Analysis of the Physical and Mechanical Properties of Expansive Soil Enhanced by Rubber-Microbial Synergy

Peng Fei[1], Liu Baohua[1], Cai Yu[1,*], Liu Xiaohu[2]

[1] Hunan Agricultural University, School of Water Resources and Civil Engineering, Changsha 410128, China

[2] China Construction Fifth Engineering, Division Third Construction Co., Ltd., Changsha 410007 China

Corresponding Author: Cai Yu (caiyu_826@163.com)

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Abstract: Expansive soil is known as "cancer soil" due to its prominent swelling and shrinkage characteristics. Traditional chemical and physical improvement methods have deficiencies in environmental protection and long-term performance. This paper proposes a novel synergistic improvement method using waste tire rubber particles combined with Microbially Induced Calcium Carbonate Precipitation (MICP). Rubber particles of 50-mesh, 20-mesh and 10-mesh with mixing ratios ranging from 5% to 15% were adopted, together with *Sporosarcina pasteurii* and cementation solution (1 mol/L urea + 1 mol/L $CaCl_2$). Compaction tests, swelling rate tests and consolidated-undrained (CU) triaxial tests were conducted to systematically investigate the physical and mechanical properties of rubber-microbe improved soil. The results show that the optimal mixing ratio for single rubber modification is 5%, and 50-mesh fine rubber particles deliver the best anti-swelling effect. When MICP is applied with the optimal rubber content, the peak deviator stress increases by approximately 30%. Calcium carbonate crystals fill pores and bridge the interfaces between soil and rubber particles, forming a rigid-flexible composite structure and achieving a synergistic reinforcement effect beyond simple superposition. This study provides a new approach for the eco-friendly improvement of expansive soil and the resource utilization of waste rubber.

Keywords: Modified expansive soil; Rubber particles; MICP technology; Triaxial test; Microstructure

1. Introduction

Expansive soil is a type of high-plastic clay widely distributed across the globe. Its clay minerals such as montmorillonite and illite possess strong hydrophilicity. Under dry-wet cycles, expansive soil expands remarkably in volume, softens and loses strength sharply after water absorption, while it shrinks drastically, cracks and hardens upon dehydration. Such unstable engineering properties earn

it the reputation of "cancer soil" in engineering construction [1-3]. China is among the countries with the most extensive distribution of expansive soil worldwide, and economic losses caused by expansive soil hazards amount to tens of billions of yuan annually. With the further advancement of the Belt and Road Initiative infrastructure construction and the dual-carbon strategy, the engineering community has put forward an urgent demand for efficient, eco-friendly and long-term stable treatment technologies for expansive soil.

Traditional improvement methods for expansive soil mainly fall into three categories: chemical modification, physical modification and biological modification. Chemical modifiers such as lime and cement alter the mineral composition of soil via cation exchange and pozzolanic reactions, and are the most widely adopted. Nevertheless, their production releases large quantities of CO_2. Besides, the treated soil features an elevated pH value, which leads to soil compaction and ecological degradation [4]. Physical modification by mixing sand or gravel requires a huge amount of foreign earth, bringing secondary damage to the ecological environment [5-6]. Microbially Induced Calcium Carbonate Precipitation (MICP) utilizes urease-producing bacteria such as Sporosarcina pasteurii to hydrolyze urea and generate calcium carbonate crystals. The crystals fill soil pores and bind particles together, making this technology green, low-carbon, cost-effective and efficient [7-8]. However, two major bottlenecks restrict the application of MICP in expansive soil. First, the low permeability of expansive soil hinders the uniform transport of bacterial and cementation solutions. Second, the rigid structure formed solely by calcium carbonate cementation is prone to fatigue failure under repeated dry-wet cycles, resulting in gradual deterioration of the improvement effect [7,13].

