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Assessing the performance of stabilized clay reinforced with waste fibrous materials under extreme environmental conditions

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ABSTRACT: The reutilization of industrial waste materials in soil stabilization not only reduces environmental challenges and conserves natural resources but also helps lower the cost of production materials. This study examines the effect of incorporating waste tire textile fibers (WTTFs) into chemically stabilized expansive soils aiming to enhance their mechanical properties and durability under freeze-thaw cycles (FTCs). To this end, the base soil was initially stabilized using a combination of calcium carbide residue (CCR=25%) and water treatment sludge (WTS replacement=10%). To address the limitations of chemical stabilization, such as low tensile strength, WTTFs were introduced in varying proportions (0%–2%), and their influence on mechanical behavior and durability was investigated through several tests, including unconfined compressive strength (UCS), indirect tensile strength (ITS), and scanning electron microscopy (SEM). The results demonstrated that the optimum WTTF content (1.5%) significantly enhanced soil performance, achieving a notable improvement in tensile strength and also freeze-thaw resistance. The addition of WTTF provided a reinforcing effect, reducing microcrack propagation and contributing to a more resilient soil matrix. These findings highlight the potential of WTTF as a sustainable reinforcement material, enhancing the durability and performance of chemically stabilized soils. By integrating WTTF with CCR and WTS, this approach offers an eco-friendly and cost-effective solution for stabilizing expansive soils, especially in regions with extreme climatic conditions.

KEYWORDS: Sustainable stabilization, Waste tire textile fiber (WTTF); Calcium carbide residue (CCR); Water treatment sludge (WTS); Waste additives; Freeze-thaw cycles (FTCs).

1 INTRODUCTION

The recycling and reuse of industrial waste can mitigate environmental impacts, conserve resources, and reduce material costs in engineering applications. One promising application is the reuse of industrial by-products in geotechnical engineering, particularly for soil stabilization. This is especially critical in cold regions, where soils are frequently subjected to numerous freeze-thaw cycles (FTCs) each year. Expansive clays, which swell and shrink with moisture changes, are especially vulnerable, prompting research into improving their durability under such conditions (Mahmoudi et al., 2025; Salimi et al., 2024). Soil stabilization methods—chemical, mechanical, and physical—offer different advantages (Firoozi et al., 2017). Among these, chemical stabilization using additives like lime, cement, or industrial wastes such as rice husk ash (RHA) and fly ash (FA) is widely adopted. However, traditional stabilizers like cement contribute substantially to CO_2 emissions. Consequently, recent research has shifted toward incorporating recycled and eco-friendly materials for stabilization purposes.

Calcium carbide residue (CCR), a by-product from acetylene production, is rich in calcium hydroxide ($Ca(OH)_2$), which creates an alkaline environment that fosters pozzolanic reactions. These reactions form cementitious gels that densify the soil matrix and enhance strength. Studies have shown CCR effectively improves strength and durability in expansive soils (Govindan et al., 2025; Anjum et al., 2025). For instance, Govindan et al. (2025) found that soil treated with 9% CCR retained 51% of its UCS after three wet–dry cycles, compared to just 23% for 6% lime-treated soil. Similarly, Eskisar (2021) observed strength gains with CCR–fly ash combinations, especially at 10% CCR after 28 days. Water treatment sludge (WTS), a by-product from drinking water purification, contains alum compounds and has also shown promise in soil stabilization. Studies highlight its cost-effectiveness and sustainable application (Salimi et al., 2025; Takao et al., 2024). For example, Suksiripattanapong et al. (2017) reported a UCS of 15 MPa in CCR–WTS geopolymer bricks after 60 days. Takao et al. (2024) validated the safe use of aluminum-based WTS in pavement materials. Other studies found WTS beneficial in improving durability and mechanical behavior of treated soils (Nguyen et al., 2023). While chemical stabilization effectively improves soil strength, it often introduces brittleness and limited tensile capacity—particularly under environmental stresses such as FTCs. To mitigate this drawback, researchers have explored hybrid stabilization approaches that combine chemical additives with mechanical reinforcements like fibers to enhance ductility and long-term performance (Jalali & Noorzad, 2021; Salimi et al., 2024). Both natural and synthetic fibers have shown efficacy in increasing tensile strength, reducing brittleness, and limiting post-peak cracking (Saygili & Dayan, 2019).

