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Effect of Polymeric Agent on the Strength and Water Stability of Cement-Stabilized Construction Waste Soil

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Abstract: Due to the large output of construction waste soils, it has become an enormous challenge for human society and the ecological environment. The purpose of this paper is to discuss the possibility of using a stabilized waste soil in road engineering. Cement and polymer stabilizers were added to the waste soil, and the effect of the stabilizer on the strength and water stability of the stabilized soil was studied. The structure and morphology of the specimens were analyzed using an X-ray diffractometer (XRD) and a scanning electron microscope (SEM). The results show that the unconfined compressive strength increases by 25.0% and the 28-day water stability coefficient, K increases by 59.6% after the addition of the stabilizer. The XRD curve shows that the addition of the new stabilizer does not produce a new characteristic peak, but the diffraction peak strength of some minerals can be improved. SEM shows that the surface of stabilized soil particles is covered by materials, and the particles show obvious agglomeration, forming a network structure, which improves the strength and water stability of the soil.

Keywords: construction waste soil; polymer stabilizer; unconfined compressive strength; water stability; microstructure

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Citation: Li, H.; Gao, P.; Zhang, C.; Guo, S.; Zhang, J. Effect of Polymeric Agent on the Strength and Water Stability of Cement-Stabilized Construction Waste Soil. *Sustainability* **2023**, *15*, 15571. https://doi.org/10.3390/su152115571

Academic Editor: Hosam Saleh

Received: 24 August 2023
Revised: 20 September 2023
Accepted: 22 September 2023
Published: 2 November 2023

1. Introduction

With urbanization and modernization in China, transportation, as the key carrier of personnel and materials flow, plays an important role in narrowing the distance between production factors. As of 2021, the total mileage of highways in China has exceeded 1.6 million Km, which has effectively alleviated the tense transportation situation in China and significantly improved the country's comprehensive national strength and competitiveness. But it also brought negative effects of environmental damage. Soil erosion is one of the main environmental problems faced by highway construction. The construction of highways inevitably involves changes in terrain, disturbance of soil structure, and destruction of vegetation. According to statistics, the average annual soil and water loss caused by development and construction activities in the country amounts to over 10,000 square kilometers, with an annual loss of over 800 million tons. It has now posed a great threat to the ecological environment of the entire region. In the context of China's imperfect highway soil and water conservation system and immature technology, in terms of highway transportation construction, the construction of a highway can generate hundreds of thousands or millions of cubic meters of construction waste soil. For example, the Changzhi to Handan Expressway only produced 993,000 tons of soil erosion due to waste soil (slag). These soils are usually of low strength and poor water stability, making it difficult to apply directly to construction [1–4], but soil replacement will greatly increase the cost, so it is important to improve the properties of the existing soil.

Landfills are still the main method for construction waste soil, and landfill waste soil is the simplest traditional way of utilizing waste soil. Generally, in the early, middle, and later stages of various construction projects, it is necessary to fill and level the pit, balance the site elevation, and absorb some newly discharged waste soil on-site. However, the waste soil used in the project must be of good properties, have suitable moisture content, not be contaminated, and have good construction performance, which is relatively rare in practical engineering.

There are also processes such as drying and dehydration that optimize the excellent physical and chemical properties. Generally, there are methods such as sun drying and forced dehydration. Sun drying doesn't require mechanical equipment and energy but requires open fields; Forced dehydration is the process of separating construction waste soil through a soil sand sieve, separating larger particles, and adding coagulants to the sludge and clay for pressurized dehydration. This method not only requires open fields but also requires some mechanical equipment and energy consumption.

By chemical treatment, the waste soil is stabilized. After comprehensive investigation, solidification technology is currently the most widely used, economical, and cost-effective method in the utilization of waste soil. Chemical treatment with traditional stabilizers such as lime and cement can effectively alter several basic engineering properties of soils [5]. However, cement stabilization in soils may increase the stiffness and may lead to brittle soil behavior. In addition, stabilizers such as cement and lime have caused serious environmental problems over the past decades, with cement production responsible for about 8% of man-made carbon dioxide emissions globally [6,7]. According to an estimation by the US Geological Survey, China, with an output of 2.5 million tons of CO_2 in 2021, continues to be the biggest cement producer. Given the carbon emission issues and non-renewable raw materials, it makes sense to develop more environmentally friendly and economical stabilizers to replace Ordinary Portland Cement (OPC) [8–10].

