Research Article

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Study on the solidification property and mechanism of soft soil based on the industrial waste residue

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Abstract: The solidification property and mechanism of soft soil based on the industrial waste residue was studied systematically. First, the properties of soft soil solidified by single blast furnace slag, phosphogypsum and cement were carried out, and the solidification effect of Portland cement was better compared with blast furnace slag and phosphogypsum. Second, the composite solidification agent formula with excellent solidification performance was developed, and the mass ratio of Portland cement, blast furnace slag and phosphogypsum was 1:2.3:0.8. At this time, compressive strength was up to 8845.1 kPa. Finally, the composition and microstructure of the solidification soft soil was studied by X-ray diffractometer and scanning electron microscope. Calcium hydroxide formed by the hydration of Portland cement and calcium sulfate in phosphogypsum were used as activators for hydration reaction of blast furnace slag, and more hydration products under the synergistic action of Portland cement hydration and blast furnace slag hydration were formed. Hydrated calcium silicate colloid and Ettringite crystal played an important role in skeleton and filling, and the structure of soft soil solidified by composite solidification agent was the most compact.

Keywords: blast furnace slag, phosphogypsum, composite solidification agent, solidification property, mechanism

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1 Introduction

The engineering soft soil had the characteristics of high clay content, high compressibility and low bearing capacity, which was difficult to be directly used as filling material in the project. The huge amount of engineering soft soil not only occupied a large amount of land resources but also needed to purchase high-quality plain soil with higher cost to meet the project demand [1–3]. Therefore, how to realize the low-cost in situ utilization of engineering soft soil had become one of the hot issues in today's society.

A lot of research work around the solidification technology of engineering soft soil had been carried out by scholars at home and abroad, and some achievements in the engineering mechanical properties of the solidification body were obtained [4–7]. At present, Portland cement was the most commonly used solidification material. However, there were many disadvantages that were difficult to overcome in the production and application of Portland cement: (1) large energy consumption: a large amount of resource and energy was consumed in the production process of Portland cement, 0.95 tons of limestone, 0.13 tons of clay and 0.11 tons of standard coal were required for each ton of Portland cement clinker produced; (2) serious environmental pollution: CO_2 and SO_2 were emitted in the production process of Portland cement, which was bound to pose a serious threat to the ecological environment; and (3) high pH value: the organic pollutants in the soft soil would inhibit the hydration reaction of Portland cement, so it was necessary to increase the Portland cement consumption; Excessive Portland cement would significantly increase the pH value of the leaching solution, which had adverse effects on the groundwater and the surrounding vegetation [8–11]. Therefore, it was urgent to develop green low-carbon cementitious materials to reduce the production and use of Portland cement [12–15].

To reduce the amount of Portland cement, the scheme of solidification engineering soft soil with blast furnace slag and phosphogypsum as main materials was proposed, and the solidification property of engineering soft soil was studied in depth. First, the properties of soft soil solidified by single blast furnace slag, phosphogypsum and cement were studied, and the influence of three material content on the solidification property was clarified. Second, orthogonal test was optimized according to the solidification effect of three materials, and the composite solidification agent formula with excellent solidification performance was developed; finally, X-ray diffractometer (XRD), scanning electron microscope (SEM) and thermogravimetric analyzer were used to analyze the composition and microstructure of the solidification soft soil, and the mechanism of the composite solidification agent was revealed.

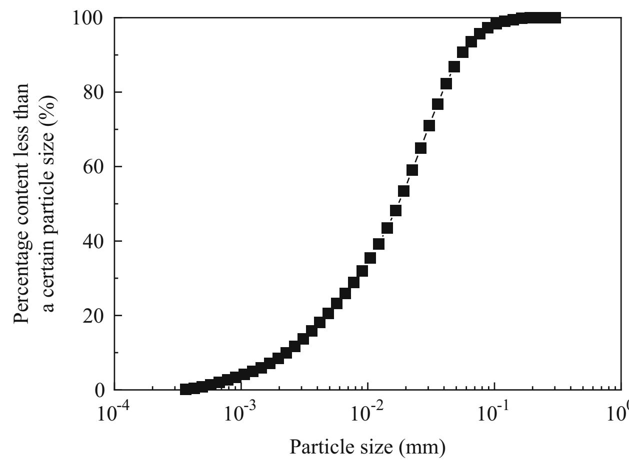

Figure 1: Particle size distribution.

