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The Influence of Biogels on the Shear Strength of Red Clay

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Abstract

Red clay is prone to stability problems in engineering due to its high porosity ratio, strong hydrophilicity, and high sensitivity of strength to water content. Traditional improvement materials (such as cement and lime) have significant effects but suffer from drawbacks like high energy consumption, high carbon emissions, and environmental damage. To explore a green and sustainable soil improvement method, this study selected three biopolymers—xanthan gum, guar gum, and carrageenan—as modifiers. Through direct shear tests, the effects of these biopolymers on the shear strength characteristics of Guilin red clay were systematically studied. Five dosages (0%, 0.5%, 1%, 1.5%, and 2%) were set, and quick shear tests were conducted under four levels of vertical pressure (100 - 400 kPa) after 7 days of curing to analyze the variation laws of cohesion and internal friction angle. The results show that all three biogels can significantly improve the cohesion of red clay; the optimal dosage of xanthan gum and guar gum is 1.5%, at which the shear strength is the highest; carrageenan achieves the best improvement effect at a dosage of 1%. Cohesion first increases and then decreases with the increase of dosage, while the variation law of internal friction angle varies with the type of biogel (xanthan gum shows an opposite change, guar gum first increases and then decreases, and carrageenan first decreases and then increases), and the overall variation range is smaller than that of cohesion. This study provides a theoretical basis and technical reference for the green improvement of red clay.

Subject Areas

Civil Engineering

Keywords

Red Clay, Biopolymer, Cohesion, Internal Friction Angle, Red Clay Improvement

1. Introduction

Red clay is widely distributed in Guilin area. Due to its high porosity ratio, strong hydrophilicity, and high sensitivity of strength to water content, it often faces insufficient stability in engineering construction [1]-[3]. Traditional soil improvement technologies mostly use inorganic cementitious materials such as cement and lime. Although the improvement effect is significant, their high energy consumption, high carbon emissions, and potential damage to the soil environment are inconsistent with the current concept of green and sustainable development [4]-[7].

In recent years, biopolymers derived from microorganisms or plants have shown great application potential in the field of environmental geotechnical engineering due to their outstanding advantages such as environmental friendliness, renewability, biodegradability, and good modification effect. These biopolymers can form a strong organic cementation network between soil particles, effectively improving the mechanical properties and water stability of soil.

Xanthan gum is currently the most widely produced and used biopolymer in the world, with advantages of safety, non-toxicity, and chemical stability. Lu Yi *et al.* [8] explored the influence of biogel content, type, and compaction degree on the disintegration resistance of improved clay samples through disintegration tests. Combined with scanning electron microscope tests, they concluded that biogels improve the disintegration resistance of samples by enhancing the cohesion between soil particles. Zhuang Xinshan *et al.* [9] studied the dynamic characteristics and mechanism of xanthan gum-improved silt under cyclic loading, and determined its optimal dosage through unconfined compressive strength tests. The results showed that the unconfined compressive strength of the improved soil increases with the increase of xanthan gum dosage and curing time, reaching a peak of 900 kPa at a dosage of 1.5%, which is 3.4 times that of the natural soil. Niu Zhuang [10] took the dispersive soil in Qian'an County, Jilin Province as the research object, and explored the effects of xanthan gum dosage and curing age on soil dispersibility and compressive strength through indoor dispersibility tests and unconfined compressive strength tests. In addition, xanthan gum is also used as a viscosity-enhancing additive in drilling mud for mining and petroleum industries, and as an anti-erosion additive in concrete. Its application in soil improvement has attracted much attention. Foreign scholars have found that the soil reinforcement effect of xanthan gum increases nonlinearly and tends to be stable at high concentrations, making it a promising eco-friendly modifier for tropical laterite.

