

Article

Application of Microbial-Induced Carbonate Precipitation for Disintegration Control of Granite Residual Soil

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Abstract: Granite residual soil is widely distributed in Southeastern China. Such soils exhibit mechanical characteristics such as loose, rich cracks and easy disintegration, resulting in severe soil erosion disasters under rainfall conditions. Microbial-induced carbonate precipitation (MICP) is a green alternative for soil stabilization. In this study, a new strategy for the disintegration control of granite residual soil using MICP technology is proposed. The effects of the bacterial solution concentration, the cementation solution concentration, and the treatment cycle are investigated through a disintegration test. The optimal treatment parameters for granite residual soil using MICP technology are determined by analyzing the disintegration processes and residual quality indicators of disintegration. The results show that the treated samples have three types of disintegration: complete disintegration, incomplete disintegration, and non-disintegration. The precipitated calcium carbonate (CaCO₃) bonds the soil particles and fills the pores. Taking into account the effectiveness and cost and a bacterial solution concentration OD₆₀₀ = 0.75, five cycles of MICP treatment with a cementation solution concentration of 1.2 mol/L is optimal for the disintegration control of granite residual soil. The cementation-action effects of CaCO₃ are verified through scanning electron microscopy (SEM) tests with an energy-dispersive X-ray (EDX) spectroscope. These findings suggest that MICP is a promising candidate to control the disintegration of granite residual soil.

Keywords: granite residual soil; microbial-induced carbonate precipitation; disintegration; bacterial solution concentration; cementation solution concentration; treatment cycle



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1. Introduction

Granite residual soil is formed by a series of physical and chemical weathering of the parent granite rock, which is widely distributed in Southeastern China. This type of soil exhibits loose, rich cracks and easy disintegration [1–3], resulting in severe soil erosion under rainfall conditions [4–6]. There are 239,125 sites in Benggang covering an area of 1220.05 km² [7,8], with an average rate of erosion of 590,000 t/(km²·y) [9]. Benggang has the characteristics of high erosion intensity and an extensive erosion area [10,11]. Yudu County, one of the counties with severe soil erosion in Jiangxi Province, China, accounts for 29.17% of the whole county due to Benggang.

The traditional slope-protection methods in Benggang areas mainly rely on plant measures and engineering measures, which have disadvantages such as a large engineering quantity, inconvenient construction, high cost, and long time [12–14]. Therefore, it is of great engineering significance to find a new slope-protection strategy that is energy-saving, environmentally friendly, and easy to construct on granite residual soil. Microbial-induced carbonate precipitation (MICP) is one of the emerging geotechnical engineering technologies in recent years [15,16]. MICP has three typical substances involved in its process: bacteria, substrate, and calcium source, which precipitates carbonate crystals around the soil particles in a biological reaction, thereby remodeling the soil structure [17,18]. Based

on a soil-enriched, urease-producing bacteria named *Sporosarcina pasteurii* (ATCC 11859), it uses urea as a substrate, catalyzes the hydrolysis of urea to generate NH_4^+ and CO_3^{2-} through metabolism, and attracts Ca^{2+} through the negative charge generated by macromolecules such as proteins inside the bacteria, thus inducing the precipitation of CaCO_3 . No toxic substances are produced during the bonding process, indicating that it is an environmentally friendly bonding material [19,20]. The MICP also demonstrates strong applicability and water stability, which can effectively improve various types of soil, such as organic soil [21], loess [22], sand [23], iron tailing [24], and desert [25]. The improvements MICP has on geotechnical materials also depend on the influencing factors of various mineralization processes, such as the calcium sources [26], the bacterial solution concentration [27], the cementation solution concentration [28], the ratio of cement solution [29], the curing age [30], and the pH value [24]. The formation of calcium carbonate crystals has a significant impact on the physical and mechanical properties of the treated soil. The soil treated with MICP is still suitable for plant growth, and its residual urea can serve as a nutrient [19]. However, there are limited studies on the MICP modification of granite residual soil in the Benggang area to improve its ability to resist rainfall erosion.

One important way to ensure soil and water loss prevention in the erosion area is to improve the water stability of the surface soil, thereby improving its erosion resistance. The shallow surface granite residual soil in the Benggang area is generally loose after long-term weathering. The calcium carbonate crystals generated by MICP can fill soil pores, and their cementation enhances the connection strength between soil particles [28]. It is crucial to determine the appropriate parameters of MICP, such as bacterial solution concentration and instrumental solution concentration [23]. Hence, a quantitative analysis is necessary for the practical engineering application of MICP in the prevention and control of soil erosion.

Soil disintegration refers to the durability of soil when in contact with still water and can be used to evaluate its water stability [31–33]. Liu et al. [34] investigated the disintegration behavior of the granite residual soil along a typical weathering profile from Xiamen City in China. Sun et al. [35] studied the disintegration amounts and disintegration ratios of soil samples treated with cement, quick lime, and kaolinite. Zhang et al. [36] revealed that the effective void ratio and soil water characteristic curves are the main control factors affecting the disintegrating velocity. Liu et al. [1] discussed the combined influences of heavy rainfall and acid rain on the disintegration characteristics of granite residual soils. However, the disintegration characteristics of granite residual soil treated with MICP technology have not received enough attention. It is necessary to study the effects of various mineralization factors on the disintegration processes. The optimal parameters of the MICP for the disintegration control of granite residual soil should be obtained.

In this paper, the MICP method is used to prevent the disintegration of granite residual soil. A series of disintegration experiments considering different bacterial solution concentrations, cementation solutions, and concentration treatment cycles are carried out to determine the optimal parameters of the MICP method. The influence mechanism of MICP on the disintegration of granite residual soil is then revealed from microstructural features. The ability to resist erosion caused by heavy rainfall will be investigated in the future. This study will prepare for the application of MICP technology in the control of Benggang erosion.

2. Materials

2.1. Sampling Conditions

The granite residual soil was collected from a Benggang erosion area at a depth of 0.5 m, located in the town of Gongjiang (25°59′24″ N, 115°26′32″ E), Yudu County, Jiangxi Province, in Southern China. The natural dry density is 1.50 g/cm^3 , the liquid limit moisture is 39.3%, the plastic limit moisture is 27.5%, the permeability coefficient is $9.7 \times 10^{-7} \text{ cm/s}$, and the specific gravity is 2.56. The grain size distribution curve is shown

in Figure 1. The mineralogical compositions determined by X-ray diffraction are composed of quartz (62.1%), kaolinite (26.1%), gibbsite (9.4%), and goethite (2.2%) [10].

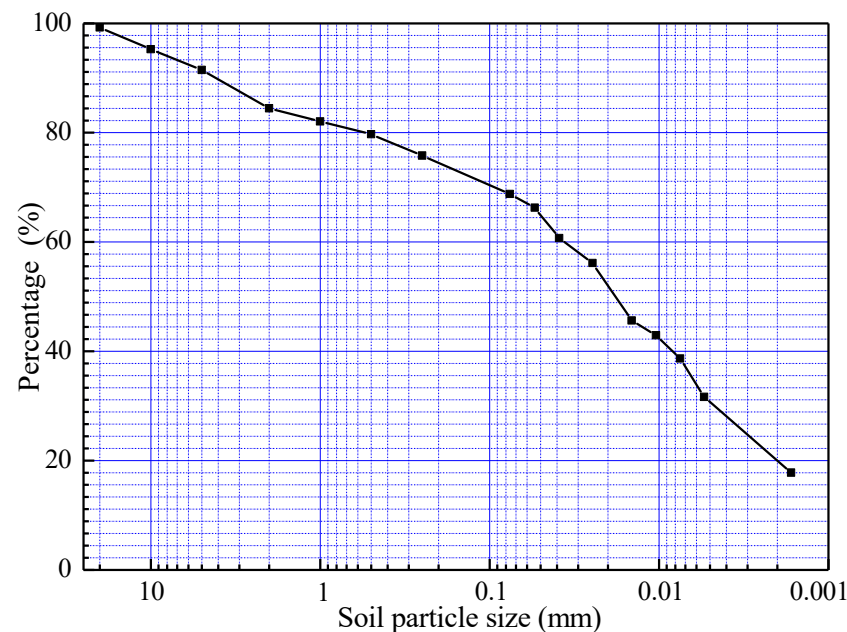


Figure 1. Grain size distribution curve.

2.2. Bacterial Solution and Cementation Solution

In this study, *Sporosarcina pasteurii* (ATCC 11859) is adopted as urease-active bacteria because of its safety (no pathogenicity) and high urease activity. The bacterial cultivation consists of three stages, namely, nutrient solution preparation, medium preparation, and bacterial inoculation and cultivation. (a) A total of 25 g/L of Luria–Bertani (LB) broth is prepared, sterilized in autoclave steam at 120 °C for 20 min, and then cooled under UV irradiation on the aseptic operating table. (b) After cooling to 40 °C, urea is added at a concentration of 1 mol/L, and the pH is adjusted to 9 via NaOH. Then, the nutrient solution is dispensed into Petri dishes and continued to be cooled under aseptic conditions until solidification. (c) *Sporosarcina pasteurii* is carefully coated onto the surface of the solidified medium and then placed in a constant temperature and humidity of 30 °C and 60% for 24 h to obtain full culturing of bacteria. The bacteria and growth medium are stored in centrifuge vials at 4 °C. The growth medium is prepared by dissolving 10 g of casein tryptone, 10.0 g of sodium chloride, and 5.0 g of yeast extract in one liter of deionized water.

The initial density (OD_{600}) of the collected bacteria culture is 1.5. Different bacterial solution concentrations can be obtained by adding physiological saline (0.9% sodium chloride solution). The OD_{600} values of bacterial solution are 0.25, 0.50, 0.75, and 1.0. The bacterial solution is stored in centrifuge vials at 4 °C.