One particularly promising option is waste tire textile fibers (WTTFs), a by-product of tire recycling that constitutes approximately 10–15% of end-of-life tires (ELTs). In 2017, the U.S. generated about 250 million scrap tires—roughly 4.2 million tons of waste (Fazli & Rodrigue, 2022). WTTFs, comprising 10–15% of end-of-life tires, have shown beneficial effects in construction materials like asphalt and shotcrete (Khosh et al., 2021; Vidal et al., 2022). In geotechnical engineering, WTTFs improve soil strength and resilience, reduce cracking, and increase strain capacity (Narani et al., 2020). Research has also shown that fiber inclusion reduces FTC-induced degradation by enhancing matrix cohesion (Roustaei et al., 2024; Shalchian et al., 2025).

Despite promising results, the combined use of WTTFs with chemical stabilizers like CCR and WTS in expansive clays under FTCs has not been fully explored. This study addresses that gap by evaluating the effects of WTTF additions (0–2%) on the strength and freeze–thaw durability of expansive clay stabilized with CCR–WTS blends. The stabilized samples were subjected to FTCs to simulate harsh climatic conditions, and their mechanical behavior was assessed through UCS and indirect tensile strength (ITS) tests were conducted, alongside scanning electron microscopy (SEM) to assess microstructural changes. The overarching objective of this study is to evaluate the effect of combined chemical and mechanical stabilization techniques on improving the strength, ductility, and freeze-thaw resistance of expansive clay soils.

2 MATERIALS AND METHODS

2.1 *Tested materials*

The expansive soil used in this study was sodium montmorillonite (Na-montmorillonite) bentonite, sourced from South Khorasan Province, Iran. According to the Unified Soil Classification System (USCS) the soil was classified as CH. Its chemical composition, determined through X-ray fluorescence (XRF) analysis revealed that SiO_2 and Al_2O_3 were the predominant oxides. Also, Hydrometer analysis indicated that more than 90% of the particles were finer than 75 µm. CCR as first addition, used was obtained from Sapra Gas Raga Company in Karaj, Iran. It was oven-dried at 100 °C for 24 hours and then sieved through a No. 40 sieve (425 µm). XRF analysis identified CaO as the major component (approximately 60%), confirming its suitability for pozzolanic reactions. second addition, WTS, was collected from the central water treatment facility in Rasht, Guilan Province. XRF analysis revealed that WTS primarily contained SiO_2 (46.5%) and Al_2O_3 (15%), both of which contribute to its pozzolanic reactivity. Also. WTTF as reinforcement, were sourced from the ELT recycling unit of the Yazd Tire Factory, where heavy-vehicle tires are processed. These fibers primarily consist of polyester and nylon (including nylon 6.6) with minor rubber residues. To ensure uniformity, the fibers were washed thoroughly and cut into lengths of 2 cm. The physical and chemical properties of all materials used in this study are summarized in Table 1

Table 1. Main physicochemical properties of the clay, CCR, WTS, and WTTF.

Property	Materials			
	clay	WTS	CCR	WTTF
G_s (-)	2.56	2.15	2.34	1.2
Liquid limit, LL (%)	280	-	-	-
Plastic limit, PL (%)	60	-	-	-
Passing No. 200 sieve (%)	92	45	28	0
Maximum dry density, (g/cm^3)	1.35	-	-	-
Optimum moisture content (%)	33	-	-	-
Main chemical composition (-)	SiO_2	CaO	SiO_2/ Al_2O_3	-
UCS (kPa)	60	-	-	-
ITS (kPa)	160	-	-	-
Elastic modulus (GPa)	-	-	-	2.65
Elongation at break (%)	-	-	-	17

