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Impact of Freezing and Thawing Cycles on Mechanical Performance of Carbon Fiber-Reinforced Cement-Stabilized Sand

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Abstract

In civil engineering, natural soils often lack the strength required for intended loads. Soil improvement techniques, such as using cement and fibers, are employed to bolster mechanical properties for engineering structures. This study evaluates the efficacy of cement-stabilized sand reinforced with carbon fibers under freezing and thawing cycles. Key variables investigated include cement and carbon fiber content, curing periods, and freeze-thaw cycles. Results show significant enhancements in unconfined compressive strength (UCS) with the addition of cement and carbon fibers. For instance, specimens with 10% cement and 2% carbon fiber achieved UCS values of up to 1717 kPa, 1521 kPa, and 1347 kPa under varying freeze-thaw cycles at 28 days. This combination also reduces crack formation by increasing strain at failure points. Specimens with 2% carbon fibers and 10% cement exhibited the highest failure strains under freeze-thaw cycles. However, increasing freeze-thaw cycles led to decreased UCS, although carbon fiber-reinforced specimens showed more resilience. The study highlights the efficacy of combining carbon fibers and cement for reinforcing sandy soil under freeze-thaw conditions. Cement enhances UCS during stabilization, while carbon fibers improve strain at failure, enhancing soil deformability and mitigating failure mechanisms. This research provides insights into optimizing soil stabilization methods for civil engineering projects in challenging environmental conditions.

Keywords: Sand, Freeze-Thaw Cycles, Soil Stabilization, Carbon Fibers, Cement.

1. Introduction

Soil stabilization, a crucial aspect of civil engineering, encompasses a variety of techniques aimed at bolstering the strength and resilience of weaker soils to meet specific engineering requirements [1–7]. This process typically involves two main methodologies: physical and chemical stabilization. Physical methods entail employing various mechanical processes to enhance soil properties, while chemical stabilization relies on the application of chemicals, emulsions, and binding agents to achieve the desired results [8].

Chemical stabilization involves the addition of substances such as cement, lime, polymers, and fibers to modify soil characteristics, bolster strength, and reduce permeability. Cement, a widely utilized stabilizing material, effectively fills the voids between soil particles, fostering bonds that enhance both mechanical and physical properties, thereby augmenting strength and overall performance [9–12]. The requisite amount of cement for soil stabilization varies depending on factors like soil plasticity, compaction level, porosity, and the proportions of course and fine materials. Typically, sandy soils necessitate a cement content ranging from 5% to 20%, with the initial moisture content exerting a notable influence; however, exceeding optimal moisture levels can compromise overall strength [13].

Furthermore, the incorporation of fibers represents another promising strategy for soil enhancement [14,14,15]. Derived from various sources such as plants, pitch-based methods, or synthetic polyacrylonitrile (PAN) processes, carbon fibers offer numerous advantages including exceptional surface coverage, low thermal expansion, high thermal stability, lightweight properties, and chemical resistance [16–18]. Both carbon nanofibers and carbon nanotubes exhibit significant potential in stabilizing degraded soils [19,20].

When combined with clayey soil, the introduction of carbon fiber elements can significantly enhance both the Unconfined Compressive Strength (UCS) and the soil's resistance to brittle failure. Notably, while the addition of carbon fibers initially strengthens the soil, an excessive increase in fiber content can lead to a decrease in strength, particularly noteworthy when carbon fiber content reaches 0.1%. Mechanistically, this improvement stems from both the reinforcement provided by individual carbon fiber threads and the formation of a three-dimensional fiber network within the soil [21].Moreover, the impact of freeze-thaw cycles on soil, especially in cold regions, is significant, altering soil structure and characteristics and potentially diminishing overall strength [16,22,23]. Thaw-freeze cycles notably affect the UCS and stress-strain curves of cement-stabilized soil samples, with an increase in cycle number

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correlating with a decrease in peak and critical state strength [24].

Although previous research extensively explores the effects of freeze-thaw cycles on soils stabilized with cement or lime, there remains a gap in understanding the specific impact on cement-stabilized soils reinforced with fibers. Hence, this study aims to evaluate the influence of carbon fiber content (ranging from 0% to 2%), cement content (ranging from 0% to 10%), the number of freeze-thaw cycles (ranging from 0 to 4), and optimum moisture content on the UCS of sandy soil.

2. Materials and Methods

2.1. Materials

The soil utilized in this study is sandy soil characterized by a uniform grain size and representative freezing and thawing conditions observed in natural environments. Sourced from sandy hills located in Varzaneh, Isfahan province, this soil reflects the climatic extremes experienced in the region, including hot and arid summers and cold, dry winters. Sandy soil was chosen for its relatively underexplored nature concerning the effects of freezing and thawing, particularly when compared to fine-grained soils [25]. Table. 1. outlines the physical and geotechnical properties of the soil, while Fig.1. illustrates its particle size distribution curve.

Table. 1. Physical and geotechnical properties of the soil.

Properties	Values
Soil Classification (USCS)	SP
Gs	2.67
γ_{dmax} (kN/m^3)	19/91
ω_{opt} (%)	9
e_{max}	0.92
e_{min}	0.516

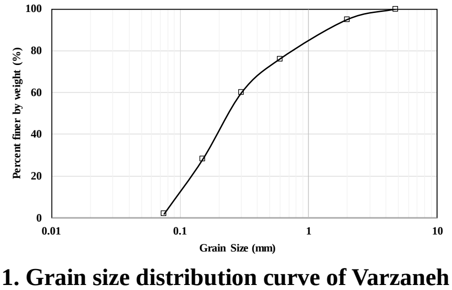


Fig. 1. Grain size distribution curve of Varzaneh sand.