Meanwhile, the disposal of waste rubber tires has become a global environmental challenge. China produces over 16 million tons of waste tires every year, with an annual growth rate of 8% to 10%, while the recycling rate is less than 50% [9]. Waste rubber particles are characterized by light weight, high elasticity and strong hydrophobicity, and have been adopted for expansive soil improvement in recent years. Relevant studies have demonstrated that rubber particles can effectively restrain soil swelling, reduce the optimum moisture content and maximum dry density, and absorb partial swelling strain energy [10-12]. Nevertheless, the inert and hydrophobic surface of rubber particles results in weak interfacial bonding with soil particles. This leads to limited improvement in shear strength, and even strength reduction at high mixing ratios [13-15]. It has become an urgent scientific issue to enhance the bonding strength at the soil-rubber interface while retaining the flexible buffering performance of rubber [16-17]. Accordingly, this study proposes a novel synergistic improvement method combining rubber and microorganisms. Calcium carbonate generated via MICP acts as a biological binder to strengthen the interfacial connection between rubber and soil particles. Meanwhile, the elasticity and hydrophobicity of rubber alleviate fatigue damage to calcium carbonate cementation caused by dry-wet cycles and improve soil permeability. The complementary advantages of flexible buffering and rigid cementation are realized to achieve a synergistic effect beyond simple superposition. Currently, relevant researches at home and abroad are rarely reported. Therefore, it is necessary to conduct systematic research on proportion optimization, mechanical performance evaluation and microscopic mechanism analysis.

2 Materials and Test Design

2.1 Test Materials

The expansive soil used in this study was collected from a construction site in Nanyang, Henan Province. The soil samples are yellowish-brown in appearance. They were dried in an oven at 105–

110 °C for 24 hours and then sieved through a 0.5 mm sieve (Fig. 1). A series of conventional geotechnical tests were carried out, including liquid and plastic limit tests, compaction tests, and swelling property tests (free swell rate, unloaded swell rate and loaded swell rate). The basic physical and swelling parameters of the raw expansive soil were obtained, as listed in Table 1.

Table 1: Basic Physical Indices of Expansive Soil.

liquid limit /%	plastic limit /%	plasticity index/Ip	optimum moisture content /%	maximum dry density /g·cm-3	free swelling rate /%	unloaded swell rate/%	loaded swell rate/%(50kPa)	swelling property
55.97	26.15	29.82	22.5	1.54	79.5	16.9	6	moderately



(a) Raw expansive soil



(b) Rubber particles



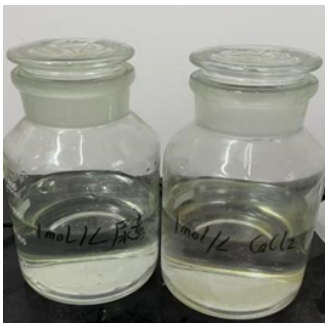
(c) Sporosarcina pasteurii



(d) Medium components



(e) Bacterial solution before activation



(f) Cementation solution

Figure 1: Test materials.

Most previous studies focused on the engineering application of coarse-grained rubber particles, which show poor compatibility with clay soils. By contrast, fine rubber particles possess better workability and are more suitable for the improvement of fine-grained soils. Therefore, three types of waste rubber particles with different particle sizes, namely 50-mesh (0.50 mm), 20-mesh (0.85 mm) and 10-mesh (2.00 mm), were adopted in this study to systematically evaluate the improvement effects of rubber with varying particle sizes and mixing ratios. The microbial strain used herein is *Sporosarcina pasteurii*. Non-toxic and harmless, this bacterium can produce abundant urease during growth and metabolism to catalyze the hydrolysis of urea. A liquid medium was selected to enhance bacterial concentration and urease activity, and its components are presented in Table 2. It is found that the optimal conditions for bacterial growth are a culture temperature of 30 °C and a pH value of 8.

Table 2: Composition of the Culture Medium.

Component Name	Liquid nutrient medium
Yeast extract	10g
ammonia sulfate,	10g
0.13M Tris buffer（PH=9）	15.7g
urea	20g
water	1.0L

Expansive soil contains a low calcium content, which leads to insufficient calcium carbonate production via Microbially Induced Calcium Carbonate Precipitation (MICP). Thus, an adequate calcium source needs to be supplemented during the MICP process. Urease secreted by *Sporosarcina pasteurii* catalyzes urea hydrolysis to form calcium carbonate precipitates and further stabilize the soil. The cementation solution provides calcium ions and urea required for the reaction. As reported in Reference, the concentration of calcium chloride should not exceed 1 mol/L. Accordingly, the cementation solution in this study was prepared as a mixed solution containing 1 mol/L urea and 1 mol/L calcium chloride.