2.2 *Experimental program*

The clay and waste materials were first passed through a No. 40 sieve (425 µm) to remove coarse particles and then air-dried for 24 hours. For chemical stabilization, CCR was mixed with the base soil at replacement levels of 5–30% (by dry weight). WTS was then added at 5%, 10%, 20%, and 30%, based on the dry mass of the optimum CCR content. UCS tests were used to identify the optimum CCR–WTS–soil ratio, determined as 25% CCR and 10% WTS. Following this, WTTFs were introduced at 0%, 0.5%, 1%, 1.5%, and 2% by dry weight, based on literature recommendations for soil reinforcement (Habibi et al., 2021). Specimens for UCS and ITS testing were prepared using Proctor compaction results to achieve maximum dry density (MDD) and optimum moisture content (OMC). The mixtures were compacted into cylindrical molds (38 mm diameter × 76 mm height) under a constant load until MDD was achieved. Samples were then sealed in plastic bags and cured at 21 °C for 7, 28, and 56 days. UCS tests followed ASTM D2166, using a strain rate of 0.6 mm/min until failure or 20% strain. ITS testing was conducted per ASTM D6931 (2012) using the same loading rate. The peak loads recorded were used to calculate ITS values using the following equation:

$$ITS = \alpha \frac{2P}{\pi DL} \tag{1}$$

where P represents to the maximum applied load, D and L stand for the diameter and length of the specimen, respectively. The shape parameter α is also equal to 0.2621k+1, where k=L/D (Salimi et al., 2024).

To examine the durability of the stabilized specimens under freeze-thaw conditions, selected mixtures with varying WTTF contents were subjected to FTCs—specifically 2, 4, 8, and 12 cycles—in accordance with ASTM D560 (2016). Each FTC consisted of 12 hours of freezing at -14 °C, followed by 12 hours of thawing at 21 °C, completing one full cycle (Roustaei et al., 2024). After the designated number of cycles, the samples were re-evaluated for UCS and ITS to assess strength degradation and structural resilience. A schematic illustration of the specimen preparation and testing procedures is shown in Figure 1. Additionally, to study the fiber–soil interaction, microstructural analysis was conducted using SEM. For SEM imaging, small air-dried fragments were carefully extracted from the UCS-tested specimens.

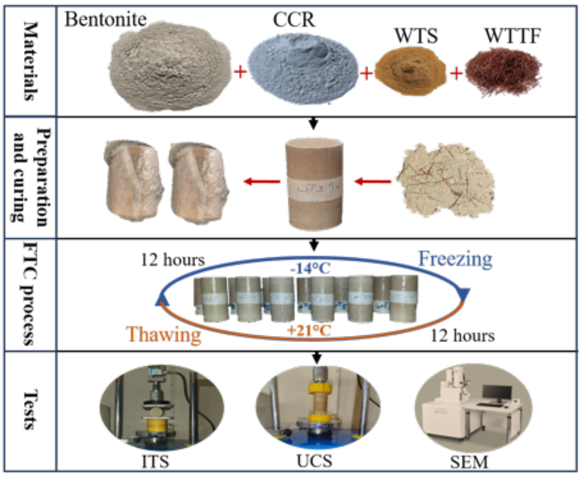

Figure 1. Schematic of the specimen preparation and testing procedures in this study.

3 RESULTS & DISCUSSION

3.1 *Chemical stabilization*

To determine the optimum chemical stabilizer content, UCS tests were conducted on samples with varying CCR and WTS proportions, as shown in Figure 2. Figure 2a presents the effect of CCR contents on UCS. Strength increased significantly with CCR up to 25%, attributed to calcium hydroxide–driven pozzolanic reactions forming cementitious C–S–H gels. For 7-day cured samples, UCS rose to 2200 kPa with 25% CCR—over four times higher than untreated soil (520 kPa). At 56 days, UCS reached 7200 kPa, a 1281% improvement, reflecting enhanced interparticle bonding and matrix densification. However, CCR contents above 25% led to reduced strength, likely due to excessive binder causing unreacted particles and weak zones. This behavior aligns with findings by Zhu et al. (2022). Therefore, 25% CCR is selected as the optimum content.

