

Article

Effects of Wetting–Drying Cycles on the Macro and Micro Properties of the Cement-Stabilized Soil with Curing Agent

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Abstract: Cement-stabilized soil is a commonly used pavement base/bottom base material. Adding a suitable curing agent to cement-stabilized soil can effectively reduce the dosage of cement, meet the strength requirements, and also greatly improve its water stability. In this paper, three kinds of cement dosage (6%, 8%, and 10%) of cement-stabilized soil were selected to add a 0.04% organic liquid curing agent, and then compared with high-dose cement (10% and 12%)-stabilized soil. The influence of wetting–drying cycles on the mechanical properties of the five stabilized soils was discussed. The mineral composition of cement-stabilized soils before and after the addition of a curing agent was analyzed by X-ray diffraction (XRD), and the microscopic morphology of 10% cement-stabilized soils with a curing agent was studied by scanning electron microscopy (SEM). The macroscopic test shows that the unconfined compressive strength of solidified cement-stabilized soil can be divided into three stages with the increase in the times of the wetting–drying cycles, which are the rapid decay stage, stable enhancement stage, and stable decay stage. The wetting–drying stability coefficient first increases, and then decreases with the increase in the times of the wetting–drying cycles. The microscopic test shows that the addition of a curing agent can enhance the content of hydration products in the cement-stabilized soil specimen; at the curing age of 28 d, with the increase in the times of the wet–dry cycles, the structure of the solidified cement-stabilized soil gradually broke down. The surface porosity P and pore diameter d showed an overall upward trend but decreased at the fifth wetting–drying cycle. The pore orientation weakened. The results show that the resistance of cement-stabilized soil with a curing agent is obviously better than that of cement-stabilized soil under wet–dry conditions.

Keywords: curing agent; cement-stabilized soil; wetting–drying cycle; macro and micro properties



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1. Introduction

As the base/bottom base material for roads, cement-stabilized soil has the following characteristics compared with cement-stabilized granules [1–6]: (1) more cement; (2) local materials can be used and stone can be saved, which can produce obvious economic and environmental benefits; (3) poor water stability; and (4) low strength. Based on the above points, by adding an organic liquid curing agent to cement-stabilized soil, the goal of reducing the cement dosage, increasing the strength, and improving the water stability can be achieved. The anti-deterioration ability of a material under the action of wetting–drying cycles is an important index to reflect its water stability. When the climate conditions change, the base/bottom base material is subjected to periodic wetting–drying cycles caused by the alternating influence of rainfall and evaporation, and the physical and mechanical properties continue to decay, which will eventually affect the regular use of the road. It is necessary to study the performance changes of solidified cement-stabilized soil in a changing environment (wetting–drying cycle). Liu Kai et al. [7] discussed the change in unconfined compressive

strength of cement light soil and geopolymer light soil during wetting–drying cycles, and the research results showed that the wetting–drying cycle had a great influence on geopolymer light soil. Hou ZJ et al. [8] studied the effects of different cement contents on the wetting–drying resistance of Pisha sandstone cement-stabilized soil and found that adding cement can effectively improve the water erosion resistance of the sample, and the optimal cement content is 20%. Li N et al. [9] studied the effect of polypropylene fiber on the wetting–drying degradation resistance of coastal cement-stabilized soil and found that the strength and brittleness index of the sample increased with the increment of the number of wetting–drying cycles. Wang J et al. [10] studied the durability of calcium carbide slag–fly ash solidified shield residuum during wetting–drying cycles and found that the first wetting–drying cycle strongly influenced the compressive strength of the specimen. After the wetting–drying cycles, the stress–strain curve of the specimen changed from strain hardening to strain softening. Yang H et al. [11] analyzed the properties of marine waste silt solidified by PZ-1 under wetting–drying cycles. Neramitkornburi A et al. [12] studied the wetting–drying cycle resistance of the cement solidified clay–fly ash light-weight material and found that the incorporation of fly ash could improve the fluidity and durability of the light-weight material, and the effect was most significant when the fly ash replacement rate was greater than 40%. Kamei T et al. [13] found that adding recycled bassanite and coal ash simultaneously can improve the durability of very soft clay in wet and dry conditions.

In summary, thus far, domestic and foreign scholars have discussed the changes in mechanical properties of different road materials during wet–dry cycles, but relatively few studies have been conducted on the deterioration properties of and microstructure changes in cement-stabilized soil with a curing agent added under wetting–drying cycles. The main test methods used in the microstructure research of solidified soil under wetting–drying cycles are as follows: X-ray diffraction (XRD) and scanning electron microscopy (SEM) [14–16]. Therefore, this study takes cement-stabilized soil and cement-stabilized soil with an organic liquid curing agent as the research objects and evaluates the evolution law and microstructure changes of its anti-deterioration ability during the wetting–drying cycle process through a wet–dry cycle test, unconfined compressive strength test, and microscopic test. The effects of different curing ages and cement contents on the mechanical strength and physical properties of cement-stabilized soil and cement-stabilized soil mixed with a curing agent were discussed. The changes in hydration products in cement-stabilized soil before and after adding a curing agent and the effects of wetting–drying cycles on the microstructure of specimens were studied. The above research results can provide technical support for solidified cement-stabilized soil used as road base/bottom base material.

The highlights are as follows:

- The macro and micro characteristics of solidified cement-stabilized soil under wetting–drying cycles were studied;
- Adding a curing agent can improve the resistance to wetting–drying cycles of cement-stabilized soil;
- The addition of a curing agent can enhance the content of hydration products in cement-stabilized soil.

2. Test Materials and Methods

2.1. Test Materials

(1) Soil sample. The test soil sample was taken from an expressway expansion project in Shandong Province. Figure 1 shows the particle distribution of the soil sample. Table 1 shows the physical property indices of the soil sample.

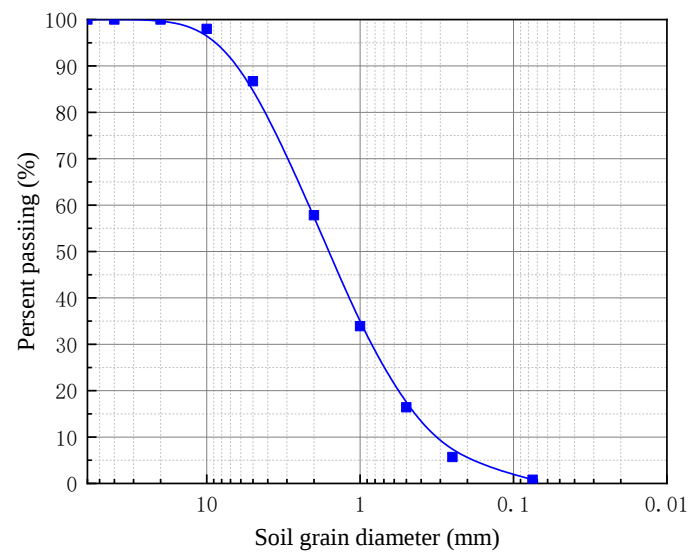


Figure 1. Particle distribution curve of the soil sample.

Table 1. Main physical property indices of the soil sample.

Natural Moisture (%)	PH	Coefficient of Curvature C_c	Coefficient of Nonuniformity C_u	Optimum Moisture (%)	Maximum Dry Density (g/cm^3)	Soil Sample ($d < 0.5 \text{ mm}$)		
						Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
3.9	8.17	1.0	6.875	12.19	1.9509	42.3	24.6	17.7

The coefficient of nonuniformity C_u is calculated with the following equation:

$$C_u = \frac{d_{60}}{d_{10}} \quad (1)$$

The coefficient of curvature C_c is calculated with the following equation:

$$C_c = \frac{d_{30}^2}{d_{60} \times d_{10}} \quad (2)$$

where d_{60} , d_{30} , and d_{10} = the cumulative percentage of soil weighing less than a certain particle size: 60%, 30%, and 10%, respectively.

