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Research Article

Study on Strength Characteristics of Solidified Contaminated Soil under Freeze-Thaw Cycle Conditions

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Cement solidification/stabilization is a commonly used method for the remediation of contaminated soils. The stability characteristics of solidified/stabilized contaminated soils under freeze-thaw cycle are very important. A series of tests, which include unconfined compressive strength tests, freeze-thaw cycle tests, and scanning electron microscopy (SEM) tests, are performed to study the variation law of strength characteristics and microstructure. It aims at revealing the microcosmic mechanism of solidified/stabilized Pb^{2+} contaminated soils with cement under freeze-thaw cycle. The results show that the unconfined compressive strength of the contaminated soils significantly improved with the increase of the cement content. The unconfined compressive strength of stabilized contaminated soils first increases with the increase of times of freeze-thaw cycle, and after reaching the peak, it decreases with the increase of times of freeze-thaw cycle. The results of the scanning electron microscopy tests are consistent with those of the unconfined compressive strength tests. This paper also reveals the microcosmic mechanism of the changes in engineering of the stabilized contaminated soils under freeze-thaw cycle.

1. Introduction

The soil was seriously contaminated by heavy metals with the arbitrary emissions of three industrial wastes in China. And the heavy metal residues existed in the soil for a long time due to its poor mobility and difficulty to degradation. Therefore, how to prevent and control heavy metal-contaminated soils have become a hot problem [1–3]. In all remediation technologies of heavy metal-contaminated soils, the solidification/stabilization technology has some advantages, for example, short cycle, easy operation, low cost, and wide applicable range. Thus, it has become one of the widely applied technologies at present [4–7]. The solidified/stabilized contaminated soils exist in complex natural environment. The engineering properties of solidified/stabilized contaminated soils may change with freeze-thaw cycle effect.

Some research studies [8] showed that the connection between the soil particles can be damaged by water when frozen, and the large aggregates were broken down into small aggregates when thawed. The adsorption of metal ions on the soil gel has been affected by quality and quantity of aggregates. With the increase of freeze-thaw cycles, the water-soluble organic matter content in soil increases significantly [9].

The mechanical properties of soil were studied with the pollution environment effect by Bai et al. in 2007 [10].

The properties of soil mechanics with freeze-thaw cycle effect had been studied by Ning et al. [11]and Pang and Shen [12], and the research studies showed that the soil degradation was very obvious after freeze-thaw cycle.

The field-monitoring analysis with a hammer and dynamic cone penetrometer showed that the loss of the strength of the upper subgrade improved by cement has reached 50% after the freeze-thaw cycle [13].

The improved soil has good durability of freeze-thaw resistance from the comparison of parameters of the unconfined compressive strength test, CBR, ultrasonic and resonance test with the lime, fly ash and cement, respectively, in freeze-thaw cycle [14].

The research result showed that the unconfined compressive strength of improved soil by lime is effective for durability under the freeze-thaw cycle [15, 16].

Many domestic and foreign scholars have realized the importance of the durability of solidified/stabilized contaminated soils. The mechanism of the contaminated soils with freeze-thaw cycle effect achieves some results, but most of the research results focused on the physical and mechanical properties of the soil, adsorption of heavy metals, and transformation with the freeze-thaw cycle effect. The durability theory and the engineering case which studied on solidified/stabilized heavy metal-contaminated soils with the freeze-thaw cycles were rare. A series of test programs, which include unconfined compressive strength tests and scanning electron microscopy tests were performed to study the variation law of strength characteristics and microstructure and reveal the microcosmic mechanism of solidified/stabilized contaminated soils with cement under freeze-thaw cycles.

2. Materials and Methods

2.1. Materials. The silty clay soil was obtained from Guang Zhou in China. It was air-dried and broken down into pieces to pass through a 2 mm sieve, and its physical properties are listed in Table 1. The cement used P.O. 42.5 ordinary Portland cement. The heavy metal pollutants used lead nitrate ($Pb(NO_3)_2$).