2 Materials and methods

2.1 Materials

The undisturbed soil selected in this test was taken from Dongliu road reconstruction and expansion project in Qixia District, Nanjing, which was gray, flow plastic, mixed with a small amount of gravel and residual plant roots. According to the relevant requirements in the code for highway geotechnical test (JTG 3430-2020), the particle size, water content, liquid plastic limit and other relevant physical indexes of soft soil were measured. The results are shown in Figure 1 and Table 1.

Ordinary Portland cement with strength grade of 42.5 MPa was used in the test, and the relative density was 3.13, while the specific surface area was 360 $m^2 \cdot kg^{-1}$. The chemical composition of Portland cement measured by X-ray fluorescence spectrum analysis is shown in Table 2.

Blast furnace slag used in the test was S105 grade slag powder produced by Gongyi Longze water purification material Co., Ltd. The particle size distribution was mainly 1–15 μm, and the specific surface area was 500–800 $m^2 \cdot kg^{-1}$. Phosphogypsum used in the test was gray powder, and the chemical composition of phosphogypsum is shown in Table 3.

2.2 Experimental design

A large number of metal oxides and silicon oxides exist in the blast furnace slag, and CaO, Al_2O_3, and MgO basic metal oxides have hydration activity, which can react with water to generate calcium silicate hydrate, calcium aluminate hydrate and other cementing materials. In the presence of phosphogypsum, ettringite can be further formed, which is helpful to improve the cementation performance. Therefore, the use of blast furnace slag and phosphogypsum will be conducive to reduce the cement consumption.

In the test, the content of Portland cement, blast furnace slag and phosphogypsum was calculated based on the mass ratio of dry soil, and the water content of remolded soil was adjusted to 50%. The solidification property of three materials was studied separately, and the influence of different content on the solidification property was determined. To reduce the use of Portland cement, six different low dosages of Portland cement were set, which was 3, 4, 5, 6, 7 and 8%, respectively. While reducing the content of Portland cement, it was necessary to increase the content of industrial waste slag to achieve the expected solidification strength. Therefore, the high content of blast furnace slag was designed, and the content was 6, 8, 10, 12 and 14%, respectively. Compared with Portland cement, the activity of industrial waste slag was relatively low, and an appropriate content of activator should be added to improve the solidification efficiency. Phosphogypsum was selected as the activator in this test, and its content was 0.5, 1, 2, 3, 4 and 5%, respectively. According to the individual solidification effects of three materials, multi-factor and multi-level orthogonal tests were designed to obtain the best formulation of the composite solidification agent.

The uniformly mixed soft soil sample was poured into a cylindrical mold with a diameter of 39.1 mm and a height of 80 mm coated with Vaseline. To make the

Table 1: Main physical indexes

Water content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index	Maximum dry density ($g\cdot cm^{-3}$)	Clay content (%)	Organic matter content (%)	pH
45.6	37.2	22.9	14.3	1.82	46	1.72	6.5

Table 2: Chemical composition of Portland cement

Chemical composition	Al_2O_3	SiO_2	P_2O_5	SO_3	CaO	Loss on ignition
Content (%)	10.96	25.74	6.16	4.03	48.24	4.87

formed sample as uniform as possible, the mold was placed on the shaking table and vibrated for 40–60 s after pouring each layer of sample. Then, the sample was put into a standard curing box for curing. The temperature was 20 ± 2°C, and the relative humidity was 95 ± 2%. The sample was demoulded after curing for 24 h, and the demoulded sample was put into the curing box for further curing. When the curing age reached 28 days, the sample was taken out for detection and analysis.

2.3 Analytical method

Compressive strength was taken as the evaluation index of the solidification effect, and it was measured by the full-automatic unconfined compressive tester produced by Nanjing Soil instrument factory. Three parallel samples were measured each time, and the average value was considered as the final solidification strength.

The sample was washed with deionized water and absolute ethanol for three times, respectively, and dried in a 60°C constant temperature oven to constant weight. Then, it was finely ground in an agate bowl. The composition was examined by XRD with Bruker D8-Discover diffractometer using graphite monochromatized high-intensity Cu Kα radiation (λ = 1.5406 Å). The scanning angle range was from 10 to 80° 2θ with the step at $0.2\, s\cdot step^{-1}$. To obtain a clearer image, the surface of the processed sample was evenly sprayed with a layer of gold. SEM (FEI Company, Netherlands) with a GENESIS 60S energy-dispersive X-ray spectroscopy system with magnification from 5,000 to 10,000 was used to observe the morphology. The accelerating voltage and spot size of the secondary electron detector were 20 kV and 4.0, respectively.

