Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-612

Macro and micro-structural analyses of expansive soils stabilized with calcium carbide residue and water treatment sludge under freeze-thaw cycles

Mohammad Dokaneh, Mahdi Salimi, Iman Hosseinpour
Department of Civil Engineering, Faculty of Engineering, University of Guilan, Rasht, Iran.

Reza Rezvani
Department of Civil Engineering, Faculty of Technology and Engineering, East of Guilan, University of Guilan, Rudsar, Iran.

Mohammad Amin Sayyah, Meghdad Payan, Mahya Roustaei, Bruno Stuyts
UGent Geotechnical Institute (UGGI), Department of Civil Engineering, Ghent University, Technologiepark 68, 9052 Zwijnaarde, Belgium, Meghdad.payan@ugent.be

ABSTRACT: Expansive soils pose significant challenges in civil engineering projects due to their high sensitivity to moisture and large volume changes under environmental fluctuations. Stabilizing these soils using industrial waste materials offers an economical and environmentally sustainable solution for geotechnical applications. This study examines the combined utilization of calcium carbide residue (CCR) and water treatment sludge (WTS) in varying proportions (i.e., up to 30%) to improve the mechanical properties and durability of swelling soils subjected to freeze-thaw cycles (FTCs). An experimental program was defined, including unconfined compressive strength (UCS), ultrasonic pulse velocity (UPV), X-ray diffraction (XRD), and scanning electron microscopy (SEM) tests, to evaluate mechanical performance and elucidate material interactions and structural improvements. The combination of 25% CCR and 10% WTS was found to significantly improve soil properties, achieving a UCS of more than 7500 kPa, outperforming soils stabilized with CCR alone. Microstructural analysis also revealed the formation of C-S-H and C-A-S-H gels through pozzolanic reactions, which densified the soil matrix and filled pore spaces. The reduction in porosity of the stabilized soils contributed to their remarkable durability and retained strength after multiple FTCs. Specifically, at the optimum CCR-WTS composition, after 12 FTCs, the UCS and UPV values reached 4500 kPa and 850 m/s, respectively. These findings highlight the effectiveness of combining CCR and WTS for stabilizing expansive soils, particularly in regions prone to extreme climatic conditions.

KEYWORDS: Expansive clays, Calcium carbide residue (CCR), Water treatment sludge (WTS), Waste additives, Freeze-thaw cycles.

1 INTRODUCTION

Expansive clay, as a type of problematic soil, presents substantial challenges in civil engineering applications due to its pronounced sensitivity to moisture and significant volumetric changes in response to environmental variations. These soils are especially susceptible to temperature fluctuations, which cause notable volume changes and result in a marked reduction in durability—particularly under freeze and thaw cycles (FTCs) in cold climates (Li et al., 2021; Roustaei et al., 2024).

One effective solution is the stabilization of expansive clay using suitable treatments. Among these, chemical stabilization is widely used to enhance soil strength and durability by altering its physical and chemical characteristics (Goodarzi & Salimi, 2015). Although traditional binders like cement and lime are common, they involve high energy demands and substantial CO_2 emissions. These environmental concerns, along with rising costs and resource constraints, have driven interest in more sustainable alternatives—especially industrial by-products and waste materials as eco-friendly stabilizers (Ghazavi & Roustaie, 2010; Salimi et al., 2025; Mahmoudi et al., 2025).

Calcium carbide residue (CCR), a by-product of acetylene production rich in calcium hydroxide, has shown promise as a recyclable stabilizer for clay-rich soils (Consoli et al., 2019). Due to its high reactivity and strong alkalinity, CCR enhances both short- and long-term soil performance. Studies confirm that CCR improves the geotechnical properties of expansive soils by increasing strength, reducing swell potential, and minimizing particle dispersion (Latifi et al., 2018; Tang et al., 2024). For instance, Latifi et al. (2018) found that adding 9% CCR increased the strength of stabilized bentonite by 500% and improved compressibility in bentonite and kaolinite. Similarly, Liu et al. (2019) showed that combining CCR with rice husk ash reduced swelling behavior, while Saleh et al. (2025) emphasized CCR's cost-effectiveness and sustainability.

Water treatment sludge (WTS), a by-product of potable water treatment, has also gained attention as a stabilizing agent. Produced through chemical coagulation with aluminum or iron salts, often with organic polymers, WTS primarily consists of non-toxic inorganic compounds like hydroxides, silica, quartz, and kaolinite. Although used in cement, ceramics, bricks, and roads (Kaish et al., 2018; Lee et al., 2021), much of the generated sludge remains underutilized. In geotechnical engineering, WTS has been mainly used as filler, but recent studies suggest it can improve soil properties when paired with reactive agents in alkaline conditions via pozzolanic reactions (Li et al., 2025; Salimi et al., 2025; Suksiripattanapong et al., 2017). For example, Li et al. (2025) reused aluminum-rich sludge with coal ash to produce permeable bricks meeting strength and permeability standards. Salimi et al. (2025) also demonstrated improved mechanical properties in geopolymer-stabilized construction and demolition (C&D) waste using 10% WTS and 15% silica fume, achieving a 56-day UCS of 2,250 kPa—suitable for pavement subbases.

