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Effects of freeze-thaw cycles on the unconfined compressive strength of lime- and cement-stabilized soils

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Abstract. Lime stabilization is a widely used technique to improve weak subgrades; however, its effectiveness under freeze-thaw cycles remains a critical challenge. This study investigates the incorporation of cementitious materials to enhance the mechanical properties and environmental resistance of lime-stabilized soils under such conditions. Two types of soils, gray shale (plasticity index of 37.8) and clay soil (plasticity index of 19.0) from Nebraska, were used. Stabilization mixtures included lime dosages of 0%, 3%, and 6% by weight, combined with either 10% fly ash or 3% and 6% cement by weight. The experimental program comprised three stages: characterization of physical properties, preparation of composite specimens for unconfined compressive strength (UCS) testing, and evaluation of environmental resistance through freeze-thaw cycles (7 cycles after 14 days of curing and 12 cycles after 28 days of curing). Results showed that lime and fly ash significantly reduced the plasticity index of gray shale, with less pronounced effects on clay soil. Cement-lime stabilization demonstrated superior UCS retention and resistance to freeze-thaw cycles for both soil types, outperforming lime alone and lime-fly ash treatments. These findings highlight the importance of incorporating cementitious materials to enhance the durability and performance of lime-stabilized soils under harsh environmental conditions.

Keywords: freeze-thaw cycles; lime stabilization; subgrade durability; unconfined compressive strength

1. Introduction

Lime stabilization has been widely recognized as a traditional chemical stabilizer for weak subgrade soils in highway projects since its initial testing in Nebraska in 1956 (Ramsey and Lund 1969). Commonly used in road construction as a modification agent or stabilizer, lime stabilization is often regarded as a cost-effective method for enhancing the strength and stiffness of weak subgrades (Rabab'ah *et al.* 2021), similar to cement and fly ash stabilization (Ibdah e*t al*. 2025, Rabab'ah *et al.* 2021, Yilmaz *et al.* 2018, Yilmaz *et al*. 2017, Ferguson and Levorson). Extensive research and literature have explored lime's ability to strengthen stabilized subgrades and mitigate swelling and shrinkage (Basma and Tuncer 1991, Bell 1996, Negi and Faizan 2013, Zivari *et al*. 2023, Al-Swaidani *et al.* 2023). Reducing the plasticity index with lime and cementitious materials improves soil workability, minimizes moisture-induced volumetric changes, and enhances load-bearing capacity (Little 1995, Little 1998). Additionally, elasticity and resilient modulus are crucial in pavement design but are susceptible to changes in water content (Eun *et al.* 2012). Lime and cementitious materials significantly enhance these properties (Abdallah *et al.* 2023).

In cold regions, transportation infrastructure, such as pavements, is frequently damaged by repeated cycles of freezing and thawing, known as frost action (Sadiq *et al.* 2023, Solanki *et al.* 2013). The formation of ice lenses between soil particles during freezing and the excess water during thawing significantly impact the mechanical properties of soils. Cryo-suction at the frost front induces a hydraulic gradient that facilitates water migration towards the frozen boundary, where it coalesces into ice lenses, resulting in increased pore size and frost heave (Philip and De Vries 1957). Upon thawing, the excess water saturates the subgrade, reducing its load-bearing capacity through a process referred to as thaw weakening (Simonsen and Isacsson 1999). Repeated freeze-thaw cycles exacerbate these effects, expanding cracks and progressively compromising the soil structure (Hohmann-Porebska 2002, Svensson and Hansen 2010, Nguyen *et al.* 2019, Olgun 2013, Yilmaz *et al.* 2019). These cycles significantly affect the dynamic response of subgrades under cyclic load (Cui *et al.* 2023, Kakroudi *et al.* 2024). These changes can significantly diminish the strength and bearing capacity of foundation soils (Hotineanu *et al*. 2015, Li *et al.* 2014). For highway agencies, it is crucial to evaluate the durability of lime-stabilized soils during the mix design, as this assessment determines the long-term effectiveness and permanency of the treatments (Lime-Treated Soil

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Construction Manual 2004, Akula *et al.* 2020, Little 1998). Environmental conditions, particularly freezing-thawing and drying-wetting cycles, can negatively affect the durability of lime stabilization (Padmaraj and Arnepalli, 2023, Olgun, 2013).

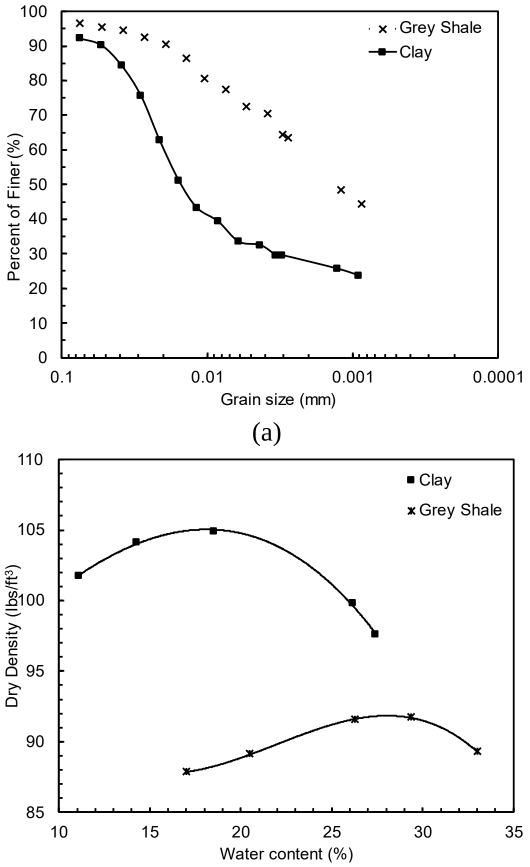
Hotineanu *et al.* (2015) studied the effect of freeze-thaw cycles on the mechanical properties of lime-stabilized soil and found that the formation of ice lenses in the pores of lime-stabilized soil caused significant damage (crack formation), leading to a degradation of soil strength. Kumar *et al.* (2024) conducted durability tests on soils stabilized with different stabilizers and observed a reduction in strength after the soils were subjected to multiple cycles. Tebaldi *et al.* (2016) examined the mechanical performance of lime-stabilized soil under freeze-thaw conditions and found that the unconfined compressive strength of the soil decreased with an increasing number of cycles, reaching an asymptotic value after five cycles. These studies investigated lime's ability to strengthen stabilized subgrades and enhance soil plasticity and mitigate swelling and shrinkage. However, there is still a limited number of studies on enhancing lime stabilization with cementitious materials to improve environmental resistance against the impacts of freezing and thawing in cold regions.