3 Results and discussion

3.1 Individual solidification effect of the three materials

As a large amount and wide range of civil engineering materials, Portland cement was a very important inorganic cementitious material, which was widely used in the field of engineering soft soil. The solidification effect of Portland cement with different content was studied, and the relationship between Portland cement content and solidification effect is shown in Figure 2. It could be seen from Figure 2 that Portland cement content had a significant impact on the solidification effect. With the increase of Portland cement content, compressive strength of the solidification soft soil increased to varying degrees. When Portland cement content was 3, 4, 5, 6, 7 and 8%, the compressive strength was 274.8, 435.9, 1114.4, 1707.1, 2916.3 and 3123.2 kPa, respectively; the lower the Portland cement content, the lower the compressive strength of the solidification soft soil. Compared with the content of 3%, compressive strength increased by 58.5, 305.5, 521.2, 961.2 and 1,036.5% when the content was 4, 5, 6, 7 and 8%, respectively. The increase of Portland cement content was beneficial to improve the solidification effect, but when Portland cement content exceeded a certain limit, the solidification effect did not increase significantly with the increase of Portland cement content. Therefore, Portland cement content should be controlled within a certain range, which not only ensured the solidification effect, but also reduced the disposal cost.

Table 3: Chemical composition of phosphogypsum

Chemical composition	Na_2O	Al_2O_3	SiO_2	P_2O_5	SO_3	CaO	Loss on ignition
Content (%)	5.00	4.39	4.55	3.92	40.72	39.08	2.34

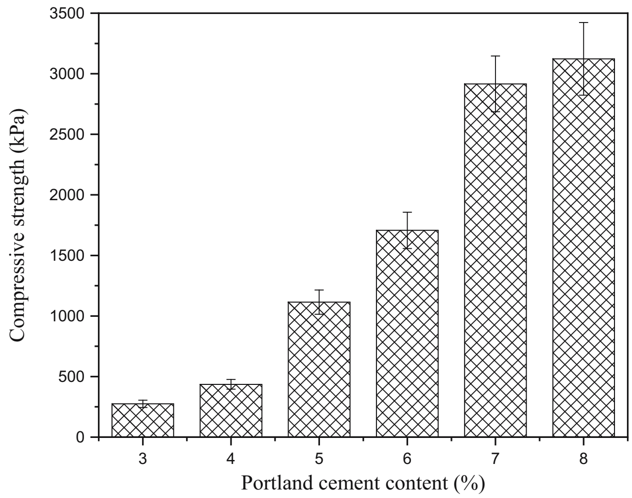

Figure 2: Influence of Portland cement content on solidification effect.

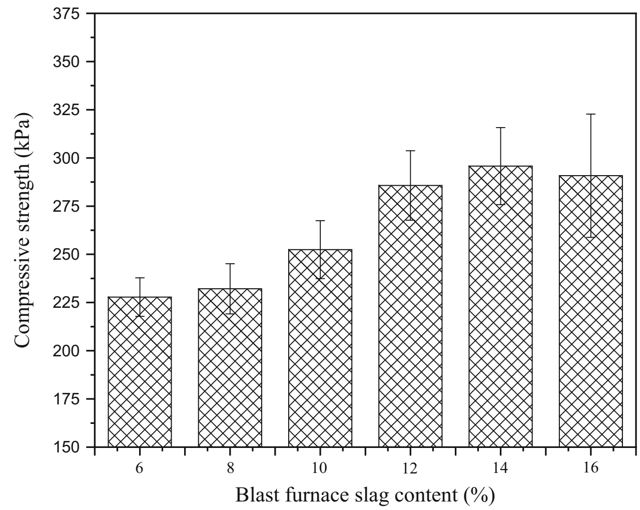

Figure 3: Influence of blast furnace slag content on solidification effect.

