Power System Technology
ISSN:1000-3673

Accepted: 28-08-2024 *Revised: 15-07-2024* *Received: 06-06-2024*

Enhancing Shear Strength of Cement-Stabilized Soils under Freeze-thaw: A Steel Fiber Reinforced Approach

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Abstract

This study examines the impact of steel fiber inclusion on the shear strength of cement-stabilized soils exposed to freeze-thaw cycles. Three distinct soil types, characterized by varying clay and sand fractions, were stabilized with 8% cement by weight and reinforced with 1%, 2%, and 3% steel fibers (diameter: 0.5 mm, length: 3 cm). Direct shear tests demonstrated a progressive increase in the internal friction angle with increasing fiber content for all soil types under non-frozen conditions. However, exposure to freeze-thaw cycles resulted in a reduction of both the internal friction angle and cohesion for all studied mixtures. Notably, steel fiber reinforcement continued to offer a significant improvement in shear strength, with a maximum observed increase of 16.7% in the internal friction angle under freeze-thaw conditions compared to unreinforced specimens. These findings suggest that steel fiber inclusion can mitigate the detrimental effects of freeze-thaw cycles on the shear strength of stabilized soils, particularly for clay-rich soils exhibiting higher susceptibility to such environmental degradation.

Keywords: Steel fiber reinforcement- Shear strength- Stabilized soil- Freeze-thaw cycles- Internal friction angle

1. INTRODUCTION

Soil stabilization is a widely used technique to improve the mechanical properties of soils for various geotechnical applications. However, the performance of stabilized soils can be significantly affected by environmental factors such as freeze-thaw cycles. These cycles can lead to a decrease in shear strength parameters like cohesion and internal friction angle, potentially compromising the stability of structures built on such soils [5].

Several studies have investigated the detrimental effects of freeze-thaw cycles on stabilized soils. Ghazavi and Roustaie (2010, 2013) observed a reduction in the unconfined compressive strength (UCS) of cement-stabilized soils after freeze-thaw cycles [1, 2]. Similarly, Shibi and

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Power System Technology
ISSN:1000-3673
Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

Kamei (2014) reported a decrease in the UCS of lime-stabilized clayey soils subjected to freezing and thawing [4]. These studies suggest that the weakening effect of freeze-thaw is likely due to internal cracking and water migration within the soil matrix .

Fiber reinforcement is a promising technique for improving the mechanical properties of stabilized soils. Steel fibers can bridge cracks, improve stress distribution, and enhance the overall post-peak behavior of the material [6]. Studies by Orakoglu et al. (2018) and Consolini et al. (2017) demonstrated that both polypropylene and steel fibers can increase the shear strength and ductility of fiber-reinforced soils [3, 7].

In situ soils at construction sites frequently exhibit mechanical properties inadequate for their intended engineering applications. These unsuitable soils, when subjected to loading conditions, can experience excessive settlements that jeopardize the structural integrity of overlying foundations or structures. To mitigate these challenges, soil reinforcement techniques have emerged as a successful strategy to enhance the geotechnical properties of weak or unsuitable soils. These techniques essentially aim to modify the soil matrix into a more robust and stable configuration, thereby achieving the desired engineering performance requirements.

In geotechnical engineering, soil reinforcement techniques have become indispensable tools for mitigating the limitations inherent to natural soils. These techniques enhance the engineering properties of weak or unsuitable soils, enabling them to satisfy the performance requirements of diverse infrastructure projects. Among the various reinforcement methodologies, fiber reinforcement has gained significant traction due to its effectiveness, ease of implementation, and cost-effectiveness.

The incorporation of fibers for material reinforcement is a well-established concept, with established applications in textile and composite engineering [1]. This principle has seen significant traction in geotechnical engineering, where various fiber types, both synthetic and natural, are employed for soil reinforcement [2]. Synthetic fibers, including glass, galvanized steel, and those derived from polymers like polyethylene, polyester, and polypropylene, offer notable advantages due to their high strength and durability characteristics [3]. Natural fibers, such as those sourced from plants (coir, sisal) or animals (hair), present a potentially sustainable and cost-effective alternative. However, further research is necessary to comprehensively evaluate their long-term performance in geotechnical applications [4].

