Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 3468900, 8 pages
https://doi.org/10.1155/2022/3468900

Research Article

Experimental Study on Strengthening Root-Soil Composite with Different Root Contents by Using MICP

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Received 28 June 2022; Revised 28 August 2022; Accepted 12 September 2022; Published 29 September 2022

Academic Editor: Yang Wu

Microbial induced carbonate precipitation (MICP) in coordination with vegetation protection is a novel technology in the field of slope reinforcement. Urea in MICP can promote vegetation growth and change the root content in the soil. However, existing studies often ignore the influence of MICP on root growth, while root content has a significant impact on the ability of vegetation to cement soil and protect slopes. In this paper, through the laboratory direct shear test, the strength variation characteristics of root-soil composites with different root contents before and after reinforcement were analyzed, and the influence of root content changes on the strength of root-soil composites in the MICP collaborative slope protection project was studied. The results showed that: (1) the strength of the root-soil composite was improved significantly after MICP treatment. When the root content was 1.5%, the maximum strength peak value was increased by 32.6%, and the cohesive force was increased by 49.2%. (2) MICP reaction has no effect on the root content of the peak intensity, indicating that MICP has no negative effect on vegetation growth and can be combined with vegetation protection. The results show that MICP synergistic slope protection has strong engineering application value.

1. Introduction

Vegetation slope protection uses mechanical effects such as reinforcement of shallow roots and anchoring of deep roots to improve slope stability and interacts with soil to form a root-soil complex, which not only strengthens the cohesive force and shear resistance of soil but also restores the ecological environment of the slope [1–4]. Since the root-soil complex is regarded as a stress structure composed of soil and roots, its slope protection effect is affected by both the soil and the root system, while the vegetation needs a certain time to grow, and the vegetation's slope protection capacity is limited in the early stage. Therefore, through other technology, scholars improved the combination of slope protection with vegetation and formed a new ecological slope protection technology (Table 1). Most of the studies in Table 1 use traditional slope protection techniques or directly reinforce soil, ignoring the role of roots in vegetation slope protection. Because root growth is easily affected by conditions such as season and space, for example, vegetation concrete in ecological slope protection will hinder the growth space of vegetation, cause some soil pollution and restrict the absorption of nutrients by vegetation. Hu et al. [9] found that when the root content of the root-soil complex formed by bermudagrass was 0.3%–0.4%, its shear strength remained unchanged or decreased. The research on root systems mainly focuses on the influence of root morphology and vegetation types on the shear strength of soil, while the influence of root content change on the strength of the root-soil complex needs further research. Therefore, it is necessary to study the effect of root content on the slope protection ability of vegetation for the establishment of new ecological slope protection technology.

In recent years, soil modification technology based on MICP has attracted extensive attention in the field of geotechnical engineering. MICP of urea hydrolysis is the most

Table 1: Slope protection technology.

Number	Solution	Reference
1	3D reinforced ecological slope protection	Wang et al. [5]
2	Vegetation concrete ecological slope protection	Li et al. [6]
3	Micropiles group-soil-vegetation ecological slope protection	Deng et al. [7]
4	Polymer soil stabilizer for ecological slope protection	Liu et al. [8]

widely used method. This technology decomposes urea into ammonium ions and carbonate ions by some naturally occurring microorganisms. The chemical equations are shown in formulas (1)~(3). In the presence of calcium ions, cementing calcium carbonate is formed, which fills the pores of the soil and increases the strength of the soil.

$$CO\left(NH_2\right)2 + 2H_2O \longrightarrow CO_{3^{2-}} - + 2NH_{4^{+}} \tag{1}$$

$$C_{a^{2+}} + \text{Cell}\left(\text{negatively charged}\right) \longrightarrow \text{Cell} - C_{a^{2+}} \tag{2}$$

$$CO_{3^{2-}} + \text{Cell} - C_{a^{2+}} \longrightarrow \text{Cell} - C_aCO_3\downarrow \tag{3}$$