(2) Cement. The ordinary silicate P.O42.5 grade cement was used in the test. The main performance indices are shown in Table 2.

Table 2. Main performance indices of cement.

Specific Surface Area (m^2/Kg)	Initial Setting Time (min)	Final Setting Time (min)	Stability	3D Bending Strength (MPa)	3D Compressive Strength (MPa)
381	115	184	Eligible	6.2	33.8

(3) Curing agent. The curing agent is an organic liquid, as shown in Figure 2. Diluting the product with a certain proportion of water and applying it to ordinary soil will completely change the hydrophilicity of the soil. The solidified soil not only has good compressive and flexural strength, but also has very prominent water stability.

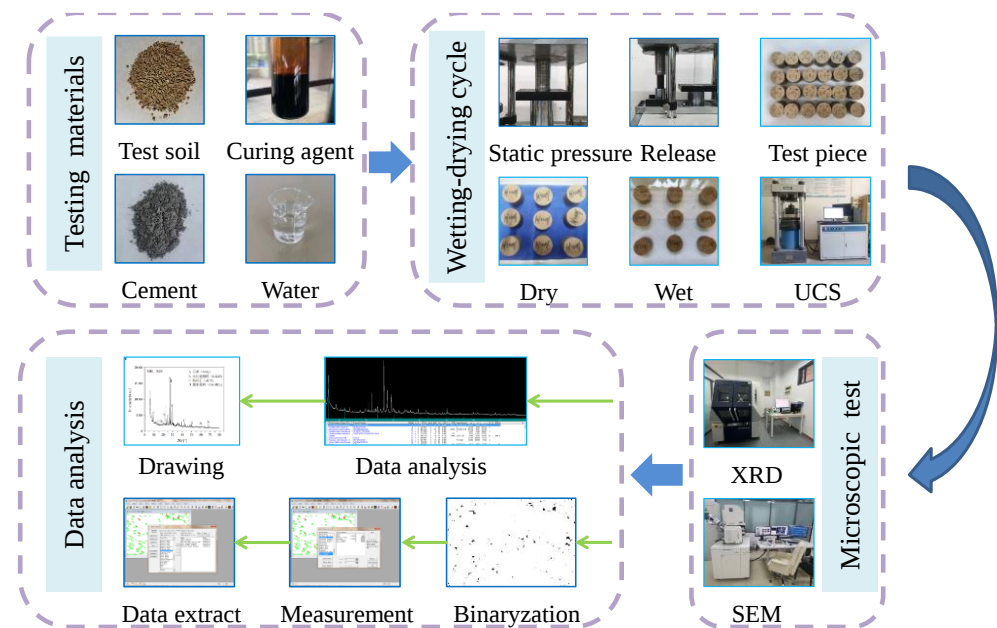


Figure 2. Flow chart of test and data analysis.

2.2. Test Method

Five sets of samples were tested. The sample numbers are shown in Table 3. The specimens used in the wetting–drying cycle test were cylinders ($d = 50$ mm, and $h = 50$ mm). The curing age is 7 days and 28 days. After completion of the maintenance, the specimens were placed indoors to air-dry for 24 h, and then wholly soaked 2.5 cm below the water surface for 24 h, which constituted a wetting–drying cycle. Nine wetting–drying cycles were carried out in this experiment. Unconfined compressive strength tests were conducted on the samples after 0, 1, 3, 5, 7, and 9 cycles, respectively. The wetting–drying cycle coefficient (K_w) was used as the evaluation index of the resistance to wetting–drying cycle strength deterioration. The larger the value, the stronger the resistance to deterioration of the specimen. The K_w is calculated with Formula (3):

$$K_w = \frac{R_t}{R_0} \times 100\% \quad (3)$$

where K_w is wetting–drying cycle coefficient (%); R_0 is the unconfined compressive strength (MPa) of the specimen without wetting–drying cycles; and R_t is unconfined compressive strength (MPa) of the specimen at the wetting–drying cycles.

Table 3. Overall test scheme design.

No.	Dosage of Curing Agent (%)	Cement Content (%)	Wetting–Drying Cycles		Microscopic Testing
			Curing Age (d)	Number of Cycles	
S6,0.04	0.04	6	7, 28	0, 1, 3, 5, 7, 9	/
S8,0.04	0.04	8	7, 28	0, 1, 3, 5, 7, 9	/
S10,0.04	0.04	10	7, 28	0, 1, 3, 5, 7, 9	XRD, SEM
S10	0	10	7, 28	0, 1, 3, 5, 7, 9	XRD
S12	0	12	7, 28	0, 1, 3, 5, 7, 9	/

After the wetting–drying cycle test, the small pieces of the samples were selected for the XRD test and scanning electron microscope test. The XRD scanning range 2θ was 5° – 80° , and the scanning speed was $2^\circ/\text{min}$. The data were analyzed using JADE software (MDI Jade 6) [17]. SEM images were first binarized by MATLAB software R2022b [18], and then Image-Pro Plus (IPP) software 6.0 was used to measure and extract the binarized

images [19–22]. The overall test scheme design of this study is shown in Table 3, and the test and data analysis process are shown in Figure 2.

3. Mechanical Properties of Stabilized Soil at Different Ages after Wetting–Drying Cycles

3.1. 7 d Curing Age

Figure 3a,b, respectively, show the unconfined compressive strength and wetting–drying cycle coefficient of solidified cement-stabilized soil and cement-stabilized soil under different wetting–drying cycle times at a 7 d curing age.

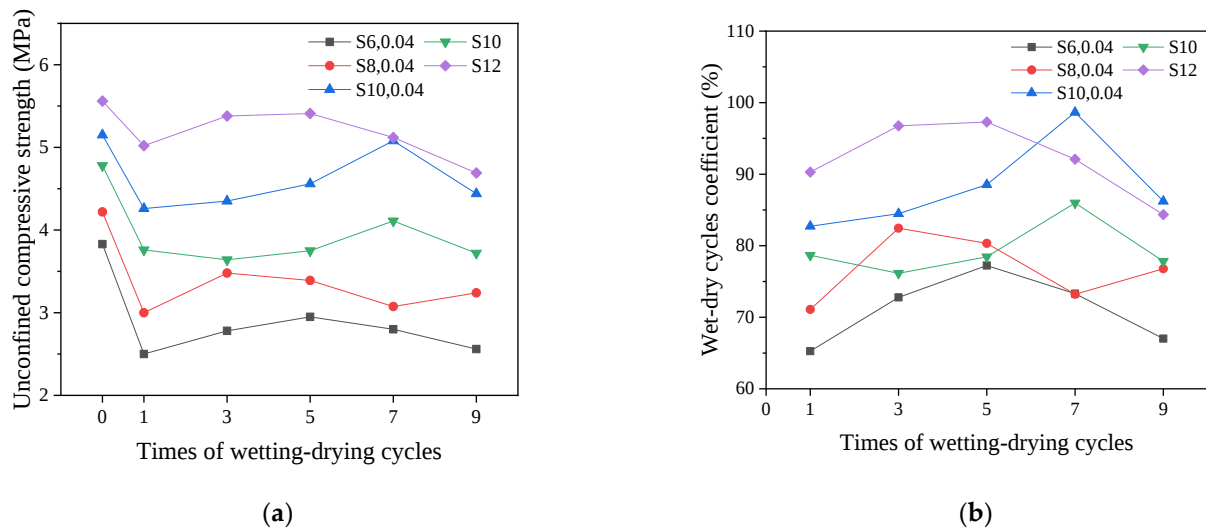


Figure 3. The influence of the number of wetting–drying cycles on unconfined compressive strength and wetting–drying cycle coefficient (7 d): (a) unconfined compressive strength; and (b) wetting–drying cycle coefficient.

As shown in Figure 3a:

(1) The unconfined compressive strength of the specimen cured for 7 days increases with the increment of cement content under the same wetting–drying cycles. The unconfined compressive strength of S10,0.04 is higher than S10, but lower than S12. It is indicated that adding a 0.04% curing agent is helpful to the resistance of specimens to dry and wet damage.