The efficacy of fiber reinforcement in soil stems from two primary mechanisms:

• Mechanical Interlocking: Fibers physically engage with soil particles, forming a network that strengthens the entire soil matrix. This interlocking mechanism restricts particle movement under applied stress, leading to increased shear resistance and a reduction in soil deformation, particularly during failure conditions.

• Frictional Mobilization: The inclusion of fibers enhances the interfacial roughness within the soil matrix. This increased roughness promotes the mobilization of internal friction between soil particles and the fibers themselves. This frictional resistance further contributes to the overall shear and tensile strength of the soil.

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ISSN:1000-3673
Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

Fiber reinforcement can be implemented through two main techniques:

• Random Dispersion: This approach involves directly mixing discrete fibers throughout the soil matrix. This method is relatively simple to implement and offers a more homogenous distribution of reinforcement across the soil mass. However, the random orientation of fibers may not always be optimal for maximizing strength enhancement.

• Targeted Placement: This technique utilizes prefabricated geosynthetics, such as geotextiles or geogrids, that incorporate fibers in a predetermined orientation. This allows for a more controlled distribution and alignment of fibers, potentially leading to improved reinforcement effectiveness for specific geotechnical applications.

In regions with seasonal freezing and thawing cycles, soils experience significant alterations in their mechanical behavior. These cycles can lead to frost heave and thaw settlement, causing damage to roadways, pipelines, and building foundations, resulting in millions of dollars in repair costs annually. These freeze-thaw cycles can lead to frost heave and thaw settlement, causing damage to structures and resulting in substantial economic losses. The degree of compaction significantly impacts the behavior of soils subjected to freeze-thaw cycles. Compaction alters the pore volume between soil particles, influencing the soil's response to freezing and thawing. Under the influence of freeze-thaw cycles, the void ratio of low-density soil samples decreases. This compaction is attributed to the rearrangement of soil particles and the expulsion of water during the freezing process. Conversely, in high-density soil samples, the void ratio increases due to the expansion of water during freezing, leading to a looser soil structure. Repeated freeze-thaw cycles induce structural transformations within the soil matrix. Initially, the soil exhibits a granular structure, characterized by loose arrangements of individual particles. As the number of cycles increases, the structure transitions into a flocculated state, where particles aggregate into larger clusters. Eventually, a cemented granular structure emerges, where particles are bound together by ice and interparticle forces. After a sufficient number of freeze-thaw cycles, typically around 60, the soil structure reaches a new equilibrium state. A cemented granular structure develops as ice lenses form between particles, acting as a binder and increasing interparticle forces. While research suggests an optimal compaction level between 90% and 95% Maximum dry density)MDD(for minimizing freeze-thaw impacts [1], some studies propose a wider range depending on soil type and grain size distribution[1]. At this compaction range, the soil matrix exhibits a balance between particle arrangement and void space, providing enhanced resistance to structural degradation during freezing and thawing.

Freeze-thaw cycles, characterized by the repeated transition of soil between frozen and thawed states, can significantly impact soil behavior, leading to frost heave and thaw settlement. These phenomena pose challenges for infrastructure development in seasonally frozen regions. The magnitude of freeze-thaw-induced deformation is influenced by various factors, including soil type, water content, and temperature conditions. Additionally, loading conditions play a crucial role in modulating soil response to freeze-thaw cycles. The application of loads during freeze-thaw cycles introduces an additional stress component that interacts with the inherent deformation mechanisms associated with freezing and thawing. Under low load conditions, freeze-thaw cycles can cause damage to the soil structure, leading to the formation of new cracks and the development of a loose, porous structure. This phenomenon is attributed