For this study, Portland cement Type II, also referred to as modified Portland cement, was employed to enhance sandy soil. carbon fibers were chosen for soil stabilization in this project based on prior research, as demonstrated by studies conducted by researchers [19,26]. These studies have highlighted the efficacy of carbon fibers in enhancing the properties of granular soils. Notably, carbon fibers exhibit a higher elastic modulus compared to glass and coir fibers, with diameters typically ranging between 5 and 10 micrometers. Carbon fibers are further categorized into two main groups based on texture: unidirectional and bidirectional. In this study, unidirectional carbon fibers were employed. Unidirectional carbon fibers offer several advantages, including surface finishing capabilities, a low thermal expansion coefficient, high thermal stability, superior strength and elastic modulus, lightweight properties, high specific surface area, and suitability for varying water and weather conditions. Initially, carbon fibers possess a unidirectional fabric texture, which necessitates chopping into sizes ranging from 8 mm to 20 mm for incorporation into soil samples. The physical and chemical properties of the applied carbon fibers are outlined in Table.2.

Table. 2. Physical and chemical properties of carbon fibers.

Properties	Values
Arial Weight (gr/m^2)	200
Color	Black
Penetrating Time (sec)	60
Weave Pattern	Unidirectional
Primary Fibre Direction	0º
Fabric Thickness (mm)	0.11
Tensile Strength-ISO 10618 (MPa)	3800-4000
Tensile Modulus-ISO 10618 (GPa)	230
Elongation-ISO 10618	1.7%
Application Methods	Hand lay-up, Spray machine, Robot processes
Compatible Resins	Epoxy, Polyester, Phenolic, Polyurethane, Vinylester
Shelf Time (years)	10
Storage Conditions	Store dry at 4ºC-40ºC

2.2. Soil Specimen Preparation

The objective of this research is to investigate the influence of adding cement and carbon fibers on the Unconfined Compressive Strength (UCS) and strain at failure of sand samples. Cement was incorporated at ratios of 5% and 10% of the sand weight, informed by prior studies such as [27], which highlighted the benefits of cement for soil enhancement, with a maximum limit of 10% cement suggested by [28]. Carbon fibers were introduced at proportions of 0.5%, 1%, and 2% of the sand weight, following the experimental approach of Li et al. [29] and another relevant research.

The samples were prepared by mixing different amounts of cement and carbon fibers, then subjected to curing and exposure to varying freezing and thawing cycles (2 and 4 cycles) prior to UCS testing. Following molding, the samples were cured in nylon bags, divided into 7-day and 28-day groups, and exposed to the specified freezing and thawing cycles. The choice of the nylon bag method for curing is based on research by [30] and [31], which demonstrated its effectiveness in mitigating evaporation effects on soil samples. Each freezing and thawing cycle involved placing the samples in a freezer for 24 hours at -23°C, followed by exposure to room temperature (21 to 25°C) for 23 hours. This protocol adheres to the ASTM D560 standard and accounts for the grain size of the sandy soil, ensuring consistent and controlled testing conditions.

2.3. Unconfined Compressive Strength (UCS) Tests

The Unconfined Compression Test, alternatively known as the Uniaxial Compression Test, is a standard method employed to evaluate the strength and deformation properties of soil. Conforming to the ASTM D2166 standard, this test involves subjecting a soil sample to axial compression without any lateral confinement. The test is conducted using a Universal Testing Machine (UTM), specifically the SANTAM model STM-150, which applies axial force to the soil specimen until failure occurs. This allows for the determination of the maximum compressive stress the soil can withstand without lateral support, known as the UCS.

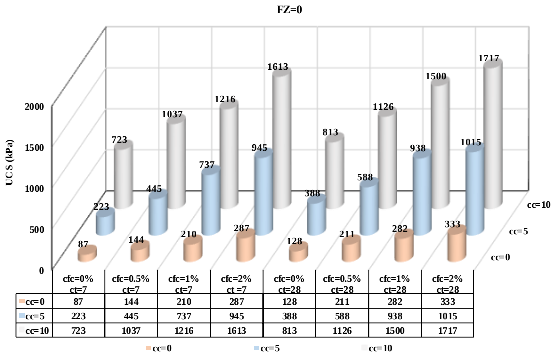
2.4. Preparation of Optical Micrograph Images

Following the completion of uniaxial compression tests, optical micrograph images of selected samples were prepared to investigate their microstructure. These images were captured using a stereomicroscope, also known as a stereoscope, which is an optical microscope designed for analyzing small-scale samples at low magnification. The stereomicroscope operates by employing reflected light from the sample's surface, rather than transmitting light through it. This device utilizes two separate optical paths, each equipped with its own eyepiece and objective lens, providing slightly different viewing angles for the left and right eyes. Through the illumination of the object via two distinct light paths, the lenses can magnify the object to approximately 160 times its original size. In this study, the equipment utilized for imaging was the SZX16 model stereomicroscope manufactured by OLYMPUS. This instrument facilitated the examination of sample microstructures, aiding in the comprehensive analysis of the uniaxial compression test results.