MICP can form a "hard shell" on the soil surface [10]. The existence of a "hard shell" can improve the strength and permeability of rock and soil and greatly improve the efficiency of slope treatment. At the same time, some scholars add fibers to the clay [11, 12], which can improve the soil strength significantly. The reason is that the fibers can be evenly dispersed in the soil and improve the properties of the soil. Therefore, the application of MICP in vegetation slope protection has sufficient feasibility in geotechnical engineering. Salifu et al. [13] showed that slope stability could be significantly improved by simulating tidal experiments with MICP as a remedial measure. Gowthaman et al. [14] also showed that the geotechnical properties of the soil were significantly improved, and it was proved that the slope soil of the Hokkaido expressway could be stabilized by using surface treatment through laboratory experiments. Jiang et al. [15] showed that the surface spraying method could effectively improve sandy-slope surface erosion. Moreover, Jiang et al. [16, 17] found that MICP can control the erosion effect inside the soil, which proves that MICP has strong feasibility in soil erosion control. Kannan et al. [18] used MICP to reinforce marine clays, showing that MICP can still improve soil strength in complex environments. Li et al. [19] proved theoretically that MICP could be combined with grass vegetation to form the protection technology of MICP in coordination with the grass checkerboard sand barrier through data arrangement and data collection.

To sum up, MICP, as a novel solidification technology, has an obvious reinforcement effect and can enhance the shear strength of the soil. On the other hand, MICP is quick and has good ecological benefits. Urea can also provide necessary growth elements for vegetation, promote vegetation growth, and then change the root content. Therefore, taking the second phase project of Binjiang Road in Beibei, Chongqing as the research background, this paper conducted grouting reinforcement for root-soil complexes with different root contents, explored the strength changes of root-soil complexes with different root contents before and after MICP reinforcement, and provided the theoretical basis for MICP cooperation with vegetation protection of slope.

2. Materials and Methods

2.1. Materials

2.1.1. Sampling Overview of Test Materials. The soil sampling site for this experiment is a certain slope on Binjiang Road, Beibei, Chongqing. The region's landscape belongs to the tectonic denudation area and erosion accumulation valley area, the area within which the air has moist weather characteristics in early spring, long summer, and a warm and foggy winter. The average temperature of the coldest month (January) is 9.9°C, and the average temperature of the hottest month (August) is 33°C. The main source of groundwater is atmospheric rainfall, with an average annual rainfall of 1163 mm. The local tall fescue was selected as the object of this study, and the soil depth was about 5 m. The properties of the soil are shown in Table 2.

2.1.2. Microbial Culture and Cementation Solution. The microorganism used in the test was *Sporosarcina pasteurii*, which was purchased from the China General Microbiological Culture Collection Center; the CGMCC number is 1.367 (Figure 1). The microbe was selected from natural soil and had no negative impact on the ecological environment. The urease production ability is outstanding and has been widely used in geotechnical engineering. The medium for cell activation was yeast extract 20.0 g/L, ammonium chloride 10.0 g/L, manganese sulfate 10 mg/L, nickel chloride 24 mg/L, adjusted to pH = 9. The bacteria were cultured at 30°C and 200 r/min in a constant temperature shock chamber for 24 h, and then the activity was measured using a conductivity meter. The bacterial activity in this study was 0.1 ms/cm/min.

The primary function of the cementation solution is to provide the necessary urea and calcium ions for the MICP process, and calcium ions in this study were provided by calcium chloride. The concentration of cementation solution was 1.0 mol/L, and the molar concentration ratio of urea and calcium chloride was 1 : 1.

2.2. Experiment Scheme

2.2.1. Vegetation Roots. The tall fescue was selected as the research object for the vegetation root system, and the diameter of the root system was selected between 0.5 mm and 1.0 mm. In order to ensure that the root system could

Table 2: Basic physical properties of soil.

Specific gravity (G_s)	Plastic limit (ω_L/%)	Liquid limit (ω_P/%)	Plasticity index (I_P)	Natural density (ρ/g·cm^{-3})	Natural moisture content (ω/%)
2.56	33.2	19.2	14	1.9	20

Figure 1: Agar slant.