The cementation solution used in this study consists of 1.0 mol/L of equimolar urea and 1.0 mol/L of calcium chloride. Four types of cementation solution concentrations of 0.4 mol/L, 0.8 mol/L, 1.2 mol/L, and 1.6 mol/L are used to treat the granite residual soil.

3. Methods

3.1. Disintegration Apparatus

As shown in Figure 2, the disintegration test is carried out using a self-made disintegration apparatus. This disintegration apparatus consists of four parts: the support framework, the sink device, the bracket device, and the weighing device. The support framework is a cubic frame made of 2.5 cm stainless steel square tube with a size of 60 cm × 60 cm × 50 cm. The sink device includes a thermostatic water box and a small glass box inside with sizes of 40 cm × 40 cm × 25 cm and 30 cm × 30 cm × 25 cm, respectively. The disintegration

test is carried out in a static water environment and at a constant temperature. The bracket device includes a metal mesh and thin string. The aperture size of the metal mesh used for supporting the soil samples is 0.9 cm.

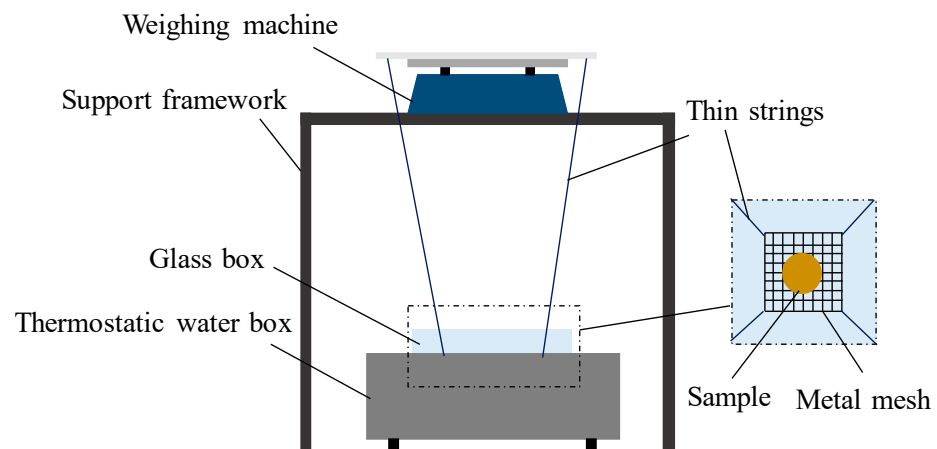


Figure 2. Schematic diagram of the experimental device.

3.2. Disintegration Test Procedure

3.2.1. Specimen Preparation

The soil passes through 2 mm sieve. Then, it is put into an oven for drying at 105 °C. The initial moisture content is controlled at a value of 15%. The test samples are remolded sample of cutting ring of 60 cm³. The soil is statically compacted to the target soil dry density of 1.5 g/cm³. The remolded sample is placed in a constant humidity sealed box for 24 h to ensure uniform distribution of water. Spraying method is adopted as MICP treatment on the surface of samples. The spraying process includes two steps. Firstly, 10 mL of bacterial solution is uniformly sprayed on the sample surface. Then, the samples are cured in the constant temperature and humidity box (room temperature of 25 °C ± 2 °C, humidity of 85% ± 5%) for 3 h to ensure the bacteria spread and multiply. Secondly, 10 mL of cementation solution is sprayed on the same surface. Then, the samples are maintained for 21 h in the constant temperature and humidity box to ensure complete action between bacterial solution and cementation solution. The curing process is shown in Figure 3. Spraying bacterial solution and cementation solution once is a cycle. This study features 1, 3, 5, and 7 cycles of MICP treatment to investigate the effect of various treatment cycles on the disintegration.

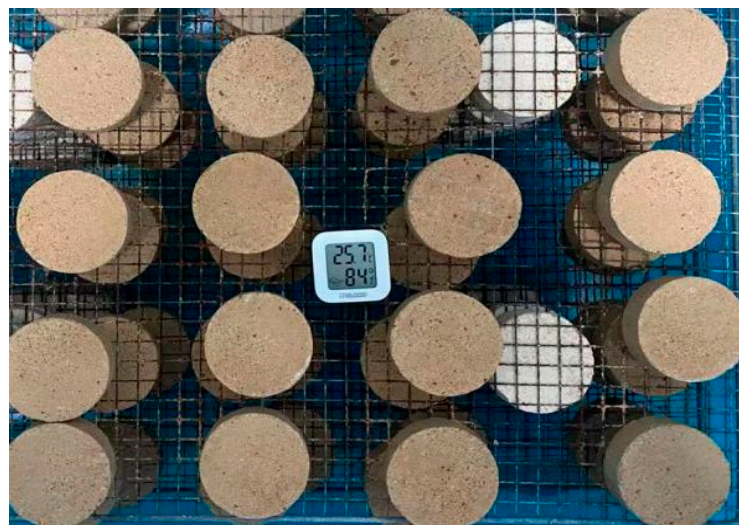


Figure 3. The curing process.

3.2.2. Test Processes

The disintegration test is carried out at the water temperature of 25 °C. The sample is placed on the metal mesh. During the test, the samples are dropped into the water. The weight is recorded according to the interval time of 5 s. Meanwhile, the disintegration morphology of the sample is recorded by camera. When the sample completely disintegrates or the balance reading changes by less than 1 g within 10 min, the test ends.

3.3. Experimental Scheme

Three factors, including the bacterial solution concentration, the cementation solution concentration, and the treatment cycle, are configured in the experimental scheme. The deionized water is used instead of the bacteria and cementation to spray the sample for the contrast group without treatment (E1~E4). The processes of disintegration are analyzed to obtain the optimal parameter. The experimental schemes are shown in Table 1.

Table 1. Experimental schemes.

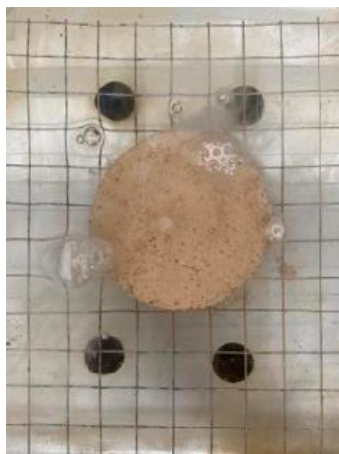
Sample Number	Bacterial Solution Concentration (OD ₆₀₀)	Cementation Solution Concentration (mol/L)	Treatment Cycle
A1~A4	0.25	0.4, 0.8, 1.2, 1.6	1
A5~A8	0.5	0.4, 0.8, 1.2, 1.6	1
A9~A12	0.75	0.4, 0.8, 1.2, 1.6	1
A13~A16	1.0	0.4, 0.8, 1.2, 1.6	1
B1~B4	0.25	0.4, 0.8, 1.2, 1.6	3
B5~B8	0.5	0.4, 0.8, 1.2, 1.6	3
B9~B12	0.75	0.4, 0.8, 1.2, 1.6	3
B13~B16	1.0	0.4, 0.8, 1.2, 1.6	3
C1~C4	0.25	0.4, 0.8, 1.2, 1.6	5
C5~C8	0.5	0.4, 0.8, 1.2, 1.6	5
C9~C12	0.75	0.4, 0.8, 1.2, 1.6	5
C13~C16	1.0	0.4, 0.8, 1.2, 1.6	5
D1~D4	0.25	0.4, 0.8, 1.2, 1.6	7
D5~D8	0.5	0.4, 0.8, 1.2, 1.6	7
D9~D12	0.75	0.4, 0.8, 1.2, 1.6	7
D13~D16	1.0	0.4, 0.8, 1.2, 1.6	7
E1~E4	0	0	1, 3, 5, 7

4. Results and Discussion

4.1. Disintegration Processes

The morphological features of soil sample E3 without MICP treatment are shown in Figure 4. When the soil sample is immersed in water, numerous bubbles appear on the surface of the soil sample, as shown in Figure 4a. At this stage, the soil disintegration rate is lower than the water absorption rate, resulting in a continuous increase in the balance reading. Due to the continuous absorption of water, the soil sample gradually saturates. Afterward, violent disintegration occurs, and cracks appear on the surface of the soil sample, as shown in Figure 4b. The sample collapses from the side to the center. Large bubbles are generated, and the water becomes turbid. At $t = 300$ s, the soil almost completely fell into the bottom of the box (complete disintegration). Water enters the pores between soil particles, leading to an increase in soil moisture content and a decrease in

suction, ultimately leading to disintegration. The disintegration processes can be divided into three processes: water absorption, exhaust, and disintegration.



(a) $t = 10$ s.



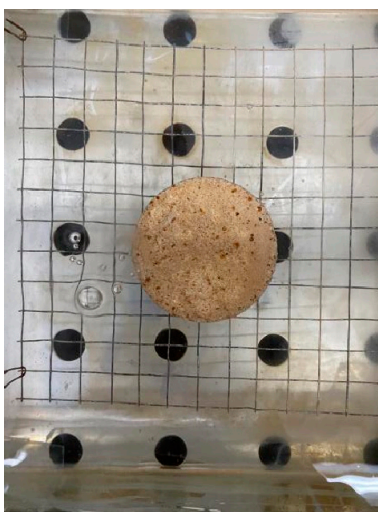
(b) $t = 60$ s.



(c) $t = 300$ s.

Figure 4. Disintegration process without treatment (complete disintegration).