Related research on guar gum has also made certain progress. Pan Xuemin [11] studied the performance of guar gum-improved residual soil through direct shear tests, and found that when guar gum is added to basalt residual soil, the shear strength is the highest at a curing age of 14 days and a dosage of 1.0%. Guar gum mainly improves the shear strength by increasing cohesion, and the cohesion of the improved soil increases with the increase of dosage and curing age. Wang Tianliang *et al.* [12] studied the influence of laws and micro-mechanisms of xanthan gum and guar gum on the mechanical properties of expansive soil through indoor mechanical property tests and micro-analysis. The results showed that the cementitious substances generated by the reaction of the two biopolymers with minerals in the soil can effectively improve the bonding strength of soil particles and soil cohesion, reduce the swelling and shrinkage of expansive soil, and enhance the shear strength and unconfined compressive strength. Yang Wanli *et al.* [13] studied the engineering characteristics and anti-erosion ability of guar gum-solidified loess based on direct shear tests, permeability tests, and simulated rainstorm slope scouring tests. By comparing the microstructures of natural loess and solidified loess, they pointed out that the high-viscosity hydrogel produced by the hydration reaction of guar gum can fill pores, cement loess particles, and significantly enhance the shear strength and impermeability of loess. Fu Hongyuan *et al.* [14] used guar gum to improve pre-disintegrated carbonaceous mudstone. The tests found that guar gum can significantly improve its mechanical properties. With the increase of dosage, the unconfined compressive strength increases greatly, the permeability coefficient decreases significantly, the disintegration rate decreases obviously, and the slope scouring rate decreases sharply, making it an excellent slope protection material.

As a natural and non-toxic biopolymer, carrageenan has functions such as coagulation, thickening, and lubrication, but its research and application in the field of civil engineering are relatively few. Liu Wenjia [15] tested the basic properties, gel properties, and cohesiveness of carrageenan and agar. Using Portland cement as the main aggregate, carrageenan and agar as foaming agents, combined with silicone-acrylic emulsion and glass fiber, he developed a cost-effective, easy-to-construct, and safe-to-use castable or spreadable foamed concrete material. Through tests, he analyzed the effects of water-cement ratio, foam volume, and other factors on the dry density and compressive strength of foamed concrete, confirming that the basic properties of biogels meet the requirements of foaming agents. At present, carrageenan is mainly used in concrete material improvement. Its improvement effect on special soils such as red clay is not clear. Therefore, carrying out research on the improvement of the mechanical properties of red clay by carrageenan can further expand the application range of carrageenan in the field of soil improvement. Fan Rui [16] studied the effects of carrageenan, xanthan gum, and their compounding on the gel hardness and water-holding capacity, determined the optimal conditions, and explored the effects of colloid modification on the physical and chemical properties of egg white liquid. His research can provide a scientific basis for the application of biopolymers.

Although existing studies have initially verified the effectiveness of xanthan gum and guar gum in partial soil improvement, and carrageenan has shown application potential in the field of concrete materials, current research still has shortcomings: first, there is a lack of research on red clay, as most existing achievements focus on dispersive soil, expansive soil or loess in other regions, which cannot directly guide engineering practice in this area; second, there is a lack of comparative studies on the three biological gels (xanthan gum, guar gum, carrageenan) under the same test conditions, making it difficult to clarify the differences in their improvement effects on the shear strength of red clay; third, the mechanism explanation of the three biological gels affecting the internal friction angle of red clay is insufficient. Most existing studies focus on the change of cohesion, and the attribution analysis of the change law of internal friction angle is relatively scattered. Taking Guilin secondary red clay as the research object, this study systematically compares the improvement effects of xanthan gum, guar gum and carrageenan on the shear strength of red clay through a unified test scheme. It quantitatively analyzes the change laws of cohesion and internal friction angle of red clay with different contents (0%, 0.5%, 1%, 1.5%, 2%) of the three biological gels, determines their optimal improvement contents, reveals the differentiated mechanisms of the three biological gels affecting the shear strength of red clay, and provides clear theoretical basis and technical parameters for the green improvement of red clay areas in Guilin.