Polymer materials have gained widespread attention as a green and economical soil stabilizer [11–20]. Adding the appropriate amount can improve the stabilization efficiency per unit of cementitious material dosage. It also alleviates to some extent, the dependence on quicklime and cement. Compared with uncured cemented soils, polymer materials have significant economic benefits when mixed with small amounts of cement or fly ash. Although the research on soil stabilizer technology has made certain improvements, the design requirements are mainly for unconfined compressive strength, some curing technology in water stability is still deficient [21], resulting in shortening the service life of the road base material. Therefore, how to improve the water stability performance of stabilizers has become a key issue for more and more scholars.

In this paper, a new polymer stabilizer and cement are used to stabilize the soil, and the soil is studied by unconfined compressive strength (UCS) test and water stability coefficient (WSC) tests with different dosing levels. This study is conducted to provide a scientific basis for the study of polymeric stabilizers and to provide theoretical support for the application of stabilizers. Polymeric stabilizers promote resource conservation and intensive utilization by improving the level of resource reuse and recycling which effectively improves the local engineering environment and achieves an organic combination of ecological protection and sustainable development such as waste reuse.

2. Materials and Methods

2.1. Materials

2.1.1. Soil

The experimental soil was taken from a disposal site in Anhui Province for a highway renovation project. Before taking the soil, impurities like surface miscellaneous fill and grassroots should be taken out. In natural conditions, the soil is yellow-brown in color, with a sticky and sandy texture when you twist it open. There are small blocks of soil with a particle size of about 5 cm, and the porosity is high, with fine-grained soil particles accounting for 60% to 70% of the total mass. The soil sample is loose. We have conducted a number of experiments on the soil, and the properties and chemical composition of the soil, as shown in Tables 1 and 2.

Table 1. Properties of selected soil.

Property	Value
Optimal Water content (%)	15.00
Maxi. dry unit weight (g/cm^3)	1.87
Liquid limit (%)	29.50
Plastic limit (%)	15.26
Plasticity index	14.24

Table 2. Chemical composition of soil.

Composition	Content (%)
SiO_2	64.50
Al_2O_3	14.74
Fe_2O_3	6.40
CaO	2.07
MgO	1.74

2.1.2. Polymeric Stabilizer

The polymer stabilizer is purchased from a company in Qingdao, China, and is a light-yellow transparent liquid in the form of a water dispersion system. It mainly consists of water-glass-modified polyurethane, carboxymethyl cellulose (CMC), $MgCl_2$ and $MgSO_4$, etc. It can quickly form a network structure on the surface and inside of the soil, and the generated colloid can bond the soil particles together, enhance the intermolecular interaction, and improve the strength and water stability (Figure 1).

Figure 1. Polymeric stabilizer.

2.1.3. Cement

The chemical composition of the Ordinary Portland Cement (P·O 42.5) used in this study is shown in Table 3, and the cement quality conforms to the American Portland Cement Standard Specification (ASTM 150) [22] and European Standard (EN196) [23].

Table 3. Chemical composition of cement.

Composition	Content (%)
CaO	56.86
SiO_2	25.07
Al_2O_3	7.40
Fe_2O_3	3.84
SO_3	2.14
MgO	0.71

2.2. Methods

For the purposes of this study, a series of unconfined compressive tests were performed on stabilized soils under standard and submerged curing conditions. Moreover, Scanning Electron Microscope (SEM) and XRD tests are also performed on the soils and stabilized soils under standard curing. The specific process for the test is as follows. Based on the preliminary experimental results, the design mix ratio is shown in Table 4.

Table 4. Experiment scheme.

