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Study on Engineering Characteristics and Mechanism of Expansive Soil Improved by Lime-zeolite Powder

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Abstract: *In order to solve the problem of high pollution and high cost of traditional lime improved expansive soil, this paper analyzes the feasibility and improvement effect of lime-zeolite powder (L-Z) improved expansive soil. Taking the typical expansive soil in Henan Province as the research object, through a series of physical properties tests, unconfined compressive strength tests (UCS), splitting tensile strength tests (STS), X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests, the effects of different lime and zeolite powder content on the physical and mechanical properties and curing mechanism of improved expansive soil were discussed. The results show that with the increase of zeolite powder, the optimal moisture content increases and the maximum dry density decreases, the plastic limit increases and the liquid limit and plastic index decrease, and the free expansion rate decreases. After adding lime and zeolite powder, the UCS and STS of the improved soil are significantly improved. When the lime content is 6 % and the zeolite powder content is 12 %, the improvement effect is the best. Zeolite powder reacts with lime to form C-S-H and C-A-H cementitious materials, which cement soil particles to form aggregates and fill pores, increase soil compactness, thus improving soil strength and engineering properties of expansive soil.*

Keywords: *expansive soil, lime, zeolite powder, engineering characteristic, curing mechanism*

1. Introduction

Expansive soil is mainly composed of hydrophilic minerals such as illite, montmorillonite and kaolinite. It has the characteristics of water absorption expansion and water loss shrinkage. When the water content of soil changes, it expands and shrinks repeatedly, cracks develop and strength decreases, which brings serious safety hazards to engineering construction and use [1]. At present, the main improvement methods are physical improvement, chemical improvement and non-traditional improvement. Lime, cement, fly ash and other materials are the most widely used in chemical improvement. Lime is added to expansive soil. By providing Ca^{2+} ions to dissolve in soil particles and react with SiO_2, hydrated calcium silicate is formed, which reacts with Al_2O_3 to form calcium aluminate compounds [2-7]. These hydration gels can cement soil particles and fill the pores between soil particles, thereby enhancing the strength and stiffness of the soil. However, due to the improvement of people's understanding of environmental problems, the use of materials such as lime and cement is more polluting and the production cost is relatively high. This has led researchers to use industrial by-product materials [8-10] or natural materials [11-12] to improve expansive soils, minimizing the use of materials such as lime and cement in engineering to mitigate negative environmental impacts, including energy consumption and greenhouse gas emissions.

Zeolite is a natural volcanic ash material with high SiO_2 and Al_2O_3 content, which is widely used in cement production as volcanic ash. On the one hand, as a volcanic ash material, zeolite powder can react with lime, cement and other materials to improve the engineering properties of soil. Arefal-Swaidani et al. [13] added natural volcanic ash to lime-improved soil, and concluded that natural volcanic ash reduced the plasticity and linear shrinkage of lime-improved soil, enhanced the compaction characteristics of lime-improved soil, and increased the California bearing ratio of lime-improved soil. On the other hand, the pozzolanic reaction of zeolite powder is related to the time factor, involving the interaction between silica and alumina and lime. The large amount of cementitious products generated by the pozzolanic reaction can improve the strength of the soil. The study of Noor Dhani et al. [14] proved that the addition of zeolite to lime-stabilized soft soil can significantly enhance the unconfined compressive strength of

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soil, and the UCS increases with the increase of curing age. MohammadReza ShahriarKian et al. [15] used zeolite to improve the performance of cement stabilized soil. Studies have shown that the addition of zeolite improves the unconfined compressive strength of cement soil, and the unconfined compressive strength of the sample increases with the increase of curing time. In addition, the addition of zeolite powder can also improve the tensile strength of the soil. A. Khajeh et al. [16] showed that the tensile strength of soil can be effectively enhanced by replacing cement with zeolite. When 30% zeolite replaces cement, the tensile strength of cement soil reaches the maximum. At this time, the content of SiO_2 and Al_2O_3 is close to CaO, and the pozzolanic reaction is the most sufficient. In summary, the addition of zeolite powder can not only improve the engineering properties of lime-modified soil and improve the strength of soil, but also reduce the amount of lime, cement and other materials, and minimize the pollution to the environment.

