 3.1. Formed cracks and fissures in macroscale can also be seen in Figure 3.12. Freeze-thaw cycles produced great effects on soil disintegrity based on electron microscopy images (Han *et. al.*, 2018).

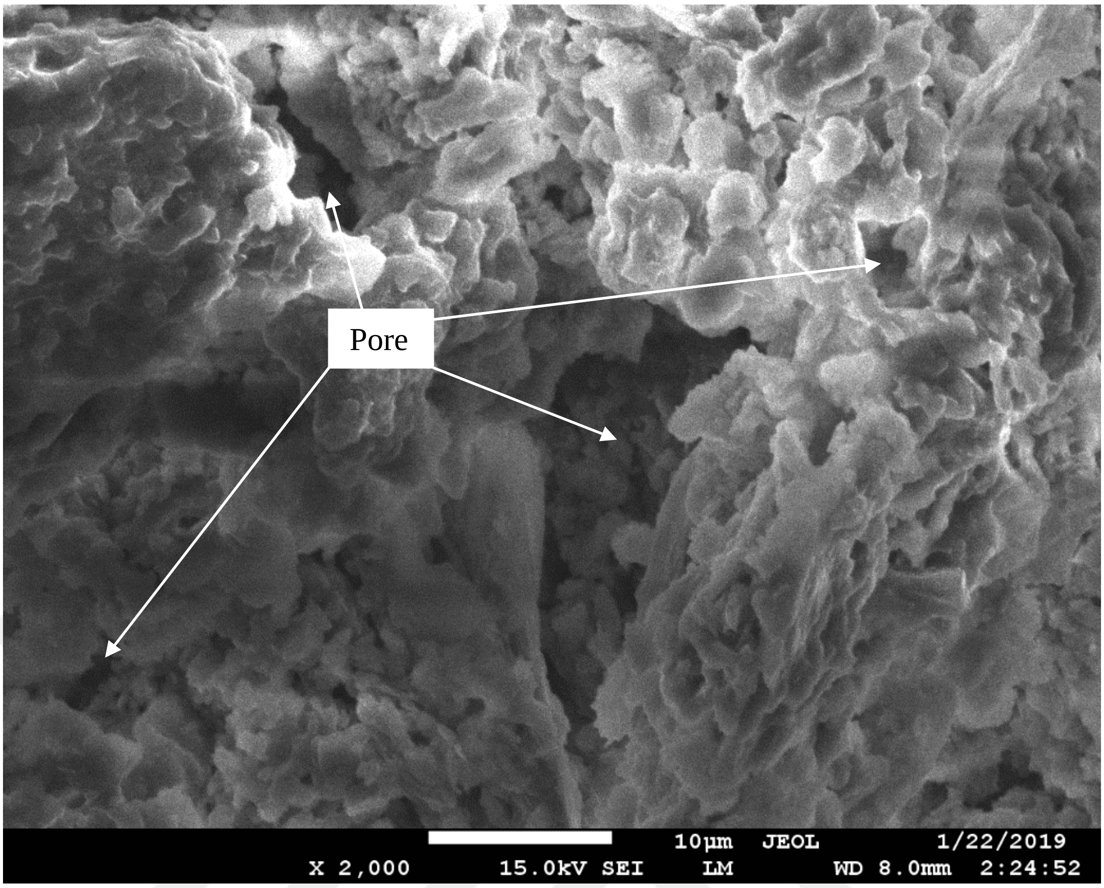


Figure 3.10. Image of fiber and silica fume modified clay with 0.25% fiber and 10% silica fume subjected to 8 freeze-thaw cycle (CF0.25S10 – magnification 2000x)

To investigate the strength loss of control and stabilized samples due to freeze-thaw action, samples were placed in the computer controlled freeze-thaw chamber. Three samples were prepared for the same mixture type and tested in freeze-thaw apparatus to provide reliability in the test results. After the completion of freeze-thaw cycles, unconfined compressive strength tests have been conducted at the laboratory. Selected control (CF0S0) and stabilized samples (CF0.25S2.5, CF0.25S5, CF0.25S10, CF0.5S10, CF1S0, CF1S5) demonstrating high performance at unconfined compressive strength tests were tested for the freeze-thaw action. Effects of freeze-thaw action on unconfined compressive strength of control and stabilized samples are shown in Figure 3.11. As seen from the test results, control and stabilized samples undergo an incremental strength loss after they were exposed to increasing numbers of freeze-thaw cycles. It is significant that stabilized samples containing silica fume were subjected to less strength loss.

