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Research Article

Effect of Freeze-Thaw Cycles on the Mechanical Properties of Polyacrylamide- and Lignocellulose-Stabilized Clay in Tibet

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Laboratory freezing experiments were conducted to evaluate the effect of polyacrylamide (PAM) and lignocellulose on the mechanical properties and microstructural characteristics of Tibetan clay. Direct shear and unconfined compressive tests and field emission scanning electron microscopy analyses were performed on clay samples with different contents of stabilizers. The test results show that the addition of PAM can improve the unconfined compressive strength and cohesion of Tibetan clay, but an excessive amount of PAM reduces the internal friction angle. After several freeze-thaw cycles, the unconfined compressive strength and cohesion of samples stabilized by PAM decrease significantly, while the internal friction angle increases. Samples stabilized by PAM and lignocellulose have higher internal friction angles, cohesion, and unconfined compressive strength and can retain about 80% of the original strength after 10 freeze-thaw cycles. PAM fills the pores between soil particles and provides adhesion. The addition of lignocellulose can form a network, restrict the expansion of pores caused by freeze-thaw cycles, and improve the integrity of PAM colloids. It is postulated that the addition of a composite stabilizer with a PAM content of 0.4% and a lignocellulose content of 2% may be a technically feasible method to increase the strength of Tibetan clay.

1. Introduction

Tibet is located in Southwest China, at a high altitude above sea level, with a dry and cold climate. In recent years, increasing state investment in infrastructure construction has led to increasing areas of Tibet being developed and utilized. This is particularly true for water conservancy projects, which have effectively alleviated energy shortage in the region. However, it should be noted that, compared with water conservancy construction in mild climate areas, water conservancy construction in cold regions should focus on the impact of climate, especially freezing and thawing.

Clay is widely distributed in Tibet and is often used as dam filling material or rockfill dam core material. However, clay is very sensitive to changes in temperature and moisture levels. Repeated freezing and thawing of clay soil affects its macrostructure and mechanical behavior. To reduce the adverse effects of freeze-thaw cycles and strengthen clay, many researchers have studied the effects of various additives to form geopolymers through chemical reactions. Ding et al. [1] studied the mechanical properties of fiber-cement composite-stabilized clay subjected to freeze-thaw cycles and proposed an empirical model for strength prediction accounting for the number of freeze-thaw cycles. Orakoglu et al. [2] studied the compressive strength of fly ash-lignin fiber-stabilized soil subjected to freeze-thaw cycles and found that the strength decreases as the blending ratio of lignin fiber increases. Hamza and Ali [3] discussed the effect of freeze-thaw cycles on the unconfined compressive strength of jute fiber, steel fiber, and lime-stabilized clay, and the results obtained from the study are fairly promising to employ jute fiber, steel fiber, and lime against freeze-thaw resistance. Due to the high cost of conventional additives and their adverse effects on the local environment, some researchers have proposed the use of nontraditional additives such as polymer materials to change the surface properties of soil particles and improve the strength of the soil. In recent years, polyacrylamide (PAM) has been widely used to improve the properties of clay because it is effective, nontoxic, and environmentally friendly.

PAM improves the resistance of soil to erosion, dispersion, collapse, and shearing. Since the 1950s, researchers [4–6] have established that PAM improves soil, reduces permeability, and improves durability. An increasing number of researchers have studied the applications of the chemical additive PAM in engineering. Lei et al. [7] studied the method of deep treatment of dredger fills with PAM, combined with vacuum preloading, by conducting indoor model tests. Gao et al. [8] discussed the mechanism of the effect of PAM on the compressibility of lime-stabilized soil. Different amounts of PAM were added to lime-stabilized soil, and the results showed that the addition of PAM to lime-stabilized soil reduces the mesopore volume and produces very large pores. Georgees et al. [9] assessed the benefits of using synthetic PAM additives to improve the performance-related properties of three pavement materials commonly used in Australian unsealed road construction. Jung and Jang [10] studied the soil-water characteristic curves for different concentrations of PAM. The results showed that PAM has a good irrigation effect with increasing water infiltration because of its ability to absorb and store a large amount of water. Zhang et al. [11] studied the consistency limit, compactness, microstructure, and cracking morphology of saline soil before and after PAM treatment. The results showed that PAM reduces the shrinkage strain and defects or pores in saline soil. Qi et al. [12] studied the cracking behavior of polyurethane (PU) and PAM-mixed clay soil for different polymer concentrations, using cracking tests for drying soil.

It is worth noting that Soltani-Jigheh et al. [13] studied the effects of water-soluble cationic PAM on the physical and mechanical properties of fine-grained soil under thawing and freeze-thaw conditions. The results showed that when soil undergoes a freeze-thaw process, the strength and durability of untreated and treated soil are greatly reduced, particularly after the first cycle. Hence, it is necessary to consider adding other modifiers to improve the applicability of environment-friendly polymer soil improvers such as PAM, to soil subjected to freeze-thaw cycles. In this study, clay samples were collected from Linzhi, Tibet, located 3500 m above sea level. The shear strength, unconfined compressive strength, and microstructure of the soil samples were studied for untreated soil and soil treated with PAM alone and with lignocellulose and PAM. A total of 10 types of stabilized soil samples with different proportions of modifiers were prepared. First, compaction and liquid-plastic limit tests were conducted on soil samples, and the compaction curves and liquid-plastic limits of the soil samples were determined. Next, changes in the mechanical properties of the samples after freeze-thaw cycles were studied by direct shear tests and unconfined compressive strength tests. Finally, the microstructures of the soil samples were studied using a scanning electron microscope.

2. Materials, Methods, and Testing Equipment

According to the standard of soil test method (GB/T 50123-2019) [14], the physical and mechanical properties of clay and stabilized clay in Tibet were studied per the standard of geotechnical tests, by laboratory tests including unconfined compression, direct shear, liquid-plastic limit, compaction, and scanning electron microscopy tests.

2.1. Materials

2.1.1. The Clay. In this paper, the test soil (as shown in Figure 1) is taken from Linzhi City, Tibet Autonomous Region, China, which is a kind of clay widely distributed in high-altitude areas of China. To purify the root systems existing in the soil, the obviously larger plant roots were picked out through the naked eye, and then the black plant root powder that is reunited in it after crushing was removed. In order to better understand its characteristics, the soil samples were crushed and passed through a sieve with a particle size of 2 mm for liquid-plastic limit, compaction, particle analysis, and specific gravity tests according to Test Methods of Soils for Highway Engineering (JTG E-2007) [15]. The basic property results are summarized in Table 1, the compaction curve is shown in Figure 2, and the gradation is shown in Figure 3.