These findings underscore the growing potential of WTS as an effective and sustainable admixture in civil infrastructure applications. However, limited research has been conducted on the durability performance of expansive clay soils stabilized with WTS and CCR, particularly under FTCs conditions. Furthermore, the effects of combining these two materials for improving the long-term stability and durability of expansive soils remain largely unexplored. This study addresses that gap by evaluating bentonite clay stabilized with CCR and WTS, individually and in combination, at various ratios. The durability and mechanical performance under FTCs were assessed using UCS, ultrasonic pulse velocity (UPV), and microstructural analysis.

2 MATERIALS AND METHODS

2.1 *Tested materials*

The bentonite clay used in this study was sourced from South Khorasan Province, Iran. This clay is characterized by high plasticity and significant swelling potential, primarily due to its dominant Na-montmorillonite content. Based on the Unified Soil Classification System (USCS), it is classified as CH (high plasticity clay). X-ray fluorescence (XRF) analysis identified silica (SiO_2) and alumina (Al_2O_3) as the predominant chemical constituents.

CCR, employed as the first industrial by-product in this study, was obtained from an acetylene gas production plant in Karaj, Iran. This fine, grayish material is composed of approximately 60% calcium oxide (CaO), with a high pH (~12.7), indicating strong alkalinity and considerable chemical reactivity. The second additive, WTS, was sourced from the Gilan water treatment facility in Rasht, Iran. This non-plastic by-product originates from the coagulation stage of the water purification process, primarily involving alum-based treatment. Chemical analysis revealed that WTS mainly comprises silicon dioxide (SiO_2, 46.52%) and aluminum oxide (Al_2O_3, 15.08%). The particle size distribution and main physicochemical properties of the raw materials are presented in Figure 1. and Table 1, respectively.

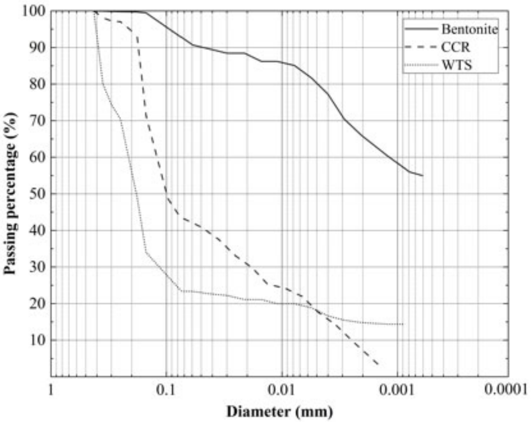

Figure 1. Grain size distribution curves of clay, CCR and WTS

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

Property	Materials		
	Clay	WTS	CCR
Specific gravity, G_s (-)	2.56	2.15	2.34
Liquid limit, LL (%)	280	-	-
Plastic limit, PL (%)	60	-	-
Color	White	Gray	Brown
Maximum dry density, MDD (g/cm3)	1.35	-	-
Optimum moisture content, OMC (%)	33	-	-
Main chemical composition (-)	SiO2	CaO	SiO2/ Al2O3
Unconfined compressive strength, UCS (kPa)	60	-	-
Ultrasonic pulse velocity, UPV (m/s)	1301	-	-
pH	9.81	12.8	8.15

2.2 *Experimental program*

For sample preparation, both the base clay and the additives were air-dried for 24 hours and then passed through a No. 200 sieve to remove coarse particles. Following CCR, used as the primary additive, was incorporated into the dry mass of the base soil at replacement levels of 5%, 10%, 15%, 20%, 25%, and 30%. For each mixture, the soil-additive blend was prepared using hand mixing to ensure homogeneity and was weighed according to the maximum dry density (MDD) obtained from the standard Proctor compaction test (ASTM D698, 2014). The optimum moisture content (OMC) determined from the compaction test was then added to the mixture. The prepared mixture was statically compacted into cylindrical metal molds (38 mm diameter × 76 mm height) using a hydraulic jack until the target dry density was achieved. The compacted samples were removed from the molds, sealed in plastic sheets, and cured at ambient room temperature (25°C) for periods of 7, 28, and 56 days.

Prior to UCS testing, all samples underwent non-destructive UPV testing in accordance with ASTM C597 (2023). The UPV test was conducted to measure the P-wave velocity using a direct transmission setup with 30 mm diameter ultrasonic transducers. The wave velocity was calculated using following Equation:

$$UPV = \frac{L}{\Delta t} \tag{1}$$

where, L is the length of the sample (mm) and Δt stands for the wave travel time (μs), determined from the ultrasonic readings at the point the waves reached the receiving transducer. Subsequently, UCS tests were conducted following ASTM D2166 (2016). Each specimen was axially loaded using an automatic loading frame at a constant strain rate of 0.6 mm/min until failure or a strain limit of 20% was reached.

