

Influence of freeze-thaw cycles on the mechanical characteristics of sand reinforced with CSA cement and polypropylene fiber

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Submitted in fulfillment of the requirements for the degree of Master of Science in Civil & Environmental Engineering



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April 2024

Declaration form

I, therefore, certify that, with the possible exception of any quotations or sources that have been correctly mentioned, this paper, entitled “Influence of freeze-thaw cycles on the mechanical characteristics of sand reinforced with CSA cement and Polypropylene fiber” is my own original work.

Moreover, to the best of my knowledge, I certify that it has never been submitted in whole or in part—either consecutively or previously—for a different degree or diploma at Nazarbayev University or any other national or foreign institution.



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Abstract

Earth structures like rail and roads are undergoing recurring freeze-thaw cycles in regions with seasonal variation. Most issues related to these structures originate from the limited scope of design guidelines, which solely focus on strength and spurn long-term stability and durability considerations. The soil stabilization approach can be applied to enhance the properties of the soil. Ordinary Portland cement (OPC) is frequently used for these applications. OPC cement emits considerable carbon dioxide, even though it is an excellent binding material. One possible substitute for OPC is calcium sulfoaluminate (CSA) cement. This investigation aims to determine the consequence of cyclic freeze-thaw action on the sample treated with CSA cement and fiber. Samples were prepared using 3% and 5% CSA cement with 0, 0.25%, 0.5%, 0.75%, and 1% polypropylene fiber (PPF) and then subjected to 0, 1, 3, 5, and 7 F-T cycles after 3, 7, and 14 days of curing period. UCS and UPV tests were conducted to monitor the change in soil strength by increasing the fiber content under F-T cycles. The results demonstrated that the optimum fiber content can vary for different cement ratios, and excess may have a negative impact on strength development. The UPV value increases with a rise in fiber content until the optimum value. For soil stabilized with 3% CSA cement, the UCS strength increases with fiber content up to 1%; however, with 5% CSA cement content, the UCS strength first increases with 0.25% of fiber, followed by a decrease in strength. After F-T cycles, a considerable decrease in strength was observed for soil samples without fiber reinforcement, as compared to fiber-cement-stabilized samples. The influence of fiber content and F-T cycles on soil structure was also determined by scanning electron microscopy, which shows that the void and pores are the reasons behind the decrease in strength. The study aims to contribute to creating more enduring and environmentally friendly construction techniques by offering insightful information about how these composite materials behave when cold outside.

Acknowledgments

I sincerely thank my supervisor, **Prof. Sung-Woo Moon** for his tireless work, invaluable advice, and many meetings, all of which have contributed to the thesis' successful completion. His scholarly background, perceptive criticism, and constant assistance have really improved the caliber of my work and assisted me in honing my research techniques.

I want to thank **Prof. Jong Kim**, my co-supervisor, for his persistent moral support while I wrote my thesis. He has been a tremendous help in getting me to the finish line, offering guidance and encouragement.

I would like to appreciate my **lab assistants** and **technicians** for their cooperation, commitment, and assistance in fostering a supportive atmosphere for research.

Finally, I sincerely thank my **parents** and friends, **Abdul Moeed Khan** and **Usama Asif**, for their unwavering support, help and unending prayers during my academic career. My achievements have been fueled by their support and blessings..

Name: Ayesha Rauf
Date: 30 /03/2024

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List of Abbreviations

CC	Cement Content
CSA	Calcium Sulfoaluminate
F-T	Freeze-Thaw
OPC	Ordinary Portland Cement
PPF	Polypropylene Fiber
SEM	Scanning Electron Microscope
UCS	Unconfined Compressive Strength
UPV	Ultrasonic Pulse Velocity test

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Chapter 1 – Introduction

1.1 Background

Due to low cost, easy availability, and transportation, numerous natural resources, such as sand, are commonly utilized as subgrade soil in various civil engineering projects, such as foundation engineering and slope surface. However, the loose structure and poor adhesion are the properties of sandy soil, which may cause various geologic disasters, such as gullies forming on the slope surface, foundation structures being prone to dynamic loading [1].

An important aspect of geotechnical engineering involves analyzing and developing strategies for enhancing soil properties and addressing the following issues: wetting-drying (W-D), freeze-thaws (F-T), soil erosion, and landslides. Seasonally frozen regions experience at least one F-T cycle annually, which can immensely alter the engineering characteristics of the soil and have a major impact on various engineering structures like roadways, railways, and building constructions. [2]

This study attempts to comprehend how cement and polypropylene fibers might improve soil's F-T resilience, resulting in more enduring and environmentally friendly building techniques. Although cement stabilization dramatically improves the stability and durability of soil, it usually indicates brittle behavior with limited flexibility, leading to cracking and decreased long-term implementation. Mixing fibers into the cement-stabilized soil matrix presents a favorable resolution by managing these drawbacks.

Fibers act as reinforcements, improving strength, crack resistance, and deformability under load [3]. Furthermore, fibers increase the material's durability against fatigue and prevent shrinkage cracking, which makes it stronger. This study explores the potential of fiber-reinforced cement-stabilized soil for several applications, such as road subgrades. The research fills significant information gaps about mixing methods, fiber optimization and selection, and developing design strategies for this novel material. Geotechnical engineering integrates sustainable materials while keeping an eye on the environment and the future. In geotechnical applications, the use of alternate remedies is encouraged by rising worries about the environmental effects of materials such as ashes, plastic, steel, and cement.

1.2 Thesis Statement

To fully grasp the material's resilience and performance in harsh environmental settings, this study intends to investigate the impact of F-T cycles on the strength characteristics of polypropylene fiber and Calcium Sulfoaluminate (CSA) cemented soil. The findings provide crucial information on how polypropylene fibers function to increase the strength of soil-cement composites, which can assist in developing more dependable and environmentally friendly building processes.

Fibers significantly increase the strength, flexibility, and resistance to F-T cycles of soil stabilized with cement. As a result, a more flexible and stable material can be used to construct infrastructure projects. This thesis investigates the optimal fiber type, dosage, and CSA cement ratio for motivating the implementation of fiber-reinforced cement-stabilized soil. It also assesses its long-term behavior and develops practical design guidelines for widespread application.

1.3 Research Gap

Previous studies examined the impacts of F-T separately on CSA cement-stabilized soils and the function of polypropylene fibers in soil reinforcement; a thorough knowledge of their combined impact is still missing. By methodically assessing the effects of fiber integration on soil strength, along with the impact of F-T cycles on the strength and durability of cement-fiber stabilized soil mixes, this study seeks to close this gap.

1.4 Objective

This study seeks to optimize the type dosage for fibers in cement-stabilized soil, estimate long-term performance, and develop practical design approaches. It investigates unique applications, analyzes cost-effectiveness, and considers sustainability, eventually enabling the adoption of this versatile and durable material.

The main goals of this investigation are given below:

1. To determine how the increase in soil strength with an increase in cement content affects the optimum fiber content.
2. To evaluate the synergistic effects of various F-T events on the mechanical properties of fiber-cement stabilized soil to monitor the soil stability in icy conditions.

3. To examine the microstructure of the composite material both before and after being exposed to F-T conditions.

Chapter 2 – Literature review

2.1 Calcium sulfoaluminate (CSA) cement

In past research, different additives, such as OPC cement, were used to stabilize the soil. However, it resulted in a significant increase in CO₂, resulting in global warming during production. Therefore, some effective alternatives are required. Early strength development may result from the presence of CSA, and such systems may be classified as low-energy cement that benefits the environment by emitting less carbon dioxide. Recent studies have found that CSA cement can achieve significant strength [4-8].

The effective utilization of CSA cement to stabilize it against F-T cycles has already been conducted by [9]. It can be observed from outcomes that increasing the dosage of fiber significantly enhances soil strength against F-T cycles. Incorporating Calcium Sulfoaluminate (CSA) cement in soil stabilization is extensively used in construction and geotechnical engineering. With the advantage of CSA cement's rapid setting and early strength development properties, this approach is intended to improve the engineering effects of diverse soil types, including clay, silty, and sandy soils. The positive impact of CSA cement is presented in Figure 2-1.

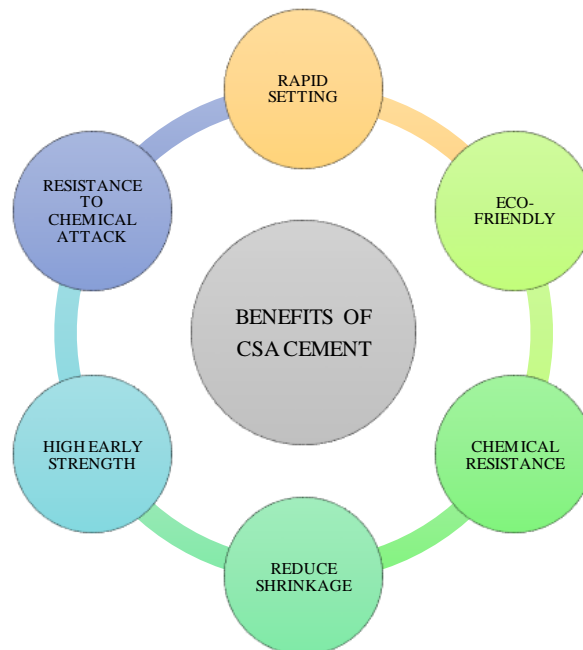


Figure 2-1 Benefit of CSA cement in construction engineering

2.2 Polypropylene Fiber (PPF)

The PPF is generally used in the building, apparel, energy, chemical, and energy-related industries [10]. The study revealed that using fiber significantly improves the unconfined compressive strength (UCS) values of soil. Investigations on unnatural fibers for soil stabilizing mainly concentrate on polypropylene, glass, basalt, and polyester fiber, showing that synthetic fiber's tensile strength and elastic modulus can enhance stabilized soil's strength and deformation resistance [11].

Polypropylene fibers are used in soil stabilization because they disperse tensile pressures across the soil matrix, hence improving the soil's tensile strength. These fibers function as secondary reinforcement by filling in the spaces and adding cohesion, enhancing the material's overall tensile properties. Consequently, the geotechnical structure is stronger and more resilient, able to endure environmental changes, settlement, and outside influences.

2.3 Gypsum

Applications for gypsum have been known throughout history. It is a naturally occurring mineral of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). During production, at around 1300°C , CSA, also known as Klein's compound or C4A3S, is quickly formed in just one phase. It is also generated at $1200\text{--}1300^\circ\text{C}$ when limestone reacts with different minerals or waste products, coupled with belite and a ferrite phase [12]. Its exceptional fire resistance, appeal, and affordability make it a popular choice for the construction industry [13]. To improve the stabilizing technique's effectiveness, gypsum is frequently added to CSA cement in soil stabilization applications [14, 15].

2.4 Overview

In civil engineering projects, the deterioration of soil brought on by environmental causes is a significant concern. Infrastructure materials are frequently exposed to thermal loads that might degrade their mechanical qualities in areas with seasonal F-T cycles. F-T cycles can induce frost action, leading to two distinct phenomena: frost heave and thaw. When the temperature goes below 0°C , the pore water gradually freezes and may cause frost heaving due to volume expansion [17]. As the temperature increases gradually, ice melts down, reducing soil stiffness; as a result, soil strength decreases, as shown in Figure 2-2.

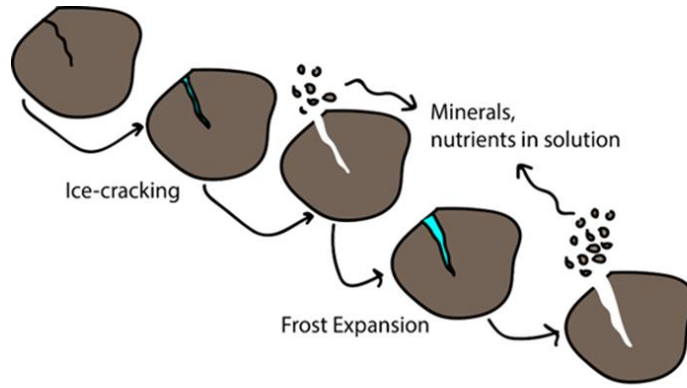


Figure 2-2 Impact of F-T cycle on soil particles [17]

Soil stabilization is the process of improving the physical properties of the soil to enhance its engineering properties, including strength, stability, workability, and other parameters required for its application in various civil engineering projects. This procedure is significant for initiatives involving the construction of roads and the development and preservation of horizontal and vertical infrastructure. However, global warming has led to several environmental changes, significantly affecting climatic conditions. Kazakhstan perceives significant temperature changes due to its extensive geographic area and variety of climate zones [18]. Figures 2-3 demonstrate the temperature variation in Astana throughout the year.

