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Patterns of Shear Stress Changes in Turfy Soil Modified by Biological Enzymes

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Abstract: ***This study investigates the coupled effects of freeze-thaw cycles and bioenzyme modification on the shear properties of grass-turfy soils in seasonally frozen zones. Through systematic laboratory experiments, undisturbed turfy soil samples collected from a typical seasonal frozen soil area in Dunhua, Jilin Province, were subjected to Terra-Zyme enzyme treatments at concentrations of 0%, 1%, 3%, 5%, 8%, and 10%. Rapid shear tests were conducted after 0, 1, 5, 10, and 15 freeze-thaw cycles. Results indicate: (1) Freeze-thaw cycles significantly degrade the shear strength of turfy soils, with strength decay concentrated in the first five cycles before stabilizing. Both cohesion and internal friction angle exhibit declining trends, revealing the cumulative and irreversible nature of freeze-thaw damage; (2) Bioenzyme modification effectively enhances turfy soil shear properties, with an optimal dosage range. When Terra-Zyme content ranges from 3% to 5%, modified soil exhibits the most significant increases in cohesion and internal friction angle, achieving peak shear strength; (3) A coupled effect exists between freeze-thaw cycles and bioenzyme modification. Bioenzyme-modified soil retains certain strength advantages after freeze-thaw cycles, but its enhancement effect gradually diminishes with increasing freeze-thaw cycles. This study elucidates the combined influence mechanism of freeze-thaw cycles and bioenzyme modification on the shear properties of turfy soils. It provides a theoretical basis for stability design and reinforcement treatment of turfy soil foundations and subgrades in seasonally frozen regions. Practical engineering applications are recommended to adopt a bioenzyme content of 3%–5% while strictly controlling the number of freeze-thaw cycles.***

Keywords: Turfy soil, Freeze-thaw cycle, Biological enzyme modification, Shear strength, Terra-Zyme**.**

1. Introduction

Seasonal frozen ground is widely distributed across numerous regions in China. Its periodic freeze-thaw cycles frequently trigger a series of geotechnical issues such as frost heave and frost heaving in roadbeds, posing severe threats to the long-term stability and safety of engineering structures [1]. As a common high-organic-matter, fibrous soil in these regions, turfy exhibits uniquely complex mechanical property evolution during freeze-thaw cycles due to its composition. Research indicates specific characteristics in turfy's direct shear behavior: its fast shear stress-strain relationship follows Mohr-Coulomb law, while consolidated fast shear curves may exhibit discontinuous transitions [2]. Furthermore, freeze-thaw cycles significantly impact its mechanical properties, exhibiting a pronounced trend of strength degradation, necessitating further investigation.

Domestic and international scholars have made progress in studying the freeze-thaw characteristics of soils and their improvement through biological enzymes. Regarding freeze-thaw cycle research, numerous studies indicate that the freeze-thaw process significantly affects shear strength by altering the internal structure of the soil. For example, research on soil-rock mixtures shows that cohesion and internal friction angle gradually decrease with increasing freeze-thaw cycles, leading to shear strength deterioration [3]. Seasonal frozen soils also exhibit declining cohesion after freeze-thaw cycles [4]. Direct shear tests at the soil-reinforcement interface similarly demonstrate that shear strength parameters (cohesion and friction angle) decrease with increasing freeze-thaw cycles and stabilize after several cycles [5]. These studies reveal the general degradation pattern of soil mechanical properties under freeze-thaw cycles, though research subjects have primarily focused on conventional soils or modified cement-stabilized soils.

Regarding soil improvement techniques, fiber modification serves as an effective alternative to bioenzymes. For instance, basalt fibers have been employed to enhance cement-stabilized red sandstone soils, effectively suppressing crack formation and propagation while improving soil strength and deformation characteristics [6].

Regarding turfy soils themselves, preliminary studies have explored the relationship between their nonlinear mechanical behavior and fiber content [7], and observed their strength degradation patterns during freeze-thaw cycles [8]. However, existing research exhibits significant limitations: First, systematic investigations into the evolution of shear stress in turfy soil under freeze-thaw cycles remain scarce. Second, empirical evidence supporting the feasibility and effectiveness of bioenzyme modification of turfy soil is lacking. Third, the coupled mechanism between freeze-thaw cycles and bioenzyme modification has yet to be elucidated.

