frontiers | Frontiers in Materials

TYPE Original Research
PUBLISHED 03 June 2025
DOI 10.3389/fmats.2025.1619118

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OPEN ACCESS

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RECEIVED 27 April 2025
ACCEPTED 26 May 2025
PUBLISHED 03 June 2025

CITATION
Benson E, Cheng P and Chao L (2025) Experimental study on the compressive strength and mechanical properties of gravelly red sandstone soil under freeze-thaw cycles. *Front. Mater.* 12:1619118.
doi: 10.3389/fmats.2025.1619118

Experimental study on the compressive strength and mechanical properties of gravelly red sandstone soil under freeze-thaw cycles

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Gravelly soils, characterized by a distinctive combination of coarse gravel aggregates and fine soil matrix, are widely distributed and play a crucial role in geotechnical engineering. This study investigates the mechanical behavior of gravelly soil subjected to simulated freeze-thaw (F-T) cycles using triaxial compressive strength tests. The long-term deviatoric stress response of specimens with varying gravel content and initial water content was analyzed under three distinct effective confining pressures (100, 200, and 300 kPa) across different F-T cycles. The results indicate that compressive strength is significantly influenced by gravel content, initial water content, and confining pressure. Notably, the rate of increase in deviatoric stress does not exhibit a proportional rise under confining pressures of 200 kPa and 300 kPa after 40 F-T cycles. However, a direct correlation is observed between deviatoric stress and increasing confining pressure (100, 200, and 300 kPa) over 2-, 4-, and 6-day intervals, this effect is more pronounced at higher confining pressures. The deviatoric stress peaks at different strain thresholds depending on the applied confining pressure; furthermore, no evident strain-softening behavior is observed across the tested conditions. These findings suggests that higher confining pressure inhibits particle displacement and interlocking failure, thereby reducing both the void ratio and axial strain within the soil matrix. Overall, these insights enhance our understanding of the complex interactions among gravel content, water content, confining pressure, and freeze-thaw effects, contributing to the understanding of the compressive strength evolution in gravelly soils under cyclic environmental loading.

KEYWORDS

gravelly soil, axial strain, deviatoric stresses, soil mechanical characteristics, freeze-thaw cycles

1 Introduction

Cyclic freezing and thawing is a significant factor influencing the deterioration of geotechnical structures in seasonally frozen regions. Engineering properties of soil, such as compressive strength, permeability, and structure, are highly susceptible to changes induced by freeze-thaw (F-T) cycles (Wang B. et al., 2024; Shirmohammadi et al., 2021; Chang and Liu, 2013). This phenomenon is particularly relevant in cold climates where sub-zero temperatures cause pore water to freeze, leading to the formation of ice lenses. Upon thawing, the structural integrity of the soil is weakened due to excess pore water pressure and the loss of interparticle cohesion (Venda Oliveira et al., 2024; Gharemahmudli et al., 2023; Qi et al., 2008). Repeated F-T cycles lead to cumulative damage, affecting the long-term stability of natural and engineered slopes, embankments, foundations, and pavements (Gharemahmudli et al., 2023; Jia et al., 2023).

Fine-grained soils, such as clay and silts, are particularly susceptible to F-T effects due to their high water retention capacity and tendency to develop ice lenses (Sun et al., 2022; Jamshidi and Lake, 2015). During freezing, ice segregation leads to volumetric expansion, and upon thawing, a loss of strength occurs due to the redistribution of pore water. Research suggests that significant deterioration occurs within the first 6–10 F-T cycles, with stabilization occurring beyond 15 cycles (Chen et al., 2024; Wei et al., 2023). Coarse-grained soils, including gravelly soils, exhibit a different response due to their relatively larger particle size, higher permeability, and lower water retention capacity. The presence of coarse particles reduces the likelihood of ice lens formation and mitigates volume change, but mechanical degradation still occurs due to particle rearrangement and loss of interlocking forces (Li, Zhu, Zhang, Chunyu, and Li, 2023).

In cold regions, soil and rocks are often exposed to different loading conditions, extreme temperatures, and cyclic freezing-thawing, therefore, will be subjected to major structural deterioration. The detrimental cycle of freezing-thawing is a multifaceted process encompassing both physical (Dong et al., 2024) and chemical (Öztürk and Kılınçkale, 2023) phenomena that commences with damage to the microstructure. During the freezing-thawing process, the physico-mechanical properties of soils and rocks could be potentially damaged and deteriorated, resulting in freeze-thaw-induced engineering failures (Wang Jy. et al., 2024; Fakhri et al., 2023; Zhang et al., 2019; Freire-Lista et al., 2015).

Extensive studies have been conducted to investigate the physico-mechanical properties and damage mechanisms of rocks subjected to freeze-thaw cycles, with a predominant focus on static loading conditions (Liu et al., 2024; Yin et al., 2023; Zhang et al., 2019). Deng et al. (2014) examined the coupled effects of chemical corrosion and freeze-thaw cycling on sandstone, and reported that there exist distinct deterioration patterns in physical and mechanical properties under varying environmental conditions. Yu et al. (2024) investigated the effects of freeze-thaw cycles on the dynamic mechanical properties of red sandstone and reported that as the number of freeze-thaw cycles increases, ductility failure begins to occur, but however, the required dissipation energy decreases. Similarly, Freire-Lista et al. (2015) performed uniaxial compression tests on freeze-thaw-exposed granite, demonstrating a progressive decline in mechanical parameters, freeze-thaw resistance coefficients, and weathering resistance coefficients with increasing cycle counts. These studies collectively highlight the significant influence of freeze-thaw processes on rock integrity, while also underscoring the variability in degradation behavior across different lithologies and environmental exposures.

Gravelly red sandstone soil is a well-known geomaterial in cold-region engineering, and has been widely used in structural projects including road embankments, railway subgrades, and slope fills in areas like North- and Southwest China (Kong et al., 2022; Yu, Chen, Li, Zhou, Cai, 2015). The prevalence of red sandstone soils stems from ubiquitous natural deposits, yet its mechanical behavior under freeze-thaw (F-T) cycles remains a critical concern as a result of adverse climate conditions (Dong et al., 2024; Wang M. M. et al., 2024; Öztürk and Kılınçkale, 2023). Red sandstone, known for its high porosity and weak cementation, is capable of undergoing accelerated weathering when exposed to freeze-thaw cycles, resulting in reduction of its load-bearing capacity and structural degradation (Liu et al., 2024; Wang B. et al., 2024). For these reasons, our study investigated the compressive strength and stress-strain characteristics of gravelly red sandstone soil under varying F-T cycles, confining pressures, and gravel and water contents with the goal of furthering a key knowledge gap in cold-region geotechnics.

