Research Article

Strength and Microscopic Characteristics of Slag-Based Geopolymer-Solidified Sludge after Dry–Wet Cycling with Chloride Salt Solutions

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As a new type of green soil-curing agent, geopolymers have the advantages of high strength, good durability, and low carbon emissions, and slag is widely used as a common geopolymer precursor in geopolymer production. Therefore, it is important to investigate the strength and durability of slag-based polymer-solidified sludge under the action of dry–wet cycling with chloride salt solutions. After curing the slag-based polymer-solidified sludge with NaOH (NO), Na_2SiO_3 (NS), and calcium carbide slag (CS) as alkali excitants to different curing ages (7, 14, 28 days), experiments involving different numbers of dry–wet cycles (0, 5, 10, 20, 30) with NaCl solutions of different concentrations (0%, 5%, 10%) were performed to investigate the unconfined compressive strength and micromorphology of the solidified sludge after undergoing dry–wet cycling. The test results showed that the strength of sludge cured with NO for 7 and 14 days showed a trend of increasing and then decreasing with an increasing number of dry–wet cycles, and the strength of sludge cured with NO for 28 days showed a trend of gradually decreasing with an increasing number of dry–wet cycles. The order of the resistance of sludge cured with the three excitants to the effect of the dry–wet cycles of chlorine salt was CS > NO > NS. After the dry–wet cycling, small cracks appeared on the surface of the NS-cured soil, the surface of the NO-cured soil was intact, and a small amount of surface peeling was observed for the CS-cured soil. Scanning electron microscopy test results showed that the chloride salt dry–wet cycles caused the formation of pores and cracks in the soil, and NaCl crystallization and Friedel's salt production were observed in the soil, thus reducing the strength of the solidified sludge.

1. Introduction

There is a large amount of sludge in coastal areas, and sludge is generally characterized by high water content, high compressibility, low strength, and poor permeability, so sludge generally cannot be directly used in engineering construction and requires hardening treatment [1]. At present, silicate cement and quicklime are commonly used as curing agents in the curing of sludge, but both have disadvantages such as high energy consumption, high carbon emissions, and unsatisfactory reinforcing effects, so it is important to find an environmentally friendly curing agent that can replace cement [2]. Geopolymers are inorganic cementitious materials formed by the arrangement of active silica-aluminides with silica aluminate-rich industrial solid wastes as precursors in the

presence of alkaline exciters [3]. The precursors used for the synthesis of geopolymers are mostly industrial wastes such as slag, fly ash, and red mud. The most commonly used alkaline exciters are NaOH, Na_2SiO_3, and KOH. Compared with ordinary silicate cement, geopolymers can not only reduce carbon emissions by 70% but also have the advantages of high early strength, low permeability, and resistance to chemical ion attack [4–6]. In recent years, many scholars have conducted a series of studies on geopolymer-cured soils, and many results have been achieved. Yi et al. [7] used NaOH, Na_2CO_3, and Na_2SiO_3 to excite slag and calcium carbide slag to cure soft soils, and the test results showed that Na_2CO_3 excitation was the least effective and Na_2SiO_3 excitation was the most effective, and NaOH caused a decrease in the strength of the cured soil. Phummiphan et al. [8] investigated the effect

(a)   (b)   (c)

FIGURE 1: Sludge used in the experiment. (a) Air-dried sludge. (b) Sludge ground with a 2 mm sieve. (c) Microscopic diagram of sludge.

TABLE 1: Basic physical properties of sludge.

Natural water content (%)	Relative density	Density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Liquidity index	Viscous particle content (%)	Powder particle content (%)	Sand content (%)
41.2	2.66	1.65	35.22	19.64	1.47	22.14	47.54	30.32

of varying the ratio of Na_2SiO_3 and NaOH on the unconfined compressive strength (UCS) of geopolymer-cured soils. The results showed that the UCS of geopolymer-cured soil reached a maximum at 7.143 MPa when $Na_2SiO_3 : NaOH = 9 : 1$, while the UCS of geopolymer-cured soil reached a minimum at 5.126 MPa when $Na_2SiO_3 : NaOH = 5 : 5$. Lv et al. [9] analyzed the effect of water glass, lime, and water glass + lime on the UCS of fly ash-based cured saline soils, and the results showed that the improvement in the UCS of the geopolymer-cured soils decreased in the order of water glass + lime, lime, and water glass. Arulrajah et al. [10] studied the effect of geopolymer precursor admixture on the strength of cured soils and found that the optimum admixture of geopolymer precursor was 20% and that more or less than 20% had a negative effect on the strength of the cured soils. Others have investigated the durability of geopolymer-cured soils in terms of resistance to freeze–thaw cycles, dry and wet conditions, and chemical ion attack. Sahoo and Singh [11] found that the mass loss of slag-based polymer-cured soil increased with the number of freeze–thaw cycles, with the maximum mass loss of the specimen occurring after the first freeze–thaw cycle, and then the rate of mass loss gradually decreased with an increasing number of freeze–thaw cycles. Noolu et al. [12] found that the strength of slag-based polymer-cured soil was reduced by only 10% after 12 dry–wet cycles, which significantly improved the resistance of the expanded soil to dry–wet cycles. Jiang et al. [13] compared the durability of geopolymer-cured soil and cement-cured soil under sulfate attack and showed that after 120 days of immersion in Na_2SO_4 solution, the surface of the geopolymer-cured soil was intact without cracks, while significant cracks were present on the surface of the cement-cured soil. In recent years, research on the durability of geopolymer-cured soils has mainly been conducted with a single variable condition,

and less research has been conducted on the durability of geopolymers under the coupling effect of multiple factors.

Based on this, the present study took slag-based geopolymer-solidified sludge as the research object, an unconfined compressive strength test and scanning electron microscope (SEM) test of slag-based geopolymer-solidified sludge under the action of dry and wet chloride cycle erosion were conducted, the strength change law and fine view characteristics of solidified sludge under the action of chlorine salt dry–wet cycles were analyzed, and the mechanical property evolution law of slag-based geopolymer-solidified sludge soil under the action of dry–wet chloride cycle erosion was revealed to perform a comprehensive assessment of the mechanical properties of ground geopolymer-solidified sludge in a complex engineering geological environment.

2. Materials and Methods

2.1. Raw Materials. The sludge was taken from a construction site pit at a depth of 0–5 m. The appearance of the sludge was gray–black, and plastic flow was used to dry the retrieved soil through a 2 ml sieve, as shown in Figure 1. Then, the soil was poured into a sealed bag and stored. The basic physical indicators of the sludge are shown in Table 1. The chemical composition is given in Table 2.

The blast furnace slag used in the test was supplied by a mining company in Henan Province as a gray powder. The chemical composition is given in Table 2. The blast furnace slag used in the test is shown in Figure 2(a).

The alkali exciters were NaOH solution, Na_2SiO_3 solution, and calcium carbide slag. Na_2SiO_3 was supplied by Henan Plutonium Run New Material Co., Ltd. The total alkali and total silica content of the anhydrous sodium silicate was ≥94%, NaOH was provided by Xinjiang Zhongtai

TABLE 2: Chemical composition of sludge, blast furnace slag, and calcium carbide slag.

Raw materials	Chemical composition and content (%)						
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	TiO_2
Sludge	70.68	15.36	1.18	4.59	0.95	0.53	1.24
Slag	35.68	17.03	34.89	0.49	6.28	1.63	0.53
Calcium carbide slag	5.69	3.68	67.84	0.56	0.31	0.22	0.32

(a)

(b)

(c)

(d)

FIGURE 2: Blast furnace slag and alkaline exciter used in the experiment. (a) Blast furnace slag. (b) Na_2SiO_3. (c) Calcium carbide slag. (d) NaOH.

Chemical Co., Ltd. with 98% analytical purity, and calcium carbide slag was provided by a mineral processing plant in Guangdong as a gray–black powder. The chemical composition is given in Table 2. The alkali exciters used in the experiment are shown in Figure 2(b)–2(d). Due to the exotherm of NaOH in water, the NaOH solution was prepared 24 hr before the test.

2.2. Test Scheme. Refer to the dry–wet cycle test method specified in ASTM D48433-88 [14]. Sludge cemented with different alkali exciters (NaOH, Na_2SiO_3, calcium carbide slag) was cured to different curing ages (7, 14, 28 days) and then placed in different concentrations (0%, 5%, 10%) of NaCl solution and 5% Na_2SO_4 solution for different numbers (0, 5, 10, 20, 30) of dry–wet cycles, and then the unconfined compressive strength of the specimens was tested after

the dry–wet cycles. The dry–wet cycle test program is shown in Table 3. To compare the effects of wet and dry cycles and long-term immersion on the strength of solidified sludge, a long-term immersion control test was setup, and the long-term immersion test program is shown in Table 4. The effects of the exciter type, NaCl solution concentration, and number of dry–wet cycles on the mechanical properties and microstructure of the solidified sludge were analyzed. The moisture content of the sludge during the test was 40%, the slag dose was 20% of the dry soil mass, and the alkali exciter dose was 20% of the slag mass.