Based on the UCS and UPV results, the optimum CCR content was identified. In the next phase, WTS was incorporated at replacement ratio of 5%, 10%, 20%, and 30% as a partial substitute for the optimum CCR dosage. The MDD and OMC values for each CCR–WTS–bentonite mixture were determined using the same compaction methodology described earlier. The prepared samples were then cured cured for 7, 28, and 56 days and then subjected to macro (UCS and UPV) and micro tests. Accordingly, microstructural analyses were conducted using XRD and SEM to further evaluate the interactions between the additives and clay particles. For SEM analysis, small air-dried fragments were extracted from UCS test specimens, while finely crushed portions of the same samples were used for XRD examination. A schematic overview of the sample preparation process and the experimental program is shown in Figure 2.

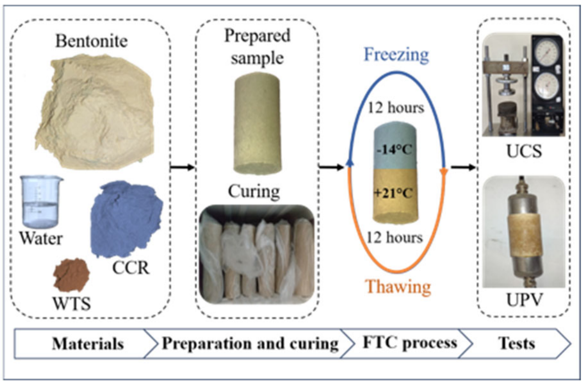

Figure 2. Schematic illustration of materials, sample preparation process, and various tests performed in this study

To evaluate the durability of the treated specimens under harsh environmental conditions, selected soil–additive mixtures containing various WTS proportions were subjected to FTCs (2, 4, 8, and 12 cycles) in accordance with ASTM D560 (2016). Each FTC began by placing the samples in a controlled freezing chamber maintained at -14°C for 12 hours. Following the freezing phase, the specimens were moved to a room with an ambient temperature of 21°C for another 12 hours, completing one full cycle (Roustaei et al., 2024). After completing the designated number of FTCs, the samples were again tested for UCS and UPV to evaluate changes in mechanical properties and structural integrity.

3 RESULTS AND DISCUSSION

3.1 *Before FTCs*

The mechanical behavior of expansive clay stabilized with CCR and WTS was assessed using UCS and UPV tests. Figure 3 represents UCS value for soils with varying additive contents over periods of 7, 28, and 56 days. Increasing CCR content up to 25% significantly improves UCS at all ages, after which strength declines. At 7 days, 5% CCR yields 1583 kPa—about 198% higher than untreated soil—due to early alkalinity and rapid cation exchange (Ca^{2+}/Al^{3+} replacing Na^+), which compresses the diffuse double layer (Goodarzi & Salimi, 2015). At 28 and 56 days, pozzolanic reactions form cementitious compounds like calcium silicate hydrate (C–S–H), improving particle bonding and reducing porosity. Peak UCS reaches ~7000 kPa at 25% CCR after 56 days. Beyond this, strength drops due to reduced reactive silica and alumina, limiting pozzolanic reactions—consistent with prior findings (Saldanha et al., 2019; Consoli et al., 2020).

Figure 3 also presents the UCS values for samples incorporating various WTS contents as partial replacements at the optimum CCR level of 25%. At 56 days, 10% WTS results in ~8000 kPa—15% more than CCR-only samples. This gain is linked to alumina-rich WTS promoting additional pozzolanic activity and forming calcium–aluminum–silicate–hydrate (C–A–S–H) gels. Higher WTS contents, however, reduce UCS due to CCR dilution and reduced $Ca(OH)_2$ availability, limiting reaction efficiency.

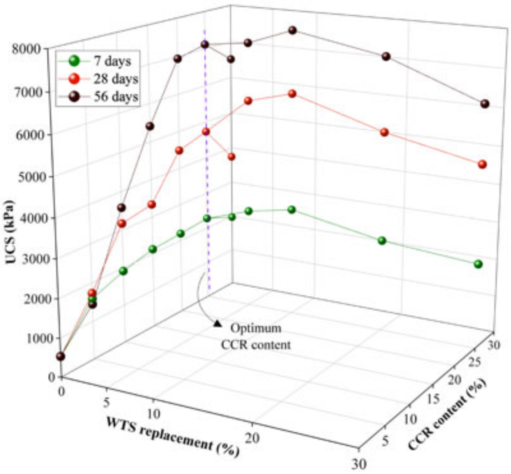

Figure 3. Variations of UCS of the expansive clay treated with different CCR contents as well as 25% CCR along with different WTS replacement dosages at varying curing times

To further assess the stabilization mechanism, Figure 4 shows UPV trends over periods of 7, 28, and 56 days. Stabilized samples exhibit higher UPV than untreated clay, indicating denser and more cohesive matrices. Figure 4 illustrates that UPV rises with CCR content up to 25%, driven by ongoing pozzolanic activity. At 7 days, 25% CCR gives ~1700 m/s, about 110% more than untreated soil. This value climbs to ~2100 m/s at 56 days, reflecting C–S–H gel development that fills voids and increases stiffness. Compression waves travel faster through denser materials; thus, porosity reduction explains the velocity gain (Payan et al., 2017, 2020). Beyond 25% CCR, UPV drops due to limited reactive components and unconsumed CCR increasing porosity—mirroring UCS trends and supporting 25% as optimum.