Figure 2b shows the effects of incorporating WTS at varying levels (5%, 10%, 20%, and 30%) as a partial replacement for the optimum CCR content (25%). The UCS results show that the inclusion of WTS enhances soil strength up to an optimum value at 10% WTS, beyond which the strength begins to decline. This improvement is attributed to the presence of alumina (Al_2O_3) in WTS, which facilitates the formation of calcium aluminosilicate hydrate (CASH) gels, complementing the pozzolanic activity initiated by CCR and further strengthening the soil matrix. However, at WTS contents above 10%, strength reduction is observed, likely due to excessive fine content disrupting the soil matrix or reducing the efficiency of gel formation. Consequently, the combination of 25% CCR and 10% WTS is identified as the optimum blend for chemical stabilization.

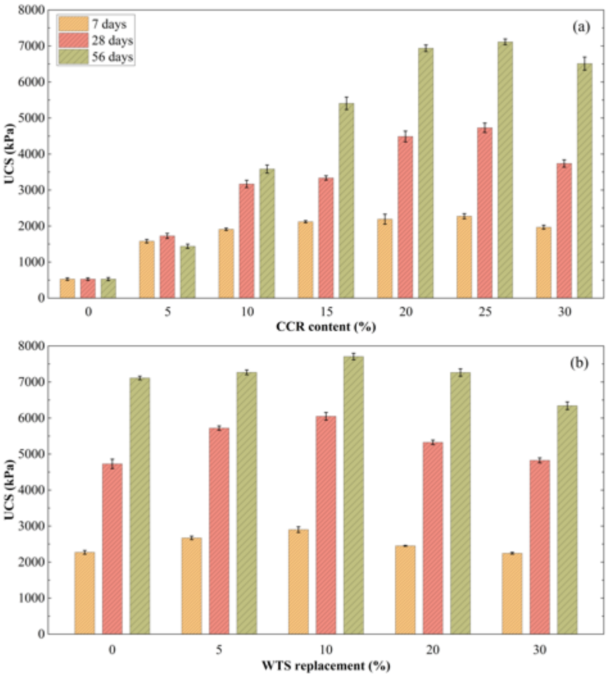

Figure 2. Variations of UCS of the expansive clay treated with (a) different CCR contents, and (b) 25% CCR content along with different WTS replacement percentages at varying curing times.

3.2 *Mechanical stabilization*

3.2.1 *Pre-FTCs*

To evaluate the tensile performance of WTTF-reinforced soils, the optimized chemically stabilized soil mixture (containing 25% CCR and 10% WTS) was combined with varying percentages of WTTF and subjected to ITS testing and the results are presented in Figure 3. In the untreated state, the soil exhibited an ITS of 160 kPa. Chemical stabilization using CCR and WTS led to an increase in tensile strength. After 7 days of curing, the ITS of the stabilized soil nearly doubled, reaching approximately 325 kPa. Continued curing over 56 days further improved tensile strength to a maximum of 730 kPa. However, despite this gain, the chemically stabilized specimens exhibited brittle failure, splitting cleanly in half upon reaching their peak tensile capacity—behavior consistent with previous studies on cementitious stabilization (Lal Mohammadi et al., 2023).

The incorporation of WTTF significantly mitigated this brittleness and enhanced tensile performance. For instance, the addition of 0.5% WTTF increased the 7-day ITS to 510 kPa, representing a 60% improvement over the fiberless stabilized samples. Increasing fiber content and curing time led to further strength enhancements. The highest ITS value of 1370 kPa was achieved in specimens containing 1.5% WTTF cured for 56 days, which corresponds to a 770% increase compared to untreated soil and a 90% improvement over fiberless stabilized soil. This improvement is attributed to the "bridging effect" of the fibers (Roustaei et al., 2023), where fiber strands are distributed throughout the soil matrix, forming interconnected networks that enhance particle interlock and stress distribution. These fiber-soil interactions dissipate tensile stresses more effectively, reduce crack propagation, and promote a more ductile failure mode. However, increasing WTTF content beyond 1.5% led to a decline in ITS values, likely due to issues such as fiber agglomeration, poor dispersion, and disruption of the soil matrix, which collectively reduce bonding efficiency. This trend is consistent with prior research by Tafti & Emadi (2016) and Dhar & Hussain (2019), who similarly reported reductions in strength at fiber contents exceeding 1.5%.