2.3. Test Apparatus and Test Design

2.3.1. Specimen Preparation and Maintenance. The samples were prepared by dry mixing method, the sieved sludge and the solidified material were mixed evenly, and then the

TABLE 3: Dry–wet cycle test program.

Number	Alkali exciter	Curing age (day)	NaCl solution concentration (%)	Na$_2$SO$_4$ solution concentration (%)	Number of dry–wet cycles
NO	NaOH	7, 14, 28			
NS	Na$_2$SiO$_3$	28	0, 5, 10	0	0, 5, 10, 20, 30
CS	Calcium carbide slag	28			
NO	NaOH	28	0	5	

TABLE 4: Long-term immersion test program.

Number	Alkali exciter	Curing age (day)	NaCl solution concentration (%)	Na$_2$SO$_4$ solution concentration (%)	Long-term immersion time (day)
NO	NaOH	28	0, 5	0	0, 5, 10, 20, 30
			0	5	

(a)   (b)   (c)
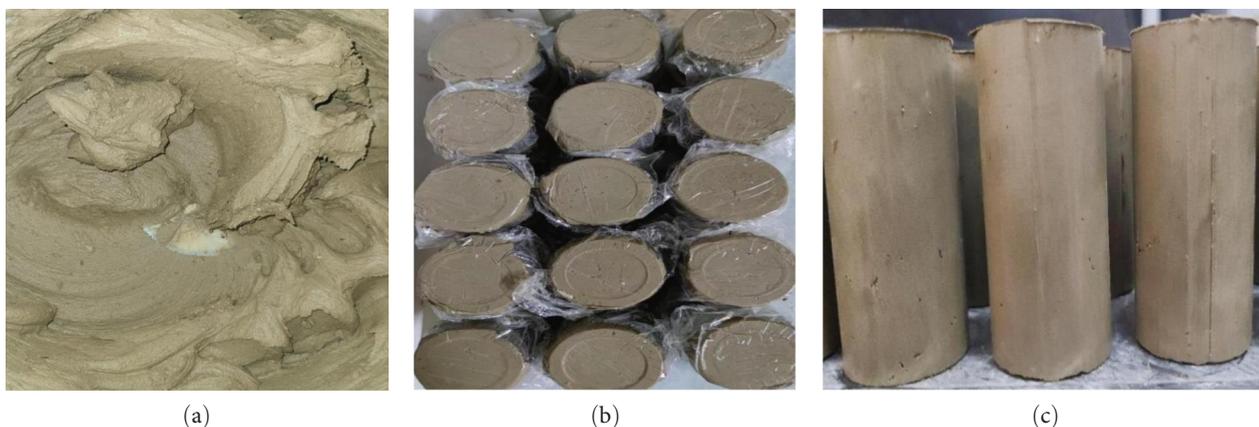
FIGURE 3: Specimen preparation process. (a) Well-mixed solidified sludge. (b) Solidified sludge loaded into the mold. (c) Cured sludge after demolding.

alkaline solution was added to form a mixture of sludge-solidified material. The detailed process of sample preparation is described as follows: (a) According to the required number of samples, the corresponding quality of air-dried soil and ground blast furnace slag was weighed and stirred for 5 min with a hand-shaking mixer; (b) the alkali activator is completely dissolved in water for more than half an hour, and then the completely dissolved alkali activator is slowly poured into the mixed sludge and slag, and then the mixer is stirred again for 5 min to obtain the sludge-curing agent mixed; and (c) the mixed solidified soil was loaded into a cylindrical steel mold with a diameter of 39 mm and a height of 78 mm in five layers by static pressure method. Each layer of cured soil was added and pounded for approximately 2 min to expel gas, and then the surface of the sample was scraped flat with a scraper, covered with plastic cling film to prevent moisture loss, and placed in a cool place for 24 hr before demolding. The sample preparation process is shown in Figure 3. In the test, three specimens were prepared for each group to reduce testing errors. After demolding, the specimens were placed in a constant temperature and humidity maintenance box, and the maintenance conditions were given as follows: maintenance temperature of $20 \pm 0.5°C$; relative humidity ≥95%; and curing ages of 3, 7, 14, and 28 days.

2.3.2. Chlorine Salt Dry–Wet Cycle Test. Specimens that were maintained to a curing age (7, 14, 28 days) were first humidified and then dried, which constituted a dry–wet cycle. In the humidification process, the specimens that reached the maintenance age were placed directly into the erosion solution for humidification, and the humidification time was 12 hr. In the drying process, the specimen immersed in the solution was removed, and the surface of the specimen was dried, and then the specimen was placed in an oven at 40°C for 12 hr to complete a dry–wet cycle.

2.3.3. Compressive Strength Test without Lateral Limit. After a certain number of dry–wet cycles on the WDW-100D universal testing machine for the unconfined compressive strength test, the axial strain rate was set to 1 mm/min. In the analysis of the unconfined compressive strength of the specimens, the average value of the strength of three specimens, the strength of the specimen, and the average value of
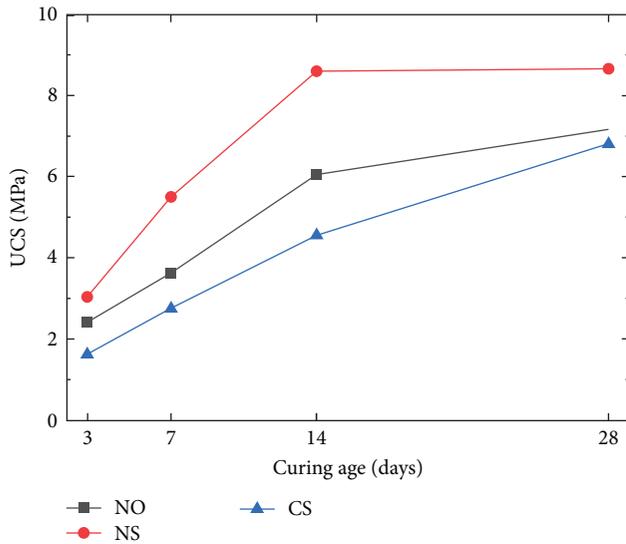
FIGURE 4: Relationship between UCS and curing age.

the difference between more than 10% were first calculated to eliminate outliers, and finally, no less than two specimens were used to calculate the average value of the strength of a group of specimens without lateral limit compressive strength. The average strength of not less than two specimens was taken as the unconfined compressive strength of the group.

2.3.4. Scanning Electron Microscopy (SEM) Test. After the lateral unconfined compressive strength test, specimens with natural sections were selected, and the section size was 1×1 cm. To stop the hydration reaction of the specimens, the specimens were first cooled under liquid nitrogen at a boiling point of $-196°C$ for 30 min and then placed in an oven for 24 hr. The instrument used for SEM experiments was a Hitachi Regulus 8100 field emission scanning electron microscope. As the specimens were not conductive, the surface charge was easy to measure, so the specimens were sprayed with gold before the test.

3. Test Results and Analysis

3.1. Effect of Curing Age on the Strength of Cured Soil. Figure 4 shows the variation law of the strength of NO-, NS-, and CS-solidified sludge with respect to the curing age. The order of the strength of the three types of solidified sludge after a curing age of 28 days was NS > NO > CS, and the strength of NS-solidified sludge with increasing curing age showed a trend of significant growth before plateauing, and the strength of NS-solidified sludge at 28 days reached 8.60 MPa. From 3 to 7 days, the strength increased by 79.67%, and from 7 to 14 days, and the strength increased by 56.93%. After 14 days of curing, the NS-solidified sludge strength reached a maximum, and from 14 to 28 days, the strength remained basically the same. The NO-solidified sludge strength increased rapidly with increasing curing age, and the strength growth rate decreased with increasing curing age. The NO-solidified sludge strength at 28 days reached 7.16 MPa, which was 83.26% of the strength of NS-solidified sludge at 28 days.

From 3 to 7 days, the strength increased by 49.87%. From 7 to 14 days, the strength increased by 68.14%. From 14 to 28 days, the strength increased by 18.37%. After 14 days, the strength increased slowly. The strength of CS-solidified sludge increased approximately linearly with increasing curing age. The strength of CS-solidified sludge cured for 28 days was 6.81 MPa, which was 71.86% of the strength of NS-solidified sludge cured for 28 days. From 3 to 7 days, the strength increased by 70.81%; from 7 to 14 days, the strength increased by 65.45%; and from 14 to 28 days, the strength increased by 49.56%.