Therefore, this study evaluated the effects of freeze-thaw cycles on lime and cementitious materials to improve stabilization techniques under freezing conditions. Two Nebraska soils, gray shale and clay, were stabilized using combinations of lime, cement, and fly ash. Unconfined compressive strength tests were conducted to assess strength degradation after 7 freeze-thaw cycles (14-day curing) and 12 cycles (28-day curing). A comparative analysis of soil properties and environmental resistance testing was performed to improve understanding of lime stabilization. Results and discussions on soil properties and resistance testing were summarized to provide insights into enhancing lime stabilization methods.

2. Materials

In this study, two types of soil were considered: clay soil obtained from Lynch, Nebraska, and grey shale obtained from the Plattsmouth site, Nebraska. Basic soil characterization tests, including hydrometer analysis, Atterberg limits, and specific gravity tests, were conducted according to respective ASTM standards (ASTM D7928-21e1, ASTM D4318-17e1, ASTM D854-23). The grain size distribution curves of the two soils are shown in Fig. 1. According to the Unified Soil Classification System (USCS), the soils were classified as silt (MH) and lean clay (CL). The physical and chemical properties of the soils are provided in Table 1.

Three types of chemical stabilizers were selected to enhance the engineering properties of the soils: hydrated lime, Portland cement (Type 1L), and Class C Fly Ash. Typical dosages of 3% lime, 6% lime, 3% cement, 6% cement, and 10% fly ash were used, as outlined in the NDOT manual guidelines for pavement design (2018). This study examines the performance of the combination of lime, fly ash, and cement under freezing-thawing cycles.



(a)

(b)

Fig. 1 (a) Hydrometer analysis, and (b) compaction curves for grey shale and clay

Table 1 Physical Properties of the Soils

Soil Properties	Grey shale	Clay
Liquid Limit (%)	67.5	43
Plastic Limit (%)	29.7	24
Plasticity Index	37.8	19
Optimum moisture content (%)	28	18
Maximum dry density (Ib/ft^3)	92	105
AASHTO Classification	A-7-6	A-7-5
UCS Classification	MH	CL
Specific Gravity (Gs)	2.69	2.75

3. Method

The experimental program was conducted in three stages. Firstly, the physical properties of the stabilizers and the two types of soils were characterized. Secondly, composite specimens were prepared for a series of unconfined compressive strength tests, focusing on soils stabilized individually by lime, fly ash, and cement, as well as combinations of these stabilizers (Table 2). Lastly, the environmental resistance of the treated soils was evaluated by subjecting the specimens to freezing-thawing cycles and measuring changes in strength and durability.

(a) A mold, four plugs, and an extruding ram (b) Static compaction

(c) Extruding UCS sample (d) UCS sample

Fig. 2 UCS sample preparation procedures

Table 2 Testing matrix with different soil and chemical additive combinations

Soil type	Grey Shale				Clay			
L	Control	C 3%	C 6%	FA 10%	Control	C 3%	C 6%	FA 10%
0%	GL0	GL0C3	GL0C6	GL0FA10	BL0	BL0C3	BL0C6	BL0FA10
3%	GL3	GL3C3	GL3C6	GL3FA10	BL3	BL3C3	BL3C6	BL3FA10
6%	GL6	GL6C3	GL6C6	GL6FA10	BL6	BL6C3	BL6C6	BL6FA10

Notes: Gray Shale (G), Clay (B), Lime (L), Cement (C), and Fly Ash (FA)

3.1 Atterberg limits of the treated samples

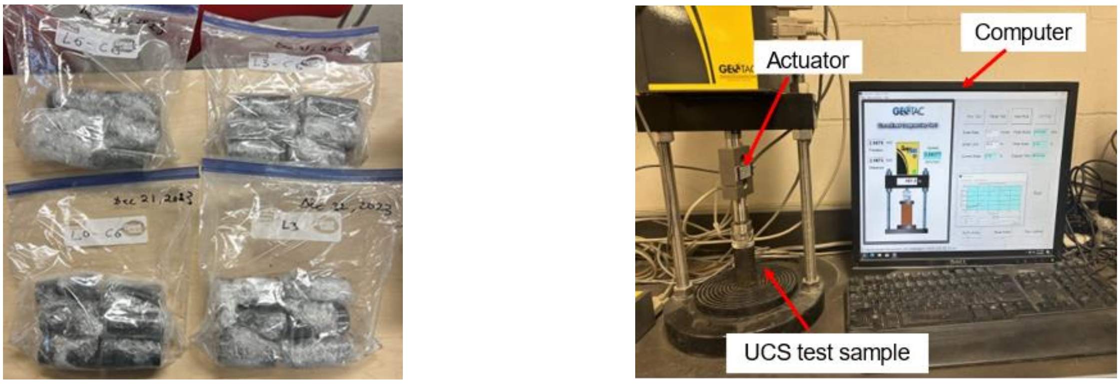
The Atterberg limit tests were performed according to ASTM D4318-17e1. Lime-treated soil mixtures and combinations with other cementitious materials were mixed with water and allowed to mellow for 30 minutes before performing the liquid limit and plastic limit tests. Cement-treated soils were excluded from this test because the mellowing period was sufficient to initiate the initial set of the cement-soil mixture (Halsted and McConnell 2008).

3.2 Unconfined compressive strength test

The unconfined compressive strength (UCS) test, conducted in accordance with ASTM D2166/D2166M and ASTM D5102/D5102M standards, is a key method for evaluating the performance of soil stabilization techniques. This test assesses the strength of both untreated and treated soils with lime, cement, fly ash, or their combinations. Two samples were prepared for each combination using a steel mold (1.3-inch diameter, 2.7-inch length) at optimum moisture content (OMC) [Fig 2(a)]. They were compacted to maximum dry density (MDD) using static compaction [Fig 2(b)]. Stabilized samples were cured for 28 days in airtight bags at 73.4°F ± 1.8°F (23°C ± 1°C) to maintain moisture and ensure proper chemical reactions [Fig 3(a)]. UCS tests were conducted using a GeoJac actuator with a load capacity of 2000 pounds (8.9 kN) and a 1.5-inch (38 mm) stroke, applying a constant loading rate of 1% per minute. This setup ensures precision and consistency in evaluating soil strength [Fig 3(b)].