2.2. Test Plan. The type of heavy metals is lead ions, and the concentration of lead ions is 0.1%, 0.5%, and 1.0% of dry soil quality, namely, 1000 mg/kg, 5000 mg/kg, and 15000 mg/kg. 5%, 10%, and 15% dosage of cement were used to solidify/stabilize contaminated soils. The experiment of solidification/stabilization of contaminated soil was carried out after 28-day curing, and the strength and microstructure characteristics of the contaminated solidified/stabilized soils under different freeze-thaw times were tested. The test procedure is as follows.

2.2.1. Sample Preparation and Maintenance. Firstly, make the soil sample dry and crush with a 2 mm sieve.

Secondly, take a certain quality of the soil sample and cement and mix fully according to the proportion plan.

Thirdly, add $Pb(NO_3)_2$ into the optimal amount of moisture content (22.3%) to dissolve and then put it in the soil sample and cement to mix.

Fourthly, the static pressure method is used to mix the soil material and made it to the columnar sample of 5 cm in diameter and 10 cm in height, and then the samples were cured in the standard condition (temperature is 20°C and humidity is 95%).

2.2.2. Unconfined Compressive Strength Tests. The operation steps are as follows:

Firstly, smear a thin layer of Vaseline at both ends of the sample; the thin layer of Vaseline is also applied to prevent moisture evaporation.

Secondly, put the sample on the base, rotate the hand wheel, and make the base rise slowly; when the sample and the pressure plate are just in contact, adjust the dynamometer reading to zero.

Thirdly, controlled unconfined compression tests were conducted using the strain instrument, and the axial strain rate should be 1% to 3% per minute.

Fourthly, when the dynamometer readings peak, continue 3% to 5% of the strain to stop the test.

Fifthly, at the end of the test, the sample is removed to describe the shape of the specimen after failure.

2.2.3. Freeze-Thaw Cycle Test. The samples were taken out after standard 28-day curing, and then the freeze-thaw cycle test was carried out according to ASTM-D560-03. And specific steps are as follows:

Firstly, the sample used a valve bag to seal in the process of freeze-thaw cycle in order to prevent moisture loss of the sample. And then take out a set of sample to test the unconfined compressive strength, and the values were used as a reference. Finally, the rest of the sample underwent freeze-thaw cycle.

Secondly, put the sample at a temperature of −15°C in a freeze-thaw box for 3 hours, transfer the sample to the standard curing room maintenance 3 hours, and then take out the sample to complete one time freeze-thaw cycle.

Thirdly, after the freeze-thaw cycle, carry out the unconfined compressive strength tests and scanning electron microscopy tests.

Fourthly, repeat the above two steps, till 11th time freeze-thaw cycle.

2.2.4. Scanning Electron Microscopy Tests. A microstructure test and analysiswere carried out on the samples using Japan's Hitachi S-3000N scanning electron microscope after 0, 1, 3, 5, 7, 9, and 11 times freeze-thaw cycle.

3. Results and Analysis

3.1. Unconfined Compressive Strength. The law of unconfined compressive strength of different samples under freeze-thaw cycle was studied, and the results are shown in Figure 1.

We can see from Figure 1 that the unconfined compressive strength of the solidified/stabilized heavy metal-contaminated soils has improved significantly with the increase of cement admixture. However, the ion exchange and crumb and hard condensation reaction had formed stable chains and crystal mesh structure between the hydrolysis and hydration reaction products of cement and soil particles. The cement wrapped the soil particle and populated the intergranular pore and formed a whole curing material.

Compared with standard curing samples, the strength of the sample under the freeze-thaw cycle had reduced at different degrees. The unconfined compressive strength of the third freeze-thaw cycle was the largest and decreased with the increase of freeze-thaw cycle. The strength was the minimum at the 11th freeze-thaw cycle and remained

Table 1: Physical and mechanical indexes of the soils of silty clay.