2.2 Test Design

The tests were divided into three groups: raw soil control group, single rubber modified group, and rubber-microbe synergistic modified group. Compaction tests, swelling property tests (loaded and unloaded swell rate) and consolidated undrained (CU) triaxial shear tests were systematically conducted on rubber-modified expansive soil to determine the optimal mixing ratio and particle size of rubber particles. On the basis of the optimal rubber content, the synergistic modification technology combining rubber and microbes was investigated. By comparing the physical and mechanical properties of soil before and after synergistic modification, the bonding reinforcement mechanism of calcium carbonate crystals at the soil-rubber interface and the synergistic strengthening effect of the rigid-flexible composite structure were revealed. The research results can provide theoretical support and optimal proportion parameters for the eco-friendly and long-term improvement of expansive soil. The detailed test groups are shown in Table 3.

Table 3: Test Grouping Design.

Experimental Group	Rubber particle size	Rubber content	MICP handle	Test project
Soil control group	—	0%	No	Compaction, expansion rate, triaxial testing
Single Rubber Group	50/20/10mesh	5%/10%/15%	No	Compaction, expansion rate, triaxial testing
Collaborative Improvement Group	50/20/10mesh	5%	Yes	triaxial testing

2.3 Test Scheme

(1) Compaction Test

The heavy compaction method was adopted to investigate the effects of rubber particle sizes (50 mesh, 20 mesh, 10 mesh) and mixing contents (5%, 10%, 15%) on the compaction characteristics of expansive soil. For each combination, five soil specimens with different moisture contents were prepared at an interval of 2% moisture content. Each specimen was compacted in five layers with 56 blows per layer. The moisture content-dry density curves were plotted based on test results, and the variation laws of optimum moisture content and maximum dry density of rubber-modified expansive soil under different particle sizes and mixing contents were analyzed. Figure 2 shows the state of compacted specimens mixed with 50-mesh rubber at different mixing contents.



(a) 5% (b) 10% (c) 15%

Figure 2: Appearance of Compacted Specimens With Different Contents of 50-Mesh

(2) Swelling Characteristic Test

The swelling tests on rubber-modified expansive soil include unloaded and loaded swell rate tests. The unloaded swell rate was measured using an oedometer. Standard ring cutter specimens with a diameter of 61.8 mm and a height of 20 mm were adopted (Fig. 3). Three rubber particle sizes (50 mesh, 20 mesh, 10 mesh) and three mixing contents (5%, 10%, 15%) were designed, with three parallel specimens prepared for each group. The loaded swell rate test was conducted under a pressure of 50 kPa with the same particle sizes and mixing contents (Fig. 4). By comparing the swell rates of expansive soil before and after modification, the improvement effect of rubber addition on the swelling-shrinkage performance of expansive soil was evaluated.

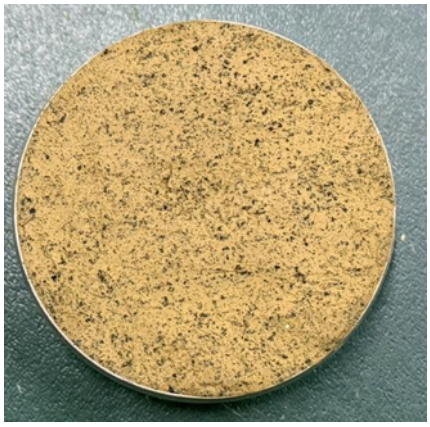


Figure 3: Ring Cutter Specimens.



Figure 4: Loaded Swell Rate Test.