2. Test Methods

2.1. Test Materials

The research object of the test is the secondary red clay in Guilin, with a sampling depth of 2 - 3 m. A series of geotechnical tests were carried out in accordance with the "Standard for Geotechnical Test Methods" (GB/T 50123-2019) [17], and the basic physical parameters of the soil sample are shown in **Table 1**. The modifiers selected in the test are three biopolymers: xanthan gum, guar gum, and carrageenan.

Table 1. Basic physical parameters of red clay.

Specific Gravity	Optimal Water Content/%	Maximum Dry Density/g·cm^{-3}	Liquid Limit/%	Plastic Limit/%
2.76	23.09	1.64	65.12	34.92

2.2. Sample Preparation

Figure 1. Ring knife samples.

Figure 2. Constant temperature curing box.

Taking the dosage of the three modifiers as variables, ring knife samples with different dosages were prepared. The water content of the sample was controlled at the optimal water content of 23.09%, and the compactness was set to 90% of the maximum dry density. The modifier dosages were 0%, 0.5%, 1%, 1.5%, and 2%. After preparation, the soil samples were sealed with plastic wrap and placed in a constant temperature curing box for 7 days (the soil samples and curing box are shown in Figure 1 and Figure 2).

2.3. Test Scheme

A ZJ-type strain-controlled direct shear apparatus was used for quick shear tests (the test instrument is shown in Figure 3), with four levels of vertical pressure: 100 kPa, 200 kPa, 300 kPa, and 400 kPa. By drawing the shear strength curves under different vertical pressures, linear fitting was performed using the Coulomb formula to determine the cohesion (c) and internal friction angle (φ) of the soil samples. The specific test scheme is shown in Table 2.

Table 2. Test scheme.

Modifier	Dosage/%	Vertical Pressure/kPa	Number of Parallel Tests/times
Xanthan gum Guar gum Carrageenan	0, 0.5%, 1%, 1.5%, 2%	100, 200, 300, 400	4

Figure 3. ZJ-type strain-controlled direct shear apparatus.

3. Test Results and Analysis

3.1. Xanthan Gum-Improved Red Clay

To explore the effect of xanthan gum dosage on the shear strength of red clay, the shear strength curves of red clay under different vertical pressures and different dosages were drawn (**Figure 4**). It can be seen from the figure that with the increase of xanthan gum dosage, the shear strength of red clay first increases and then decreases, and reaches the maximum at a dosage of 1.5%.

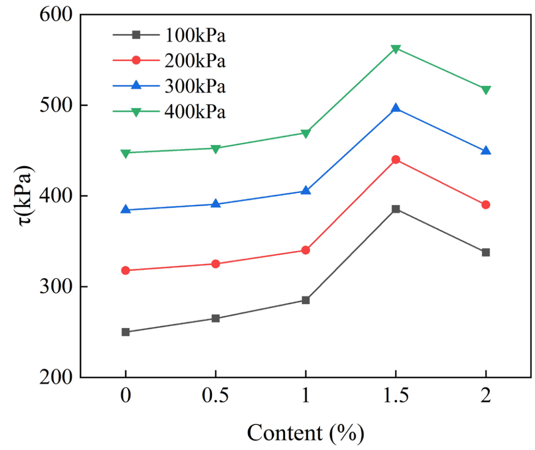

Figure 4. Shear strength curves of red clay under different vertical pressures and different xanthan gum dosages.

Further, the variation curves of cohesion and internal friction angle of red clay under different xanthan gum dosages were drawn (**Figure 5**). The results show that cohesion first increases and then decreases with the increase of dosage, while the internal friction angle shows an opposite change trend. The variation range of cohesion is much larger than that of internal friction angle, indicating that xanthan gum mainly affects the shear strength of red clay by changing cohesion.