The three alkaline exciters increased the strength of polymer-cured slag-based sludge in the order of Na_2SiO_3, NaOH, and calcium carbide slag. This is because Na_2SiO_3 not only provides an alkaline environment to stimulate the activity of the slag but also provides more active $[SiO_4]^{4-}$ to participate in the reaction and thus produce more gelling products. At the same time, the Na_2SiO_3 solution itself is a mineral binder that binds soil particles, making the soil structure denser, so the strength of the NS-cured soil rapidly increased. As the reaction progresses, an increasing amount of gelling products from the soil envelop the unreacted slag, resulting in the reaction not continuing and the strength growth rate decreasing or even going to zero [15, 16]. NaOH can provide a sufficient alkaline environment to fully stimulate the activity of the slag, so that the strength of the NO-cured soil increases more rapidly in the early stages. CS-cured soil mainly depends on the reaction of CaO with water to form $Ca(OH)_2$ to provide an alkaline environment. $Ca(OH)_2$ provides a weaker alkaline environment, and the stimulation of slag activity is not sufficient, so the strength of CS-cured soil increased more slowly.

3.2. Variation Pattern of NO-Solidified Sludge Strength with Dry–Wet Cycles at Different Curing Ages. Figure 5 shows the curves of the strength change law of NO-solidified sludge after dry–wet cycles in solutions with different chloride ion concentrations after 7 and 28 days of curing. Figure 5(a) shows that the 7-day NO-solidified sludge strength increased by 12.94%, 18.90%, and 23.36% after 10 dry–wet cycles in distilled water, 5% NaCl solution, and 10% NaCl solution, respectively. The strength decreased by 14.12% and 23.02% between 10 and 30 dry–wet cycles in 5% NaCl and 10% NaCl solutions, respectively. The strength increased by 3.82% between 10 and 20 dry–wet cycles in distilled water and decreased by 6.28% between 20 and 30 dry–wet cycles in distilled water. After 30 cycles, the order of the strength of NO-solidified sludge in different concentrations of NaCl solution after 7 days of curing was distilled water >5% NaCl solution >10% NaCl solution. The strength of NO-solidified sludge cured for 7 days in different concentrations of NaCl solution after dry–wet cycling showed a trend of increasing and then decreasing with an increasing number of dry–wet cycles. This is because the degree of hydration reaction in the solidified sludge for 7 days was low, and the unreacted cementitious material was in contact with sufficient moisture in the process of dry–wet cycling, which promoted the hydration reaction in the cured soil. As the
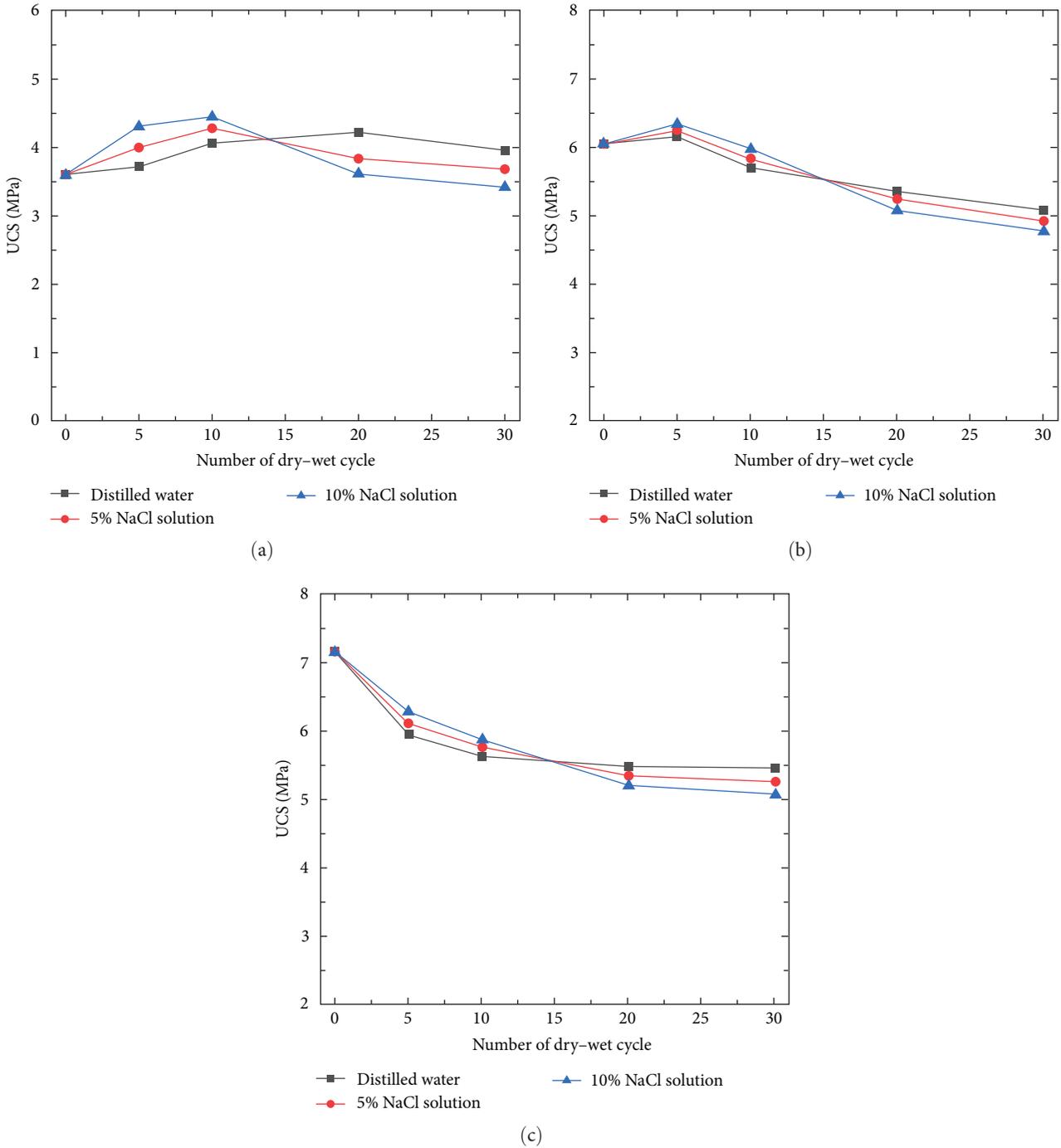
(a)

(b)

(c)

FIGURE 5: UCS of NO-solidified sludge versus the number of dry–wet cycles. (a) 7 days of curing. (b) 14 days of curing. (c) 28 days of curing.

number of dry-wet cycles increases, the hydration reaction in the soil gradually weakened, and the erosion by moisture in the soil cracks dominated, leading to the destruction of the cementation system in the soil and resulting in the loss of strength of the cured soil. With the higher concentration of NaCl in the dry–wet cycle solution, the strength increase rate of the NO-solidified sludge at 7 days in the early stage of dry–wet cycling was also faster, and at the same time, the strength reduction rate in the late stage of dry–wet cycling was also faster. This is because during the wetting process of

solidified sludge in dry–wet cycling, the NaCl solution enters the soil through the tiny cracks in the soil body, and during the drying process, the water in it volatilizes out through the pores in the soil body, while the NaCl in the solution remains in the soil. With dry–wet cycling, a large amount of NaCl crystallizes inside the soil, increasing the compactness of the soil and, thus, increasing the strength of the NO-solidified sludge. As the number of dry–wet cycles continues to increase, more and more NaCl crystallizes inside the sample cycled in the chloride salt solution, and the NaCl crystals
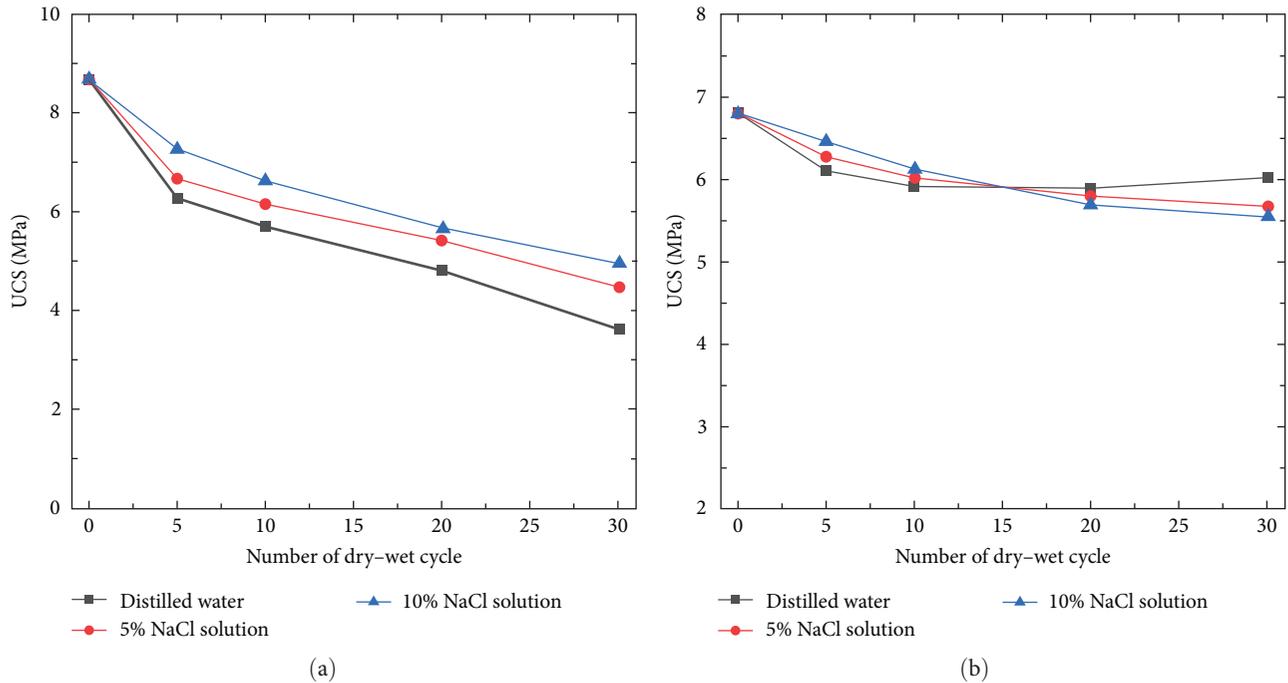
FIGURE 6: UCS of NS- and CS-solidified sludge versus the number of wetting and drying cycles. (a) NS-solidified sludge. (b) CS-solidified sludge.