Figure 5 depicts the disintegration process of soil treated by MICP technology. Due to the cementation and filling effect of calcium carbonate crystals on surface soil particles, the disintegration process of soil samples treated with MICP is different from that of soil samples without treated samples. The disintegration time of soil samples with one cycle of treatment is considerably longer than those without treatment, and the soil sample is also completely disintegrated. The disintegration process of soil sample B11 shows that its water absorption rate has slowed down, and the water absorption time has been significantly prolonged. Due to the formation of a reinforcement layer on the surface of the soil after MICP treatment, which allows the sample to remain relatively complete after absorbing water, the turning point from water absorption to collapse is significantly prolonged. The residual quality of the soil sample decreases, but the speed is relatively slow. When the residual mass decreases to around 40 g, the sample remains stationary on the wire mesh and no longer disintegrates. As shown in Figure 5, due to the cementation effect of the reinforcement layer, the soil particles are tightly bound, resulting in incomplete disintegration.



(a) $t = 10$ s.



(b) $t = 60$ s.



(c) $t = 300$ s.

Figure 5. Disintegration process of incomplete disintegration.

Soil sample D11 has no traditional disintegration processes within 300 s. After the water enters the soil sample, only a slow water-absorption process occurs. This is because the surface reinforcement layer of the soil sample can fully wrap the entire soil sample to prevent disintegration after multiple cycles of MICP treatment. The crust-like layers cover the soil particles, which has a significant impact on the interaction between particles and reduces erosion [37]. However, water can still slowly infiltrate, leading to an increase in moisture content. As shown in Figure 6, this situation is called the non-disintegration type. Therefore, the disintegration process of soil samples treated with MICP can be classified into three types: complete disintegration, incomplete disintegration, and non-disintegration.

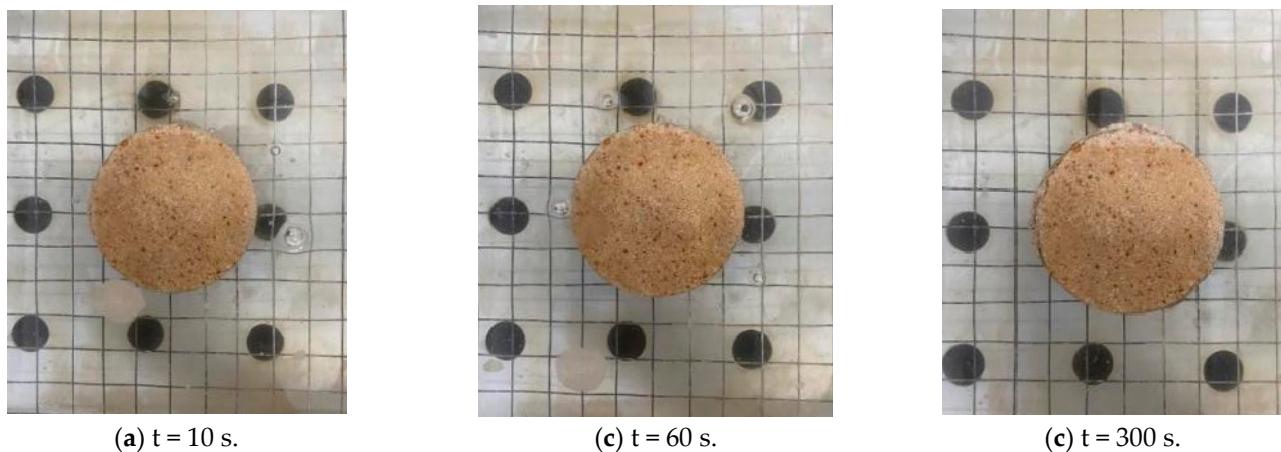


Figure 6. Disintegration process of non-disintegration.

4.2. Effect of Bacterial Solution Concentration on Disintegration

Figure 7 shows the disintegration curves of different bacterial solution concentrations of $OD_{600} = 0.25, 0.5, 0.75$, and 1.0 with one treatment cycle. At the given cementation solution concentration of $0.4, 0.8, 1.2$, and 1.6 , the MICP can improve the resisting disintegration ability of granite residual soil after one treatment cycle. However, the improvement is relatively limited. The disintegration time of the sample has been extended, and the sample completely disintegrates. This is because the reaction of the bacterial solution and cementation solution on the surface of the sample forms a small amount of reinforcement layer after one cycle of treatment. However, the reinforcement layer is too small and thin and thus does not create significant improvement.

Disintegration curves with three treatment cycles are shown in Figure 8. All samples are the incomplete disintegration type. For the cementation solution concentrations of $0.4, 0.8$, and 1.2 , the residual mass of disintegration is the highest when the bacterial solution concentration is 0.75 . At the same time, it should be noted that the impact of the bacterial solution concentration varies under different cementation solution concentrations. When the cementation solution concentration is 0.4 , the reinforcement effects affected by the bacterial solution concentration are $0.75 > 0.5 > 1.0 > 0.25$. When the cementation solution concentrations are 0.8 and 1.2 , respectively, the reinforcement effects of the bacterial solution concentration are $0.75 > 1.0 > 0.5 > 0.25$. When the cementation solution concentration is 1.6 , the reinforcement effect is more significant due to the increase in the bacterial solution concentration. However, the difference in the reinforcement effect between 0.75 and 1.0 is not significant. This indicates that the bacterial solution concentration of 0.75 is more suitable for forming a certain thickness layer to reinforce the soil samples.

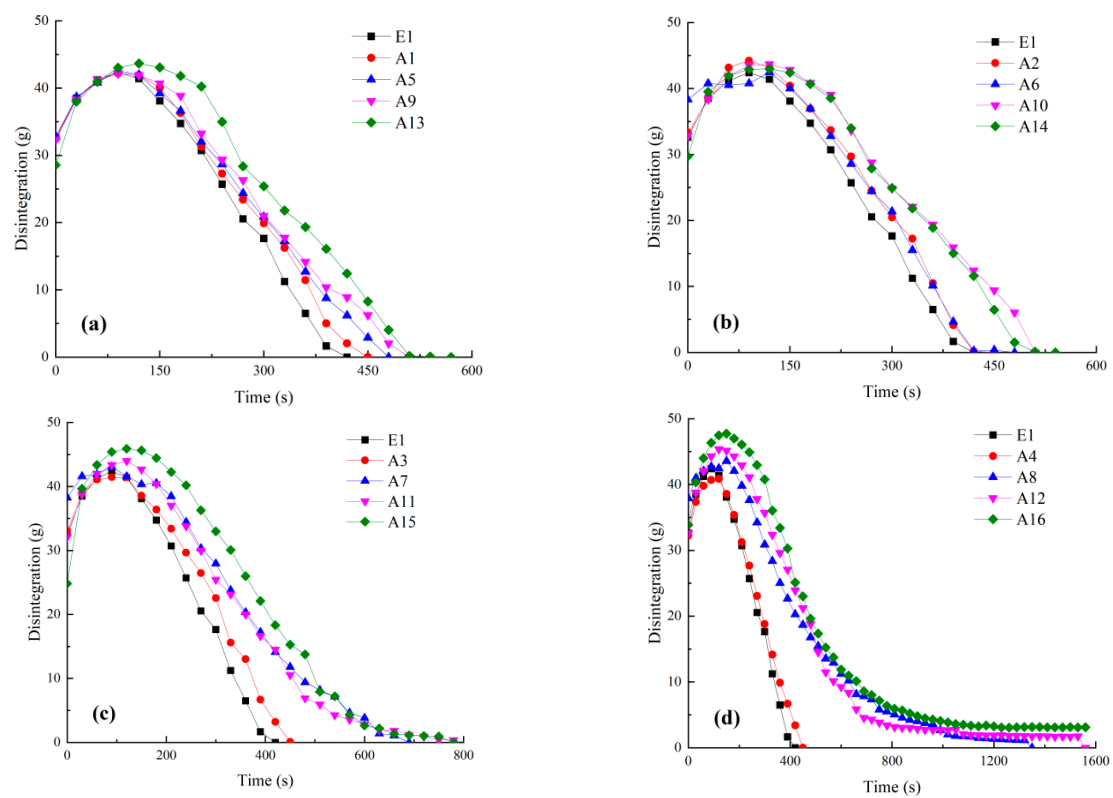


Figure 7. Disintegration curve with one treatment cycle of different bacterial solution concentrations: (a) 0.4, (b) 0.8, (c) 1.2, and (d) 1.6.