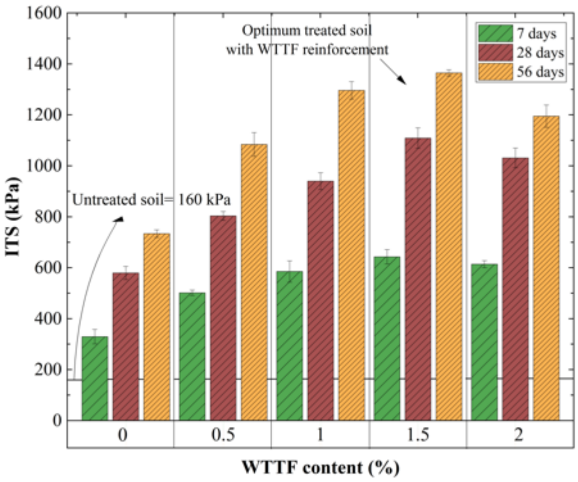

Figure 3. Magnitude of ITS for samples treated with 25% CCR and 10% WTS replacement, incorporating different percentages of WTTF across varying curing times.

Figure 4 presents the results of UCS tests on specimens treated with varying percentages of WTTF within the optimized chemically stabilized mixture, cured for 7, 28, and 56 days. The inclusion of WTTFs not only improves tensile strength but also enhances compressive strength by serving as nucleation sites for the formation of CSH gels. At 7 days of curing, the addition of 1.5% WTTF led to a 21% increase in UCS, rising from 2900 kPa (without fibers) to 3500 kPa. This early-age improvement highlights the role of fibers in mitigating brittleness and promoting more uniform stress distribution throughout the matrix. As curing progressed, the effect became more pronounced. At 56 days, the same 1.5% WTTF-reinforced mixture achieved a peak UCS of 9000 kPa, representing a 17%

improvement over the fiberless control sample. The increase in compressive strength is primarily attributed to the bridging effect of the WTTFs. The fibers form an interwoven network within the matrix that supports load redistribution, limits crack propagation, and increases the material's overall resistance to compressive stress. However, consistent with tensile strength trends, increasing WTTF content beyond 1.5% led to a reduction in UCS. While incorporating up to 1.5% WTTF is relatively straightforward, higher fiber contents introduce challenges related to mixing homogeneity. Excessive fiber content may lead to fiber clumping or knotting, which disrupts the hydration and cementation processes, resulting in localized weak zones and reduced bonding efficiency between soil particles and fibers (Narani et al., 2020). Therefore, 1.5% WTTF is identified as the optimum content for enhancing both tensile and compressive strength in CCR-WTS stabilized soils, providing a balanced improvement in mechanical performance without compromising mixture uniformity.

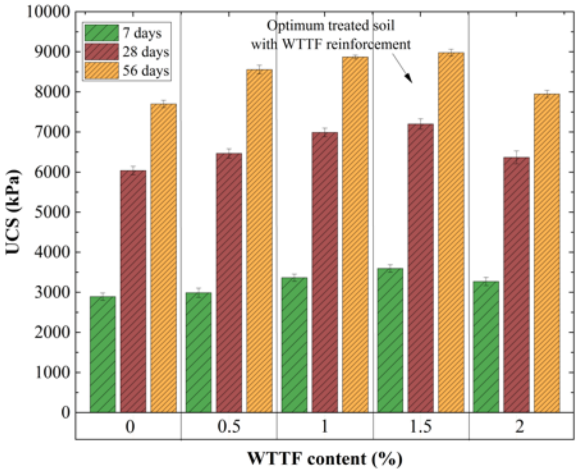

Figure 4. Magnitude of UCS for samples treated with 25% CCR and 10% WTS replacement, incorporating different percentages of WTTF across varying curing times.