2. Experimental Materials and Methods

2.1 Turfy Soil

Figure 1: Turfy soil sampling

Table 1: Physical and Mechanical Properties of Turfy Soil

Soil Layer ID	Natural Moisture Content	Natural Density	Organic Matter Content	Degree of Decomposition	Clay Content	Silt content	Silt Content
	ω/%	ρ/(g/cm³)	Organic Matter Content (%)	D_d /%	Cclay/%	Csilt/%	Csand/%
1	239.71	1.267	0.567	0.722	8.68	70.92	20.4

The turfy soil used in this study was collected from the wetland section along National Highway G201 in Jiangyuan Town, Dunhua City, Jilin Province, China. This region exhibits typical seasonal permafrost characteristics [9]. Sampling was conducted in September using a static-pressure PVC soil sampler to collect undisturbed soil samples in layers at depths of 10–30 cm below ground level. Samples were immediately sealed after collection to prevent moisture evaporation and photodegradation.

Turfy soils primarily consist of organic fibers and soil particles forming aggregate structures, necessitating appropriate adjustments to the methods for determining their basic physical properties. Moisture content was determined using low-temperature drying at 60°C to avoid high-temperature decomposition of organic matter. Decomposition degree was measured using the boiling NaOH solution method proposed by Lang Huiqing et al. [10]. Specific experimental procedures followed the "Standard for Geotechnical Test Methods" (GB/T 50123-2019) [11]. The basic properties of samples from each soil layer are summarized in Table 1.

2.2 Biological Enzyme

This experiment employed Terra-Zyme (Terra-Zyme), produced by NATURE PLUS Inc. of the United States, as the solidifying agent. This enzyme is a transparent brownish-yellow liquid derived from plant fermentation, with a density of approximately 1.05 g/cm³, a pH value of 4.8, and is non-toxic, non-corrosive, and readily soluble in water. Terra-Zyme reduces soil permeability, enhances water stability, and improves mechanical properties by promoting particle bonding and optimizing pore structure.

Figure 2: Terra-Zyme solutions at different concentrations

2.3 Sample Preparation

First, mix the biological enzyme with water at a specific ratio to prepare five different concentrations of biological enzyme conditioner: 1%, 3%, 5%, 8%, and 10%, as shown in Figure 2. Distribute these solutions into separate spray bottles. Next, use an angle grinder to slowly cut and remove the undisturbed soil sample sealed within the first layer of the PVC pipe. Then, spray the conditioners of varying concentrations onto the surface of the undisturbed soil.as shown in Figure 3. After a five-minute rest period, the samples were sealed with plastic wrap and cured for 7 days. Following the curing period, the samples were used for subsequent experiments.

Figure 3: Bioenzyme-amended turfy soil samples

2.4 Freeze-Thaw Cycling Test

The cured soil samples were placed in a temperature-controlled freezer and frozen at -20°C for 12 hours. They were then transferred to a 20°C environment to thaw for 12 hours. This process constituted one freeze-thaw cycle. Based on preliminary tests, the number of freeze-thaw cycles was set to 0, 1, 5, 10, and 15. The experiment included six enzyme dosage levels ranging from 0% to 10% to systematically investigate their effects.

2.5 Direct Shear Test

The rapid shear test method was employed using a WI-1 strain-controlled direct shear apparatus. Testing strictly adhered to the Standard Test Methods for Geotechnical Engineering (GB/T 50123-2019) [11]. Specimens were ring-cut samples with a diameter of 61.8 mm and a height of 20 mm. Each test group included four parallel specimens subjected to shear under four vertical pressures: 100 kPa, 200 kPa, 300 kPa, and 400 kPa. The tests employed a stepwise automatic loading method without confining pressure, with a uniform shear rate of 1 mm/min. Considering the high organic content, fibrous nature, and strong compressibility of turfy soils, the tests were terminated at a shear displacement of 10 mm, with stress and displacement data collected simultaneously. The specific test plan is detailed in Table 2.