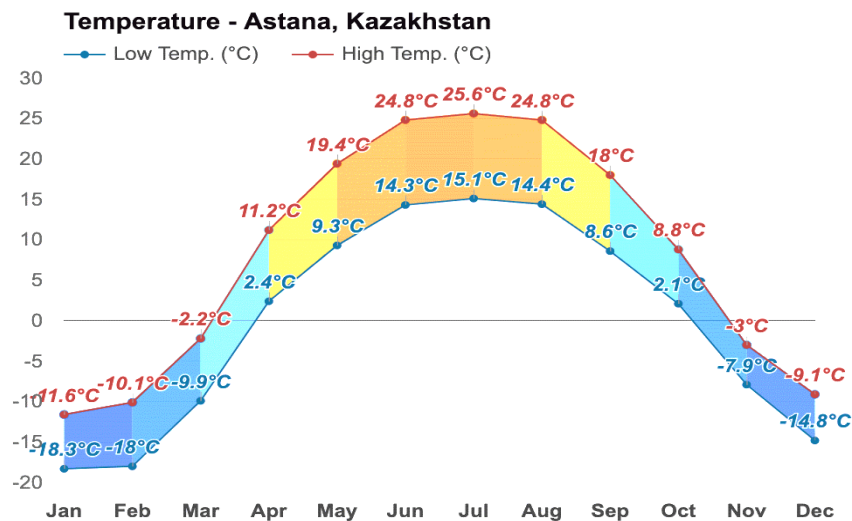


Figure 2-3 Temperature deviation in Astana [18]

Due to the impact of these seasonal factors, the soil is periodically subjected to the F-T thaw state known as the F-T cycle. This process drastically alters the mechanical properties of soil, which significantly impacts its application in geotechnical engineering. A soil's strength, resilience, and properties like volume, compressibility, cohesion, pre-consolidation, and bearing capacity can be impacted by the F-T cycles of soil [19-21].

Various stabilizing techniques, including physical and chemical methods, have been used to overcome weakened soil problems caused by climatic variation. Different studies have been done to treat sub-grade soil using chemical stabilization methods. Maaitah [22] reported that using Na_2SiO_3 and CaO with various ratios can develop the geotechnical properties of soil, and the optimum percentage of lime and sodium silicate was 4 and 2%. Abid [23] utilized sodium hydroxide as a chemical additive for soil stabilization to investigate its effectiveness using 1,2,4,8 molar concentrations. Results indicated that the shear strength parameter increases as the concentration of NaOH increases from 1 to 8 for cohesionless soil and 10 M for cohesive soil, and further addition decreases soil strength. Because more cementitious compounds are formed when clay is treated with cement rather than lime, Barman [24] found that while lime improves workability, cement-treated clay has a greater compressive strength. Figure 2-4 illustrates how cementitious chemicals from pozzolanic processes enhance strength.

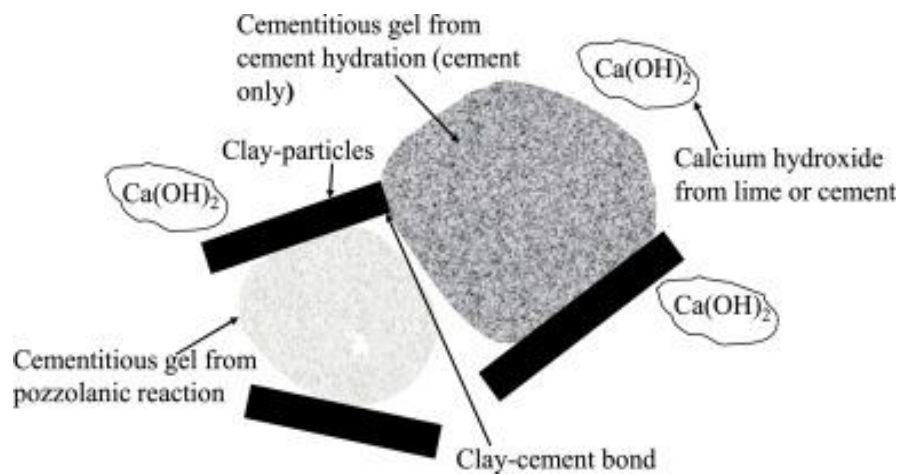


Figure 2-4 Strength development from $\text{Ca}(\text{OH})_2$ [24]

In the late 1950s, the idea of adding additives to cement-soil mixes to increase their shear strength was developed. An alkaline-activated solution containing geopolymer has also been presented as a substitute for the traditional conservative techniques of stabilizing soil, as shown in Figure 2-5. The alkaline solution of sodium hydroxide and silicate was shown to increase strength [25]. Improving the mechanical qualities of soil and industrial waste may be accomplished economically and effectively through soil stabilization using a geopolymer based on slag. Lambe and Moh [26] utilized 29 different additives, including salts, alkalis, synthetic resins, dispersants, and waterproofing agents, to enhance the strength of the soil. The results show that increasing the sodium carbonate concentration from 0.5 to 1% positively impacted the 7-day strength but had a negative impact on the 28-day strength. Additionally, chemical additives can be more effective than an increase in the amount of cement added. To define and monitor the strength of the treated soil properties, some research works promote innovative soil stabilizer methods while considering the associated expenses, accessibility, and transportation of the materials.

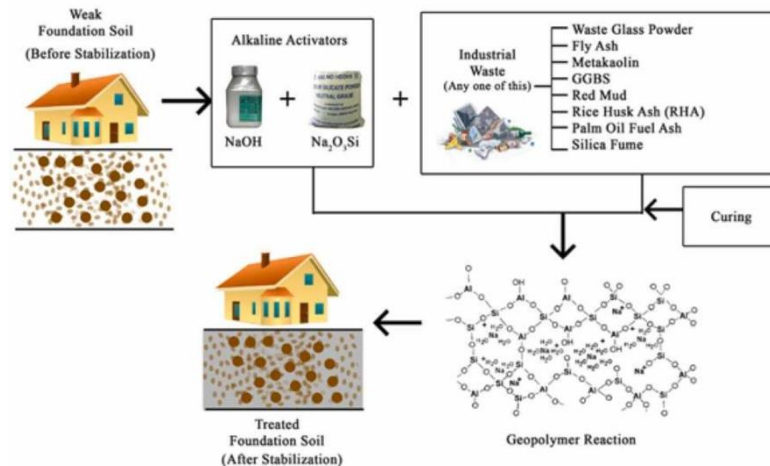


Figure 2-5 Soil stabilization by polymers [25]

Eskişar [27] carried out the feasibility of using OPC to stabilize the soil against F-T cycles, and the outcomes display that the UCS strength increased with cement content (CC); however, the compressive strength decreased with the increase in F-T cycles by preventing the strength loss. Regardless of the numerous benefits of using OPC cement in soil stabilization, finding an alternative to OPC cement is necessary due to the excessive carbon dioxide emission in the

atmosphere during its production, which results in various consequences, as illustrated in Figure 2-6.

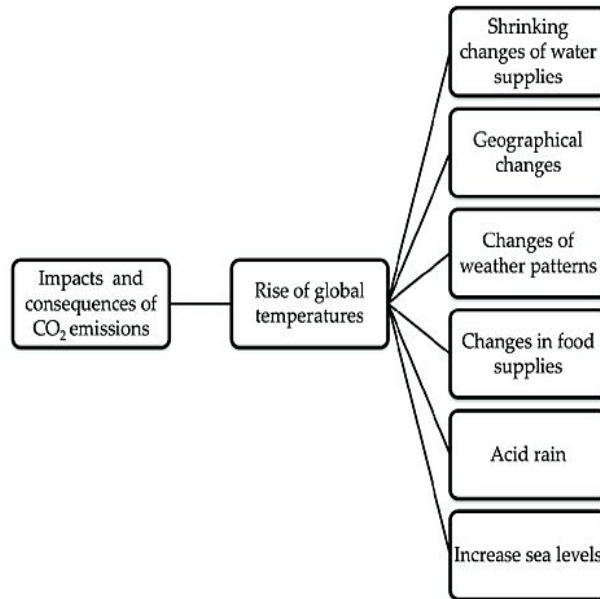


Figure 2-6 Impact of CO₂ on the atmosphere [23]

Researchers have recently utilized CSA cement as an alternative to OPC cement to stabilize the soil against F-T cycles [29]. The usage of CSA cement enhanced the soil's resistance to F-T cycles, improving its compressive strength and durability [30]. In the literature, different experimental research has been focused on reinforced soil with varying kinds of fiber, such as jute and basalt, to improve the properties of soil against F-T cycles [31, 32]. By evaluating the performance of UCS, the optimal dosages of lime, jute, and steel fiber are 4%, 0.75%, and 0.25%, with practical cost benefits. Based on the investigations with basalt fiber, Ekaterina [33] indicated that adding 0.75% basalt fiber improved the strength by 41.2% before freezing and 27.1% after the 15 F-T cycles.

In OPC cemented-treated soil, Maoting [34] discovered that the addition of PPF fibers raises the UCS value and strengthens the soil against F-T cycles. After ten F-T cycles, the UCS decrease ratio ranges from 42% to 69%. PPF can be used to enhance the subgrade soil and pavement performance. Hayder et al. [35] conducted experimental research to analyze the influence of mixing PPFs in asphalt mixtures to monitor the engineering characteristics. The results showed a considerable impact of the reinforced combinations with PPF on the tensile strength, fatigue

The fibers can ensure the stabilized soil's long-term durability in various engineering applications by assisting in mitigating the negative impacts of environmental conditions on it. [41]. The addition of PPF in the soil is intended to enhance its mechanical properties, particularly its tensile strength and resistance to cracking, especially when subjected to W-D and F-T cycles. These preliminary results shed important light on the study's potential significance for infrastructure design and construction in areas subject to F-T conditions and the direction of future research.

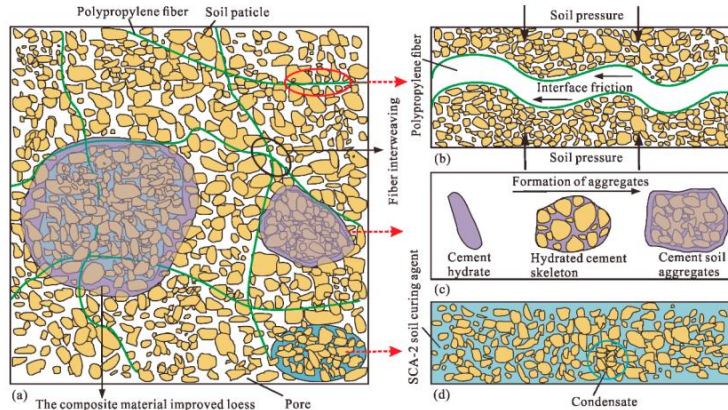


Figure 2-8 Diagram of the mechanism of fiber-improving soil

Cycles of F-T are one such phenomenon which can have a negative impact on the mechanical and physical characteristics of soils. These issues frequently affect sand, a common building material, lowering its strength and life expectancy. A standard method for enhancing the engineering qualities of soils, especially silty sands, is stabilization. The development and lifespan of diverse geotechnical constructions must comprehend how F-T cycles affect cement-treated silty sand. PPF and cement have shown promise in reducing these problems when added to soil matrices[36]. In the past, to stabilize weakened soil, a mixture of soil with different additives such as ordinary Portland cement (OPC), lime, and fly ash was used to increase the strength and deformation characteristics of the subgrade [41-43].