3. Results and Discussion

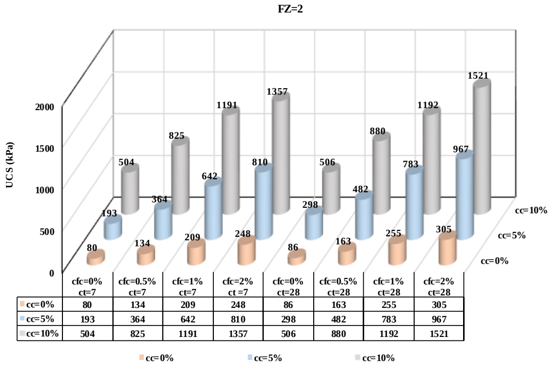
To elucidate the distinct alterations in the mechanical behavior of both pure and reinforced soil influenced by 0, 2, and 4 freeze-thaw cycles, uniaxial compression tests were conducted on specimens before and after freezing and thawing. These specimens comprised a blend of cement and carbon fibers and were evaluated following 7-day and 28-day curing periods. The abbreviations utilized in the graphs and presentation of results are as follows: cement percentage (cc), carbon fiber percentage (cfc), freezing and thawing cycles (FZ), and curing time (ct).

3.1. Effect of Freeze-Thaw Cycles on UCS



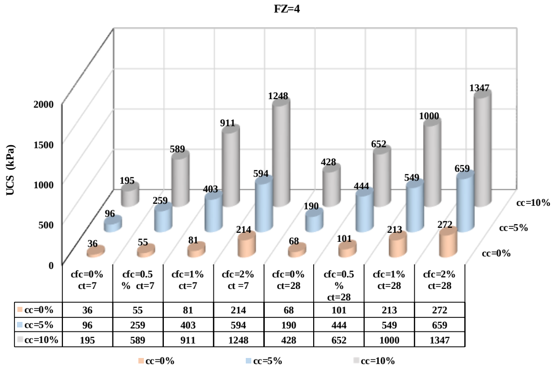
	cfc=0% ct=7	cfc=0.5% ct=7	cfc=1% ct=7	cfc=2% ct =7	cfc=0% ct=28	cfc=0.5% ct=28	cfc=1% ct=28	cfc=2% ct=28
cc=0	87	144	210	287	128	211	282	333
cc=5	223	445	737	945	388	588	938	1015
cc=10	723	1037	1216	1613	813	1126	1500	1717

Fig. 2. UCS of samples without freeze-thaw cycles at 7 and 28 days of age with varying percentages of cement and fibers.



	cfc=0% ct=7	cfc=0.5% ct=7	cfc=1% ct=7	cfc=2% ct =7	cfc=0% ct=28	cfc=0.5% ct=28	cfc=1% ct=28	cfc=2% ct=28
cc=0%	80	134	209	248	86	163	255	305
cc=5%	193	364	642	810	298	482	783	967
cc=10%	504	825	1191	1357	506	880	1192	1521

Fig. 3. UCS of samples with 2 freeze-thaw cycles at 7 and 28 days of age with varying percentages of cement and fibers.



	cfc=0% ct=7	cfc=0.5 % ct=7	cfc=1% ct=7	cfc=2% ct =7	cfc=0% ct=28	cfc=0.5 % ct=28	cfc=1% ct=28	cfc=2% ct=28
cc=0%	36	55	81	214	68	101	213	272
cc=5%	96	259	403	594	190	444	549	659
cc=10%	195	589	911	1248	428	652	1000	1347

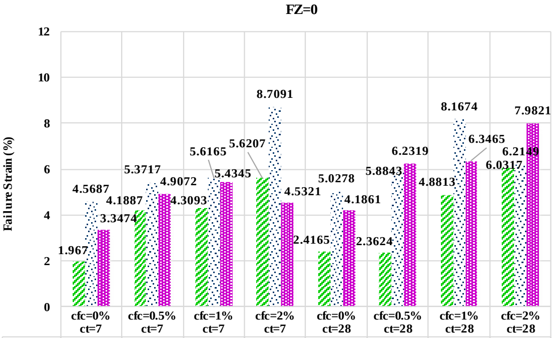
Fig. 4. UCS of samples with 4 freeze-thaw cycles at 7 and 28 days of age with varying percentages of cement and fibers.

In Fig. 1. to Fig. 3., the UCS of the control sample without any cycles, 2 cycles, and 4 cycles of freezing and thawing at 7 and 28 days is measured as follows: 87 kPa, 80 kPa, and 36 kPa at 7 days, and 128 kPa, 86 kPa, and 68 kPa at 28 days. The strength of the control samples exhibits an increase with longer curing times, consistent with findings reported in previous studies [32–34]. The UCS of the control samples decreases by approximately 8%

and 59% for the 7-day samples, and around 33% and 47% for the 28-day samples under 2 and 4 freeze-thaw cycles, respectively. This trend of strength reduction with an increasing number of freeze-thaw cycles aligns with findings from previous studies [35–37].Moreover, an increase in the amount of both cement and carbon fibers in the specimens leads to an improvement in UCS, consistent with findings of [38] and [39]. The samples with the highest UCS are those with a 10% cement ratio combined with varying percentages of carbon fibers. Conversely, samples without cement exhibit the lowest UCS. The addition of cement to samples without carbon fibers results in an enhancement of UCS, consistent with studies by previous studies [40–42], under non-freezing and thawing conditions, as well as by previous studies [43,44] under freezing and thawing cycles. In fact, the specimens at 7-day curing period, containing 5% and 10% cement, achieve more than 2.5 times, 2 times, and 2.6 times, and over 8 times, 6 times, and 5.4 times the strength of the control specimens at 7-day curing period, respectively. Additionally, as the curing time extends to 28 days, the specimens containing only 5% and 10% cement exhibit a threefold enhancement in UCS compared to the control specimens for each set of freeze-thaw cycles (Fig. 2.to Fig. 4.), and greater than sixfold enhancement in UCS compared to the 28-day control specimens. This improvement in structure aligns with results reported by [45].The inclusion of carbon fibers also enhances the UCS of the tested specimens after 7 days and 28 days, as shown in Fig. 2. to Fig. 4. In the absence of cement, the addition of 0.5%, 1%, and 2% carbon fibers results in approximately 65%, 120%, and 160% higher UCS, respectively, for the 28-day samples without freezing and thawing cycles. Additionally, with an increase in the number of freezing and thawing cycles up to 4 cycles, the UCS of these samples increases by approximately 49%, 213%, and 300% compared to the control samples. The beneficial impact of fibers on enhancing the compressive strength properties of soil has been observed in experiments conducted by previous studies [46,47], without freezing and thawing cycles, as well as by [48], under freezing and thawing conditions. Consequently, the simultaneous increase in curing duration, cement content, and carbon fibers results in the most significant rate of improvement in unconfined compressive strength. This is evident in the 28-day sample containing 10% cement and 2% carbon fibers, which exhibited a compressive strength of 1717 kPa, as shown in Fig. 1., without the influence of freezing and thawing. This finding is supported by previous studies by [30]. Considering the impact of freezing and thawing in the samples subjected to 2 and 4 cycles (illustrated in Fig. 3. and Fig. 4.), the respective values are 1521 kPa and 1347 kPa.