Scheme Number	Cement (%)	Stabilizer (‰)	Test Items
0	0.0	0.0	UCS test
1-1	0.0	3.0	UCS test, SEM
1-2	2.0		UCS test
1-3	4.0		UCS test
1-4	6.0		UCS test
1-5	10.0		UCS test
2-1	8.0	0.0	UCS test, Water stability test, XRD test and SEM
2-2		1.0	UCS test, Water stability test
2-3		2.0	UCS test, Water stability test
2-4		3.0	UCS test, Water stability test, XRD test and SEM
2-5		4.0	UCS test, Water stability test
2-6		5.0	UCS test, Water stability test

2.2.1. Unconfined Compression Tests

Before preparing the test samples, the soil was dried in an oven at 105 °C for 10 h, ground, and sieved. The amount of water added to each sample was calculated according to the optimal moisture content and the amount of stabilizer, which was weighed in advance of the stabilizer dissolved in water, made into a solution, and then the water (to facilitate the molding, reserved 1% of the water in the molding of the test piece to be used) and the stabilizer solution was added to the dry material mix to produce a homogeneous mixture, which was then put in a plastic bag stuffy material for 12 h.

The molding of the specimen must be completed within one hour. One hour before the specimen was molded, a predetermined amount of cement and water was added and mixed well, the specimen was loaded into a φ 50 mm × h 50 mm test mold, the upper and lower pressure columns were pressed into the mold, and then the specimen was made by a pressure tester. In addition, after each compaction, the static pressure was continued for 5 min to prevent rebound. After completion, the molds were removed and placed in a plastic bag. 6 samples need to be made for each ratio. The specimens were cured in a standard curing room at a temperature of (20 ± 2) °C and relative humidity > 95% for 7 days, and then the UCS test was performed.

The USC of the specimens was tested using a 1C-200 pavement material strength composite tester.

2.2.2. Water Stability Test

For the water stability test, the specimen preparation process is the same as the UCS test, with the difference that after 7 days in the conditioning room, instead of testing, the specimens continue to be immersed in water for 3, 7, and 28 days. Prior to testing, the specimens are removed and left to stand for 30 min. The surface water was absorbed with a soft cloth and weighed, and the UCS was subsequently determined. A series of UCS tests were carried out on these specimens according to the Chinese Test Methods of Soils for Highway Engineering (JTG E40-2020) [24] and the Chinese Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering (JTJ E51-2009) [25] an index of water stability.

The USC of the specimens was tested using the 1C-200 type pavement material strength comprehensive measuring instrument.

$$K = \frac{q_{wt}}{q_t} \tag{1}$$

where q_{wt} is the average UCS of the specimens under immersion curing for t days, q_t is the average UCS of the specimens under standard curing for t days.

2.2.3. Scanning Electron Microscope (SEM)

The Scanning Electron Microscope (SEM) technique is widely used in the analysis of micro-structure and micro-material of soils. After the 7 d UCS test, place the soils in anhydrous ethanol for 24 h and stop hydration. The soils are then dried in a vacuum drying oven (40 °C) for 24 h and cut into small pieces less than 2 mm in thickness, 3 mm in width, and 8 mm in length. The SEM of the specimens was tested using a scanning microscope JSM-6510 (Starjoy Limited, Japan) to observe the microscopic morphology of the soil.

2.2.4. X-ray Diffraction (XRD) Testing

X-ray diffraction (XRD) is widely used as a common basic detection technique for the interpretation of soil minerals. In this paper, we analyze the soil's structural mineralogical changes induced by cement and stabilizer to determine and identify whether new crystalline compounds are formed during the stabilization process. After the 7 d UCS test, place the soils in anhydrous ethanol for 24 h and stop hydration, then place in an oven at 40 °C for 24 h. The dried specimens are ground and passed through the 0.125 mm sieve and analyzed for stabilized soil phase composition using an X-ray diffractometer (Bruker-Axs D8 DISCOVER, Bruker-Axs, Germany).

3. Results and Discussion

Table 5 presents the results of the average UCS and K of soils. Each UCS test in Table 5 is a one-form six, the abnormal test data is excluded according to statistical theory.

Table 5. UCS and K of soils.