Index	Wet density (g/cm^3)	Void ratio	Liquid limit (%)	Plastic limit (%)	Water content (%)
Silty clay	2.72	0.619	36.7	24.5	22.42

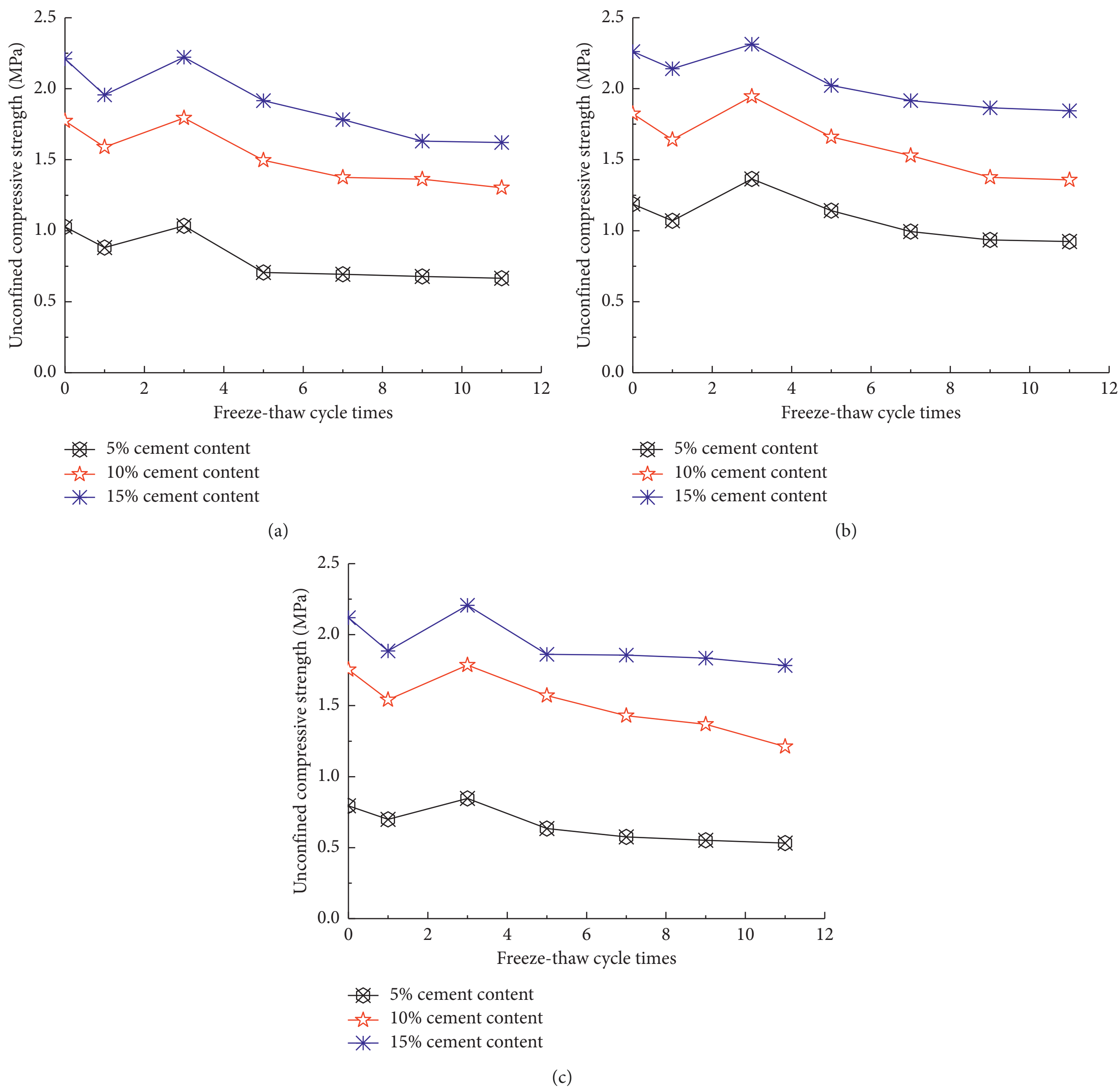

Figure 1: Relationship between unconfined compressive strength and times of freeze-thaw cycle of solidified/stabilized contaminated soils. (a) Pb^{2+} concentration with 1000 mg/kg; (b) Pb^{2+} concentration with 5000 mg/kg; (c) Pb^{2+} concentration with 15000 mg/kg.

stable. Taken the 5000 mg/kg lead-contaminated soils solidified/stabilized by 15% cement as an example, the largest unconfined compressive strength was 2.313 MPa, and the minimum was 1.845 MPa and declined 20.23%.

