Study on the Improvement of Waterproof Performance of Historical Silt Sites with Silicone Waterproofing Agent

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Abstract: Silt has the characteristics of obvious capillary water effect and strong water sensitivity. The flooding of the Yellow River caused the water level in Kaifeng to be high, and the damage of capillary water to the silt site of Kaifeng Zhouqiao site is increasing day by day. In order to improve the waterproof performance of the site soil, three kinds of silicone waterproof materials were selected, and the site soil was improved by internal mixing. The improvement effects of different materials were compared through the capillary water rise test, and the contact angle of the modified soil with the optimal ratio was measured. Microscopic tests were conducted to evaluate its wetting properties and reveal the mechanism of action of the modified materials. The results show that the three kinds of silicone waterproofing agents can improve the waterproofing effect of soil, among which 0.5% sodium methylsilicate modified soil has the most significant waterproofing effect; its capillary water absorption inhibition effect can reach 98.34%, and the contact angle is 137.06. The surface of the modified soil is hydrophobic after the addition of sodium methylsilicate. An evenly distributed waterproof film is thus formed on the surface of the soil particles, which changes the contact mode between the soil particles and strengthens the connection between the soil particles, so that the proportion of large pores decreased. The proportion of mesopores and small pores increased, which made the soil sample more compact. These results explain the improvement of the waterproof performance of the soil sample.

Keywords: earth sites; silicone waterproofing agents; capillary rise; microscopic mechanism analysis

1. Introduction

Earthen sites are remaining traces of human activities in a certain environment, representing the prosperity of China’s history and culture. They are scientific, historical, artistic and non-renewable. The main component of the exploratory wall of Kaifeng Zhouqiao site is silt. Silt is a typical poorly graded soil, which often has the characteristics of poor stability of particle skeleton structure and large capillary porosity. Therefore, the harm of capillary water to silt sites is more serious than that of general soil sites [1,2]. Therefore, it is necessary to study the methods to control the capillary rise in silt sites.

At present, silicone-based water repellents are used in various buildings for their excellent waterproof performance. Silicon-acrylic emulsion was applied to soil ruins, and its reinforcement effect was evaluated through a series of laboratory tests, and it was found that it had good reinforcement strength and permeability [3,4]. Sodium methylsilicate showed an obvious effect in inhibiting shale hydration swelling and slurrying experiments, which prevented water from entering shale through the adsorption of a hydrophobic film formed by organosilicate [5,6]. Sodium methylsilicate can reduce the water absorption of concrete to a certain extent. The test results show that the microstructure of the sample with added sodium methylsilicate is more compact, and that insoluble crystals of various shapes block the pores and cracks of the concrete. As a result, the macroscopic properties of concrete, including waterproofing and impermeability, are improved [7,8]. Sodium methylsilicate has also been used to improve the silt soil in the yellowing area. Through
the compaction test, strength test and permeability test of the silt soil in the yellowing area mixed with sodium methylsilicate, it is considered that it can obviously improve the mechanical and impermeability of silt soil in the yellow-flooded area [9]. Polymethyltrietiethoxysilane is widely used in the hydrophobic modification of various materials, and different contents of methyltrietiethoxysilane have different modification effects on silica sol at different temperatures [10,11]. In the study of the effect of different amounts of polymethyltrietiethoxysilane on the structure and properties of the film, it was found that with the increase of the amount of methyltrietiethoxysilane, the hydrophobicity of the reflective film increased, and the contact angle increased from 11° to 93° [12,13].

Sodium methylsilicate, Polymethyltrietiethoxysilane and Silicone acrylic emulsion showed excellent waterproof performance in the above experiments, among which sodium methylsilicate and polymethyltrietiethoxysilane are relatively rarely used in the protection of soil sites [14,15]. In order to compare the improvement effects of three silicone-based waterproof materials on the site soil, the materials with the best waterproof effect and their proportions were selected through the capillary water rise experiment, and passed the contact angle test, X-ray diffraction (XRD) [16,17]. Ray fluorescence (XRF) and scanning electron microscopy (SEM) were used to evaluate their wetting properties and reveal the microscopic action mechanism of the modified materials, providing a feasible method for inhibiting the rise of capillary water in silt sites.

2. Materials and Methods

2.1. Materials and Sample Preparation

Kaifeng Zhouqiao is an ancient bridge over the Bian River in Kaifeng, Henan Province, China. The site was built in the Tang Dynasty, showing the development and evolution of the Bian River from the Tang and Song Dynasties to the present, such as the construction, use, prosperity and decommissioning, and is of great significance to the study of the Bian River section of the Grand Canal in China.