(2) The development of the unconfined compressive strength of solidified cement-stabilized soil and cement-stabilized soil at the age of 7 days can be divided into the following three stages with the number of wetting–drying cycles:

① The rapid attenuation stage. This mainly occurs during the process of the first wetting–drying cycle. The binding materials in the sample are damaged under the action of the wetting–drying cycles, and the viscosity of the soil mass decreases, which leads to a rapid decrease in the strength of the specimen. The attenuation range of the unconfined compressive strength of the specimen is extensive; The maximum is 34.7% (S6,0.04), and the minimum is 10% (S12).

② The stable enhancement stage. This stage mainly occurs during the third, fifth, and seventh wetting–drying cycles. With the increase in the number of wetting–drying cycles, the internal hydration reaction of the specimen was more sufficient, the hydration products were increased, and the pores of the specimen were filled, which led to a gradual increment of the unconfined compressive strength of the specimen. In this stage, the unconfined compressive strength of the S6,0.04, S8,0.04, and S10,0.04 specimens increased by more than 10% compared with the strength after rapid decay. The unconfined compressive strength of the S10 and S12 specimens increased less than 10% compared with the strength after rapid decay.

③ The stable attenuation stage. This stage occurs after the fifth wetting–drying cycle. The internal hydration reaction of the solidified soil sample is completed. With the continuous increment of the number of wetting–drying cycles, the internal structure of the sample is damaged, resulting in the unconfined compressive strength of the solidified cement-stabilized soil decreasing.

As shown in Figure 3b, the wetting–drying cycle coefficients of the specimens cured for 7 days under different dosages increased first, and then decreased with the increment of the number of wetting–drying cycle. At the ninth wetting–drying cycle, the wetting–drying cycle coefficients of the S6,0.04, S8,0.04, S10,0.04, S10, and S12 specimens were 67.02%, 76.78%, 86.21%, 77.82%, and 84.35%, respectively. It shows that the addition of curing agents and the increment of cement content can significantly improve the ability of the specimen to resist failure under a wetting–drying cycle.

Figure 4 shows the appearance changes in the specimens cured for 7 days after nine wetting–drying cycles. As shown in the pictures, the increment of cement content and the addition of curing agents affect the failure state of the sample appearance under wetting–drying cycles. The higher the dosage of the cement and curing agent is, the more intact the specimen's appearance is after 9 wetting–drying cycles. Among them, S6,0.04 experienced the most severe morphological damage, with many surface and edge parts falling off. S12 has a relatively intact shape, with some shallow pits on the surface of the specimen and the edge parts remaining intact.

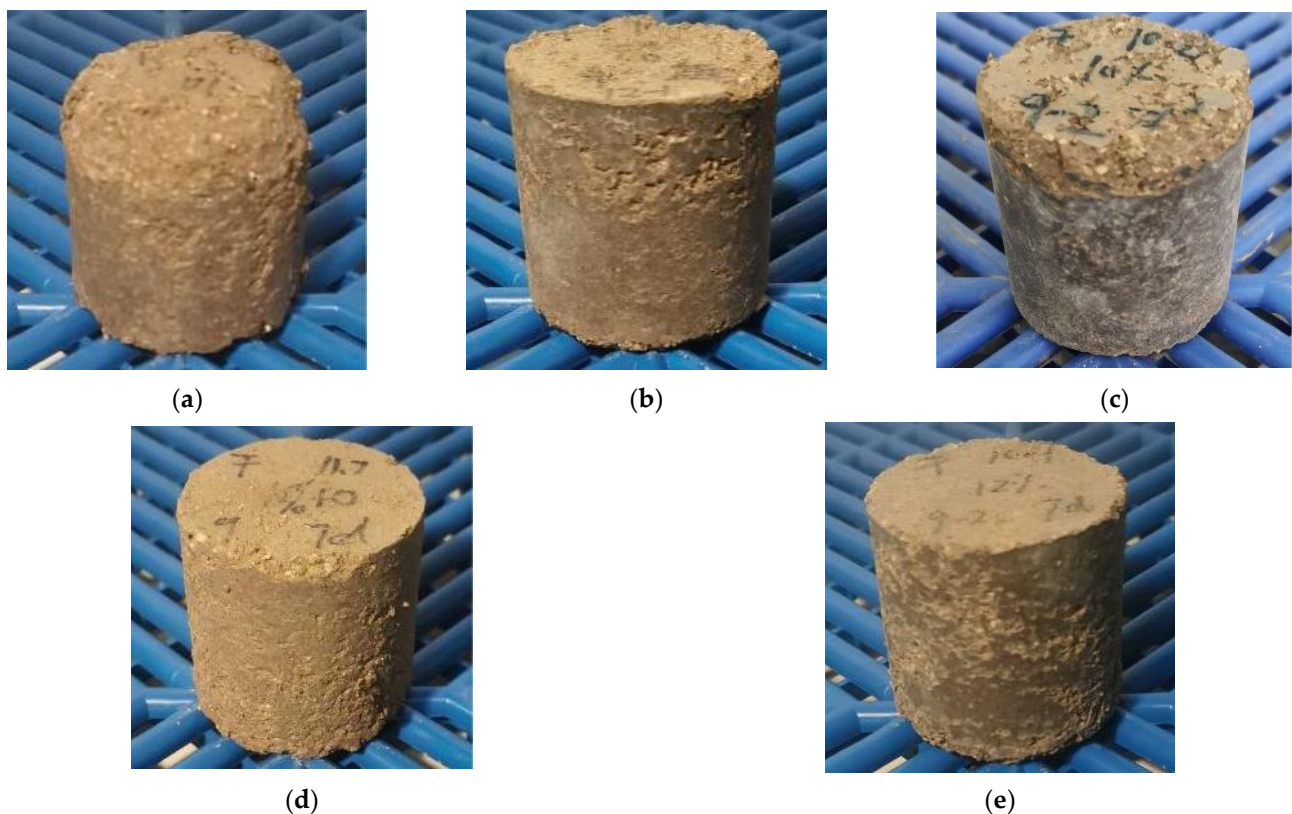


Figure 4. The appearance changes of the specimens cured for 7 days after 9 wetting–drying cycles: (a) S6,0.04; (b) S8,0.04; (c) S10,0.04; (d) S10; and (e) S12.

3.2. 28 d Curing Age

Figure 5a,b, respectively, show the unconfined compressive strength and wetting–drying cycle coefficient of the specimens cured for 28 days after nine wetting–drying cycles.

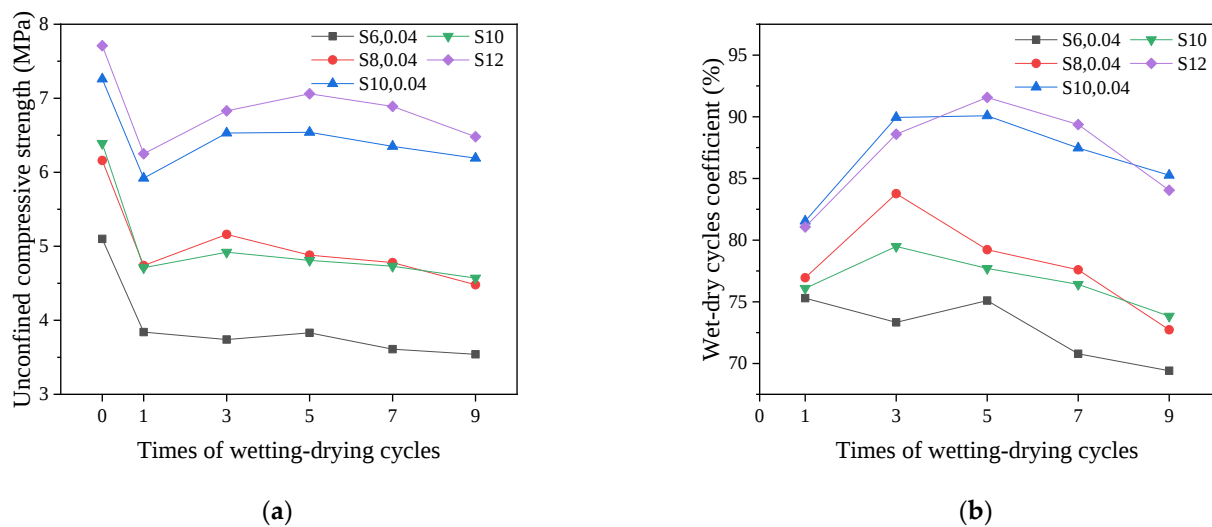


Figure 5. Influence of the number of wetting–drying cycles on unconfined compressive strength and wetting–drying cycle coefficient (28 d): (a) unconfined compressive strength; and (b) wetting–drying cycle coefficient.