Scheme Number	UCS (MPa)	K		
		3 d	7 d	28 d
1-1	1.0	-	-	-
1-2	1.7	-	-	-
1-3	2.5	-	-	-
1-4	3.5	-	-	-
1-5	4.5	-	-	-
2-1	4.0	0.58	0.54	0.52
2-2	4.2	0.75	0.72	0.70
2-3	4.5	0.87	0.81	0.74
2-4	5.0	0.92	0.87	0.83
2-5	4.7	0.89	0.82	0.81
2-6	4.3	0.84	0.79	0.76

3.1. Results of UCS of Stabilized Soil

3.1.1. Effect of Cement Content on UCS

As shown in Figure 2, the UCS shows a trend of increasing and then decreasing with the increase in cement content. When the cement content is 8%, the specimen has the largest strength of 5.0 MPa, which is 11.1% to 400.0% higher than the UCS of the other five groups of specimens, higher than the highest standard in Chinese regulations of 4.5 MPa. This implies the existence of an optimum cement admixture. This finding is similar in nature to the existence of an optimum mixing level for lime-stabilized soils. In a water-rich environment, lime reacts with the alumina in the soil to form calcium aluminate hydrate, which further reacts with the ions in the soil to form calcium sulphoaluminate hydrate (AFt) to produce volume expansion, which increases in volume by about 120%, eventually leading to expansion and destruction of the subgrade.

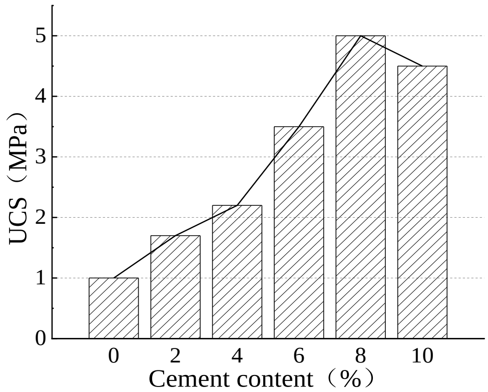


Figure 2. Effect of cement content on UCS.

The reason for this phenomenon is [26–29] the water content in the soil is limited, and when the cement content is small, the stabilizer is unevenly distributed in the soil and can only partially fill the pores; with the increase of the content, a spatial network structure is formed, the pores are gradually reduced, the densification is increased, and the colloidal bonding effect is enhanced, therefore the strength is increased. However, if the content is too much, the generation of colloids increases, and the internal expansion destroys the formation of the skeleton. At the same time, it reduces the connection between particles, which easily causes separation between particles and reduces the strength.

When the cement dosage is low, the strength of the soil is very low (around 1–2 MPa), and if the strength is to be guaranteed, it must contain more cement content. However, an increase in cement content will increase the cost, and shrinkage and cracking may occur. In the test process, it was found that after adding cement, the UCS damage of the soil was mostly brittle, and with the increase of cement content, the brittle damage became more and more obvious, and even a clear crumbling sound could be heard. So, it's best to keep the cement content in the right range.

3.1.2. Effect of Stabilizer Content on UCS

As shown in Figure 3, the UCS of the soil increases after mixing with the stabilizer, but obviously not as much as the effect of cement content. When the cement content is 8% and the stabilizer content is 3‰, the USC of the soil is 5.0 MPa, which increased by 25% compared to the 2-1 group without stabilizer; the remaining USC increased by 5–17.5%, indicating that the stabilizer used has a good stabilizing effect.

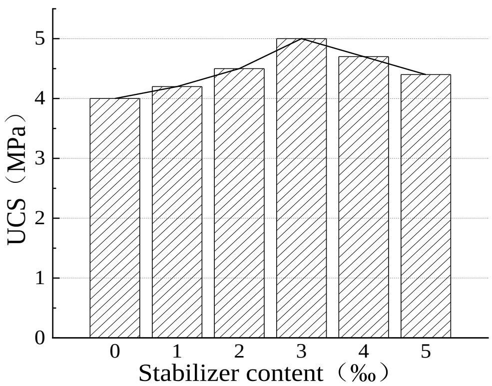


Figure 3. Effect of stabilizer content on UCS.