As an active mixed material, blast furnace slag was a soft particle formed by rapid cooling of molten slag. The purpose of rapid cooling granulation was to prevent crystallization and become unstable vitreous body, which stored high potential chemical energy. There was active silica, active alumina and a small amount of calcium oxide in blast furnace slag, which could be hydrated to form hydrated calcium silicate and hydrated calcium aluminate with gelling property. The solidification effect of blast furnace slag with different content was studied, and the result is shown in Figure 3. With the increase in blast furnace slag content, the compressive strength of solidification soft soil showed a trend of first increasing and then decreasing. When the content was less than 14%, compressive strength increased with the increase of the content; When the content was more than 14%, compressive strength began to decrease with the increase of the content. It could be seen that there was a reasonable content of blast furnace slag on solidification soft soil. The reason was that the calcium oxide content in blast furnace slag was relatively low, and only relatively few hydration products could be produced. With the hydration reaction, calcium oxide was consumed, and the hydration process was difficult to continue. Less hydration products could not meet the needs of solidification soft soil and blast furnace slag at the same time.

Phosphogypsum was a solid waste produced in the production of phosphoric acid, and its main component was calcium sulfate. Among inorganic cementitious materials, phosphogypsum was a kind of pneumatic cementitious material, which was widely used in civil engineering. When the single phosphogypsum was used to solidify soft soil, its strength came from two aspects: on the one hand, there was a small amount of active silica and active alumina in the soft soil, and it could produce ettringite to cement some soft soil particles; on the other hand, a small amount of hemihydrate gypsum in phosphogypsum reacted with water to produce dihydrate gypsum, and the soft soil particles were cemented in this process. The solidification effect of phosphogypsum content was studied, and the result is shown in Figure 4. It could be seen from Figure 4 that phosphogypsum content had no obvious influence on the solidification effect. With the increase of phosphogypsum content, compressive strength showed no regular change and no obvious growth trend. So, the increase in phosphogypsum content was not conducive to the improvement of solidification effect.

3.2 Solidification effect of composite solidification agent

According to the previous test results, it could be seen that the solidification effect of each material was different, and each material content was also different. To determine the formula of composite solidification agent, it was necessary to clarify the combination relationship of various factors and levels. Therefore, compressive strength was taken as the evaluation index in this test, and the orthogonal table L9 (33) of three factors and three levels was selected to design orthogonal test. The orthogonal test design is shown in Table 4, and the results of orthogonal test are shown in Table 5.

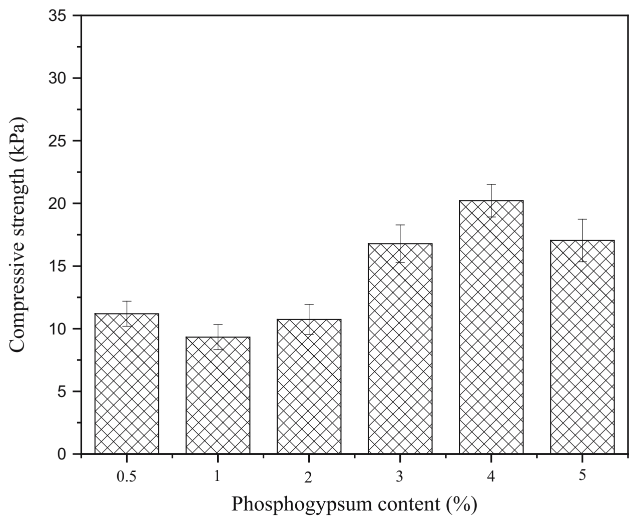

Figure 4: Influence of phosphogypsum content on solidification effect.

It could be seen from Table 5 that the solidification effect of test combination A1B3C3 was the best, and compressive strength was up to 8845.1 kPa. At this time, each material content was 6% of Portland cement, 14% of blast furnace slag and 5% of phosphogypsum. The mass ratio of Portland cement, blast furnace slag and phosphogypsum was 1:2.3:0.8, which was the best formula of composite solidification agent. The solidification effect of composite solidification agent was greatly improved, which formed an extremely strong contrast with the single material test. The results of orthogonal test were further analyzed, and the variance reflected the primary and secondary relationships of the influencing factors; the larger the *R* value, the greater the influence of the corresponding factors on compressive strength, which was the main factor; the smaller the *R* value, the smaller the influence of the corresponding factors on compressive strength, which was the secondary factors. From Table 5, Portland cement content was the main factor, while blast furnace slag and phosphogypsum content was the secondary factor.