It has been reported that the unique weathering properties of red sandstone such as clay mineral expansion and fissure development is capable of exacerbating F-T engineering failures, distinguishing it from conventional granular soils (Zhang et al., 2019; Freire-Lista et al., 2015). Experimental results reveal that increasing gravel content mitigates strength loss by improving drainage and reducing ice lens formation, while higher confining pressures partially counteract F-T-induced weakening. These findings align with prior studies on similar lithologies (Yu et al., 2024; Yin et al., 2023; Yu et al., 2015; Chamberlain and Gow, 1979), but this work specifically quantifies the coupled effects of gravel fraction and F-T cycles, offering practical insights for engineering design.

Recent studies have explored the laboratory simulation of freeze-thaw effects on soils through direct and indirect methods. The direct method involves exposing soil specimens to controlled freezing and thawing temperatures, replicating natural conditions observed in cold regions (Liu et al., 2022; Kong et al., 2020). The indirect method, on the other hand, simulates ice lens formation by applying osmotic suction to induce freeze-thaw effects (Lu et al., 2021). These laboratory methods have significantly improved with the advent of advanced soil testing apparatus, such as Automated Soil Water Characteristic Models (SWCMs), which provide more precise control over soil moisture conditions and freeze-thaw cycles (Gharemahmudli et al., 2023; Liu et al., 2023).

Although the influence of F-T cycles on fine-grained soils has been extensively documented, gravelly soils remain an under-explored area of research (Yang et al., 2024; Jia et al., 2023). Some studies suggest that gravelly soils with 30% gravel content exhibit optimal compactness, minimal heat loss, and reduced water migration, leading to increased resistance to freeze-thaw degradation (Cheng, Wang, Liang, Zheng, and Liu, 2023; Chen et al., 2022; Zou, Ding et al., 2020; Liu et al., 2016; Xie et al., 2015). However, the interplay between gravel fraction, initial water content, confining stress, and freeze-thaw cycles remains complex and requires further investigation (He et al., 2022; Deprez et al., 2020). Understanding these factors is crucial for designing more resilient geotechnical structures in regions subjected to seasonal freezing.

This study aims to systematically investigate the mechanical behavior of gravelly soil under cyclic freezing and thawing. By evaluating stress-strain characteristics, compressive strength variations, and deformation mechanisms, this study advances the understanding of gravelly red sandstone soils mechanical responses to freeze-thaw cycles in cold environments. The findings are vital for optimizing the design and maintenance of pavements, embankments, and foundation structures exposed to seasonal freeze-thaw conditions, ultimately enhancing the durability and stability of geotechnical infrastructure in cold regions.

2 Materials and methods

2.1 Experimental design

The experimental procedure used for the present work was conducted to evaluate the effects of freeze-thaw (F-T) cycles and varying crushed stone content on the mechanical behavior of red sandstone gravelly soil. The test procedure consisted of three major steps including sample preparation, freeze-thaw cycling, and triaxial shear testing. For the purpose of the present research to investigate, red sandstone gravelly soil samples were prepared with varying crushed stone contents of 0%, 20%, 40% and 60%. The experimental design included the application of five major treatments each subjected to 0, 2, 4, six and eight freeze-thaw cycles. In each group, three replicate samples were prepared, giving a total of 60 tests (5 F-T cycles × 4 stone contents × 3 replicates). To simulate realistic field conditions in engineered fills (e.g., embankments and sub-grades), the water content was adjusted according to gravel content (25 g at 8.3 g water content for three soil mixtures), 17 g at 5.66 g water content for three soil mixtures, 17 g at 5.66 g water content for three soil mixtures, and 12 g at 4 g water content for three soil mixtures, respectively), reflecting natural variations due to differences in fine-grained matrix retention (Tao et al., 2022; Yu et al., 2015). The specimens were prepared at optimal compaction states, ensuring representative density and stability for each mixture. Triaxial shear tests were conducted after F-T cycling to assess mechanical degradation, with the experimental design prioritizing field-relevant conditions over measured moisture levels to better capture the influence of gravel on F-T resistance and stress-strain response. Unconsolidated undrained (UU) triaxial shear tests were performed with confining pressures of 100, 200, and 300 kPa to assess the reduction of shear strength. The tests were performed at a controlled strain rate of 0.8 mm/min until 20% axial strain was reached.

2.2 Sample preparation

The red sandstone cores used in this study were extracted from a single, intact block to ensure uniformity and consistency in material properties. This block was carefully quarried from a red sandstone formation in Hengyang, Hunan Province, China. Hengyang's red sandstone was selected due to its low exposure to freeze-thaw cycles, minimizing material degradation compared to sandstone from other regions. The extraction process involved controlled cutting techniques to preserve the integrity of the rock, ensuring minimal fractures or inherent structural weaknesses. To categorize the red sandstone into various particle size distributions, a multi-layered vibrating screening system was employed. This system effectively segregated sandstone particles into predefined size ranges between 0.1 mm and 2 mm, ensuring uniform gradation for experimental consistency. The classified red crushed sandstone samples were then measured, placed in a triaxial saturator cylinder, and subjected to compaction to replicate natural field conditions before testing.

FIGURE 1
Processed red sandstone specimens used in the experiment.

To prepare the cylindrical specimens, the sandstone block underwent multiple processing steps, including cutting, drilling, leveling, and polishing to conform to international testing standards. Standard cylindrical specimens (diameter = 39.1 mm, height = 80 mm) were prepared by compacting soil-rock mixtures in three layers within a triaxial sampler, with both ends precisely machined to maintain parallel surfaces, ensuring even distribution of load during mechanical testing. The soil mixtures were proportioned according to predetermined gradation curves, with crushed red sandstone contents of 0%, 20%, 40%, and 60%. Each sample was uniformly compacted to ensure consistent density and minimize variability. Any specimens exhibiting visible heterogeneity, excessive deviations in dimensions, or joint fractures were excluded to eliminate the influence of rock dispersion on test results. A selection of processed sandstone specimens used in this study is shown in Figure 1. The image highlights the precision in specimen preparation, ensuring uniformity in shape and surface finish.