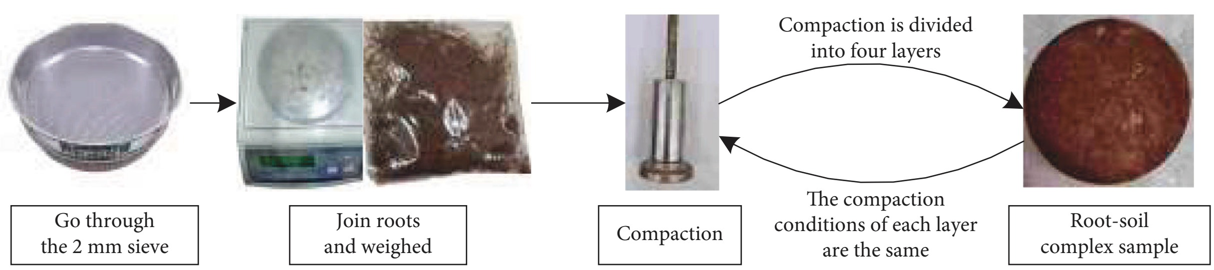

Figure 2: Sample production process.

provide strong shear strength, the root system length was greater than 10 mm and less than 20 mm. The root content was expressed by the biomass concentration of roots, and the root content was 0%, 0.5%, 1.0%, 1.5%, and 2.0% of the soil mass (Table 3). The effect of MICP on vegetation growth was simulated by different root content representing different growth conditions.

Table 3: Root content test plan.

Groups	Soil mass (g)	Root content (%)	Root mass (g)
T1	94	0	0
T2	94	0.5	0.47
T3	94	1.0	0.94
T4	94	1.5	1.41
T5	94	2.0	1.88

2.2.2. Sample Preparation. The soil samples were passed through a 2 mm sieve, and soil particles with a particle size greater than 0.5 mm were selected for the preparation of root-soil composite samples. The specific sample preparation process is shown in Figure 2. In this study, two groups of soil samples were prepared; one group was modified with MICP technology (experimental group, EG), and the other group was used as the control group (CG), as shown in Figure 3. The soil sample mold and vegetation process of the two groups were kept the same, and the sample height was 20 mm and the diameter was 80 mm.

2.2.3. MICP Grouting Experiment. Harkes et al. [20] proposed the step-by-step grouting method, in which bacterial and cementation solutions were poured into the soil in steps. On this basis, the surface percolation method [21] and the immersing method [22] are also proposed. For clay, the permeability of soil samples will change with the increase of curing times, thus reducing the curing effect. Therefore, step-controlled pressure grouting [23] and step-controlled grouting [24] are generally adopted, but uneven curing of soil is always unavoidable. Therefore, the MICP treatment process based on the injection method is proposed in this

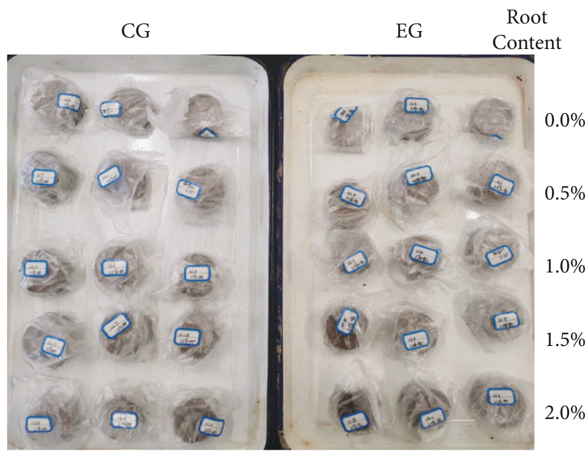

Figure 3: Root-soil composite sample.