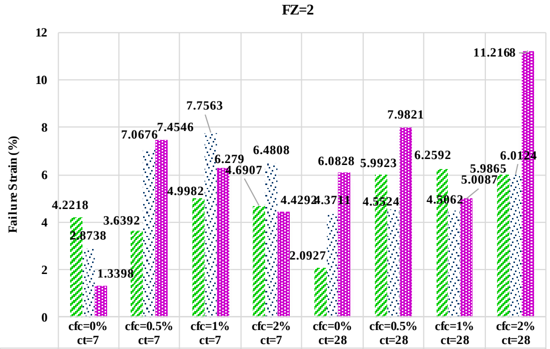
3.2. Effect of Freeze-Thaw Cycles on the Results of Failure Strain and Failure Pattern

Fig. 5. to Fig. 7. illustrate the failure strain of specimens subjected to varying percentages of cement and fibers at 7-day and 28-day ages, under 0, 2, and 4 freeze-thaw cycles.



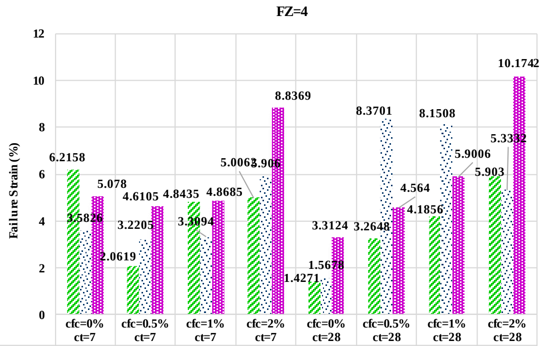
	cfc=0% ct=7	cfc=0.5% ct=7	cfc=1% ct=7	cfc=2% ct=7	cfc=0% ct=28	cfc=0.5% ct=28	cfc=1% ct=28	cfc=2% ct=28
▨cc=0%	1.967	4.1887	4.3093	5.6207	2.4165	2.3624	4.8813	6.0317
▨cc=5%	4.5687	5.3717	5.6165	8.7091	5.0278	5.8843	8.1674	6.2149
▨cc=10%	3.3474	4.9072	5.4345	4.5321	4.1861	6.2319	6.3465	7.9821

Fig. 5. Failure strain of samples without freeze-thaw cycles at 7 and 28 days of age with varying percentages of cement and fibers.



	cfc=0% ct=7	cfc=0.5% ct=7	cfc=1% ct=7	cfc=2% ct=7	cfc=0% ct=28	cfc=0.5% ct=28	cfc=1% ct=28	cfc=2% ct=28
▨cc=0%	4.2218	3.6392	4.9982	4.6907	2.0927	5.9923	6.2592	5.9865
▨ cc=5%	2.8738	7.0676	7.7563	6.4808	4.3711	4.5524	4.5062	6.0124
▨cc= 10%	1.3398	7.4546	6.279	4.4292	6.0828	7.9821	5.0087	11.2168

Fig. 6. Failure strain of samples with 2 freeze-thaw cycles at 7 and 28 days of age with varying percentages of cement and fibers.



	cfc=0% ct=7	cfc=0.5% ct=7	cfc=1% ct=7	cfc=2% ct=7	cfc=0% ct=28	cfc=0.5% ct=28	cfc=1% ct=28	cfc=2% ct=28
▨cc=0%	6.2158	2.0619	4.8435	5.0062	1.4271	3.2648	4.1856	5.903
▨cc=5%	3.5826	3.2205	3.3094	5.906	1.5678	8.3701	8.1508	5.3332
▨cc=10%	5.078	4.6105	4.8685	8.8369	3.3124	4.564	5.9006	10.1742

Fig. 7. Failure strain of samples with 4 freeze-thaw cycles at 7 and 28 days of age with varying percentages of cement and fibers.

In these figures, it is observed that a higher presence of carbon fibers in the samples leads to a more significant increase in failure strain under the same conditions. Samples containing 2% carbon fibers exhibit an increased failure strain, indicating improved ductility. This suggests that carbon fibers play a crucial role in enhancing the ductility of the samples, preventing them from becoming brittle or fragile, and thereby improving their overall performance. This finding is consistent with prior research by [49] and [50], which demonstrated that the presence of fibers alters the strain-hardening behavior from brittle to ductile. Similarly, the addition of cement to the samples also increases the failure strain. This observation is supported by the study by [51], although it indicates that the increase is not linear. With the enhancement in cement content up to approximately 5%, the samples experience a greater increase in failure strain compared to samples with 10% cement. The presence of carbon fibers along with cement in the samples results in a higher failure strain when exposed to freeze-thaw cycles. This aligns with the results of [24], suggesting that carbon fibers to some extent compensate for the reduction in failure strain caused by freeze-thaw cycles. Fig. 8. displays images of the 28-day samples without cement and containing varying percentages of carbon fibers, subjected to different freeze-thaw cycles. The aim is to examine the precise impact of fiber addition on the samples and their fracture behavior under different freeze-thaw conditions. Upon considering the deformed shape of the samples at their failure point, it becomes evident that those containing 2% carbon fibers exhibit a higher failure strain and improved ductility. Carbon fibers establish strong bonds with the soil, effectively preventing notable separation or general failure in the samples.