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to the unconstrained expansion and contraction of soil particles during freezing and thawing cycles. In contrast, the application of high loads during freeze-thaw cycles can promote the formation of a dense, compacted porous structure. The imposed stress restricts the movement of soil particles, minimizing the disruption of the soil matrix and potentially enhancing its overall strength and stability. A critical loading condition exists, referred to as the "freezing load" or "thawing load," at which the net change in soil volume upon reaching a frozen or thawed state is zero. This critical load represents the threshold beyond which the application of additional stress during freeze-thaw cycles transitions the soil's response from structural degradation to structural densification. The characteristics of the soil's porous structure under different loading conditions exhibit significant variations. Under low load conditions, the porous structure becomes looser and more susceptible to deformation. Conversely, high load conditions promote the development of a denser, more compact porous structure, enhancing the soil's resistance to freeze-thaw-induced deformation [2].

Freeze-thaw cycles, characterized by the repeated transition of soil between frozen and thawed states, can pose significant challenges in geotechnical engineering, particularly in regions experiencing seasonal freezing and thawing. The introduction of rubber particles into soil can modify its behavior, potentially mitigating the detrimental effects of freeze-thaw cycles. The incorporation of rubber into soil can enhance its mechanical performance under freeze-thaw conditions. Small amounts of rubber can reduce the soil's susceptibility to swelling and shrinkage, thereby improving its strength and reducing its permeability. This effect is attributed to the elastic properties of rubber, which can accommodate the volume changes associated with freezing and thawing without causing significant structural damage. The presence of rubber significantly influences the stress-strain behavior of soil-rubber mixtures under freeze-thaw conditions. Rubber particles can alter the stiffness, ductility, and failure mode of the mixture. In general, increasing rubber content leads to a decrease in stiffness and an increase in ductility, making the mixture more resilient to deformation and less prone to brittle failure. Freeze-thaw cycles can induce different failure patterns in soil-rubber mixtures compared to pure soils. Rubber particles can act as stress concentrators, leading to localized failures within the mixture. However, the elastic properties of rubber can also help to distribute stresses more evenly, potentially reducing the overall severity of failure. The shape retention capacity of soil-rubber mixtures under freeze-thaw cycles is crucial for maintaining the integrity of geotechnical structures. Rubber particles can enhance the shape retention of the mixture by providing additional support to the soil matrix and reducing the tendency for frost heave and thaw settlement.

Exposure to wet-dry cycles can lead to a reduction or complete loss of strength in stabilized soils, primarily attributed to the propagation of microcracks within the soil matrix. Wet-dry cycles can pose a significant challenge to the performance of stabilized soils, potentially leading to strength degradation and even failure [4].

Ouria et al. (2016) emphasized that In mechanically stabilized earth (MSE) walls employing continuous reinforcing elements like geotextiles, geogrids, and similar materials, the soil mass behaves as a non-homogeneous medium, creating a distinct interface between the reinforcing materials and the soil. In these systems, due to the significantly higher strength of the reinforcing elements compared to the soil, ensuring adequate embedment length of the reinforcements to prevent their pullout from the soil mass is a critical design parameter.

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Consoli et al. (2007) examined the influence of stress path on the shear strength of sand under triaxial conditions and concluded that the failure criterion for such soils should be bilinear, accounting for the non-linearity of sand behavior under different stress paths [6].

Noorzad et al. (2015) investigated the behavior of fiber-reinforced sand and found that the influence of fibers on the shear strength of soil is more significant in triaxial tests compared to direct shear tests (7). Overall, research findings indicate that utilizing fibers for stabilizing and enhancing the behavior of loose soils can be expected to yield favorable performance under various environmental conditions, such as freeze-thaw cycles.

Keyser et al. (2011) observed that the influence of cement on the soil matrix commences at 0.6% and extends up to 3.8%, likely due to improved particle bonding. All fiber percentages contributed positively to compressive strength, with the most significant effect observed at 0.75% fiber content, possibly due to fiber bridging and reinforcement [8].