At present, there are few studies on the composite improvement of expansive soil with lime and zeolite powder in China. Therefore, this paper takes the typical expansive soil in Nanyang area of Henan Province as the research object, and intends to use lime-zeolite powder to improve expansive soil. Through a series of physical properties tests, the influence of lime and zeolite powder content on the physical properties of the improved soil was discussed. The unconfined compressive strength test and splitting tensile strength test of samples with different mix ratios at different ages were carried out to study the effect of improved material content and age on the mechanical properties of the improved expansive soil. In addition, combined with X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests, the microstructure characteristics and reinforcement mechanism of lime-zeolite powder modified expansive soil were studied.

2. Experimental

2.1 Testing material

The expansive soil used in the test was taken from a highway in Neixiang County, Nanyang City, Henan Province. The depth of the soil was 2~3 m, and the soil was yellowish brown. The basic physical properties of the soil samples were measured, as shown in Table 1. The free expansion rate of the expansive soil is 58%. According to the" Technical Code for Buildings in Expansive Soil Areas" (GB 50112-2013), it is judged to be a typical weak expansive soil. The lime used in the test is high-purity lime powder, which is selected from Jiangxi Xinyu Huihui Ash Co., Ltd. The CaO content is 95.6%, which belongs to grade II lime powder, and the zeolite powder is produced by Gongyi Water Purification Filter Plant. The main chemical composition of lime and zeolite powder is shown in Table 2.

Table 1: Basic physical indexes of expansive soil.

Natural water content/%	Optimum moisture content/%	Maximum dry density/($g\cdot cm^{-3}$)	Liquid limit/%	Plastic limit/%	Plasticity index	Free swelling ratio/%
23.1	18.6	1.642	49.1	27.8	21.3	58

Table 2: Main chemical composition of lime and zeolite powder.

Composition	Mass fraction/%							
	Cao	MgO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Others	Loss of machine on ignition
Lime	95.6	0.96	—	—	—	0.06	3.38	—
Zeolite	2.42	2.37	62.87	13.46	1.33	—	2.87	14.68

2.2 Test method

The retrieved expansive soil was air-dried and crushed, sieved and dried in an oven at 108 °C for later use. In this paper, the test admixture adopts the internal mixing method. The lime content is 2%, 4%, 6%, and 8% (mass fraction, the same below), and the zeolite powder content is 0%, 4%, 8%, 12%, and 16%, respectively. At the same time, the plain soil sample is prepared to compare the improvement effect.

The test method is carried out in strict accordance with the' standard of geotechnical test method ' (GB/ T50123-2019) and' test specification for highway inorganic binder stabilized materials ' (JTG E51-2009). Compaction test, free expansion rate test and liquid plastic limit test are carried out respectively to determine the relevant parameters of improved expansive soil with different lime and zeolite powder

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contents.

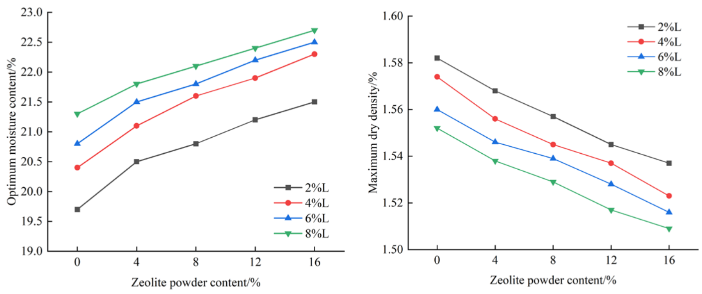
The height and diameter of the sample in the unconfined compressive strength test and the splitting tensile strength test are 5 cm cylinders. The static pressure method is used to prepare the sample, and the compactness is 95%. After the sample was prepared, it was cured for 7, 14 and 28 days under standard curing conditions (temperature control of 20±2°C, humidity control of 95±2%). The test equipment is CBR-III unconfined compressive strength tester, and the axial loading rate is controlled to be 1mm/ min.

The samples of unconfined compressive test with curing age of 28 d were selected, and the powder and block samples were made after air drying treatment. The SmartLab SE model X-ray diffractometer of Rigaku company in Japan was used for XRD test, and the Sigma 300 model scanning electron microscope of ZEISS company in Germany was used for SEM test.

3. Results and analysis

3.1 Compaction test

Fig.1 is the relationship between the optimal water content and the maximum dry density of the expansive soil improved by lime-zeolite powder and the dosage. It can be seen that when lime is added alone, with the increase of lime content, the optimal water content of expansive soil gradually increases, and the maximum dry density gradually decreases. When the lime content is constant, the zeolite powder content increases from 0% to 16%, the optimal water content of the composite improved expansive soil increases, and the maximum dry density decreases. This is because: the pozzolanic reaction between lime and zeolite powder promotes the improvement of expansive soil to consume more water, so that the optimal water content increases, so that the optimal water content increases; the pozzolanic reaction produces a gel material, which reduces the compactness of the improved soil, and the fine zeolite powder particles and hydration products fill the pores of the soil particles, making the soil more dense, resulting in a decrease in the maximum dry density [13].