The materials used in the experiment are from the soil excavated during the excavation of Zhouqiao site in Kaifeng City, Henan Province. The experimental sample is light yellowish brown silt. First steps in treatment of the sample were as follows: Send the soil samples to the laboratory, and test the physical properties of the samples according to the standard for soil testing (gb/t50123-2019) [18]. The analysis results are shown in Table 1. Before the soil modification experiment, clear the obvious debris in the soil, grind the soil and pass through the 2 mm sieve. Then, take an appropriate amount of screened soil samples and dry them in an oven at 105 °C for at least 12 h to prepare the pretreated dry silt. Select three kinds of organosilicon materials for water-proofing: sodium methylsilicate, silicon-acrylic emulsion, polymethyltrietiethoxysilane. Their specific properties are shown in Table 2, and their chemical structure is shown in Figures 1–3.

| Soil Type | Density/g cm$^{-3}$ | Initial Water Content/% | Porosity/% | Liquid Limit/% | Plastic Limit/% | Plasticity Index |
|-----------|---------------------|-------------------------|------------|---------------|-----------------|-----------------|
| Silt      | 1.7                 | 6.8                     | 33.8       | 23.4          | 18.1            | 8.9             |

| Material                                      | Content | pH     | Save State        |
|-----------------------------------------------|---------|--------|-------------------|
| Sodium methyl silicate (SMS)                   | ≥99%    | 11–13  | Colorless Liquid  |
| Polymethyltrietiethoxysilane (POL)             | ≥99%    | ≥5     | Colorless Liquid  |
| Silicone acrylic emulsion (SAE)                | ≥48%    | 7–8    | White Lotion      |
After the initial testing and preparation, mix the three materials into the site soil in appropriate mass ratios and compare with the original soil samples. The ratios are shown in Table 3.

**Table 3. Different materials and proportions.**

| Numbering | Material                  | Content/% | Numbering | Material                  | Content/% | Numbering | Material                  | Content/% |
|-----------|---------------------------|-----------|-----------|---------------------------|-----------|-----------|---------------------------|-----------|
| SMS-1     | Sodium methyl silicate    | 0.1       | POL-1     | Polymethyltriethoxysilane | 0.5       | SAE-1     | Silicone acrylic emulsion  | 5         |
|           | Sodium methyl silicate    | 0.3       | POL-2     | Polymethyltriethoxysilane | 1         | SAE-2     | Silicone acrylic emulsion  | 10        |
| SMS-3     | Sodium methyl silicate    | 0.5       | POL-3     | Polymethyltriethoxysilane | 1.5       | SAE-3     | Silicone acrylic emulsion  | 15        |

Taking the sample SMS-1 as an example, the preparation process of the sample is as follows: first, put 2 kg of dry soil, 0.05 kg of water and 2 g of sodium methyl silicate into different containers; second, add 0.05 kg of water in small amounts to the container with sodium methyl silicate, and slowly stir the solution with a glass rod; third, slowly add the sodium methyl silicate solution to the dry soil, stir the soil sample fully and put it in a sealed bag for 12 h to make the solution evenly distributed in the whole soil sample; finally, the fully mixed soil sample is put into the mold. The manufacturing process of the test piece is shown in the Figure 4 and the completed sample is shown in Figure 5.

**2.2. Capillary Water Rise Testing**

In order to study the inhibitory effect of different modified materials and proportions on the capillary water absorption of silt, the capillary water rising test was carried out on the soil samples of the above groups. The specific test process is as follows: place a
permeable stone in a plexiglass water tank, add water to the water tank so that the water level is the same as the top surface of the permeable stone; take a sample that has been cured for 28 days according to the experimental design, dry it, and weigh its initial mass; put it on the permeable stone of the water tank, take out and weigh the mass every 0.5 h and put it back, and record the data; continue for 24 h, and terminate the test.

Figure 4. Sample production flow chart.

Figure 5. The finished sample.

2.3. Contact Angle Testing

The contact angle between liquid and solid material surface is an important parameter to measure the wettability of the liquid on the material surface, which is usually recorded as $\omega$. Measuring the contact angle can obtain information about the interaction of various interfaces on the material surface. First, observe the water repellency of the soil by dripping water, and then measure the contact angle with the contact angle tester (HuashitongSDC-100, Foshan, China). The contact angle test was carried out on the original soil sample and the SMS-3 soil sample. The test was carried out at room temperature. After the water droplets fell on the surface of the soil sample and stabilized (about 1 min), the morphology of the water droplets on the sample surface was recorded by computer.