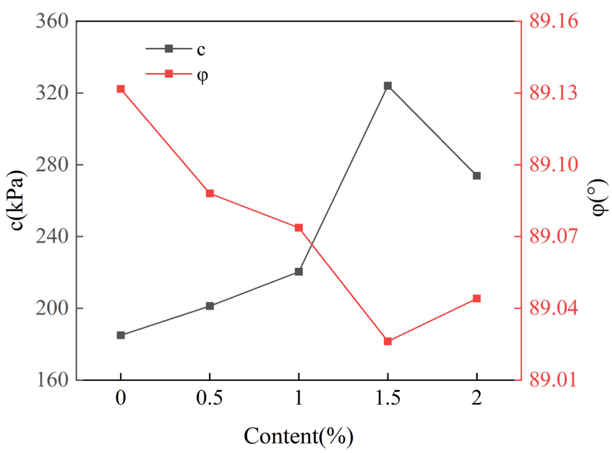

Figure 5. Variation curves of cohesion and internal friction angle of red clay under different xanthan gum dosages.

At the low dosage stage, xanthan gum molecular chains can be firmly adsorbed on the surface of negatively charged clay particles through hydrogen bonds, van der Waals forces and cationic bridges. Due to the length of a xanthan gum molecular chain being much larger than the spacing between soil particles, it can be adsorbed on two or more non-adjacent soil particles simultaneously, forming firm cementitious bonds. With the increase of dosage, the number of these cementitious bonds increases, leading to a continuous enhancement of cohesion, which reaches the maximum value at a dosage of 1.5%. As the dosage continues to increase, the cementation causes soil particles to agglomerate into larger irregularly shaped aggregates, weakening the effective connections between particles and changing the failure path, thus resulting in a decrease in effective cohesion.

Regarding the internal friction angle, before the dosage of 1.5%, these irregularly shaped aggregates have not been fully formed. The incorporation of xanthan gum mainly forms a hydrated xanthan gum molecular film on the surface of soil particles, which plays a lubricating role, weakens the frictional resistance and causes a continuous decrease in the internal friction angle. After the dosage of 1.5%, irregularly shaped soil particle aggregates are gradually formed. The mechanical interlocking effect between these aggregates increases the frictional force, leading to a rebound of the internal friction angle.

3.2. Guar Gum-Improved Red Clay

The shear strength curves of red clay under different vertical pressures and different guar gum dosages are shown in **Figure 6**. It can be seen from the figure that the shear strength of guar gum-improved red clay first increases and then decreases with the increase of dosage, reaching the maximum at a dosage of 1.5%.

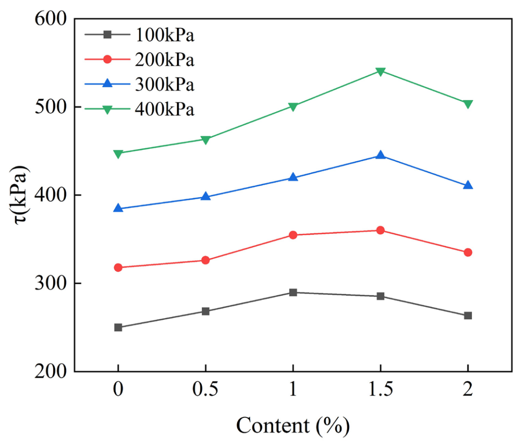

Figure 6. Shear strength curves of red clay under different vertical pressures and different guar gum dosages.

The variation curves of cohesion and internal friction angle of red clay under different guar gum dosages are shown in **Figure 7**. Both cohesion and internal friction angle first increase and then decrease. Cohesion reaches the maximum at a dosage of 1%, and the internal friction angle reaches the peak at a dosage of 1.5%.

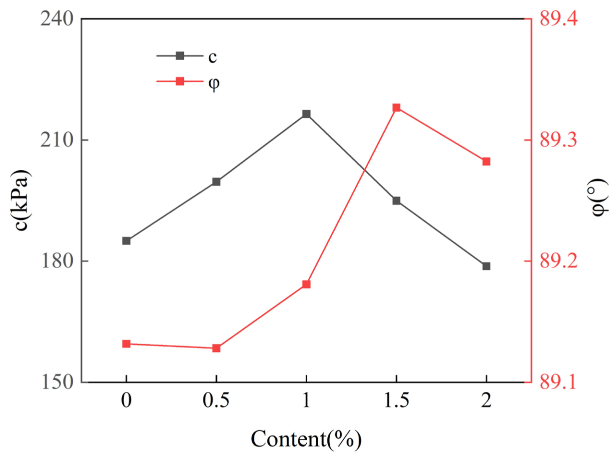

Figure 7. Variation curves of cohesion and internal friction angle of red clay under different guar gum dosages.