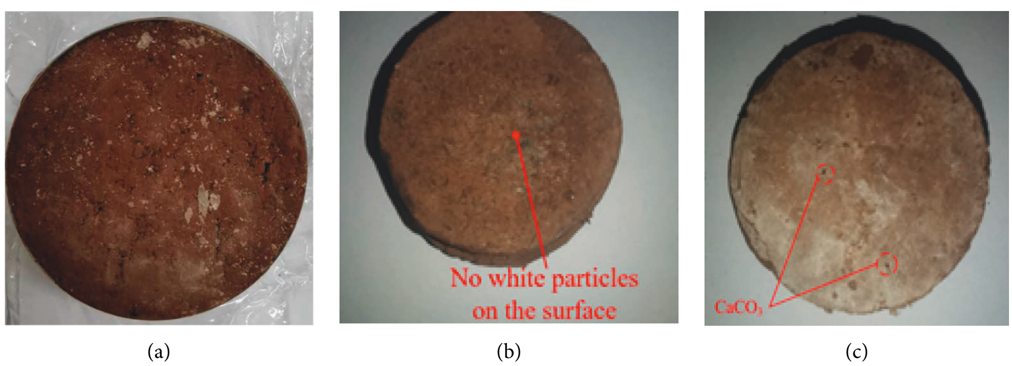

Figure 4: Comparison of MICP-treated root-soil composites. (a) Root-soil composites before MICP-treated; (b) root-soil composites without MICP-treated; and (c) root-soil composites after MICP-treated.

study, in which bacterial and cementation solutions are injected into the soil by a syringe. The specific process is as follows: for experimental groups T2, T3, T4, and T5, 1.5 ml of bacterial solution and 1.5 ml of cementation solution were injected into the soil evenly at regular intervals every day. After the injection, the soil sample was left for 12 h to ensure that the microorganisms and cementation solution could fill the soil and fully react. After the cementing process is completed, the soil sample is flipped, and MICP is processed in the other direction. In the T1 group, an equal volume of water was injected each time. The comparison of the root-soil composite treated with MICP is shown in Figure 4.

2.2.4. Direct Shear Test. Direct shear tests were carried out on the samples. The ZJ-3 strain-controlled direct shear instrument was used to control the shear rate of 0.8 mm/min according to the "standard for geotechnical test methods" (GB/T 50123–2019), and shear tests were carried out under vertical pressures of 100 kPa, 200 kPa, and 300 kPa, respectively. A stress-strain curve was drawn, and the maximum shear stress on the curve was taken as the shear strength of the sample under the current vertical pressure. For the strain hardening curve, the shear displacement of 4 mm was taken as the shear strength.

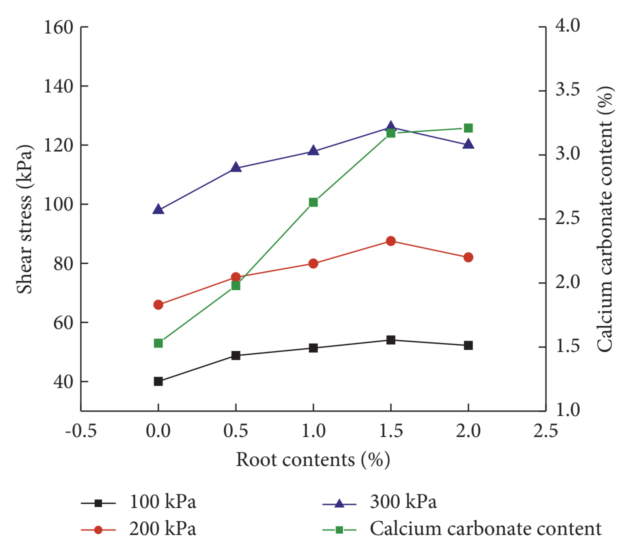

Figure 5: Relationship3 between shear strength, calcium carbonate content, and root content.