Cristelo et al. (2017) observed that increasing cement content diminishes the influence of polypropylene fibers on soil behavior, likely due to a greater contribution from cementitious bonding. Conversely, increasing fiber content enhances the ultimate stress, possibly by providing additional bridging and reinforcement mechanisms. The effect of fiber content on pre-peak behavior exhibits an increasing influence, while its influence on post-peak behavior shows a decreasing trend with respect to cement content, respectively [9].

Chen et al. (2018) observed that polypropylene fibers enhanced the uniaxial compressive strength and ductility of soil, possibly by bridging soil particles and providing additional reinforcement, with the optimal performance achieved at a fiber content of 0.15% and a length of 6 mm [10].

Ahmadi et al. (2015) demonstrated that zeolite incorporation led to a more homogeneous microstructure and refined pores in soil-cement composites, as observed by scanning electron microscopy (SEM). This improvement is attributed to the reduced calcium hydroxide content due to pozzolanic reactions and the increased production of calcium silicate hydrate gels, ultimately enhancing the durability of the material [11].

Clay soils are a major challenge in road construction due to their inherent instability [12]. Soil stabilization offers a solution by improving the engineering properties of these soils, making them suitable for specific applications. This process typically involves incorporating additives into the soil matrix. The selection of these additives depends on various factors, including soil type, environmental conditions, the desired outcome of stabilization (e.g., strength improvement, reduced moisture sensitivity), and economic considerations.

Soil additives can be broadly categorized as conventional (lime, cement, asphalt) and unconventional (silicates, mineral additives, salts, acids, enzymes, polymers, and resins) [13]. Conventional additives often react chemically with soil minerals, altering the soil structure. Conversely, unconventional additives primarily enhance particle interaction and promote aggregation without necessarily triggering chemical reactions.

The effects of these additives are well-documented in the literature. Studies on lime stabilization typically report reductions in the liquid limit, plasticity index, and maximum dry density, along with a decrease in swell potential. Conversely, lime addition often increases the optimum moisture content for compaction and leads to improved strength characteristics [14].

Bell (1952) investigated the influence of lime on the compaction and strength properties of kaolinite, montmorillonite, and quartz, representing different clay mineralogies [15]. His findings demonstrated that lime reduces the maximum dry density but increases the optimum

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moisture content, California bearing ratio, and elastic modulus for all three clay types. Notably, curing time and temperature significantly affect the degree of strength improvement. In cases where soils lack sufficient silicates and aluminates, limiting lime's effectiveness, a combination of lime with pozzolanic materials such as fly ash or silica fume can be employed.

Several amendments, including lime, cement, and fly ash, are widely employed for stabilizing diverse soil types, encompassing clay soils [16]. Amu et al. (2005) explored the potential of eggshell powder-lime combinations for stabilizing a clay soil. Their investigation assessed the impact on soil properties and identified an optimal eggshell powder-lime ratio [17]. Additionally, fly ash-lime blends have demonstrated effectiveness in stabilizing soils with lower clay content and coarser textures [18].

Cement acts as a primary binding agent in concrete and aggregate stabilization, effectively bonding sand and gravel particles. In fine-grained clay soils, a pozzolanic reaction takes place between the calcium hydroxide liberated during cement hydration and the aluminates and silicates present in the clay matrix. This reaction contributes to a reduction in liquid limit, plasticity index, and swell potential, ultimately leading to enhanced overall strength characteristics However, the use of lime for soil stabilization presents challenges related to worker safety, environmental impact, and transportation costs [19].