As shown in Figure 5a:

(1) The variation rules of the unconfined compressive strength of the specimens cured for 28 days is the same as those cured for 7 days, which also decrease, then increase, and then decrease. But the duration and the strength growth of the stable strengthening stage decreased. In this stage, the S10,0.04 and S12 specimens showed a relatively noticeable strength growth.

(2) After each wetting–drying cycle, the unconfined compressive strength of S10,0.04 and S12 was almost the same. Under the same number of wetting–drying cycles, the compressive strength curves of the two specimens are also similar, indicating that the addition of a curing agent can reduce the cement content while maintaining the wetting–drying cycle resistance of the sample.

As shown in Figure 5b, the wetting–drying cycle coefficients of the specimens cured for 28 days also showed a tendency to rise up at the beginning and decline at a later stage with the increment of the number of wetting–drying cycles. At the ninth wetting–drying cycle, the wetting–drying cycle coefficients of S6,0.04, S8,0.04, and S10,0.04 were 69.4%, 72.7%, and 85.3%, respectively. It can be seen that the higher the cement dosage, the stronger the specimen's resistance to the wetting–drying cycle damage. S10,0.04 and S12 had similar wetting–drying cycle coefficients under different wetting–drying cycles, and the change trend was the same. At the ninth wetting–drying cycle, the wetting–drying cycle coefficient of sample S10,0.04 was slightly higher, indicating that, with the joining of a curing agent, the ability of the sample to resist wetting–drying cycle erosion was also enhanced.

The influence of the number of wetting–drying cycles on the appearance change in specimen S10,0.04 cured for 28 d is shown in Figure 6. As can be seen from Figure 6, the surface of S10,0.04 did not change significantly after the first wetting–drying cycle, and the edge fell off slightly after the third wetting–drying cycle. The damage was the most serious after the ninth wetting–drying cycle, with shallow pits on the surface and edge caused by repeated erosion. Due to the water loss and absorption at the edge of the sample surface, the particle shedding first occurred in this area [23].

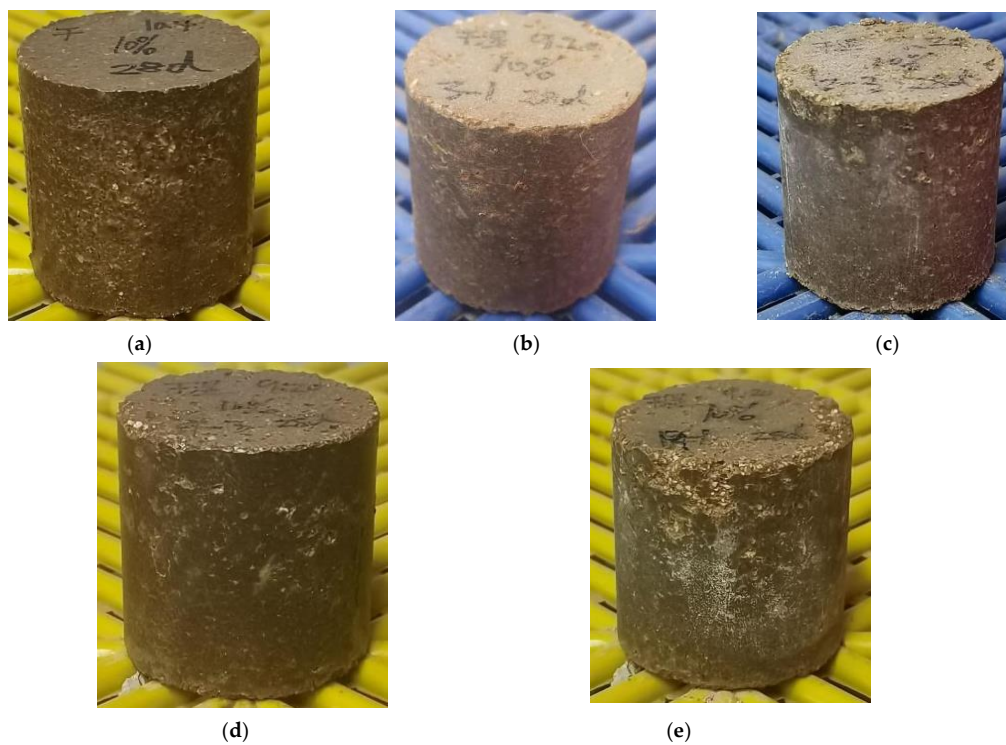


Figure 6. The influence of the number of wetting–drying cycles on the appearance changes of S10,0.04 (28 d): (a) one wet–dry cycle; (b) three wetting–drying cycles; (c) five wetting–drying cycles; (d) seven wetting–drying cycles; and (e) nine wetting–drying cycles.

4. Mechanical Properties of Stabilized Soil at Different Ages after Wetting–Drying Cycles

4.1. XRD Analysis

An XRD phase analysis was conducted on S10 and S10,0.04 cured for 28 days. Figure 7 shows that the mineral composition of the two soil samples mainly include quartz, calcium silicate hydrate, ettringite, etc. Both S10 and S10,0.04 have a crystal diffraction peak. However, the diffraction peaks of AFt and C-S-H crystals in S10,0.04 increase. It can be seen that the main change in the sample before and after the joining of the curing agent is the content of hydration products. The curing agent plays a role in accelerating the cement hydraulic and pozzolanic reaction.

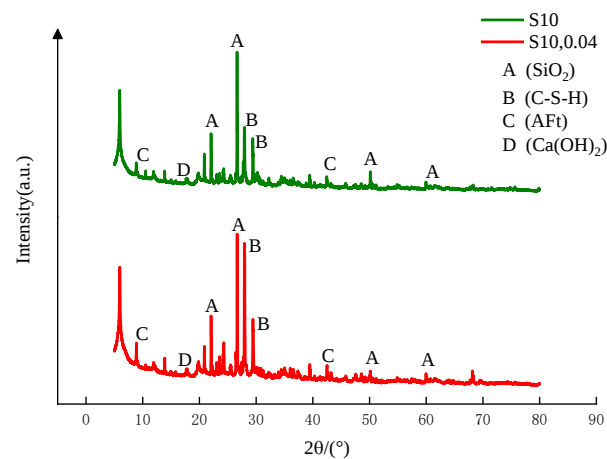


Figure 7. XRD phase analysis of S10 and S10,0.04 (28 d).

4.2. SEM Analysis

S10,0.04 cured for 28 d was tested by SEM after zero, one, five, and nine wetting–drying cycles, at magnifications of 200 times and 2000 times. The SEM results are shown in Figures 8 and 9. As can be seen from the figures, with the increment of the wetting–drying cycles, soil particles were broken, the pore structure was gradually loosened, and the cementation between soil grain was obviously weakened. The contact mode of particles changed from close contact to point or surface contact, and the structure became loose. The number of large pores in the soil pores obviously increased, and the strength property of the soil was weakened. This indicates that S10,0.04 experienced repeated expansion and contraction deformation during the wetting–drying cycles, soil particles were scoured by water flow, and the corresponding material components and hydration products in the soil continued to migrate and disperse, resulting in changes in soil micromorphology and severe damage to mechanical properties.