2.2.5. Methods for Measuring Calcium Carbonate. Calcium carbonate was measured by applying the gravimetric acid washing method. Firstly, the sample fragments were selected and put into the oven to dry to a constant

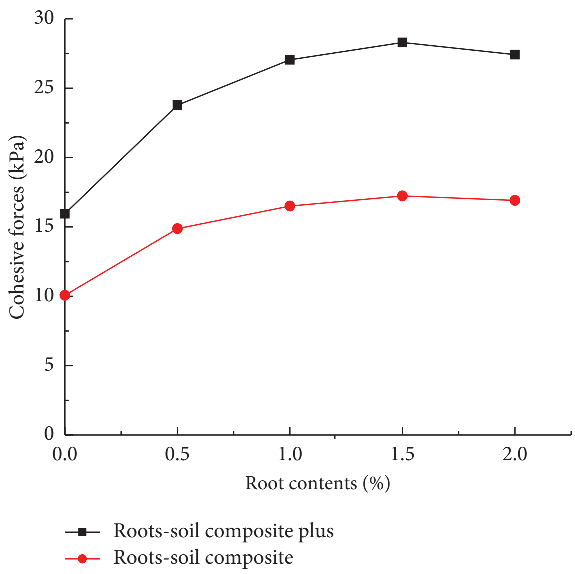

Figure 6: Comparison of the cohesion force after MICP-treated.

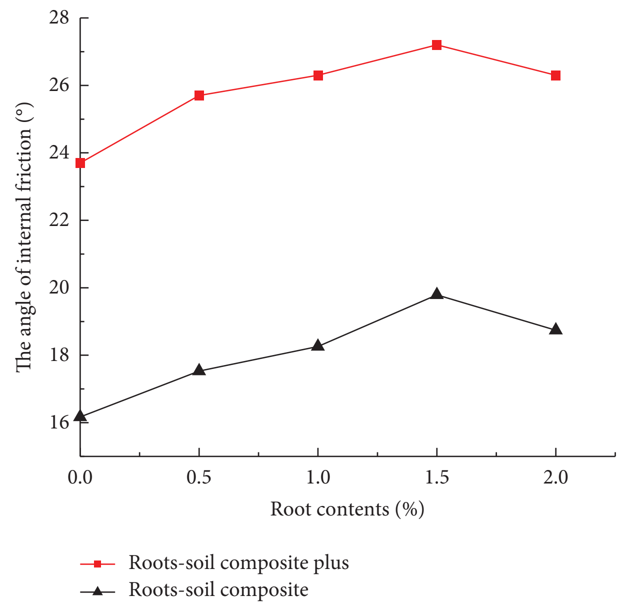

Figure 7: Comparison of internal friction after MICP-treated.

weight, and the weight was recorded as M_1. Then, an excess of hydrochloric acid with a concentration of 2.0 mol/L was added for acid washing treatment, and the calcium carbonate crystal was fully dissolved by constant stirring. The completely dissolved soil samples were rinsed with deionized water several times and dried in the oven until the constant weight was recorded as M_2. The formula of calcium carbonate content can be expressed as $(M_1\text{-}M_2)/M_2 \times 100\%$.