3.3 Assessment of environmental resistance

The UCS is a key input for stabilized subgrade design in the Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO 2008). UCS indicates subgrade strength, but freezing-thawing cycles weaken it, causing failures and increasing costs. Accounting for strength loss helps mitigate these issues, making stabilization and



(a) Wrapped UCS samples for curing (b) UCS test apparatus

(c) Stored UCS samples in the freezer (d) UCS sample after testing

Fig. 3 Experimental setup and sample conditions for UCS testing and FT cycles

Table 3 Curing durations and freezing-thawing cycles for UCS test samples

Set#	Curing		FT	
1	14	Days	# of Cycles	7
2	28	Days	# of Cycles	12

drainage crucial. With 113 annual freezing-thawing cycles in Omaha, Nebraska, it is essential to consider these cycles in subgrade design to ensure long-term performance and durability (National Weather Service, 2022). Therefore, a comprehensive methodology was adopted to assess the environmental resistance of stabilized soil treated with lime, cement, fly ash, and their combinations.

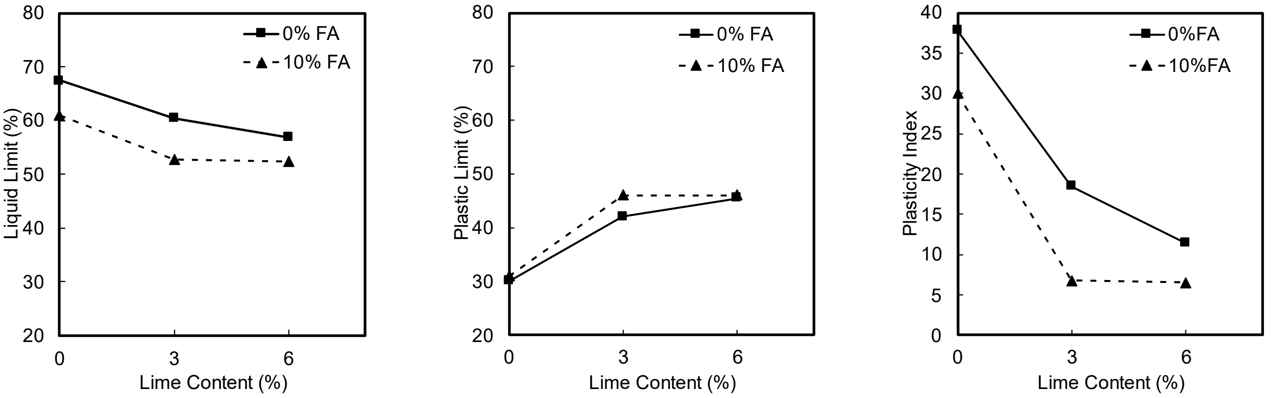
The freeze-thaw (FT) test was selected in this study to assess the environmental resistance of stabilized soil samples, focusing on strength degradation under repeated FT cycles to simulate real-world conditions in Nebraska. An FT cycle consists of 24 hours of storing the stabilized soil sample at -31°F ± 2.5°F in the freezer [Fig. 3(c)], followed by thawing at 73°F ± 2.5°F for 24 hours (ASTM D560/D560M). The degradation in UCS due to FT cycles was used as an indicator to assess the environmental resistance of the stabilized samples.

Two sets of FT cycles were designed to estimate the strength degradation of the samples over increasing cycles. The first set, developed by the research team, aimed to examine the impact of FT cycles during the early stage of stabilization. This set involved 7 FT cycles conducted after 14 days of curing to ensure the total duration of curing and FT cycles equaled 28 days. This approach allowed a direct comparison with samples cured for 28 days without being subjected to freeze-thaw cycles. The second set evaluated the environmental effect on soil strength during the later phase of stabilization with 12 FT cycles (ASTM D560/D560M) after 28 days of curing (Table 3). Two UCS samples were prepared for each combination in each set of FT cycles. The UCS test was conducted after completing the FT cycles in accordance with ASTM D5102 [Fig 3(d)].

The reduction factor was calculated to examine the influence of FT cycles on stabilized soil using Eq. (1). The reduction factor was calculated for both stabilized and untreated soils to evaluate the performance of each mixing combination against two sets of environmental tests. Further discussion will be provided in subsequent sections.

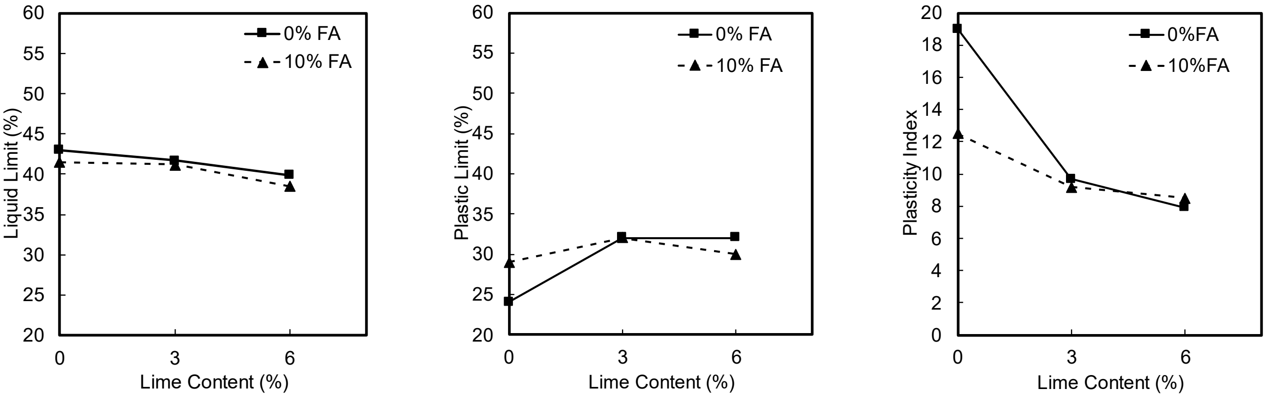
$$RDF = \frac{UCS_0 - UCS_{FT}}{UCS_0} \tag{1}$$

where UCS_0 represents the unconfined compressive strength of the soil samples without FT cycles, and UCS_{FT} represents the unconfined compressive strength of the soil samples subjected to FT cycles.