Table 2: Direct Shear Test Design

Sample No.	Biological Enzyme Dosage	Freeze-Thaw Cycles				
		Group A: 0 cycles	Group B: 1 cycle	Group C: 5 times	Group D: 10 times	Group E: 15 times
1	0%	A1	B1	C1	D1	E1
2	1%	A2	B2	C2	D2	E2
3	3%	A3	B3	C3	D3	E3
4	5%	A4	B4	C4	D4	E4
5	8%	A5	B5	C5	D5	E5
6	10%	A6	B6	C6	D6	E6

3. Test Results and Analysis

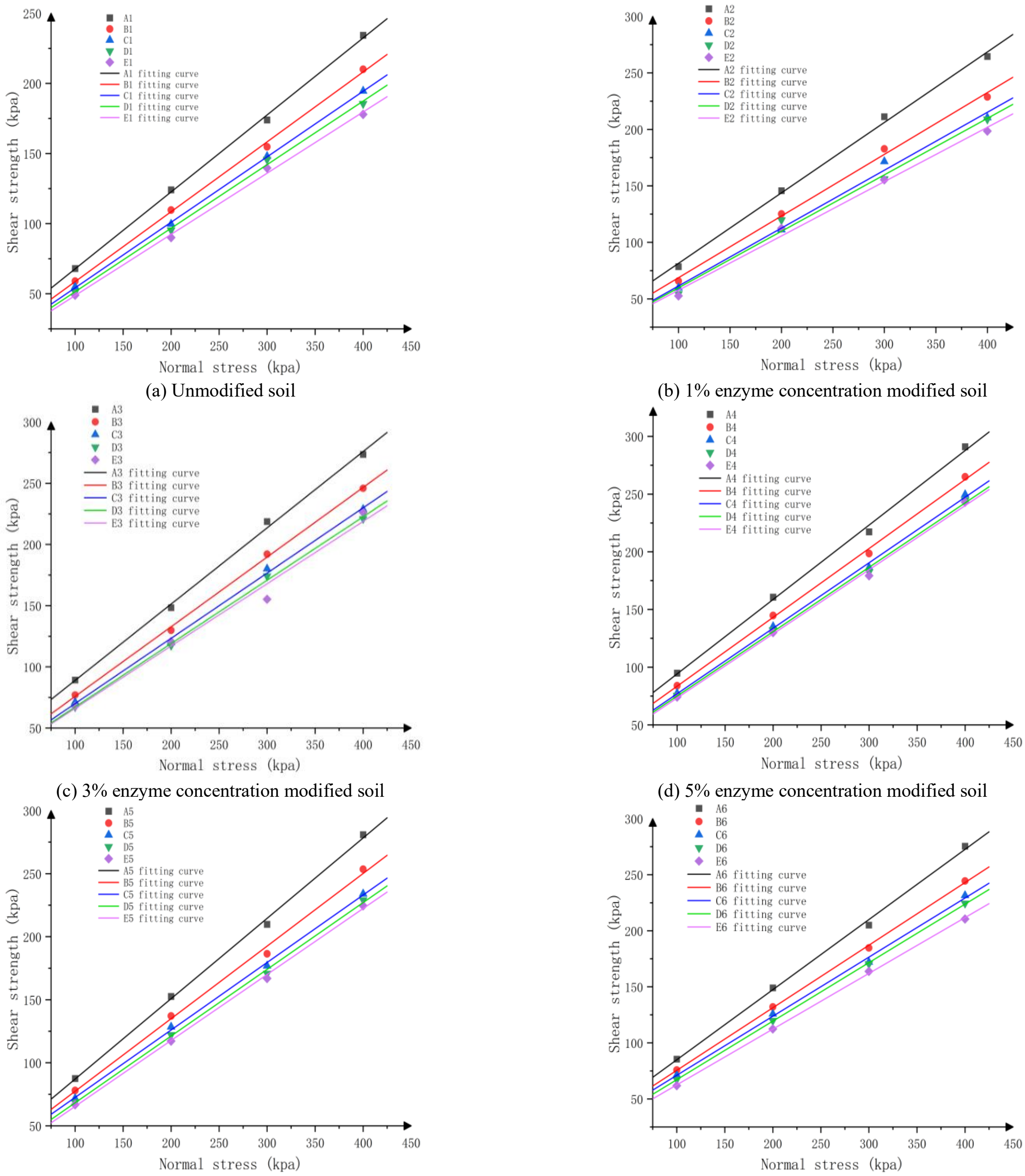
3.1 Effect of Freeze-Thaw Cycle Count on the Results of the Direct Shear Test for Modified Soil

3.1.1 Effect of Freeze-Thaw Cycling on the Shear Strength of Modified Soil

According to the Standard for Geotechnical Test Methods (GB/T 50123-2019), when the curve exhibits no peak, the shear stress corresponding to a shear displacement of 6 mm is taken as the shear strength. Extensive testing indicates that organic soils inherently satisfy the Mohr-Coulomb strength criterion. Therefore, the direct shear data for turfy soils also conform to this criterion:

$$\tau = c + \sigma tan\varphi \tag{1}$$

Linear fitting of the test data according to the formula yielded stress-shear strength relationship curves for modified peat-soil mixtures under different freeze-thaw cycle counts, as shown in Figure 4.