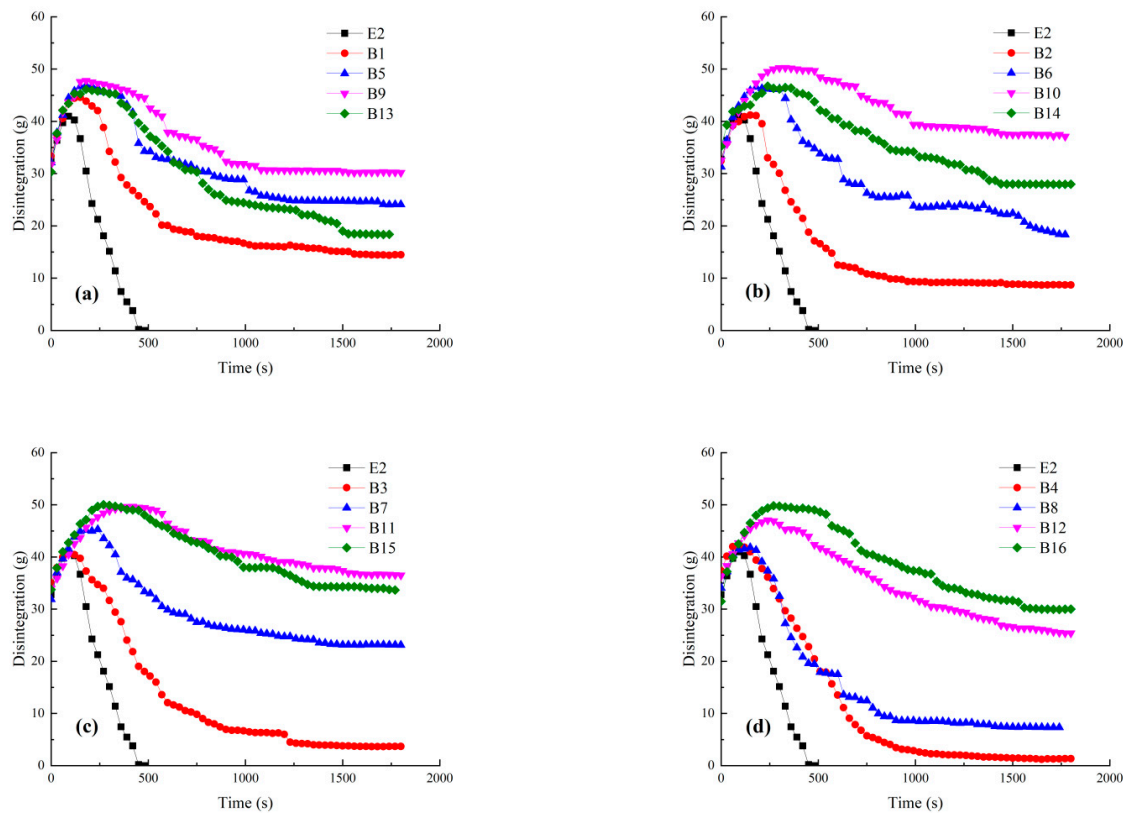


Figure 8. Disintegration curves with three treatment cycles of different cementation solution concentrations: (a) 0.4, (b) 0.8, (c) 1.2, and (d) 1.6.

Due to the short treatment time, the MICP reaction is not fully carried out in one cycle treatment. At a lower cementation solution concentration, when the bacterial solution concentration is greater than 0.5, the reaction can be completely carried out. This will lead to a rapid reaction. If the bacterial solution concentration is too high, a large amount of calcium carbonate crystals is produced to fill the surface pores of the soil. The reinforcement layer only stays on the surface, making it difficult for bacteria and cementitious to continue infiltrating. Disintegration curves with five and seven treatment cycles are shown in Figures 9 and 10, respectively. Some samples exhibit non-disintegration phenomena after five and seven treatment cycles.

The effect of the bacterial solution concentration on treated samples varies according to different treatment cycles. After multiple cycles of treatment, the effect of the MICP reaction is limited. A proper combination of the bacterial solution concentration and the cementation solution concentration can achieve good reinforcement under sufficient reaction conditions. A lower bacterial solution concentration is suitable for lower concentration solution concentrations. Meanwhile, when the cementation solution concentration is ≤ 1.2 , the most suitable bacterial solution is 0.75. When the cementation solution concentration is 1.6, the most suitable bacterial solution is 1.0. However, there is not much of a difference compared to the bacterial solution of 0.75. Therefore, it can be concluded that, taking into account the treatment effect and economic benefits, the bacterial solution concentration of 0.75 is effective in MICP reinforcement of granite residual soil.

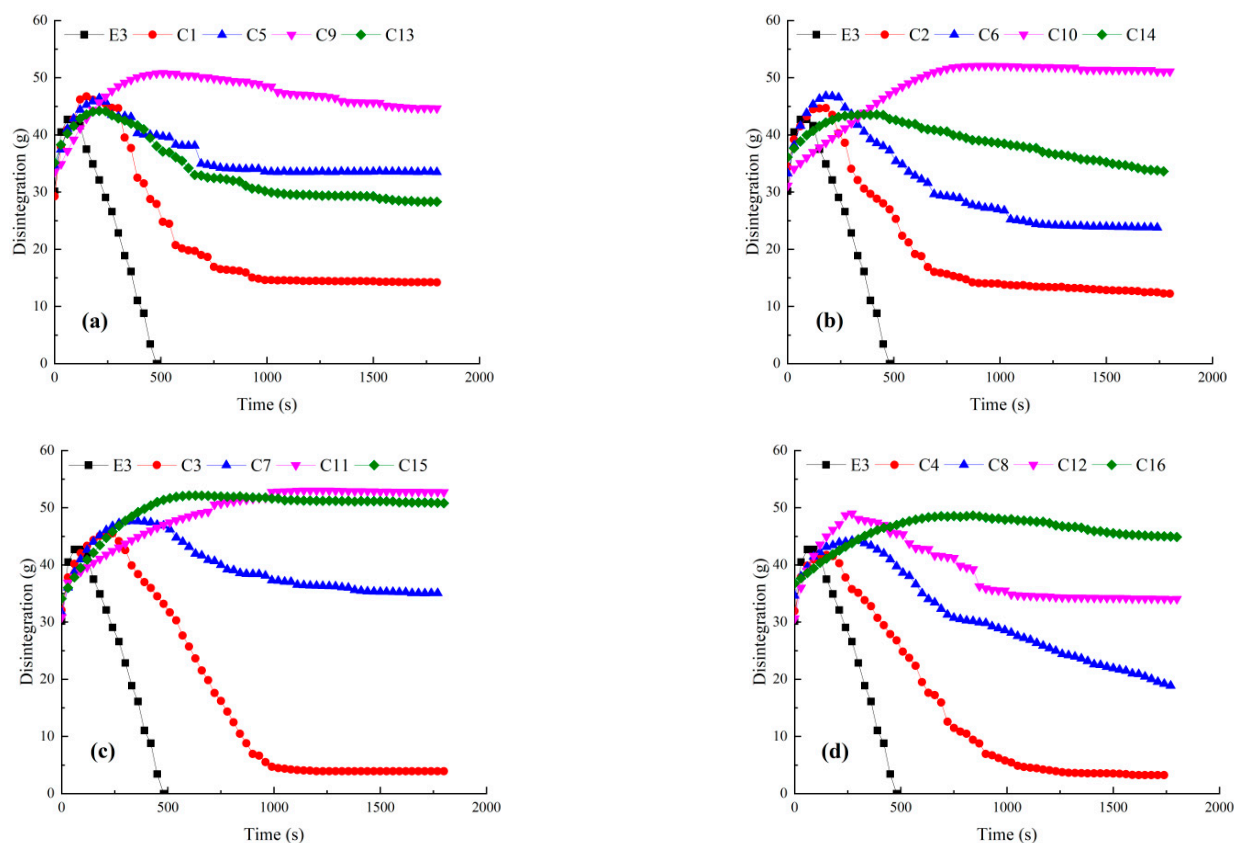


Figure 9. Disintegration curve with five treatment cycles of different cementation solution concentrations: (a) 0.4, (b) 0.8, (c) 1.2, and (d) 1.6.

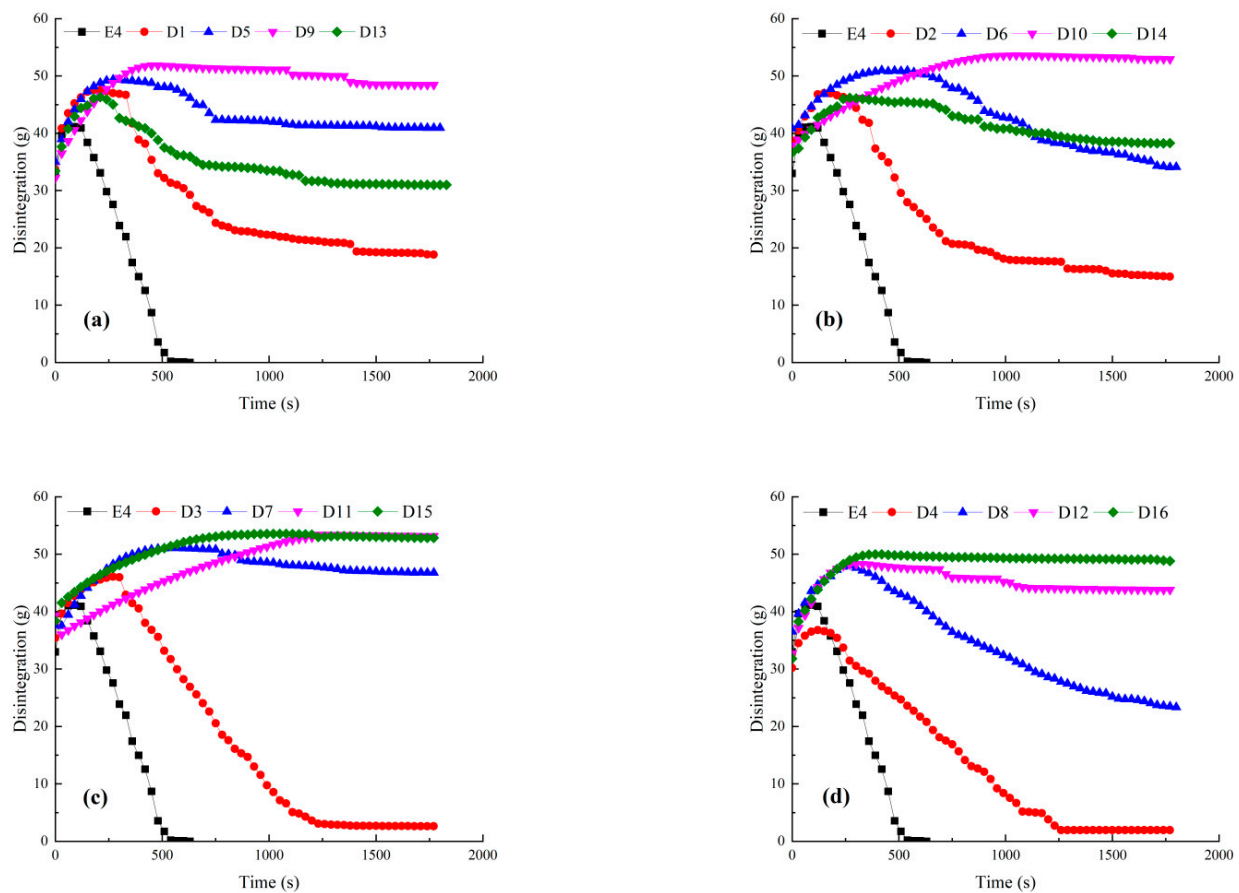


Figure 10. Disintegration curve with seven treatment cycles of different cementation solution concentrations: (a) 0.4, (b) 0.8, (c) 1.2, and (d) 1.6.