2.4. X-ray Diffraction (XRD) Testing

The mineral composition of soil is an important factor affecting the structural characteristics of soil materials, and it is also an important basis for determining the physical properties of soil. Through this test, the changes of soil composition and elements before
and after adding the modified material can be analyzed. The test instrument was an Smartlab intelligent X-ray diffractometer (Bruker D8-ADVANCE-X, Billerica, MA, USA). The phase compositions of the original soil samples and SMS-3 soil samples were analyzed. The scanning angle is 5–50°, which basically reflects the mineral composition in the soil.

2.5. Scanning Electron Microscopy (SEM) Testing

The principle of the scanning electron microscope (SEM) (quanta 650, Portland, OR, USA) is to obtain physical information through the interaction between high-energy electron beam scanning and sample materials. The contact relationship between particles and pores can be directly reflected by magnifying and displaying this information through the microscope [19,20]. The microscopic morphologies of the original soil samples and SMS-3 soil samples were compared and observed. When observing the microscopic appearance of soil, the selected magnifications were 200 times, 500 times, 1000 times and 2000 times in turn.

2.6. Mercury Intrusion Porosimetry (MIP) Testing

MIP test, also known as mercury porosity method, can measure the pore radius in the range of 3.75–750 nm. By measuring the amount of mercury entering the pore under different external pressures, the equivalent volume of the pore can be evaluated, and the pore size distribution of porous media can be accurately quantified. MIP has been widely used in the fields of material science and engineering [21]. MIP tests were performed on the original soil samples and the SMS-3 soil samples to better understand the pore size of the soil samples before and after adding the modified material. The MIP test instrument used in this test is AutoPore IV9500 produced by Mike Company (Atlanta, GA, USA) in the United States.

3. Results and Discussion

3.1. Capillary Water Rise Testing Results and Analysis

In order to accurately express the relationship between the water absorption quality and water absorption time of different proportions of soil samples, a curve diagram of the relationship between water absorption time and water absorption quality was drawn, as shown in the following figure. The figure shows:

(1) All three silicone water repellents can improve the capillary water absorption characteristics of soil samples, and with the increase of water repellent content, the effect of inhibiting water absorption of soil samples is more obvious. When the content of triethoxysilane is 1.5%, capillary water absorption basically does not occur, and the soil sample is dry; when the content of silicone-acrylic emulsion is 5%, the water absorption reduction rate can reach 60%, and the appearance of the soil sample is complete.

(2) The upward trend of capillary water in soil samples with different materials and dosages is roughly the same, and they all tend to be stable after a rapid increase, which is in line with the characteristics of well-developed pores and strong capillary effect of silt. The capillary water of the plain soil sample rose to the top of the soil sample within 10 min. As shown in Figure 6, in the soil sample of group A added with sodium methyl silicate, the capillary water of the SMS-1 soil sample showed an upward trend in the first 4 h, and became flat after 4 h; the capillary water of the SMS-2 soil sample showed an upward trend in the first 3 h, and tended to be flat after 3 h, and the capillary water of the SMS-3 soil sample basically did not increase. As shown in Figure 7, in the soil samples of group B with added polymethyltriethoxysilane, the capillary water of the POL-1 soil sample showed an upward trend in the first 6 h, and then became flat after 6 h. The capillary water of the POL-2 soil sample showed an upward trend in the first 4 h and became flat after 4 h. In the POL-3 soil sample, the capillary water continued to rise slowly, but the increase in height was very low. As shown in Figure 8, in the C group soil samples with added silicone-acrylic emulsion,
the capillary water of the SAE-1 soil sample rose rapidly in the first 8 h, and rose slowly after 10 h, while the SAE-2 and the capillary water of the SAE-3 soil sample increased rapidly in the first 6 h, and increased slowly after 6 h.

(3) As shown in Figure 9, it can be seen from the comparison that the three kinds of silicone water repellants can effectively improve the capillary water absorption of soil samples. In the screening of waterproof materials, sodium methyl silicate was selected as the waterproof material in this study, and the follow-up contact angle and a series of microscopic tests were carried out on sodium methyl silicate modified soil.