3. Results and Analysis

3.1. Shear Strength Analysis. The variation of shear strength with root content before the MICP treatment is shown in Figure 5. When the root content is less than 1.5%, the shear strength of the root-soil composite increases with the increase of root content. It indicates that the MICP treatment makes the connection between soil particles closer, and the generated calcium carbonate enters the root network to fill the pores, so the shear strength increases with the root content. When the root content was greater than 1.5%, the shear strength of the root-soil composite decreased with the increase of root content. Under the three kinds of vertical stresses of 100 kPa, 200 kPa, and 300 kPa, the maximum shear strength is 54 kPa, 88 kPa, and 126 kPa, respectively, and the corresponding root content of the peak strength is 1.5%. The results show that the root content has a significant effect on the shear strength of soil, and the reinforcement effect is the best when the root content is 1.5%. Liao et al. [25] also have similar conclusions; they showed that with the increase of the root area ratio, the shear strength of the root-soil complex first increased and then decreased. This is because when the root-soil complex is sheared, part of the root system is stretched, and the root system in the shear plane can provide tensile strength. The shear strength of the root-soil composite was improved by resisting displacement deformation when the soil was displaced. Due to the addition of the root system, the pores in the soil decrease, the pore water drains out, and the effective stress of the soil increases. Secondly, the frictional force on the interface between the effective root system and soil particles inhibits the dislocation and displacement of soil particles, which increases the external force required for soil failure and increases the shear strength of the soil. However, when there are too many roots, the contact area between soil and root will decrease, and then the strength of the soil will decrease. According to the gravimetric acid washing method, the calcium carbonate contents with root contents of 0%, 0.5%, 1%, 1.5%, and 2% were obtained as 1.53%, 1.98%, 2.63%, 3.17%, and 3.21%, respectively. With the increase of root content, the content of calcium carbonate showed basically the same increasing trend. By analyzing the reasons, it is found that the roots can provide a certain colonization area for calcium carbonate; that is, the calcium carbonate particles can be better adsorbed on the roots and fill the pores between the roots and soil particles. However, the results showed that the promoting effect of the root content on calcium carbonate had a certain limit, and the promoting effect was no longer obvious when the root content reached 2%. With the increase of calcium carbonate content, the shear strength of the samples is also significantly improved. The main reason is that the calcium carbonate deposited by microorganisms fills a large number of pores in the soil, which makes the loose soil particles partially bonded together and effectively improves cohesion. Furthermore, calcium carbonate particles are formed near the roots and soil particles, which effectively increases the roughness between particles, increases the internal friction angle, and improves the strength.

3.2. Cohesive Force Analysis. As can be seen from Figure 6, the cohesive force of the root-soil complex increases with the increase of root content between 0% and 1.5%. When the

Table 4: MICP contribution rate.

Root content (%)	Cohesive force contribution rate (%)	Internal friction angle contribution rate (%)
0.0	58.39	5.99
0.5	59.92	4.64
1.0	63.94	4.53
1.5	64.19	3.78
2.0	62.15	4.12

root content is greater than 1.5%, the cohesive force begins to decrease. When the root content increases from 0% to 1.5%, the cohesive force of the root-soil complex increases from 10.1 kPa to 17.2 kPa. When the root content is between 1.5% and 2.0%, the cohesive force of the root-soil complex decreases from 17.3 kPa to 16.9 kPa. After MICP, the cohesive force increases to 5.88 kPa, 8.91 kPa, 10.55 kPa, 11.06 kPa, and 10.51 kPa within the range of 0%–2.0%, respectively. The results showed that the cemented calcium carbonate formed after MICP treatment could adsorb on the root surface and make the root network closer. Therefore, it can be considered that MICP curing has a positive correlation with the increase in the strength of the root-soil composite plus solid. However, the cohesive force of the root-soil composite reinforcement decreases between 1.5% and 2.0% of the root content. The reason is that the more the root content is, the more the water in the root is drained out under the action of external forces during the loading process, resulting in the formation of a water film on the root surface, which reduces the cohesive interface force between root and soil. Thus, the cohesive force of soil decreases.

3.3. Analysis of Internal Friction Angle. It can be seen from Figure 7 that with the increase of the root content, the internal friction angle of soil first increases and then decreases, but the overall change range is not large. The internal friction angle mainly reflects the dynamic friction and occlusal friction between soil particles, and the change in internal friction angle is mainly related to the change in soil particles' structure and shape. However, the change in root content has little influence on the friction of soil particles, so it is difficult to change the friction between soil particles. Shen et al. [26] pointed out that in sandy viscous purple soil, the influence of root content on the internal friction angle of the root-soil complex was almost negligible, while MICP solidification also had a small effect on the internal friction angle of the root-soil complex, which also increased first and then decreased. After the MICP reinforcement, some fine calcium carbonate is absorbed on the surface of the soil, which increases the static friction of the soil and requires greater stress to change into sliding friction, so it can withstand greater deformation. However, compared with the friction between soil particles, the static friction forces provided by MICP solidification and roots are very small, so both roots and MICP have little influence on the internal friction angle of the root-soil complex.