Tao [31] concentrated on stabilizing soil against wet-dry cycles using cement and various fibers. Under the same conditions, it was followed that 0.15% PPF improves UCS more than 1.0% basalt fiber. The results concluded a strong linear relationship between the UCS value and the resilient modulus of the fiber-treated soil. The study emphasizes how cement stabilization can reduce the negative impacts of F-T cycles and increase its resistance to degradation. Through

enhanced structural sustainability and endurance against F-T-induced damage, cement-stabilized sand can be used in cold climate locations.

Kou [44] examined the influence of F-T cycles on the ductility, strength, and microstructure of cement-treated silt reinforced with PPF. The investigation examines how repeated F-T cycles affect the material's internal structure and mechanical characteristics. The results show the material's suitability for cold areas and performance during F-T conditions. They also provide a basis for optimizing its composition for increased strength and resilience.

The F-T test conditions and requirements for experimental tasks in various research projects are compared in Table 2.1. After examining earlier studies and scrutinizing the literature, the curing days and other variables for the present experimental endeavor were determined.

Table 2.1 Comparison of various parameters from different experimental work

Reference	Cement (%)	Fiber (%)	Curing (days)	F-T cycle	Temp. Range (°C) F-T	F/T (hrs)
Ding, et al. [45]	3,6,9,12	0.05, 0.1, 0.2, 0.3	7	0,1,5,10	-10 - 23	18/6
Wang, et al. [46]	0, 5, 10, 15, 20	0.1	28	0,25,50,7 5,100	-18 - 5	18/5
Tao, et al. [47]	6	0.15,0.25	28	1, 3, 6, 9	-15 - 21	12/12
Tiwari, et al. [48]	-	0.25, 0.5, 1%	7,14,28	2,4,6,8,1 0	-20 - 20	12/12
Zaimoglu and technology [49]	-	0,0.25, 0.5, 0.75, 1, 1.25, 1.5, 2%	7	12	-23 - 21	24/23

Chapter 3 –Experimental work

3.1 Introduction

This chapter provides a detailed explanation of the materials utilized in the experiments, and by following a defined methodology, researchers can optimize sample quality, minimize delays, and enhance the reliability of the following analyses. Before starting the experiments, a thorough review of the information was conducted to determine the most effective approach for the experimental work.

3.2 Materials

The study involved the use of the following raw materials:

- ❖ Sand
- ❖ Calcium sulfoaluminate (CSA)
- ❖ Polypropylene fiber (PPF)
- ❖ Gypsum

3.2.1 Particle size distribution

In this experimental study, quartz sand was employed as the primary material. It is light brown and composed of rounded grains of silicon dioxide, making it an ideal choice for various applications. Its primary ingredient, silicon dioxide, gives it high strength, excellent drainage, and resistance to weathering. The distribution of soil particle sizes was examined using the Qicpic Particle Size analyzer. Analysis from Figure 3-1 revealed that the sand particles were predominantly of a small and uniform size.

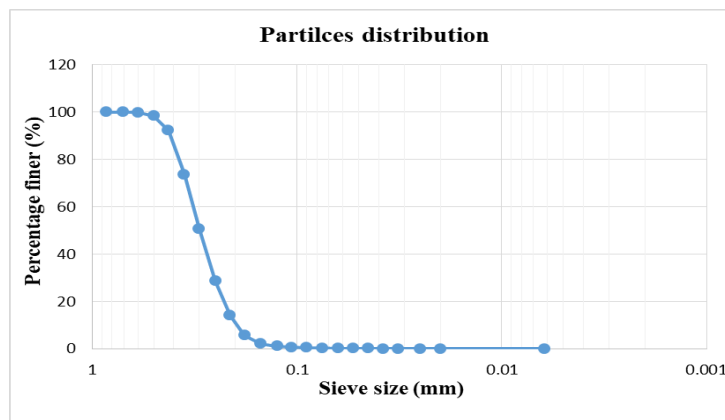


Table 3.1 summarizes the fundamental properties of the sand. These parameters play a significant role in determining the sand's suitability for various engineering applications.

Table 3.1 Properties of Sand

Property	Value	ASTM
D10	0.19	ASTM D1921
D30	0.25	ASTM D1921
D60	0.32	ASTM D1921
Cc	1.01	ASTM D1921
Cu	1.63	ASTM D1921
LL	13.9	ASTM D4318
USCS	SP	ASTM D1921

3.2.2 Calcium Sulfoaluminate cement

When used as a rapid binder in geotechnical engineering, Calcium Sulfoaluminate (CSA) cement offers advantages over typical Portland cement, including early strength development and less environmental impact. Because of its adaptability, it may be used for soil stabilization and offers efficient solutions for various ground improvement applications. The quick-setting quality of CSA cement helps improve construction productivity and overall geotechnical performance, making it a valuable choice for time-sensitive projects. CSA cement for this project is displayed in Figure 3-2.



Figure 3-2 CSA cement

The primary clinker phases of CSA cement, such as free lime, belite, ye'elimate, and gehlenite, were identified by XRD analysis, as shown in Figure 3-3. Belite (Ca_2SiO_4) helps to produce long-term strength; ye'elimate ($\text{Ca}_4(\text{AlO}_2)_6\text{SO}_4$) controls quick early strength development. Gehlenite (C_2AS) is a minor phase usually found in CSA cement and is crucial to the hydration process and impacts the factors of the finished cement paste. XRD can measure the degree of hydration and track long-term composition changes by examining the strength of peaks.

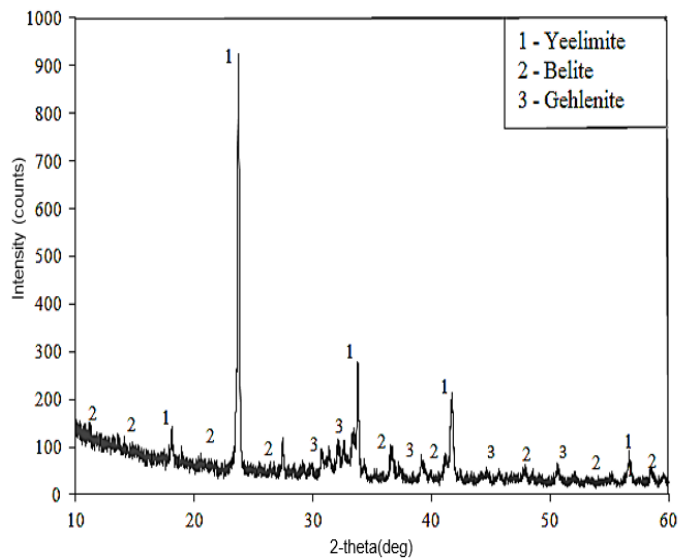


Figure 3-3 XRD analysis

3.2.3 Gypsum

The degree of hydration product that results influences the UCS value of soil treated with CSA, which the inclusion of gypsum may control. High initial strength increases and improved strength growth are achieved when gypsum replaces 30% of the CSA cement content, according to Subramanian et al. [50]. Consequently, for this research, gypsum was added to CSA cement to replace 30% of its entire mass.



Figure 3-4 Gypsum

3.2.4 Polypropylene Fiber

Synthetic fiber, known as PPF, is a type of linear polymer produced by the polymerization of propylene [51]. Its benefits include its lightweight, high strength, corrosion resistance, and toughness. These fibers are frequently added to improve the mechanical qualities and longevity of concrete, mortar, or soil [52]. Building materials function better when they contain PPF because they are tougher, less prone to breaking, and have better resistance to impact and shrinkage.



Figure 3-5 Polypropylene fiber

The properties of fiber presented are given in Table 3.2 below:

Table 3.2 Properties of fiber

Property	Value
Fiber types	Polypropylene Fiber
Length(mm)	6
Specific gravity(kg/m ³)	0.92
Longitudinal elastic modulus (N/mm ²)	3500
Tensile Strength (N/mm ²)	360-560
Softening temperature (°C)	150-170
Color	White

3.3 Sample Preparation

Sample preparation was a crucial phase in experimental work to achieve the research goal. Initial testing was conducted to classify the soil, including sieve analysis and Atterberg limits. The water content of sand was determined considering 3%, 5%, and 7% of CSA cement. The sample was cured for 3, 7, and 14 days and then subjected to 0, 1, 3, 5, and 7 F-T cycles. Standardized procedures in soil sample preparation are required to ensure precise and reliable research outcomes.

3.4 Compaction test

Standard proctor tests were done to analyze the compatibility of CSA cemented soil with optimum moisture content (OMC) and maximum dry density (MDD) based on ASTM/698. To determine OMC, the soil mixture was made using various water-to-cement ratios. Three layers of the mixture were layered into a mold, and each layer was compressed using equipment for measuring soil compaction. To obtain the results, the weight of the soil was recorded before and after being placed in the oven. A compaction curve was plotted using several experiments to determine the OMC and MDD for each percentage of cement content.

3.5 UPV test

A practical method for assessing the impact of repeated F-T cycles on CSA cement-stabilized soil is the UPV test. This non-destructive technique analyzes cementitious stabilized materials quickly and accurately [53]. A cylindrical block was used to calibrate the device before starting the test. To establish a relationship between the UCS and the UPV of samples, the UPV test was performed using the PUNDIT apparatus. The deterioration of the sample characteristics brought on by the F-T cycles was seen after the decrease in UPV results. The equipment used for the UPV test, seen in Figure 3-6, was repeated many times to get more precise and dependable findings.



Figure 3-6 UPV equipment

3.6 UCS test

UCS testing was conducted at the end of each curing period (3, 7, 14, and 28 days) to monitor the strength of a sample after each F-T cycle. The test was performed by applying a load at a 1 mm/min rate to a specimen until it failed. The following factors influence the UCS values of cement-treated soil: (a) Curing duration, (b) Cement content, and (c) Fiber Content. The sample was placed on a lower plate while the upper plate was adjusted for optimal contact with the specimen. Test loads were applied until the specimen's failure pattern was visible. The UCS data were calculated each time the treated soil underwent an F-T cycle. The UCS test machine arrangement is depicted in Figure 3–7. The UCS test results were examined using the average of three samples to find more dependable findings.

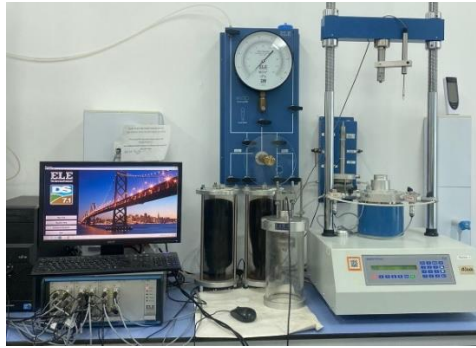


Figure 3-7 UCS machine

3.7 SEM

Scanning electron microscope (SEM) offers a high-resolution image with electromagnetic lenses thinned in a similar vacuum space as the electron beam used to evaluate the material [54]. SEM is a powerful tool for the following reasons: (1) To monitor the change in microstructure before and after the F-T cycle; (2) To observe the rise in pores and cracks with an increase in F-T cycles. Microstructural assessments were made using a Zeiss Crossbeam 540 high-resolution, which is displayed in Figure 3-8. Imaging was performed on 14-day treated samples subjected to the following cycles: 0,1,3,5 and 7. Before the procedure, sample preparation was done for more precise outcomes; otherwise, the images would be unfocused. Concerning the specimen type, the sample is required to be coated [54]. Several magnifications of SEM pictures were taken to analyze changes in the soil microstructure after every cycle.

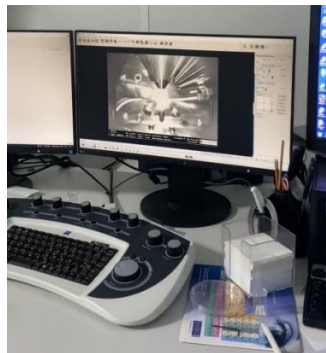


Figure 3-8 SEM device

3.8 Testing

The UPV and UCS tests were conducted for samples before and after the specimen was subjected to F-T cycles. The SEM was examined to inspect the difference in the microscopic structure of soil species after 14 days of curing.