wrap around the surface of the soil and slag, preventing the hydration reaction and affecting the increase in the cured soil strength. At the same time, more and more NaCl crystals produce crystalline swelling force inside the soil, thus reducing the strength of cured soil.

As shown in Figure 5(b), the strength of the NO-solidified sludge after 14 days of curing first increased and then decreased with an increasing number of dry–wet cycles with the three solutions. The strength of NO-solidified sludge curing in distilled water, 5% NaCl solution, and 10% NaCl solution increased by 1.66%, 3.17%, and 4.94%, respectively, after five dry–wet cycles for 14 days. The strength of NO-solidified sludge cured in distilled water, 5% NaCl solution, and 10% NaCl solution decreased with an increasing number of dry–wet cycles after five dry–wet cycles for 14 days. The intensity decreased by 17.57%, 21.31%, and 24.85% after 5–30 dry–wet cycles in distilled water, 5% NaCl solution, and 10% NaCl solution, respectively. The strength of the NO-solidified sludge cured for 14 days showed the same overall trend as that of the NO-solidified sludge cured for 7 days. The difference was that the strength of the 7-day NO-solidified sludge increased with the number of dry–wet cycles for the first 10 cycles and decreased with the number of dry–wet cycles from 10 to 30 cycles. In contrast, the strength of the 14-day NO-solidified sludge increased with the number of dry–wet cycles only after five cycles and decreased with the number of dry–wet cycles from 5 to 30 cycles. This is because the hydration reaction of the solidified sludge at 14 days was already prominent, and for the five cycles, sufficient moisture drove the hydration reaction in a positive direction to some extent. As the degree of the hydration reaction in the soil became increasingly higher, the erosive effect of moisture

and Cl⁻ on the soil dominated, and the strength of the solidified sludge then decreased.

As shown in Figure 5(c), the strength of the solidified sludge after 28 days of curing was gradually reduced with an increasing number of dry–wet cycles in all three solutions, and the strength of the NO-solidified sludge after 28 days was reduced by 21.33%, 19.50%, and 17.93% after 10 dry–wet cycles in distilled water, 5% NaCl solution, and 10% NaCl solution, respectively, and after 10–30 dry–wet cycles, the strength was reduced by 3.17%, 8.79%, and 13.60%, respectively. The strength reduction rate of NO-solidified sludge decreased with an increasing number of dry–wet cycles, and the order of the strength of NO-solidified sludge in different concentrations of NaCl solution after 30 dry–wet cycles for 28 days of curing was distilled water >5% NaCl solution >10% NaCl solution, which was consistent with the pattern of NO-solidified sludge after 30 dry–wet cycles for 7 days of curing. This is because the sample after 28 days of maintenance was highly hydrated, the erosion of the dry–wet cycle dominated, and the strength of the solidified sludge decreased with an increasing number of dry–wet cycles, while the solidified sludge cycled in NaCl solution was not only subject to the erosion of water but also to the erosion of Cl⁻ ions in the solution and the crystallization expansion force generated by NaCl crystallization inside the soil; therefore, the strength of NO-solidified sludge after 30 dry–wet cycles decreased with increasing NaCl concentration in the solution.

3.3. Strength of NS- and CS-Solidified Sludge. Figure 6 shows the variation pattern of strength with the number of dry–wet cycles for NS- and CS-solidified sludge after 28 days of curing in different concentrations of NaCl solution. As shown in

Figure 6(a), the strength of NS-solidified sludge continued to decrease uniformly with an increasing number of dry–wet cycles in different concentrations of NaCl solution, and the strength of NS-solidified sludge cured for 28 days decreased by 58.01%, 48.16%, and 42.34% after 30 cycles in distilled water. The order of the strength of NS-solidified sludge after 30 cycles in different concentrations of NaCl solution was 10% NaCl solution >5% NaCl solution > distilled water, which was different from the pattern exhibited by NO-solidified sludge. This is due to the poor water stability of Na_2SiO_3, which plays some binding role in NS-solidified sludge and is easily dissolved in water. During the dry–wet cycling, a large amount of Na_2SiO_3 dissolved in the water, thus creating more pores inside the soil, which significantly reduced the strength of NS-solidified sludge, while NaCl crystals were produced inside the specimens in NaCl solution, and these NaCl crystals occupied part of the space within the pores, making the internal pores of NS-solidified sludge relatively smaller. It makes the internal structure of NS-solidified sludge circulated dry–wet in NaCl solution more dense than NS-solidified sludge circulated in distilled water, resulting in the strength of NS-solidified sludge after cycling in NaCl solution being higher than that after cycling in distilled water.

As shown in Figure 6(b), the strength of CS-solidified sludge gradually decreased with the number of dry–wet cycles, and the strength of CS-solidified sludge cured for 28 days decreased by 11.32%, 16.76%, and 18.53% after 30 cycles in distilled water, 5% NaCl solution, and 10% NaCl solution, respectively, and by 53% after 30 cycles of distilled water, 5% NaCl solution, and 10% NaCl solution, respectively. The strength of CS-solidified sludge for 28 days decreased after 30 cycles in different concentrations of NaCl solution. The order of the strength was distilled water >5% NaCl solution >10% NaCl solution, which was the same pattern as that of NO-solidified sludge. It is worth noting that when the number of cycles was increased from 20 to 30, the strength of CS-solidified sludge after dry–wet cycles in distilled water appeared to increase slightly, while that in NaCl solution continued to decrease slowly because as the dry–wet cycle test progressed, the erosive effect of the dry–wet cycle led to a decrease in specimen strength, and at the same time, the erosive effect led to an increase in the surface voids of the specimens, some of the structures fell off, and the specimens failed. The unreacted gelling material inside the specimen came into contact with moisture and underwent a hydration reaction, resulting in some increase in the strength of the specimen, while NaCl crystals formed inside the specimen cycled in NaCl solution, and the NaCl crystals enveloped the unreacted gelling material and inhibited the hydration reaction. A comparative analysis of Figures 5(c), 6(a), and 6(b) shows that the strength loss of NO- and CS-solidified sludge mainly occurred in the first 10 cycles, and the reduction rate gradually decreased from the 10th to the 30th cycle, while the reduction rate of NS-solidified sludge strength with the number of dry–wet cycles remained basically the same.