A more interesting thing is that there is also an optimal amount of the stabilizer, and simply increasing cement and stabilizer content couldn't effectively improve the strength. This is because adding stabilizers could generate calcium silicate and silica particles with multivalent metal ions and pore water in the soil, filling the gaps between soil particles and improving soil strength. By combining the adsorption groups on the polymer chains with the surface of soil particles, a spatial network structure was formed on the surface and inside, filling the pores and wrapping particles, which causes particles to aggregate, thus improving the soil strength. The hydrolyzed Sulfate-ion reacted with Calcium-ions to react with Alumina to form AFt. The generation of AFt increased, which could fill the pores of stabilized soil, improving its compactness and strength. However, if an excessive amount of stabilizer is added, the excessive products would destroy the stable structure because the stabilizers that cannot participate in the reaction are acting as a "lubricant" in the soil, which may lead to structural damage and reduced strength.

3.1.3. Results of *K* of Stabilized Soil

Since scholars have studied the water stability of hydraulic soil more, this paper is no longer aimed at the effect of cement content on stabilized soil and mainly focuses on the effect of stabilizers on the water stability of the soil.

The results of the effect of stabilizer content on water stability coefficient *K* are shown in Figure 4. Similar to the results of the UCS test, *K* also shows a tendency to increase and then decrease with the increase of stabilizer content. This result verifies the inference that there is also an optimal content of stabilizer.

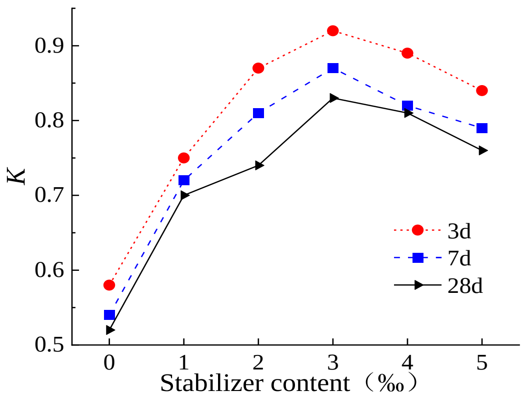


Figure 4. Effect of Stabilizer content on *K*.

It can be noted that the incorporation of a stabilizer can improve the water stability of the stabilized soil more significantly than the cement soil without a stabilizer. The addition of different amounts of stabilizer can increase the *K* of 7 d by 34.6% to 59.6%.

When the content of the stabilizer is lower than 3‰, and with the increase of stabilizer content, the stabilizer carries out the reaction to fill the pores inside the soil, therefore the strength loss of the specimen is slowed down, but the effect is not obvious when the doping amount is low.

When the stabilizer content is higher than 3‰, because of too much stabilizer content, although the reaction occurs, the reaction product produces volume expansion, which makes it easy for water to enter the interior of the soil body from the pores produced by the expansion, but due to the repulsive nature of the stabilizer itself, it can reduce the water that enters the interior of the soil body, so the loss of strength is small compared to the low stabilizer content.

We can also see that: when the stabilizer content is 3‰, the water immersion time increases from 3 days to 7 days, *K* decreases from 0.92 to 0.86, a decrease of 6.52%; the water immersion time increases from 7 days to 28 days, *K* decreases from 0.86 to 0.84, a decrease of 2.33%. This is due to the initial completion of the reaction of cement and stabilizer in the soil after 7 days of immersion, the internal structure of the soil body is gradually stabilized, the pore space is basically filled, and the path for water to enter the internal soil body is reduced, so the change of K in the early stage is more obvious.

The results also show that [18,30,31] the increase in immersion time has a negative effect on the water stability of the soil. Under the condition of prolonged soaking, water would gradually infiltrate through the pores leading to the gradual enlargement of the pores of the soil, and the enlargement of the pores would not only make it easier for water to enter but also make particles connection gradually weaken, which would destroy the mechanical structure of the soil and reduce the K of the stabilized soil.