2.1.2. Polyacrylamide. Polyacrylamide (PAM) (as shown in Figure 4) is mainly used in industry and is often used in soil stabilization. It is a high molecular weight synthetic waterborne polymer additive with low cost. It is adsorbed to the soil by an exchangeable cationic bridge through the connection between its ionic groups and negatively charged soil components. The polymer creates a long chain that binds soil particles together, improving soil resistance to erosion, dispersion, collapse, and shear. Table 2 shows the characteristic parameters of the PAM used in the test.

2.1.3. Lignocellulose. Lignocellulose (as shown in Figure 5) is an organic flocculent fiber material obtained from natural renewable wood by chemical treatment and mechanical processing. It is often used in road engineering; the material has a small specific gravity, large specific surface area, thermal insulation, sound insulation, insulation, and air permeability and can achieve resistance to low-temperature deformation and improve adhesion with minerals without adding any stabilizer. Table 3 shows the characteristic parameters of lignocellulose used in the experiment.

2.2. Testing Methods. Stabilized soil samples with different proportions of PAM were prepared. The amounts and proportions of different modifiers used to prepare the samples are listed in Table 4. Eighteen unconfined samples of stabilized soil with a height of 10 cm and a

Figure 1: The sampled clay.

Table 1: Basic properties of clay.

Natural dry density, ρ (g/cm^3)	Optimal moisture, content ω_{op} (%)	Maximum dry density, ρ_d (g/cm^3)	Plastic limit, ω_L (%)	Liquid limit, ω_P (%)	Plasticity index, I_L (%)	Specific gravity, G_s
1.52	14.3	1.605	19.8	27.4	7.6	2.74

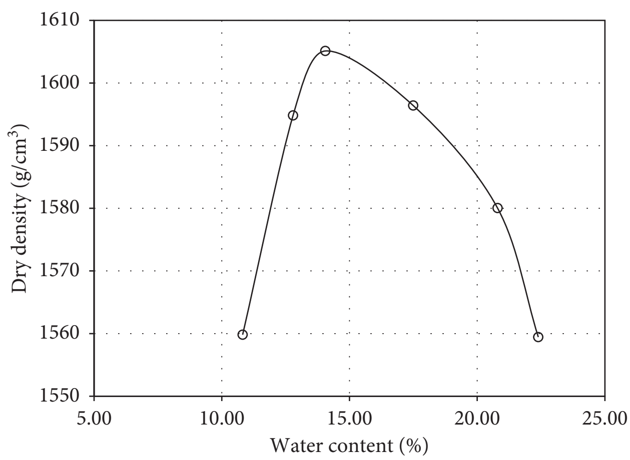


Figure 2: Compaction curve.

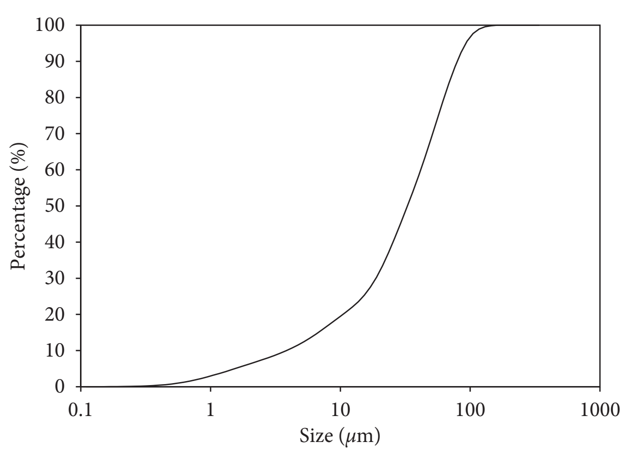


Figure 3: Gradation curve.

diameter of 5 cm were prepared based on optimal moisture content. Also, a quick shear of 72 samples with a height of 20 mm and a diameter of 61.8 mm was conducted. After curing for 7 days under standard curing conditions (as shown in Figure 6) following the Specification of Soil Test (JTGE51-2009) [16], the samples were subjected to freeze-thaw cycle tests of different durations. After a specified number of freeze-thaw cycles, follow-up direct shear, unconfined, and electron microscope scanning tests were conducted.

Figure 4: The PAM used in the test.

Table 2: Basic properties of PAM.

Average particle size (μm)	pH	Ion type	Molecular weight	Water solubility time (min)	Solid content
250~180	7.4	Cation ion	13 million	40	≥ 90%

Figure 5: The lignocellulose used in the test.

Table 3: The characteristic parameters of lignocellulose.

Fiber length (μm)	Density (g/cm^3)	Heat resistance (°C)	pH	Fiber content (%)	Color
200	1.76	260	6	99.5	White

Table 4: Sample preparation.

Test group	Sample number	PAM content (%)	Lignocellulose content (%)	Number of freeze-thaw cycles
Soil type A (nonstabilized soil)	1	0	0	
	2	0.1	0	
	3	0.2	0	
Soil type B (PAM only)	4	0.4	0	
	5	0.6	0	
	6	0.8	0	0, 1, 3, 5, 7, and 10
	7	0.4	1	
Soil type C (PAM and lignocellulose)	8	0.4	2	
	9	0.4	3	
	10	0.4	4	

Figure 6: Standard maintenance.

2.3. Freeze-Thaw Cycles. A self-made freeze-thaw cycle device, suitable for soil conditions in Tibet, tested freeze-thaw cycles. After the sample was prepared and cured for seven days, the sample was wrapped with plastic film and placed in a self-made closed test chamber with adjustable temperature for freeze-thaw cycle testing. For the freeze-thaw tests, the specimens were subjected to 1, 3, 5, 7, and 10 freeze-thaw cycles. According to meteorological data, summer temperatures in Tibet range between 18 and 24°C, and winter temperatures range from −13 to −22°C. To better simulate the freezing and thawing process of soil under local climatic conditions, during each freeze-thaw cycle, the samples were first frozen at −20°C for 12 hours and then thawed at 20°C for 12 hours. At the end of ten cycles, three unconfined samples and 12 quick shear samples were taken from each group, and follow-up experiments were conducted after determining the moisture content change.