(a) Liquid limit vs lime content (b) Plastic limit vs lime content (c) Plastic index vs lime content

Fig. 4 Comparison of the impact of different lime contents with 0% and 10% fly ash on the Atterberg limit of grey shale



(a) Liquid limit vs lime content (b) Plastic limit vs lime content (c) Plastic index vs lime content

Fig. 5 Comparison of the impact of different lime contents with 0% and 10% fly ash on the Atterberg limit of clay soil

4. Results and discussion

4.1 Atterberg limits

The liquid limit (LL), plastic limit (PL), and plasticity index (PI) for the grey shale and clay soil samples treated with lime and fly ash are shown in Figs. 4 and 5, respectively.

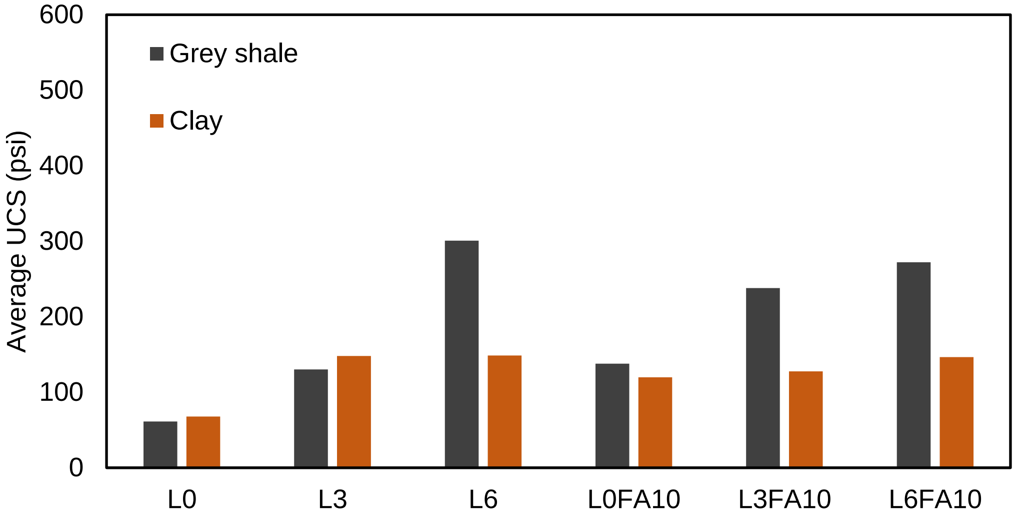
For grey shale, the LL decreased with increasing lime content, with a more pronounced reduction observed upon the incorporation of 10% fly ash. The PL exhibited a consistent increase with lime content for both 0% and 10% fly ash treatments. Consequently, the PI demonstrated a substantial decrease. The untreated grey shale had a PI of 37.8. Following the addition of 3% lime, the PI decreased to 18.5, and with 6% lime, it further reduced to 11.4, reflecting reductions of 51% and 70%, respectively. The inclusion of 10% fly ash amplified this reduction, with the PI decreasing to 30 for 0% lime, 6.8 for 3% lime and 6.5 for 6% lime, corresponding to reductions of 20%, 82% and 83%, respectively. These findings highlight the effectiveness of the combined lime and fly ash technique in reducing the plasticity of grey shale soil.

Similarly, for clay soil, the LL, PL, and PI values exhibited notable changes with the application of lime and fly ash. The untreated clay soil had a PI of 19. With the addition of 3% lime, the PI decreased to 9.7, and with 6% lime, it further reduced to 7.9, reflecting reductions of 49% and 58%, respectively. When 10% fly ash was added, the PI values were 12.5 for untreated soil, 9.2 for soil treated with 3% lime, and 8.5 for soil treated with 6% lime, corresponding to reductions of 52% and 55%, respectively. These results indicate that the application of lime alone achieves similar PI reductions as lime combined with 10% fly ash.

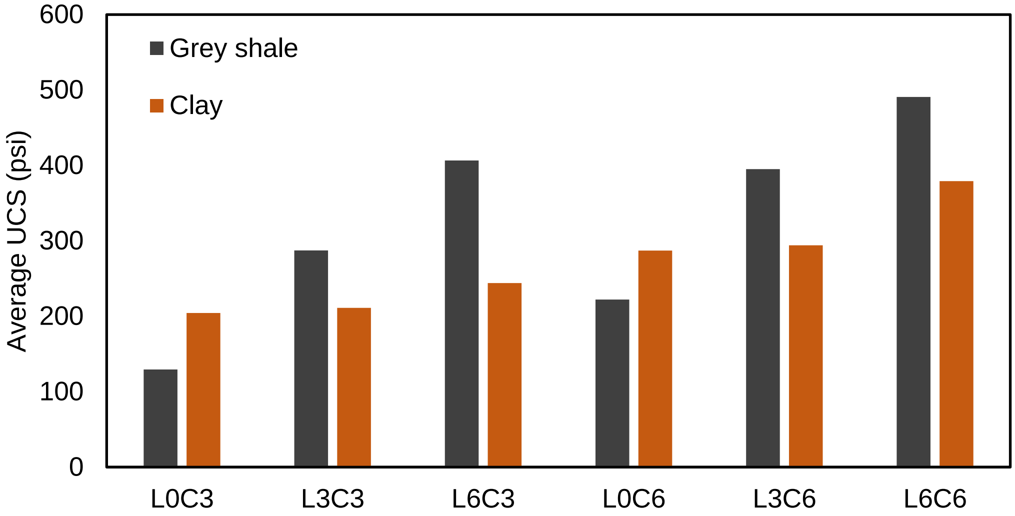
The addition of fly ash and lime reduced the liquid limit of the soil by decreasing the thickness of the diffuse double layer. This reduction occurred due to cation exchange and flocculation processes triggered by calcium ions in fly ash and lime (Sivapullaiah *et al.* 1996). Moreover, combining lime and fly ash increased the soil's plastic limit. The presence of free lime in these stabilizers further diminished the diffuse double layer’s thickness and enhanced flocculation of soil particles, plasticity index" to ensure correct terminology.