3.4. Strength Change Patterns of Different Solidified Sludge under the Action of Dry–Wet Cycles of Chloride Salt.

Figure 7 shows the variation pattern of strength with the number of dry–wet cycles for NO-, NS-, and CS-solidified sludge after 28 days of curing in NaCl solutions of different concentrations. As shown in Figure 7(a)–7(c), the strength of the three NO-, NS-, and CS-solidified sludge decreased by 23.9%, 58.3%, and 11.5% after 30 cycles in distilled water, with strengths of 5.4, 3.61, and 6.03 MPa, respectively. The strength of NS-solidified sludge after cycling was much lower than that of NO- and CS-solidified sludge, and after 30 cycles in 5% NaCl solution, the strength of the three solidified sludge decreased by 26.5%, 48.5%, and 16.8%, with strengths of 5.26, 4.46, and 5.66 MPa, respectively, and after 30 cycles in 10% NaCl solution, the strengths of the three solidified sludge were reduced by 29.1%, 42.7%, and 18.6%, with strengths of 5.08, 4.96, and 5.54 MPa, respectively. The strength of NS-solidified sludge after cycling in NaCl solution was still lower than that of NO- and CS-solidified sludge. It was found that the strength of solidified sludge with different alkali exciters varied with the number of dry–wet cycles. The strength of NO-solidified sludge after cycling in both distilled water and NaCl solution showed a rapid decrease and then a slow decrease with an increasing number of dry–wet cycles. The strength of NS-solidified sludge after cycling in distilled water and NaCl solution decreased uniformly and rapidly with an increasing number of dry–wet cycles, and the strength after cycling in distilled water was lower than that after cycling in NaCl solution. The strength of CS-solidified sludge in distilled water showed a tendency to first decrease and then slightly increase with an increasing number of dry–wet cycles, while the strength of CS-solidified sludge showed the same pattern as that of NO-solidified sludge after dry–wet cycling in NaCl solution: both showed a rapid decrease and then a slow decrease with an increasing number of dry–wet cycles. The strength of CS-solidified sludge showed a rapid decrease and then a slow decrease with an increasing number of dry–wet cycles. A comparative analysis of Figure 7(a)–7(c) showed that the order of the strength of the three types of solidified sludge without dry–wet cycling after 28 days of curing was NS > NO > CS. After 30 dry–wet cycles in NaCl solutions of different concentrations, the order of the strength of the three types of solidified sludge was CS > NO > NS, indicating the resistance of the slag-based polymer-solidified sludge to chlorine salt dry–wet cycling. The ability of the slag-based polymer-solidified sludge to resist the erosion of chlorine salt dry–wet cycling was related to the type of alkali exciter. The order of the resistance of the three alkali exciter-initiated slag-based polymer-solidified sludge to the erosion of chlorine salt dry–wet cycling was calcium carbide slag > NaOH > Na_2SiO_3.

3.5. Effect of Erosion Mode on the Strength of Solidified Sludge.

Figure 8(a)–8(c) shows the variation patterns of strength with erosion time for the 28-day NO-solidified sludge under long-term immersion in distilled water, 5%
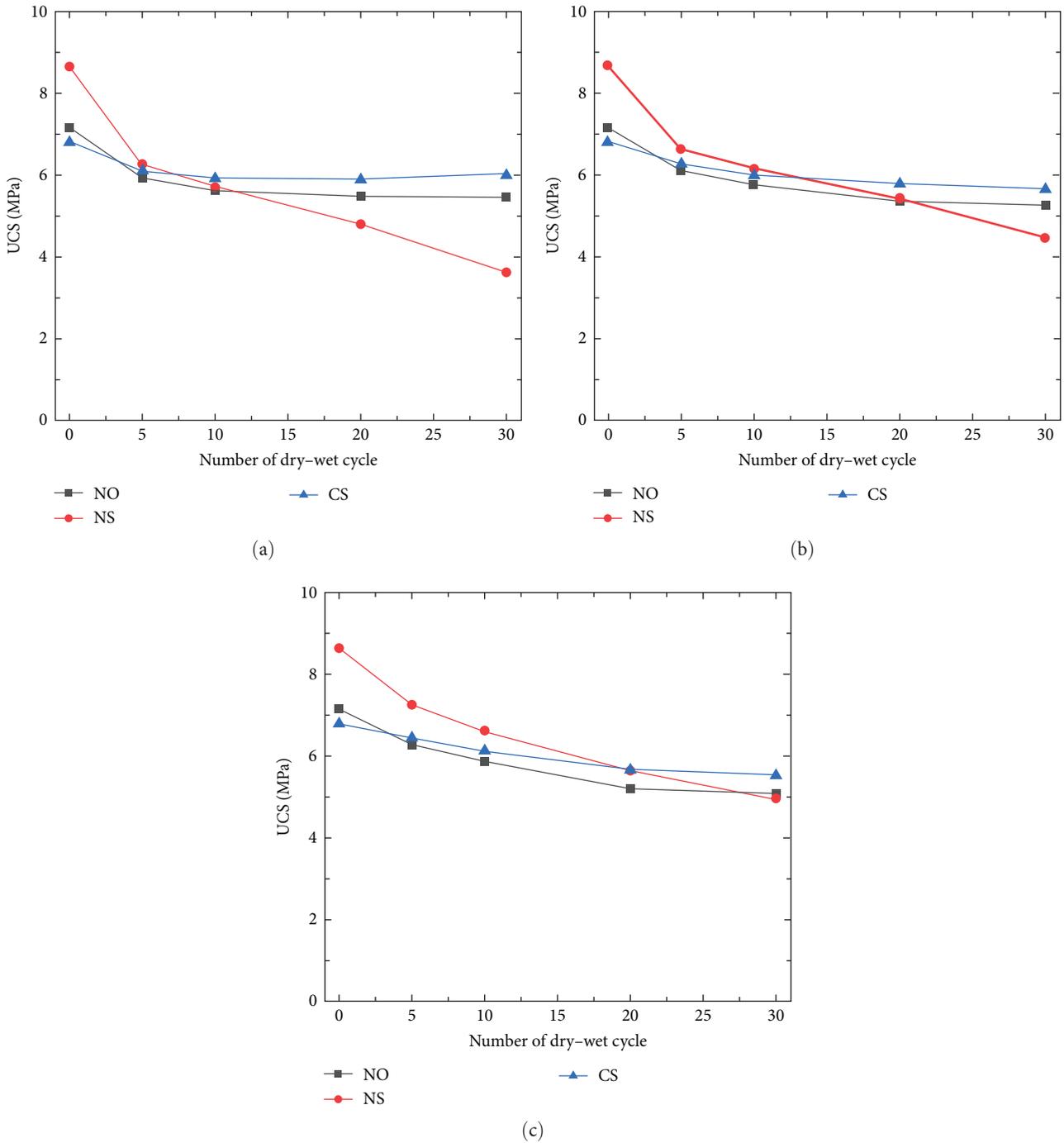
FIGURE 7: UCS of solidified sludge versus the number of dry–wet cycles in different solutions. (a) Dry–wet cycling in distilled water. (b) Dry–wet cycling in 5% NaCl solution. (c) Dry–wet cycling in 10% NaCl solution.

NaCl solution, and 5% Na_2SO_4 solution and dry–wet cycling, respectively. As shown in Figure 8(a), the strength of NO-solidified sludge showed a trend of increasing and then decreasing with increasing immersion time when immersed in distilled water, while the strength of solidified sludge decreased with an increasing number of dry–wet cycles in distilled water, and the rate of decrease was reduced with an increasing number of dry–wet cycles. The strength of 28-day NO-solidified sludge after 30 days of soaking in distilled

water was 7.89 MPa, which increased by 10.21% compared to that before immersion, and the strength of 28-day NO-solidified sludge after 30 dry–wet cycles in distilled water was 5.46 MPa, which decreased by 23.73% compared to that before the dry–wet cycling. As shown in Figure 8(b), when NO-solidified sludge was soaked in the 5% NaCl solution, the strength showed a trend of increasing and then decreasing with increasing soaking time, while the strength decreased with an increasing number of dry–wet cycles, and this
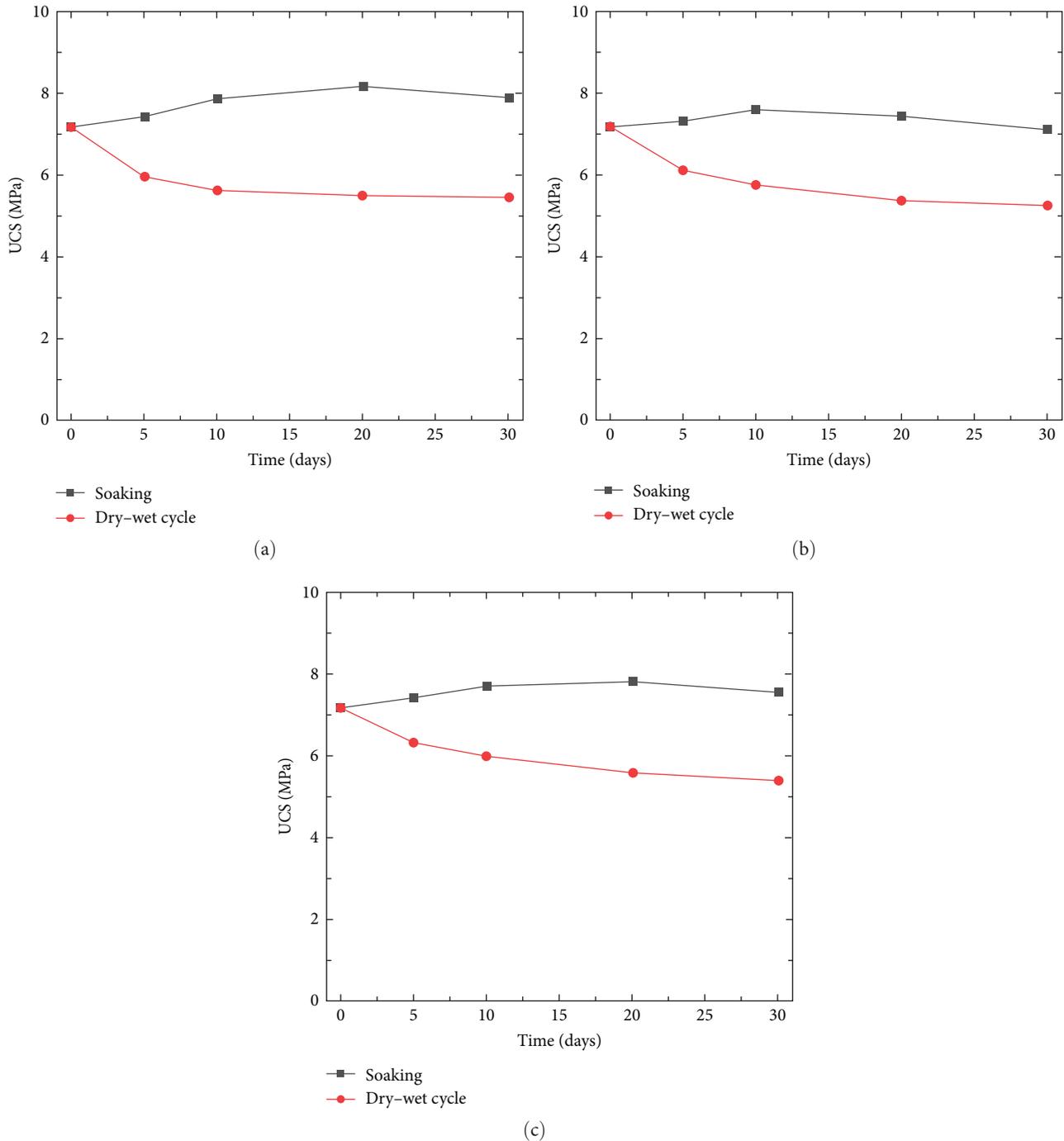
(a)