Figure 4 also presents the UPV values for mixtures with different WTS additions at 25% CCR. The highest UPV occurs with 10% WTS, especially after 56 days, due to enhanced gel formation and void filling by C–A–S–H. Over time, gel development creates a denser structure, raising wave velocity. Beyond 10% WTS, UPV decreases due to CCR dilution, reduced $Ca(OH)_2$ availability, and less gel formation, which increases porosity and lowers material integrity.

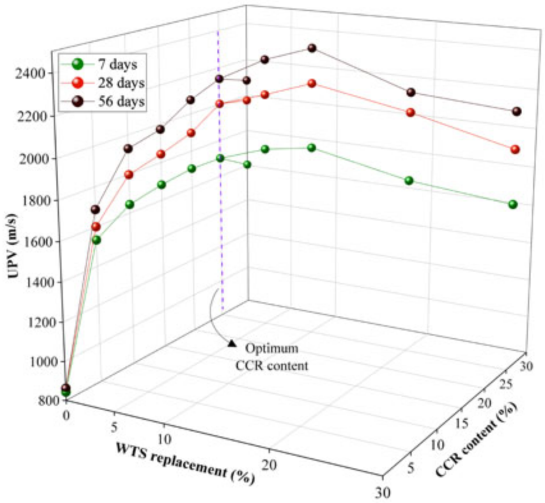

Figure 4. Variations of UPV of the expansive clay treated with different CCR contents as well as 25% CCR along with different WTS replacement dosages at varying curing times.

3.2 *After FTCs*

To evaluate the durability of stabilized samples under freeze–thaw conditions, the reduction in UCS and UPV values was examined across different curing durations and WTS contents. Figure 5 presents the normalized UCS values (UCS/UCS_0) for samples with varying WTS replacement levels, cured for 7, 28, and 56 days, and subjected to up to 12 FTCs. Here, UCS_0 refers to the strength of the sample before any FTC exposure. As expected, the UCS values declined with increasing FTCs due to the formation of ice lenses within the soil matrix. These ice lenses cause expansion and increase the spacing between clay particles, disrupting interparticle bonding and leading to structural weakening. Similar trends have been reported in previous studies (Roustaei et al., 2023; Salimi et al., 2024). However, the inclusion of WTS mitigated the negative effects of FTCs, resulting in smaller strength reductions compared to samples stabilized with CCR alone (i.e., CCR25%). In the 7-day-cured samples, UCS values fluctuated irregularly during the 12 FTCs. An initial decrease was observed after the 2 FTCs, but partial recovery occurred by the eighth cycle, likely due to ongoing pozzolanic reactions during thawing phases. For example, the UCS of the sample containing 5% WTS decreased to 0.67 of its original value after four FTCs, but subsequently improved, reaching 0.9 by the 12 FTCs.

In contrast, the 28- and 56-day-cured specimens showed a consistent decline in UCS with increasing FTCs, as most pozzolanic activity had concluded prior to FTC exposure. For example, after 12 FTCs, the normalized UCS of the 10% WTS sample dropped to 0.70 (28-day cure) and 0.62 (56-day cure), whereas the 7-day counterpart retained 0.9 of its initial strength. Notably, WTS incorporation improved long-term freeze–thaw durability. For 56-day-cured samples, the UCS reduction after 12 FTCs was 48% without WTS and only 38% with 10% WTS, demonstrating the beneficial role of WTS in enhancing resistance to freeze–thaw damage. This improved durability is attributed to the formation of more gels through pozzolanic reactions, which fill voids, densify the matrix, and increase particle bonding—thereby reinforcing structural integrity over time.

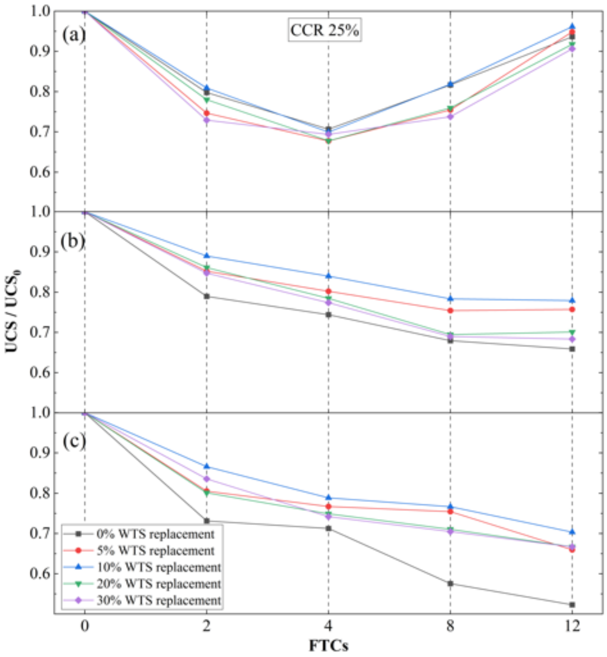

Figure 5. Normalized UCS of the specimens versus FTCs: (a) curing time = 7 days, (b) curing time = 28 days, (c) curing time = 56 days.