4.2 Unconfined compressive strength

The UCS results for grey shale and clay soils stabilized with lime and lime-fly ash combinations are presented in



(a) Average UCS of grey shale and clay soils stabilized with combination lime and fly ash



(b) Average UCS of grey shale and clay soils stabilized with combination lime and cement

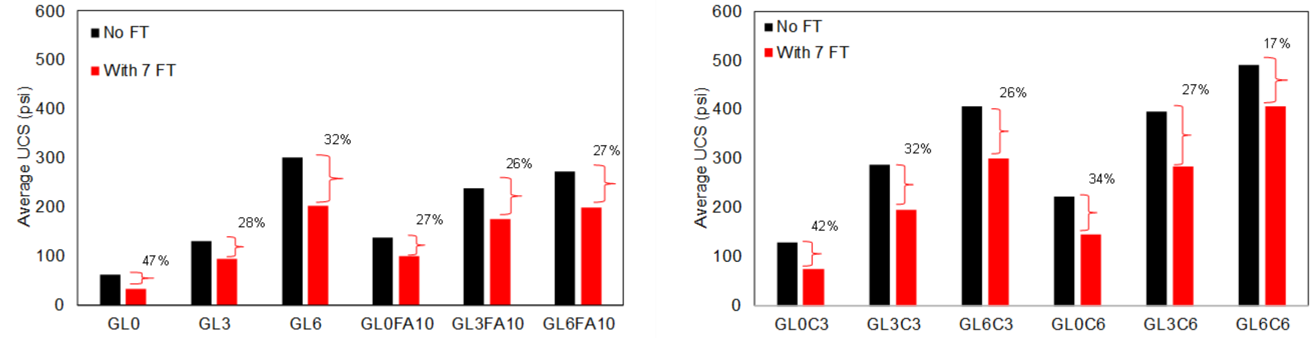
Fig. 6 Comparison of average UCS values for grey shale and clay soils stabilized with different treatments

Fig. 6(a). For grey shale, the UCS exhibited a significant increase with the addition of lime. Each 3% increment in lime content resulted in approximately a 200% improvement in UCS, with values rising from 61.2 psi (GL0) to 130.3 psi (GL3) and further to 300.7 psi (GL6). The inclusion of 10% fly ash alongside 3% lime (GL3FA10) enhanced the UCS to 238.0 psi, marking a 150% improvement over lime-only stabilization (GL3). However, the UCS values for GL6 and GL6FA10 were comparable, indicating that adding fly ash at higher lime content provided limited additional strength gains for grey shale.

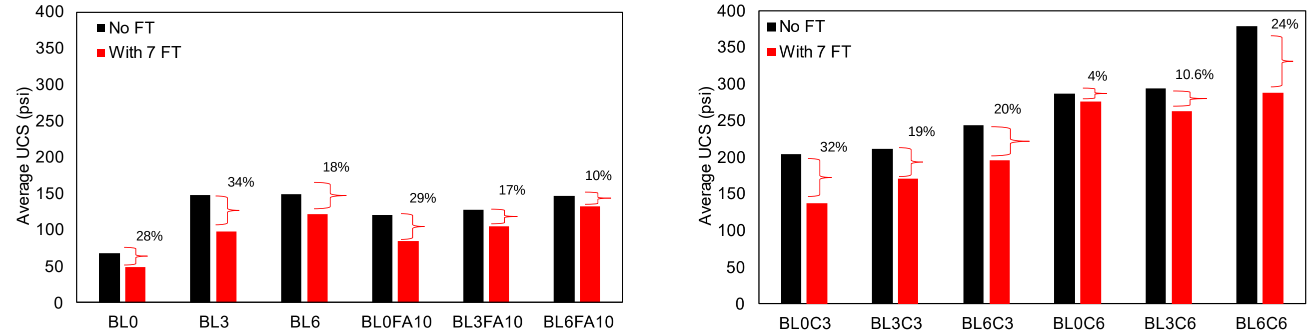
For clay soil, the UCS results revealed a similar trend, though with less pronounced improvements compared to grey shale. The UCS increased from 67.9 psi (BL0) to 147.9 psi (BL3), representing an enhancement of approximately 118.6%. A slight increase was observed for BL6, where UCS stabilized at 148.7 psi. The addition of 10% fly ash resulted in UCS values of 119.8 psi for BL0FA10, 127.7 psi for BL3FA10, and 146.5 psi for BL6FA10, highlighting a limited effect of fly ash on enhancing clay soil strength.

The UCS results for lime- and cement-stabilized grey shale and clay are presented in Fig. 6(b). For grey shale soil, the addition of cement led to significant strength improvements, with UCS values increasing from 61.2 psi (GL0) to 129.6 psi (GL0C3) and further to 287.3 psi (GL3C3). The UCS for GL6C3 reached 406.7 psi, which is comparable to the UCS value of 395.2 psi for GL3C6. The highest UCS value was observed for GL6C6 at 490.8 psi, representing an increase of 702% compared to unstabilized grey shale.

For clay soil, lime- and cement-stabilization also enhanced UCS values, though to a lesser extent than grey shale. The UCS increased from 67.9 psi (BL0) to 204.4 psi (BL0C3), marking a 201% improvement. For BL3C3 and BL6C3, UCS values reached 211.2 psi and 244.1 psi, reflecting increases of 211% and 259%, respectively.



(a) UCS of grey shale with lime and lime-fly ash (b) UCS of grey shale with lime and lime-cement



(c) UCS of clay with lime and lime-fly ash (d) UCS of clay with lime and lime-cement

Fig. 7 Comparison of UCS results for grey shale and clay stabilized with lime, fly ash, cement, and their combinations after 28 days of curing and after 14 days of curing followed by 7 FT cycles

Interestingly, the UCS results for BL0C6 and BL3C6 were quite similar, with values of 287.1 psi and 294.2 psi, respectively. The highest UCS was recorded for BL6C6 at 379.2 psi, corresponding to a 458% increase over the untreated clay.