2.4. Unconfined Compression Experiment. UCS tests have been conducted following the Specification of Soil Test (JTGE51-2009) [16]. The testing equipment used accurately and reliably measured a large data set (over 3000) for drawing the stress-strain curves for the tested specimens. The strain rate of this test was 1.5 mm/min, and the test stopped when axial deformation reached 25 mm. The peak load was determined according to the test data, and the unconfined compressive strength was calculated. Figure 7 shows the unconfined compression test samples, and Figure 8 shows the sample damaged during that test.

2.5. Direct Shear Test. The direct shear test is carried out in an electric quadruple shear apparatus according to soil test standard (GB/T 50123-2019) [14]; the test equipment and samples are shown in Figures 9 and 10. The effective consolidation pressures were 50, 100, 150, and 200 kPa. When the shear displacement reached 4 mm, the test stopped. Based on these data, the peak shear stresses under different vertical pressures were obtained, and linear fitting determined the cohesion and internal friction angle of the sample.

2.6. Scanning Electron Microscope Experiment. The microstructure of soil stabilized by different modifiers after the freeze-thaw cycle was analyzed by field emission scanning electron microscope (as shown in Figure 11). The sample destroyed by the unconfined compression test is dried in the oven. After the moisture is completely evaporated, the sample with a thickness of about 1 mm and a diameter of 5 mm is gilded to improve its electrical conductivity. Each sample was examined and imaged to depict its microstructure.

3. Results and Analysis

3.1. Effect of Freeze-Thaw Cycles on Shear Strength

3.1.1. Effect of Freeze-Thaw Cycles on the Shear Strength of PAM-Stabilized Soil Samples. Figures 12 and 13 show the variations of shear strength parameters of nonstabilized clay samples and PAM-stabilized clay samples with freeze-thaw cycles. As shown in Figure 14, when the number of freeze-thaw cycles is small, the internal friction angle of nonstabilized clay generally decreased as the number of freeze-thaw cycles increased, in agreement with previously reported results [17]. In this experiment, the internal friction angle decreased mainly in cycles 1–5, from 28.3° to 21.9° (22.6%), which was smaller than that of cohesion. The internal friction angle increased slightly after five freeze-thaw cycles and decreased only 17.6% after 10 freeze-thaw cycles. The phenomenon that the internal friction angle decreased slightly shows that the internal friction angle of soil is not significantly weakened by freeze-thaw cycles because the internal friction angle of soil relates primarily to the friction between soil particles. The first few cycles resulted in greater

Figure 7: Samples for unconfined compression test.

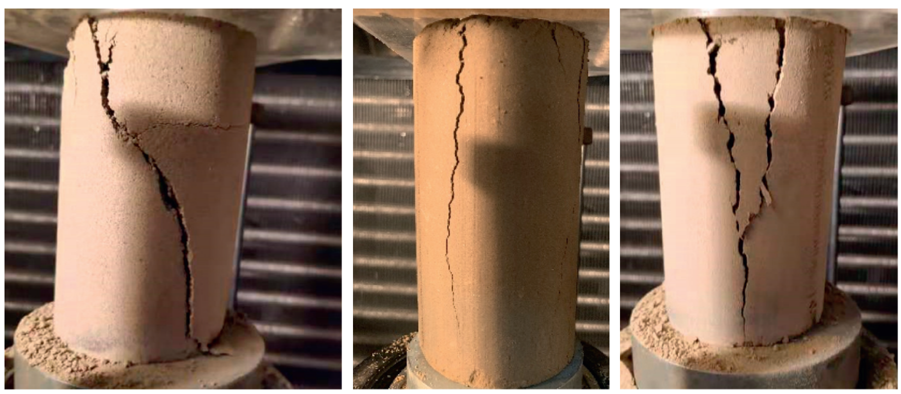


Figure 8: Samples damaged during unconfined compression test.

Figure 9: Ring cutter sample.

particle rearrangement caused by the freeze-thaw, so the angle of internal friction decreased and the rearrangement of soil particles gradually stabilized with additional cycles.

As shown in Figure 13, cohesion decreased for initial freeze-thaw cycles (<3). Soil specimens between 3–10 cycles yielded similar internal friction angles and ranged between 22.1 and 19.8 kPa. Compared with nonfreeze-thawed soil samples, cohesion decreased by 30% after three cycles and then stabilized. The total decrease in cohesion was as much as 41.2% after 10 cycles; hence, the effect of freeze-thaw cycles on the shear strength of soil cannot be ignored, and multiple freeze-thaw cycles can easily lead to slope landslides in practical engineering applications. For example, for the slope at K4213 + 50 of Sichuan-Tibet Highway 318 (as shown in Figure 14), due to shear strength decreases in the soil after multiple freeze-thaw cycles, the shallow soil becomes unstable and collapses along the slope direction due to gravity.

Freeze-thaw cycles can increase the internal friction angle of PAM-stabilized soil. Increasing the number of freeze-thaw cycles gradually increased the internal friction angle before stabilizing or decreasing slightly after seven cycles. However, the internal friction angle appeared to

Figure 10: Electric quadruple direct shear apparatus.

Figure 11: Field emission scanning electron microscope.

decrease for specimens with a large amount of PAM added (more than 0.6%), and the internal friction angle was lower for higher PAM content.

The reason for the above is that an excessive amount of added PAM affects the friction between soil particles and reduces the internal friction angle of soil. The internal friction angle gradually increased with more freeze-thaw cycles, which showed that the amount of PAM added should not be excessive. For example, when 0.8% of PAM was added, the internal friction angle of the unfrozen-thawed soil was 12.8°, which was 45% of that of nonstabilized soil.

The cohesion of PAM-stabilized samples decreased with an increase in the number of freeze-thaw cycles. The cohesion of samples with higher PAM levels decreased by more than 60% after three cycles and by more than 70% after 10 cycles. At a PAM level of 0.1%, cohesion decreased by 47% after ten freeze-thaw cycles due to the freezing of additional water in the pores of soil during the freeze-thaw cycles, which increased pore sizes after thawing and weakened the cementing effect of PAM on soil particles. The colloid produced by PAM also caused cracks, which led to changes in soil structure and decreased soil cohesion on a macroscopic level. Therefore, during construction processes, attention should be paid to the adverse effects of freeze-thaw cycles on PAM-stabilized clay.