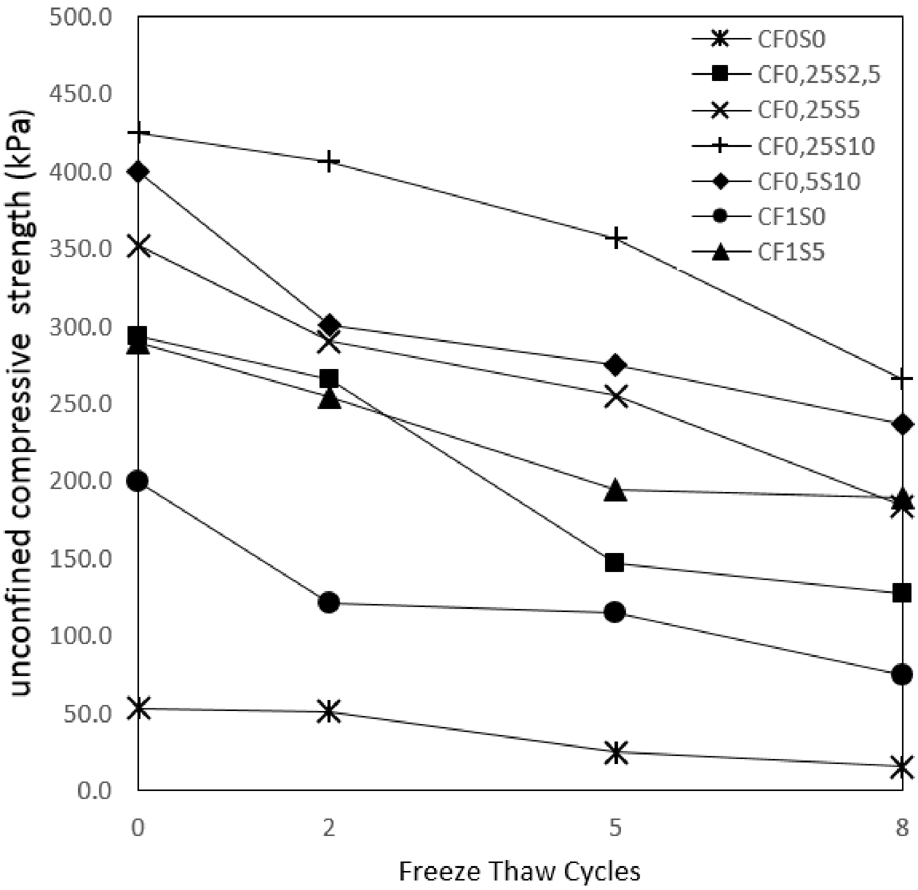


Figure 3.11. Effect of fiber and silica fume addition on unconfined compressive strength values of samples exposed to freeze-thaw cycles.

Strength loss in samples exposed to eight freeze-thaw cycles having silica fume are in the range of 37.5 to 56.5 percent as shown in Table 3.1. Samples only modified with fiber showed 62.6 percent strength loss and control samples showed 70.9 percent strength loss after exposure to eight freeze thaw cycles. Fiber was not able to act properly alone against freeze-thaw durability (Jafari and Esna-ashari, 2012). The freeze-thaw durability has increased with silica fume and fiber addition to lime rich kaolinite samples. Silica fume and fiber created a coupled effect and created a high performance and more durable soil. At the 8 freeze-thaw cycle test results, strength loss decreased from 70.9 percent to 37.5 percent for the stabilized samples containing 0.25 percent fiber and 10 per cent silica fume.