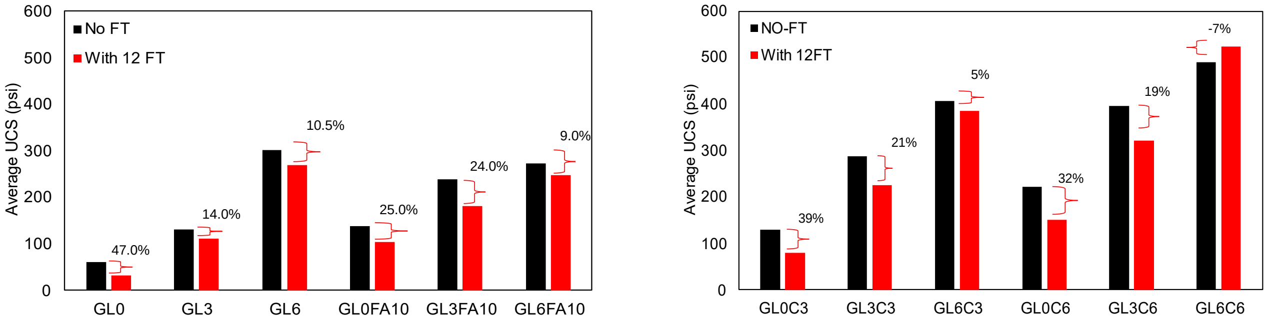
The increase in UCS for two types of soil treated by lime and cementitious materials is an immediate response to adding lime and cementitious materials, caused by cation exchange, flocculation, and aggregation as calcium ions (Ca^{2+}) replace sodium ions (Na^{+}), reducing the diffuse double layer and forming a more granular structure (Bell, 1996). The improvement in soil strength when using lime, cement, fly ash, or their combinations is primarily driven by hydration and pozzolanic reactions. These reactions form cementitious compounds that coat and bind soil particles together, enhancing the soil structure (Ferguson and Levorson 1999, Ural 2016). Fly ash, in particular, boosts this process by increasing the availability of silica and alumina, which react with calcium hydroxide to form additional calcium silicate hydrates, further strengthening the soil matrix and improving its durability (Rabab'ah *et al.* 2021, Ferguson and Levorson 1999).

4.3 Assessment of environmental resistance

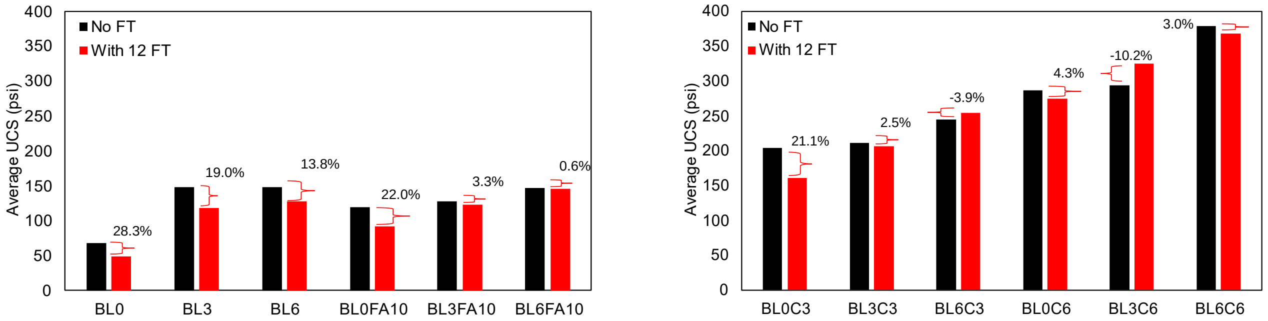
The results of assessing the environmental resistance of stabilized soils are presented in Figures 7 and 8. The UCS was used as the key indicator to evaluate the mechanical integrity and durability of soils, particularly under stabilization treatments aimed at enhancing lime stabilization with cementitious materials. This section focuses on the performance of grey shale and clay soils under FT conditions. The assessment involved evaluating the performance of stabilized samples under freeze-thaw cycles.

For unstabilized grey shale (GL0), the UCS decreased from 61.2 psi to 32.4 psi after 7 FT cycles, representing a reduction of approximately 47%. Grey shale stabilized with 3% lime (GL3) experienced a reduction from 130.3 psi to 93.7 psi, a 28% decrease. Samples treated with 6% lime (GL6) showed a reduction from 300.7 psi to 202.7 psi, a 32% decrease. The addition of fly ash also showed reductions. For GL0FA10, UCS decreased by 27%, while GL3FA10 and GL6FA10 experienced reductions of 26% and 27%, respectively. Among these combinations, GL3FA10 exhibited the least reduction in strength [Fig. 7(a)].

The UCS results for clay soil stabilized with lime and lime-fly ash are also presented to assess the effectiveness of stabilization combinations in enhancing resistance to freeze-thaw cycles. For unstabilized clay (BL0), UCS decreased from 67.9 psi to 48.6 psi after 7 FT cycles, representing a 28% reduction. Clay stabilized with 3% lime (BL3) saw a reduction in UCS from 147.9 psi to 97.1 psi, a 34% decrease. Samples with 6% lime (BL6) showed a reduction from 148.7 psi to 121.8 psi, corresponding to an 18% decrease. For BL0FA10, UCS dropped from 119.8 psi to 84.3 psi, a 29% reduction. Similarly, BL3FA10 and BL6FA10 experienced reductions of 17% and 10%, respectively. Among the tested combinations, BL6FA10 exhibited the least reduction in strength, suggesting that 6% lime and 10% fly ash provided superior resistance to freeze-



(a) UCS of grey shale with lime and lime-fly ash (b) UCS of grey shale with lime and lime-cement



(c) UCS of clay with lime and lime-fly ash (d) UCS of clay with lime and lime-cement

Fig. 8 Comparison of UCS results for grey shale and clay stabilized with lime, fly ash, cement, and their combinations after 28 days of curing and after 28 days of curing followed by 12 FT cycles

thaw cycles relative to other lime-fly ash combinations [Fig. 7(c)].

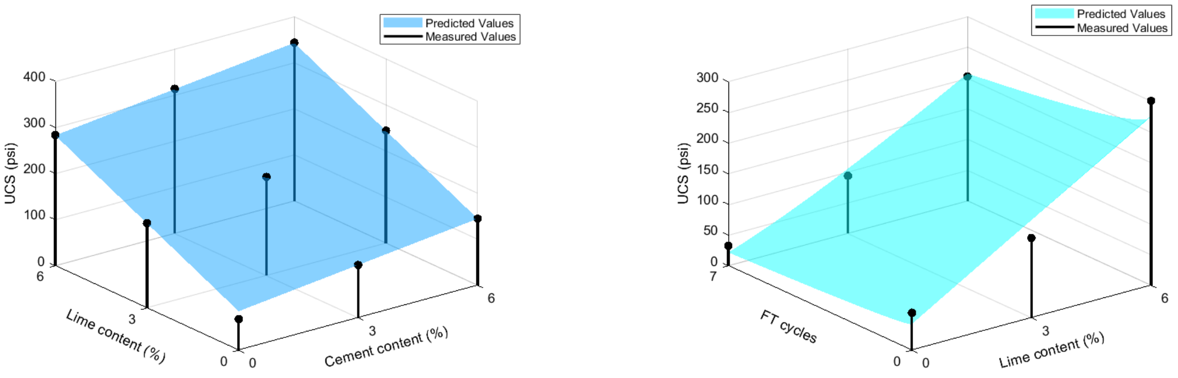
Grey shale stabilized with 3% cement (GL0C3) showed a UCS decrease from 129.6 psi to 74.9 psi after 7 FT cycles, corresponding to a 42% reduction. In comparison, grey shale stabilized with 3% lime and 3% cement (GL3C3) experienced a UCS reduction from 287.3 psi to 195.0 psi, a 32% decrease. When stabilized with 6% lime and 3% cement (GL6C3), UCS dropped by 26%, from 406.7 psi to 300.2 psi. Grey shale stabilized with 6% cement (GL0C6) decreased from 222.2 psi to 145.2 psi, a 34% reduction. Grey shale stabilized with 3% lime and 6% cement (GL3C6) exhibited a 27% decrease, dropping from 395.2 psi to 284.7 psi. Finally, the combination of 6% lime and 6% cement (GL6C6) demonstrated the highest UCS retention, decreasing from 490.8 psi to 406.0 psi, a reduction of only 17% [Fig. 7(b)].