2.3 Experimental procedures for freeze-thaw cycling

The prepared samples were subjected to 0, 2, 4, 6, or eight freeze-thaw cycles to simulate the seasonal weathering effects on the red sandstone gravelly soils. Based on the experimental design, each cycle consisted of freezing at −20°C for 12 h followed by thawing at room temperature (20°C) for 12 h. This process was adopted to ensure the complete phase transition and moisture redistribution within the samples. The procedure adopted for the present work followed the standard freezing and thawing protocols reported by He et al. (2024), He and Lu (2024a), He and Lu (2024b). Once the samples were prepared, triaxial shear tests were conducted using a fully automated TSZ triaxial shear testing system. The TSZ triaxial shear equipment, shown in Figure 2, provided precise control over

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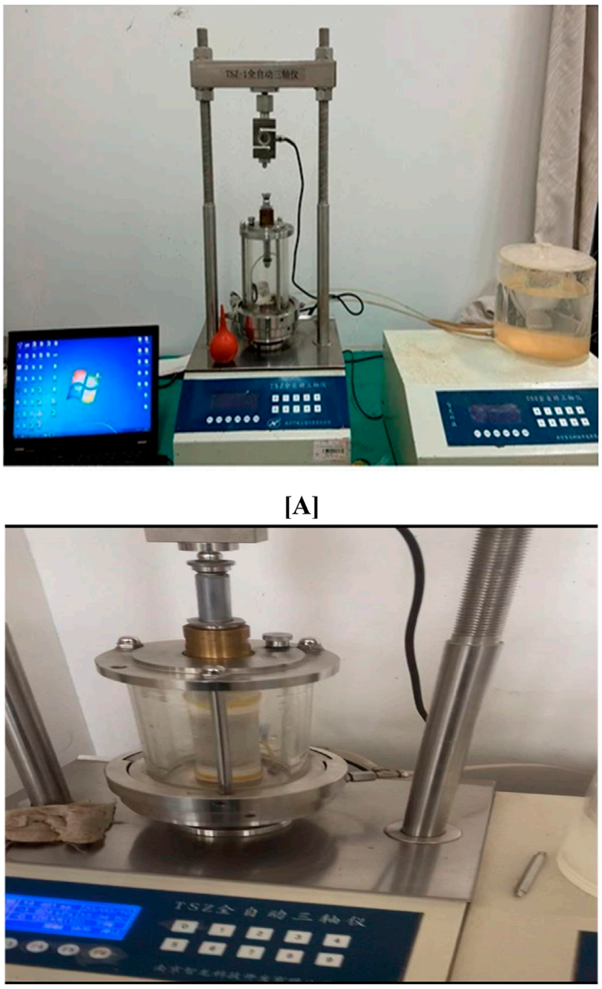

[A]
[B]

FIGURE 2
The TSZ full-automatic triaxial shear testing device **(A)** used for mechanical characterization involving actual soil specimens **(B)**.

confining pressures, axial stress, and displacement rates, ensuring high reproducibility and accuracy in mechanical characterization.

2.4 Experimental equipment and testing parameters

Following the freeze-thaw cycling, the soil-rock mixture samples were subjected to triaxial shear testing under unconsolidated undrained (UU) conditions using a strain-controlled triaxial apparatus (Figure 2). Based on the experimental design for the present work, three confining pressures of 100, 200, and 300 kPa were applied to investigate the mechanical properties of the samples under different stress conditions. The tests were conducted at a constant shear rate of 0.8 mm/min until 20% axial strain was achieved, allowing for the determination of peak and residual shear strengths. The results of the stress-strain responses obtained were recorded and used to evaluate the influence of freeze-thaw-induced effects and associated impacts on the mechanical behaviour of red stone gravelly soils in cold regions. The detailed parameters of each group are shown in Table 1.

The TSZ full-automatic triaxial shear testing apparatus used in this study is a high-capacity system with a maximum axial load capacity of 1000 kN. This advanced system allowed for precise stress-strain measurement under controlled laboratory conditions. Figure 2 presents the TSZ full-automatic triaxial shear testing device used for axial compressive testing of the soil specimens. This high-precision apparatus ensures accurate measurement of stress-strain responses under different test conditions.

The uniaxial compressive strength (UCS) tests were performed in displacement-control mode, with a constant displacement rate of 0.8 mm/min, following internationally recognized testing standards for rock and granular materials. The axial stress and strain relationship was continuously monitored throughout the experiment, providing critical insights into the mechanical behavior and deformation characteristics of red sandstone under controlled loading conditions.

3 Results and discussion

3.1 Weathering classification of gravelly soil under freeze-thaw cycles

The weathering of soil is commonly classified into four primary categories: intact, slightly weathered, moderately weathered, and highly weathered. In this study, the classification was determined based on the gradation of freeze-thaw (F-T) cycles, with 0% and 20% cycles representing intact and slightly weathered soils, respectively, while 40% and 60% cycles correspond to moderately weathered and highly weathered soils, respectively. This classification aligns with prior studies, which have reported that upper limits for F-T weathering cycles typically range between 40 and 60 cycles. Therefore, to effectively assess the impact of F-T cycles on the strength characteristics of gravelly soil, these upper weathering categories were adopted. By selecting 0, 20, 40, and 60 F-T cycles, this study effectively evaluates the progressive influence of initial (intact), slightly, moderate, and highly weathered conditions on the mechanical properties of gravelly soils. The intact and slightly weathered samples maintain structural integrity, whereas the moderately and highly weathered samples exhibit visible cracks and micro-fractures induced by the cyclic freezing-thawing process. These fractures suggest that prolonged F-T cycling significantly alters the structural integrity of gravelly soil, reducing its mechanical strength and increasing susceptibility to further degradation.

All figures (Figures 3–7) show shear stress plotted against axial strain (%). The curves typically exhibit an initial linear elastic region, followed by yielding and eventual failure or degradation. The general soil-rock mixtures impact indicated that as gravel content increases, the stress-strain curves shift, indicating changes in soil strength and stiffness. More so, higher gravelly soil content generally results to higher peak stress and stiffness which might have been associated with the granular nature of gravel improving load-bearing capacity. However, the number of F-T cycles (0, 2, 4, 6, and 8 days) affects the curves, with more cycles often reducing peak stress and stiffness due to soil structure degradation from ice formation and thawing.

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TABLE 1 Freeze-thaw cycle times, soil-rock contents and testing parameters used.