Fig. 8. Images of 28-day samples lacking cement and containing various percentages of carbon fibers under different freeze-thaw cycles.

As the percentage of fibers increases, the occurrence of general failure is further mitigated due to the efficient performance of carbon fibers, leading to a more ductile behavior.

In Fig. 8., with an increase in the number of freeze-thaw cycles, samples with higher proportions of carbon fibers demonstrate reduced crack formation. This suggests that the presence of carbon fibers effectively preserves the structure and shape of the samples even with more freeze-thaw cycles. This conclusion is supported by previous studies [52–54].

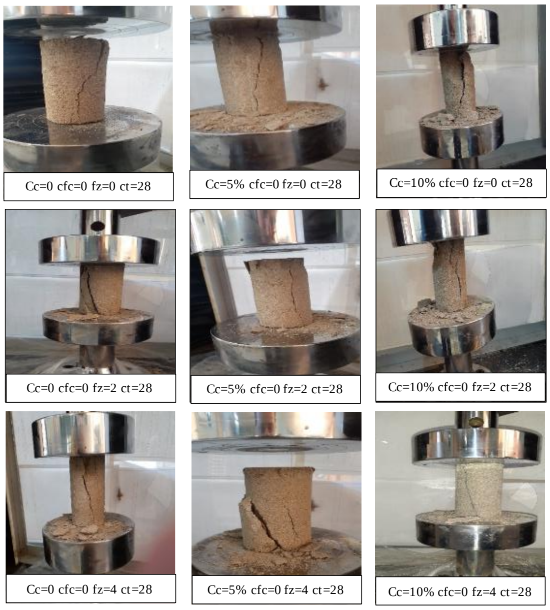


Fig. 9. Images of 28-day samples containing various percentages of cement and lacking carbon fibers under different freeze-thaw cycles.

In Fig. 9., images of the 28-day samples without carbon fibers and containing varying contents of cement are presented under different freeze-thaw cycles. This analysis aims to investigate the precise influence of cement presence and its impact on the fracture behavior of the samples under different freeze-thaw conditions.

In the strain-to-failure diagrams, it is observed that compared to the 7-day and 28-day samples, the 28-day samples combined with 5% and 10% cement exhibit higher strain-to-failure values and demonstrate maximum ductility.

Fewer cracks and fractures are observed in these samples, indicating their improved resistance to failure. Conversely, in the samples without cement content, the failure strain is significantly lower, suggesting their brittleness and tendency for rapid fracturing.

As depicted in Fig. 9., with an increase in the number of freeze-thaw cycles, samples containing higher proportions of cement demonstrate a reduced occurrence of cracks, leading to the effective preservation of structure. These observations align with research by [55].

Generally, samples containing cement are more prone to brittleness and exhibit a higher overall occurrence of cracks compared to samples containing carbon fibers. Previous research have emphasized the use of fibers in cement-stabilized soils to maximize failure strain and improve the ductile behavior of the soil [12,16,24,56].

3.3. Optical Micrograph Images of the Tested Samples

To provide a comprehensive evaluation of the behavior of soil stabilized with carbon fibers and cement, optical micrograph images of some samples have been included in this study. The analysis of soil microstructure is crucial, as changes in microstructure lead to alterations in soil properties [57].Fig. 10. to Fig. 13. depict optical micrograph images of 28-day samples with varying percentages of cement and carbon fibers, both without any cycles and subjected to four freeze-thaw cycles. These images clearly show the strong bonding between soil particles, cement, and carbon fibers in the samples before undergoing freeze-thaw cycles. This adhesive behavior aligns with observations in optical images of carbon fiber-reinforced sandy soil samples by previous studies [58,59].

The presence of this adhesion indicates that the cement and carbon fibers effectively act as stabilizers in the samples. Furthermore, a strong bond is observed between the soil and cement, as well as between the soil and carbon fibers. However, after completing the freeze-thaw cycles, the adhesion between the components decreases slightly, causing them to lose their initial state.

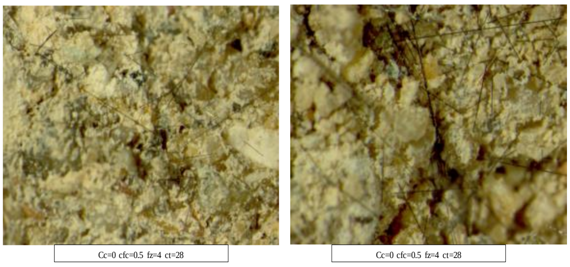


Fig. 10. Optical micrograph images of 28-day samples with 0.5% carbon fibers and lacking cement subjected to 4 freeze-thaw cycles.

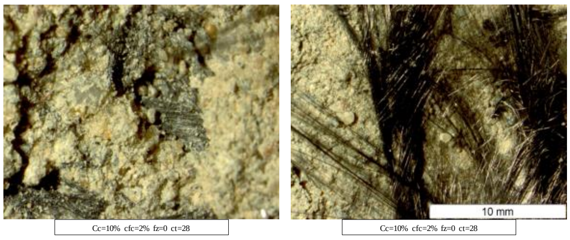


Fig. 11. Optical micrograph images of 28-day samples with 10% cement and 2% carbon fibers without freeze-thaw cycles.