Table 3.1. Unconfined compressive strength values after freeze-thaw cycles

	UCS (kPa)						
F-T Cycles	**CF0S0**	**CF0,25S2,5**	**CF0,25S5**	**CF0,25S10**	**CF0,5S10**	**CF1S0**	**CF1S5**
0	53.0	293.0	352.0	425.0	400.0	200.0	289.0
2	51.0	265.8	289.9	406.4	300.8	120.9	253.9
5	24.9	146.4	254.8	356.5	275.3	114.3	194.1
8	15.4	127.3	183.7	265.7	236.2	74.9	189.3
Strength Loss (0 to 8 cycles) (%)	70.9	56.5	47.8	37.5	41.0	62.6	34.5

The main reason for the changes in strength loss due to freeze-thaw action is the change in the soil structure. The strength loss between control and stabilized samples are attributed to crack formations and particle reorientation due to changes in the soil structure (Cruzda and Hohmann, 1997; Viklander and Eigenbrod, 2000). Crack growth within the specimens increase with the increasing number of freeze-thaw cycles. This condition can be seen with increasing deformations on the test specimens in Figure 3.12.

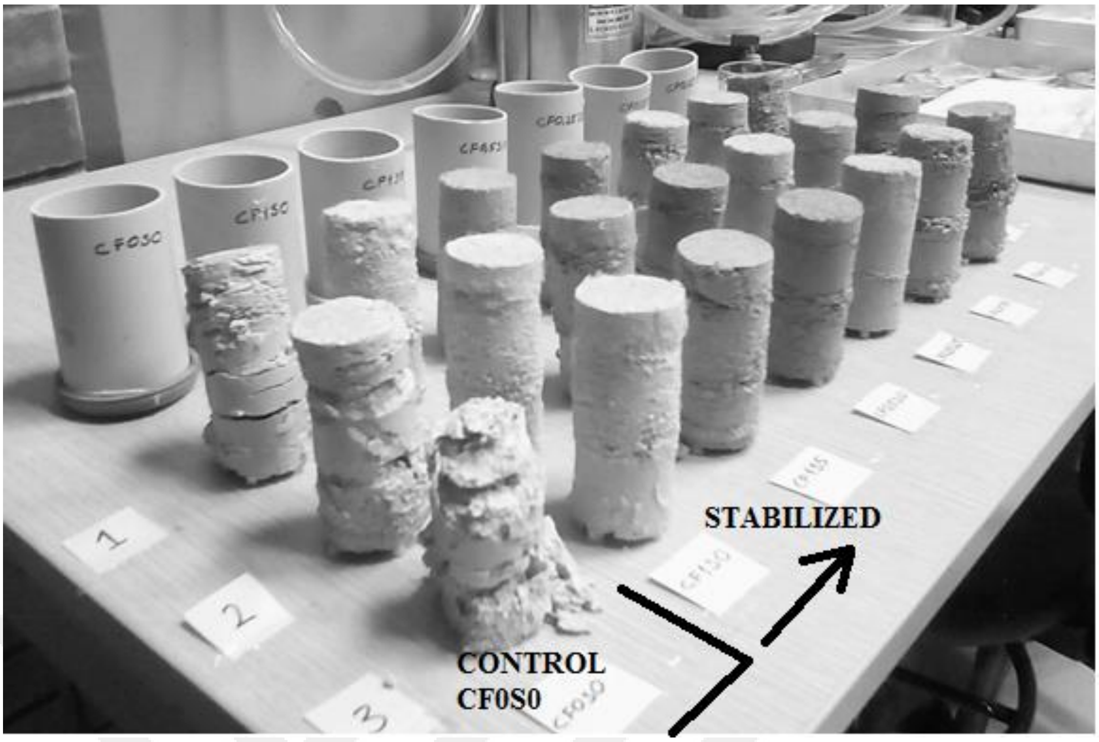


Figure 3.12. Samples after 8 freeze thaw cycle.