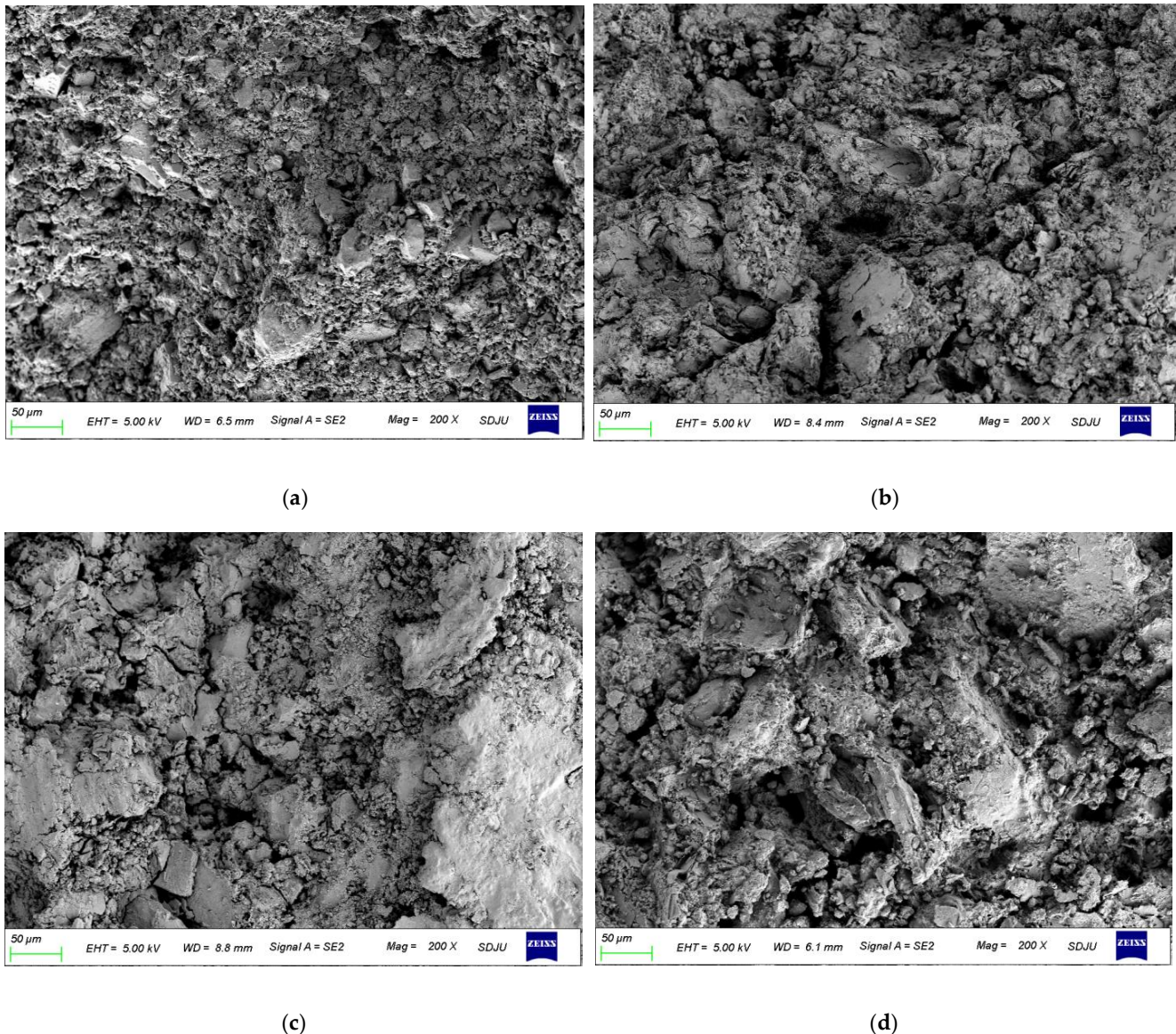


Figure 8. S10,0.04. SEM image $\times 200$ times after wetting–drying cycles: (a) zero wetting–drying cycle; (b) one wetting–drying cycle; (c) five wetting–drying cycles; and (d) nine wetting–drying cycles.

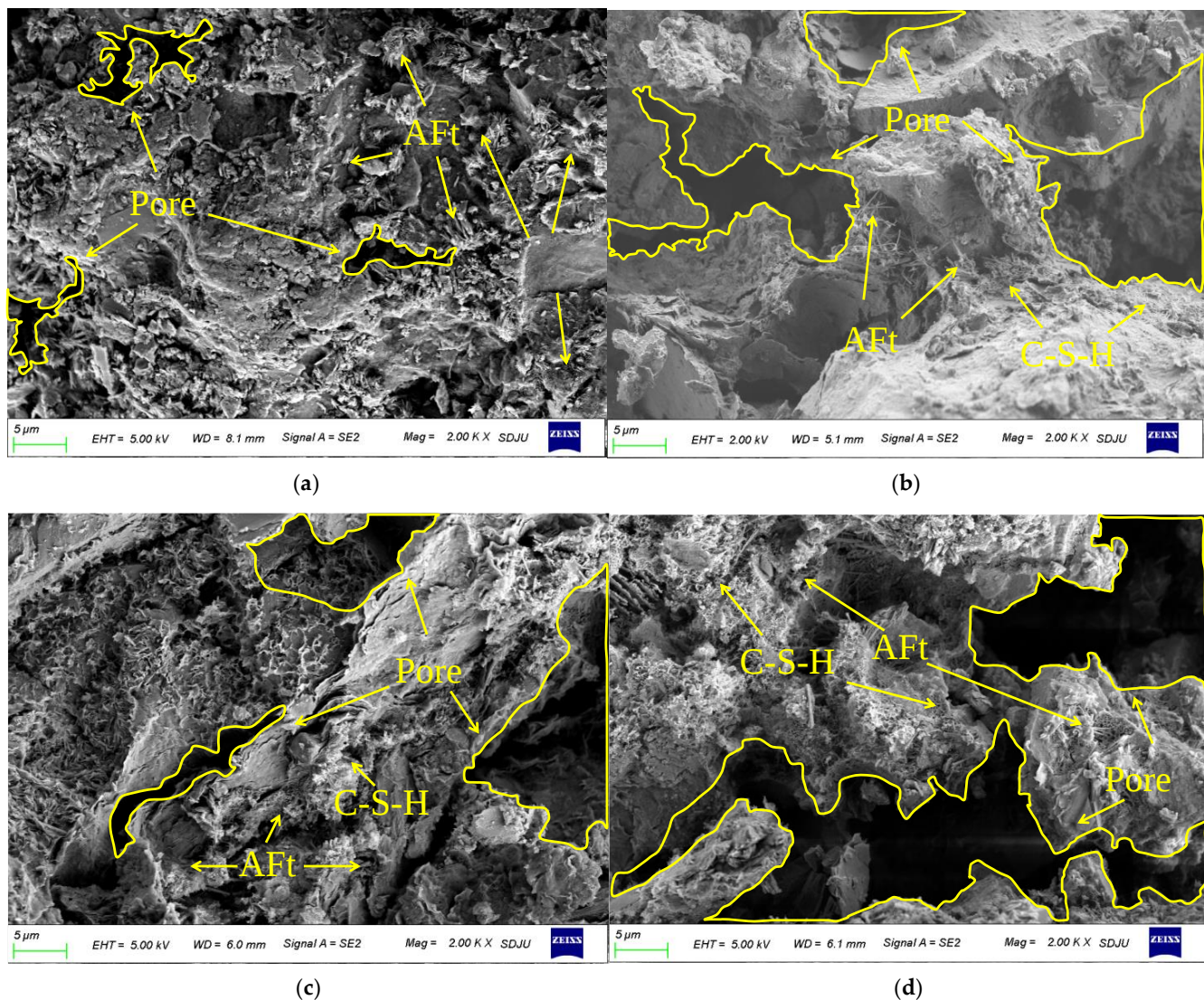


Figure 9. S10,0.04. SEM image $\times 2000$ times after wetting–drying cycles: (a) zero wetting–drying cycle; (b) one wetting–drying cycle; (c) five wetting–drying cycles; and (d) nine wetting–drying cycles.