(b)

(c)

FIGURE 8: Variation pattern of UCS of 28-day NO-solidified sludge with erosion time. (a) Distilled water. (b) 5% NaCl solution. (c) 5% Na_2SO_4 solution.

change pattern was the same as that in distilled water. The strength of 28-day NO-solidified sludge after 30 days of immersion in 5% NaCl solution was 7.10 MPa, which was 0.82% lower than that before immersion, and the strength of 28-day NO-solidified sludge after 30 dry–wet cycles in 5% NaCl solution was 5.26 MPa, which was 26.53% lower than that before the dry–wet cycling. As shown in Figure 8(c), the strength of the solidified sludge immersed and cycled in 5% Na_2SO_4 varies with erosion time changed in the same pattern

as that in both distilled water and 5% NaCl solution: the strength decreased with the number of dry–wet cycles, and the strength increased and then decreased with increasing immersion time. The strength of 28-day NO-solidified sludge after 30 days immersion in 5% Na_2SO_4 solution was 7.53 MPa, which increased by 5.18% compared to that before immersion, and the strength of 28-day NO-solidified sludge after 30 dry–wet cycles in 5% Na_2SO_4 solution was 5.38 MPa, which decreased by 24.85% compared to that before the
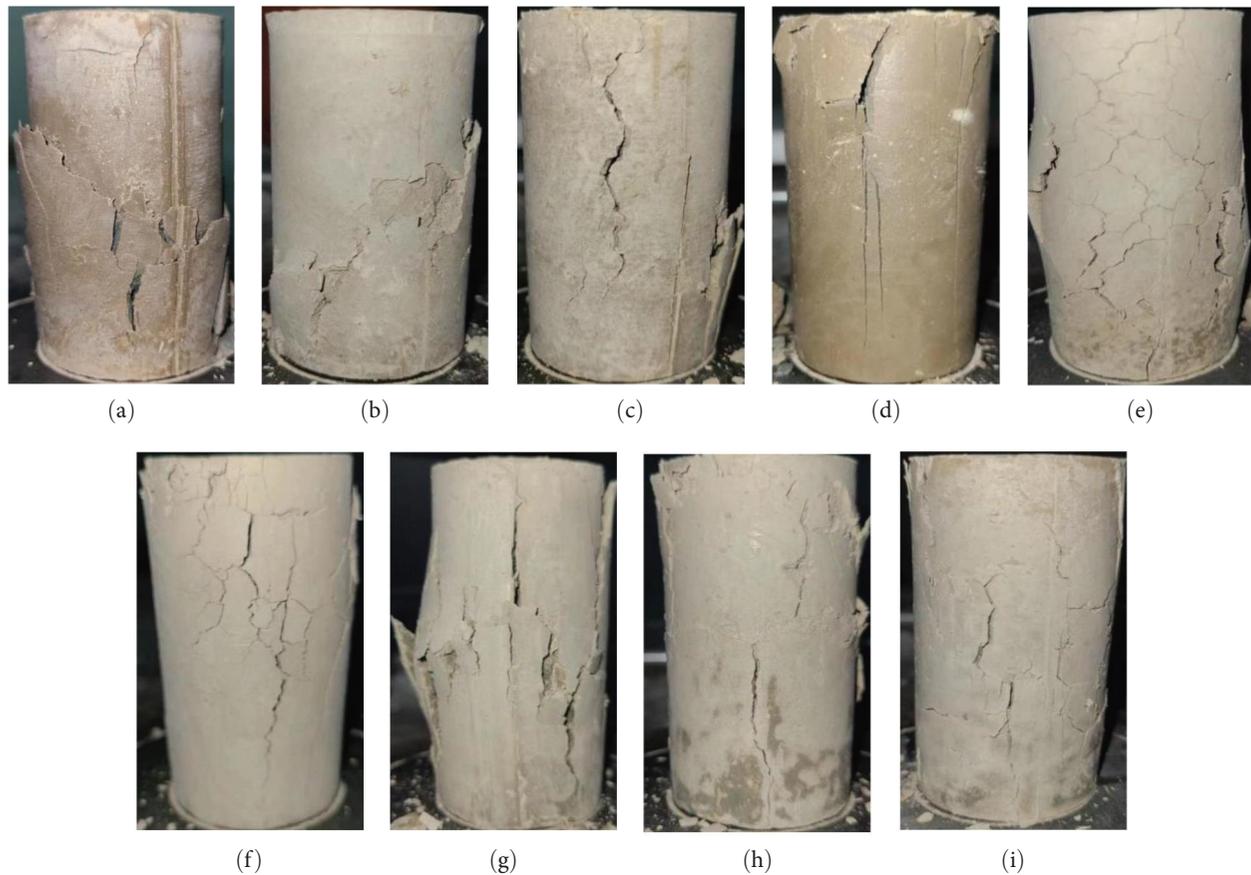
FIGURE 9: Failure characteristics of NO-, NS-, and CS-solidified sludge before and after dry–wet cycling. (a) 28-day NO-solidified sludge. (b) 28-day NO-solidified sludge after 30 dry–wet cycles in distilled water. (c) 28-day NO-solidified sludge after 30 dry–wet cycles in 10% NaCl solution. (d) 28-day NS-solidified sludge. (e) 28-day NS-solidified sludge after 30 dry–wet cycles in distilled water. (f) 28-day NS-solidified sludge after 30 dry–wet cycles in 10% NaCl solution. (g) 28-day CS-solidified sludge. (h) 28-day CS-solidified sludge after 30 dry–wet cycles in distilled water. (i) 28-day CS-solidified sludge after 30 dry–wet cycles in 10% NaCl solution.

dry–wet cycling. It was found that for the slag-based polymer-solidified sludge in the same solution for immersion and dry–wet cycling, the strength change pattern was very different; the strength after immersion slightly increased, while the strength after dry–wet cycling significantly decreased. This is because in the dry–wet cycling, during the wetting and drying of the soil, the internal network of the soil was filled with water during the wetting process, while during the drying process, the CO_2 in the air reacted with the water and the soil to carbonize, resulting in a reduction in the strength of the hardened sludge. Additionally, the solidified sludge in NaCl solution and Na_2SO_4 solution crystallized inside the soil during the dry–wet cycling and generated crystalline swelling forces. Friedel's salt inside the samples cycled in NaCl solution and caliche inside the samples cycled in Na_2SO_4 solution formed with dry–wet cycling, both of which generated crystalline swelling forces inside the soil, resulting in a reduction in the strength of the solidified sludge. In the process of soaking, the solidified sludge was in contact with a sufficient amount of water, which promoted the positive progress of the ceased hydration reaction, resulting in the increase of the strength of the solidified sludge, and at the same time, the soaking process isolated the CO_2 in the air, so the CO_2 could

not enter the inside of the soil and the carbonation reaction could not be carried out, so the strength of the solidified sludge slightly increased after 30 days of soaking. Samantasinghar et al. [17] found that the strength of slag fly ash-based polymers only decreased by 2.87%, 5.17%, and 8% after 365 days of immersion in H_2SO_4, NaOH, and NaCl solutions, respectively, indicating that the erosive effect of Cl^- on the geopolymer-solidified sludge was greater than that of SO_4^{2-} and that the strength loss of geopolymer-solidified sludge after long-term immersion in the solution was less, which is consistent with the results obtained in this study.