F-T cycle times	Stone content	Water content	Confining pressure (kPa)
0	0%	25 g @ 8.3 g for 3 mixtures	100,200,300
	20%	17 g @ 5.66 g for 3 mixtures	100,200,300
	40%	17 g @ 5.66 g for 3 mixtures	100,200,300
	60%	12 g @ 4 g for 3 mixtures	100,200,300
2	0%	25 g @ 8.3 g for 3 mixtures	100,200,300
	20%	17 g @ 5.66 g for 3 mixtures	100,200,300
	40%	17 g @ 5.66 g for 3 mixtures	100,200,300
	60%	12 g @ 4 g for 3 mixtures	100,200,300
4	0%	25 g @ 8.3 g for 3 mixtures	100,200,300
	20%	17 g @ 5.66 g for 3 mixtures	100,200,300
	40%	17 g @ 5.66 g for 3 mixtures	100,200,300
	60%	12 g @ 4 g for 3 mixtures	100,200,300
6	0%	25 g @ 8.3 g for 3 mixtures	100,200,300
	20%	17 g @ 5.66 g for 3 mixtures	100,200,300
	40%	17 g @ 5.66 g for 3 mixtures	100,200,300
	60%	12 g @ 4 g for 3 mixtures	100,200,300
8	0%	25 g @ 8.3 g for 3 mixtures	100,200,300
	20%	17 g @ 5.66 g for 3 mixtures	100,200,300
	40%	17 g @ 5.66 g for 3 mixtures	100,200,300
	60%	12 g @ 4 g for 3 mixtures	100,200,300

3.2 Stress-strain behavior of gravelly soil

A series of triaxial compressive tests were conducted to evaluate the freeze-thaw (F-T) characteristics of gravelly soils with varying gravel contents. Figures 3–7 illustrate the variations of stress with axial strains (%) for gravelly soil samples subjected to different freeze-thaw (F-T) cycles (0, 2, 4, 6, and 8 days) and varying gravelly soil contents (0%, 20%, 40%, and 60%). The results indicate that the stress-strain behavior of gravelly soil is significantly influenced by both freeze-thaw duration and gravel content. The stress response typically increases with gravel content, although prolonged freeze-thaw cycling leads to a reduction in peak strength due to the degradation of particle interlocking and increased pore water expansion.

Figure 3 (with four subplots (a–d), each representing the different gravel contents) shows the baseline mechanical behavior of gravelly soils before the freeze-thaw (F-T) cycles were applied, serving as the critical control for this experimental series. The four stress-strain curves clearly demonstrate how increasing gravel content (0%, 20%, 40%, and 60%) enhances soil performance, with the 0% gravel sample showing the characteristic low strength and high ductility of fine-grained soils, while the 60% gravel blend exhibits nearly triple the peak stress and significantly greater stiffness. These baseline measurements reveal gravel's immediate structural benefits - the coarse particles create a load-bearing skeleton that improves stress distribution and limits particle rearrangement, while simultaneously reducing the water-holding fines responsible for weakness in pure clay/silt mixtures. The progressive stiffening and strengthening across the gravel percentages provide valuable reference points for evaluating subsequent F-T damage.

The stress-strain relationship between the 0% and 60% gravel soil samples underscores why pure fine soils are avoided in load-bearing applications, while the intermediate curves (20% and 40% gravel) offer engineers a gradient of options for balancing material costs with performance requirements. Notably, the 40% gravel mix showed about 80% of the strength benefit of the 60% mix, potentially representing a cost-effective compromise for geotechnical applications. These baseline results prove that gravel modification alone - even before considering F-T resistance -

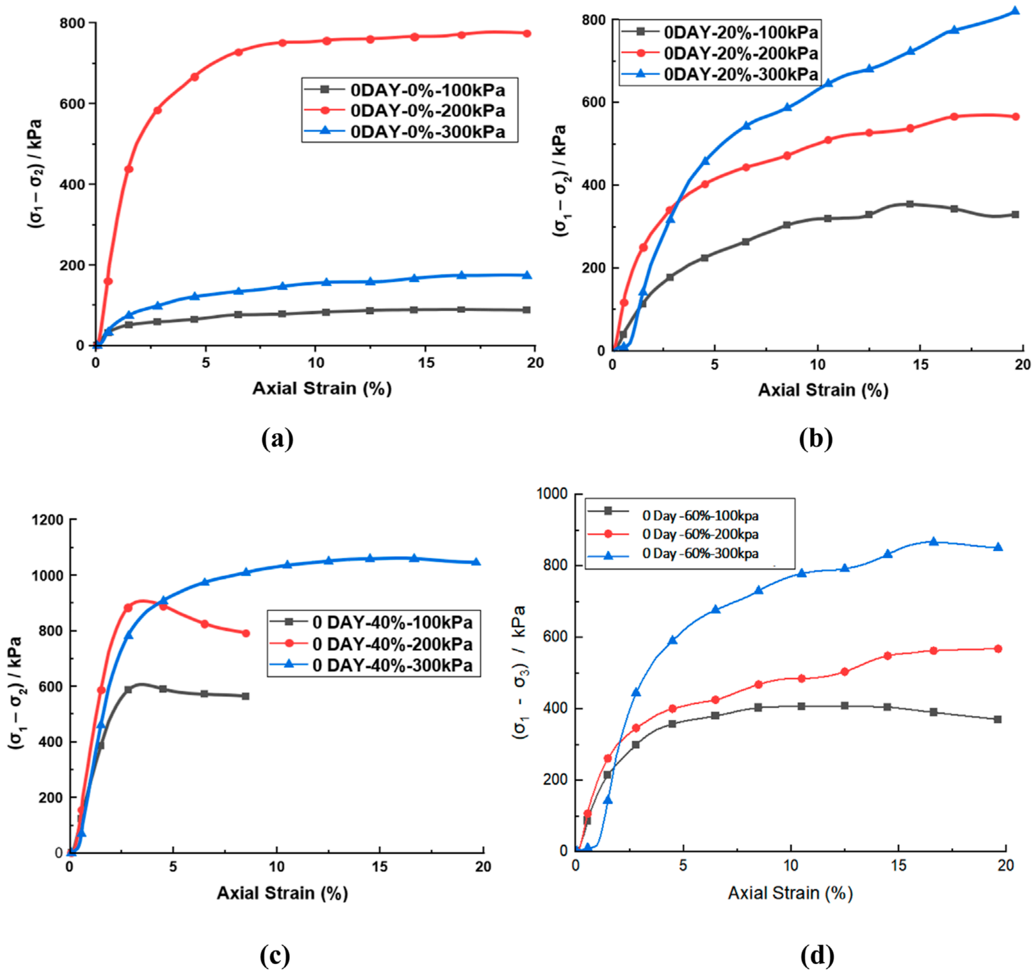

FIGURE 3
Variations of stress with axial strains (%) with varying percents [0 **(a)**, 20 **(b)**, 40 **(c)**, and 60% **(d)**] gravelly soil contents on freezing-thawing characteristics after 0 days.

can transform unsuitable fine soils into competent engineering materials.