Chapter 4 – Results and Discussions

4.1 Compaction test result

As the standard proctor test indicated [55], the cement-soil was formulated at the optimum moisture content (OMC). The OMC and maximum dry density (MDD) metrics for soil specimens incorporating 3%, 5%, and 7% cement are plotted in Figure 4-1. The OMC values are recorded as 16.4%, 16%, and 15.6%, respectively, with corresponding MDD values of 1.66, 1.67, and 1.69 kN/m. However, there is an observable pattern, as the OMC reduces and, at the same time, the MDD increases with a rise in cement content—the soil-cement mixture was prepared as per the compaction test standards.

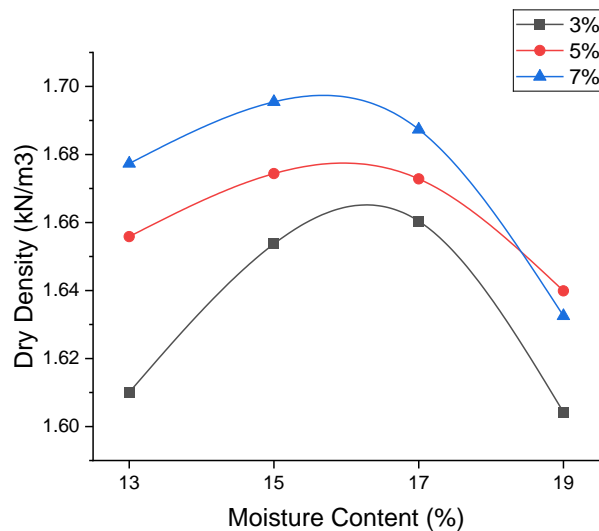


Figure 4-1 Standard compaction test result

4.2 Ultrasonic Pulse Velocity

The UPV test was conducted on all samples before they were subjected to the UCS test to check the quality and integrity of the assessed samples. The UPV results assist in identifying any variances or weaknesses within the specimen to direct UCS testing and guarantee more precise and focused assessments of the soil's compressive strength. Figure 4-2 demonstrates the results of 3% and 5% stabilized soil with a different fiber ratio after 3, 7, and 14 curing days. The increase in curing days increases the UPV values of soil specimens.

Overall, the UPV values improve with the addition of fiber, but only up to the optimum level, and further addition may have a negative impact on the soil sample. An increase in the concentration of PPF can positively impact the UPV value of cement-stabilized soil. The interlocking mechanism in the soil-cement matrix is improved by PPF, resulting in a more consistent and well-organized structure. The UPV value rises as the fiber content does because it reduces voids and improves the integrity of the cement-soil composite.

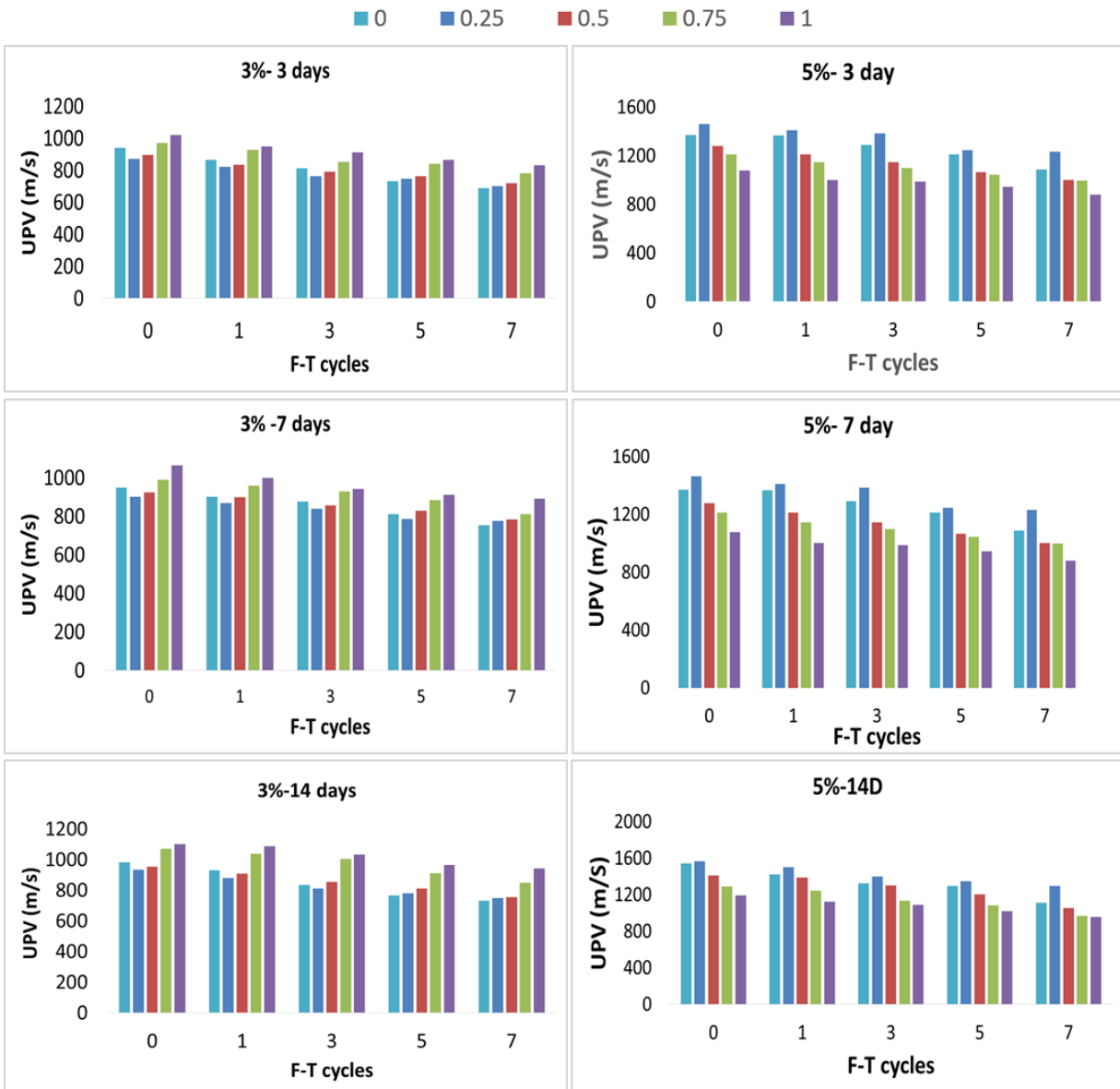


Figure 4-2 UPV test results

It was observed that an increase in fiber content from 0.25% to 1% linearly increased the UPV values with 3%CC soil. The UPV value of 1%PPF is 1.12 times higher than zero-PPF. However, for 5%CC, adding fiber beyond 0.25% considerably reduces the UPV result. The UPV value for 0.25% PPF was 1567m/s, which reduces to 1190 for 1%PPF. The density and rigidity of the cement-stabilized soil typically rise with increasing cement concentration. Despite strengthening the material, including PPF may cause voids and alter the sample's homogeneity. These alterations may make it more difficult for sound waves to pass through the soil matrix, lowering UPV.

As the number of F-T cycles increases, the UPV gradually decreases. For 3%CC, the UPV values for zero and 1%PPF declined to 25% and 14% after seven F-T cycles. The UPV value for 5% CC soil using 0.25%PPF decreased to 17% after seven F-T cycles, while its UPV reduction for the remaining samples was more than 20%. A decreased UPV value can result from ultrasonic wave propagation through the soil being impeded by the reduced density and increased presence of voids caused by the F-T cycles. Repetitive F-T cycles cause the material's structure to become interrupted, which deteriorates the material's mechanical qualities and lowers UPV. A similar trend has been found in research by Tiwari et al. (2020), where F-T causes a decrease in UPV value despite adding fiber [56].

4.2 UCS test result

For this project, to examine the impact of fiber, four different fiber doses (0.25%, 0.3%, 0.75%, and 1%) were combined with 3% and 5% CSA cement to stabilize the soil. Overall, the strength of the soil increased by adding fiber to soil-cement mixtures; however, the optimum amount of fiber depends on the cement percentage.

Figure 4-3 presents the UCS results for stabilized soil reinforced with 3% CSA cement fibers. The UCS soil strength increases, and the number of curing days rises from 3 to 14. It can be seen that an increase in fiber content results in an increase in the strength of the soil. The soil reinforced with 0.25% and 0.5%PPF has less UCS strength than zero-PPF; however, an increase in fiber beyond 0.75% increases strength up to 13%. Various researchers also found an improvement in UCS value through integrating PPF in soil [57]. On completion of the curing period for 3, 7, and 14 days, samples were subjected to various F-T cycles to monitor the influence of cyclic variation.

After F-T cycles, the overall strength of all specimens decreases as the number of cycles increases from one to seven. However, the strength reduction for 1% PPF is 19%, zero-PPF specimens is 31%, and for the rest of the fiber contents, it is more than 21%.

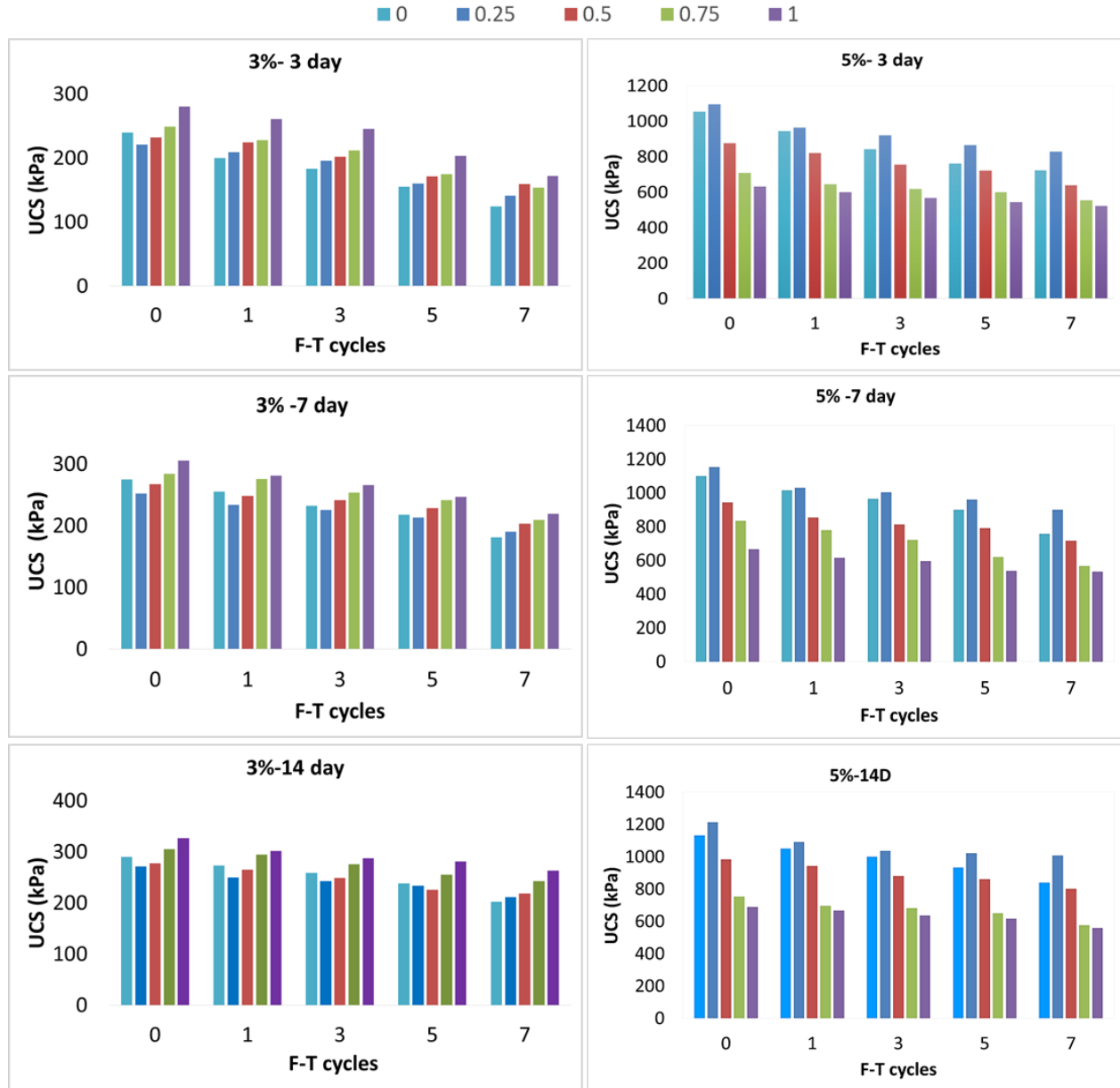


Figure 4-3 UCS test results

The UCS results of soil reinforced with 5% CC and different PPF ratios are also demonstrated in Figure 4-3. The UCS value of soil stabilized with 5% CSA cement with fiber ratios

shows varied behavior. The strength of soil first increases with the addition of fiber, followed by a decrease in strength with further integration of fibers beyond 0.25%. The UCS value for 5% CSA cement stabilized soil increased at 0.25% PPF and is 7.2% higher than untreated soil. Thus, the optimum dose to increase the UCS strength of the soil was 0.25% PPF. Various research has shown that utilizing fibers in excess beyond the optimum level can reduce the strength of soil [58-61]. After seven F-T cycles, the UCS value of 5% stabilized, demonstrating that the soil strength with 0.25%-PPF declined to 16%; it decreased to 26% for zero-PPF stabilized soil. The trend of increasing F-T cycles on cement-fiber stabilized soil demonstrating the decrease in UCS values aligns well with various research studies [34].