Cement presents another effective stabilization option for diverse soil types, including clays. Its inherent pozzolanic nature, when activated by water, transforms it into a cementitious material, effectively binding soil particles together. Amo et al. (2005) investigated the use of a combined cement-fly ash mixture for stabilizing an expansive clay, analyzing its compaction and strength characteristics [20]. Their study compared three different mixtures: untreated soil, soil stabilized with 5% cement only, and soil stabilized with a combination of 3% cement and 9% fly ash. The findings revealed that the combination of 3% cement and 9% fly ash yielded the highest improvement in strength. However, for fine-grained soils with high plasticity indices, cement utilization is not generally recommended due to potential drawbacks. In such cases, lime often offers superior performance [21].

Haji Ali et al. (2005) investigated the potential of rice husk ash (RHA) as a stabilizer for clay soils, comparing its effectiveness with conventional stabilizers like cement and lime [22]. Their findings indicated that lime offered superior performance in stabilizing clay soils compared to RHA, while RHA proved to be more effective than cement.

Santoni et al. (2003) investigated the influence of a wide range of stabilizers on the characteristics of a sandy loam soil [22]. Their study employed a comprehensive suite of stabilizers, encompassing nine conventional options such as lime, cement, and emulsified asphalt, alongside a diverse array of 59 unconventional stabilizers including sulfonated resins, enzymes, polymers, oil emulsions, and tree adhesive compounds.

Enzyme-based liquid additives have also been demonstrated to improve soil properties. A study reported positive effects on plasticity characteristics, compressive strength, and maximum dry density [23].

Polymers represent another promising class of soil stabilizers. Researchers have explored the use of various polymers, including polyvinyl acetate (PVAc), polyvinyl alcohol (PVA), polyvinyl acrylic (PVAc), and polyacrylamide (PAM), to enhance soil behavior [24]. Tingel's investigation employed unconfined compressive strength tests on sandy loam samples stabilized with six different polymers, primarily acrylic and vinyl types, alongside varying cement contents (all at 9%). Interestingly, the results revealed that polymer-stabilized samples

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ISSN:1000-3673
Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

achieved higher strengths compared to their cement-stabilized counterparts. Notably, the specific polymer chemistry did not significantly influence strength, suggesting a potentially common mechanism across these polymer types. Furthermore, curing time emerged as a more critical factor for strength development in stabilized soil compared to the specific polymer selection.

A synthetic derivative material offers a unique soil stabilization approach. It functions by forming a hydrophobic (water-repellent) oily protective layer on the surfaces of clay particles. This mechanism disrupts internal water absorption sites within the clay matrix, effectively mitigating the soil's sensitivity to moisture fluctuations. Consequently, enhanced compaction efficiency is achieved, leading to a combined increase in strength and load-bearing capacity [25]. However, the applicability of this specific stabilizer is restricted to soils with a minimum clay content. Therefore, stabilizing non-cohesive soils using this method requires pre-treatment through the incorporation of a specific amount of clay [26].

Yu et al. (2014) employed numerical modeling to analyze the pullout behavior of short fibers from reinforced soil. Their investigation identified five distinct stages in the fiber pullout process: pure elasticity, elastic-plastic, pure plastic, plastic-residual stress, and pure residual phase. Notably, during the pullout of polypropylene fibers, the two transition phases (phases 2 and 4) exhibit less pronounced behavior compared to the other stages. Additionally, the shear resistance and residual stress at the fiber-soil interface are significantly influenced by the compaction level of the soil[27].

Studies investigating the impact of freeze-thaw cycles on soil stress-strain behavior have consistently reported a significant degradation of mechanical properties [reference source]. This phenomenon can be attributed to the transformation of pore water into ice as the soil temperature descends below freezing (0°C). Ice formation disrupts the soil structure by separating individual particles and weakening the interparticle bonds. These alterations demonstrably affect several key soil characteristics, including porosity, density, water holding capacity, and hydraulic gradient [reference source]. The combined effects of these changes ultimately lead to a reduction in soil cohesion and mechanical strength.