4.2.1. Surface Porosity P

Surface porosity is calculated according to Formula (4):

$$P = \frac{\sum_{i=1}^N S_i}{S_{\text{total}}} \quad (4)$$

where N is the total number of pores in the electron microscope picture; S_i is the area of the i th pore (μm^2); and S_{total} is the area of the picture (μm^2).

The variation of the surface porosity P of S10,0.04 under different wetting–drying cycles is shown in Figure 10. The surface porosity of S10,0.04 showed an overall upward trend with the increment of the number of wetting–drying cycles, but the surface porosity decreased after five wetting–drying cycles. This indicates that, under wetting–drying cycles, the internal structure of the sample gradually broke down, and pores and cracks increased continuously. After the fifth wetting–drying cycle, the decrease in surface porosity was due to the wetting–drying cycle process promoting the internal hydration reaction, and the hydration products generated filled the expanded pores and cracks. After the fifth wetting–drying cycle, the hydration reaction was nearly complete. AFt, C-H-S, and other hydration products no longer increased significantly, and the surface porosity of S10,0.04 increased again.

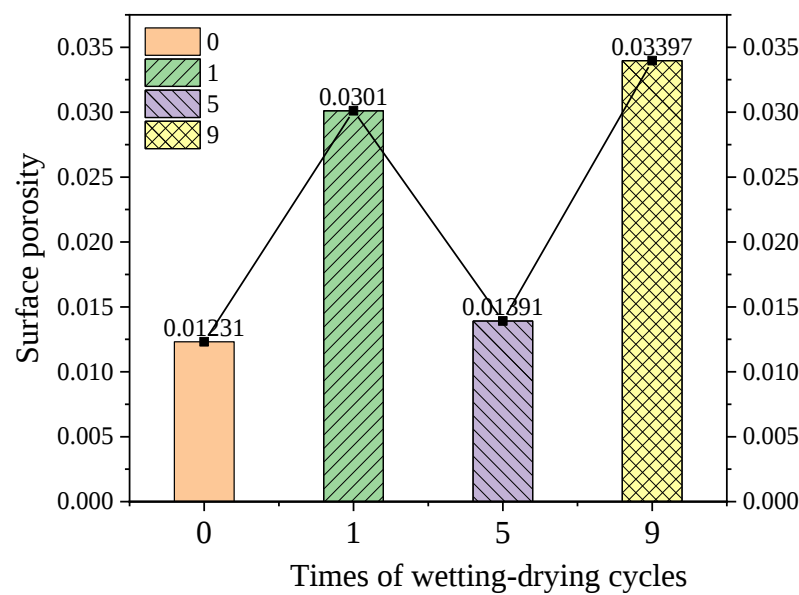


Figure 10. Changes in surface porosity of S10,0.04 under different wetting–drying cycles.

4.2.2. Pore Diameter d

The pore diameter distribution of S10,0.04 under different wetting–drying cycles is shown in Figure 11a, and the change in the average pore diameter is shown in Figure 11b. The pore diameter of S10,0.04 was mainly concentrated within 1~5 μm under the wetting–drying cycles. With the increment of the number of wetting–drying cycles, the tiny pores with a diameter of less than 1 μm gradually decreased; in contrast, the large pores with a diameter of more than 10 μm continuously increased, and the average pore diameter showed an upward trend. After the ninth dry–wet cycle, the average pore size of S10,0.04 is 1.41 times that of the sample without wetting–drying cycles, and 1.14 times that of the sample after the first wetting–drying cycle.

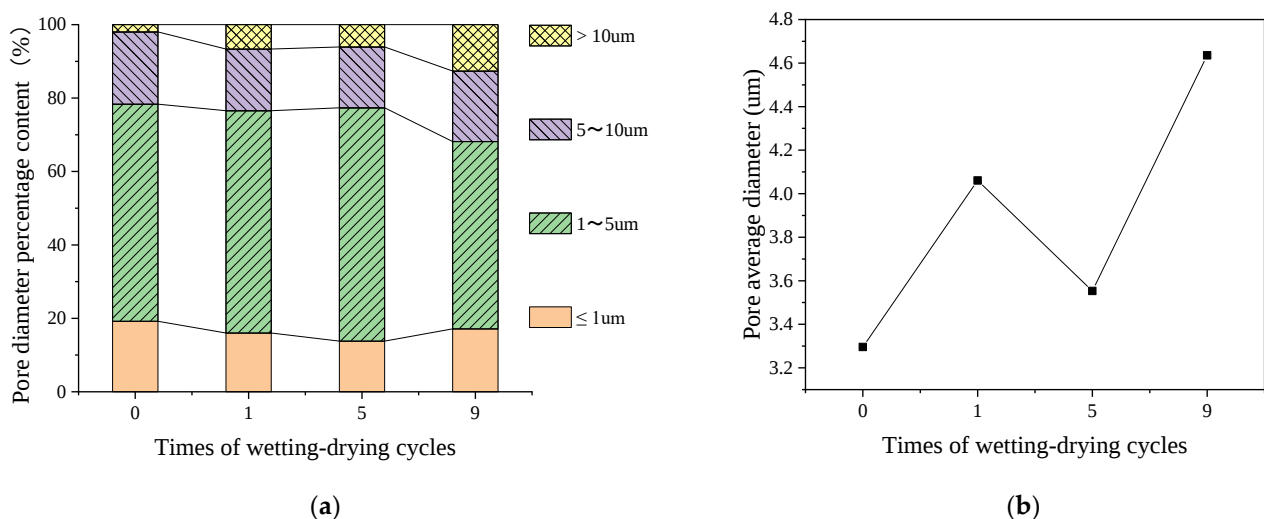


Figure 11. Changes in pore diameter of S10,0.04 under different wetting–drying cycles: (a) distribution pattern of pore diameter; and (b) variation pattern of average pore diameter.

According to the pore diameter distribution of S10,0.04 under different wetting–drying cycles, the relationship between pore diameter distribution and surface porosity was established, and the fitted results are demonstrated in Figure 12. As can be seen from Figure 12, $\leq 1 \mu\text{m}$ and 1~5 μm apertures have the worst correlation with surface porosity. The contribution rate of $\leq 1 \mu\text{m}$ and 1~5 μm apertures to the porosity increase is negative.

>10 μm and 5~10 μm apertures have a higher correlation with surface porosity. The contribution rate of >10 μm aperture to the increment of porosity is positive, and the contribution rate of the 5~10 μm aperture is negative. This shows that the rise in surface porosity is mainly related to the >10 μm aperture.

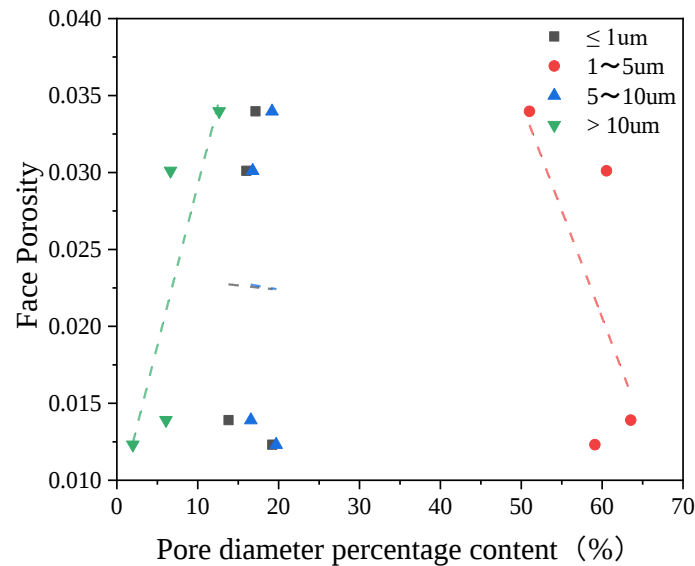


Figure 12. Relationship between pore diameter distribution and surface porosity under different wetting–drying cycles.