Figure 6 illustrates the normalized UPV values for specimens containing varying percentages of WTS, cured for 7, 28, and 56 days and subjected to different numbers of FTCs. Similar to UCS, the UPV values decreased with increasing FTCs. This decline is primarily attributed to the formation of ice lenses within the soil matrix during freezing, which expands pore volume, increases porosity, and disrupts internal bonding, thereby lowering wave propagation speed. However, the inclusion of WTS mitigated this reduction, with samples containing WTS exhibiting smaller decreases in UPV than those without. In the 7-day-cured samples, UPV values initially declined up to the fourth FTC, owing to crack formation and increased porosity. Interestingly, a partial recovery in UPV occurred in subsequent cycles, likely due to ongoing pozzolanic reactions during thawing phases, which promoted secondary gel formation and microcrack healing. Conversely, 28- and 56-day-cured samples exhibited a gradual and continuous decline in UPV throughout the 12 FTCs, indicating that pozzolanic activity had largely ceased, and the matrix was unable to self-repair. After 12 FTCs, the normalized UPV of the 56-day-cured sample containing 10% WTS remained at 0.86, compared to approximately 0.80 for the sample without WTS. This suggests that 10% WTS is an optimum replacement level for enhancing long-term resistance to freeze–thaw degradation, by reducing porosity and strengthening internal bonds. Beyond this optimum, further WTS addition led to decreased UPV, indicating diminishing returns at higher replacement levels.

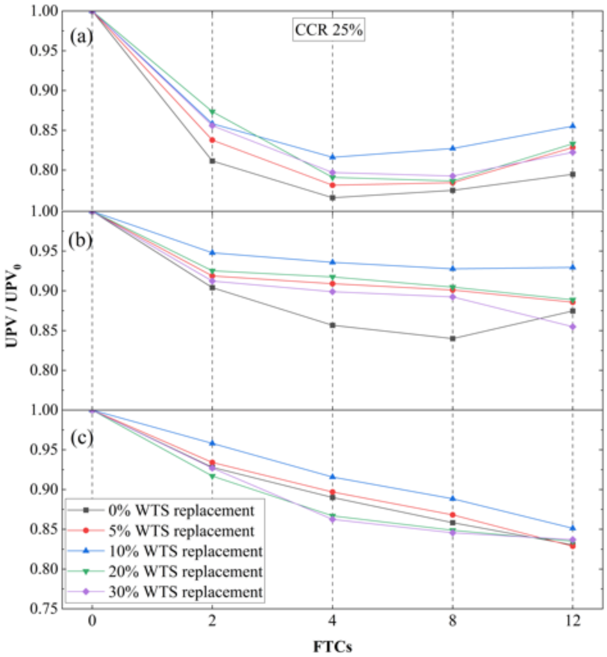

Figure 6. Normalized UPV of the specimens versus FTCs: (a) curing time = 7 days, (b) curing time = 28 days, (c) curing time = 56 days.

3.3 *Empirical correlations*

Analyzing the results of UCS and UPV tests, a strong linear correlation was observed between these two parameters for CCR-WTS-stabilized samples, as shown in Figure 7. To ensure the reliability of this correlation and exclude variability due to environmental degradation, only specimens not exposed to FTCs were included. The regression analysis revealed a coefficient of determination (R^2) of 0.96, indicating a highly reliable linear relationship between UCS and UPV. Accordingly, the fitted equation describing this relationship (with UCS in kPa and UPV in m/s) is:

$$UPV = 0.1055 \times UCS + 1477 \tag{2}$$

This empirical model provides a practical and efficient tool for predicting UPV from UCS (and vice versa) measurements in similar chemically stabilized expansive soils, thus enhancing geotechnical evaluation and quality control procedures in the field.

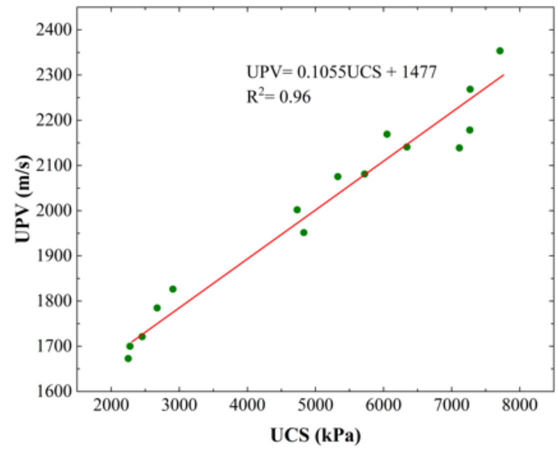

Figure 7. Estimation of UPV for CCR-WTS-stabilized samples based on measured UCS.