3.1.2. Effect of Freeze-Thaw Cycles on the Shear Strength of PAM and Lignocellulose-Stabilized Specimens. Figures 15 and 16 depict the effect of freeze-thaw cycles on the shear strength parameters of composite-stabilized clay. Multiple freeze-thaw cycles had little effect on the internal friction

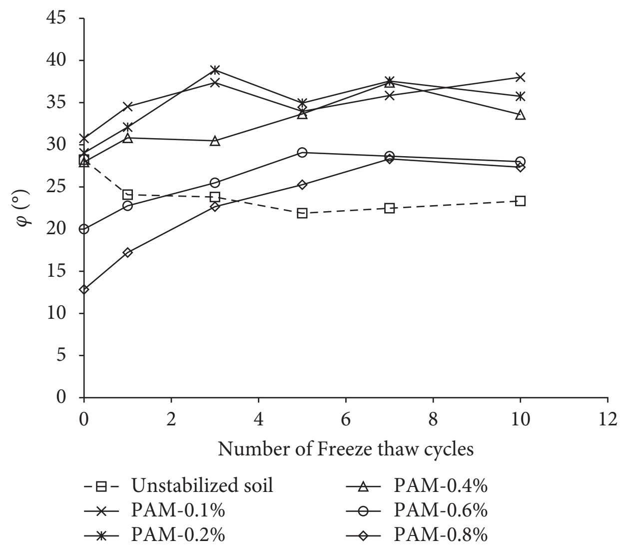


Figure 12: Changes of internal friction angle of PAM-stabilized samples with freeze-thaw cycles.

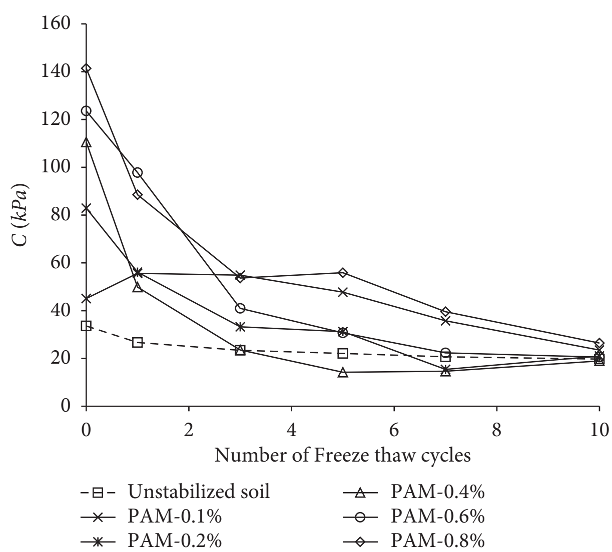


Figure 13: Changes of cohesion of PAM-stabilized samples with freeze-thaw cycles.

angle, even if the content of PAM added increased. As the number of freeze-thaw cycles increased, the shear strength parameters showed a fluctuating trend upward. The cohesion of stabilized PAM and lignocellulose samples decreased with additional freeze-thaw cycles. Only when the lignocellulose content was 2%, the cohesion of samples increased before three freeze-thaw cycles, after which it decreased. Cohesion decreased slightly after ten freeze-thaw cycles, in successive drops of 28.57%, 6.28%, 14.49%, and 21.66%. The change in cohesion was small when the amount of lignocellulose was 2%. Tibetan clay soils improved with the addition of composites such as PAM and lignocellulose and resulted in shear strength increases, stabilized soil, and maintained high cohesion after many freeze-thaw cycles. From a cost standpoint, 0.4% PAM and small amounts of lignocellulose (1%, 2%) are feasible for soil improvement. Such composite-based improvements not only increase the shear strength of Tibetan clay and prevent local slopes from being easily affected by freeze-thaw cycles but also provide a novel method for local soil improvement engineering and reduce environmental pollution.

3.2. Effect of Freeze-Thaw Cycles on Unconfined Compressive Strength

3.2.1. Effect of Freeze-Thaw Cycles on the Strength of Nonstabilized Specimens. Figure 17 shows the change in unconfined compressive strength of nonstabilized soil after freeze-thaw cycles. The results show that soil pores were enlarged due to interpore water freezing, but the increased pores could not be restored during the thawing process.

Figure 14: Shallow landslide due to multiple freeze-thaw cycles.

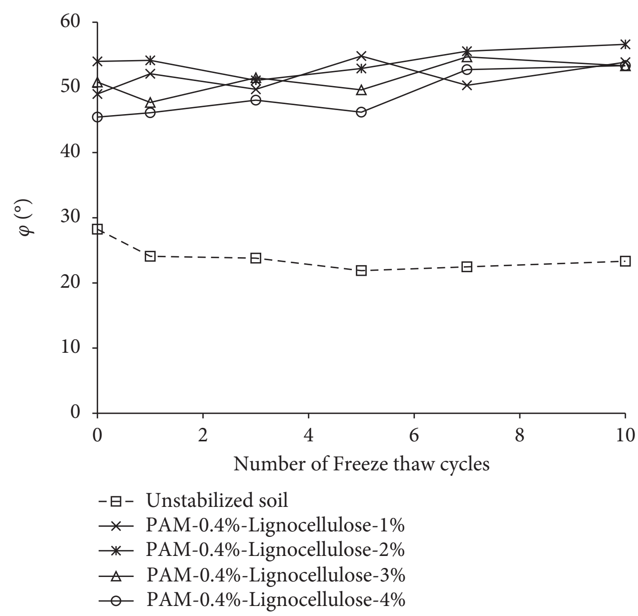


Figure 15: Changes of internal friction angle of stabilized PAM and lignocellulose samples with freeze-thaw cycles.

Hence, the spacing between soil particles increased, and the compressive strength of unstable clay decreased noticeably after the first freeze-thaw cycle from an initial value of 108.1 kPa to 61.6 kPa, representing a decrease of 43%. After the third freeze-thaw cycle, the strength increased slightly, which may be due to the low moisture content of the sample due to improper operation during sample preparation. After 5, 7, and 10 freeze-thaw cycles, the strength continued to decline. After 10 freeze-thaw cycles, the strength was only 42.4 kPa, less than 50% of the initial strength, indicating that the compressive strength of Tibetan clay is greatly affected by freeze-thaw cycles, and long-term freeze-thaw cycles decrease soil strength. Therefore, the improvement of this type of soil should be considered in engineering construction.