![Figure 6. Group A capillary water absorption test results.](image)

![Figure 7. Group B capillary water absorption test results.](image)

3.2. Water Resistance Testing Results and Analysis

Figure 10 shows the different forms of water droplets on the surface of different soil samples, and Figure 11 shows the contact angle images of SMS-3. As shown in Figure 10, when the droplets landed on the surface of sample 0, the droplets immediately penetrated into the soil, indicating that the material is hydrophilic, and the contact angle was recorded as 0°. At the same time, the water droplets fell on the SMS-3 to form an obvious ellipsoid shape with a contact angle of 137.06°. When the contact angle was greater than 90°, the material was generally considered to be hydrophobic.
Figure 8. Group C capillary water absorption test results.

Figure 9. Bar graph of sample water absorption error.

Figure 10. Water droplets on the surface of different soil samples: (a) Water droplets on the surface of original soil sample; (b) Water droplets on the surface of Sample SMS-3.
According to the physicochemical theory of surfaces, when a liquid is in contact with a solid, the liquid tends to diffuse. For the liquid phase, there are two main forces: cohesion $W_c$ and adhesion $W_a$. Cohesion is the attraction between the parts of the water molecule whereas adhesion is the attraction between the liquid and solid phase molecules. The formulas for cohesion and adhesion are shown in Equations (1) and (2), respectively.

\[
W_c = 2\sigma_{LG} \tag{1}
\]

\[
W_a = \sigma_{LG} + \sigma_{SG} - \sigma_{SL} \tag{2}
\]

Here, $\sigma_{LG}$ is the liquid–gas interface attraction; $\sigma_{SL}$ is the liquid–solid interface attraction; $\sigma_{SG}$ is the solid–gas interface attraction.

The expression of Gibbs surface free energy is shown in Equation (3).

\[
\Delta G / A_S = \sigma_{SL} + \sigma_{LG} - \sigma_{SG} \tag{3}
\]

We can substitute Formulas (1) and (2) into Formula (3) to obtain Formula (4).

\[
\Delta G / A_S = W_a - W_c \tag{4}
\]

According to the second law of thermodynamics, when the reaction is a spontaneous process, we have $\Delta G < 0$. That is, when the cohesion is less than the adhesion, the water will spread and deepen on the surface of the material; when the adhesion is less than the cohesion, water will self-gather on the surface of the material, forming an ellipsoid shape as shown in Figure 10.

3.3. XRD/XRF Test Results and Analysis

Figures 12 and 13 are the XRD diffraction patterns of the original soil sample and the SMS-3 soil sample. It can be seen from the peak curve in the figure, before and after adding the modified material, that the three soil samples are mainly composed of quartz, albite, illite and calcite. Overall, the XRD patterns of the three soil samples are basically the same, and no new diffraction peaks and diffraction eigenvalues appear. The quartz with higher peaks comes from the soil itself, and a small amount of albite is contained in the soil; illite and calcite did not change significantly due to the incorporation of modified materials. It can be seen that the incorporation of sodium methyl silicate does not significantly affect the composition of the soil.

3.4. SEM Testing Results and Analysis

Figure 14 is a typical SEM image of silt. From the two low magnification images in Figure 14a,b, it can be seen that there are some cracks and holes of different sizes in the original soil sample in its natural state, which seriously affects the integrity of the structure. In the two sets of high-magnification images in Figure 14c,d, it can be seen that the silt soil sample skeleton is dominated by sand particles, with obvious edges and corners. The
particle surface is rough, the intergranular space is large, and the contact mode between the skeleton particles is point or surface contact, with obvious boundaries between skeleton units. The pores in the soil are mainly overhead pores, and the pores are irregular in shape, while there is basically no filler in the pores.

![Figure 12. XRD diffraction pattern of different soil samples.](image)

![Figure 13. XRD diffraction pattern of Sample SMS-3.](image)

It can be seen from Figure 15a,b that compared with the SEM microstructure of the original soil sample, the surface of the SMS-3 soil sample is more compact, the surface of the soil particles becomes relatively smooth, the contact mode between particles is mainly surface contact, and the number and size of pores have been significantly reduced. In the high-magnification images Figure 15c,d, it can be seen that there are many attachments on the surface of soil particles, the flaky structures are in parallel layers, the flaky particles are in very close contact in the form of surface-to-surface. A dense film forms on the surface of the particles, preventing the entry of water and strengthening the bond between the soil particles.