3.4 *Microstructure analysis*

3.4.1 *XRD analysis*

Figure 8 shows the XRD patterns of untreated soil and soil stabilized with the optimum mixtures—25% CCR alone and 25% CCR + 10% WTS replacement—after 56 days of curing. The untreated soil pattern displays dominant peaks of montmorillonite, sepiolite, and quartz, with no evidence of cementitious gel formation, confirming its natural mineralogy. In contrast, CCR-stabilized samples show notable mineralogical changes due to pozzolanic activity. Quartz and sepiolite peaks are reduced, indicating the consumption of silica-rich phases in reactions with calcium hydroxide from CCR. A broad hump between 25°–35° 2θ signals the formation of amorphous C–S–H gels. The absence of a distinct $Ca(OH)_2$ peak suggests most available Ca^{2+} ions reacted with siliceous minerals to form gels—consistent with Li et al. (2021), who observed similar transformations in CCR-treated coal tailings. Adding 10% WTS, which is rich in Al_2O_3, further modifies the pattern. The CCR+WTS mixture shows a broader bulge between 22°–30° 2θ, reflecting additional C–A–S–H gel formation. This aligns with Zhu et al. (2024), who also detected C–S–H and C–A–S–H gel signatures in XRD profiles.

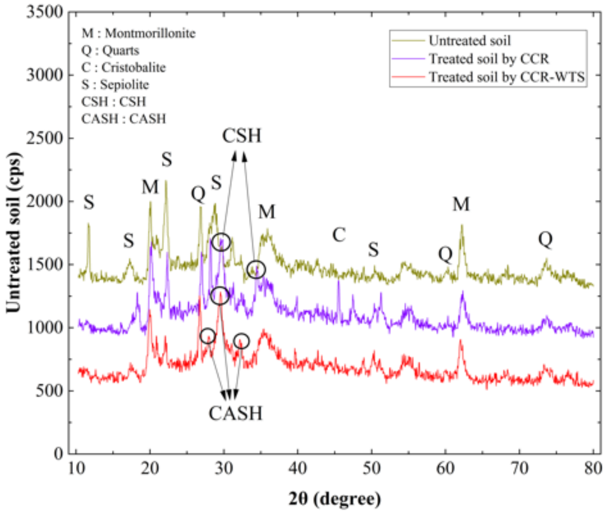

Figure 8. XRD patterns of untreated soil, the soil treated with 25% CCR, and the soil treated with 25% CCR and 10% WTS replacement.

3.4.2 *SEM analysis*

Figure 9 presents SEM images of untreated soil and soil stabilized with the optimum additive combinations (25% CCR + 10% WTS) after 56 days of curing. The untreated soil (Figure 9a) exhibits a highly porous microstructure, characterized by loosely bound particles, wide voids, and weak interparticle bonding. This morphology reflects the low mechanical strength and poor durability of the natural soil, making it highly susceptible to deformation and environmental degradation. In contrast, the CCR-WTS-stabilized sample (Figure 9b) demonstrates a significantly denser and more compact microstructure. The introduction of calcium and aluminum ions from CCR and WTS and pozzolanic reactions with the soil's siliceous components result in the formation of C–S–H and C–A-S–H gels. These hydration products coat and bind soil particles, filling voids and reducing porosity. This reduction in porosity directly correlates with increased resistance to FTCs, as fewer microcracks and capillary pores are available for ice lens formation and expansion. The presence of such cementitious gels in SEM micrographs has been corroborated by prior research (Parsaei et al., 2021; Salimi et al., 2025).

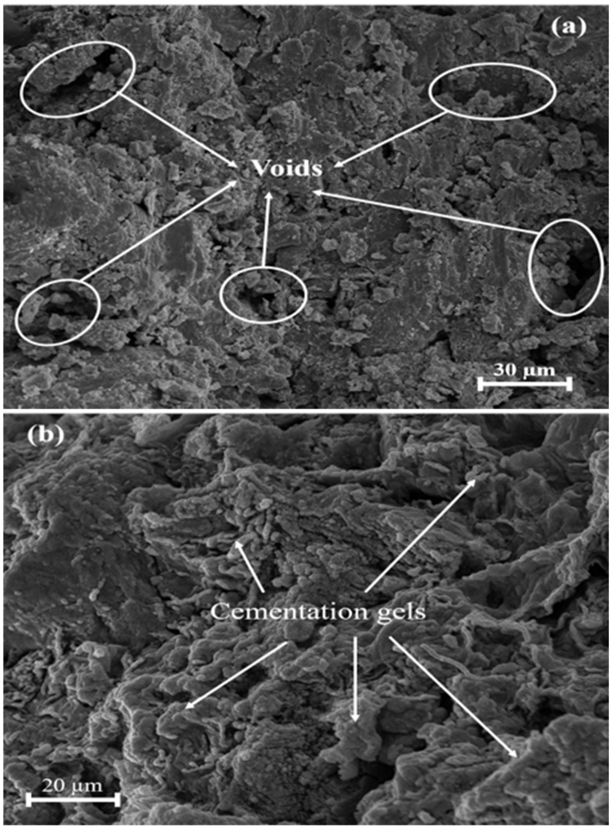

Figure 9. SEM micrographs of (a) untreated soil and (b) soil treated with 25% CCR and 10% WTS replacement.