3.2.2 *Post-FTCs*

To evaluate the brittleness and durability of fiber-reinforced stabilized soil under harsh environmental conditions, specimens were subjected to varying numbers of FTCs. Figure 5 presents the results of normalized ITS (UCS/UCS$_0$) for soils stabilized with the optimum CCR–WTS combination and reinforced with different percentages of WTTF. Here, ITS$_0$ refers to the tensile strength of the sample before any FTC exposure. Overall, exposure to FTCs resulted in a decrease in ITS across all samples. However, the rate of degradation varied significantly depending on fiber content. In 7-day cured samples, ITS values fluctuated throughout the 12 FTCs due to ongoing pozzolanic reactions. The absence of a consistent degradation trend at this early curing stage is attributed to the continued hydration and gel formation of CCR and WTS during the thawing phases (12 hours at 21 °C). As a result, strength initially declined until the fourth cycle, followed by a partial recovery due to resumed chemical activity during thawing. This highlights the time-dependent nature of pozzolanic stabilization.

Crucially, the incorporation of WTTF substantially improved durability and mitigated strength loss. For instance, after four FTCs, the normalized ITS of unreinforced samples declined to 0.60, while samples containing 1.5% WTTF retained a higher normalized ITS of 0.75, indicating enhanced resistance to FTC-induced deterioration. This improvement is primarily due to the bridging effect of the fibers, which reduce matrix porosity and inhibit the initiation and propagation of microcracks under cyclic thermal stress. In 56-day cured specimens, fiber reinforcement proved even more effective. After 12 FTCs, samples with 1.5% WTTF maintained a normalized ITS of 0.85, representing only a 15% reduction from pre-FTC strength. This demonstrates the critical role of fibers in preserving structural integrity and enhancing ductility under environmental cyclic loading. These findings are consistent with the literature (Shalchian et al., 2025)

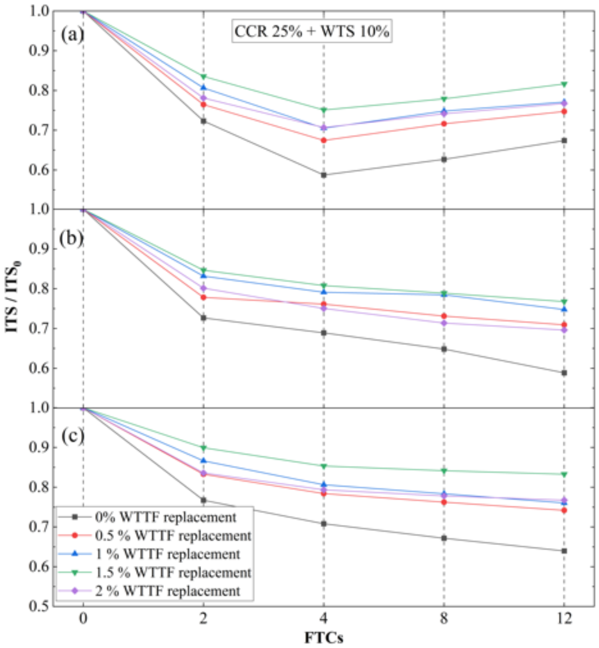

Figure 5. Normalized ITS of the specimens versus FTCs: (a) curing time = 7 days, (b) curing time = 28 days, (c) curing time = 56 days.

Figure 6 illustrates the influence of FTCs on the normalized UCS of stabilized soil specimens incorporating the optimum CCR–WTS combination and varying WTTF contents. In general, an increase in the number of FTCs led to a gradual reduction in UCS for all stabilized samples, with the exception of 7-day cured specimens, which exhibited fluctuating behavior over 12 FTCs—consistent with observations from the ITS results. These fluctuations are attributed to the continued pozzolanic activity during the thawing phases, where incomplete early-age hydration resumes at room temperature (21 °C), temporarily enhancing strength. Importantly, WTTF reinforcement markedly improved UCS retention under FTCs. Regardless of curing duration or FTC exposure, higher fiber contents were consistently associated with greater durability and elevated normalized UCS. For example, in 7-day cured specimens, the normalized UCS dropped to 0.70 after 12 FTCs without fibers. However, with the addition of just 0.5% WTTF, this value increased to approximately 0.83, highlighting the beneficial role of fiber inclusion even at early stages of curing. The highest durability was observed in samples reinforced with 1.5% WTTF, where, after 56 days of curing and 12 FTCs, the normalized UCS remained above 0.85. This demonstrates the robust strengthening effect of WTTF, which enhances interparticle bonding, reduces porosity, and mitigates the propagation of microcracks—key mechanisms in resisting FTC-induced degradation. These findings are in line with previous research (Saygili & Dayan, 2019), and further substantiate the conclusion that WTTF reinforcement improves the compressive and tensile strength retention and long-term durability of chemically stabilized soils exposed to severe environmental conditions.