Furthermore, at 0 days of freeze-thaw cycles, gravelly soil samples exhibited higher peak stress values, particularly for specimens with higher gravel content. The intact soil structure provided strong interparticle bonding, resulting in greater resistance to compressive loading. The stress-strain curves at this stage demonstrate a steady increase in stress with axial strain, indicating the material's ability to sustain higher loads before failure (Figure 3). However, there is an unexpected elevation of the 200 kPa curve above the 300 kPa response in Figure 3a which might likely be attributed to material heterogeneity and dilation effects (Yu et al., 2015; Yuanming et al., 2010). At intermediate confinement, soil dilation may temporarily enhance shear resistance, while higher pressure (300 kPa) could suppress this mechanism, promoting particle rolling instead. Alternatively, freeze-thaw-induced micro-cracking might disproportionately weaken the 300 kPa specimen. Such nonlinear pressure-strength relationships have been reported in frozen soils, where ice-bond disruption and compaction variability create complex mechanical interactions (Zhou et al., 2024; Yuanming et al., 2010). This finding highlights the complex pressure-strength characteristics of gravelly soils under combined confinement and thermal cycling. More so, the distinct peaks at ~3% strain for 100 and 200 kPa specimens (Figure 3c) reflect brittle failure caused by ice cementation and soil particle interlock. Lower confinement allows sudden rupture as ice bonds break, while higher pressures (300 kPa) tends to promote the ductile behavior of the sample through particle rearrangement, thus leading to suppression of peak formation (Wang B. et al., 2024; Yu et al., 2024; Qi and Ma, 2006).

After 2 days, minor micro-fractures began forming, leading to slight reductions in peak strength, especially in fine-grained samples. The stress-strain relationship begins to show signs of weakening, as indicated by a gradual decrease in stress resistance, particularly in samples with 0% and 20% gravel content. This suggests that finer particles are more prone to structural degradation under early freeze-thaw cycling (Figure 4).

Figure 4 illustrates how two freeze-thaw (F-T) cycles affect the stress-strain response of gravelly soils with varying gravel contents (0%, 20%, 40%, and 60%). In comparison with Figure 3 (F-T cycles on 0 days), all samples exhibit reduced peak stress and stiffness, indicating F-T-induced degradation. The 0% gravel sample showed

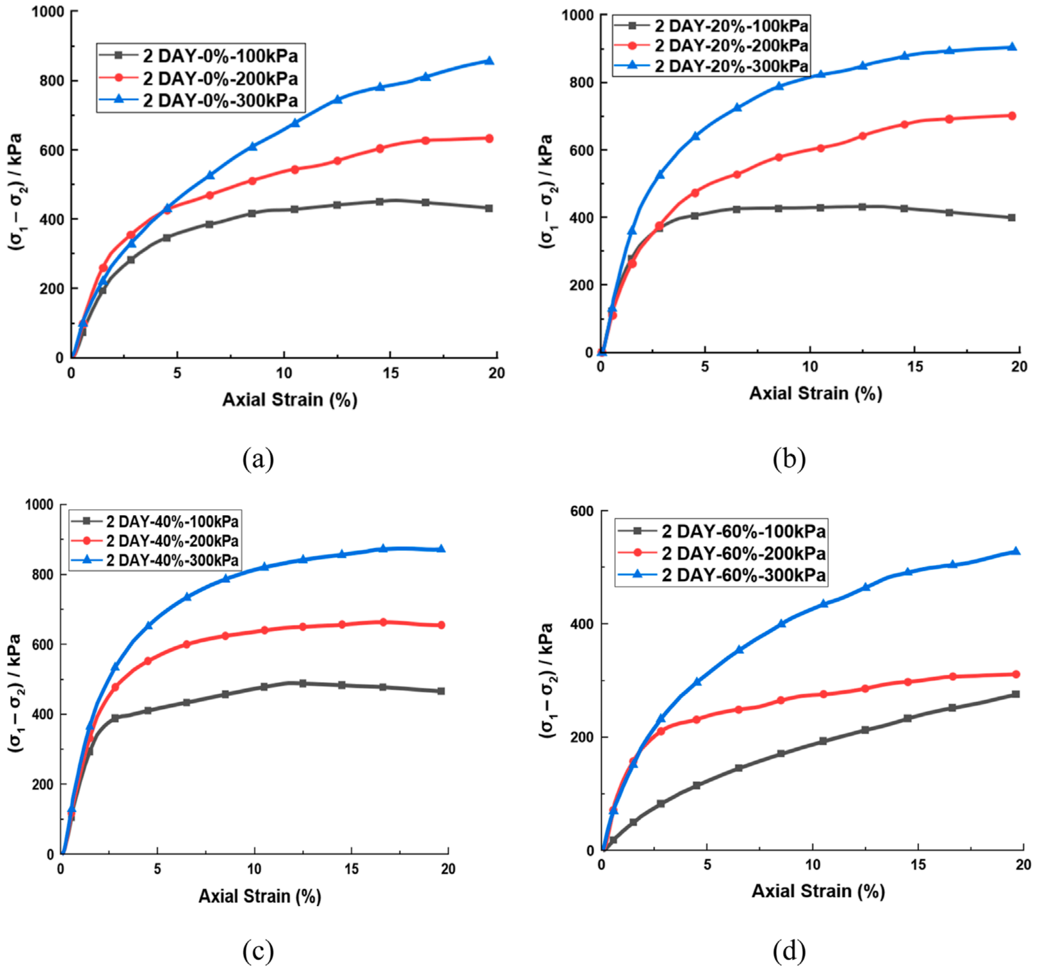

FIGURE 4
Variations of stress with axial strains (%) with varying percents [0 **(a)**, 20 **(b)**, 40 **(c)**, and 60% **(d)**] gravelly soil contents on freezing-thawing characteristics after 2 days.

the most severe decline, with a flattened curve suggesting significant structural damage from ice expansion in the fine gravelly soil matrix. In contrast, higher gravel soil contents (40%–60%) indicated better resistance to weathering degradation process, thus maintaining steeper initial slopes and higher peak stresses. This might have been due to reduced water retention and improved load distribution. However, even these samples demonstrated slight softening, which confirmed that gravel mitigated F-T damage. The result showed the importance of gravel soils in cold-region engineering, where minimizing F-T cycles or supplementing with soil stabilizers may be necessary for long-term stability. The data obtained in this study confirms previous reports and emphasized a clear trend: while gravel enhances durability, prolonged environmental exposure still compromises performance (Jia et al., 2023; Li et al., 2023; Chang and Liu, 2013).