The large number of hydroxyl groups on the guar gum molecular chain can form a strong hydrogen bond network with the hydroxyl groups and oxides on the surface of red clay particles. At the low dosage stage, guar gum can be fully dispersed, and the molecular chain can effectively wrap soil particles and bridge adjacent particles to form a strong "polymer bridge", improving cohesion; however, excessive guar gum molecules will aggregate near the formed cementation points or entangle themselves, forming locally enriched gel agglomerates instead of creating new effective inter-particle connections. This leads to excessive cementation and brittleness in some areas, and reduced connection strength in other areas due to too thick a gel layer. Shear failure is prone to occur in the weak polymer-enriched areas, resulting in a decrease in effective cementation efficiency and cohesion.

The change of internal friction angle is related to the interaction between the granulation effect and the lubrication effect. Initially, the cementation effect of guar gum aggregates fine clay particles into larger and stronger aggregates. The interlocking effect between aggregates is stronger than that of original dispersed particles. With the increase of dosage, the granulation effect is strengthened, and the internal friction angle increases; when the dosage exceeds 1.5%, a large amount of free or enriched guar gum gel in the system plays a "lubricant" role, significantly reducing the sliding friction coefficient between aggregates. The lubrication effect overwhelms the aggregate interlocking effect, and the internal friction angle turns to decrease.

3.3. Carrageenan-Improved Red Clay

The shear strength curves of red clay under different vertical pressures and different carrageenan dosages are shown in Figure 8, and the variation curves of cohesion and internal friction angle are shown in Figure 9. It can be seen from the figures that the shear strength of red clay first increases and then decreases with the increase of carrageenan dosage, and the enhancement effect is significant at a dosage of 1%; cohesion first increases and then decreases with the increase of dosage, reaching the maximum at a dosage of 1%; the variation trend of internal friction angle is opposite to that of cohesion, reaching the minimum at a dosage of 1%.

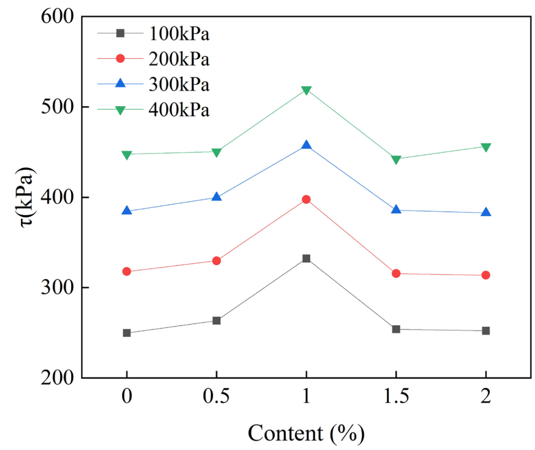

Figure 8. Shear strength curves of red clay under different vertical pressures and different carrageenan dosages.

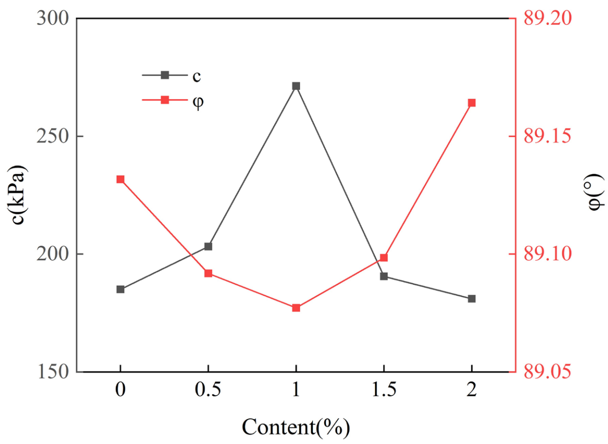

Figure 9. Variation curves of cohesion and internal friction angle of red clay under different carrageenan dosages.