(a) Unmodified soil
(b) 1% enzyme concentration modified soil
(c) 3% enzyme concentration modified soil
(d) 5% enzyme concentration modified soil
(e) 8% enzyme concentration modified soil
(f) 10% enzyme concentration modified soil

Figure 4: Stress-Shear Strength Relationship Curves of Modified Turfy Soil Under Different Freeze-Thaw Cycle Counts

As shown in Figure 4, the relationship curve between normal stress and peak shear stress in the quick shear test exhibits linearity, with little variation in quick shear strength. As the number of freeze-thaw cycles increases (0 → 15 cycles), the overall shear curve shifts downward, indicating a gradual decrease in shear strength. During freezing, water migrates toward the freezing front, forming ice lenses. After thawing, the soil structure becomes loose, leading to reductions in cohesion and internal friction angle. Volume changes and water redistribution during freeze-thaw cycles disrupt enzyme-mediated cementation, further diminishing shear strength.

3.1.2 Effects of Freeze-Thaw Cycles on Cohesion and Internal Friction Angle

Based on the properties of linear functions, the intersection point of the fitted curve with the y-axis represents cohesion, and the slope corresponds to the tangent of the internal friction angle. This yields the curves showing cohesion and internal friction angle versus freeze-thaw cycle count, as depicted in Figures 5 and 6.

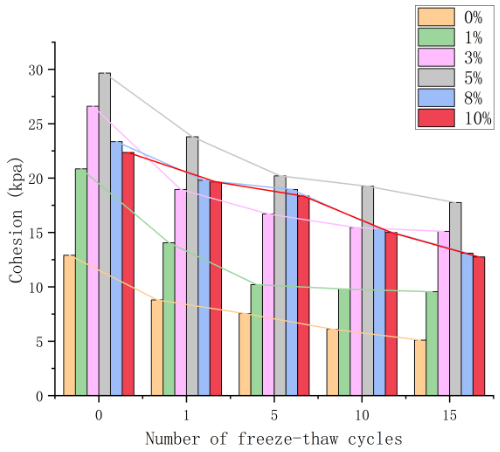


Figure 5: Curve of cohesion versus number of freeze-thaw cycles

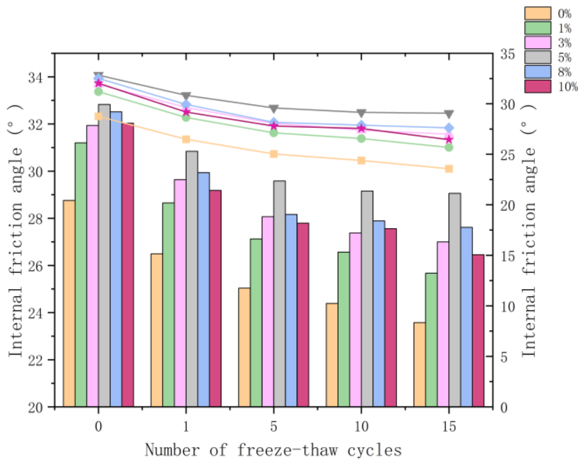


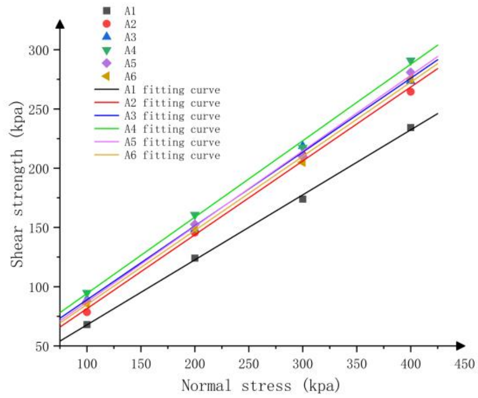
Figure 6: Curve of internal friction angle versus freeze-thaw cycle count

Regardless of enzyme content, all curves exhibit a general downward trend with increasing freeze-thaw cycles. This indicates that freeze-thaw cycles cause cumulative and irreversible damage to soil structure, representing the primary external factor driving cohesion decay. The figures reveal that cohesion degradation occurs predominantly within the first five freeze-thaw cycles. The slope of nearly all curves is steepest within the 0–5 cycle range, after which the decay trend gradually slows. This indicates that after undergoing initial severe freeze-thaw destruction, the soil structure tends toward a new, weaker state of unstable equilibrium.