The impact of freeze-thaw cycles on the resilient modulus of subgrade soils is a critical research area in pavement engineering. The behavior of subgrade soils under repeated traffic loading is a fundamental design consideration for roads [29]. Due to the compacted and engineered nature of subgrade soils, cyclic triaxial testing of compacted specimens is a standard practice to determine their resilient modulus [30]. Understanding the degradation mechanism of resilient modulus caused by freeze-thaw cycles is essential for designing pavements that can endure seasonal variations and maintain long-term serviceability.

The specific effect of steel fibers on mitigating the negative impacts of freeze-thaw on stabilized soils is an emerging area of research. The current study investigates this crucial aspect by analyzing the influence of steel fiber content on the shear strength of cement-stabilized soils subjected to freeze-thaw cycles. The findings of this study are expected to contribute to a better understanding of how steel fibers can be used to enhance the durability of stabilized soils in harsh environments with frequent freeze-thaw cycles. This knowledge can be valuable for engineers designing and constructing infrastructure on expansive or frost-susceptible soils.

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The soil samples used in the experiments were prepared according to standard D422 by combining fine-grained clay soils and coarse-grained sandy soils, as shown in Figure 1. All tested soils were stabilized with 8% cement by weight.

TABLE 1. Strouhal number for different geometric cases

USCS	Sand	Clay	Soil Sampel
SC	85	15	1
SC	70	30	2
SC	55	45	3

Fibers

In this research, steel fibers with a diameter of 0.5 millimeters, a length of 3 centimeters, and a specific gravity of 7.85 g/cm3 were employed.

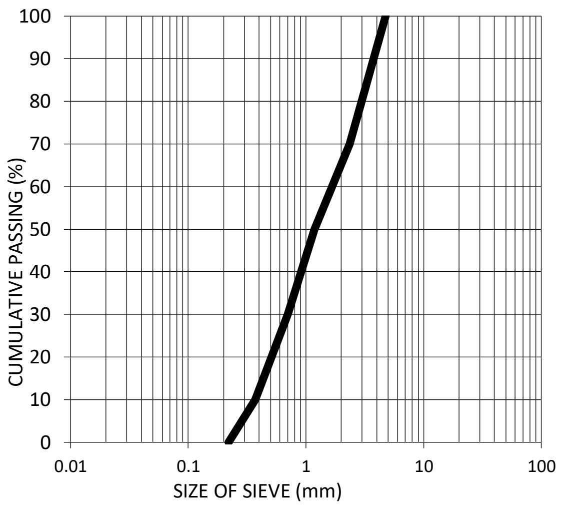

Figure 1. Unified Soil Classification(USC)

Sample Preparation

This study investigated the influence of steel fiber content on fiber-reinforced soil behavior. Soil samples were prepared with varying fiber weight percentages: 0% (control), 1%, 2%, and 3%. The weight percentage signifies the ratio of fiber weight to the dry weight of the soil[31]. The preparation process involved thoroughly drying the soil followed by moistening it to 50% of its optimal moisture content. Next, the predetermined quantity of steel fibers was incorporated into the mix. Finally, additional water was meticulously added to achieve the optimal moisture content for the soil.

Direct Shear Tests

Standard and Equipment

Direct shear tests were conducted in this study following standard D3080 (ASTM, 2013) using a 10-centimeter direct shear device. After preparation and homogenization, the soil-fiber

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ISSN:1000-3673
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mixture was placed in the shear box. All direct shear tests were performed under controlled strain conditions at a loading rate of 0.5 millimeters per minute. Applied normal stresses were 50, 100, and 200 kilopascals. Shear strength parameters, including cohesion (c) and internal friction angle (φ), were determined using the Mohr-Coulomb criterion (Mohr, 1926).

Freeze-Thaw Cycles To investigate the impact of freeze-thaw cycles, identical samples were subjected to 100 cycles of 6-hour freezing and 2-hour thawing at an ambient temperature of 25 degrees Celsius with a tolerance of 2 degrees Celsius. The samples were placed inside the shear box during the freeze-thaw cycles.