4.3. Effect of Cementation Solution Concentration on Disintegration

In order to analyze the effect of the cementation solution concentration on the disintegration, the disintegration curves under varying cementation solution concentrations of 0.4, 0.8, 1.2, and 1.6 mol/L are presented for a given bacterial solution concentration. The disintegration curve with one treatment cycle is shown in Figure 11. When one cycle of treatment is carried out, there is a limited improvement in the resisting disintegration ability using MICP technology, and the sample completely disintegrates.

Disintegration curves under different cementation solution concentrations and three treatment cycles for a given bacterial solution concentration are presented in Figure 12. All samples exhibit the incomplete disintegration type. When the bacterial solution concentration is 0.25, the reinforcement of the concentration solution concentration is $0.4 > 0.8 > 1.2 > 1.6$. When the bacterial solution concentration is 0.5, the reinforcement of the concentration solution concentration is $1.2 \approx 0.4 > 0.8 > 1.6$. When the bacterial solution concentration is 0.75, the reinforcement of the concentration solution concentration is $1.2 \approx 0.8 > 0.4 > 1.6$. When the bacterial solution concentration is 1.0, the reinforcement of the concentration solution concentration is $1.2 > 1.6 > 0.8 > 0.4$. This also indicates that the cementation solution concentration needs to be combined with the bacterial solution concentration to achieve a good treatment effect. At lower bacterial solution concentrations, the ions contained in the high-concentration cementitious solution significantly inhibit the urease activity in the bacterial solution [38]. Under this circumstance, the MICP reaction rate is decreased, and thus, the final reaction products are decreased.

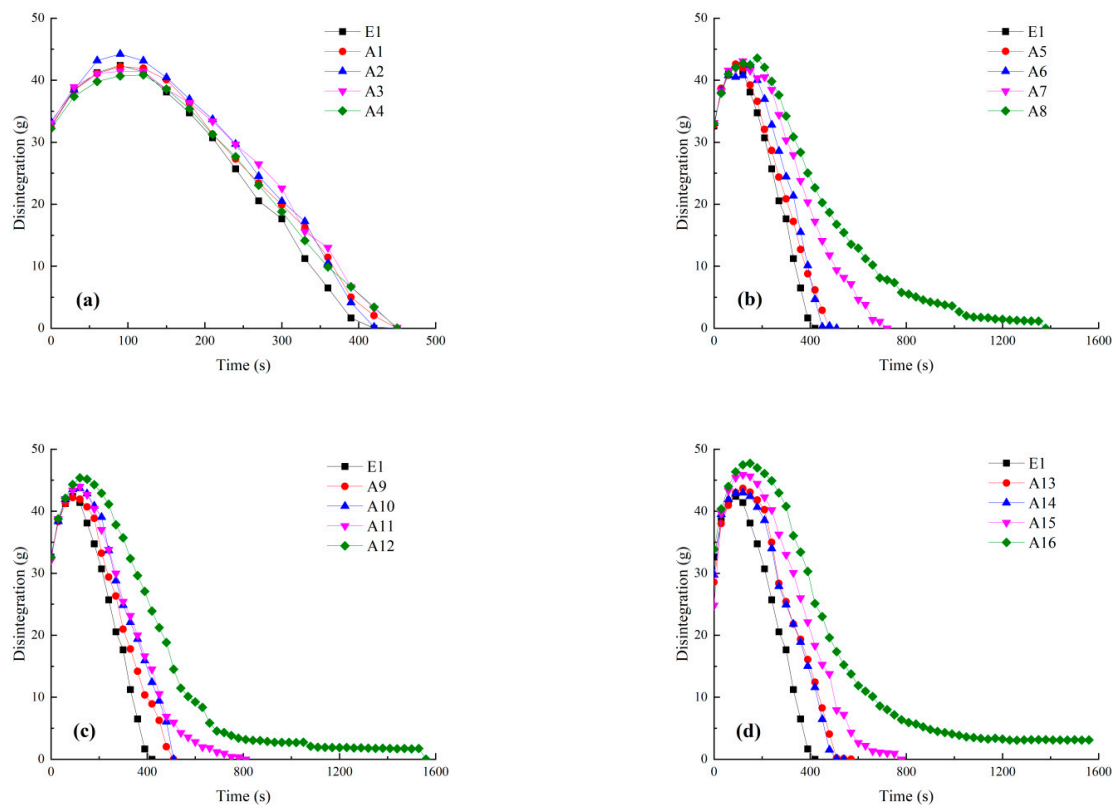


Figure 11. Disintegration curve with one treatment cycle of different cementation solution concentrations: (a) 0.25, (b) 0.5, (c) 0.75, and (d) 1.0.

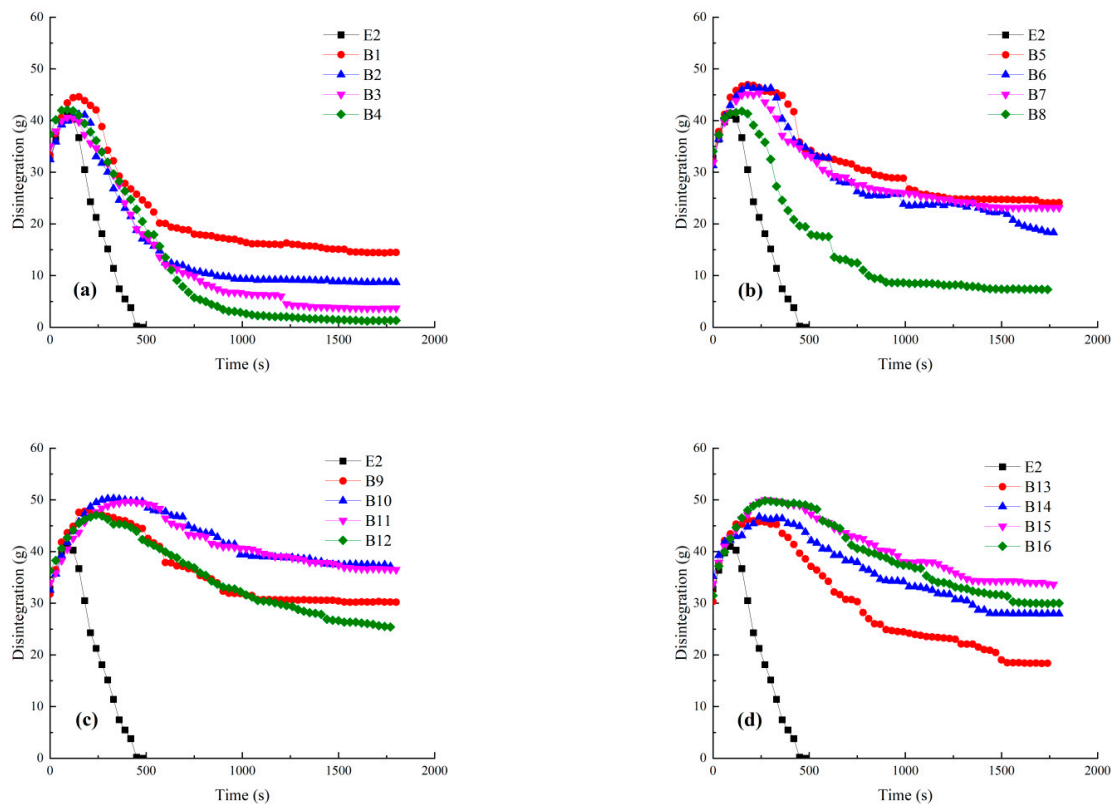


Figure 12. Disintegration curve with three treatment cycles of different bacterial solution concentrations: (a) 0.25, (b) 0.5, (c) 0.75, and (d) 1.0.

After five cycles of MICP treatment, a large amount of CaCO_3 crystals is generated. The disintegration curves of the cementation solution concentration with five and seven treatment cycles are presented in Figures 13 and 14, respectively. However, when the bacterial solution concentration is 0.25, the overall bonding effect is poor, which is significantly different from that when the bacterial solution concentration is greater than 0.5. Therefore, when considering the optimal instrumentation solution concentration, only the case where the bacterial solution concentration ≥ 0.5 is considered. The optimal cementation solution concentration is at a value of 1.2 when the bacterial solution concentration is ≥ 0.5 . After treatment, a large amount of CaCO_3 is attached to the surrounding particles and fills the gaps in the soil particles.