In order to better predict the effect of stabilizer content on K, we fit the curve of water stability coefficient K, which can be obtained in Figure 5. The fitting results are in good agreement with the experimental data, and the correlation coefficient R-squared and the adjusted R-squared are both greater than 0.9.

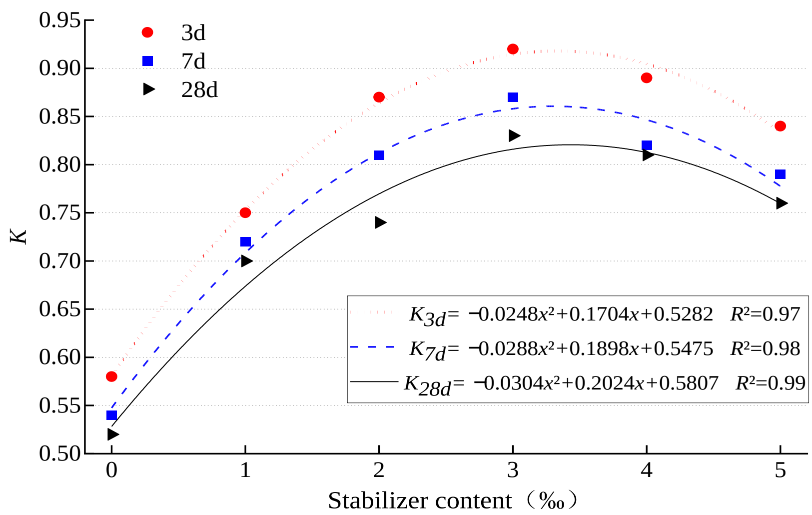


Figure 5. Fitting results on K.

4. Microscopic Analysis of Stabilized Soil

The addition of a polymer stabilizer leads to a change in microstructure. Also, the strength of the soil changes with the microstructure. Microstructure analysis helps to analyze the mechanism of soil stabilization and strength development by the addition of stabilizers.

4.1. XRD Analysis

To further clarify the mechanism of the effect of the polymeric stabilizer on cement soil, X-ray diffraction (XRD) tests were performed on the specimen without stabilizer and the specimen with 3‰ stabilizer. The results of the XRD analysis are shown in Figure 6.

The result shows that no new characteristic peaks were generated in the diffraction curves and that there was no significant difference in the material composition of the specimens before and after stabilization. This indicates that no chemical reaction or no new compounds were generated in the cement soil by adding the stabilizer. It is presumed that [32–34] the reactive groups of water-glass-modified polyurethane and CMC physically interact with the surface groups of soil particles to form a reticular structure and gel; cement can react in soil to produce water-insoluble silicate lime hydrate (C-S-H) and aluminate lime hydrate (C-A-H), etc., while water-glass can also react with cement to produce C-S-H, so the original characteristic peaks are enhanced.