(3) Static Triaxial Test

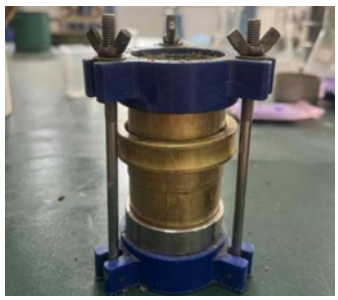
The static triaxial tests were carried out using the LFTD1820 triaxial testing apparatus. The consolidated undrained (CU) shear test was adopted to analyze the influences of rubber particle sizes (50 mesh, 20 mesh, 10 mesh) and mixing contents (5%, 10%, 15%) on the shear strength of expansive soil, so as to determine the optimal particle size and mixing content. Three parallel specimens were prepared for each group and fabricated at the optimum moisture content. On the basis of the determined optimal parameters, expansive soil was uniformly blended with rubber particles of the optimal size and content. The cultured *Sporosarcina pasteurii* solution and cementation solution were mixed at a volume ratio of 1:1, and the mixture was added into the rubber-amended expansive soil according to the optimum moisture content for specimen preparation. All specimens were sealed with plastic film and cured for 48 h, then subjected to consolidated undrained triaxial tests on rubber-microbe modified expansive soil (Fig. 5). The detailed test conditions are listed in Table 4.

Table 4: Working Conditions of Static Triaxial Tests.

Study Subject	Rubber particle size	Rubber content	Rate of shear	Confining pressure（kPa）	Drainage condition	End condition
Rubber-modified expansive soil	50 mesh, 20 mesh, 10 mesh	5%, 10%, 15%	0.5mm/min	50, 100, 150	Consolidated undrained soil	The axial strain reaches 20%.
Rubber-microbial modified expanded soil	50 mesh, 20 mesh, 10 mesh	5%	0.5mm/min	50, 100, 150	Consolidated undrained soil	The axial strain reaches 20%.



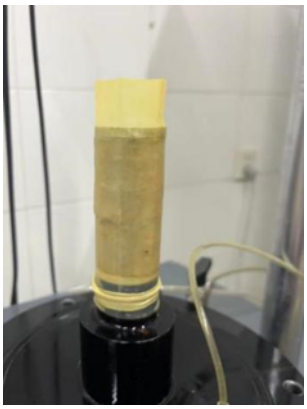
(a) LFTD1820 Triaxial Tester



(b) Specimen preparation



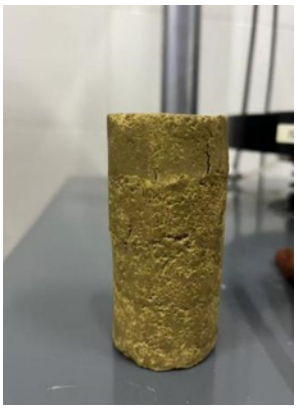
(c) MICP solidification



(d) Specimen installation stage



(e) Loading stage



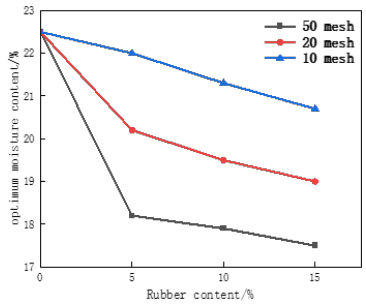
(f) Specimen failure

Figure 5: Triaxial test of rubber-microbe modified expansive soil.