According to the pore diameter distribution of S10,0.04 under different wetting–drying cycles, the relationship between pore diameter distribution and unconfined compressive strength was established, and the fitted results are demonstrated in Figure 13. It can be seen from Figure 13 that the four aperture ranges all had an impact on the unconfined compressive strength. The pore diameter ≤ 1 μm , 1 μm ~5 μm , and 5 μm ~10 μm have a low correlation with the strength, and the correlation index R^2 is 0.27064, 0.03754, and 0.31628, respectively, and they are all positively correlated. The pore diameter >10 μm has a high correlation with the strength, and the correlation index R^2 is 0.50022, showing a negative correlation.

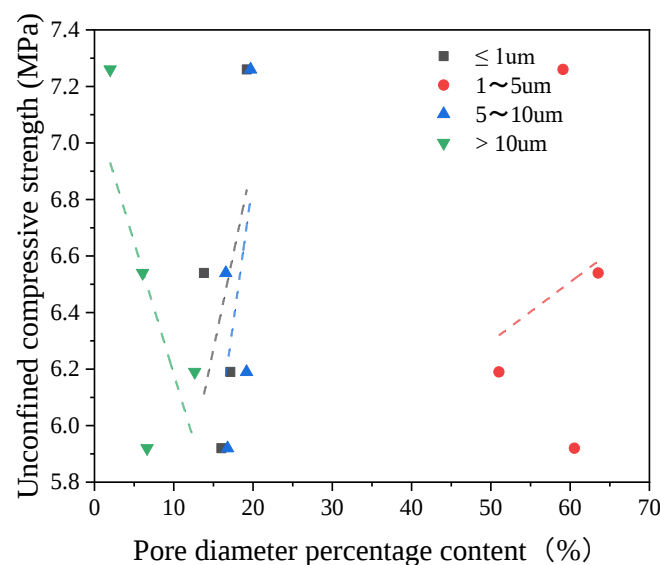


Figure 13. The relationship between pore diameter distribution and unconfined compressive strength under different wetting–drying cycles.

4.2.3. Pore Abundance

The porosity is calculated according to Formula (5):

$$C = \frac{B}{L} \quad (5)$$

where B is the pore short-axis length (μm); L is the long-axis length of the pore (μm).

The pore abundance distribution of S10,0.04 under different wetting–drying cycles is shown in Figure 14a, and the change in average pore abundance is shown in Figure 14b. As can be seen from Figure 14a, the porosity of S10,0.04 was mainly concentrated in the range of 0.4~0.6, and the porosity of 0.0~0.2 accounts for a very tiny proportion during the wetting–drying cycles, indicating that most of the pore shapes tended to be elliptical and elongated pores were very rare. As shown from Figure 14b, the average pore abundance of S10,0.04 fluctuated within the small range of 0.4~0.6 under different wetting–drying cycles, indicating that the wetting–drying cycles had little influence on the pore shape.

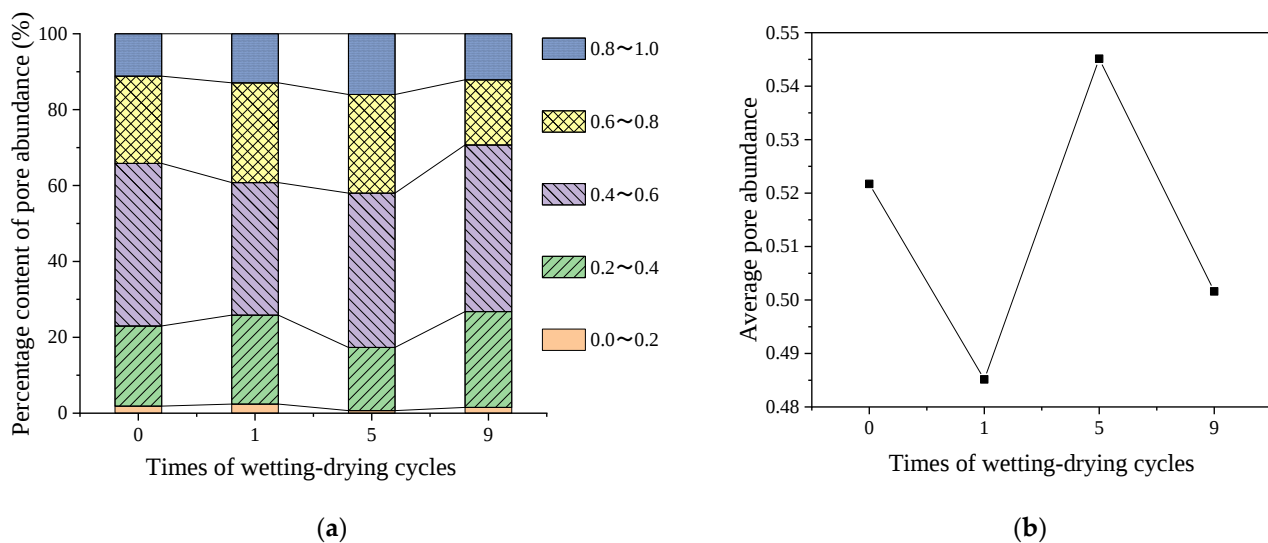


Figure 14. Changes in pore abundance of S10,0.04 under different wetting–drying cycles: (a) distribution rule of pore abundance; and (b) variation rule of average pore abundance.

4.2.4. Fractal Dimension

The fractal dimension is calculated according to Formula (6), which reflects the complicity of the pore shape. Its value is generally between 1 and 2. The greater the value, the more multiple the pore profile [24,25].

$$D = -\lim_{\varepsilon \rightarrow 0} \frac{\ln N(\varepsilon)}{\ln \varepsilon} \quad (6)$$

where ε is the pore diameter (μm); and $N(\varepsilon)$ is the percentage (%) of the total number of pores greater than this diameter.

The variation law of the mean fractal dimension of S10,0.04's pores under different wetting–drying cycles is shown in Figure 15. The mean fractal dimension of S10,0.04's pores decreased first, then increased with the increment of the number of wetting–drying cycles, mainly between 1.108 and 1.115. The average fractal dimension of pores after the ninth wetting–drying cycle increased by 0.36% compared with that without wetting–drying cycles, and by 0.51% compared with that after the first wetting–drying cycle, indicating that the wetting–drying cycle process had a limited influence on the average fractal dimension of pores.

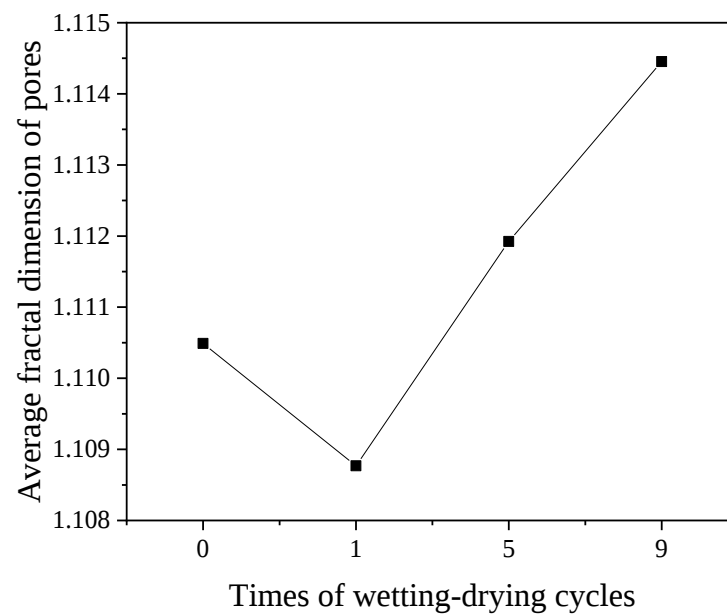


Figure 15. Changes in S10,0.04's mean fractal dimension of pores under different wetting–drying cycles.