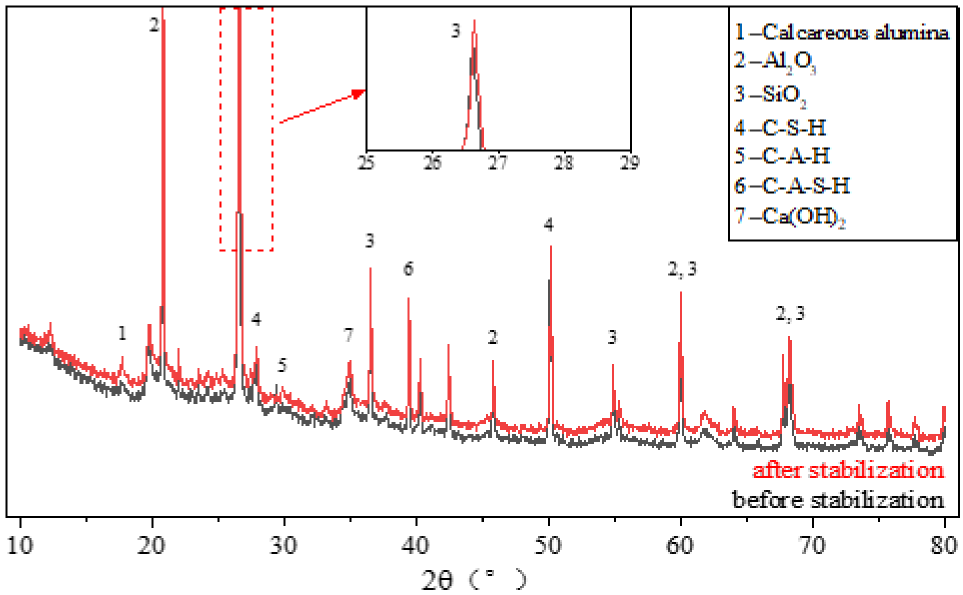
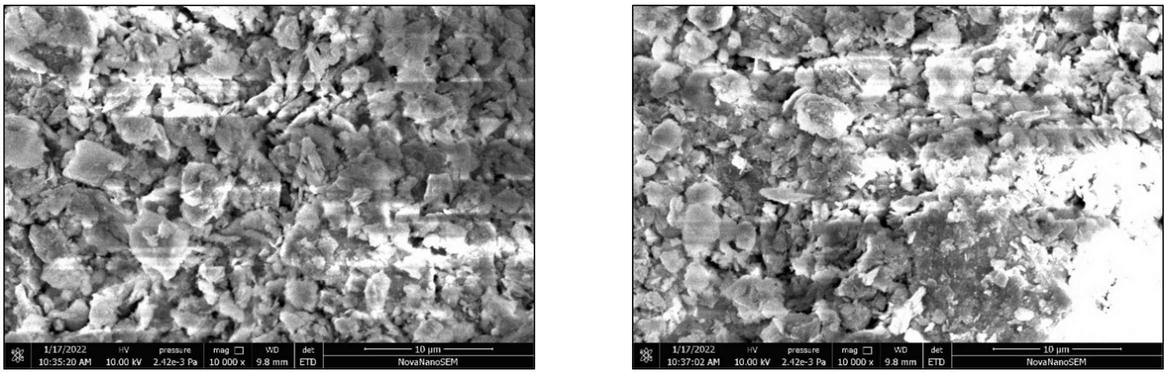


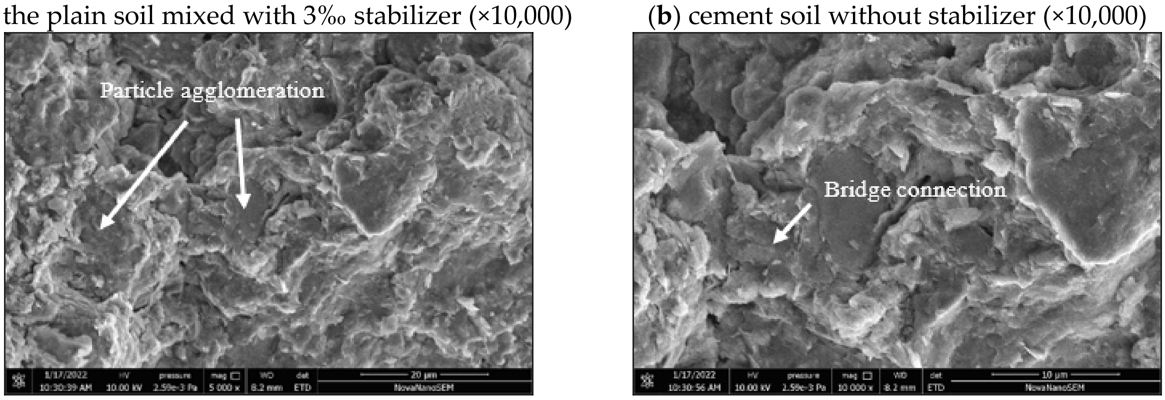
Figure 6. XRD patterns of the specimens.

4.2. SEM Analysis

To evaluate the soil structure changes and clarify the interaction between the stabilizer and soil particles, the plain soil mixed with 3‰ stabilizer, cement soil without stabilizer, and the cement soil mixed with 3‰ stabilizer were subjected to SEM images analyses (5000–10,000 times magnified), as shown in Figure 7.