Test Results

The parameters obtained from the direct shear tests under normal conditions are presented in Table 2. According to the results, the cohesion of Type 1 soil exhibits a 178% increase with the incorporation of 3% steel fibers. This value is 118% for Type 2 soil and 103% for Type 3 soil. The values mentioned for Type 1 and Type 2 soils decrease to 72% and 58%, respectively, after subjecting the soils to freeze-thaw cycles. However, for Type 3 soil, the cohesion slightly increases to 107%.

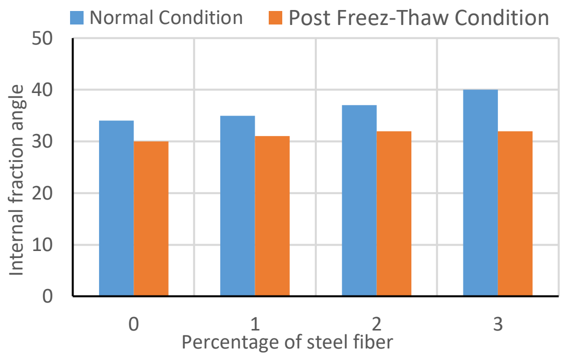

Figure 2. Internal fraction angle of soil with steel fiber content in type 1 soil

TABLE 2. Cohesion and Internal Friction Angle of Fiber-Reinforced Soils

Type of Soils	Percentage of steel fiber	Internal fraction angle	soil cohesion
Soil 1	0	34	2.3
	1	35	3.5
	2	37	4.9
	3	40	6.4
Soil 2	0	29	2.8
	1	31	3.3
	2	33	4.2

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ISSN:1000-3673
Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

	3	36	6.1
Soil 3	0	20	3.7
	1	23	4.9
	2	25	6.4
	3	30	7.5

Influence of Freeze-Thaw Cycles

The parameters obtained from the direct shear tests after subjecting the samples to freeze-thaw cycles are presented in Table 3. According to the results, the incorporation of steel fibers plays a significant role in preserving and enhancing the shear strength of the soils under the influence of freeze-thaw cycles.

TABLE 3. Cohesion and Internal Friction Angle of Fiber-Reinforced Soils After Freeze-Thaw Cycles

Type of Soils	Percentage of steel fiber	Internal fraction angle	soil cohesion
Soil 1	0	30	1.8
	1	31	2.5
	2	32	2.8
	3	32	3.1
Soil 2	0	25	2.6
	1	25	3.1
	2	26	3.3
	3	27	4.1
Soil 3	0	18	2.8
	1	19	3.6
	2	20	4.5
	3	21	5.8

As illustrated in Figure 2, the internal friction angle exhibited an increase of 17.6% with the addition of steel fibers. However, after subjecting the samples to freeze-thaw cycles, the overall internal friction angle decreased. Notably, for soils containing 2% and 3% fibers, the positive influence of fibers on enhancing the internal friction angle was maintained, albeit to a limited extent of 6%. The incorporation of steel fibers generally mitigated the detrimental effects of freeze-thaw cycles on the internal friction angle of the soils. This observation aligns with the findings of previous studies that have demonstrated the effectiveness of fiber reinforcement in preserving soil strength under adverse environmental conditions.

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ISSN:1000-3673
Accepted: 28-08-2024 *Revised: 15-07-2024* *Received: 06-06-2024*

As depicted in Figure 3, the internal friction angle of the soils exhibited a relatively consistent upward trend with the incorporation of steel fibers, reaching a maximum increase of 24% for soils containing 3% fibers. However, upon exposure to freeze-thaw cycles, the enhancement in internal friction angle became less pronounced and, in the most favorable case (3% fibers), was limited to an increase of 8%.