3.6. Damage Characteristics of Cured Soil under Dry–Wet Cycles of Chloride Salt. Figure 9 shows the damage characteristics of NO-, NS-, and CS-solidified sludge before and after dry–wet cycling. Figure 9(a) shows the damage characteristics of NO-solidified sludge cured for 28 days without dry–wet cycling. The surface of the NO-solidified sludge was intact and dense before cycling, and the surface color of the specimen was darker. Figure 9(b) shows the damage characteristics of NO-solidified sludge after 30 dry–wet cycles in distilled water for 28 days. Even after 30 dry–wet cycles in distilled water, there were no obvious cracks on the surface of the

specimens and no disintegration. The surface of the specimen after 30 wet–dry cycles in distilled water became lighter in color compared to the surface of the specimen without the dry–wet cycling, probably because the water soluble components on the surface of the specimen dissolved in water during the dry–wet cycling process. However, as the structure of the geopolymer-solidified sludge at the slag base was relatively dense, the dry–wet cycling did not cause significant structural damage to the soil, so the surface of the soil still appeared relatively dense. Figure 9(c) shows the specimens of NO-solidified sludge after 30 dry–wet cycles in 10% NaCl solution after 28 days of curing. The surface color of the specimens after 30 dry–wet cycles in the 10% NaCl solution also became lighter compared to that of the specimens that did not undergo dry–wet cycling. The surface color of the samples cycled in 10% NaCl solution was darker than that of the samples cycled in distilled water. The surface of the specimen after dry–wet cycling in 10% NaCl solution also had no obvious cracks or epidermal peeling phenomenon, and the darkening of the surface color may have been due to the crystallization of NaCl on the surface of the specimen during the dry–wet cycling. Figure 9(d) shows the damage characteristics of NS-solidified sludge without dry–wet cycling after 28 days of curing, and it was found that the surface of NS-solidified sludge was smoother than that of NO-solidified sludge. Figure 9(e) shows the damage characteristics of NS-solidified sludge after 30 dry–wet cycles in distilled water for 28 days of maintenance. After 30 dry–wet cycles of NS-solidified sludge in distilled water, many cracks appeared on the surface, and the cracks were uniformly distributed on the specimens, which also bulged and cracked preferentially from the cracks during uniaxial compression damage. Figure 9(f) shows the damage characteristics of NS-solidified sludge after 30 dry–wet cycles in 10% NaCl solution. There were still many cracks on the surface of the specimen, and there were more cracks on the surface of NS-solidified sludge after dry–wet cycling in distilled water than after dry–wet cycling in 10% NaCl solution. This is because the Na_2SiO_3 solution itself is a mineral binder that not only provides an alkaline environment to stimulate the activity of the slag in the geopolymer-cured soil but also binds the soil particles, thus improving the strength of the cured soil. However, Na_2SiO_3 has poor water resistance and is easily dissolved in water. During the dry–wet cycling, the Na_2SiO_3 that played a binding role in NS-solidified sludge dissolved in water, creating pores in the soil, and as an increasing number of pores were created in the solidified sludge, an increasing number of cracks were created in the solidified sludge. While Na_2SiO_3 in NS-cured soil also dissolved in NaCl solution with dry–wet cycling, the dry–wet cycling caused the NaCl in solution to crystallize inside the specimen, and part of the NaCl crystallization filled the void left by the dissolution of Na_2SiO_3, so the fine cracks on the surface of the specimen after dry–wet cycling in NaCl solution were fewer than those on the surface of the specimen after cycling in distilled water. Figure 9(g) shows the damage characteristics of 28-day CS-solidified sludge without dry–wet cycling. The surface color of 28-day CS-solidified sludge was lighter than that of NO- and NS-solidified sludge. Figure 9(h)

shows the damage characteristics of CS-solidified sludge after 30 dry–wet cycles in distilled water. It was found that the surface of CS-solidified sludge after 30 cycles in distilled water did not show any obvious cracks, but the surface crumb of the specimens peeled off. Figure 9(i) shows the damage characteristics of CS-solidified sludge after 30 dry–wet cycles in 10% NaCl solution. It was found that the surface of the specimens cycled in 10% NaCl solution also showed crumb peeling, but the area peeled off was larger for the specimens after 30 cycles in distilled water than for the specimens after 30 cycles in 10% NaCl solution. This may have been because salt crystals were produced inside the samples cycled in 10% NaCl solution, and these salt crystals filled the pores inside the soil to some extent, making the soil structure denser. On the other hand, no salt crystals were produced inside the samples cycled in distilled water, so the epidermal peeling of the samples after 30 cycles in 10% NaCl solution was less than that of the samples cycled 30 times in distilled water. All three types of solidified sludge broke along one of the major interfaces when they broke before the dry–wet cycles. When the NO-solidified sludge broke after the dry–wet cycles, the number of cracks produced increased; when the NS-solidified sludge broke after the dry–wet cycles, the specimens cracked along the cracks produced in the dry–wet cycles; and when the CS-solidified sludge broke after the dry–wet cycles, the number of cracks produced also increased.

4. Microscopic Mechanism

To analyze the effects of different factors on the micromorphology of the solidified sludge under the action of dry–wet cycling, SEM technology was used on NO-, NS-, and CS-solidified sludge before and after dry–wet cycling in different concentrations (0%, 10%) of NaCl solutions after 28 days of curing, as shown in Figure 10. Figures 10(a), 10(d), and 10(g) show the electron microscope scans of NO-, NS-, and CS-solidified sludge after 28 days of curing, respectively. The solidified sludge had a relatively dense internal structure, and the soil surface was cross-covered by a large amount of hydrated calcium silicate aluminate (C-A-S-H) gel and a small amount of hydrated sodium silicate aluminate (N-A-S-H) gel, which increased the structural compactness of the soil. Figure 10(b) shows the micrographs of the specimens after 30 dry and wet cycles in distilled water for the NO-solidified sludge cured for 28 days. From the previous work, it was clear that the strength of the NO-solidified sludge decreased by 23.76% after 30 cycles in distilled water for 28 days. It was found that cracks and pores appeared on the NO-solidified sludge after 30 cycles in distilled water. This may have been due to the erosive effect of the dry–wet cycles, which destroyed the otherwise dense structure, leading to a reduction in the strength of the solidified sludge. Figure 10(c) shows the micrographs of the specimens after 30 dry–wet cycles in 10% NaCl solution for NO-solidified sludge cured for 28 days. It was observed that there were fewer pores and cracks in the specimens cycled in NaCl solution compared to those in the solidified sludge cycled in distilled water. The structure was still loose compared to
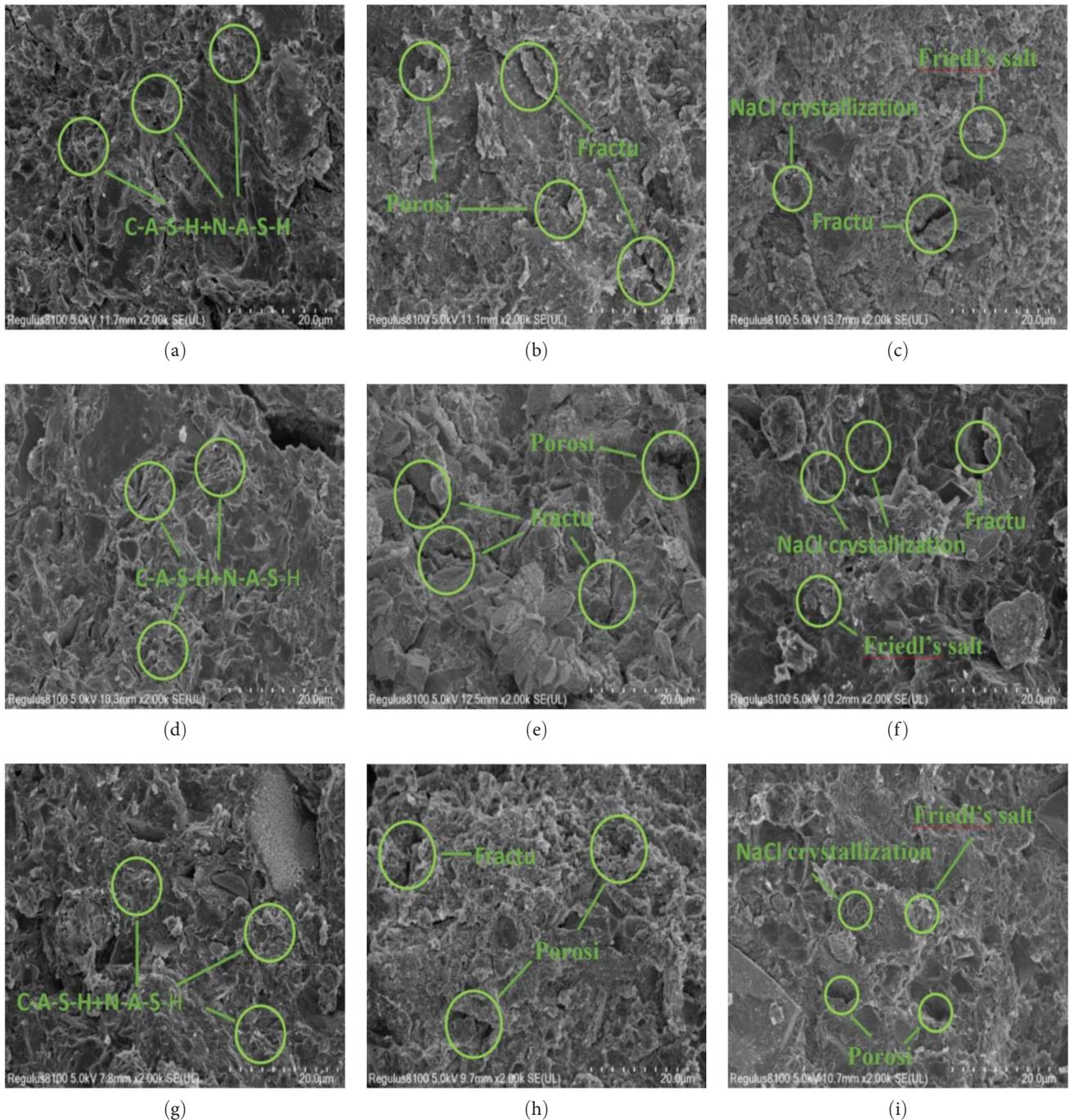
FIGURE 10: SEM image of solidified sludge before and after dry–wet cycling. (a) 28-day NO-solidified sludge. (b) 28-day NO-solidified sludge after 30 dry–wet cycles in distilled water. (c) 28-day NO-solidified sludge after 30 dry–wet cycles in 10% NaCl solution. (d) 28-day NS-solidified sludge. (e) 28-day NS-solidified sludge after 30 dry–wet cycles in distilled water. (f) 28-day NS-solidified sludge after 30 dry–wet cycles in 10% NaCl solution. (g) 28-day CS-solidified sludge. (h) 28-day CS-solidified sludge after 30 dry–wet cycles in distilled water. (i) 28-day CS-solidified sludge after 30 dry–wet cycles in 10% NaCl solution.