(**a**) the plain soil mixed with 3‰ stabilizer (×10,000) (**b**) cement soil without stabilizer (×10,000)



(**c**) cement soil mixed with 3‰ stabilizer (×5000) (**d**) cement soil mixed with 3‰ stabilizer (×10,000)

Figure 7. SEM images of the specimens.

As seen in the SEM image, the soil particle morphology of the plain soil sample mixed with 3‰ stabilizer is still angular and sub-angular, with clear angles. The particles in the soil are mostly in point contact, with a small contact area, larger inter-particle pores, and looser structure (vide Figure 7a). The degree of compactness of the microscopic morphology of cement soil without stabilizer is increased. Some of the particles are covered or connected by flocculent C-S-H gel and agglomerated, but the pores between the particles can still be seen (vide Figure 7b). The particle morphology is mainly sub-angular and sub-round which increases the contact area and makes the interparticle connection force stronger, therefore the particles bond to form a more densely structured whole, and the strength is significantly improved.

For the cement soil mixed with 3‰ of stabilizer, compared with Figure 7b, the membrane structure on the particle surface is more obvious after adding this stabilizer, and the morphology of the soil particles could not be distinguished (vide Figure 7c,d). The soil particles show an obvious agglomeration phenomenon between each other and form a large number of "bridge" connections, which form a larger and more stable agglomerate, thus improving the overall strength.

In addition, the formed film structure and "bridges" not only make the structure dense and reduce the infiltration rate of water but also have better adsorption of water and reduce the contact between water and soil particles, so that the water stability of the soil is improved.

5. Conclusions

The following conclusions can be drawn from the experimental results and analyses provided above:

(1) The water-glass-modified polyurethane within the stabilizer itself has active groups interacting with the surface groups of the soil particles, forming a spatial network structure, while the water-glass from hydrolysis reacts with water, $Ca(OH)_2$ and metal ions produced by hydrolysis of cement to generate a gel, which fills in the pores and enhancing the adsorption between particles.

(2) CMC mixed with soil containing certain moisture will also produce a gel, fill the pores, and play a bonding role, forming the soil's mechanical structure.

(3) The mechanical structure and colloid formed by the addition of the stabilizer makes the pores in the soil decrease, blocking the channels for water to enter the interior, increasing the strength of the connection between the particles, reducing the strength loss, and increasing K.

(4) $MgCl_2$ and $MgSO_4$ can provide Mg^{2+}, enhance the interaction between polymer chains through ion exchange, improve the strength of the mesh structure, and thus improve the UCS. Mg^{2+} can also reduce the adsorption capacity of soil particles to water, thus improving water stability.

The polymer stabilizer can improve the UCS and the water stability properties of the cement soil more obviously. Compared with cement soil, the soil added with this stabilizer has characteristics of high strength and a high water stability coefficient, indicating that waste soil can be used for road bases after stabilization; the stabilized soil is mainly made of "waste soil" as the main material, without the need for excavation or transportation of waste original soil. The on-site collection of materials for solidification saves a large amount of transportation and labor costs, shortens the construction period, and compared with traditional technologies, the soil solidification agent solidification construction waste technology can reduce the comprehensive cost by more than 30%.

Author Contributions: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Writing—Original Draft, H.L., Validation, Writing-Review & Editing, Supervision, Project administration, P.G., Resources, Data Curation, C.Z., Validation, Writing-Review & Editing, S.G., Supervision, Project administration, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded in part by the Natural Science Foundation of Jiangsu Province (BK20200429), the National Natural Science Foundation of China (Grant No. 52308470), National Key R & D Program of China (Grant No. 2022YFC3102902), Natural Science Basic Research Program of Shaanxi (Grant No. 2023-JC-YB-375), Technology Innovation Center Project of Shanxi (202104010911016), CRCC Fourth Engineering Bureau (22040), China Design Group (KFB21498) and Suzhou Rail Transit Group Co., Ltd. (22088).

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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