3.2.2. Effect of Freeze-Thaw Cycles on the Strength of PAM-Stabilized Samples. Figures 18 and 19 show the relationship between the unconfined compressive strength of PAM-stabilized samples and the number of freeze-thaw cycles. The characteristics of PAM help protect the local environment in Tibet and provide an alternative for soil from being contaminated by traditional modifiers such as cement and lime. The figures show that unconfined compressive strength increased significantly with additional PAM but decreased with an increasing number of freeze-thaw cycles. This observation indicated that PAM addition substantially improved the unconfined compression strength of clay in Tibet. This was attributed to the fact that the colloid formed by PAM wraps around the surface of soil

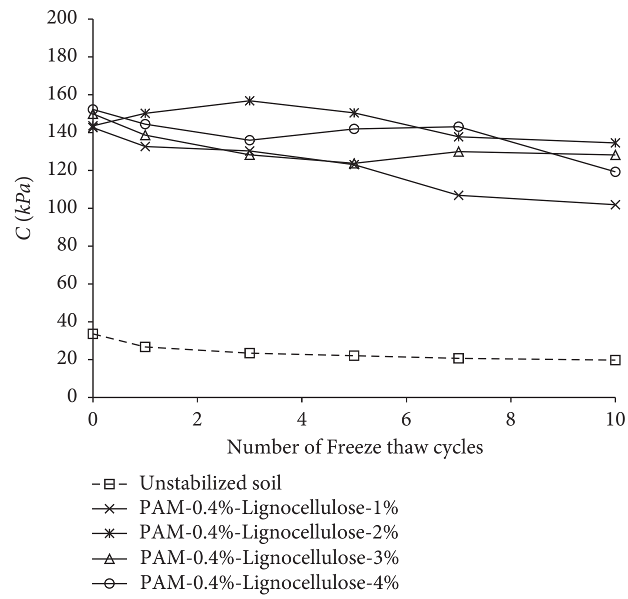


Figure 16: Changes of cohesion of stabilized PAM and lignocellulose samples with freeze-thaw cycles.

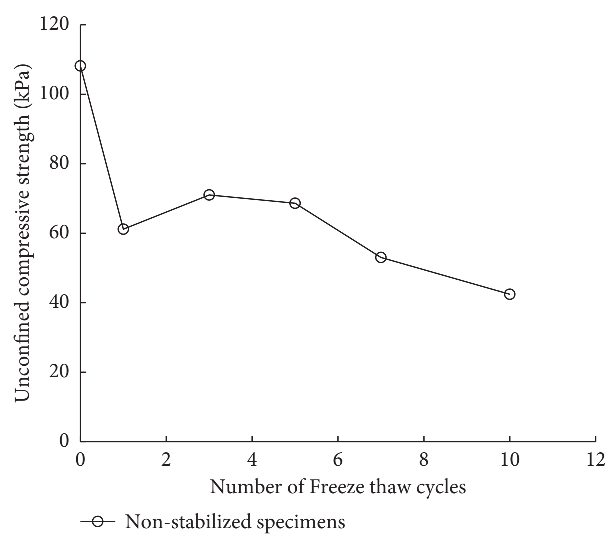


Figure 17: Changes of unconfined compressive strength of nonstabilized specimens with freeze-thaw cycles.

particles and provides adhesion between soil particles, fills soil pores, and forms a relatively stable spatial structure. This led to strength increases; however, subsequent freeze-thaw cycles weakened this filling and bonding effect.

As shown in Figures 18 and 19, after the addition of 0.1%, 0.2%, 0.4%, 0.6%, and 0.8% additives, the strength reached 245.3, 297.8, 343.4, 369.4, and 389.9 kPa, respectively, which was more than twice the strength of the nonstabilized samples. It is worth noting that when the added amount exceeded 0.4%, strength increases gradually decreased; this indicated that merely adding stabilizer was not cost-effective. As the number of freeze-thaw cycles increased, the strength of the stabilized samples with lower levels of added stabilizers increased slightly after the first freeze-thaw cycle because the initial freeze-thaw cycle played a role in healing the damaged structure [18], which resulted in a gradual soil strength increase. The first freeze-thaw cycle healed the soil structure and slightly increased the strength of the soil skeleton but was not observed in subsequent freeze-thaw cycles. When the added amount exceeded 0.4%, the strength of the samples decreased after the first freeze-thaw cycle, and the decrease was the most significant when the content was 0.8%. This indicated that excessive addition of PAM inhibited the healing of damaged structures by the initial freeze-thaw cycle.

To evaluate the magnitude of freeze-thaw weakening effects on degradation of unconfined compressive strength, the strength attenuation is defined as

$$\eta_i = \frac{q_i - q_0}{q_0}, \tag{1}$$

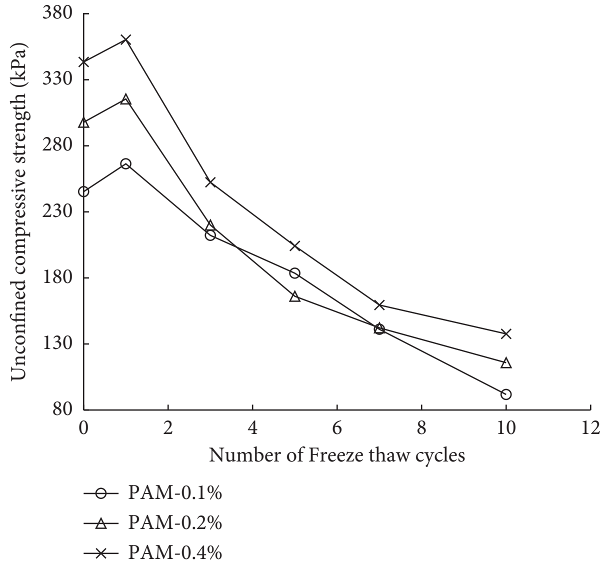


Figure 18: Changes of unconfined compressive strength of PAM (low content) stabilized specimens with freeze-thaw cycles.

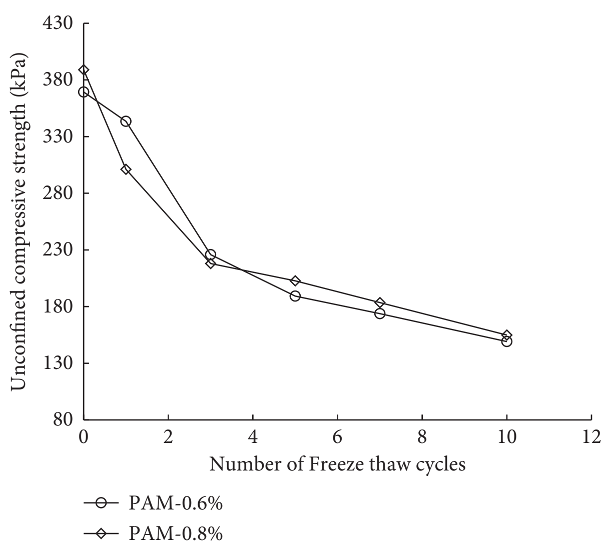


Figure 19: Changes of unconfined compressive strength of PAM (high content) stabilized specimens with freeze-thaw cycles.

where η_i is the strength decay rate after the i freeze-thaw cycle, q_i is the unconfined compressive strength after the i freeze-thaw cycle, and q_0 is the unconfined compressive strength before freeze-thaw cycles.