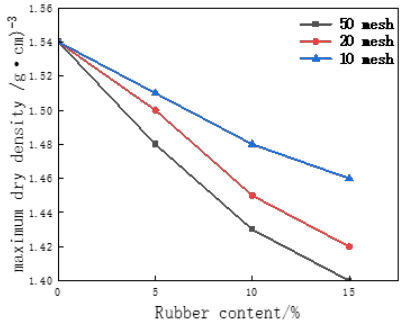
3. Test Results and Discussion

3.1 Effect of Rubber on Compaction Performance of Expansive Soil

The variation of optimum moisture content and maximum dry density of rubber-modified expansive soil with rubber content was obtained via compaction tests, as shown in Figure 6. Both indicators decreased monotonously with the increase of rubber content. The optimum moisture content of raw expansive soil was 22.5%. For soil modified with 50-mesh rubber, the values decreased to 18.2%, 17.9% and 17.2% in sequence; those for 20-mesh rubber were 20.2%, 19.5% and 19.0%; and those for 10-mesh rubber were 22.0%, 21.3% and 20.7%. Smaller rubber particle size led to a more remarkable modification effect. The optimum moisture content dropped most rapidly at the rubber content of 5%, because hydrophobic rubber particles replaced water-absorbing clay minerals and reduced the water demand of the mixed soil. In terms of maximum dry density, the value of raw expansive soil was 1.54 g/cm³. For 50-mesh rubber modified soil, the dry density declined from 1.48 g/cm³ to 1.40 g/cm³ with increasing rubber content; the values for 20-mesh rubber decreased from 1.50 g/cm³ to 1.42 g/cm³, and those for 10-mesh rubber dropped from 1.51 g/cm³ to 1.46 g/cm³. Similarly, finer particles exerted a greater influence. A sharp reduction in density was observed when the rubber content increased from 0 to 10%. The elastic rubber particles loosened the soil matrix and reduced compaction degree. When the content rose from 10% to 15%, the density continued to decrease. The voids between soil particles expanded, and the contact among rubber particles increased, which further enlarged the internal pores of the soil.



(a) Variation curve of optimum moisture content with mixing content

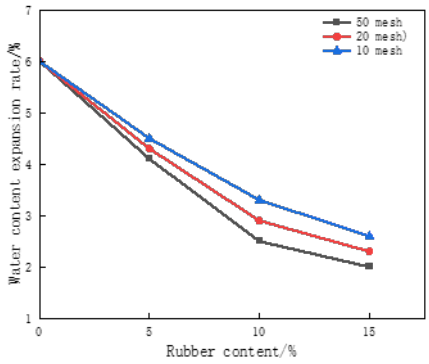


(b) Variation curve of maximum dry density with mixing content

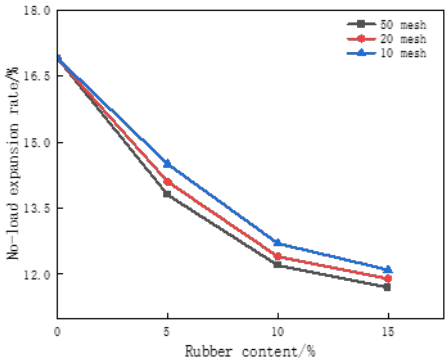
Figure 6: Curves of optimum moisture content and maximum dry density versus mixing content for rubber with different particle sizes.

3.2 Inhibitory Effect of Rubber on Swelling Characteristics

Figure 7 presents the variation curves of unloaded and loaded swell rates of rubber-modified expansive soil with rubber content for different particle sizes. It can be seen that the addition of rubber leads to a continuous decrease in swell rate whether under overburden load or not. The unloaded swell rate of raw expansive soil is 16.9%, which drops to 11.7% after incorporating 50-mesh rubber, proving that rubber can effectively restrain soil swelling. The main mechanism is that rubber particles replace part of hydrophilic clay minerals. Their strong hydrophobicity reduces the overall hydrophilicity of the soil and weakens the driving force of swelling. Under unloaded conditions, the elasticity of rubber only provides slight internal restraint through inter-particle contact, yet the swell rate still declines. When subjected to an external load of 50 kPa, rubber particles act as numerous tiny compressible springs. The swelling force generated by water absorption causes elastic compression of rubber, which absorbs and stores part of strain energy and further reduces the macroscopic swelling deformation. Overall, the reduction of loaded swell rate results from the combined effects of three mechanisms under external load: reduced swelling potential by hydrophobicity, absorbed swelling energy by elastic particles, and improved deformation resistance by the composite soil skeleton. In addition, the curves drop sharply when the rubber content ranges from 0 to 10% and tend to flatten beyond 10%, indicating an optimal content range generally below 10%. Within this range, the swell rate decreases rapidly with the increase of rubber content. When the content exceeds this range, the decreasing trend slows down; the swell rate may even rise due to rubber agglomeration and excessive loosening of the soil skeleton.