4 CONCLUSIONS

This study investigated the use of two industrial by-products—Calcium Carbide Residue (CCR) and Water Treatment Sludge (WTS)—for stabilizing expansive clay soil and improving its mechanical performance and durability under freeze–thaw cycles (FTCs). The performance of stabilized soils was evaluated through UCS and UPV tests after 7, 28, and 56 days of curing. The key findings of the study are summarized below:

- Results indicated that increasing CCR content up to 25% significantly improved the soil's mechanical strength and density. At this optimum level, UCS reached approximately 7000 kPa and UPV about 2100 m/s after 56 days of curing. The addition of 10% WTS to the 25% CCR mix further increased UCS to ~8000 kPa, due to enhanced pozzolanic activity and the formation of C–A–S–H gels, which contributed to improved matrix cohesion.
- All samples exhibited reductions in UCS and UPV after exposure to FTCs, indicating environmental vulnerability. However, the combined use of CCR and WTS, particularly at 10% WTS, significantly mitigated these effects. In 56-day cured samples, the strength loss after 12 FTCs was reduced from 48% (CCR-only) to 38% (CCR + WTS). UPV retention also improved, demonstrating the positive effect of WTS on freeze–thaw resistance.
- A strong linear correlation was observed between UCS and UPV values of stabilized samples prior to FTC exposure, with a coefficient of determination (R^2) of 0.96. This relationship supports the practical use of UPV as a non-destructive method for estimating the mechanical performance of stabilized soils in the field.
- XRD analyses confirmed the formation of C–S–H and C–A–S–H gels in the stabilized specimens, evidenced by a broad amorphous hump, indicative of ongoing pozzolanic activity. SEM imaging further supported these findings,

showing a transition from the porous and weakly bonded structure of untreated soil to the dense, gel-rich matrix in stabilized samples. The observed reduction in voids and increase in gel content correlate directly with the mechanical improvements and enhanced durability under FTC conditions.

Overall, these findings underscore an effective strategy for the beneficial reuse of industrial wastes in geotechnical engineering. The use of CCR and WTS significantly enhances the strength, durability, and microstructural integrity of expansive soils. This study demonstrates the potential of chemical stabilization using waste-derived binders as a viable and environmentally responsible solution for improving soil performance, particularly in cold-climate infrastructure applications exposed to freeze–thaw stresses.

5 REFERENCES

ASTM:D 2487 -11. (2013). Standard Practice for classification of Soils for Engineering purposes. ASTM International, 1–8.

ASTM C597-22. (2023). Standard Test Method for Ultrasonic Pulse Velocity Through Concrete.

ASTM D2166/D2166M-13. (2016). Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International, January, 1–7.

ASTM D560/D560M-16. (2016). Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures.

ASTM D698-12. (2014). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)).

Consoli, N. C., Carretta, M. da S., Leon, H. B., Scheuermann Filho, H. C., & Tomasi, L. F. (2019). Strength and Stiffness of Ground Waste Glass–Carbide Lime Blends. Journal of Materials in Civil Engineering, 31(10). https://doi.org/10.1061/(asce)mt.1943-5533.0002862

Consoli, N. C., Scheuermann Filho, H. C., Godoy, V. B., Rosembach, C. M. D. C., & Carraro, J. A. H. (2020). Durability of reclaimed asphalt pavement–coal fly ash–carbide lime blends under severe environmental conditions. Road Materials and Pavement Design, 21(2), 557–569. https://doi.org/10.1080/14680629.2018.1506354

Ghazavi, M., & Roustaie, M. (2010). The influence of freeze–thaw cycles on the unconfined compressive strength of fiber-reinforced clay. Cold Regions Science and Technology, 61(2–3), 125–131. https://doi.org/10.1016/J.COLDREGIONS.2009.12.005

Goodarzi, A. R., & Salimi, M. (2015). Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag. Applied Clay Science, 108, 61–69. https://doi.org/10.1016/J.CLAY.2015.02.024

Kaish, A. B. M. A., Breesem, K. M., & Abood, M. M. (2018). Influence of pre-treated alum sludge on properties of high-strength self-compacting concrete. Journal of Cleaner Production, 202, 1085–1096. https://doi.org/10.1016/J.JCLEPRO.2018.08.156

Latifi, N., Vahedifard, F., Ghazanfari, E., & A. Rashid, A. S. (2018). Sustainable Usage of Calcium Carbide Residue for Stabilization of Clays. Journal of Materials in Civil Engineering, 30(6). https://doi.org/10.1061/(asce)mt.1943-5533.0002313

Lee, K. H., Lee, K. G., Lee, Y. S., & Wie, Y. M. (2021). Manufacturing and application of artificial lightweight aggregate from water treatment sludge. Journal of Cleaner Production, 307. https://doi.org/10.1016/j.jclepro.2021.127260

Li, P., Sun, F., Dong, Y., Wen, L., Lin, L., & LI, X. yan. (2025). Utilization of drinking water treatment sludge with coal fly ash to make permeable bricks for low impact development. Resources, Conservation and Recycling, 212, 107932. https://doi.org/10.1016/J.RESCONREC.2024.107932

Li, T., Kong, L., & Guo, A. (2021). The deformation and microstructure characteristics of expansive soil under freeze–thaw cycles with loads. Cold Regions Science and Technology, 192, 103393. https://doi.org/10.1016/J.COLDREGIONS.2021.103393