Figures 20 and 21 show the changes of strength decrease of PAM-stabilized specimens with freeze-thaw cycles. During freeze-thaw cycles, the strength of the samples stabilized with low amounts of stabilizers decreased significantly after three freeze-thaw cycles and continued to decrease after 5, 7, and 10 freeze-thaw cycles; however, the decrease was slightly less than previously observed. Among them, the strength attenuating trends of the samples stabilized, with 0.2% and 0.4% PAM content showing similar trends, but unconfined compressive strength trends differed slightly. The strength of high content samples decreased substantially after five freeze-thaw cycles but decreased slightly after each freeze-thaw cycle thereafter. The attenuating trend was linear overall. Although PAM effectively stabilized the sample strength initially, there was little difference between the strengths of the stabilized and non-stabilized soil samples after seven freeze-thaw cycles, and the strength was essentially the same after ten cycles. The strength attenuation reached 60%, indicating that freeze-thaw cycles had a significant effect on the cementation of PAM and that multiple freeze-thaw cycles greatly weakened the enhancing effect of the stabilizer. Although the PAM colloid filled the pores between soil particles and provided adhesion, it did not restrict soil particle displacement and limited the increase in the number of pores. After several freeze-thaw cycles, the cementation force of the colloid wrapped around the surface of the soil particles decreased. The strength of the PAM colloid between the pores

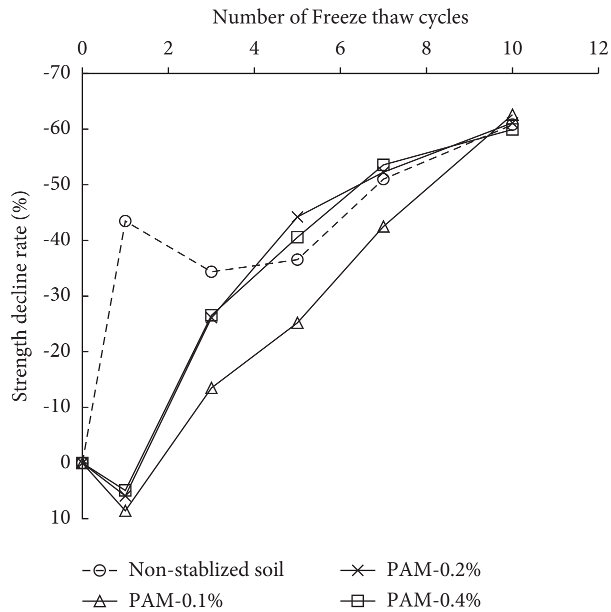


Figure 20: Changes of strength decrease of PAM (low content) stabilized specimens with freeze-thaw cycles.

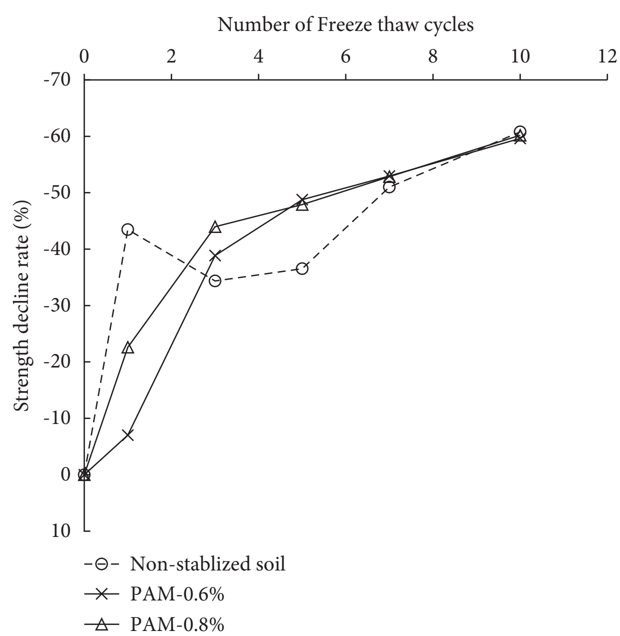


Figure 21: Changes of strength decrease of PAM (high content) stabilized specimens with freeze-thaw cycles.

decreased, and the soil readily fractured under an external load. The filling effect also decreased and a large stable structure did not form; hence, the adhesive force provided decreased significantly.

3.2.3. Effect of Freeze-Thaw Cycles on the Strength of PAM and Lignocellulose-Stabilized Samples. Figure 22 shows the relationship between the unconfined compressive strength of the samples stabilized with PAM and lignocellulose and the number of freeze-thaw cycles. Lignocellulose addition improved the frost resistance of the samples. The unconfined compressive strength increased significantly with lignocellulose addition. As shown, after adding 0.4% PAM and 1, 2, 3, and 4% lignocellulose, the strength of the unfreeze-thawed cyclic sample reached 493.8, 562.8, 594.9, and 615.1 kPa, respectively, and the strength was more than 1.5 times than when the level of PAM was 0.4%. Also, the strength of the sample increased gradually during the first three freeze-thaw cycles; this indicated that lignocellulose addition benefitted the aging of the freeze-thaw cycles and stabilized the soil skeleton strength. After the first three freeze-thaw cycles, the strength of the sample started decreasing, but the decrease was not significant and