4.2.5. Pore Orientation Angle

The angle between the long axis of the pores in the binarized picture and the Y-axis of the picture co-ordinate system is called the pore orientation angle [26]. The distribution frequency of the pores in a specific direction is equally divided in the interval range of 0~180° by every 10°, so that, within the range of 0~180°, the orientation frequency of the pores in the i interval can be calculated according to Formula (7) [27]:

$$F_i = \frac{m_i}{M} \times 100\% \quad (7)$$

where m_i is the number of pores in the i interval in the binary picture; and M is the total number of pores.

In the range of 0°~360°, the data are processed in mirror symmetry. The pore orientation frequency of S10,0.04 under different wetting–drying cycles is shown in Figure 16. As seen from Figure 16, the porosity has a specific orientation, and its orientation angle is mainly distributed in the range of 90°~100°. With the increment of the number of wetting–drying cycles, the pore orientation gradually decreased, and the pore distribution became more disordered, showing a trend of uniform distribution at all angles. However, the proportion of the orientation angle within 90°~100° was still considerable.

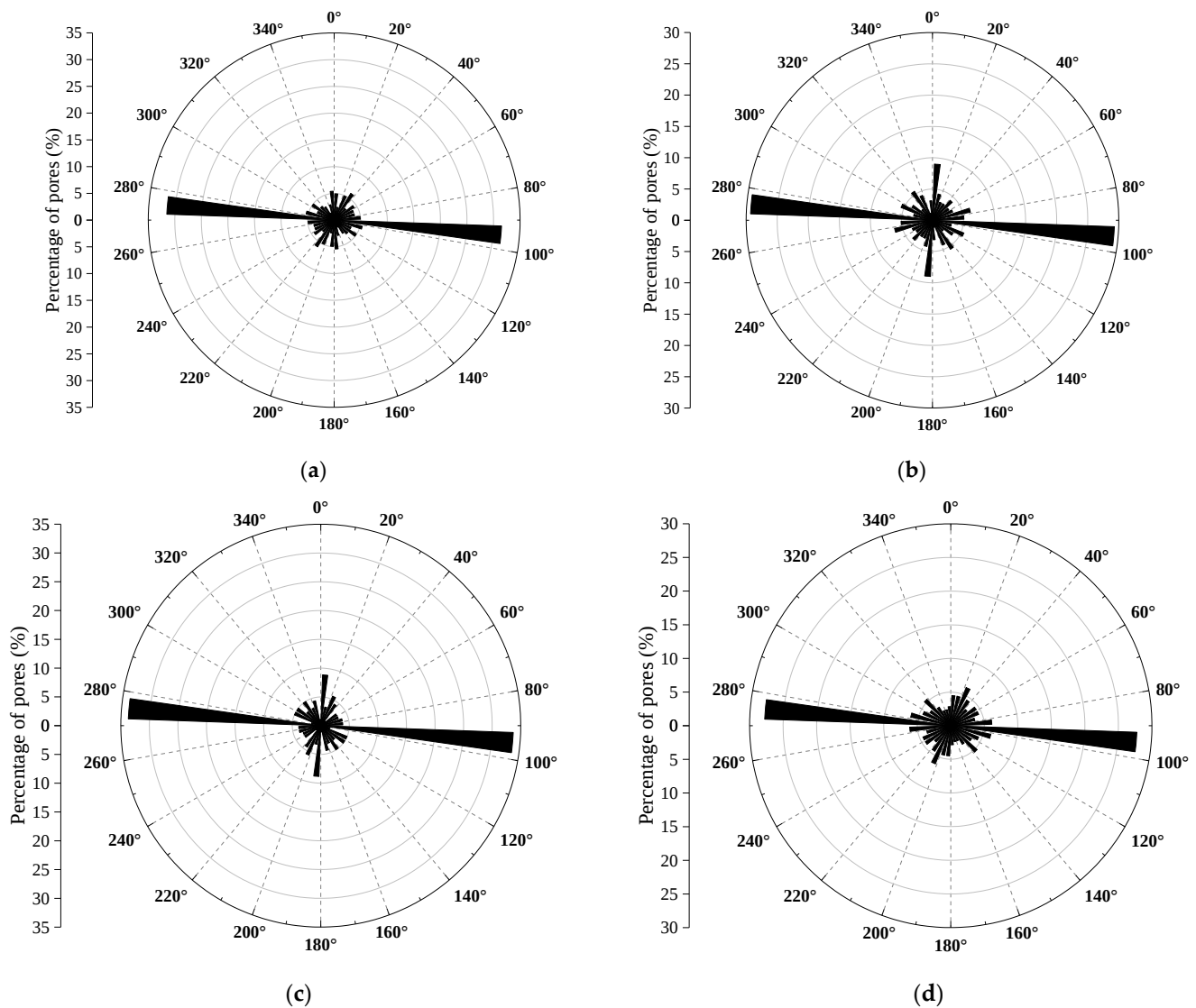


Figure 16. Pore orientation frequency of S10,0.04 under different wetting–drying cycles: (a) pore orientation frequency after zero wetting–drying cycle; (b) pore orientation frequency after one wetting–drying cycle; (c) pore orientation frequency after five wetting–drying cycles; and (d) pore orientation frequency after nine wetting–drying cycles.

5. Conclusions

The macro and micro characteristics of solidified cement-stabilized soil under wetting–drying cycles were studied. The effects of wetting–drying cycles on the mechanical properties of solidified cement-stabilized soil (S6,0.04, S8,0.04, and S10,0.04) and cement-stabilized soil (samples S10 and S12) were investigated through compressive strength tests. The mineral composition changes of cement-stabilized soil before and after the addition of the curing agent (S10, and S10,0.04) were analyzed by X-ray diffraction (XRD), and the microscopic morphological changes of solidified cement-stabilized soil (S10,0.04) under different wetting–drying cycles were further studied by scanning electron microscopy (SEM). The conclusions are as follows:

(1) With the increase in the number of wetting–drying cycles, the unconfined compressive strength of all samples decreased first, and then increased, and decreased finally. It indicates that the specimen underwent significant damage in the early stage of the wetting–drying cycles, the hydration reaction was enhanced in the middle period in the immersed water environment, and the strength could be restored. In the later stage, the

hydration reaction was completed, and no hydration products were produced. Therefore, the unconfined compressive strength of the specimen declined again.

(2) With the increase in wetting–drying cycles, the wetting–drying cycle coefficient of solidified cement-stabilized soil first increased, and then decreased, the specimen structure was gradually damaged, the surface shallow pits gradually increased, and the edge parts continued to fall off. The erosion of S6,0.04 was the most serious, and the increment of cement content and the incorporation of the curing agent could effectively improve its resistance to wetting–drying erosion.

(3) The addition of the curing agent effectively promoted the hydration reaction and improved the resistance to deterioration of the samples during the wetting–drying cycles. The unconfined compressive strength, wetting–drying cycle stability coefficient, and mass change rate of S10,0.04 were superior to that of S10. The performance of S10,0.04 was very similar to that of S12.

(4) With the increase in the times of the wetting–drying cycles, the surface porosity P and pore diameter d of S10,0.04 showed an overall upward trend, and decreased at the fifth wetting–drying cycle. The pore orientation was weakened, and the changes in pore abundance and fractal dimension were small. The unconfined compressive strength of S10,0.04 was inversely proportional to the pore percentage content of a >10 μm pore diameter, and proportional to the pore percentage contents of a ≤ 1 μm , 1 μm –5 μm , and 5 μm –10 μm pore diameter.

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Nomenclature

XRD	X-ray Diffraction
SEM	Scanning Electron Microscopy
UCS	Unconfined Compressive Strength
d	day

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