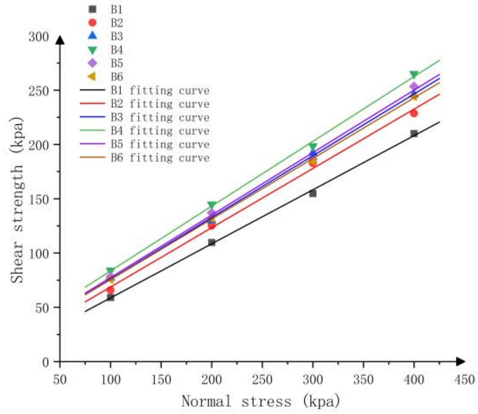
3.2 Effect of Bioenzyme Concentration on the Results of Direct Shear Tests for Modified Soil

3.2.1 Effect of Enzyme Concentration on Shear Strength of Modified Soil

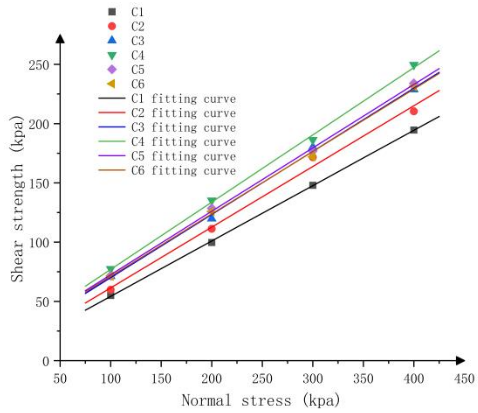
Similarly, linear fitting of the experimental data using Equation (1) yielded stress-shear strength relationship curves for modified turfy soils at different enzyme concentrations, as shown in Figure 7.



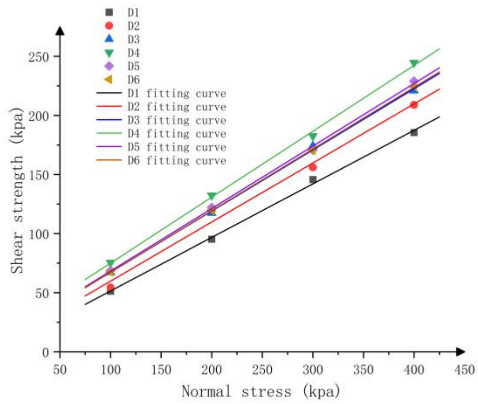
(a) 0 freeze-thaw cycles



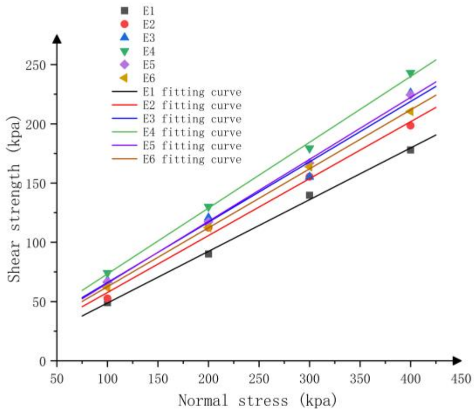
(b) 1 freeze-thaw cycle



(c) 5 freeze-thaw cycles



(d) 10 freeze-thaw cycles



(e) 15 freeze-thaw cycles

Figure 7: Stress-Shear Strength Relationship Curves for Modified Turfy Soil at Different Enzyme Concentrations

3.3.2 Effect of Enzyme Concentration on Shear Strength of Modified Soil

Based on the properties of linear functions, the fitted curve intersects the y-axis at cohesion, and its slope corresponds to the tangent of the angle of internal friction. This yields the curves showing cohesion and angle of internal friction versus enzyme concentration, as depicted in Figures 8 and 9.