Table 5: The results of orthogonal test

Number	Influence factor			Compressive strength (kPa)
	A (%)	B (%)	C (%)	
1	1 (6%)	1 (10%)	1 (1%)	4905.9
2	1 (6%)	2 (12%)	2 (3%)	6138.2
3	1 (6%)	3 (14%)	3 (5%)	8845.1
4	2 (7%)	1 (10%)	2 (3%)	4237.6
5	2 (7%)	2 (12%)	3 (5%)	5703.8
6	2 (7%)	3 (14%)	1 ((1%)	4382.6
7	3 (8%)	1 (10%)	3 (5%)	4562.5
8	3 (8%)	2 (12%)	1 (1%)	5105.0
9	3 (8%)	3 (14%)	2 (3%)	4541.0
K_1	19889.4	13706.1	14393.6	
K_2	14324.1	16947.1	14916.9	
K_3	14208.6	17768.8	19111.5	
$\bar{K}_1$	6629.8	4568.7	4797.8	
$\bar{K}_2$	4774.7	5649.0	4972.3	
$\bar{K}_3$	4736.2	5922.9	6370.5	
R	1893.5	1354.2	1572.6	

3.3 Composition and microstructure of solidification soft soil

Compared with the single material, the solidification effect of composite solidification agent significantly improved. The main reason might be the interaction between the materials and the production of more gelling products. To confirm the speculation, the composition and microstructure of solidification soft soil were further analyzed by XRD and SEM, and the results are shown in Figures 5 and 6.

Phase retrieval of XRD patterns was carried out by MDI jade 5.0, and it was found that the composition of solidification soft soil under different conditions was mainly silica and aluminum oxide. Figure 5(a) shows that new minerals such as hydrated calcium silicate, calcium hydroxide and Ettringite appeared in addition to silicon dioxide and aluminum oxide. The composition of these new minerals with cementitious property was basically the same as that of the hydration products of

Table 4: Factor and level of orthogonal test

Level	Factor		
	Portland cement content [A] (%)	Blast furnace slag content [B] (%)	Phosphogypsum content [C] (%)
1	6	10	1
2	7	12	3
3	8	14	5