Upon addition to the soil-cement mixture, PPF disperses throughout the matrix and reinforces the soil by arranging itself into the network and creating linkages. This bridging action decreases the possibility of failure under load and prevents fracture progression, and as a result, the UCS strength increases. Figure 4-4 demonstrates the mechanism of strength improvement in soil due to fiber integration.

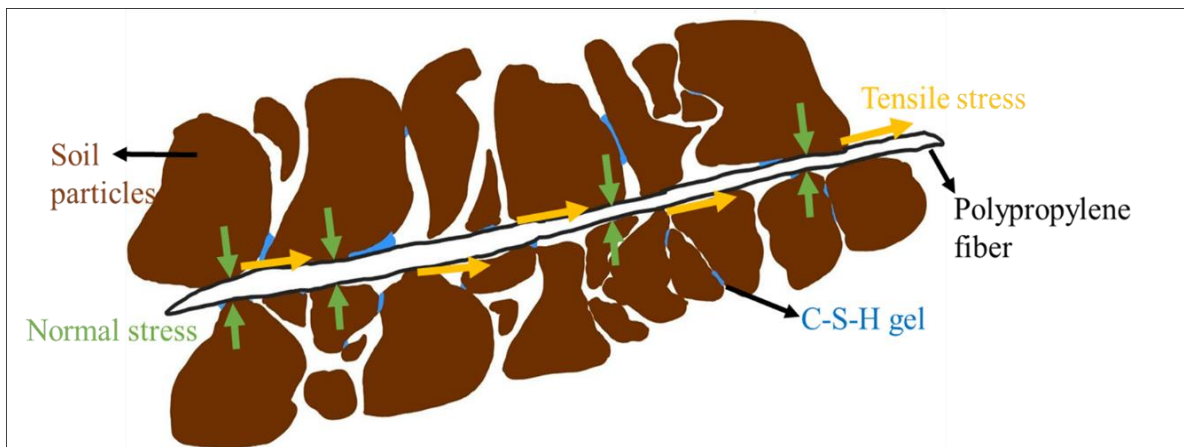


Figure 4-4 Mechanism of fiber interlocking in soil

When fibers are added to soil, they interlock with soil particles to form a reinforced matrix, which increases strength. These fibers serve as an additional reinforcement by dispersing stress and enhancing cohesiveness within the soil structure. Normal stress, which acts perpendicular to the fiber surface, plays an important role in strength improvement, as the interlocking fibers keep the soil particles from easily compacting; they withstand typical pressures and increase overall strength.

By bridging gaps between particles, fibers anchored in the soil offer resistance to tensile stresses. The interconnecting fibers form a strengthening network that, particularly under strain, prevents fractures from spreading and aids in preserving the soil's structural integrity.

Figure 4-5 explains how an increase in PPF content causes the fibers to mix and lose their tendency to interact with soil particles, which is why strength decreases as fiber content increases. The increase of cement content from 3% to 5% CC might make the matrix stiffer, which hinders the fibers' capacity to interlock successfully with soil particles. Higher cement concentration can cause the fibers to become more rigid, which could restrict their ability to move around and create a cohesive network in the soil. Reduced overall soil strength and localized vulnerabilities may arise from this uneven distribution.

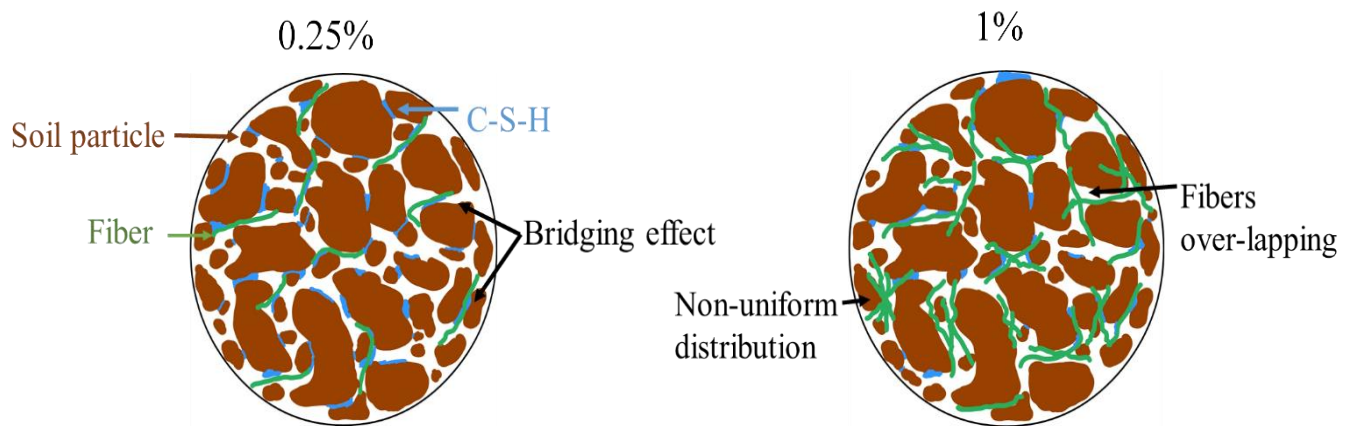


Figure 4-5 Influence of excess fiber in cement-stabilized soil

4.3 Stress-Strain behavior

By examining the stress-strain analysis, it is possible to gain further insight into how adding fibers and cement affects soil behavior. This section has specifically covered how soil treatment with fiber has affected brittleness, ductility, and post-peak strength. Figure 4-6 displays the stress-strain curves acquired from the UCS test on the cement-reinforced specimens integrated with various fiber dosages. Overall, it was observed that the integration of fiber in soil improves the stress-strain behavior of soil. For 3% CC, it can be seen that the peak stress increases with the addition of fiber beyond 0.5%, although the post-peak strength of all fiber content is higher than the zero-PPF specimen; however, by using 5% CC, the peak stress decline after addition of fiber

more than 0.25%.

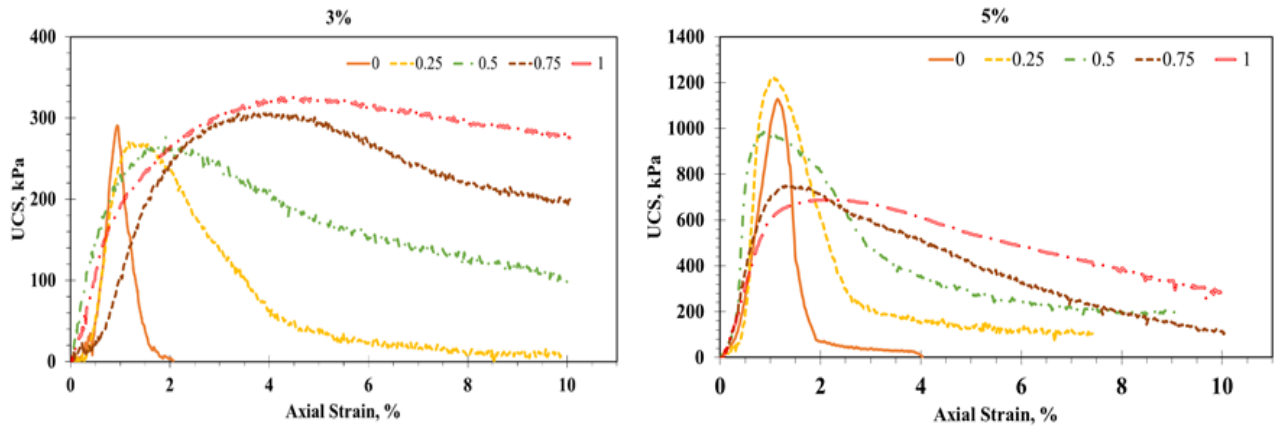


Figure 4-6 Stress-strain behavior of cement-stabilized soil

The stress-strain result for the optimum fiber ratio for 3% and 5% stabilized soil, after being subjected to 0, 1, 3, 5 and 7 F-T cycles, is shown in Figure 4-7. It was observed that the stress-strain relationships were significantly impacted by the F-T cycles. The peak stress decreased as F-T cycles rose from zero to seven. The cement and fiber composition affect the peak stress reduction. The decrease is most likely the result of stabilized soil structural deterioration.

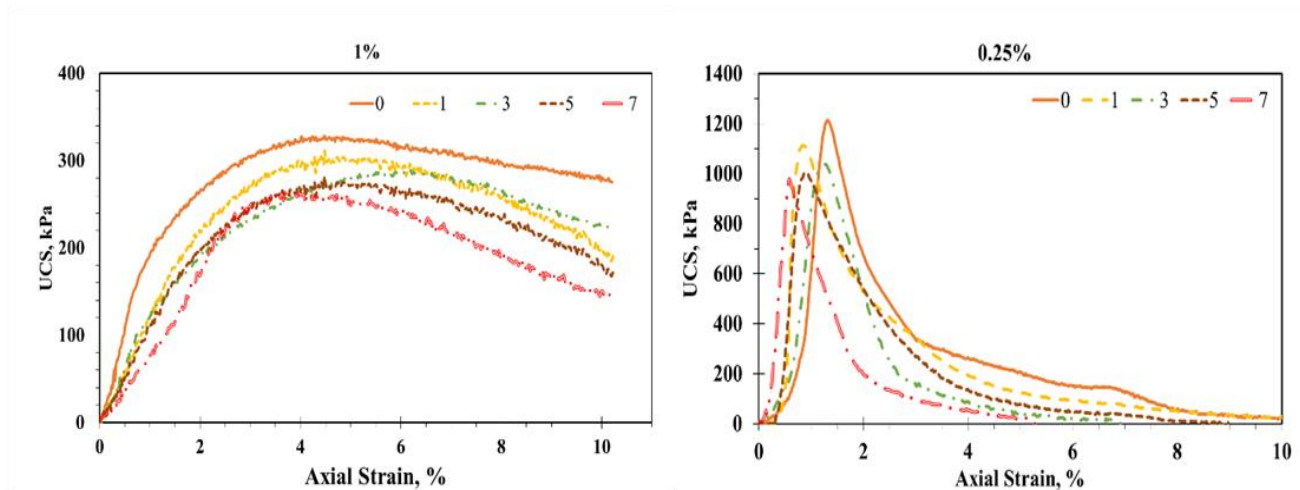


Figure 4-7 Impact of F-T cycles on stress-strain curve of stabilized soil

Figure 4-8 displays the sample before and after the F-T cycles. During the icy phase, the pore water becomes ice crystals and expands by 9% in volume [62, 63]. Ice crystals fracture and partially split the initial fiber fabrication and soil particle structure, cementing the soil-fiber particle bond. The ice crystals dissolve as the outside temperature rises, and soil particle spots are partially

reserved and retained. As a result, several new voids and macro-cracks are created during the F-T cycles. According to similar experimental experiments on un-stabilized soil, this new structure might affect the mechanical behaviors.