The sulfate groups ($-OSO_3^-$) on the carrageenan molecular chain carry strong negative charges, which can strongly interact with cations such as Ca^{2+}, Mg^{2+}, and Al^{3+} in red clay. Cations act as "bridges" between negatively charged clay particles and carrageenan molecules, forming a strong "soil-cation-carrageenan" ternary composite structure; at the same time, the hydroxyl groups on the carrageenan molecular chain form hydrogen bonds with soil particles, further enhancing the cementation effect. When the dosage increases to 1%, carrageenan molecules are fully dispersed, and soil particles are closely connected through cementation to form a stable three-dimensional spatial network structure, significantly improving cohesion; excessive carrageenan causes molecular chains to entangle and aggregate, forming overly enriched gel areas. During shearing, the failure surface preferentially passes through these soft gel-enriched areas instead of damaging the stronger "soil-gel" connection points, resulting in a decrease in the effective cohesion of the system.

The change of internal friction angle is the result of the ebb and flow of the "lubrication effect" and the "granular structure effect". At the low dosage stage, the strong hydrophilicity of carrageenan makes it quickly absorb pore water, form a viscous gel, and wrap around the surface of soil particles, forming a continuous and smooth "polymer-water" composite lubricating film. This film separates rough soil particles, reducing sliding friction and interlocking resistance. With the increase of dosage, the lubricating film becomes more continuous and thicker, and the lubrication effect dominates, so the internal friction angle continues to decrease, reaching a minimum near a dosage of 1%; when the dosage continues to increase, carrageenan closely cements soil particles into larger and stronger aggregates, enhancing the interlocking effect between aggregates and offsetting part of the lubrication effect, so the internal friction angle begins to increase.

3.4. Comparative Analysis of Test Results

All three biological gels can improve the shear strength of red clay, and the strength shows a consistent trend of "first increasing and then decreasing" with the change of their own dosages. Xanthan gum and guar gum have the same optimal dosage, and the shear strength reaches the highest when the dosage is 1.5%; carrageenan has a lower optimal dosage, and the best improvement effect can be achieved only when the dosage is 1%. In terms of the magnitude of strength improvement, xanthan gum has the most significant improvement effect at the optimal dosage.

Cohesion is the core factor for the three gels to enhance the shear strength of red clay. The cohesion of red clay modified by all three gels "first increases and then decreases" with the increase of dosage. At low dosages, gel molecules form a cementitious network through bonding, leading to a gradual increase in cohesion; when the dosage exceeds the optimal value, molecular chains entangle and agglomerate to form invalid gel zones, resulting in a subsequent decrease in cohesion. Among them, xanthan gum has the highest peak cohesion and the largest improvement range. After the dosage of carrageenan exceeds the optimal value, the attenuation rate of cohesion is the slowest, indicating that the cohesion of red clay modified by carrageenan has stronger stability.

The three gels have different influence trends on the internal friction angle, but they all share the common characteristics of "small influence range and low contribution to the total shear strength". Xanthan gum and carrageenan show a trend of "first decreasing and then increasing": at low dosages, a lubricating film is formed to reduce friction, leading to a decrease in the internal friction angle; at high dosages, particles agglomerate and interlock, making friction rebound and the internal friction angle increase. Guar gum shows a trend of "first increasing and then decreasing": at low dosages, it directly promotes the cementation and agglomeration of soil particles to enhance interlocking, resulting in an increase in the internal friction angle; at high dosages, the lubrication effect of free gel dominates, leading to a decrease in the internal friction angle. The three gels have a small influence on the internal friction angle, and their contribution to the total shear strength is much lower than that of cohesion, serving only as auxiliary factors.

