# Study on Mechanical Properties and Fracture Characteristics of Composite Stabilized Saline Soil under Alternating Wet-Dry and Freeze-Thaw Cycles

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**Abstract: Saline soils in semi-arid and seasonally frozen regions are prone to deterioration due to evaporation, salt crystallization, and repeated wet–dry–freeze–thaw cycles, compromising engineering performance. This study investigates saline soil from Qian'an County, western Jilin Province, and evaluates a composite stabilization approach using sulfonated-free lignin, basalt fiber, and a hydrophobic polymer. Microstructural analyses and simulated environmental cycles demonstrate significant improvements in strength, durability, crack resistance, and long-term stability compared with untreated soil.**

**Keywords:** ***Saline Soil, Wet-Dry and Freeze-Thaw Cycles, Microstructural characterization.***

## Introduction

Saline soils in semi-arid regions and areas subjected to seasonal freeze–thaw processes often experience significant degradation of their physical and structural properties. Periodic evaporation and repeated freeze–thaw cycles promote salt migration, crystallization pressure, soil softening, and cracking, all of which compromise the mechanical stability of engineering foundations constructed on such soils. Addressing this challenge is particularly important for infrastructure projects in northern China, where seasonal climatic variations intensify deterioration.

This study investigates saline soil from Qianan County in western Jilin Province and explores the potential of three environmentally friendly solidification materials, sulfonated-free lignin, basalt fiber, and a hydrophobic polymer, to enhance soil stability, durability, and resistance to freeze–thaw damage.

## Saline Soil in the Qianan Region

A systematic evaluation of the distribution patterns, salt content, and basic physicochemical properties of the local saline soil was conducted to determine the severity of salinization and its implications for engineering behavior.

Laboratory tests revealed that the soil exhibits pronounced salt accumulation, high dispersivity, and weak structural integrity, making it vulnerable to climatic and hydrological fluctuations. Understanding these characteristics established the baseline for designing a composite solidification approach tailored to the region's environmental conditions.

## Composite solidification and mechanisms

To develop a sustainable and efficient reinforcement strategy, three novel materials were introduced for synergistic solidification. Sulfonated-free lignin was selected for its natural polymeric structure and binding ability, basalt fiber for its mechanical reinforcement capacity, and a hydrophobic polymer for its ability to reduce moisture ingress and inhibit salt migration.

Microstructural characterization techniques, including scanning electron microscopy, energy-dispersive spectroscopy, and water contact angle measurements, were applied to clarify the solidification mechanisms. The hydrophobic polymer was found to form a moisture-resistant film that inhibited capillary rise, while lignin improved interparticle bonding and basalt fiber enhanced tensile resistance. The combined effects resulted in a denser, more connected soil matrix with enhanced resistance to cracking and moisture-induced deterioration.

## Assessment of physicochemical and mechanical properties

The modified soils were subjected to detailed analyses to evaluate changes in moisture retention, pore distribution, permeability, and mechanical behavior. The introduction of composite solidification materials markedly reduced permeability and delayed the progression of salt crystallization. Mechanical tests showed significant improvements in unconfined compressive strength, cohesion, and crack propagation resistance compared to untreated soil. These enhancements provided critical evidence of the potential of composite reinforcement for stabilizing saline soils under variable climate conditions.

## Simulation of Wet–Dry–Freeze–Thaw Cycles

To replicate realistic environmental conditions, a self-developed testing apparatus was used to simulate alternating wet–dry–freeze–thaw (WDFT) cycles, reflecting the dynamic deterioration experienced in the field. Both untreated and solidified soil specimens underwent multiple WDFT cycles, and their mechanical properties, surface morphology, and microstructural changes were monitored throughout the process.

The WDFT cycles induced notable degradation in untreated saline soil, particularly during the initial cycles. Most mechanical deterioration occurred within the first five cycles, with a gradual decrease in the degradation rate after approximately ten cycles.

## Results and Performance Evaluation

The composite solidified soils demonstrated substantial improvements in durability under WDFT conditions. Strength enhancement reached levels up to 85.27 percent relative to untreated soil, indicating the effectiveness of the solidification materials in resisting degradation. The residual strength ratio of the treated soil remained significantly higher across all cycles, reflecting strong resilience against coupled wetting, drying, and freeze–thaw effects.

Importantly, the solidification effectiveness coefficient consistently exceeded 1 throughout the WDFT cycles, confirming the reliable and long-term reinforcement performance of the composite materials.

## Conclusion

This study provides a comprehensive evaluation of a novel, green, and synergistic solidification approach for saline soils exposed to fluctuating climatic conditions. The combined use of sulfonated-free lignin, basalt fiber, and hydrophobic polymer effectively improved soil structure, enhanced mechanical strength, and increased resistance to deterioration under alternating WDFT cycles. The findings demonstrate the potential of environmentally friendly composite stabilizers for long-term improvement of saline soil foundations in cold and semi-arid regions.