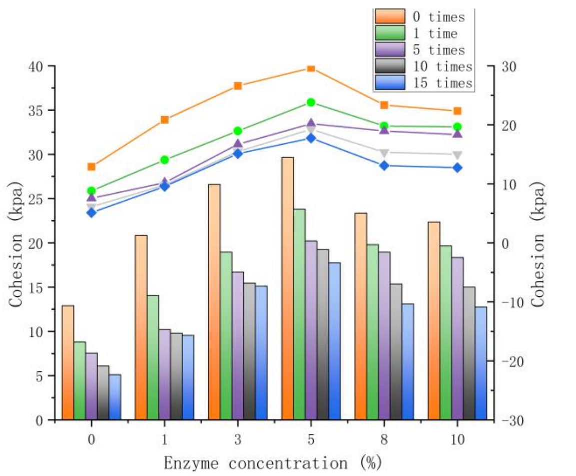


Figure 8: Column-line chart of cohesion versus biological enzyme concentration

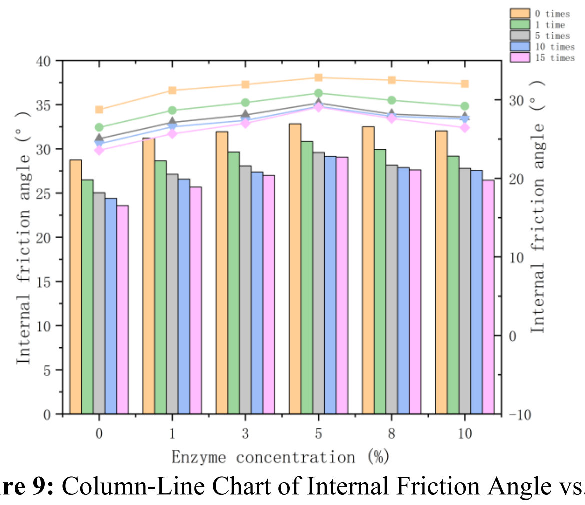


Figure 9: Column-Line Chart of Internal Friction Angle vs. Enzyme Concentration

The overall trend across all curves is an initial increase followed by a decrease as the enzyme content rises. This indicates an optimal enzyme concentration, which is the primary factor governing the changes in cohesion and internal friction angle. As shown in the figures, the ascending phase for cohesion and internal friction angle spans 0%-5%, while the decaying phase occurs between 5%-10%. At 5%, both internal friction angle and cohesion reach their peak values, confirming 5% enzyme concentration as the optimal dosage.

4. Conclusions

This study investigated the effects of freeze-thaw cycles and enzyme concentration on the shear properties of turfy using freeze-thaw cycle tests and direct shear tests. The main conclusions are as follows:

1) Freeze-thaw cycles significantly reduced the shear strength of turfy soil. As freeze-thaw cycles increased, the shear stress-shear displacement curve exhibited a systematic downward shift, with shear strength continuously weakening. Strength decay was primarily concentrated within the first five freeze-thaw cycles, with subsequent changes becoming more gradual. Both cohesion and internal friction angle decreased with increasing freeze-thaw cycles, reflecting the cumulative damage and irreversible nature of freeze-thaw action on soil structure.

2) Enzymatic modification effectively enhances the shear properties of turfy soil, with an optimal dosage range. When the enzyme content of TaiRan Enzyme ranged from 3% to 5%, the cohesion and internal friction angle of the modified turfy soil showed the most significant improvement, and the shear strength reached its maximum value. When the enzyme content exceeded 5%, the enhancement effect weakened, and some strength indicators even declined, indicating that excessive enzyme addition may lead to loosening of the cemented structure.

3) Coupling effects exist between freeze-thaw cycles and bioenzymatic improvement. Bioenzymatically modified soils retain certain strength advantages after freeze-thaw cycles, but the improvement effect gradually diminishes after multiple cycles. This indicates that enzyme-induced cementation structures exhibit some resistance to freeze-thaw action, yet they cannot fully offset the structural damage caused by freeze-thaw cycles.

This study elucidates the combined influence mechanism of freeze-thaw cycles and bioenzymatic modification on the shear properties of turfy soils, providing theoretical foundations and engineering references for turfy soil foundation treatment and subgrade improvement in seasonally frozen regions. It is recommended to use a bioenzyme dosage of 3%–5% for turfy soil modification in practical engineering applications, while strictly controlling the number of freeze-thaw cycles the soil undergoes.

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