For clay soil stabilized with 3% cement (BL0C3), UCS decreased from 204.4 psi to 137.7 psi after 7 FT cycles, a 32% reduction. Clay stabilized with 3% lime and 3% cement (BL3C3) saw a UCS drop from 211.2 psi to 170.7 psi, a 19% decrease. Samples with 6% lime and 3% cement (BL6C3) exhibited a 20% reduction, from 244.1 psi to 196.1 psi. For clay stabilized with 6% cement (BL0C6), UCS decreased from 287.1 psi to 275.7 psi, a 4% reduction. Clay stabilized with 3% lime and 6% cement (BL3C6) exhibited a UCS reduction of 10.6%, dropping from 294.2 psi to 262.8 psi. Finally, the combination of 6% lime and 6% cement (BL6C6) achieved the highest UCS reduction, decreasing from 379.2 psi to 275.7 psi, corresponding to a reduction of 24% (Fig. 7(d)).

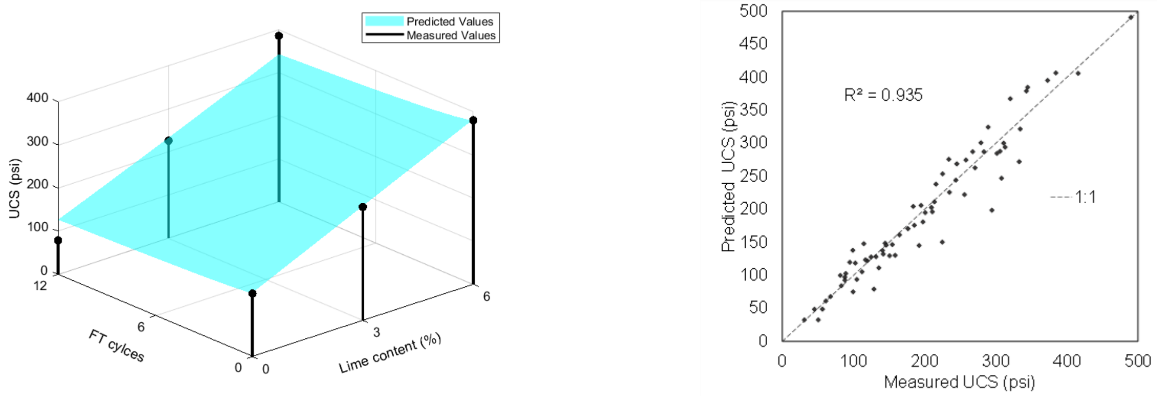
For grey shale, the UCS of the unstabilized soil (GL0) decreased significantly by 47%, from 61.2 psi to 32.4 psi after 12 FT cycles. This reduction is comparable to that observed after 7 cycles. The sample stabilized with 3% lime (GL3) experienced a 14% reduction, decreasing from 130.3 psi to 111.3 psi. The sample stabilized with 6% lime (GL6) showed a decrease from 300.7 psi to 268.9 psi, a 10.5% reduction. This indicates that increasing lime content improved resistance to freeze-thaw degradation. The addition of fly ash also demonstrated improvements. GL0FA10 showed a UCS reduction of 25%, from 137.8 psi to 102.8 psi, while GL3FA10 and GL6FA10 had reductions of 24% and 9%, respectively. The best performance was observed with GL6FA10, which had the smallest reduction in strength after 12 FT cycles [Fig. 8(a)].

For unstabilized clay soil (BL0), UCS decreased by 28.3%, from 67.9 psi to 48.7 psi after 12 FT cycles. This is similar to the reduction observed after 7 cycles, suggesting stabilization over extended cycles. Samples with 3% lime (BL3) saw a 19% reduction, from 147.9 psi to 118.5 psi, while samples with 6% lime (BL6) decreased from 148.7 psi to 128.1 psi, a 13.8% reduction. The addition of fly ash improved performance, with BL0FA10 showing a UCS reduction of 22%, from 119.8 psi to 92.5 psi. BL3FA10 had a reduction of only 3.3%, from 127.7 psi to 123.4 psi, while BL6FA10 demonstrated the least reduction, with a negligible 0.6% decrease, from 146.5 psi to 145.6 psi [Fig. 8(c)].

Grey shale samples with 0% lime and 3% cement (GL0C3) showed a UCS reduction of 39%, from 129.6 psi to 79.1 psi. For samples stabilized with 3% lime and 3% cement (GL3C3), UCS dropped by 21%, from 287.3 psi to



(a) Grey shale soil stabilized by lime-cement (b) Clay stabilized by 3% of cement with vary lime content



(c) Caly stabilized with vary lime content (d) Predicted and measured UCS samples

Fig. 9 Comparison of measured and predicted UCS

225.8 psi. Samples with 6% lime and 3% cement (GL6C3) showed the smallest reduction of 5%, from 406.7 psi to 384.8 psi. GL0C6 experienced a 32% decrease, from 222.2 psi to 150.3 psi, while GL3C6 dropped by 19%, from 395.2 psi to 321.6 psi. The best performance was observed with GL6C6, which showed a 7% increase in UCS, from 490.8 psi to 523.8 psi. This increase is attributed to ongoing pozzolanic reactions and cement hydration, enhancing soil strength under freeze-thaw conditions [Fig. 8(b)].