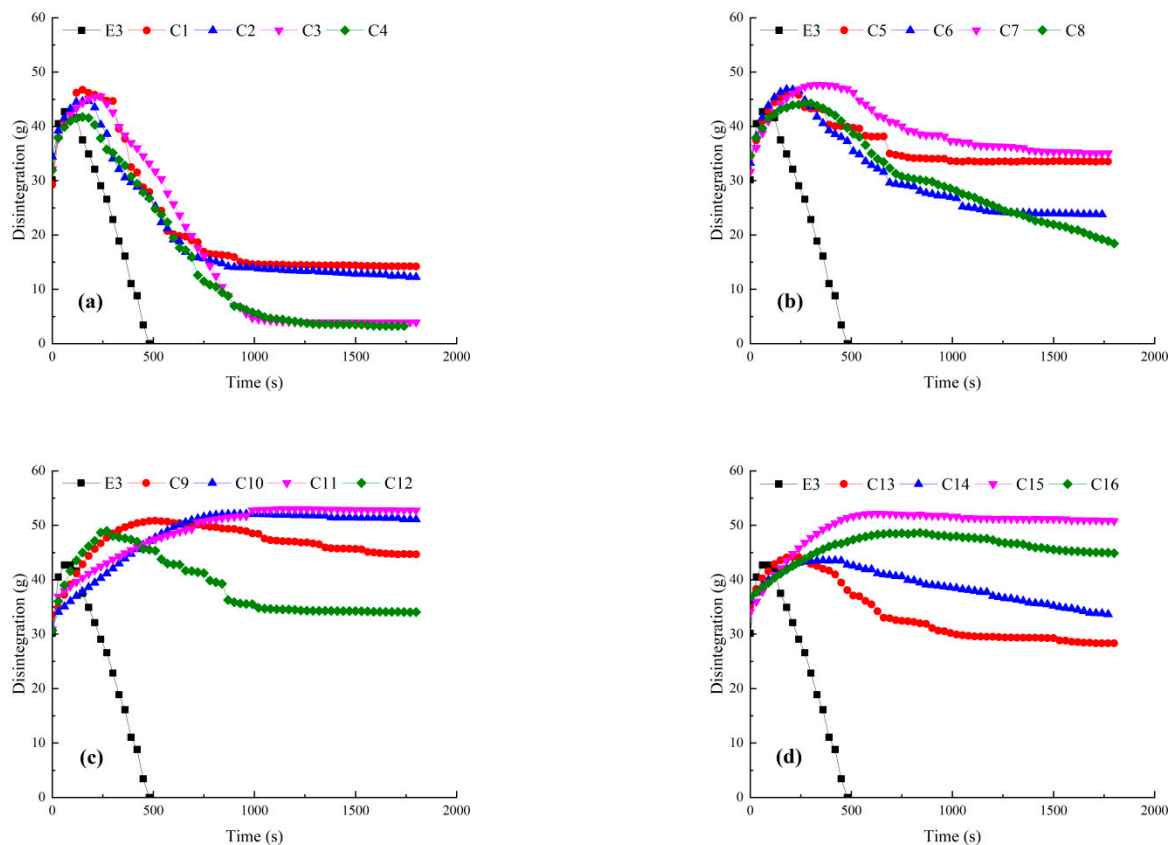


Figure 13. Disintegration curve with five treatment cycles of different bacterial solution concentrations: (a) 0.25, (b) 0.5, (c) 0.75, and (d) 1.0.

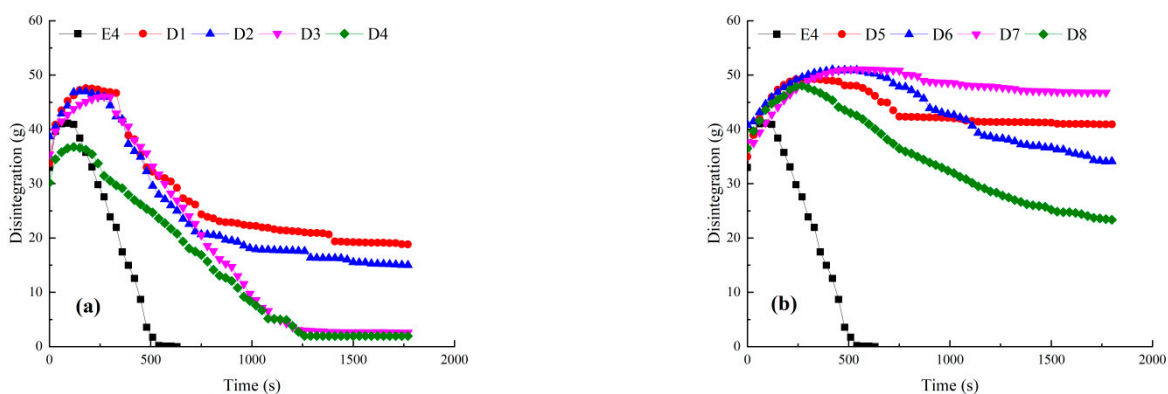


Figure 14. *Cont.*

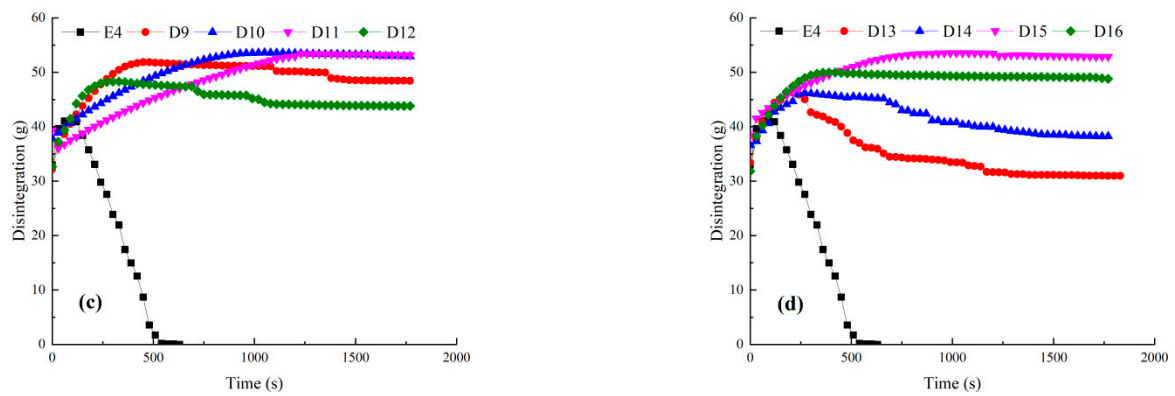


Figure 14. Disintegration curve with seven treatment cycles of different bacterial solution concentrations: (a) 0.25, (b) 0.5, (c) 0.75, and (d) 1.0.

4.4. Effect of Treatment Cycle on Disintegration

To analyze the effect of the treatment cycle on the disintegration process, the disintegration curves of soil samples treated with different treatment cycles are plotted in Figure 15. At the given bacterial solution concentration (BS) and cementation solution concentration (CS), the disintegration amount of 1, 3, 5, and 7 treatment cycles can be then analyzed. Series A, Series B, Series C, and Series D correspond to the treatment cycles of 1, 3, 5, and 7 in Figure 15, respectively.

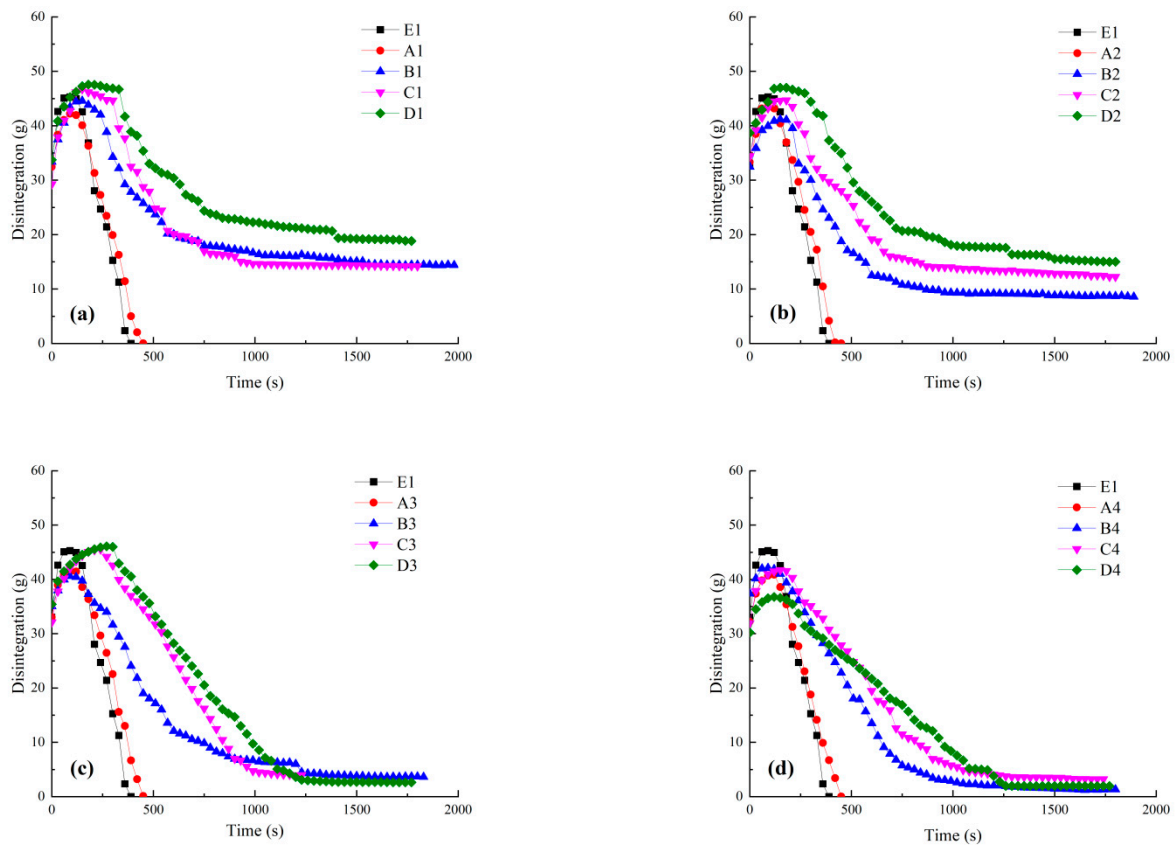


Figure 15. Cont.