Figure 5 presents the variations of stress with axial strains (%) for gravelly soil samples (0, 20, 40, and 60% gravel content) after 4 days of freeze-thaw cycles. A noticeable decline in peak stress values is observed, particularly in specimens with lower gravel content, due to the development of initial microfractures. By day 4, a more pronounced decline in stress was observed, with finer-grained soils losing more strength due to increased particle rearrangement and moisture migration. The stress-strain curves indicate a clear shift towards a more ductile failure mode, as samples with 0% and 20% gravel content show significant strain softening, meaning that after peak stress, the material rapidly loses its ability to withstand additional load (Figure 5).

In comparison to Figures 3, 4, the degradation under the cumulative effect of F-T is more pronounced, with all soil-rock samples showing further reductions in peak stress and stiffness. The 0% gravel sample exhibited near-complete loss of structural integrity, behaving almost like a viscous fluid with minimal stress resistance. Meanwhile, the 20% gravel mix showed significant softening, though it retained marginally better performance than the pure gravelly fine soil sample. The 40% and 60% gravel samples maintained higher stress capacities, but their curves revealed noticeable post-yield weakening, indicating that even robust gravel blends are not immune to extended F-T exposure.

The divergence in behavior between low- and high-gravel samples highlighted gravel's role in mitigating damage. At 40%–60%

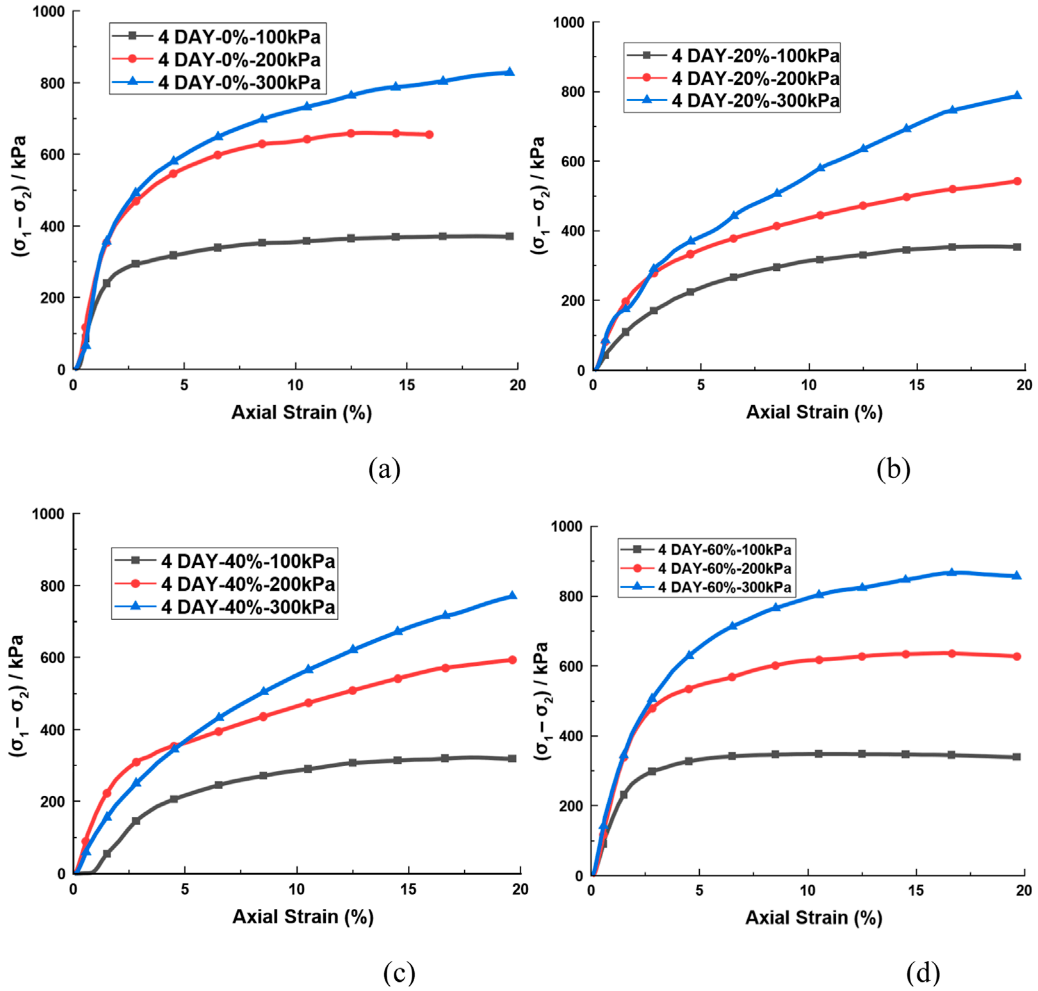

FIGURE 5
Variations of stress with axial strains (%) with varying percents [0 **(a)**, 20 **(b)**, 40 **(c)**, and 60% **(d)**] gravelly soil contents on freezing-thawing characteristics after 4 days.

gravel, the coarse particles showed limited water retention and ice lens formation, preserving the skeletal structure of the soil. However, the persistent decline in performance after four cycles suggests that gravel alone cannot entirely prevent long-term F-T deterioration. These findings emphasized the need for additional stabilization method such as the use of chemical additives or geosynthetics especially in cold-region environment prone to repeated F-T cycles.

After 6 days, the mechanical response exhibited a brittle failure mode, indicating significant deterioration. The stress-strain curves reveal that samples with higher gravel content (40% and 60%) still retain some strength, but a rapid decline in stress after peak loading is observed in finer-grained samples. This suggests that the coarse fraction contributes to residual strength, while finer materials experience more severe degradation (Figure 6)

Figure 6a–d presents the progressive deterioration of gravelly soils subjected to freezing-thawing cycles, marking a critical threshold in material performance. The 0% gravel sample indicated negligible stress resistance, behaving more like a loose sediment than an engineered material. The result showed that the extreme vulnerability of fine-grained soils to repeated F-T impact. Although the 20% gravel mix was marginally better, the sample exhibited severe strength loss and near-complete loss of stiffness. In contrast, the 40% and 60% gravel samples retained measurable load-bearing capacity, although the peak stresses of the mixture were significantly reduced compared to earlier cycles. The curves for these higher-gravel mixtures flattened post-yield, indicating a shift from brittle to more ductile failure modes. This potentially means that the soil matrix might be increasingly compromised despite the reinforcing effects of the gravelly soil.

However, while the 60% gravel mix still outperforms others, its declining performance after six cycles suggested that the infrastructure in severe cold-region climates may require additional safeguards, such as drainage systems or lime stabilization. This figure also provides practical insights for maintenance planning; structures using 40%–60% gravel may need inspections or repairs after 5–6 F-T cycles to prevent failure. It reinforces the finding that samples with higher gravel content retain greater mechanical stability, while finer-grained samples exhibit more drastic strength loss.