The visible effect of undergoing freeze-thaw cycles is a reduction in adhesion among cement, carbon fibers, and the soil. Consequently, the soil samples become more vulnerable to disintegration and experience a faster decline in their UCS as the number of freeze-thaw cycles increases.

In contrast, samples that were not stabilized with cement and carbon fibers exhibit greater brittleness after undergoing freeze-thaw cycles, leading to a decline in their strength. It is noteworthy that samples reinforced with carbon fibers demonstrate more favorable performance and behavior in response to freeze-thaw cycles.

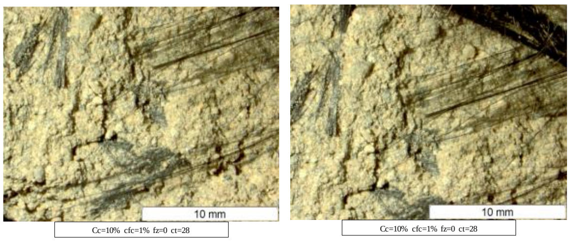


Fig. 12. Optical micrograph images of 28-day samples with 10% cement and 1% carbon fibers without freeze-thaw cycles.

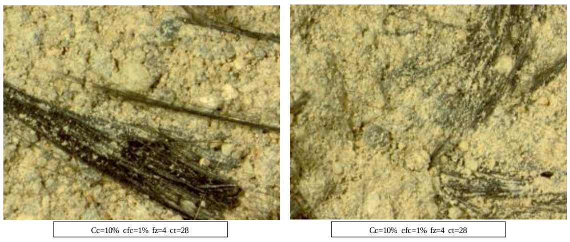


Fig. 13. Optical micrograph images of 28-day samples with 10% cement and 1% carbon fibers subjected to 4 freeze-thaw cycles.

4. Conclusion

1. Extending the curing time in reinforced soil, whether with cement, carbon fiber, or both, consistently improves the UCS and strain at failure of all samples. The 28-day samples exhibit the highest strength increase compared to the 7-day samples. Samples with the highest cement percentage (10%), varying carbon fiber proportions, and subjected to 28-day curing demonstrate the maximum strength enhancement, reaching up to 23%, 12%, and 119% compared to the 7-day samples, respectively. Longer curing times allow for better hydration, resulting in well-developed crystals and stronger chemical bonding between soil particles and cement, enhancing strength and stiffness. Additionally, extended curing improves moisture distribution, resulting in a denser and more durable matrix, enhancing resistance against environmental factors and promoting long-term stability.

In soil reinforced by carbon fiber, an extended curing time improves bonding between carbon fibers and the soil or soil-cement matrix, leading to improved mechanical properties.

2. Adding carbon fibers, especially in samples without cement, increases the UCS of all specimens, including those subjected to freeze-thaw cycles. The highest UCS is observed in samples reinforced with 2% carbon fibers, with up to 160%, 255%, and 300% improvement compared to control samples with (0, 2, 4) freeze-thaw cycles. Carbon fibers enhance soil particle strength and create a network structure, effectively transmitting compressive stresses and improving bonding with the soil matrix. Additionally, the flexibility and high tensile strength of carbon fibers contribute to higher strain at failure, indicating better deformability and resistance to brittle failure.
3. The addition of cement significantly improves UCS in all specimens, especially those containing 10% cement, which exhibit the highest strength. Samples with 10% cement and subjected to freeze-thaw cycles show growth rates of up to 1240%, 1670%, and 1880% compared to control samples. Cement reduces permeability, limits water infiltration, and mitigates the detrimental effects of freeze-thaw cycles by forming denser microstructures.
4. Simultaneously adding cement and carbon fibers results in a significant increase in UCS, with the highest strength observed in samples containing both materials. The sample with 2% carbon fibers and 10% cement shows the greatest improvement, exhibiting approximately 14%, 52%, and 111% higher UCS compared to samples containing (1%, 0.5%, 0%) carbon fibers and 10% cement, respectively. Additionally, failure strain increases, indicating excellent ductility and resistance to brittle failure.
5. Carbon fibers effectively prevent instability and extensive fracturing, while cement alone displays a more brittle behavior. Carbon fibers offer flexibility and ductility, accommodating stresses more effectively and ensuring long-term stability. Cement, though initially providing strength, may degrade over time, compromising stability. Carbon fibers allow for targeted reinforcement, optimizing stability based on anticipated stresses.
6. Freeze-thaw cycles decrease UCS and failure strain in all samples, but samples with carbon fibers exhibit better performance. Carbon fibers mitigate freeze-thaw damage by distributing stresses and maintaining structural integrity. Cement-only samples show less resilience to freeze-thaw cycles due to their brittle nature. Samples containing both carbon fibers and cement demonstrate the best performance under freeze-thaw conditions, exhibiting minimal reduction in strength and the highest failure strain among all specimens.

References

[1] Asgari MR, Baghebanzadeh Dezfuli A, Bayat M. Experimental study on stabilization of a low plasticity clayey soil with cement/lime. Arab J. Geosci., 2015;8:1439-52.

[2] Bayat M, Asgari MR, Mousivand M. Effects of cement and lime treatment on geotechnical properties of a low plasticity clay. Int. Conf. Civil Eng. Archit. Urban Sustain. Dev. 27&28 November, 2013.