(a) Optimum moisture content *(b) Maximum dry density*

Figure 1: Relationship between the optimal water content and the maximum dry density and the dosage

3.2 Free swell test

Fig.2 is the relationship between the free expansion rate and the dosage of lime-zeolite powder modified expansive soil. It can be seen from Fig.2 that the addition of lime and zeolite powder effectively reduces the free expansion rate of expansive soil. Even if a small amount (2%) of lime is added, the free expansion rate of soil decreases significantly. The free expansion rate of unimproved expansive soil is 58%. When lime is added alone, the lime content increases from 2% to 6%, and the free expansion rate decreases from 38% to 29%. With the increase of lime content, the free expansion rate gradually decreases. When the lime content is 2%, 4% and 6%, the addition of zeolite powder significantly reduces the free expansion rate of expansive soil. Taking 6% lime content as an example, with the increase of zeolite powder content from 0% to 12%, the free expansion rate of the composite improved soil decreases from 29% to 22%, and decreases with the increase of zeolite powder content. When the zeolite powder content reaches 16%, the inhibition effect on the free expansion rate is weakened. When the lime content is 8%, with the increase of zeolite powder content, the free expansion rate of composite improved soil shows a continuous upward trend.

This is due to: the addition of lime will release Ca^{2+} ions, due to cation exchange and flocculation, resulting in the aggregation of soil particles, thereby reducing the free expansion rate [5]. With the addition of zeolite powder, the pozzolanic reaction occurs between lime and zeolite powder, which

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enhances the cation exchange and flocculation, thus reducing the free expansion rate. However, when the lime is excessive, too much flocculent material is generated and accumulated in the upper part of the sample, resulting in an increase in the free expansion rate. At this time, the addition of zeolite powder further increases the flocculent material, resulting in a higher free expansion rate.

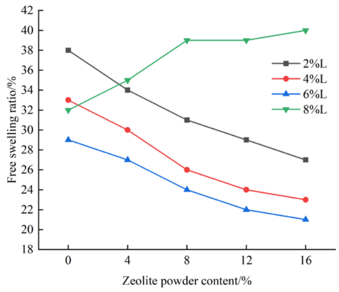
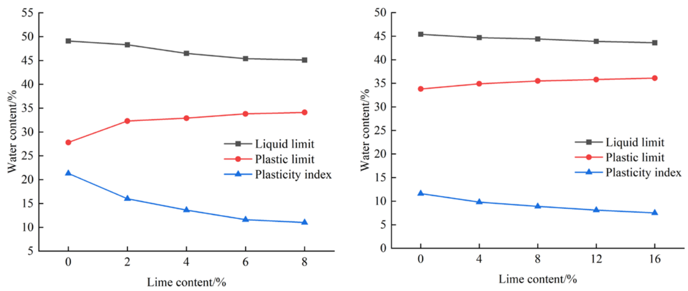


Figure 2: Relationship between free expansion rate and dosage

3.3 Liquid plastic limit test

Fig.3 is the relationship between the liquid plastic limit and the dosage of lime-zeolite powder modified expansive soil. The relationship between the liquid plastic limit and the dosage of lime-modified expansive soil is shown in figure 3 (a). It can be seen that with the increase of lime content, the liquid limit and plasticity index of lime-modified expansive soil gradually decrease, and the plastic limit gradually increases. Both tend to be stable when the lime content reaches 6%. When 6% lime is added alone, the liquid limit of lime-improved expansive soil is 45.4%, which is 3.7 percentage points lower than that of plain soil (49.1%). The plastic limit of improved soil is 33.8%, which is 6 percentage points higher than that of plain soil (27.8). The plasticity index of improved soil is 11.6, which is 9.7 percentage points higher than that of plain soil (21.3).