In this paper, the dimensionless variable "contribution rate" is introduced. The contribution rate (RC) is the ratio between the difference before and after material strength improvement and the original strength, which plays a great role in analyzing the influence of a single factor variable. Therefore, the contribution rate is adopted to analyze the influence of MICP reinforcement on shear strength parameters, and the results were calculated according to the following formula:

$$\mathrm{R_c} = \frac{(\alpha M - \alpha_s)}{\alpha_s} = \frac{\alpha M}{\alpha_s - 1}, \tag{4}$$

where αM and αS are numerical values of a physical property before and after the treatment of a certain factor, and for cohesive force and internal friction angle

$$\text{Cohesive force contribution rate: } Rc = \frac{(C_M - C_s)}{C_s} = \frac{C_M}{C_s - 1}, \tag{5}$$

$$\text{Internal friction angle contribution rate: } Rc = \frac{(\varphi M - \varphi s)}{\varphi_s} = \frac{\varphi M}{\varphi_S - 1}. \tag{6}$$

In the formula, CM and CS are the cohesion value of MICP root-soil composite and the cohesion value of root-soil composite, respectively. φM and φS are the internal friction angles of the MICP root-soil composite and the internal friction angle of the root-soil composite, respectively. Calculating the above contribution rate, as shown in Table 4

The results show that the influence of MICP on cohesive force ranges from 58.39% to 64.19%, and that of MICP on internal friction angle ranges from 3.78% to 5.99%, indicating that the influence of MICP on cohesive force is much larger than that of internal friction angle. This phenomenon is very similar to the reinforcement effect in literature [27], which indicates that MICP has a certain influence on the cohesive force of the root-soil complex, but the content of calcium carbonate produced by MICP reaction is small, so the internal friction angle has a minimal effect. It shows that the MICP reaction can significantly improve the strength of the root-soil complex, and its effect is mainly reflected in the cohesive force, while the internal friction angle has little influence.

4. Conclusion

In this paper, the roots of herbaceous plants were taken as the research object, and the MICP technology was used to strengthen the root-soil complex of vegetation. On the basis of considering the root content, a series of root-soil composite and solid direct shear tests were carried out. To explore the mechanical change rule of root content on root-soil composite reinforcement, analyze the solidification effect of MICP, and reveal the strength change mechanism of the root-soil composite reinforced by microbial mineralization. The main achievements and conclusions of this paper are as follows:

(1) MICP technology can be used to modify the root-soil complex, and cohesive force has an obvious effect on improving the peak strength and cohesive force of the root-soil complex. Under the condition of 1.5% root content, the maximum strength peak value can be increased by 32.56%, and the cohesive force can be increased by 58.39%. The internal friction angle increased by 3.78%.

(2) The contribution rate of the sample treated with MICP is analyzed, and it is concluded that with the change of root content, the MICP curing effect does not change significantly, and the contribution rate of MICP reinforcement to the cohesive force is between 58.39% and 64.19%. The influence of MICP on the internal friction angle is between 3.78% and 5.99%. It shows that with the change of root content, the effect of MICP reinforcement on the cohesive force is gradually increasing, and the effect on the internal friction angle is small.

(3) With the increase of the root content, the cohesive force and internal friction angle increase firstly and then decrease. However, the variation trend of the root-soil composite with MICP treatment is basically the same as that of the root-soil composite without MICP treatment. Only its strength peak, cohesion force and internal friction angle change increase. It indicates that the cohesive force between root and soil is improved by adding roots to the soil, which provides nucleation sites for microbial cells and facilitates the nucleation of microbial cells on the root surface, thus generating more calcium carbonate crystals.

Data Availability

All the data in the tests of this study have been listed in the paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

This research was subsidized by the National Natural Science Foundation of China (Grant No. 51908097), the Natural Science Foundation of Chongqing (Grant Nos. cstc2020jcyj-msxm1078, cstc2019jcyj-msxmX0258), and the Chongqing University of Science and Technology Research Program under grant Nos. ck2017zkyb013 and ck2017zkyb010.

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