We can see from Figure 2 the unconfined compressive strength of solidified/stabilized contaminated soils increased first and then decreased with the increase of heavy metal content. When the heavy metal content was 5000 mg/kg, the unconfined compressive strength of solidified/stabilized contaminated soils was the largest.

Some research studies showed that a certain dosage of heavy metal ions can delay the early hydration of cement [17, 18]. Therefore, the solidified/stabilized contaminated soils after 28-day curing, the physical-chemical action

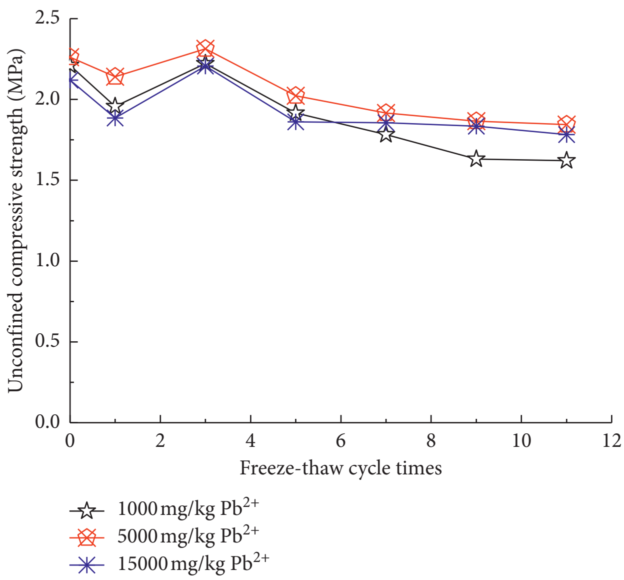

FIGURE 2: Relationship between unconfined compressive strength and times of freeze-thaw cycle of 15% cement solidified/stabilized contaminated soils with different heavy metal contents.

between the hydrates and soils may still be ongoing. So, at early freeze-thaw cycle, the strength of solidified/stabilized contaminated soils increased.

3.2. Microstructure Analysis of the Freeze-Thaw Cycle Sample. The microstructure analysis of the solidified/stabilized contaminated soils after several freeze-thaw cycle had used SEM, and the results are shown from Figures 3–6.

Figure 3 shows that without the freeze-thaw cycle effect, a large number of pores exist, and the calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) hydration gel underdevelopment in the sample were not fully covering grain surface and pore filling. In addition, a tabular crystal portlandite ($Ca(OH)_2$) can be seen in the picture. These indicate that the hydration reaction of cement is not complete, and still ongoing. So, we can confirm that the heavy metal ions can delay the hydration reaction of cement.

After three times freeze-thaw cycle, the platy calcium hydroxide content was greatly reduced and great gel formed and covered the particle surface and extended in the pore. Compared with the sample that had not undergone the freeze-thaw cycle, the internal structure of soil was more complete and dense and illustrated that physical-chemical action was still ongoing between the hydration reaction of cement and its hydrolysate product in this stage with the soil. In this stage, the unconfined compressive strength of solidified/stabilized contaminated soils increased.

After ninth times freeze-thaw cycle, the hydration gel was broken and scattered compared with three times freeze-thaw cycle. This showed that the sample structure had been destroyed significantly by the freeze-thaw cycle. This also agreed with the strength decreased.

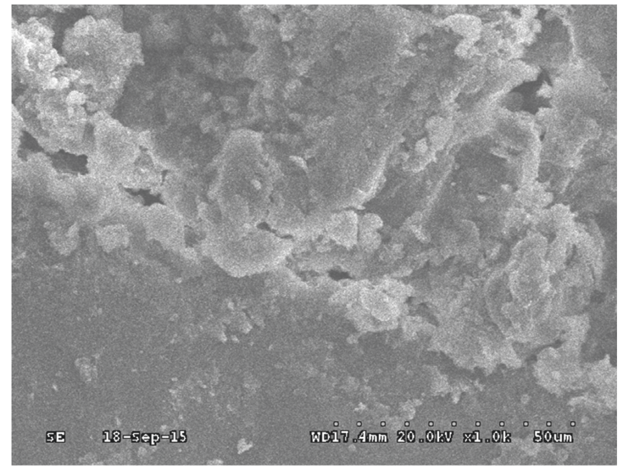

FIGURE 3: Microstructural feature of Pb-5000 mg/kg contaminated soils stabilized by 15% cement under 0 freeze-thaw cycle.