(a) Variation of unloaded swell rate with rubber mixing content

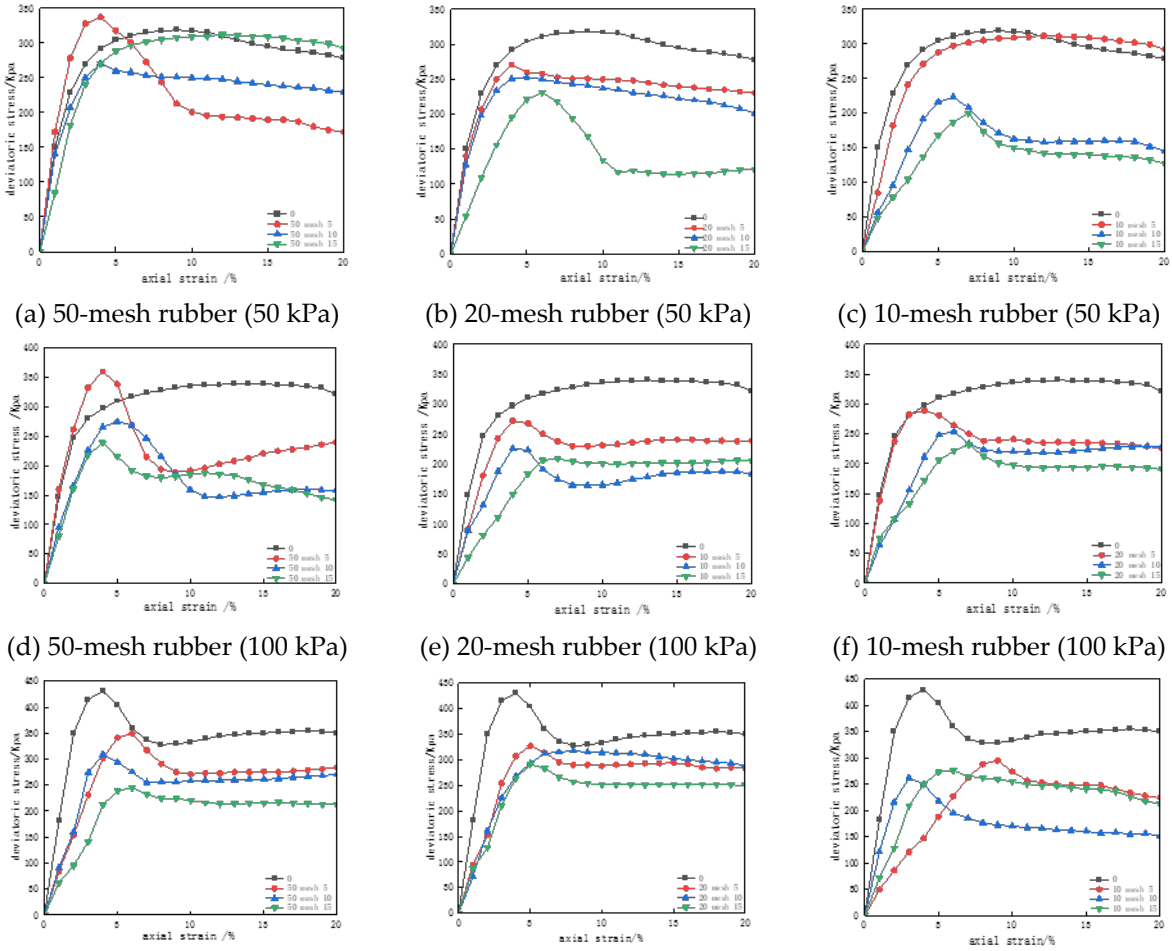


(b) Variation of loaded swell rate with rubber mixing content

Figure 7: Curves of unloaded and loaded swell rates versus rubber mixing content.

3.3 Strength Characteristics of Expansive Soil

Modified by Single Rubber Triaxial tests were conducted on rubber-modified expansive soil with different particle sizes and mixing contents. The stress-strain curves varying with rubber content under different confining pressures were obtained, as shown in Figure 8.