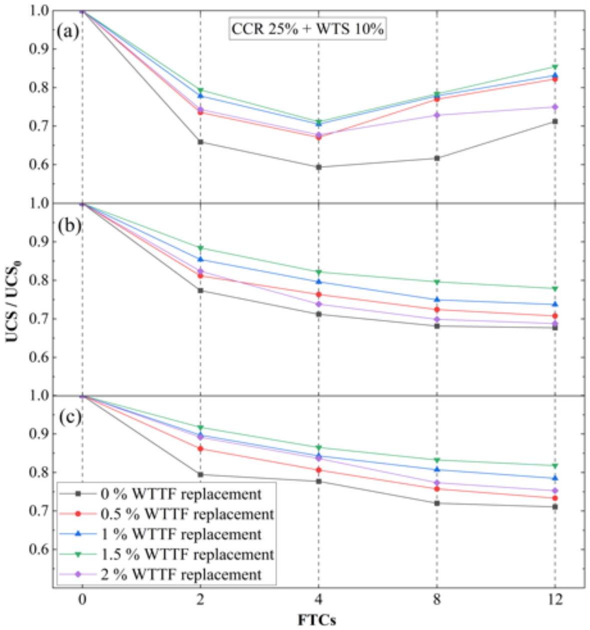

Figure 6. Normalized UCS of the specimens versus FTCs: (a) curing time = 7 days, (b) curing time = 28 days, (c) curing time = 56 days.

3.3 *Correlation between UPV and UCS*

The result of UCS and ITS tests across varying WTTF contents reveal a clear and consistent linear relationship between these two mechanical properties. Specifically, increases or decreases in UCS are proportionally reflected in ITS values. This observed correlation is particularly valuable for geotechnical engineers, as it enables the prediction of tensile strength based on compressive strength data (and vice versa).

Figure 7 illustrates the UCS–ITS relationship for WTTF-reinforced specimens at different curing durations, based on linear regression analysis. To ensure the reliability of the correlation and minimize the influence of external variables, only specimens not subjected to FTCs were considered. Linear regression analysis confirms a strong correlation, with an R^2 of 0.9, indicating high predictive reliability. The derived regression equation for the stabilized specimens, with both UCS and ITS expressed in kilopascals (kPa), is as follows:

$$ITS = 0.1255 \times UCS + 131.3 \qquad (2)$$

This equation serves as a practical empirical model for estimating one mechanical parameter from the other in similarly treated expansive soils, aiding efficient design and evaluation in stabilization projects.

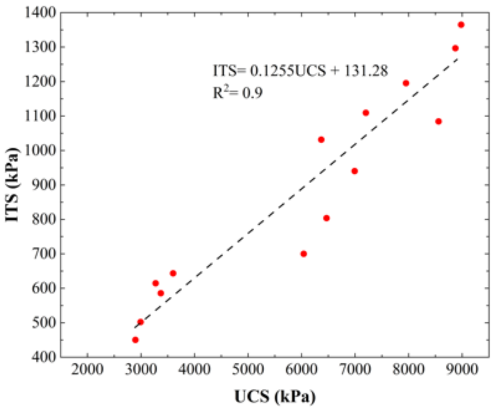

Figure 7. Relationships between UCS and ITS for stabilized samples reinforced with WTTFs.