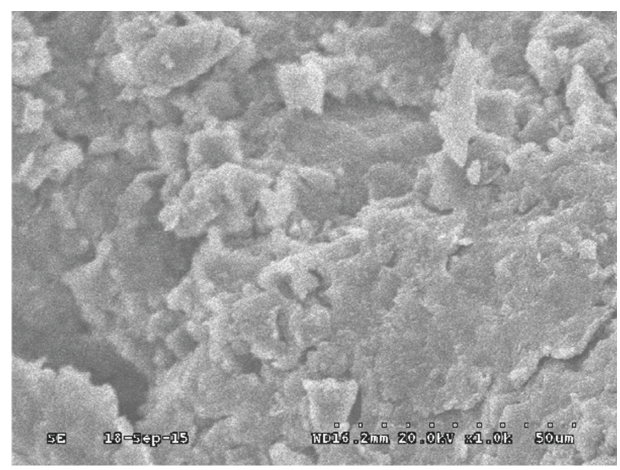

FIGURE 4: Microstructural feature of Pb-5000 mg/kg contaminated soils stabilized by 15% cement under 3 freeze-thaw cycle.

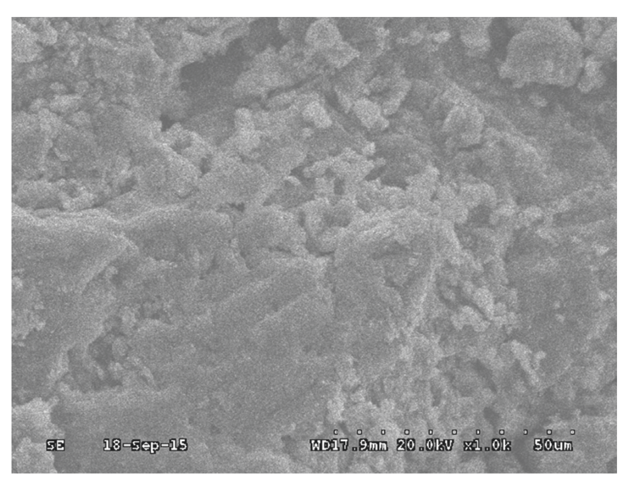

FIGURE 5: Microstructural feature of Pb-5000 mg/kg contaminated soils stabilized by 15% cement under 7 freeze-thaw cycle.

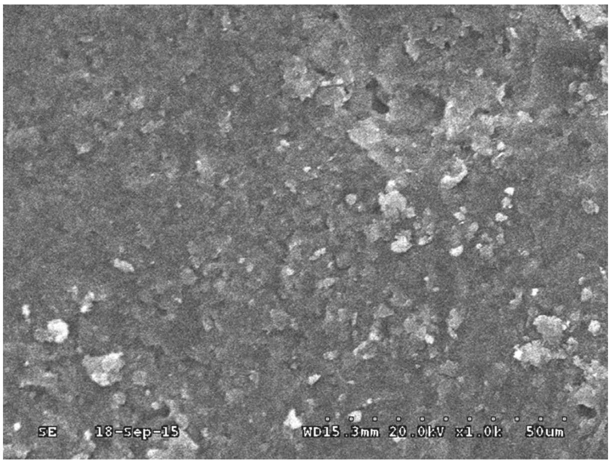

Figure 6: Microstructural feature of Pb-5000 mg/kg contaminated soils stabilized by 15% cement under 9 freeze-thaw cycle.

4. Conclusion

Firstly, the test results show that the unconfined compressive strength of stabilized contaminated soils is significantly improved with the increase of the cement content.

Secondly, the unconfined compressive strength of stabilized soils first increases with the increase of times of the freeze-thaw cycle, and after reaching the peak at the third freeze-thaw cycle, it decreases with the increase of freeze-thaw cycle times, and the unconfined compressive strength of the third freeze-thaw cycle was the largest.

Thirdly, the results of SEM tests are consistent with those of the unconfined compressive strength tests.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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