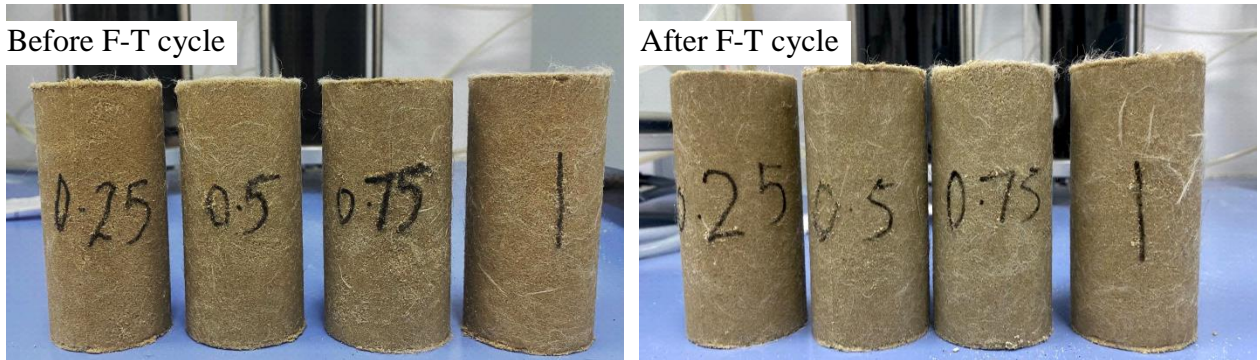


Figure 4-8 Samples before and after F-T cycles

On the other hand, it was found that the inclusion of fiber caused the soil to transition from brittle to ductile because of the fiber's ductile characteristic, which makes it contribute more to post-peak stress than cement. Figure 4-9 displays the failure pattern of 3% and 5% CC with all fiber content. The addition of fibers to cement-stabilized soil causes a significant change in its failure pattern, causing it to become ductile versus brittle, as the fibers function as microscopic bridges inside the soil matrix. Many researchers have also discussed the phenomenon of change in the failure pattern of soil [32, 34, 57].

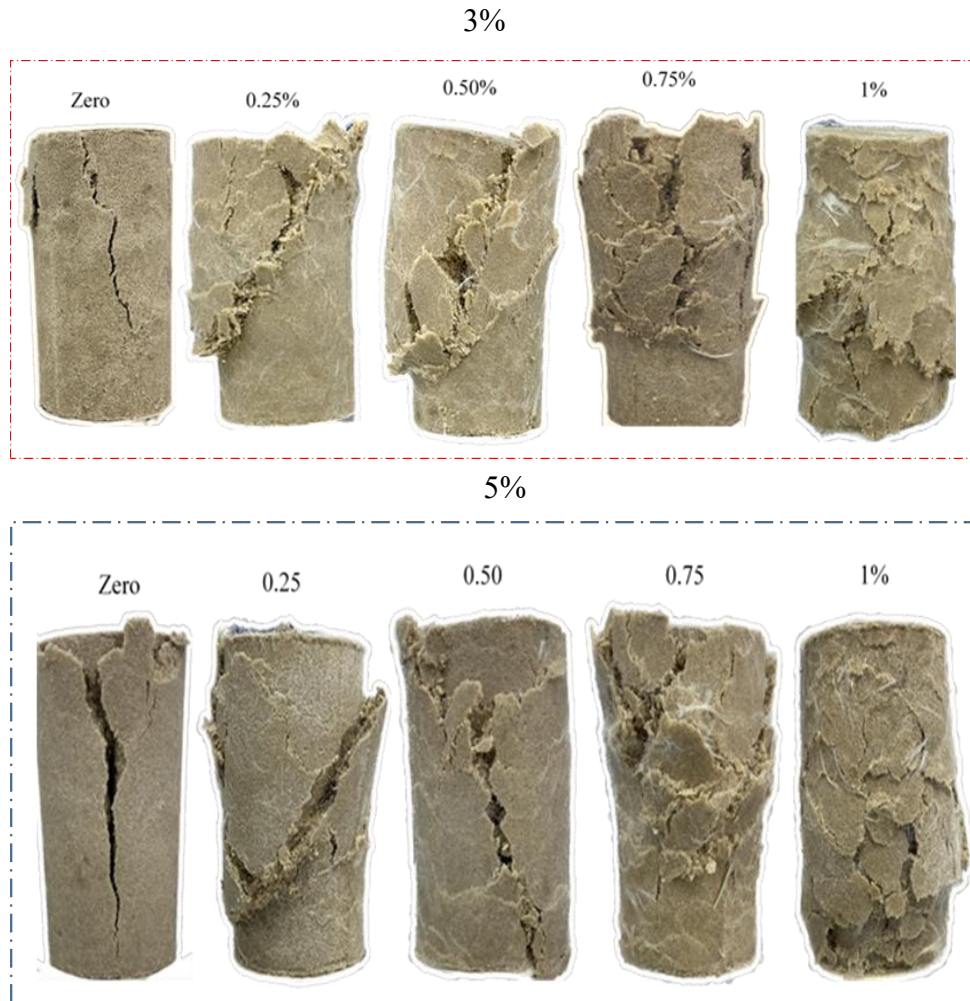


Figure 4-9 Failure pattern of soil samples

Fibers act as a bridge when fractures appear, keeping the soil together and avoiding total separation, as seen in Figure 4-10. In contrast to the brittle behavior of cement-stabilized soil, which splits and breaks quickly, fibers permit the soil to undergo plastic deformation, which means it may bend and flex to some amount without breaking apart. As a result, the fibers enhance the ductility of the soil, increasing its resistance to cracking and providing additional warning indicators before abrupt failure.

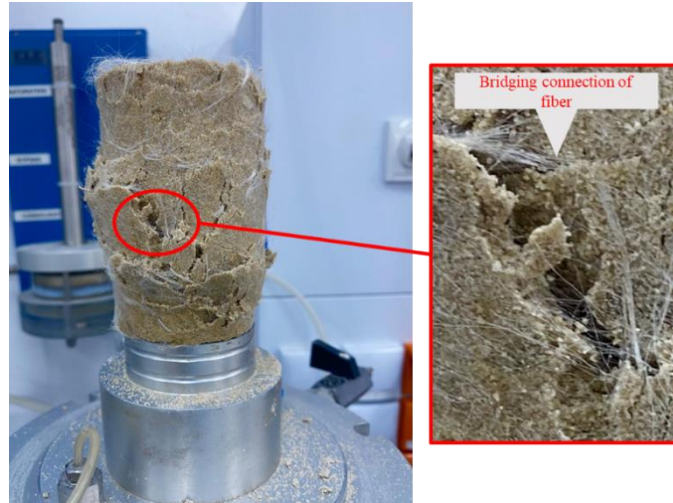


Figure 4-10 Bridging action of fiber for soil stabilization

4.4 SEM

Scanning Electron Microscope (SEM) examination was performed on the soil sample's surface to examine the fiber's improvement mechanism from a microcosmic perspective and understand the interaction between soil and fiber. The SEM test result for the stabilized 3%CC sample with 0, 0.25%, 0.5%, 0.75%, and 1% PPF is displayed in Figure 4-11. Microscopic analysis showed a clear correlation between higher fiber content and improved soil strength. The microstructure of the soil was analyzed, and the results showed that fibers tie the soil-cement matrix together well, creating a stronger network. This enhanced resistance to deformation and fracture, which results from this more powerful interconnectivity, eventually leads to the strengthening effect, which can be noticed.

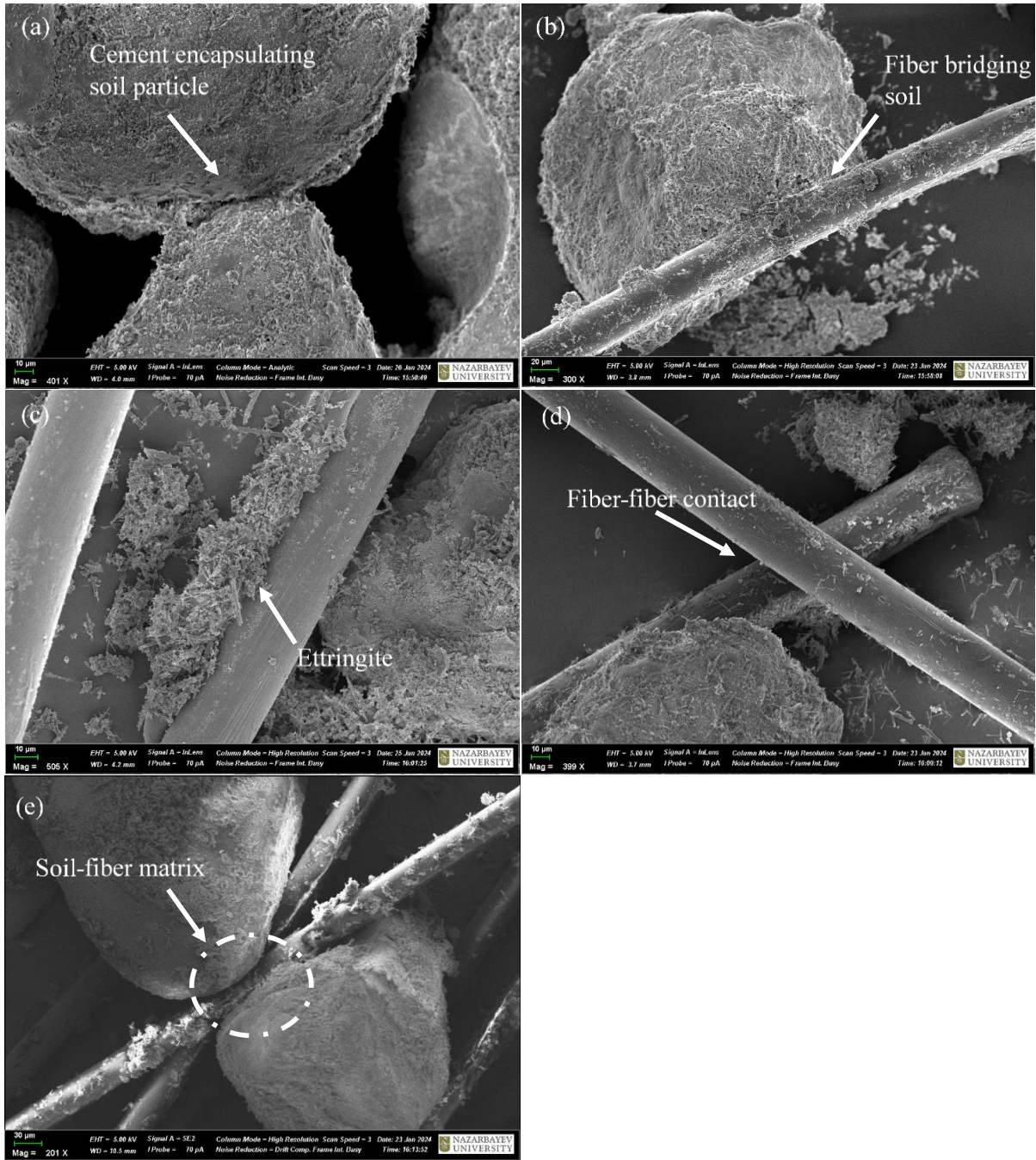


Figure 4-11 SEM result for soil with 3% CC with fiber contents (a) 0%; (b) 0.25%; (c) 0.5%; (d) 0.75%; (e) 1%

The SEM results for 5%CC reinforced soil are shown in Figure 4-12. The microstructure analysis revealed that cement-stabilized soil with fiber content beyond the optimum level (0.25%) interfered with developing a cementitious bond between soil particles, causing voids and leading

the fibers to be distributed randomly. This resulted in a decrease in strength despite the presence of fibers that weakened inter-particle binding and compromised the overall structural integrity due to fiber-fiber interaction and overlapping.