Li, Y., Li, J., Cui, J., Shan, Y., & Niu, Y. (2021). Experimental study on calcium carbide residue as a combined activator for coal gangue geopolymer and feasibility for soil stabilization. Construction and Building Materials, 312, 125465. https://doi.org/10.1016/J.CONBUILDMAT.2021.125465

Liu, Y., Chang, C. W., Namdar, A., She, Y., Lin, C. H., Yuan, X., & Yang, Q. (2019). Stabilization of expansive soil using cementing material from rice husk ash and calcium carbide residue. Construction and Building Materials, 221, 1–11. https://doi.org/10.1016/j.conbuildmat.2019.05.157

Mahmoudi, R., R. Rezvani, I. Hosseinpour, M. Payan and A. G. Astaneh (2025). "Effects of hydrated lime and zeolite on the mechanical behavior of calcareous sand subjected to wet–dry cycles." Journal of Materials in Civil Engineering 37(1): 04024478.

Parsaei, M., Vakili, A. H., Salimi, M., Farhadi, M. S., & Falamaki, A. (2021). Effect of electric arc and ladle furnace slags on the strength and swelling behavior of cement-stabilized expansive clay. Bulletin of Engineering Geology and the Environment, 80(8), 6303–6320. https://doi.org/10.1007/S10064-021-02316-0/METRICS

Payan, M., Khoshini, M., & Jamshidi Chenari, R. (2020). Elastic Dynamic Young's Modulus and Poisson's Ratio of Sand–Silt Mixtures. Journal of Materials in Civil Engineering, 32(1). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002991

Payan, M., Senetakis, K., Khoshghalb, A., & Khalili, N. (2017). Characterization of the small-strain dynamic behaviour of silty sands; contribution of silica non-plastic fines content. Soil Dynamics and Earthquake Engineering, 102, 232–240. https://doi.org/10.1016/j.soildyn.2017.08.008

Roustaei, M., Pumple, J., Hendry, M. T., Harvey, J., & Froese, D. (2024). Effect of freeze–thaw cycles on the macrostructure and failure mechanisms of fiber-reinforced clay using industrial computed tomography. Canadian Geotechnical Journal, 61(9), 2007–2021.

Roustaei, M., Sabetraftar, M., Taherabadi, E., & Bayat, M. (2023). Compressive and tensile strength of nano-clay stabilised soil subjected to repeated freeze–thaw cycles. Sciendo.ComM Roustaei, M Sabetraftar, E Taherabadi, M BayatStudia Geotechnica et Mechanica, 2023•sciendo.Com, 45(3), 221–230. https://doi.org/10.2478/SGEM-2023-0009

Saldanha, R. B., Scheuermann Filho, H. C., Mallmann, J. E. C., Consoli, N. C., & Reddy, K. R. (2018). Physical–Mineralogical–Chemical Characterization of Carbide Lime: An Environment-Friendly Chemical Additive for Soil Stabilization. Journal of Materials in Civil Engineering, 30(6). https://doi.org/10.1061/(asce)mt.1943-5533.0002283

Saleh, S., Surajo, I., Surajo, M., Idris, A. T., & Umar, A. (2025). Calcium Carbide and Wood Ash as Environmentally Friendly Soil Stabilizers for Enhanced Subgrade Performance. Archives of Advanced Engineering Science, 3(1), 22–28. https://doi.org/10.47852/BONVIEWAAES42022403

Salimi, M., Payan, M., Hosseinpour, I., Arabani, M., & Ranjbar, P. Z. (2024). Effect of glass fiber (GF) on the mechanical properties and freeze-thaw (F-T) durability of lime-nanoclay (NC)-stabilized marl clayey soil. Construction and Building Materials, 416, 135227. https://doi.org/10.1016/J.CONBUILDMAT.2024.135227

Salimi, M., Payan, M., Hosseinpour, I., Arabani, M., & Zanganeh Ranjbar, P. (2025). Geopolymer Stabilization of Construction and Demolition Waste Using Water Treatment Sludge and Silica Fume for Pavement Applications. Journal of Materials Research and Technology. https://doi.org/10.1016/J.JMRT.2025.06.096

Suksiripattanapong, C., Horpibulsuk, S., Phetchuay, C., Suebsuk, J., Phoo-ngernkham, T., & Arulrajah, A. (2017). Water Treatment Sludge–Calcium Carbide Residue Geopolymers as Nonbearing Masonry Units. Journal of Materials in Civil Engineering, 29(9). https://doi.org/10.1061/(asce)mt.1943-5533.0001944

Tang, P., Javadi, A. A., & Vinai, R. (2024). Sustainable utilisation of calcium-rich industrial wastes in soil stabilisation: Potential use of calcium carbide residue. Journal of Environmental Management, 357. https://doi.org/10.1016/j.jenvman.2024.120800

Zhu, J. F., Wang, Z. Q., Tao, Y. L., Ju, L. Y., & Yang, H. (2024). Macro–micro investigation on stabilization sludge as subgrade filler by the ternary blending of steel slag and fly ash and calcium carbide residue. Journal of Cleaner Production, 447. https://doi.org/10.1016/j.jclepro.2024.141496