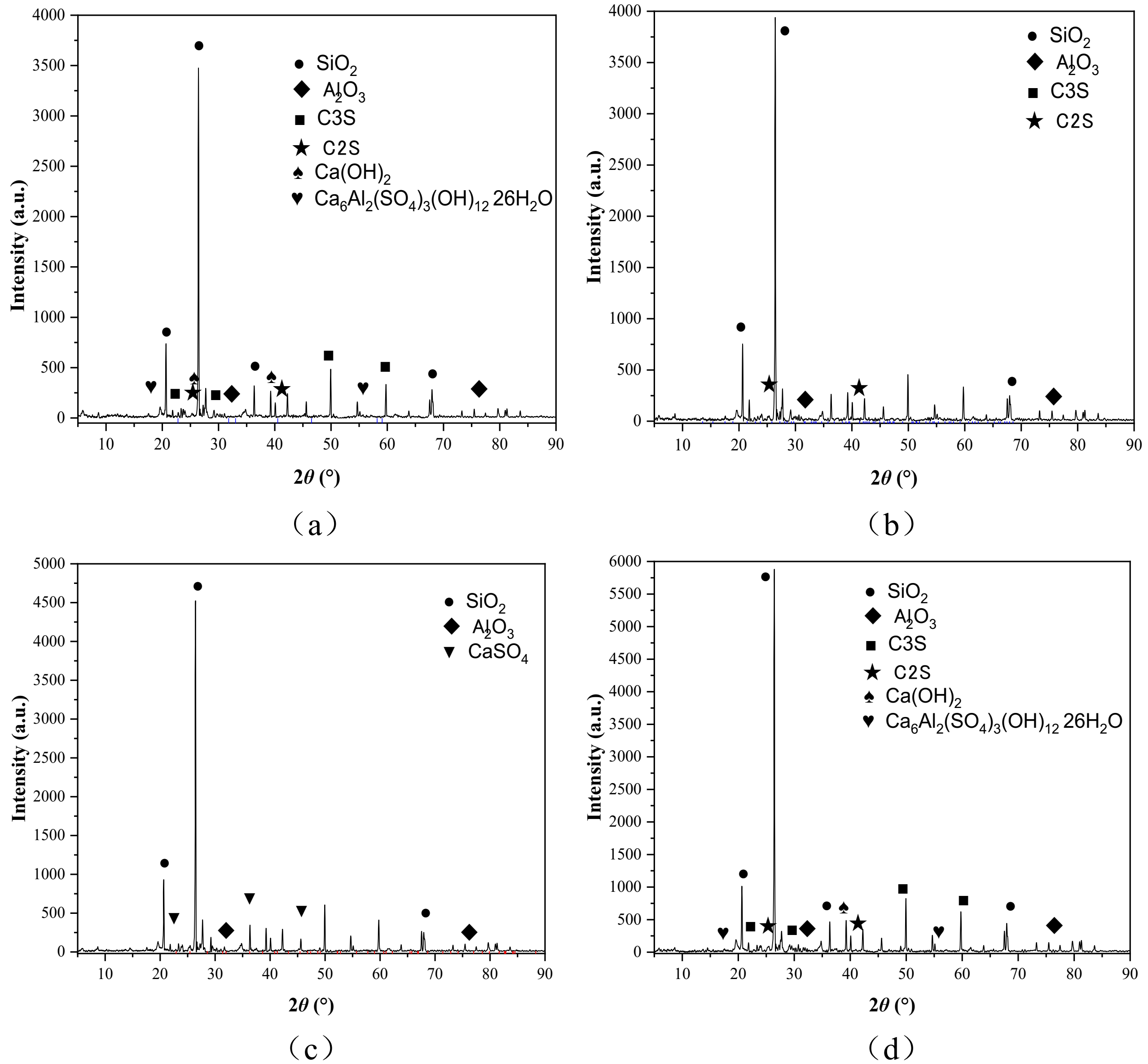

Figure 5: X-ray diffraction spectra of solidification soft soil under different conditions. (a) 6% of Portland cement. (b) 14% of blast furnace slag. (c) 5% of phosphogypsum. (d) Composite solidification agent.

Portland cement, which was the fundamental reason for the high strength of soft soil solidified by Portland cement. Blast furnace slag contained active silicon oxide, active aluminum oxide and a small amount of calcium oxide, which had pozzolanic reaction activity. In the absence of an external activator, a low degree of hydration reaction could occur to generate hydrated calcium silicate and hydrated calcium aluminate (Figure 5(b)). As shown in Figure 5(c), only new mineral calcium sulfate appeared in soft soil solidified by phosphogypsum. As an industrial waste residue, phosphogypsum had no reaction activity and would not undergo hydration reaction in the presence of water. Therefore, calcium sulfate existing in phosphogypsum was only found. Figure 5(d) shows that hydrated calcium silicate, calcium hydroxide and ettringite appeared in soft soil solidified by composite solidification agent, and the results were similar to those of Portland cement. However, the diffraction peak intensity of calcium hydroxide was obviously weakened, indicating that the crystallinity of calcium hydroxide was low and the content was small. In the meantime, the mineral calcium sulfate was not found. This was mainly because calcium hydroxide formed by the hydration of Portland cement and calcium sulfate in phosphogypsum were