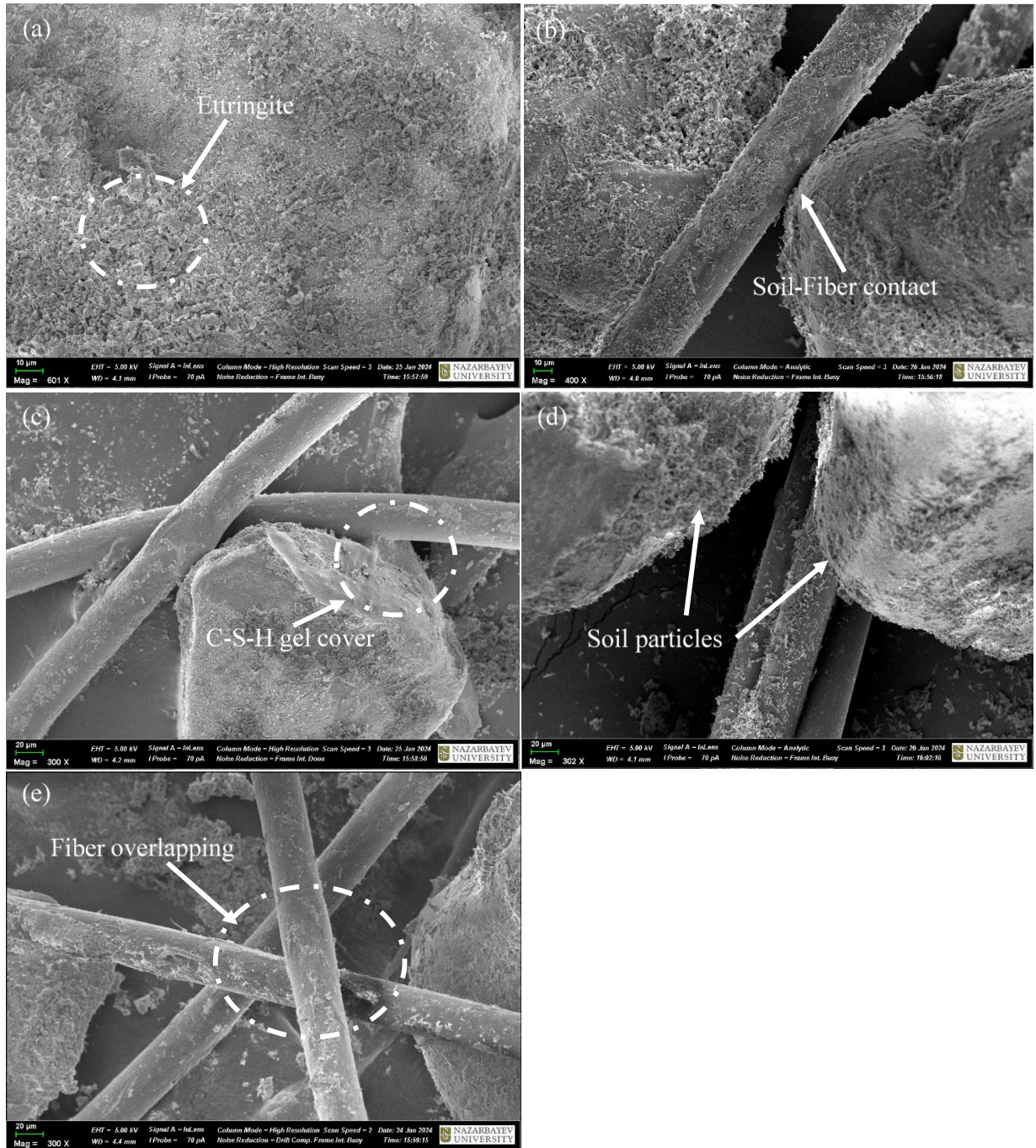


Figure 4-12 SEM analysis for soil with 5% CC with fiber contents (a) 0%; (b) 0.25%; (c) 0.5%; (d) 0.75%; (e) 1%

After seven F-T cycles, the SEM pictures were captured for the optimum fiber to examine the microstructure alterations, shown in Figure 4-13. The formation of voids and pores between the cement-fiber and soil causes the soil binding to weaken as the number of F-T cycles increases. The integrity of the binding network between cemented-soil particles and fibers was disrupted by the expansion of water during freezing, which resulted in these pores. The formation of ice lenses causes the gaps between soil particles to widen, increasing volume, which then reduces during expansion, resulting in the disturbance of the soil-fiber connection by weakening the sample. The noticed drop in UCS strength with increasing F-T cycles was caused by the weaker microstructure's decreased capacity to withstand compressive stresses. Roustaei et al. (2015) also illustrate in a microscopic study that the inclusion of fiber in cement soil cannot deny the influence of F-T cycles[64].

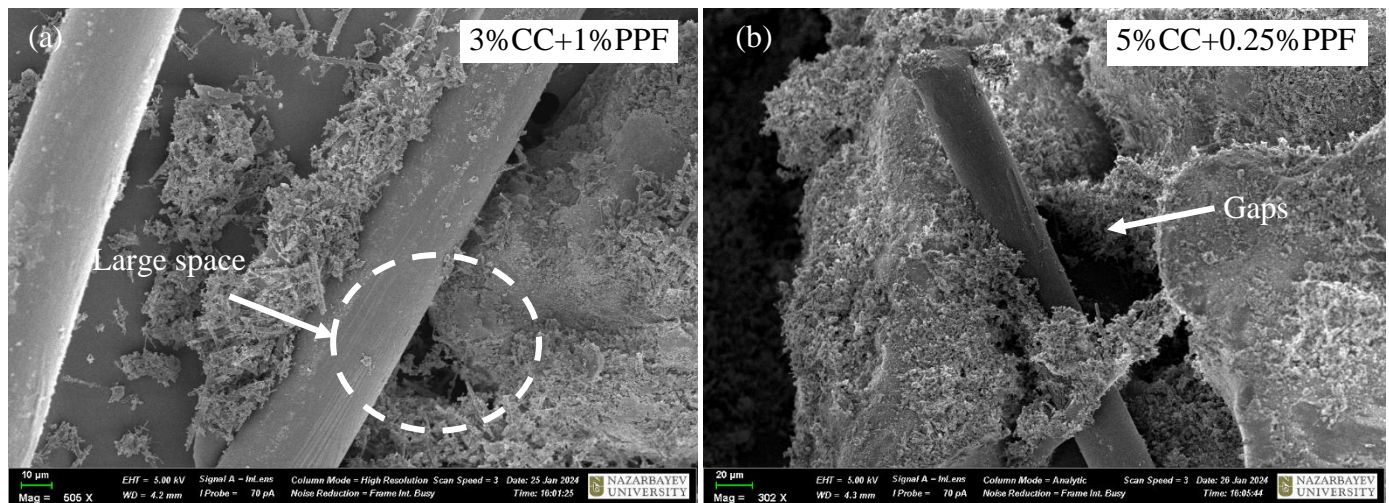


Figure 4-13 Impact of F-T cycles on reinforced soil specimen

Chapter 5 – Conclusion and Recommendation

This research thoroughly investigates how F-T cycles affect the mechanical characteristics of cement-stabilized soil and PPF. The influence of 3% and 5% cement content with different fiber ratios on soil strength was considered. Laboratory testing was carried out to demonstrate the impact of PPF during F-T cycles under various F-T cycles (0, 1, 3, 5, and 7). The following outcomes were observed from the experimental study:

1. The properties of the soil were enhanced by adding CSA cement, and as the cement concentration rose, the soil's strength rose even after the initial days of curing, demonstrating CSA cement's high early strength.
2. The optimum dosage of fiber to enhance soil strength varies by the ratio of cement content.
3. The UPV values rise with an increase in fiber content up to the optimum level, followed by a decrease in trend as fiber content increases. The UPV test result showed soil behavior; as the F-T cycles increased, the UPV values of every sample decreased.
4. The inclusion of 0.75%–1% PPF in 3%CC increases the UCS strength of the soil, while the integration of PPF exceeding 0.25% in 5%CC decreases the UCS value. The loss of strength for 3%CC+1%PP and 5%CC+0.25% was 19% and 16% after seven F-T cycles.
5. The stress-strain behavior of soil changes drastically from brittle to ductile with adding fibers. It was found that the F-T cycles had a major effect on stress-strain behavior. The peak stress decreased as there were more F-T cycles—from zero to seven.
6. The SEM was conducted to analyze the mechanism and influence of fiber integration in soil, which increases strength. The effect of F-T cycles on soil structure was elucidated by SEM images captured before and after the cycle. During thawing, ice melts, which begins pores in the soil, altering its properties and contributing to the soil's subsequent loss of strength; however, fiber addition lessens the influence of F-T cycles.

The research aims to close the knowledge gap between fiber-cement stabilization and F-T effects, therefore offering significant insights into geotechnical engineering. Its purpose is to aid in the construction of more durable and resilient structures in cold regions. To minimize potential risks, future research should concentrate on developing innovative strategies to increase the resilience of soil-cement composites under varied climatic conditions. To enhance the soil properties, it is required to determine the optimum proportion of fibers in cement compositions, which results in

improving the interaction between soil particles and cement-fibers to achieve maximum strength. More experimental work can also provide a comprehensive understanding of the effects of climate variation on the behavior of soil stabilized with fiber and cement. This understanding can be used to develop practical and sustainable guidelines and standards for developing long-lasting infrastructure in the face of changing environmental dynamics. By proactively addressing these problems, it would be easier to design adaptable and resilient building systems that can withstand the challenges posed by the F-T cycles brought on by climate change.

References

- [1] J. Liu *et al.*, "An experimental study on the shear behaviors of polymer-sand composite materials after immersion," *Polymers*, vol. 10, no. 8, p. 924, 2018.
- [2] E. Kravchenko, J. Liu, A. Krainiukov, and D. Chang, "Dynamic behavior of clay modified with polypropylene fiber under freeze-thaw cycles," *Transportation Geotechnics*, vol. 21, p. 100282, 2019.
- [3] M. V. Mohod, "Performance of polypropylene fibre reinforced concrete," *IOSR Journal of Mechanical and Civil Engineering*, vol. 12, no. 1, pp. 28-36, 2015.
- [4] J. I. Ocheme, S. O. Olagunju, R. Khamitov, A. Satyanaga, J. Kim, and S.-W. Moon, "Triaxial shear behavior of calcium sulfoaluminate (CSA)-treated sand under high confining pressures," *Geomechanics and Engineering*, vol. 33, no. 1, pp. 41-51, 2023.
- [5] S.-W. Moon, G. Vinoth, S. Subramanian, J. Kim, and T. Ku, "Effect of fine particles on strength and stiffness of cement treated sand," *Granular Matter*, vol. 22, no. 1, p. 9, 2020.
- [6] G. Vinoth, S.-W. Moon, J. Moon, and T. Ku, "Early strength development in cement-treated sand using low-carbon rapid-hardening cements," *Soils and Foundations*, vol. 58, no. 5, pp. 1200-1211, 2018.
- [7] G. Vinoth, S.-W. Moon, J. Kim, and T. Ku, "Effect of fine particles on cement treated sand," in *Proceedings of China-Europe Conference on Geotechnical Engineering: Volume 1*, 2018: Springer, pp. 847-851.
- [8] A. Rauf, A. Tussupbekova, and S.-W. Moon, "Effect of Drying-Wetting Cycles on the Mechanical Behavior of Cement-Treated Soil," *대한토목학회/ 학술대회*, pp. 259-260, 2023.
- [9] N. Sagidullina, S. Abdialim, J. Kim, A. Satyanaga, and S.-W. J. S. Moon, "Influence of Freeze–Thaw Cycles on Physical and Mechanical Properties of Cement-Treated Silty Sand," vol. 14, no. 12, p. 7000, 2022.
- [10] Y. Xiao, L. Tong, H. Che, Q. Guo, H. J. C. Pan, and B. Materials, "Experimental studies on compressive and tensile strength of cement-stabilized soil reinforced with rice husks and polypropylene fibers," vol. 344, p. 128242, 2022.
- [11] P. Venda Oliveira, A. S. Correia, J. Teles, and D. Custódio, "Effect of fibre type on the compressive and tensile strength of a soft soil chemically stabilised," *Geosynthetics International*, vol. 23, no. 3, pp. 171-182, 2016.
- [12] J. Sharp, C. Lawrence, and R. J. A. i. C. R. Yang, "Calcium sulfoaluminate cements—low-energy cements, special cements or what?," vol. 11, no. 1, pp. 3-13, 1999.
- [13] Q. Yu, J. Brouwers, and A. De Korte, "Gypsum hydration: a theoretical and experimental study," in *17th International Conference on Building Materials, ibausil*, 2009: Bauhaus-Universität Weimar, pp. 1-0783-1-0788.
- [14] F. Winnefeld, L. H. Martin, C. J. Müller, and B. Lothenbach, "Using gypsum to control hydration kinetics of CSA cements," *Construction and Building Materials*, vol. 155, pp. 154-163, 2017.
- [15] P. Li *et al.*, "Effect of gypsum on hydration and hardening properties of alite modified calcium sulfoaluminate cement," *Materials*, vol. 12, no. 19, p. 3131, 2019.
- [16] C. Tang, B. Shi, W. Gao, F. Chen, and Y. Cai, "Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil," *Geotextiles and Geomembranes*, vol. 25, no. 3, pp. 194-202, 2007.