(a) Single doped L *(b) 6%L+Z*

Figure 3: Relationship between liquid plastic limit and dosage

In view of the fact that the liquid plastic limit of the composite improved expansive soil with different lime content is similar to that of the zeolite powder content, this paper only lists the relationship between the liquid plastic limit and the content of the composite improved expansive soil when the lime content is 6%, as shown in Fig.3 (b). It can be seen from Fig.3 (b) that when the lime content is 6%, under the combined action of lime and zeolite powder, the plastic limit of the composite improved soil increases with the increase of zeolite powder content, and the liquid limit and plasticity index decrease with the increase of zeolite powder content. When the content of zeolite powder increased to 12%, the liquid limit of the composite improved soil decreased to 43.9%, the plastic limit increased to 35.8, and the plastic index decreased to 8.1%. This is because lime can produce ion exchange with the mineral composition in the soil, so that the electric double layer of the soil particles becomes thinner, the bound water is reduced, and the soil particles are flocculated, so that the liquid limit of the improved soil is reduced and the plastic limit is increased, resulting in a decrease in the plasticity index [17]. The addition of zeolite powder stimulates the activity of zeolite powder under alkaline conditions, and the pozzolanic reaction with lime continues to consume water. The resulting cementitious material reduces the specific surface area, and the fine zeolite powder particles fill the pores inside the soil and attach to the surface of the soil particles, which further reduces the plasticity index of the improved soil.

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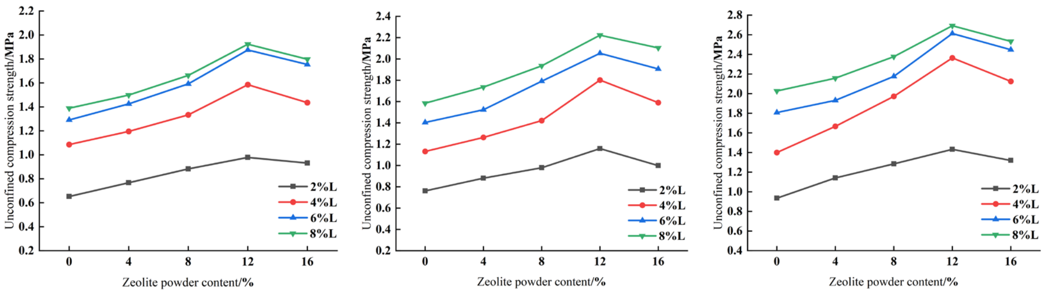
3.4 UCS test

The relationship between unconfined compressive strength and dosage of lime-zeolite powder modified expansive soil is shown in figure 4. It can be seen that at the age of 7 d, 14 d and 28 d, at the same lime content, the incorporation of zeolite powder effectively enhances the compressive strength of lime-improved soil. The compressive strength of the composite improved soil increases first and then decreases with the increase of zeolite powder content. When the content of lime is 2%, the content of zeolite powder increases from 0% to 12%, and the 7 d unconfined compressive strength of the composite improved expansive soil increases from 0.65 MPa to 0.98 MPa, which is 151% and 228% higher than that of the plain soil. When the content of zeolite powder increases to 16%, the compressive strength decreases. When the content of zeolite powder is 12% and the content of lime is 4%, 6% and 8%, the compressive strength is 1.59 MPa, 1.88 MPa and 1.92 MPa respectively, which is 370%, 437% and 447% higher than that of plain soil. This is due to the fact that the zeolite powder contains a large amount of SiO_2 and Al_2O_3, which reacts with lime to form a large amount of cementitious materials. These cementitious materials can fill the pores between the soil particles and cement the soil particles to form aggregates, thereby enhancing the strength of the soil. When the lime content is constant and the zeolite powder content is too much, there is not enough lime to react with it, which reduces the strength of the improved soil.



(a) 7 d *(b) 14 d* *(c) 28 d*

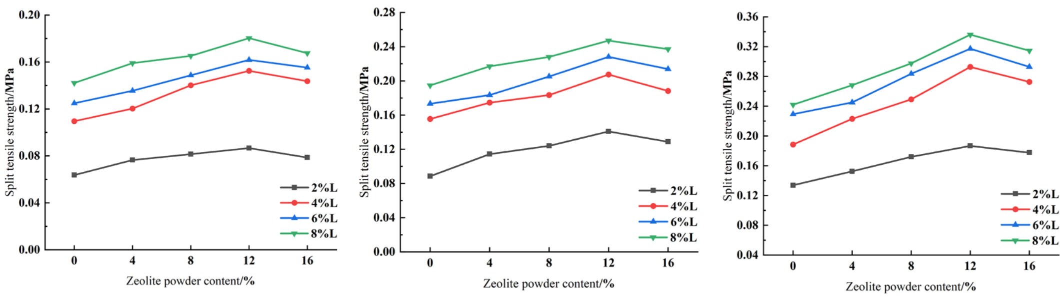
Figure 4: Relationship between UCS and dosage