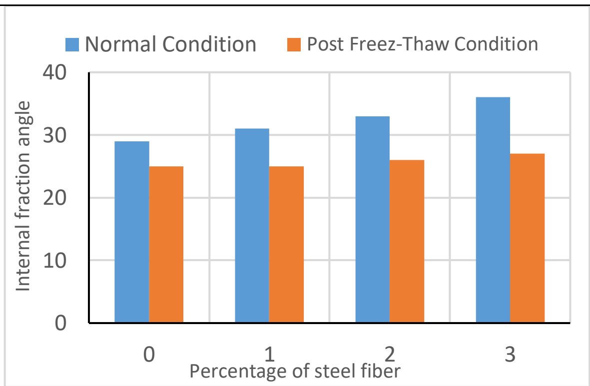

Figure 3. Internal fraction angle of soil with steel fiber content in type 2 soil

As illustrated in Figure 4, the effectiveness of steel fibers in enhancing the internal friction angle is more prominent in Type 3 soil, which is attributed to the higher clay content and lower sand content compared to the other soil types. With the incorporation of 3% fibers, Type 3 soil exhibits a remarkable 50% increase in internal friction angle.

Similar to the other soil types, Type 3 soil also experiences a reduction in internal friction angle upon exposure to freeze-thaw cycles. However, the presence of steel fibers helps mitigate this detrimental effect, as evidenced by the gradual increase in internal friction angle with increasing fiber content. In the most favorable scenario (3% fibers), the internal friction angle of Type 3 soil subjected to freeze-thaw cycles still achieves a notable 16.6% increase.

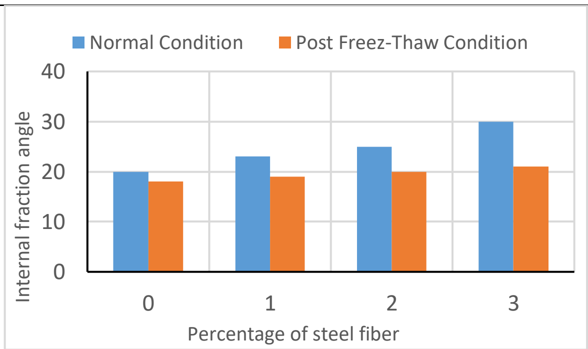

Figure 4. Internal fraction angle of soil with steel fiber content in type 3 soil

This study provides compelling evidence for the efficacy of steel fibers in augmenting the shear strength of soil. The observed improvement can be ascribed to two primary mechanisms:

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Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

1) **Enhanced Interparticle Bonding:** Steel fibers bridge soil particles, fostering a mechanical interaction that strengthens the overall soil matrix. This interlocking effect impedes particle movement under shear stress, leading to increased resistance to failure.
2) **Friction Mobilization:** The introduction of steel fibers introduces a new surface texture within the soil matrix. This increased surface roughness promotes the generation of internal friction between soil particles and the fibers themselves. This frictional resistance further contributes to the soil's overall shear strength.

Furthermore, the study demonstrates the remarkable resilience of steel fiber reinforcement. The inclusion of steel fibers not only improves the shear strength of all three soil types in their natural state but also helps mitigate the detrimental effects of freeze-thaw cycles. Notably, Type 3 soil, characterized by a higher clay content, exhibited the most significant improvement. This suggests a potential synergy between clay mineralogy and steel fiber reinforcement, warranting further investigation.

In conclusion, this study demonstrates the promising potential of steel fiber reinforcement as a viable method for augmenting soil shear strength. The observed improvements, particularly the enhanced resilience against detrimental environmental factors such as freeze-thaw cycles, offer significant advantages for geotechnical applications. Future research efforts should be directed towards elucidating the specific mechanisms governing the interaction between steel fibers and diverse soil types. Additionally, investigating the long-term performance of fiber-reinforced soils under various environmental exposures and conducting a comprehensive cost-benefit analysis of this technique would provide valuable contributions to the field of geotechnical engineering.

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Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

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Power System Technology
ISSN:1000-3673
Accepted: 28-08-2024 Revised: 15-07-2024 Received: 06-06-2024

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