This explains why the addition of sodium methylsilicate can effectively improve the waterproof performance and mechanical properties of the soil. The XRD analysis results show that the addition of sodium methylsilicate to the silt does not affect the chemical composition of natural silt crystals, but affects its properties. There should be a methyl group attached to the silt surface. When the potassium methyl silicate solution penetrates into the soil, it reacts with water and carbon dioxide, decomposes into methyl silicic acid, and rapidly forms a polymethylsiloxyne film covering the soil surface. A layer of waterproof membrane is attached between the particles, which changes the connection mode between the particles, increases the contact area between the particles, reduces the
channels required for water circulation, and improves the integrity of the soil structure. The reaction is as follows:

$$2\text{CH}_3\text{Si(OH)}_2\text{ONa} + \text{CO}_2 + \text{H}_2\text{O} \rightarrow 2[\text{CH}_3\text{Si(OH)}_3] + \text{Na}_2\text{CO}_3\text{n}[\text{CH}_3\text{Si(OH)}_3]$$

$$\rightarrow [\text{CH}_3\text{SiO}_{1.5}]_{1n} + 1.5\text{H}_2\text{O}$$  \hfill (5)

![Microscopic image of the original soil sample.](image)

**Figure 14.** Microscopic image of the original soil sample. (a) 200 times; (b) 500 times; (c) 1000 times; (d) 2000 times.

### 3.5. MIP Testing Results and Analysis

The MIP test was performed on the original soil sample and the SMS-3 soil sample. Figure 16 is the mercury injection-mercury removal curve of the two soil samples, and Figure 17 is the pore size distribution density curve of the two soil samples.

By comparing the mercury injection-mercury removal curves of the two soil samples in Figure 16, it can be seen that the growth rate of the cumulative mercury injection of the plain soil sample with the increase of pressure is first fast and then slow, while the mercury injection curve of the modified soil sample shows first slow growth, then sharp growth, and finally slow growth. Before the pressure increased to 100 Pa, the amount of mercury injected into the modified soil sample was significantly lower than that of the plain soil sample, indicating that the pore size of the plain soil sample was larger than that of the modified soil sample, while the opposite was true after 100 Pa, indicating that the unmodified soil sample had a smaller pore size than the modified soil sample. The number of apertures increases. As can be seen from Figure 17, the peak value of the pore size density of the modified soil sample is obviously shifted to the left, indicating that the pore size of the modified soil is smaller as a whole.
Figure 15. Microscopic image of the sample SMS-3. (a) 200 times; (b) 500 times; (c) 1000 times; (d) 2000 times.

Figure 16. Mercury injection-mercury-ejection curve of soil samples.
Soil pore size distribution density curve.

Studies have shown that soil microstructure may change after the addition of reagents, especially its pore structure. The difference of soil microstructure directly leads to the wide variation in its pore size and distribution, and the distribution of pore size is the main factor that affects the rise of capillary water. The classification of pore size is based on the classification of pores proposed by Shear [22]: (1) large pores (D > 10 µm), pores between aggregates; (2) mesopores (2.5–10 µm), pores within aggregates; (3) small pores (0.4–2.5 µm), mainly inter-particle and partly intra-agglomerate pores; (4) Micro-pores (0.03–0.4 µm), inter-particle pores; (5) Ultra-micro pores (<0.03 µm), intragranular pores.

Based on the experimental data, the characteristic parameters of the pore structure are shown in Table 4.

Table 4. Characteristic parameters of pore structure of mercury intrusion test.

| Sample No     | Total Porosity Volume (mL/g) | Total Pore Area (m²/g) | Pore Volume Percentage (µm) | Porosity (%) |
|---------------|-----------------------------|------------------------|------------------------------|--------------|
|               |                             |                        | 0.000–0.03 | 0.03–0.4 | 0.4–2.5 | 2.5–10 | >10    |                |              |
| original soil | 0.1865                      | 2.976                  | 34.1     | 39.73   | 15.01   | 10.88  | 0.27   | 28.47           |
| SMS-3         | 0.1988                      | 2.841                  | 11.52    | 55.73   | 20.12   | 12.47  | 0.15   | 28.21           |

It can be seen from the table that the porosity, pore volume and pore area of the two groups of soil samples are not much different, while the proportion of pores of different sizes is significantly different. The proportion of pores in soil sample A-0 is dominated by large and medium pores, accounting for 34.1% and 39.73%, respectively. According to Figure 16, it can be seen that most of the pores are close to 10 µm. The soil sample D-3 is dominated by medium and small pores, accounting for 55.73% and 20.12%, respectively; most of the medium pores are close to 2.5 µm, and the pore diameter is significantly reduced. This shows that the addition of the composite modified material does not reduce the porosity of the soil, but makes the soil more compact by reducing the size of the pores, which shows the improvement of the waterproof performance and mechanical properties of the soil from the macroscopic level.