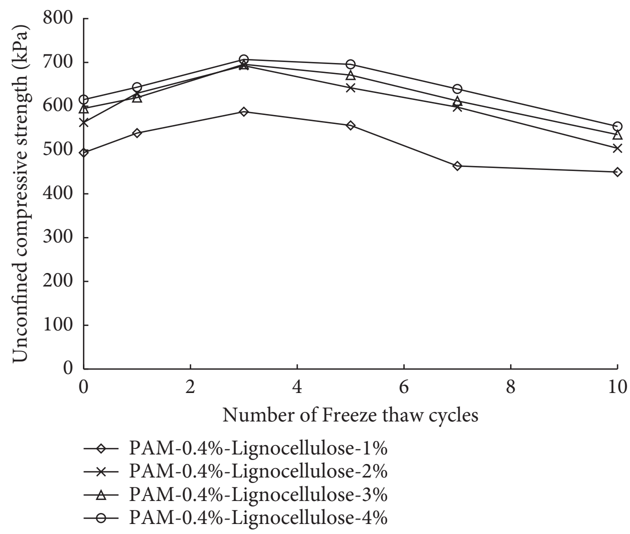


Figure 22: Changes of unconfined compressive strength of PAM and lignocellulose-stabilized specimens with freeze-thaw cycles.

much lower than that of each freeze-thaw cycle of the sample stabilized by PAM alone. This was due to wood fiber, which formed a network between the soil particles that partially limited dislocation between the particles, protected the colloid formed by PAM, and increased the energy needed to break the stable specimen.

When the content of lignocellulose exceeded 1%, strength increases decreased significantly and were seen in the strength change of the sample stabilized with a lignocellulose content of 2%, which remained the same after several freeze-thaw cycles. This indicated that a lignocellulose content of 2% (and a PAM level of 0.4%) significantly improved the frost resistance of the soil.

As shown in Figure 23, the attenuation of the strength of the composite-stabilized samples differed from that of nonstabilized soil and soil stabilized with PAM alone. Before three freeze-thaw cycles, the strength of the samples with 2% lignocellulose increased the most, and those increases were 23% and 14.9% after three cycles. In subsequent freeze-thaw cycles, the strength of all stabilized samples decreased continuously, but the rate of strength attenuation after ten freeze-thaw cycles was not high, ~10%, which was much smaller than nonstabilized soil and soil stabilized with PAM alone. This indicated that lignocellulose addition stabilized the frost resistance of the sample and helped maintain a high strength of PAM colloids with an optimal lignocellulose level of 2%.

3.3. Microscopic Analysis. To better understand the improvement due to different modifiers after freeze-thaw cycles, the microstructure of nonstabilized soil, PAM-stabilized soil, PAM, and lignocellulose composite-stabilized soil before and after a freeze-thaw cycle was analyzed by field emission scanning electron microscopy; the porosity and pore sizes of the sample cross-sections were calculated by Nano Measurer software and the MATLAB program.

Figure 24 shows the microstructural images of nonstabilized soil samples before and after freeze-thaw cycles. Due to the high degree of compaction, the soil particle samples without undergoing a freeze-thaw cycle were closely arranged and the pores were small. Among them, the maximum pore diameter was 17.2 μm, the average pore diameter was 6.43 μm, and the porosity was 0.12.

However, after many freeze-thaw cycles, the untreated samples had porous and discontinuous layered textures, and there were many pores (the maximum pore diameter was 32.4 μm, the average pore diameter was 13.7 μm, and the porosity was 0.26.) with many small particles on the surface. There were many pores between the particles due to pore enlargement after water freezing, which led to soil particle rearrangement; hence, the strength of the soil skeleton decreased after freeze-thaw cycles.

Figure 25 shows the microstructure of a PAM-stabilized soil sample before and after several freeze-thaw cycles. After adding PAM, a portion of the soil particles were coated with a colloid layer formed by PAM (as shown in Figure 25(a)), which resulted in a glue-like strong bond between particles. This led to tighter bonds between individual particles, the contact area between the adjacent particles increased and increased the energy needed for dislocating the soil particles. The inherent strength of the clay increased. Also, due to the high density of the samples, flake and needle-like PAM colloids were observed in the pores (as shown in Figure 25(b)), indicating that PAM colloids were filled with micropores during hydration; hence, the addition of PAM stabilized the strength of clay. After several freeze-thaw cycles, the PAM colloid was affected. As shown in Figure 25(c), the colloid wrapped around the surface layer of the soil particles was not smooth. Some pores between soil particles remained, and it was apparent that there were colloids in the pores, but most of the colloids were broken and did not form a good whole, indicating that the connection of the colloids was destroyed by repeated freeze-thaw cycles. Although the addition of PAM absorbed some

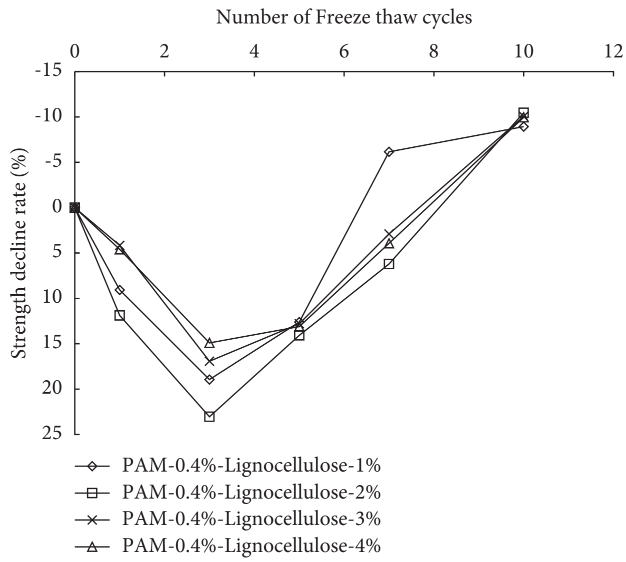
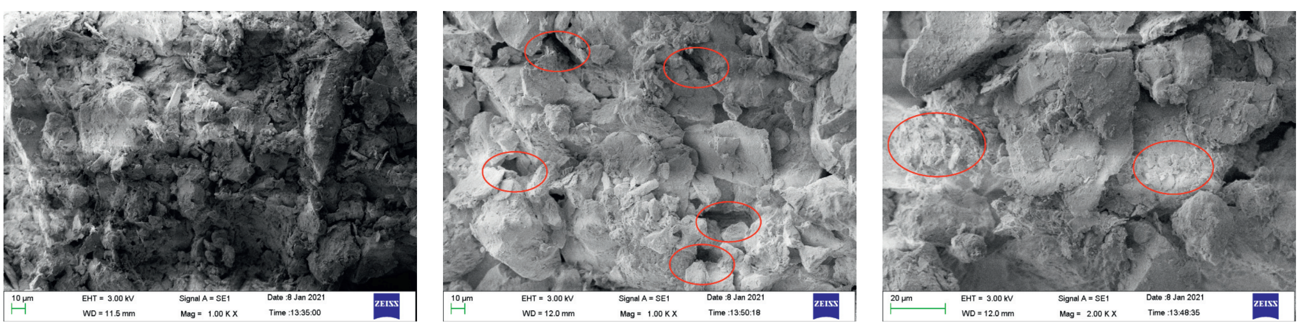
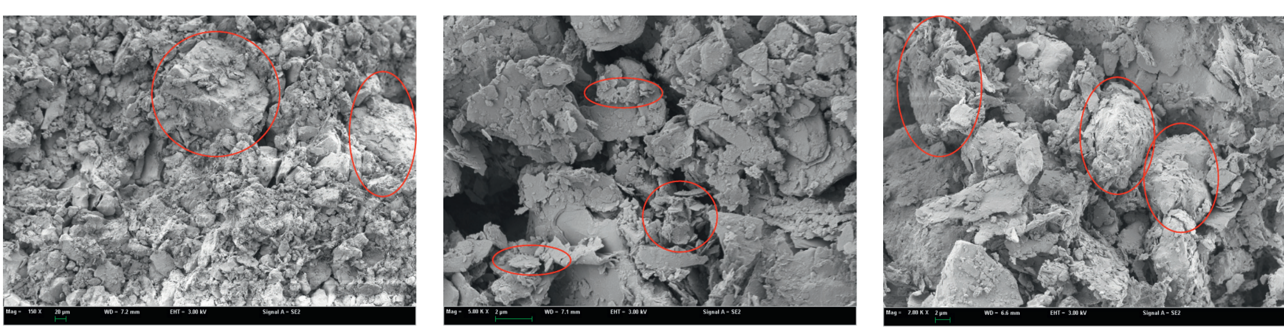