At 8 days, the stress-strain curves showed a stabilized degradation threshold, where additional freeze-thaw cycling

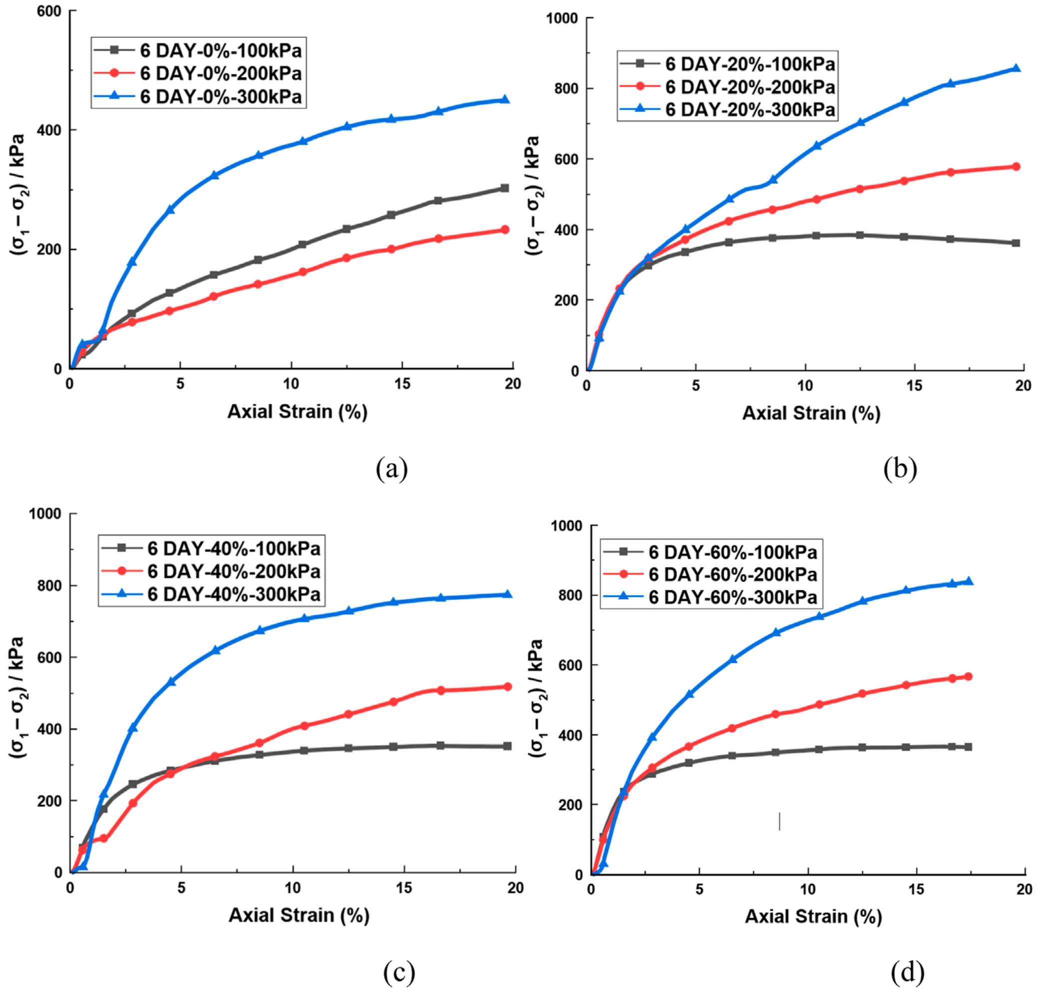

FIGURE 6
Variations of stress with axial strains (%) with varying percents [0 **(a)**, 20 **(b)**, 40 **(c)**, and 60% **(d)**] gravelly soil contents on freezing-thawing characteristics after 6 days.

produced minimal further weakening. The degradation appears to reach an equilibrium state, indicating that beyond this point, the material has already undergone most of its mechanical deterioration. Higher gravel content samples still maintain some structural integrity, whereas lower gravel content samples exhibit significantly reduced peak stress (Figure 7).

Figure 7 presents the critical endpoint of this experimental series, demonstrating the devastating cumulative effects of eight F-T cycles on soil stability. The complete collapse of the 0% gravel sample's stress-strain curve confirmed that fine-grained soils became essentially non-structural after prolonged F-T exposure, with bearing capacity reduced to near-zero levels. Furthermore, while the 20% gravel mixture indicated marginally better performance, its extremely flattened curve indicated that the stress-strain relationship had reached practical failure. Most significantly, even the previously resilient 40% and 60% gravel mixtures exhibited severe degradation, with peak stresses reduced by approximately 60%–70% compared to their baseline (0 days) values in Figure 3. The near-convergence of all curves at higher strains suggests that beyond 8 days exposure, the gravel contents could become less relevant as all samples approach a similar compromised state. Worded differently, the curves suggest that mechanical degradation stabilizes beyond 8 days, with peak stress values reaching their lowest for fine-grained samples.

3.3 Analysis of stress with axial strains

A total of twenty-four (24) gravelly soil samples were tested under triaxial loading conditions in freeze-thaw (F-T) cycles of 0, 20, 40, and 60% at confining pressures of 100, 200, and 300 kPa for duration of 0, 2, 4, and 8 days. In line with the study objectives, four soil samples were analyzed for each F-T cycle to ensure consistency and statistical relevance. The compressive strength tests were conducted in accordance with the standardized method proposed by the International Society for Rock Mechanics (ISRM, 1981). The variations in deviatoric stress (σ_1-σ_3) with axial strain for different weathering conditions (0%–60% F-T cycles) are illustrated in Figures 3–7.