The microcracks created by freeze-thaw action is the main reason for the decrease in the strength values (Yarbasi et al., 2007). As seen from Figure 3.11 and Figure 3.12, there is a significant decrease in the strength values of the control samples (CF0S0) compared to fiber and silica fume added samples. The strength loss varied with changes in the fiber and silica fume additive percentages. Samples having higher strength values in unconfined compressive strength measurements were the most durable samples in the freeze-thaw tests with lower strength loss. Interlock mechanism between fiber, silica fume and clayey soil increased the resistance between soil particles with increased friction at the contact points. Friction between polypropylene fibers and clayey soil transformed into tension in the fiber elements in the matrix which helped resisting expansion during freezing (Jafari and Esna-ashari, 2012). The minimum effect of freeze-thaw action was observed on fiber modified specimens with higher silica fume contents (5 and 10%). Because of the pozzolanic properties (cementation reactions with time) and small grain size of silica fume particles, (filling voids of the composite clay matrix with extra fine particles) modified test samples lost less strength and are more durable to freeze-thaw action due to fiber elements and extra cementitious products formed. Pores within clayey soil are filled with cementitious products formed with silica fume and lime addition. This led to disconnections and decrease in pore volume which minimizes water intrusion into pores and less formation of ice lenses during freezing stage.

The soil matrix including higher strength tensile elements (fibers) and extra fine (pozzolanic) silica fume particles had a stronger structure after the curing period and caused a significant increase in durability, strength and ductility behavior as seen from the experimental results.

4. CONCLUSION

The following outcomes are obtained from this study:

- Addition of silica fume, synthetic polypropylene fiber and their mixtures increased the compressive strength and changed the ductility behavior of lime rich kaolinite specimens. The cementation effect was the leading factor on the ductility behavior of the stabilized clay samples with the increase in the silica fume content in the matrix. Due to the change in the stress-strain curves, the characteristic of the modified clay soils shifted from ductile to brittle.
- The addition of silica fume and synthetic fiber improved the freeze-thaw performance of lime rich kaolinite specimens. Although unconfined compressive strength values decreased with increasing number of freeze-thaw cycles, modified kaolinite specimens showed less strength loss.
- Silica fume-synthetic fiber mixture caused improvements in the load transfer mechanism in the clayey soil. Silica fume with lime helped to fill the pores with cementitious products and bonded fibers, which effectively worked for tension. Due to the coupled effect of silica fume and fiber, the durability of the clayey soil increased.
- From the SEM micrographs it is visible that silica fume addition with lime promoted the creation of CSH gel. Pores filled with hydration products modified structure of the soil matrix and enhanced the strength and durability. During the freezing process, water in the pores were frozen into ice, resulting in increased volume and creation of cracks and fissures in the matrix. Freeze-thaw cycles produced great effects on soil disintegrity based on SEM images.
- This study revealed that fiber-silica fume addition to lime rich kaolinite samples can be an environmentally friendly alternative in soil stabilization projects.

To conclude, fiber-silica fume mixture can be utilized in kaolinite clay stabilization. This method decreases the stabilization costs by utilizing a by-product material (silica fume) in an advantageous manner in geotechnical applications susceptible to freeze-thaw action.

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Bachelor’s Degree	Muğla Sıtkı Koçman University Department of Civil Engineering	2016

Work Experience

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2017 January - 2017 December	Yenihisar Yapı Denetim Ltd. Şti.	Project Control Engineer
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2018 February - 2018 August	Muğla Menteşe Yapı Denetim Ltd. Şti.	Project Control Engineer
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Foreign Languages

-English

-French (Beginner)

Project Experience

Scientific Research Project

Saygılı, A., Dayan, M. and Kahyaoğlu M.Rifat (2016-2017), "Silis Dumanı ve Sentetik Fiberlerle Modifiye Edilmiş Killerin Mukavemet Özelliklerinin Araştırılması", MSKU BAP 16-057

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Publications

Saygılı, A. and Dayan, M. (2019), Freeze-thaw behavior of lime stabilized clay reinforced with silica fume and synthetic fibers, Cold Regions Science and Technology, 161 (2019) 107–114

Hobbies

1. Novels – Books- Bibliophil

2. Doing Sport

3. Painting