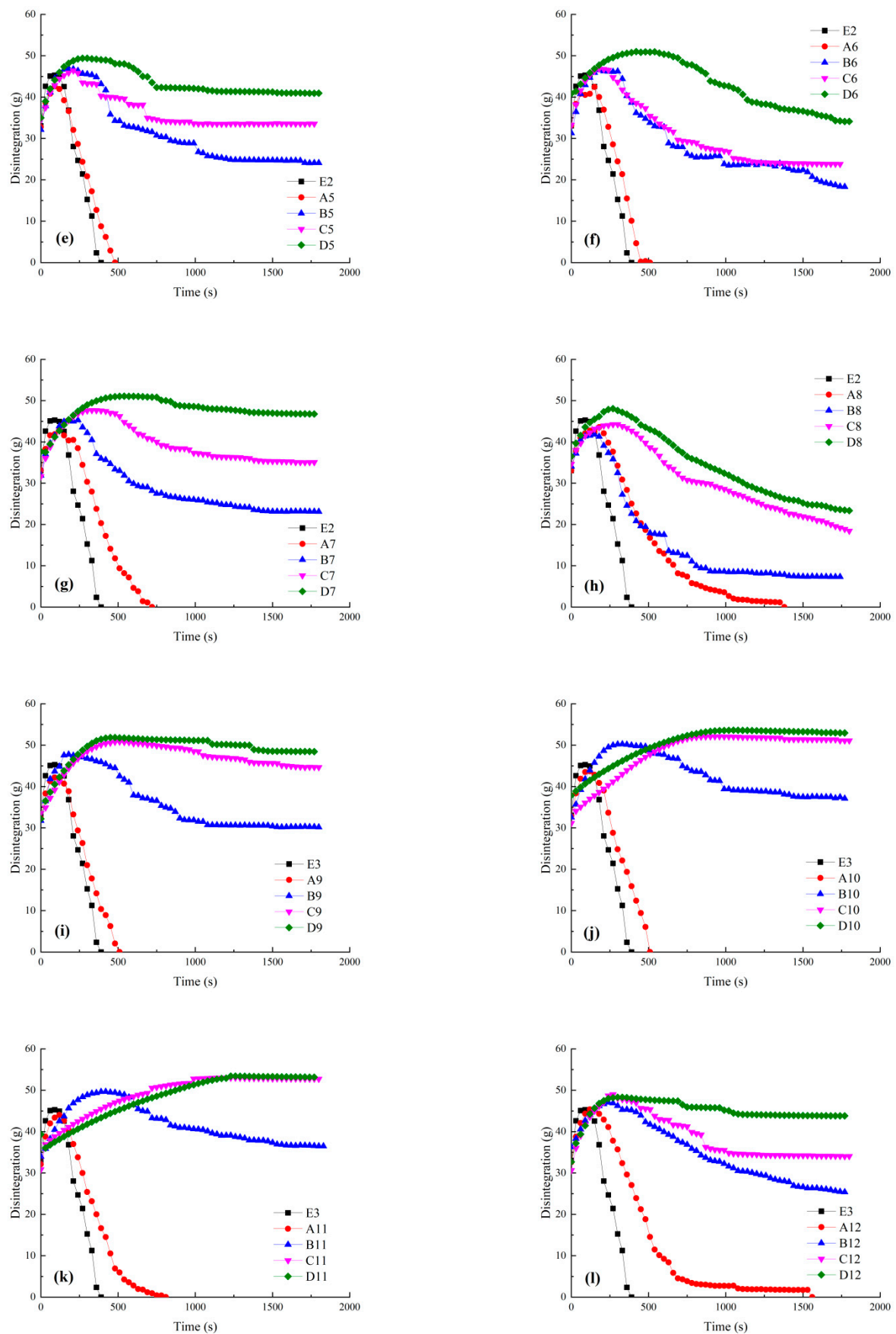


Figure 15. Cont.

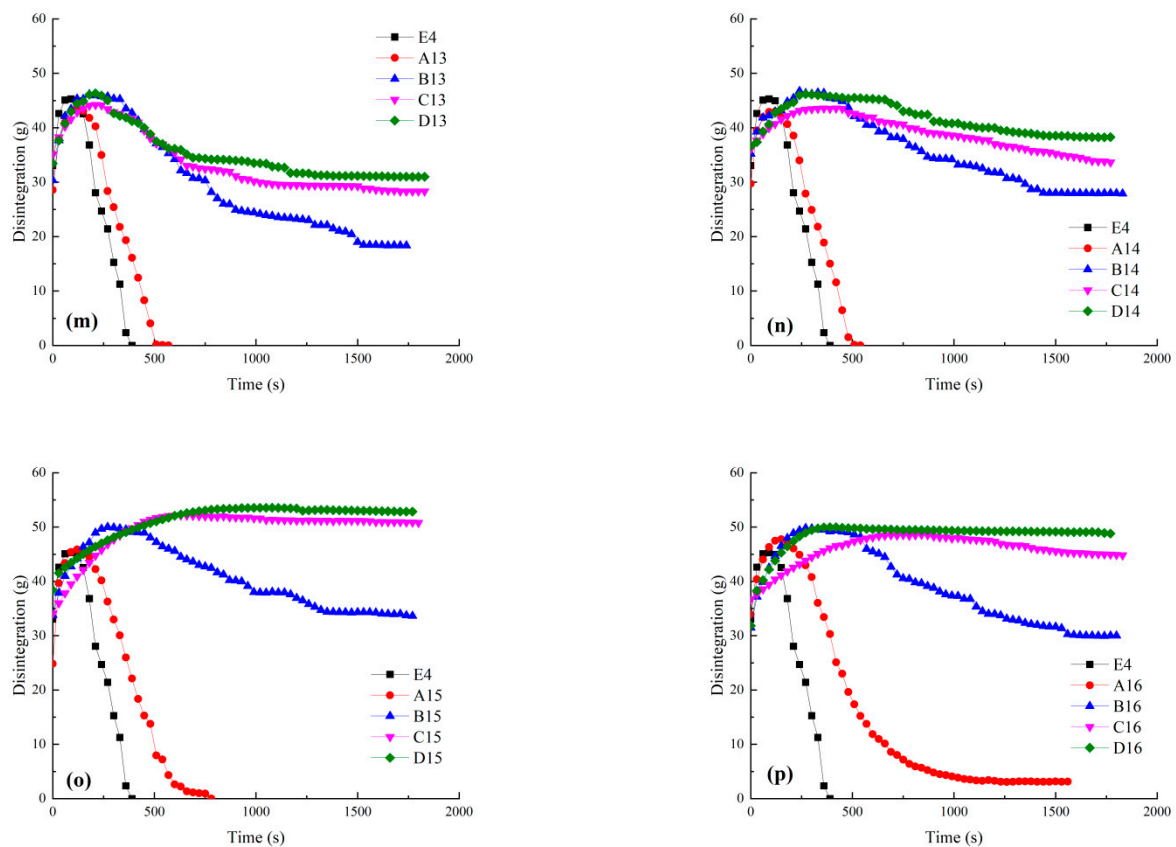


Figure 15. Disintegration curve with different treatment cycles: (a) BS 0.25, CS 0.4; (b) BS 0.25, CS 0.8; (c) BS 0.25, CS 1.2; (d) BS 0.25, CS 1.6; (e) BS 0.5, CS 0.4; (f) BS 0.5, CS 0.8; (g) BS 0.5, CS 1.2; (h) BS 0.5, CS 1.6; (i) BS 0.75, CS 0.4; (j) BS 0.75, CS 0.8; (k) BS 0.75, CS 1.2; (l) BS 0.75, CS 1.6; (m) BS 1.0, CS 0.4; (n) BS 1.0, CS 0.8; (o) BS 1.0, CS 1.2; (p) BS 1.0, CS 1.6.

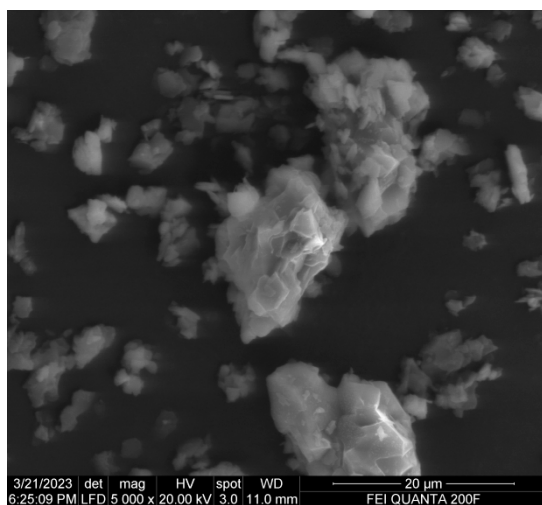
At a given bacterial solution concentration and cementation solution concentration, the more cycles, the longer the disintegration time. The ability to resist disintegration improves with the increase in treatment cycles. There is no significant change in the disintegration characteristics of the sample after one cycle of treatment. The sample undergoes complete disintegration. After three cycles of treatment, the sample presents incomplete disintegration. The ability to suppress disintegration is further improved after five cycles of treatment. The formation of microorganism surface crusts becomes more apparent when increasing the number of treatments [39]. The samples of BS 0.75, CS 0.8; BS 0.75, CS 1.2; BS 1.0, CS 1.2; BS 1.0, and CS 1.6 present non-disintegration. The resisting disintegration ability of the seven-cycles treatment has a smaller improvement compared to the five-cycle treatment. The reason for this is that after a five-cycle treatment, the sample shell forms a sufficient cover layer, making it difficult for the liquid to continue infiltrating. Five cycles of treatment can effectively complete the process of MICP reinforcement of granite residual soil. Meanwhile, the soil structure is not changed by spraying, and a hard crust is formed on the soil surface, making it more suitable for practical applications [40]. The mechanical stability and ability to resist erosion by heavy rainfall will be investigated in the future.