Figure 23: Changes of strength decrease of PAM and lignocellulose-stabilized specimens with freeze-thaw cycles.



(a) (b) (c)

Figure 24: The microstructure of nonstabilized soil. (a) 0 cycles. (b) 7 cycles. (c) 10 cycles.

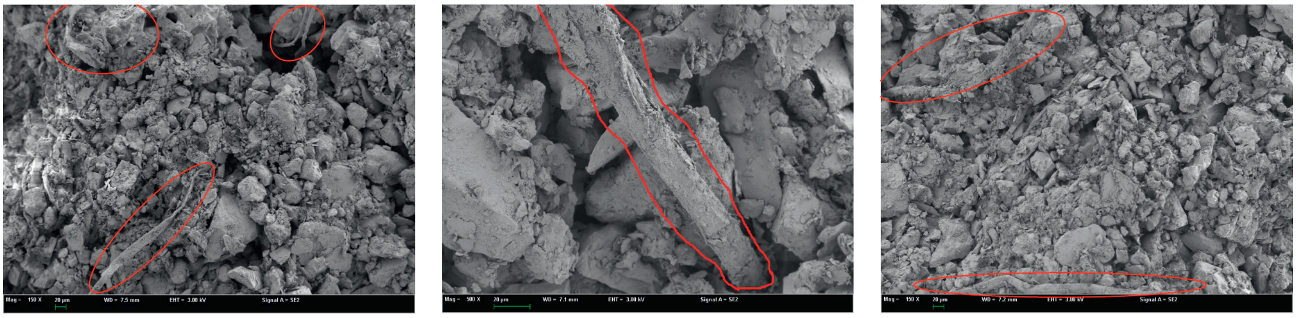


(a) (b) (c)

Figure 25: The microstructure of PAM-stabilized soil. (a) 0 cycles. (b) 0 cycles. (c) 10 cycles.

water in the pores and reduced pore increases during the freeze-thaw process, most of the colloids were fractured after repeated cycles, and the cohesion between soil particles decreased significantly. The effect of pore-filling was also poor; hence, the soil improvement effects of PAM after several cycles were limited.

Figure 26 shows the soil sample microstructures stabilized by PAM and lignocellulose before and after multiple freeze-thaw cycles. The gap between soil particles changed slightly before and after these cycles because the added fibers were intertwined with each other to form a network; hence, the gap between soil particles did not increase significantly after repeated cycles. Discrete fibers were intertwined with each other to form a spatial stress network between soil particles that contributed to maintaining its shear strength. Under external loads, when relative displacement between a



(a) (b) (c)

Figure 26: The microstructure of PAM and lignocellulose composite-stabilized soil. (a) 0 cycles. (b) 3 cycles. (c) 10 cycles.

fiber in the network and soil particles occurred, other adjacent fibers limited relative displacement and restricted the rearrangement of soil particles during the freeze-thaw cycle. Consequently, soil particles were not easy to move and the strength decreased by a smaller amount. Also, due to the constraint of the fiber network, increasing the number of pores was limited, the cement was not easily fractured, the colloid formed by PAM had good integrity, the effect of filling pores improved, and cohesion was conserved between the particles.

4. Conclusions

In this study, the change in the strength of clay samples stabilized by PAM, PAM and lignocellulose subjected to freeze-thaw cycles, and the mechanism of action of soil improvers were studied using unconfined compression and direct shear tests and scanning electron microscopy. The main conclusions of this study are as follows:

(1) The addition of PAM can improve the unconfined compressive strength and cohesion of Tibetan clay, but a large amount of PAM reduces the internal friction angle of soil. With an increase in the number of freeze-thaw cycles, the unconfined compressive strength and cohesion of clay samples stabilized by PAM decrease significantly, but the internal friction angle increases.

(2) Compared with nonstabilized clay, PAM and lignocellulose composite-stabilized clay has a higher internal friction angle, cohesion, and unconfined compressive strength and can retain about 80% of its original strength after 10 freeze-thaw cycles.

(3) PAM fills the pores between soil particles and provides adhesion. The adhesion between particles is higher, the contact area between the adjacent particles increases, and the strength of the sample increases. However, after several freeze-thaw cycles, the bonds between soil particles are destroyed and most of the colloids are fragmented. The addition of lignocellulose can form a network, restrict the expansion of pores caused by freeze-thaw cycles, and improve the integrity of PAM colloids.

(4) Based on test data and project cost considerations, it is recommended that a compound stabilizer consisting of 0.4% PAM and 2% lignocellulose be used to improve clay in Tibet, control local slopes, reduce landslide disasters caused by freeze-thaw cycles, improve roadbed strength, and reduce environmental pollution.

Data Availability

The results of the experiments used in this paper are available from the corresponding author by request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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