For clay samples, BL0C3 dropped by 21.1%, from 204.4 psi to 161.3 psi. BL3C3 had a minor reduction of 2.5%, from 211.2 psi to 205.9 psi, while BL6C3 showed a 3.9% increase, from 244.1 psi to 253.7 psi. For clay with 6% cement, BL0C6 dropped by 4.3%, from 287.1 psi to 274.6 psi. BL3C6 showed an increase of 10.2%, from 294.2 psi to 342.4 psi, while BL6C6 exhibited a reduction of 3%, from 379.2 psi to 367.5 psi. For combined lime and cement in clay soil, the recommended combinations are 6% lime and 3% or 3% lime and 6% cement, as these demonstrated strong performance against freeze-thaw cycles [Fig. 8(d)].

The application of FT cycles modifies the soil microstructure at the aggregate scale, reducing the UCS strength of both stabilized and untreated grey shale and clay. FT cycles induce physical changes in the soil matrix, including increased voids due to ice lens formation and water flow. These changes propagate cracks within the soil matrix as repeated cycles exacerbate crack growth and expansion (Hohmann-Porebska 2002, Svensson and Hansen 2010, Nguyen *et al.* 2019, Olgun 2013). Heating and freezing change soil particle orientation and overall structure, potentially altering and further reducing the soil's strength and stability (Jaradat *et al.* 2017).

When comparing the UCS reduction of two types of soils stabilized with lime, cement, and fly ash, the observed differences are primarily driven by the soil's mineralogical composition, plasticity index, and the chemical reactivity of the stabilizing agents curing period. Hotineanu *et al.* (2015) and Nguyen *et al.* (2019) observed a similar phenomenon in their studies on lime-stabilized soils, noting that higher plasticity soils are more vulnerable to FT cycles due to significant structural damage at the aggregate scale.

As discussed above, the unconfined compressive strength of stabilized soil is influenced by the stabilizer content, curing period, and number of freeze-thaw cycles. These three factors play a critical role in determining the UCS. To account for these effects, an empirical model for estimating the UCS was proposed

$$UCS = (a_1.L + a_2.C + a_3.FA + a_4.UCS_{un})(1 - RDF) \quad (2)$$

$$RDF = \left(\frac{b_1 N_{FT}}{(L + C + FA + C_u)^{b_2}}\right)^{b_3} \quad (3)$$

where L, C, and FA are the lime content, cement content, and fly ash content, respectively. N_{FT} is the number of

Table 4 Regression coefficient for empirical model of UCS

Regression coefficient	Grey shale	Clay
a_1	39	10
a_2	35.1	33
a_3	5.37	1
a_4	0.7	1.25
b_1	400	450
b_2	3.5	3.33
b_3	0.545	0.54

freeze-thaw cycles, Cu is the curing period (in days), and UCS_{un} is the UCS of untreated soil. a_1, a_2, a_3, b_1, b_2, and b_3 are the regression coefficients of the empirical formulas.

This model integrates the combined effects of stabilizer contents and environmental conditions to predict the UCS of treated soils under various scenarios. The parameters can be calibrated using experimental data to reflect site-specific soil and stabilization characteristics.

The UCS of stabilized clay consists of four main components: the contributions from lime, cement, fly ash, and the initial UCS values. These components exhibit a linear relationship, as represented in Equation 2. The reduction in UCS due to freeze-thaw cycles is described by a composite function, as shown in Equation 3. The reduction factor demonstrates a positive relationship with the number of freeze-thaw cycles and an inverse relationship with stabilizer content and curing period.

After calibrating the parameters using MATLAB software, all the regression coefficients for the empirical model and the correlation coefficients were obtained and are summarized in Table 4. Notably, a_1 in grey shale soil is four times higher than in clay, which means that lime is more effective in enhancing the strength of grey shale soil. This significant increase in a_1 can be attributed to the mineralogy of grey shale. a_2 is similar for both types of soil, indicating consistent stabilization behavior across different mineralogical compositions for this parameter.

Fig. 9 illustrates the comparison between the measured and predicted UCS values. In Figs. 9(a)-9(c), the tested UCS values are represented as lines, while the predicted UCS values, calculated using Eq. (2), are shown as surfaces. Fig. 9(d) plots the predicted results against the tested results. The comparison highlights that the predicted UCS values from the empirical model align closely with the tested results, with an R^2 value of 0.935, indicating a strong agreement between the predicted and measured UCS values.

5. Conclusions

This study demonstrated the efficacy of incorporating cementitious materials into lime stabilization to improve soil performance, particularly under freeze-thaw (FT) cycles. The findings from this study underscore the importance of enhancing lime stabilization to improve soil performance:

The plasticity index was dramatically reduced by the inclusion of lime and fly ash in grey shale soil, transforming it from a high-plastic material to low-plastic materials, with an 82% reduction using 3% lime and 10% fly ash. However, adding more lime with 10% fly ash did not yield further significant improvement. For clay soil, the combination of fly ash and lime did not reduce the plasticity index significantly compared to lime alone.

Stabilization with lime significantly increased the UCS of grey shale, with strength improving progressively beyond 3% lime content. Specifically, UCS improvements were substantial with 3% lime and further enhanced with 6% lime.

In contrast, clay soil exhibited a plateau in UCS improvement after 3% lime, with no significant gains at higher lime content. This highlights the greater efficacy of lime stabilization for grey shale and the limited benefits for clay soil beyond initial stabilization.

The combined use of lime with fly ash or cement provided superior UCS results for grey shale compared to clay soil. For grey shale, the combination of 6% lime and 6% cement yielded significant UCS gains. Conversely, clay soil exhibited minimal UCS improvement with lime and fly ash. Interestingly, clay soil treated with cement alone delivered higher UCS values at both 3% and 6% cement content compared to grey shale under similar conditions.

The reduction in UCS after FT cycles highlights the effectiveness of stabilization techniques. For grey shale, combining lime with cement demonstrated superior performance compared to lime alone. In clay soil, lime and fly ash combinations were less effective, while cement-based stabilization consistently outperformed other methods. For both 7 and 12 FT cycles, the trend remained consistent, with lime-cement stabilization providing the best UCS retention for both soil types.

Overall, these findings highlight the critical role of cementitious materials in enhancing the durability and mechanical performance of lime-stabilized soils, particularly for applications requiring resilience to freeze-thaw cycles. Statistical analysis further validated the model's predictive accuracy ($R^2 = 0.935$), reinforcing the practical applicability of the proposed stabilization methods.

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