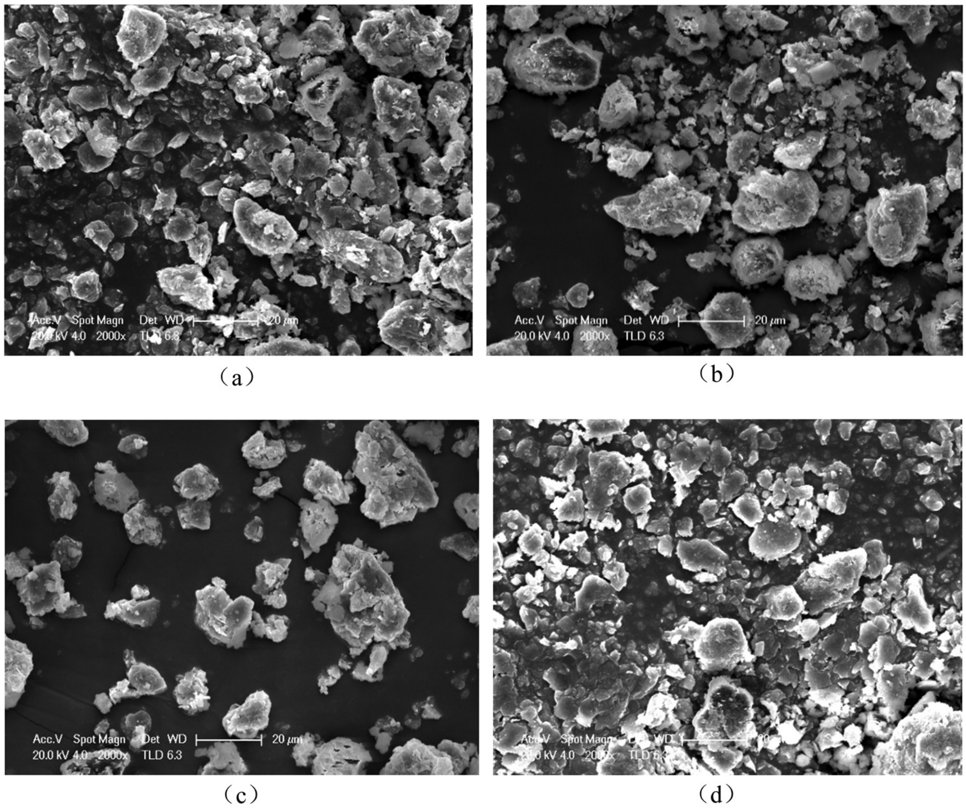

Figure 6: SEM image of solidification soft soil under different conditions. (a) 6% of Portland cement. (b) 14% of blast furnace slag. (c) 5% of phosphogypsum. (d) Composite solidification agent.

used as activators for hydration reaction of blast furnace slag, and the hydration reaction consumed calcium hydroxide and calcium sulfate; in this process, hydrated calcium silicate gel and ettringite crystal with gelling property were prepared. Based on the hydration of Portland cement, more hydration products were formed by the hydration reaction of blast furnace slag. Therefore, the composite solidification agent had better solidification performance.

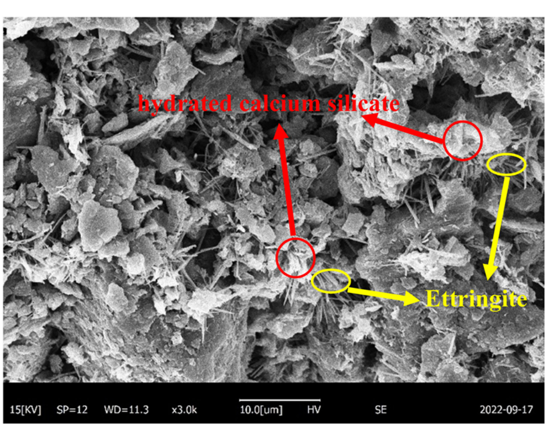

Figure 7: SEM image of hydrated calcium silicate and ettringite.

As shown in Figure 6, there were significant differences in the microstructure of soft soil solidified under different conditions. For the soft soil solidified by Portland cement, soft soil particles were cemented and filled by the hydration products and formed a relatively dense structure (Figure 6(a)); The structure compactness of soft soil solidified by blast furnace slag was poor due to less hydration products formed (Figure 6(b)); since there was no hydration product, phosphogypsum without gelling property could not solidify the soft soil to form a dense structure (Figure 6(c)); combined with the results in Figure 5, more hydration products under the synergistic action of Portland cement hydration and blast furnace slag hydration were formed (Figure 6(d)). Hydrated calcium silicate colloid and ettringite crystal played an important role in skeleton and filling, and the structure of soft soil solidified by composite solidification agent was the most compact (Figure 7).

4 Conclusions

In this article, the solidification property and mechanism of soft soil based on industrial waste residue was studied systematically. Compared with blast furnace slag and phosphogypsum, the solidification effect of Portland cement was better. According to the solidification effect of three materials, orthogonal test was optimized. The composite solidification agent formula with excellent solidification performance was developed, and the mass ratio of Portland cement, blast furnace slag and phosphogypsum was 1:2.3:0.8, which was the best formula of composite solidification agent. At this time, compressive strength was up to 8845.1 kPa. The composition and microstructure of the solidification soft soil was studied by XRD and SEM, and the mechanism of the composite solidification agent was revealed. Calcium hydroxide formed by the hydration of Portland cement and calcium sulfate in phosphogypsum were used as activators for hydration reaction of blast furnace slag, and the hydration reaction consumed calcium hydroxide and calcium sulfate; more hydration products under the synergistic action of Portland cement hydration and blast furnace slag hydration were formed. Hydrated calcium silicate colloid and ettringite crystal played an important role in skeleton and filling, and the structure of soft soil solidified by composite solidification agent was the most compact. The results of this article provided a reference for engineering soft soil solidified by industrial waste residue.

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