that of the hardened sludge that had not undergone dry–wet cycling. The formation of NaCl crystals and Friedel's salts was observed in the solidified sludge after dry–wet cycling in 10% NaCl solution. It was found in a previous paper that the strength of the NO-solidified sludge decreased by 29.10% after 30 cycles in 10% NaCl solution for 28 days. The strength of the solidified sludge cycled in 10% NaCl solution was

reduced more than that of the solidified sludge cycled in distilled water. This was due to the crystalline swelling force generated by NaCl crystals and Friedel's salt crystals within the solidified sludge. Figure 10(e) shows the micrographs of the specimens after 30 dry–wet cycles in distilled water for the NS-solidified sludge cured for 28 days. In the previous section, it was found that the strength of the NS-solidified

sludge decreased by 58.01% after 30 cycles in distilled water for 28 days. Compared to that of the solidified sludge before the dry–wet cycling, the surface of the specimen after 30 cycles in distilled water was uneven, and the hydrated calcium silicate aluminate gel (C-A-S-H) and hydrated sodium silicate aluminate gel (N-A-S-H) that were originally wrapped around the soil were lost in large quantities. This was related to the poor water stability of Na_2SiO_3, as mentioned above. Figure 10(f) shows the micrographs of the specimens after 30 dry–wet cycles in 10% NaCl solution for the NS-solidified sludge cured for 28 days. The surface of the NS-solidified sludge after cycling in NaCl solution was flatter than that of the NS-solidified sludge cycled in distilled water. In a previous paper, it was found that the strength of NS-solidified sludge decreased by 42.34% after 30 cycles in 10% NaCl solution for 28 days, which was less than the strength loss after cycling in distilled water. This was due to the pores caused by the dissolution of Na_2SiO_3 being partially filled by NaCl crystals and Friedel's salt. Figure 10(e) shows the micrographs of the specimens after 30 dry–wet cycles in distilled water for the CS-solidified sludge cured for 28 days. The surface structure of the CS-solidified sludge was also partially destroyed after 30 cycles in distilled water, accompanied by the appearance of some pores and cracks. In the previous section, it was found that the strength of CS-solidified sludge after 28 days of 30 cycles in distilled water was only reduced by 11.32%. Compared to NS- and NO-solidified sludge, CS-solidified sludge had the least loss of strength after 30 cycles in distilled water. This was partly due to the slow hydration reaction of the CS-solidified sludge and the long duration of the reaction, and the hydration reaction of the CS-solidified sludge did not completely stop after 28 days. On the other hand, it may have been that the dry–wet cycling caused the C-A-S-H and N-A-S-H gels encapsulating the gelling material to breakdown, exposing the unreacted gelling material inside and thus promoting the hydration reaction. As a result, the CS-cured slurry had a lesser loss of strength under the action of dry–wet cycling. Figure 10(i) shows the micrographs of the specimens after 30 dry–wet cycles in 10% NaCl solution for the CS-solidified sludge cured for 28 days. The CS-solidified sludge cycled in NaCl solution had fewer surface pores compared to the CS-solidified sludge cycled in distilled water, and the formation of NaCl crystals and Friedel's salt on the surface was also observed. In a previous paper, it was found that the strength of CS-solidified sludge decreased by 18.53% at 28 days after 30 cycles in 10% NaCl solution, which was greater than the strength loss of CS-solidified sludge cycled in distilled water.

5. Conclusions

In this study, unconfined compressive strength tests were conducted on specimens of slag-based geopolymer-solidified sludge after dry–wet cycles of chlorine salt. The influence of the number of dry–wet cycles, the type of alkali exciter, the curing age, and the concentration of NaCl solution on the strength of cured soil under the action of dry–wet cycles

were studied, and the microscopic mechanism of strength deterioration of cured soil under the action of dry–wet cycling in chlorine salt solutions was analyzed by SEM tests. The following conclusions were obtained:

(1) NS-solidified sludge had the fastest strength growth rate in the early stage, and the strength remained basically unchanged after 14 days of maintenance. The strength growth of NO-solidified sludge was also mainly concentrated in the first 14 days, and the strength growth rate gradually decreased after 14 days. The change curve of the strength of cured soil excited by calcium carbide slag with curing age was approximately linear and still had a high strength growth rate after 14 days of curing.

(2) The three types of solidified sludge cured for 28 days were subjected to 30 dry–wet cycles in different concentrations of NaCl solution, and it was found that the strength loss of NS-solidified sludge was the largest, and the higher the concentration of NaCl in the solution was, the smaller the strength loss of NS-solidified sludge, while the strength loss of NO- and CS-solidified sludge increased with increasing NaCl concentration. The strength loss of NO- and CS-solidified sludge after 30 dry–wet cycles increased with increasing NaCl concentration, and the order of the resistance of the three types of solidified sludge to the erosive effect of chlorine salt dry–wet cycling was CS > NO > NS.

(3) The strength of NO-solidified sludge cured for 28 days varied with erosion time under the effect of long-term immersion and dry–wet cycling. The strength of solidified sludge after 30 days of immersion in distilled water and 5% Na_2SO_4 solution increased slightly, and the strength of solidified sludge after 30 days of immersion in 5% NaCl solution decreased by only 0.82%, while the strength of solidified sludge after 30 cycles in the three solutions under the effect of dry–wet cycling decreased by an average of 25.04%, indicating that the erosive effect of dry–wet cycling on slag-based polymer-solidified sludge was greater than that of long-term immersion.

(4) From the damage characteristics of the three cured soils after dry–wet cycling, it was observed that the NO-solidified sludge had more surface integrity after 30 dry–wet cycles, with almost no cracking and skin peeling, while the surface of the NS-solidified sludge had many small cracks after 30 dry–wet cycles. Moreover, there were more cracks on the surface of the specimen cycled in distilled water than in NaCl solution, and the CS-solidified sludge had some skin peeling after 30 dry–wet cycles.

(5) SEM results showed that the amorphous C-A-S-H and N-A-S-H gels formed in the slag-based polymer made the soil structure more compact by cementation, and the internal structure of the soil after dry and wet cycling was slightly loose, forming pores and

cracks, and NaCl crystals and Friedel's salts were formed in the soil after cycling in NaCl solution.

Data Availability

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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