5. Microstructure of Soil Samples

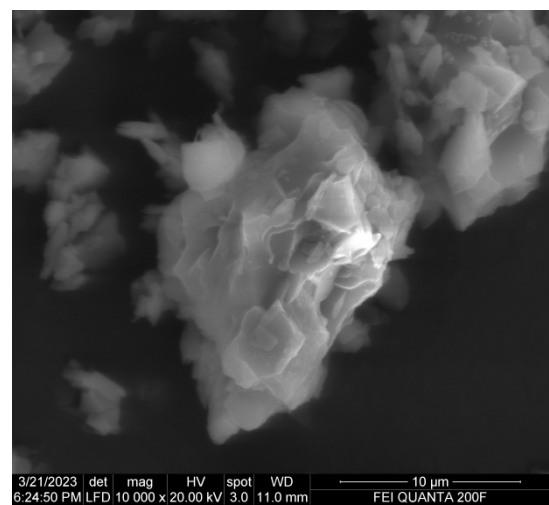
MICP technology generates calcium carbonate through bacteria metabolism between soil particles to fill soil pores, thereby improving soil performance. To analyze the effect of the microstructure and morphology on macroscopic mechanical properties, representative samples were collected from the surface of the sample. The specimen surface was sputter-

coated with gold and then observed using a field emission scanning electron microscope (Quanta 200FEG03040702) produced by FEI Corporation in the Hillsboro, the State of Oregon, USA.

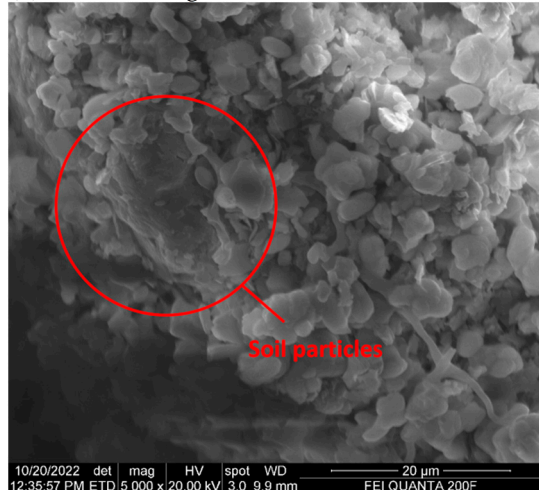
Figure 16 presents the SEM images of the MICP treatment samples and without treatment samples. It shows magnified images from the samples at 5000 $\times$ and 10,000 $\times$ magnifications, respectively. The without-treatment samples are relatively loose, and no other particles adhere to the surface of the particles, as shown in Figure 16a,b. The dense and smooth crust layer of precipitated CaCO_3 exists at the surface of the sample after the MICP treatment, as shown in Figure 16c,d. Then, it still has a lot of microscopic voids. The CaCO_3 is formed and accumulated locally. The soil particles are also bonded together by CaCO_3 around the loose particle contacts. Through the interactions of CaCO_3 precipitates and particles, a stable soil structure is generated with high water stability. The disintegration is suppressed significantly due to surrounding CaCO_3 precipitations.



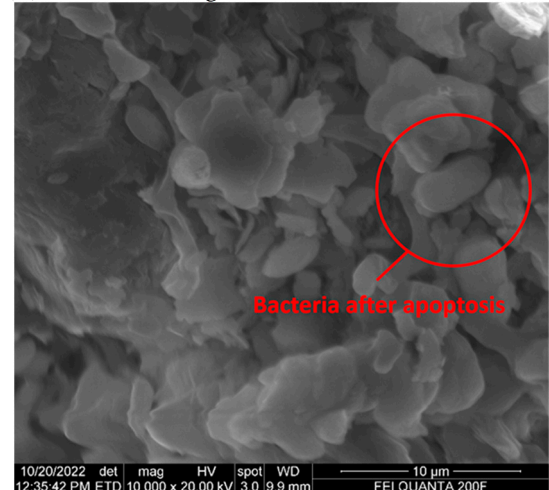
(a) A 5000 $\times$ magnification without treatment.



(b) A 10,000 $\times$ magnification without treatment.



(c) A 5000 $\times$ magnification of treatment.



(d) A 10,000 $\times$ magnification of treatment.

Figure 16. SEM images of treatment sample and without-treatment sample.

To investigate the composition of particles attached to the surface of treatment samples, an EDS energy spectrum analysis was performed, as shown in Figure 17. EDS in Figure 17 shows that there are O, C, and Ca, and C occupies about 13.18%, representing a plentiful existence in samples after MICP treatment [22]. The bonding material among the particles on the surface is CaCO_3 . CaCO_3 precipitation is produced by the MICP process and bonds

the soil particles together. Therefore, the biocementation effect significantly suppresses decomposition.

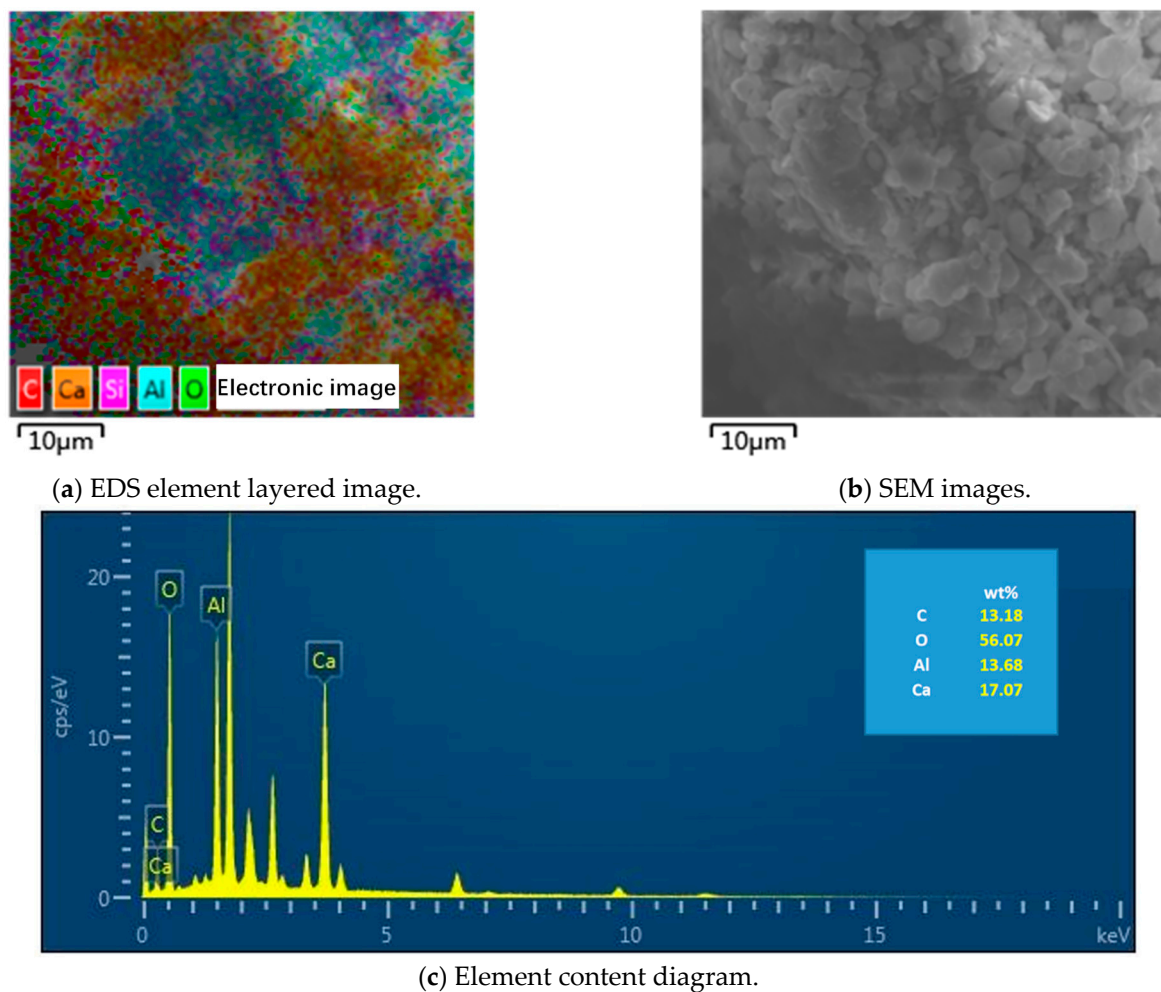


Figure 17. EDS energy spectrum analysis diagram.

6. Conclusions

In this study, a new strategy of MICP technology is used to resist the disintegration of granite residual soil for Benggang erosion prevention. The effects of the bacterial solution concentration, cementation solution concentration, and treatment cycle on disintegration are discussed. The conclusions can be drawn as follows:

- (1) MICP technology with a spraying method for treating granite residual soil can effectively generate calcium carbonate (CaCO_3) between soil particles. In this way, a crust layer on the surface is formed, which can significantly resist disintegration.
- (2) The bacterial solution concentration at a value of 0.75 and the cementation solution concentration at a value of 1.2 are optimal for resisting disintegration. An insufficient concentration of urease is produced by a low bacterial solution concentration, which makes it difficult to generate sufficient calcium carbonate to bond particles. An excessive bacterial solution concentration can lead to the premature formation of a dense layer on the soil surface, preventing further infiltration of bacteria and cementitious. A low cementation solution concentration cannot provide sufficient calcium ions, resulting in the insufficient generation of calcium carbonate. An excessive cementation solution concentration significantly inhibits the activity of urease.
- (3) Due to the formation of a sufficiently thick protective layer, five cycles of MICP treatment effectively suppresses disintegration. The thickness of the reinforcement

layer generated by one or three cycles of reinforcement is not sufficient to completely wrap the surface.

- (4) Further research is underway to investigate the mechanical stability and ability to resist erosion by heavy rainfall. The long-term durability of cemented granite residual soil also needs to be considered to achieve the effective regulation of mineralization reaction efficiency.

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