3.4 *SEM analysis*

SEM analyses were conducted to evaluate the microstructural interactions between WTTF and the stabilized soil matrix. Figure 8 presents SEM images of specimens treated with 25% CCR, 10% WTS, and 1.5% WTTF after 56 days of curing. As shown in Figure 8a, the WTTF fibers are randomly distributed throughout the soil matrix, forming an interwoven network that enhances matrix cohesion. This network contributes to increased tensile strength and improved resistance to FTC-induced cracking by providing a bridging mechanism that distributes and absorbs applied stresses (Roustaei et al., 2023). Figure 8b illustrates the densification of the soil structure as a result of pozzolanic reactions, where cementitious gels—primarily C–S–H and C–A–S–H—fill voids and bond clay particles, thereby significantly reducing porosity. This observation is consistent with findings from previous studies (Salimi et al., 2025). Notably, Figure 8c shows the adherence of these cementitious gels to the surface of WTTF fibers, indicating strong interfacial bonding between the fibers and the surrounding matrix. This adhesion improves the frictional resistance and mechanical interlock at the fiber–matrix interface, enhancing the sample's overall structural integrity (Salimi et al., 2024). These findings confirm the beneficial role of WTTF in reinforcing chemically stabilized expansive soils.

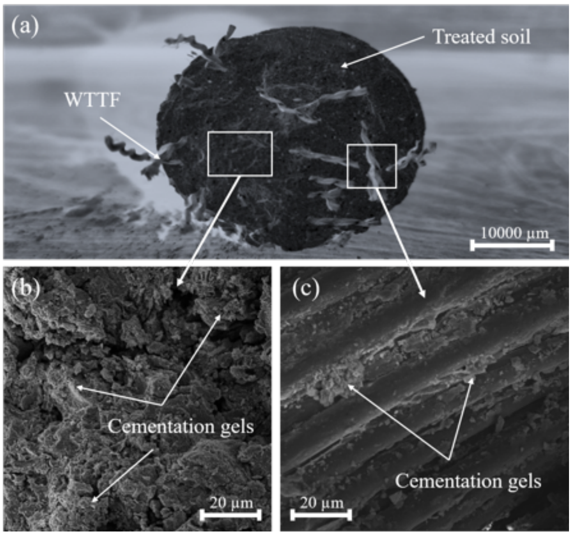

Figure 8. SEM Images of (a) treated soil with 25% CCR + 10% WTS + 1.5% WTTF, micrographs of (b) treated soil with 25% CCR and 10% WTS replacement and (c) WTTF in the treated soil.

4 CONCLUSIONS

The primary objective of this research was to assess the feasibility of recycling industrial and municipal wastes—calcium carbide residue (CCR), water treatment sludge (WTS), and waste tire textile fibers (WTTFs)—for the stabilization of expansive clay. This study aimed to evaluate both chemical and mechanical improvements imparted by these additives, with emphasis on durability under freeze–thaw conditions. UCS, ITS, and SEM analyses were employed. Key findings include:

- The combination of 25% CCR and 10% WTS replacement yielded the highest stabilization performance, increasing UCS to approximately 7200 kPa after 56 days of curing—representing an improvement of over 1280% compared to untreated soil.
- Incorporating WTTF significantly enhanced both tensile and compressive strengths. The optimum fiber content was determined to be 1.5%, which resulted in a 90% increase

in ITS and a 17% increase in UCS compared to fiberless stabilized specimens.
- WTTF incorporation significantly enhanced FTCs resistance. At 56 days of curing, specimens reinforced with 1.5% WTTF retained over 85% of their original strength after 12 FTCs, while unreinforced samples exhibited strength losses of up to 40%. In contrast, the 7-day cured specimens showed no consistent trend due to ongoing pozzolanic reactions during the cycles.
- A strong linear correlation ($R^2 = 0.90$) was observed between UCS and ITS in WTTF-reinforced soils, allowing for reliable prediction of one parameter based on the other, which is valuable for design and quality control in field applications.
- SEM analyses confirmed the development of dense and cohesive soil matrices with well-dispersed WTTF strands. Cementitious gels—C–S–H and C–A–S–H—were observed to form strong bonds with fiber surfaces, reducing porosity and enhancing the mechanical interlocking and durability of the composite material.

The simultaneous use of use of CCR, WTS, and WTTF presents a viable, eco-friendly solution for stabilizing expansive clay soils, particularly in regions subjected to cyclic freeze–thaw conditions. This integrated approach not only improves geotechnical performance but also supports waste management through the beneficial reuse of industrial by-products.

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