(a) 50-mesh rubber (50 kPa) (b) 20-mesh rubber (50 kPa) (c) 10-mesh rubber (50 kPa)

(d) 50-mesh rubber (100 kPa) (e) 20-mesh rubber (100 kPa) (f) 10-mesh rubber (100 kPa)

(g) 50-mesh rubber (150 kPa) (h) 20-mesh rubber (150 kPa) (i) 10-mesh rubber (10 kPa)

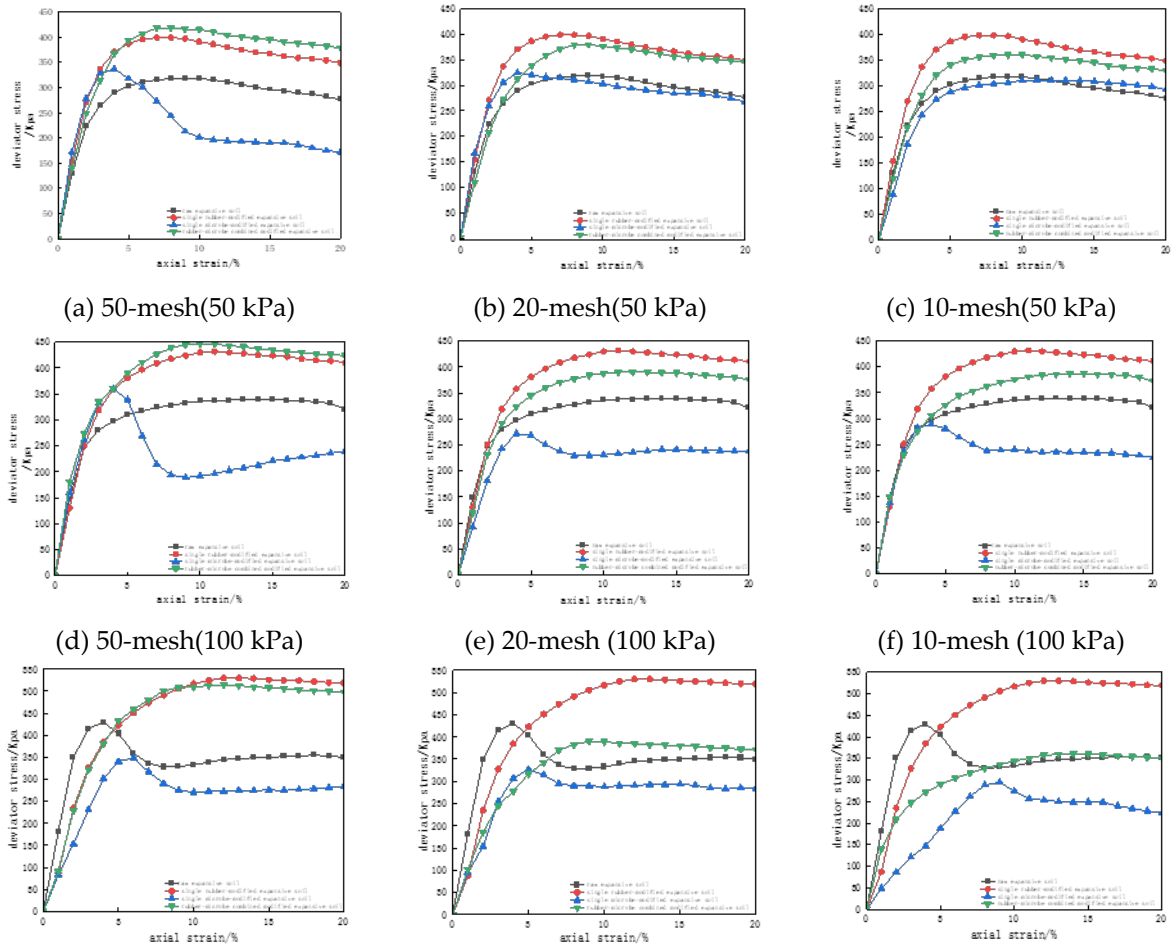
Figure 8: Stress-Strain Curves of Rubber-Modified Expansive Soil Under Different Confining Pressures.