When the content of lime and zeolite powder is constant, the unconfined compressive strength of the improved soil shows the same trend under the standard curing condition, and increases with the increase of age. Taking 6% lime and 12% zeolite powder as an example, the unconfined compressive strength of the composite improved soil increased from 1.88 MPa to 2.61 MPa when the age increased from 7 d to 28 d, which was 473% and 607% higher than that of the plain soil, respectively. It shows that the pozzolanic reaction of lime and zeolite powder is related to the age, because the degree of pozzolanic reaction increases with the increase of curing time, resulting in the increase of hydration products, thus improving the unconfined compressive strength of improved expansive soil, which is consistent with the research results of MohammadReza ShahriarKia et al. [15].

3.5 STS test

The relationship between splitting tensile strength and dosage of lime-zeolite powder modified expansive soil is shown in figure 5. It can be seen that, similar to the law of compressive strength curve, when the same lime content, with the increase of zeolite powder content, the splitting tensile strength of the composite improved soil increases first and then decreases, and reaches the maximum when the zeolite powder content is 12%. When the lime content is 2%, the zeolite powder content increases from 0% to 12%, and the 7 d tensile strength of the composite improved soil increases from 0.064 MPa to 0.087 MPa, which is 136% higher than that of the composite improved soil. When the lime content is 6%, the zeolite powder content increases from 0% to 12%, and the 7 d tensile strength increases from 0.125 MPa to 0.162 MPa, an increase of 129.6%. When the content of lime and zeolite powder is constant, the tensile strength increases with the increase of age under standard curing conditions. Taking 6% lime and 12% zeolite powder as an example, when the age increased from 7 d to 28 d, the tensile strength increased from 0.162 MPa to 0.317 MPa, an increase of 195.7%.

In summary, the amount of lime and zeolite powder is not the more the better. Considering the amount of material and the improvement effect, it can be concluded that the lime content of 6% and the zeolite powder content of 12% have the best improvement effect on expansive soil.



(a) 7 d *(b) 14 d* *(c) 28 d*

Figure 5: Relationship between STS and dosage

4. Microscopic mechanism

4.1 XRD test

In order to study the mineral changes of lime-zeolite powder improved expansive soil, the XRD spectrum of lime-zeolite powder improved soil at 28 d age is shown in figure 6. It can be seen that the main mineral components of the unimproved expansive soil are quartz and montmorillonite, and contain a small amount of feldspar and chlorite. Before and after the improvement of expansive soil, the peak shape in the XRD spectrum does not change much, and no new peak appears, but the diffraction intensity is different, indicating that there is no new mineral formation. The diffraction intensity of the main peak of quartz ($2\theta=26.8$) of the single-doped 6% lime-modified soil is significantly reduced, and the peak intensity of clay minerals is reduced, indicating that the hydration reaction between lime and minerals in expansive soil occurs, and C-S-H and C-A-H gel substances are generated. The diffraction peak intensity of 6%L+12%Z composite improved soil is further reduced. This is because the addition of zeolite powder increases the SiO_2 and Al_2O_3 required for pozzolanic reaction, which makes the pozzolanic reaction more sufficient and generates more gel material, so that the cohesive force between soil particles is enhanced, thus enhancing the strength of soil.