[3] ShahriarKian M, Kabiri S, Bayat M. Utilization of Zeolite to Improve the Behavior of Cement-Stabilized Soil. Int. J. Geosynth. Ground. Eng. 2021;7:35.

[4] Rezaei-Hosseinabadi MJ, Bayat M, Nadi B, Rahimi A. Sustainable utilisation of steel slag as granular column for ground improvement in geotechnical projects. Case Stud. Constr. Mater., 2022;17:e01333.

[5] Hakimelahi N, Bayat M, Ajalloeian R, Nadi B. Effect of woven geotextile reinforcement on mechanical behavior of calcareous sands. Case Stud. Constr. Mater., 2023;18:e02014.

[6] Roustaei M, Tavana J, Bayat M. Influence of adding waste polyethylene terephthalate plastic strips on uniaxial compressive and tensile strength of cohesive soil. Geopersia 2021,30;12(1):39-51.

[7] Cheshomi A, Sahragard A. Use of fine-grained soil for improvement of density and bearing capacity of aeolian sand. Geopersia 202327;13(2):261-74.

[8] Bayat M, Saadat M, Hojati A. Optimization of Dynamic Compaction Procedure for Sandy Soils. Civ. Eng. Infrastruct J. 2023.

[9] Salehi M, Bayat M, Saadat M, Nasri M. Experimental Study on Mechanical Properties of Cement-Stabilized Soil Blended with Crushed Stone Waste. KSCE J. Civ. Eng. 2021;25:1974-84.

[10] Salehi M, Bayat M, Saadat M, Nasri M. Prediction of unconfined compressive strength and California bearing capacity of cement- or lime-pozzolan-stabilised soil admixed with crushed stone waste. Geomech. Geoeng. 2023;18:272-83.

[11] Puppala AJ, Wattanasanticharoen E, Hoyos LR. Ranking of Four Chemical and Mechanical Stabilization Methods to Treat Low-Volume Road Subgrades in Texas. Transp. Res. Rec. 2003;1819:63-71.

[12] Ayeldeen M, Azzam W, Arab MG. The Use of Fiber to Improve the Characteristics of Collapsible Soil Stabilized with Cement. Geotech. Geol Eng. 2022;40:1873-85.

[13] Kulkarni PP, Mandal JN. Strength evaluation of soil stabilized with nano silica-cement mixes as road construction Material. Constr. Build. Mater. 2022;314:125363.

[14] Ghanbari M, Bayat M. Effectiveness of reusing steel slag powder and polypropylene fiber

on the enhanced mechanical behavior of cement-stabilized sand. Civ. Eng. Infrastruct J. 2022.

[15] Eshaghzadeh M, Bayat M, Ajalloeian R, Hejazi SM. Mechanical behavior of silty sand reinforced with nanosilica-coated ceramic fibers. J.Adhes Sci. Technol., 2021;35:2664-83.

[16] Hadi Sahlabadi S, Bayat M, Mousivand M, Saadat M. Freeze–Thaw Durability of Cement-Stabilized Soil Reinforced with Polypropylene/Basalt Fibers. J Mater. Civ. Eng. 2021;33:04021232.

[17] Ahmadi H, Janati S, Jamshidi Chenari R. Strength Parameters of Stabilized Clay Using Polypropylene Fibers and Nano-MgO: An Experimental Study. Geotech. Geol. Eng. 2020;38:2845-58.

[18]Eissa A, Yasien AM, Bassuoni MT, Alfaro M. Nano-modified cementitious binders reinforced with basalt fiber/polymer pellets as a stabilizer for weak soils. Can J. Civ. Eng., 2023;50:879-91.

[19] Cui H, Jin Z, Bao X, Tang W, Dong B. Effect of carbon fiber and nanosilica on shear properties of silty soil and the mechanisms. Constr. Build. Mater. 2018;189:286-95.

[20] Tavakolipour M, Salemi N. Durability assessment of soft clay soil stabilized with halloysite nanotubes. Acta J Geodyn.Geromater. 2021;18:429-37.

[21] Gao L, Zhou Q, Yu X, Wu K, Mahfouz AH. Experimental study on the unconfined compressive strength of carbon fiber reinforced clay soil. Mar. Georesour. Geotechnol. 2017;35:143-8.

[22] Huang Y, Chen Y, Wang S, Wu M, Wang W. Effects of freeze–thaw cycles on volume change behavior and mechanical properties of expansive clay with different degrees of compaction. Int. J.Geomech.2022;22:04022050.

[23] Roustaei M. Shear modulus and damping ratio of clay soil under repeated freeze-thaw cycles. Acta Geodyn et Geomater. 2021:71-81.

[24] Ding M, Zhang F, Ling X, Lin B. Effects of freeze-thaw cycles on mechanical properties of polypropylene fiber and cement stabilized clay. Cold Reg.Sci.Technol. 2018;154:155-65.

[25] Qi J, Vermeer PA, Cheng G. A review of the influence of freeze-thaw cycles on soil geotechnical properties: Freeze-thaw and Soil Properties. Permafr. Periglacial Process.2006;17:245-52.

[26] Bao X, Huang Y, Jin Z, Xiao X, Tang W, Cui H, Chen X, Experimental investigation on mechanical properties of clay soil reinforced with carbon fiber. Constr. Build. Mater. Environ. Eng. Mater. Sci. 2021;280:122517.

[27] Bell F. Eng.Treat.Soil. CRC Press; 1993.

[28] Consoli NC, Vendruscolo MA, Fonini A, Dalla Rosa F. Fiber reinforcement effects on sand considering a wide cementation range. Geotext.Geomembr. 2009;27:196-203.

[29] Li M, He H, Senetakis K. Behavior of carbon fiber-reinforced recycled concrete aggregate. Geosynth.Int. 2017;24:480-90.