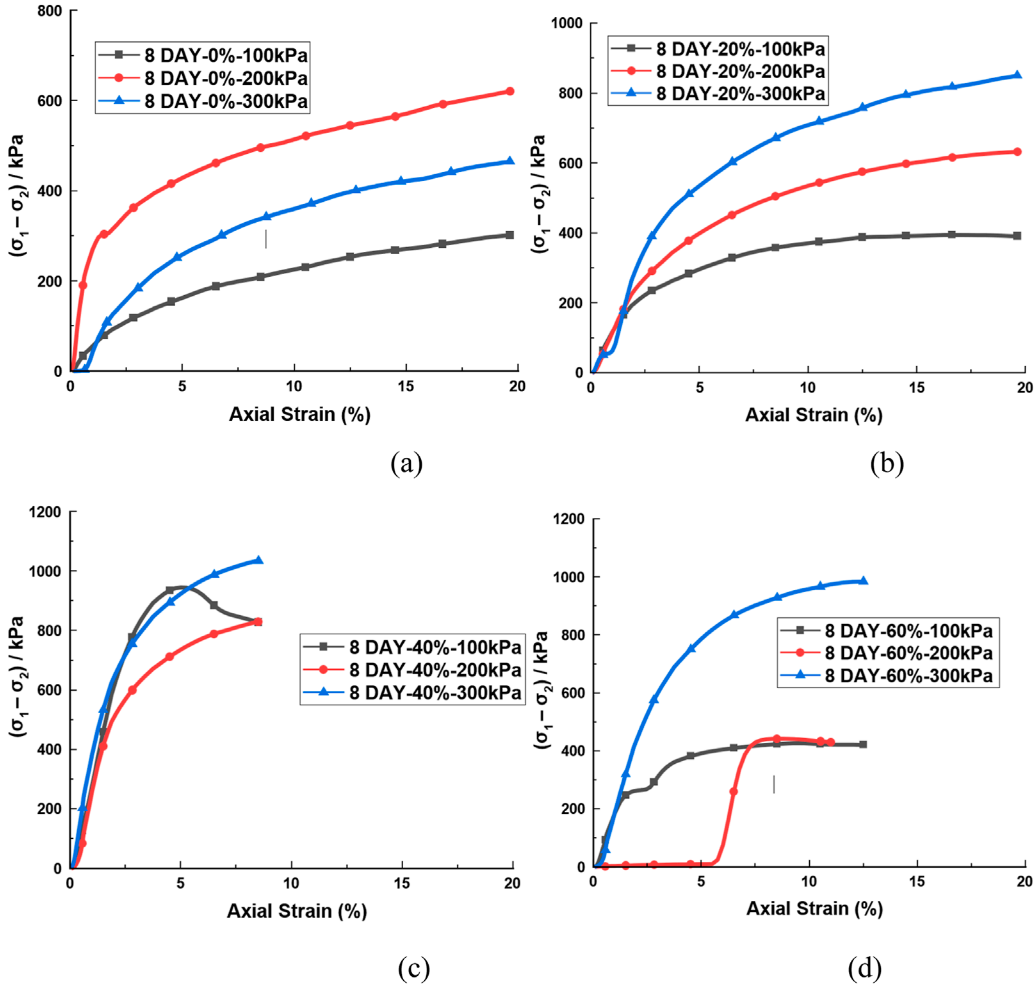

FIGURE 7
Variations of stress with axial strains (%) with varying percents [0 **(a)**, 20 **(b)**, 40 **(c)**, and 60% **(d)**] gravelly soil contents on freezing-thawing characteristics after 8 days.

The results indicate that the initial deviatoric stress points are nearly aligned with the coordinate origin in almost all cases. This observation suggests that the soil samples were uniformly consolidated under anisotropic stress conditions, leading to a relatively consistent trend. However, exceptions were noted at 8 days for the 40% and 60% F-T cycles, particularly at 200 and 300 kPa confining pressures, where deviations were observed, indicating possible irregular consolidation effects.

At 0 days (0% weathering, Figure 3), the deviatoric stress increases sharply, reaching its peak at a moderate strain level under 200 kPa confining pressure. The rate of increase in stress, however, does not show a proportional intensification at 200 and 300 kPa for 40% F-T cycles, suggesting a threshold beyond which further confining pressure does not significantly contribute to strength retention. In contrast, for 2, 4, and 6 days of freeze-thaw exposure (Figures 4–6), a direct correlation between deviatoric stress and increasing confining pressure (100, 200, and 300 kPa) was observed. This confirms that higher effective confining pressure enhances soil resistance to deformation, particularly in less weathered samples.

At 8 days of freeze-thaw exposure (Figure 7), the deviatoric stress-strain relationship presents anomalous behavior, particularly for 40% and 60% F-T cycles at 200 and 300 kPa. This suggests that soil specimens under prolonged freeze-thaw cycling exhibit localized structural failures, microcracking, and increased void formation, potentially due to non-uniform consolidation or strain localization. Previous studies have reported that under high pressure and extreme environmental conditions, soil specimens become more prone to microfracturing and progressive disintegration (Pan et al., 2023; Han et al., 2020; He et al., 2020).

Interestingly, strain-softening behavior was not evident across all three distinct effective confining pressures. This suggests that higher confining pressure serves as a constraint against excessive particle displacement and overriding, thereby improving soil stability. However, minor abrupt stress drops were noted, likely due to internal particle rearrangements and breakage of angular grains under high-stress conditions. These sudden fluctuations indicate fracture propagation along weak planes, particularly when the contact stress exceeds the particle strength threshold.

4 Conclusion

This study systematically investigated the mechanical behavior of gravelly soil under varying freeze-thaw (F-T) cycles, different strain thresholds, three distinct effective confining pressures, and initial water content. The major findings can be summarized as follows:

1. The compressive strength of gravelly soil is significantly influenced by three key factors: gravel content, initial water content, and confining stress. These factors collectively determine the soil's resilience under cyclic freezing and thawing conditions.
2. The deviatoric stress (σ_1-σ_3) does not increase proportionally with rising confining pressure at 200 and 300 kPa during 40% freeze-thaw cycles in the initial compact state. This suggests a potential saturation limit where additional confinement does not contribute significantly to strength enhancement.
3. A direct correlation exists between deviatoric stress and increasing confining pressure (100, 200, and 300 kPa) over 2, 4, and 6 days of freeze-thaw cycling. The rate of increase in stress is more pronounced at higher effective confining pressures, indicating that greater confinement mitigates strength loss in weathered soil samples.
4. No strain-softening behavior was observed across the range of confining pressures. This phenomenon indicates that higher confining pressure acts as a constraint against excessive particle displacement and overriding, enhancing soil stability even under prolonged freeze-thaw exposure.

These findings provide valuable insights into the mechanical degradation and stress-strain behavior of gravelly soils subjected to freeze-thaw cycles. The results have significant implications for the design and stability assessment of geotechnical structures in cold climates, emphasizing the importance of optimizing gravel fraction, moisture control, and confining stress in infrastructure projects.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

EB: Data curation, Investigation, Conceptualization, Formal Analysis, Visualization, Writing – review and editing, Writing – original draft. PC: Writing – original draft, Supervision, Writing – review and editing, Conceptualization, Validation, Methodology. LC: Visualization, Formal Analysis, Writing – review and editing, Writing – original draft, Software.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

The research in this paper was supported in part by International Postgraduate Student Scholarship, University of South China.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2025.1619118/full#supplementary-material

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