As shown in the figure, with the increase of rubber content, the deviator stress of specimens rises rapidly to a peak and then gradually levels off. The peak strength of soil mixed with 5% rubber is higher than that of raw expansive soil. When the rubber content exceeds 5%, the peak strength declines below that of the raw soil, and a higher content corresponds to a delayed peak value. This indicates that rubber content exerts a nonlinear influence, and there exists an optimal content range. Within this range, the deviator stress reaches its peak and the soil performs best. Beyond this range, the strength deteriorates, and the stress-strain behavior changes from strain softening to strain hardening. The modified soil maintains relatively high bearing capacity after failure and exhibits good ductility, achieving simultaneous improvement in strength and toughness. In terms of particle size, 50-mesh rubber presents a much better modification effect than 20-mesh and 10-mesh rubber. In addition, as the confining pressure increases from 50 kPa to 150 kPa, the failure mode transforms from brittle splitting to plastic bulging, accompanied by a transition from strain softening to strain hardening on the stress-strain curves. Under high confining pressure, the elastic compression and lateral expansion of rubber dominate the mechanical behavior, which effectively absorbs strain energy and enhances the ductility of the soil.

3.4 Strength Characteristics of Expansive Soil Modified by Combined Rubber and Microorganism

According to the triaxial test results of single rubber-modified expansive soil, the optimal

modification effect is achieved when the rubber content of all particle sizes is 5%. Therefore, the rubber content was set at 5% for the triaxial tests of rubber-microbe modified expansive soil. The strength characteristics of raw expansive soil, single rubber-modified soil, single microbe-modified soil and combined rubber-microbe modified soil under different confining pressures were compared and analyzed. The test results are shown in Figure 9.



(a) 50-mesh(50 kPa) (b) 20-mesh(50 kPa) (c) 10-mesh(50 kPa)

(d) 50-mesh(100 kPa) (e) 20-mesh (100 kPa) (f) 10-mesh (100 kPa)

(g) 50-mesh (150 kPa) (h) 20-mesh (150 kPa) (i) 10-mesh (150 kPa)

Figure 9: Stress-strain relationships of expansive soil modified with rubber of different particle sizes and microorganisms.

As illustrated in the figure, compared with raw expansive soil, single rubber-modified soil and single microbe-modified soil, the shear strength is obviously improved after microbial treatment. At the rubber content of 5%, the peak deviator stress of specimens with different particle sizes increases greatly after MICP treatment, exceeding that of raw soil and single rubber-modified soil. Taking 50-mesh rubber as an example, under the confining pressure of 100 kPa, the peak deviator stress rises from approximately 350 kPa for single rubber modification to 480 kPa, with a strength increase of about 30%. The strength of specimens blended with 50-mesh rubber and microorganisms is slightly higher than that of single microbe-modified soil. By contrast, the strength declines when adopting 20-mesh and 10-mesh rubber, and the reduction becomes more pronounced as confining pressure rises. The test results reveal that microorganisms effectively enhance the bonding force between soil particles and rubber. This reinforcing effect is more prominent for finer rubber particles, and the

stress-strain behavior changes from strain softening to strain hardening.

4. Conclusions

This study systematically investigated the effects of rubber particle size and mixing content on the basic physical properties, swelling characteristics and shear strength of expansive soil. The modification performances of single rubber treatment and combined rubber-microbial treatment were also compared and analyzed. The main conclusions are drawn as follows: (1) Rubber can effectively improve the compaction and swelling characteristics of expansive soil. The addition of rubber particles reduces the optimum moisture content and maximum dry density of expansive soil, and both parameters decrease with the increase of rubber content. Meanwhile, rubber exerts a remarkable inhibitory effect on soil swelling. Fine rubber particles (50 mesh) show better modification performance than coarse ones (20 mesh and 10 mesh). (2) There exists an optimal rubber content of 5% for single rubber modification. At this content, the shear strength of modified soil is higher than that of raw expansive soil. The strength decreases when the rubber content exceeds 5%, and the stress-strain curve transforms from strain softening to strain hardening. With the increase of confining pressure, the failure mode changes from brittle splitting to plastic bulging, and the ductility of soil is improved. (3) When MICP technology is adopted at the rubber content of 5%, the shear strength of modified soil with different particle sizes is significantly enhanced. The combination with 50-mesh rubber achieves the best synergistic effect, with the peak deviator stress increased by approximately 30%. (4) The optimal proportion recommended in this study is as follows: rubber particle size of 50 mesh and mixing content of 5%; microbial culture at 30 ℃ with pH value of 8; cementation solution with equal molar concentration at a mixing ratio of 1:1; curing time longer than 48 h.

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