[30] Rahmannejad M, Toufigh V. Influence of curing time and water content on unconfined compressive strength of sand stabilized using epoxy resin. Int. J. Eng.2018;31:1187-95.

[31] Moayyeri N, Oulapour M, Haghighi A. Study of geotechnical properties of a gypsiferous soil treated with lime and silica fume. Geomech. Eng.2019;17:195-206.

[32] Park K, Jun S, Kim D. Effect of strength enhancement of soil treated with environment-friendly calcium carbonate powder.Sci. World J. 2014;2014.

[33] Banu SA, Attom MF. Effect of Curing Time on Lime-Stabilized Sandy Soil against Internal Erosion. Geosci.2023;13:102.

[34] Aiban SA. A study of sand stabilization in eastern Saudi Arabia. Eng. Geology.1994;38:65-79.

[35] Graham J, Au VCS. Effects of freeze–thaw and softening on a natural clay at low stresses. Can Geotech. J.1985;22:69-78.

[36] Aldaood A, Bouasker M, Al-Mukhtar M. Impact of freeze–thaw cycles on mechanical behaviour of lime stabilized gypseous soils. Cold Reg. Sci. Technol., 2014;99:38-45.

[37] Liu C, Lv Y, Yu X, Wu X. Effects of freeze-thaw cycles on the unconfined compressive strength of straw fiber-reinforced soil. Geotext.Geomembr., 2020;48:581-90.

[38] Hejazi SM, Sheikhzadeh M, Abtahi SM, Zadhoush A. A simple review of soil reinforcement by using natural and synthetic fibers, Constr. Build. Mater.2012;30:100-16.

[39] Jumassultan A, Sagidullina N, Kim J, Ku T, Moon S-W. Performance of cement-stabilized sand subjected to freeze-thaw cycles. Geomech. Eng.2021;25:41.

[40] Saxena SK, Lastrico RM. Static Properties of Lightly Cemented Sand. J. Geotech. Eng. Div.1978;104:1449-64.

[41] Mohamadi M, Choobbasti AJ. Stabilization of sandy soil using microfine cement and nanosilica grout. Arab J.Geosci.2021;14:1617.

[42] Ahmadi H. Experimental study of the effect of nano-additives on the stiffness of cemented fine sand. Int. J. Geotech. Eng.2021;15:433-46.

[43] Yarbaşı N, Kalkan E, Akbulut S. Modification of the geotechnical properties, as influenced by freeze–thaw, of granular soils with waste additives. Cold Reg. Sci. Technol.2007;48:44-54.

[44] Quang ND, Chai JC. Permeability of lime- and cement-treated clayey soils. Can Geotech. J.2015;52:1221-7.

[45] Sagidullina N, Abdialim S, Kim J, Satyanaga A, Moon S-W. Influence of Freeze–Thaw Cycles on Physical and Mechanical Properties of Cement-Treated Silty Sand. Sustain.2022;14:7000.

[46] Zhao Y, Yang Y, Ling X, Li G, Gong W. Mechanical behaviors of natural sand soils and modified soils in heavy-haul railway embankment. Adv. Civ. Eng.2020;2020:1-12.

[47] Ren Q, Li Z. Experimental study on the influence of curing methods on the compressive strength of improved sand., Case. Stud. Const. Mater. 2023;19:e02626.

[48] Zaimoglu AS. Freezing–thawing behavior of fine-grained soils reinforced with polypropylene fibers. Cold Reg. Sci. Technol.2010;60:63-5.

[49] Roustaei M, Eslami A, Ghazavi M. Effects of freeze–thaw cycles on a fiber reinforced fine grained soil in relation to geotechnical parameters. Cold Reg. Sci. Technol.2015;120:127-37.

[50] Abdi MR, Ghalandarzadeh A, Chafi LS. An investigation into the effects of lime on compressive and shear strength characteristics of fiber-reinforced clays. J. Rock. Mech. Geotech. Eng.2021;13:885-98.

[51] Rezaeian M, Ferreira PMV, Ekinci A. Mechanical behaviour of a compacted well-graded granular material with and without cement. Soil. Found., 2019;59:687-98.

[52] Ple O, Lê TNH. Effect of polypropylene fiber-reinforcement on the mechanical behavior of silty clay. Geotext.Geomembr.2012;32:111-116.

[53] Yadav JS, Tiwari SK. Behaviour of cement stabilized treated coir fibre-reinforced clay-pond ash mixtures. J. Build. Eng., 2016;8:131-40.

[54] Wei L, Chai SX, Zhang HY, Shi Q. Mechanical properties of soil reinforced with both lime and four kinds of fiber. Construct. Build.Mater.2018;172:300-8.

[55] Chen S, Zheng Y. Study on the Evolutionary Model and Structural Simulation of the Freeze–Thaw Damage of Cemented Sand and Gravel (CSG). J. Inst. Eng. India Ser. A 2018;99:699-704.

[56] Maher MH, Ho YC. Behavior of fiber-reinforced cemented sand under static and cyclic loads. Geotech. Test. J. 1993;16:330-8.

[57] Hohmann-Porebska M. Microfabric effects in frozen clays in relation to geotechnical parameters. Appl. Clay Sci., 2002;21:77-87.

[58] Qiu R, Tong H, Gu M, Yuan J. Strength and micromechanism analysis of microbial solidified sand with carbon fiber. Adv. Civ. Eng.2020;2020:1-10.

[59] Ji Y, Zou Y, Ma Y, Wang H, Li W, Xu W. Frost Resistance Investigation of Fiber-Doped Cement. Compos. Mater. 2022;15:2226.