3.5. Discussion

This study systematically investigated the improvement effects of three biological gels on the shear strength of Guilin red clay through indoor direct shear tests. However, limited by test conditions, research scope and objective factors, it still has certain limitations.

In terms of test conditions, this study only set a fixed curing age of 7 days and did not consider the influence of different curing times on the improvement effect of biological gels. In practical engineering, the improved red clay mass needs to undergo long-term natural environmental effects, while the cementitious network of biological gels may age or undergo secondary crosslinking with the extension of curing time, resulting in dynamic changes in mechanical indicators such as cohesion and internal friction angle. Therefore, the current short-term test results are difficult to fully reflect in the long-term engineering performance. Meanwhile, the tests were carried out under ideal conditions of constant temperature, without wet-dry cycles and freeze-thaw cycles, and did not take into account the actual environmental factors in Guilin such as heavy rainfall, high temperature and seasonal temperature fluctuations. Rainwater infiltration may cause biological gels to lose with pore water, and high temperature may accelerate the degradation of gel molecular chains. These factors may weaken the improvement effect, but the current test results cannot quantify the impact of such environmental disturbances on the stability of the improved mass.

In terms of test indicators and mechanism analysis, the tests only obtained indicators including shear strength, cohesion and internal friction angle through direct shear tests, and did not detect other key engineering properties of biological gel-improved red clay, such as compression modulus, permeability coefficient and disintegration rate. These indicators are crucial for the design of projects such as subgrades and slopes, and the current single-index analysis is difficult to comprehensively evaluate the engineering applicability of biological gels.

In addition, although the improvement mechanism was explained from the perspective of molecular forces, microscopic testing methods such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) were not used to intuitively observe the interface interaction morphology between biological gels and red clay particles. This leads to the lack of microscopic observation data to support the mechanism explanation, making it difficult to accurately reveal the essential reasons for the differences in improvement effects among different biological gels.

4. Conclusions

(1) The three biopolymers—xanthan gum, guar gum, and carrageenan—can all effectively improve the shear strength characteristics of Guilin red clay. The core mechanism is to form a cementation network through intermolecular forces (hydrogen bonds, van der Waals forces) and cationic bridges, significantly enhancing soil cohesion.

(2) The optimal improvement dosages of the three biogels are different: the optimal dosage of xanthan gum and guar gum is 1.5%, at which the shear strength of red clay is the highest; the optimal dosage of carrageenan is 1%, and excessive dosage will lead to a decline in improvement effect due to gel enrichment or particle agglomeration.

(3) The three biogels have the same influence law on the cohesion of red clay, which first increases and then decreases with the increase of dosage; their influence on the internal friction angle varies with the type. Xanthan gum shows an opposite change, guar gum first increases and then decreases, and carrageenan first decreases and then increases. The overall variation range of the internal friction angle is smaller than that of cohesion, indicating that the improvement of the shear strength of red clay by biogels mainly depends on the increase of cohesion.

(4) As environmentally friendly and renewable biological modifiers, xanthan gum, guar gum, and carrageenan overcome the drawbacks of traditional inorganic cementitious materials such as high energy consumption and large carbon emissions, providing a green and sustainable soil improvement solution for engineering construction in Guilin's red clay areas.

In the reinforcement of highway and railway subgrades, targeting the problem that red clay is prone to strength attenuation due to rainwater infiltration, adding biological gel at the optimal dosage can improve the shear strength and water stability of subgrades, and reduce the risk of settlement or slide.

In slope protection projects, they are particularly suitable for temporary or small-to-medium-sized slopes. Applied by spraying and mixing, they can enhance the cementation capacity of red clay and form a "biological gel-vegetation" composite protection system in combination with vegetation, thereby reducing the risk of slumping.

In the foundation treatment of low-rise civil buildings, improving red clay with biological gel can replace traditional high-energy-consumption processes, which not only meet the bearing capacity requirements but also reduce carbon emissions.

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Conflicts of Interest

The authors declare no conflicts of interest.

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