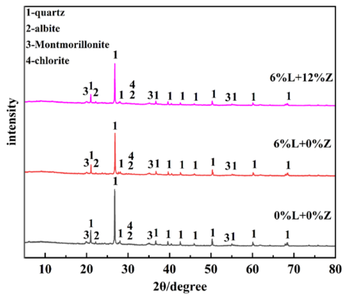
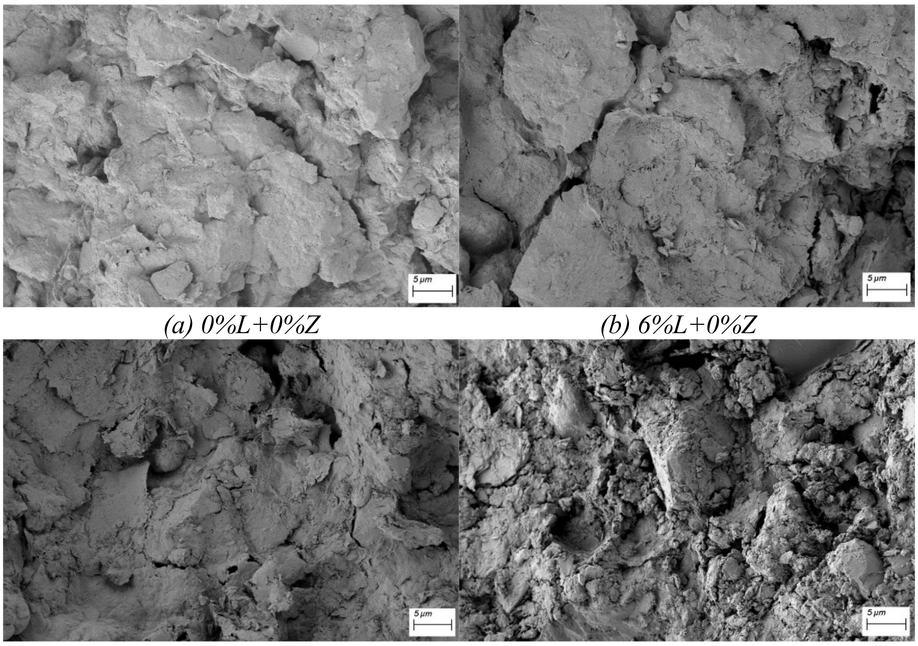


Figure 6: XRD diffraction results

4.2 SEM test

In order to study the microstructure change of strength development of lime-zeolite powder, the SEM photos of lime-zeolite powder modified expansive soil at 28 d age were 2000 times as shown in figure 10. It can be seen from Fig.7 (a) that the soil particles of the unimproved expansive soil mostly exist in the form of flakes or layers. The surface pores of the soil are large and the number is large. The contact between the soil particles is mainly surface-surface contact and edge-surface contact. It can be seen from Fig.7 (b) that the hydrates generated by the hydration reaction of 6% lime-improved soil mainly exist in the form of flocculation and aggregates. The hydrates cement the soil particles to form aggregates, fill the pores between the soil particles, reduce the pores, and enhance the supporting effect of the soil skeleton.

It can be seen from Fig.7 (c) that when the content of zeolite powder is 4%, the number and size of pores on the surface of the soil are further reduced. The addition of zeolite powder reacts with lime to form more hydration products, which makes the cementation between soil particles closer and improves the integrity of the soil, thus further improving the strength of the soil. It can be seen from Fig.7 (d) that when the zeolite powder content is 12%, the pozzolanic reaction is more sufficient due to the increase of the zeolite powder content. On the one hand, a large amount of cementitious material is generated after the reaction, which fills the pores between the soil particles and cements the soil particles to form aggregates. On the other hand, the zeolite powder particles that are not involved in the reaction attach to the surface of the soil, fill the pores, improve the compactness of the soil, and enhance the mechanical bite force between the soil, thereby improving the overall strength of the soil.



(a) 0%L+0%Z *(b) 6%L+0%Z*

(c) 6%L+4%Z *(d) 6%L+12%Z*

Figure 7: SEM images of different dosage of improved soil

5. Conclusion

(1) The incorporation of zeolite powder increases the optimal water content of lime-modified expansive soil and reduces its maximum dry density. The incorporation of lime can effectively reduce the free expansion rate of expansive soil. When the lime content is 2%~6%, the free expansion rate of lime-modified soil is further reduced after the incorporation of zeolite powder. When the lime content is 8%, the incorporation of zeolite powder will increase the free expansion rate. With the increase of lime and zeolite powder content, the liquid limit and plasticity index of the improved expansive soil decrease, and the plastic limit increases.

(2) The incorporation of lime and zeolite powder can effectively improve the unconfined compressive strength and splitting tensile strength of expansive soil. When the content of zeolite powder increases from 0% to 12%, the compressive strength and tensile strength show an increasing trend, but when the content of zeolite powder reaches 16%, the strength decreases. The compressive strength and tensile strength increased gradually with the increase of curing age from 7 d to 28 d. Considering the material dosage and the improvement effect of the strength of the improved expansive soil, the optimum dosage of the improved material is determined to be 6% lime content and 12% zeolite powder content.

(3) Zeolite powder reacts with lime to form C-S-H and C-A-H gel materials, which fill the pores between soil particles and cement soil particles to form aggregates, making the soil structure more dense and enhancing the soil strength. The zeolite powder particles that are not involved in the reaction are attached to the surface of the soil, which increases the interlocking effect between the soil particles, thereby improving the strength of the soil.

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