- [17] U. Chaduvula, A. K. Desai, and C. Solanki, "Application of triangular polypropylene fibres on soil subjected to freeze–thaw cycles," *Indian Geotechnical Journal*, vol. 44, pp. 351-356, 2014.
- [18] V. Salnikov *et al.*, "An Assessment of the Present Trends in Temperature and Precipitation Extremes in Kazakhstan," *Climate*, vol. 11, no. 2, p. 33, 2023.
- [19] W. Fan, P. Yang, and Z. J. Yang, "Impact of freeze-thaw on the physical properties and compressibility of saturated clay," *Cold Regions Science and Technology*, vol. 168, p. 102873, 2019.
- [20] J. Qi, W. Ma, and C. Song, "Influence of freeze–thaw on engineering properties of a silty soil," *Cold regions science and technology*, vol. 53, no. 3, pp. 397-404, 2008.
- [21] S. Kawabata, T. Ishikawa, and S. Kameyama, "Effects of freeze-thaw history on bearing capacity of granular base course materials," *Procedia engineering*, vol. 143, pp. 828-835, 2016.
- [22] O. N. Maaitah, "Soil stabilization by chemical agent," *Geotechnical and Geological Engineering*, vol. 30, pp. 1345-1356, 2012.
- [23] M. S. Abid, "Stabilization of soil using chemical additives," *Glob Res Dev J Eng*, vol. 1, no. 12, pp. 74-80, 2016.
- [24] D. Barman and S. K. Dash, "Stabilization of expansive soils using chemical additives: A review," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 14, no. 4, pp. 1319-1342, 2022.
- [25] D. Parthiban *et al.*, "Role of industrial based precursors in the stabilization of weak soils with geopolymer–A review," *Case Studies in Construction Materials*, vol. 16, p. e00886, 2022.
- [26] T. W. Lambe and Z.-C. J. H. R. B. B. Moh, "Improvement of strength of soil-cement with additives," no. 183, 1958.
- [27] T. Eskişar, S. Altun, and İ. Kalıpcılar, "Assessment of strength development and freeze–thaw performance of cement treated clays at different water contents," *Cold Regions Science and Technology*, vol. 111, pp. 50-59, 2015.
- [28] K. Ahmed Ali, M. I. Ahmad, and Y. Yusup, "Issues, impacts, and mitigations of carbon dioxide emissions in the building sector," *Sustainability*, vol. 12, no. 18, p. 7427, 2020.
- [29] N. Sagidullina, S. Abdialim, J. Kim, A. Satyanaga, and S.-W. Moon, "Influence of freeze–thaw cycles on physical and mechanical properties of cement-treated silty sand," *Sustainability*, vol. 14, no. 12, p. 7000, 2022.
- [30] A. Jumassultan, N. Sagidullina, J. Kim, T. Ku, and S.-W. Moon, "Performance of cement-stabilized sand subjected to freeze-thaw cycles," *Geomechanics and Engineering*, vol. 25, no. 1, p. 41, 2021.
- [31] Z. Tao, Y. Zhang, X. Chen, and X. Gu, "Effects of freeze-thaw cycles on the mechanical properties of cement-fiber composite treated silty clay," *Construction and Building Materials*, vol. 316, p. 125867, 2022.
- [32] H. Güllü and A. Khudir, "Effect of freeze–thaw cycles on unconfined compressive strength of fine-grained soil treated with jute fiber, steel fiber and lime," *Cold Regions Science and Technology*, vol. 106, pp. 55-65, 2014.
- [33] E. Kravchenko, J. Liu, W. Niu, and S. Zhang, "Performance of clay soil reinforced with fibers subjected to freeze-thaw cycles," *Cold Regions Science and Technology*, vol. 153, pp. 18-24, 2018.
- [34] M. Ding, F. Zhang, X. Ling, and B. Lin, "Effects of freeze-thaw cycles on mechanical properties of polypropylene fiber and cement stabilized clay," *Cold Regions Science and*

- Technology*, vol. 154, pp. 155-165, 2018.
- [35] H. K. Shanbara, S. S. Musa, and A. Dulaimi, "The Effect of polypropylene fibres on the tensile performance of asphalt mixtures for road pavements," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 888, no. 1: IOP Publishing, p. 012082.
- [36] X. Yang, S. Liang, Z. Hou, D. Feng, Y. Xiao, and S. J. A. S. Zhou, "Experimental study on strength of polypropylene fiber reinforced cemented silt soil," vol. 12, no. 16, p. 8318, 2022.
- [37] A. Jumassultan, N. Sagidullina, J. Kim, T. Ku, S.-W. J. G. Moon, and Engineering, "Performance of cement-stabilized sand subjected to freeze-thaw cycles," vol. 25, no. 1, p. 41, 2021.
- [38] J. Varghese, U. Remya, and V. Snigdha, "The effect of polypropylene fibre on the behaviour of soil mass with reference to the strength parameters," *Inter. J. of Eng. Res. & Tech.*, vol. 5, no. 3, pp. 781-784, 2016.
- [39] S. Gowthaman, K. Nakashima, and S. Kawasaki, "A state-of-the-art review on soil reinforcement technology using natural plant fiber materials: Past findings, present trends and future directions," *Materials*, vol. 11, no. 4, p. 553, 2018.
- [40] C. Hu, X. Weng, C. Liu, L. Jiang, J. Liu, and W. Li, "Performance of polypropylene fiber-reinforced solidified soil," *Advances in Civil Engineering*, vol. 2021, pp. 1-16, 2021.
- [41] S. Aryal and P. Kolay, "Long-term durability of ordinary Portland cement and polypropylene fibre stabilized kaolin soil using wetting–drying and freezing–thawing test," *International Journal of Geosynthetics and Ground Engineering*, vol. 6, pp. 1-15, 2020.
- [42] C. Han and P. Cheng, "Micropore variation and particle fractal representation of lime-stabilised subgrade soil under freeze–thaw cycles," *Road Materials and Pavement Design*, vol. 16, no. 1, pp. 19-30, 2015.
- [43] Y. Zhang, A. E. Johnson, and D. J. White, "Freeze-thaw performance of cement and fly ash stabilized loess," *Transportation Geotechnics*, vol. 21, p. 100279, 2019.
- [44] H.-l. Kou, J.-h. Liu, W. Guo, S.-d. Hua, and Y.-t. J. A. G. Pan, "Effect of freeze–thaw cycles on strength and ductility and microstructure of cement-treated silt with polypropylene fiber," vol. 16, no. 11, pp. 3555-3572, 2021.
- [45] M. Ding, F. Zhang, X. Ling, B. J. C. R. S. Lin, and Technology, "Effects of freeze-thaw cycles on mechanical properties of polypropylene fiber and cement stabilized clay," vol. 154, pp. 155-165, 2018.
- [46] L. Wang *et al.*, "Research on Flexural and Freeze–Thaw Properties of Polypropylene-Fiber-Reinforced Pavement Concrete Containing Waterborne Epoxy," vol. 13, no. 6, p. 1035, 2023.
- [47] Z. Tao, Y. Zhang, X. Chen, X. J. C. Gu, and B. Materials, "Effects of freeze-thaw cycles on the mechanical properties of cement-fiber composite treated silty clay," vol. 316, p. 125867, 2022.
- [48] N. Tiwari, N. Satyam, and K. J. S. R. Singh, "Effect of curing on micro-physical performance of polypropylene fiber reinforced and silica fume stabilized expansive soil under freezing thawing cycles," vol. 10, no. 1, p. 7624, 2020.
- [49] A. S. J. C. r. s. Zaimoglu and technology, "Freezing–thawing behavior of fine-grained soils reinforced with polypropylene fibers," vol. 60, no. 1, pp. 63-65, 2010.
- [50] S. Subramanian, Q. Khan, and T. Ku, "Strength development and prediction of calcium sulfoaluminate treated sand with optimized gypsum for replacing OPC in ground improvement," *Construction and building materials*, vol. 202, pp. 308-318, 2019.
- [51] D. Bracho, V. N. Dougnac, H. Palza, and R. J. J. o. N. Quijada, "Functionalization of silica nanoparticles for polypropylene nanocomposite applications," vol. 2012, pp. 19-19, 2012.

- [52] M. R. Latifi, Ö. Biricik, and A. Mardani Aghabaglou, "Effect of the addition of polypropylene fiber on concrete properties," *Journal of Adhesion Science and Technology*, vol. 36, no. 4, pp. 345-369, 2022.
- [53] T. Mandal, J. M. Tinjum, and T. B. Edil, "Non-destructive testing of cementitiously stabilized materials using ultrasonic pulse velocity test," *Transportation Geotechnics*, vol. 6, pp. 97-107, 2016.
- [54] N. J. O. G. Ural, "The significance of scanning electron microscopy (SEM) analysis on the microstructure of improved clay: An overview," vol. 13, no. 1, pp. 197-218, 2021.
- [55] D. Astm, "698; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort," *ASTM International: West Conshohocken, PA, USA*, no. 19428-2959, 2007.
- [56] N. Tiwari, N. Satyam, and K. Singh, "Effect of curing on micro-physical performance of polypropylene fiber reinforced and silica fume stabilized expansive soil under freezing thawing cycles," *Scientific Reports*, vol. 10, no. 1, p. 7624, 2020.
- [57] X. Yang, S. Liang, Z. Hou, D. Feng, Y. Xiao, and S. Zhou, "Experimental study on strength of polypropylene fiber reinforced cemented silt soil," *Applied Sciences*, vol. 12, no. 16, p. 8318, 2022.
- [58] S. K. Mohanty, D. R. Biswal, B. G. Mohapatra, B. Beriha, R. Pradhan, and H. Sutar, "Strength and Stiffness Evaluation of a Fiber-Reinforced Cement-Stabilized Fly Ash Stone Dust Aggregate Mixture," *Journal of Composites Science*, vol. 7, no. 11, p. 459, 2023.
- [59] P. Kulanthaivel, S. Selvakumar, B. Soundara, V. Kayalvizhi, and S. Bhuvaneshwari, "Combined effect of nano-silica and randomly distributed fibers on the strength behavior of clay soil," *Nanotechnology for Environmental Engineering*, vol. 7, pp. 1-12, 2022.
- [60] L. Wei, S. X. Chai, H. Y. Zhang, and Q. Shi, "Mechanical properties of soil reinforced with both lime and four kinds of fiber," *Construction and Building Materials*, vol. 172, pp. 300-308, 2018.
- [61] L. Gao, G. Hu, N. Xu, J. Fu, C. Xiang, and C. Yang, "Experimental study on unconfined compressive strength of basalt fiber reinforced clay soil," *Advances in Materials Science and Engineering*, vol. 2015, 2015.
- [62] A. Zeinali, T. Edeskär, and J. Laue, "Mechanism of thawing," *Cogent Engineering*, vol. 7, no. 1, p. 1716438, 2020.
- [63] L. Zhang, F. Ren, H. Li, D. Cheng, and B. Sun, "The influence mechanism of freeze-thaw on soil erosion: A review," *Water*, vol. 13, no. 8, p. 1010, 2021.
- [64] M. Roustaei, A. Eslami, and M. Ghazavi, "Effects of freeze-thaw cycles on a fiber reinforced fine grained soil in relation to geotechnical parameters," *Cold Regions Science and Technology*, vol. 120, pp. 127-137, 2015.