4. Conclusions

(1) The capillary water absorption quality of soil samples is directly related to the type and dosage of silicone water repellent. Among them, sodium methyl silicate has the best waterproof effect. With the increase of its content, the maximum mass of capillary water absorption is from 43.63 to 0.72 g, and the inhibition ratio reaches 98.34%. When the content of sodium methylsilicate is 0.5%, the contact angle reaches 137.06°, which proves that the modified soil has good water repellency.
(2) After adding sodium methyl silicate, methyl silicic acid will contact with water and carbon dioxide to quickly form a polymethylsiloxane film with waterproof properties, which makes the surface of the soil sample denser and the surface of soil particles becomes relatively smooth. The contact mode between particles is mainly surface contact, and the number and size of pores are significantly reduced. There are many attachments on the surface of soil particles, and the flaky structures are in parallel layers. The flaky particles are very close in the form of surface-surface contact. The dense film formed on the surface of soil particles strengthens the connection of soil particles and improves the integrity of soil structure.

(3) Through the comparative analysis of the above tests, it can be concluded that among the three silicone waterproofing agents, sodium methylsilicate at 0.5% has the best effect on improving the water resistance of silt. Restoration materials can realize the prevention and control of diseases in the water environment of silt sites. When the existing capillary water disease control data is insufficient, the results of this study can provide an engineering basis for the control of capillary water disease at silt sites.

Author Contributions: Data curation, Y.J. and K.C.; Project administration, Q.M.; Validation, Z.S.; Writing—original draft, X.L. All authors have read and agreed to the published version of the manuscript.

Funding: The conducted research work in this paper was funded by Key Scientific Research projects of Henan Provincial Department of education in 2018 (Project No. 18A560023), Key R&D and promotion projects of Henan Province in 2021 (Science and Technology tackling Key Problems, Project No.212102310947). This financial support is gratefully acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References
1. Liu, H.; Feng, Q.; Yang, Y.; Zhang, J.; Zhang, J.; Duan, G. Experimental Research on Magnesium Phosphate Cements Modified by Fly Ash and Metakaolin. Coatings 2022, 12, 1030. [CrossRef]
2. Dunčková, L.; Durneková, T.; Adamcová, R.; Bednarík, M. Laboratory Assessment of Selected Protective Coatings Applied on Two Sandstone Types. Coatings 2022, 12, 761. [CrossRef]
3. Lu, X.; Fan, L.; He, N.; Lin, X. Experimental Study on Engineering Characteristics of Cement-Lime-Improving Silt in Eastern Henan Province. Coatings 2022, 12, 501. [CrossRef]
4. Kong, X.; Wang, G.; Liang, Y.; Zhang, Z.; Cui, S. The Engineering Properties and Microscopic Characteristics of High-Liquid-Limit Soil Improved with Lignin. Coatings 2022, 12, 268. [CrossRef]
5. Ma, Q.; Liu, S. Effect on Silt Capillary Water Absorption upon Addition of Sodium Methyl Silicate (SMS) and Microscopic Mechanism Analysis. Coatings 2020, 10, 724. [CrossRef]
6. Ma, Q.; Liu, Q.; Cheng, K.; Liu, S. Study on the Durability of Hydraulic Lime Soil Mixed with Sodium Methyl Silicate. Coatings 2022, 12, 903. [CrossRef]
7. Liu, C.H. Study on the Water Movement of Silt and the Seepage Characteristics of the City Wall Considering Clay Content. Master’s Thesis, Zhongyuan Institute of Technology, Henan, China, April 2019.
8. Li, L. Study on the Freeze-Thaw Cycle Effect and Micromechanism of the Strength and Disintegration of the Silt at the Site. Master’s Thesis, Zhongyuan Institute of Technology, Henan, China, April 2019.
9. Wang, Y. Research and new formulation of silicone-acrylic emulsion for reinforcement and protection of soil sites. Sichuan Build. Res. 2011, 37, 227–229.
10. Yu, L.; Wang, J.; Zhang, J. Research on the properties of reinforcement materials and reinforcement effect of soil sites. In Proceedings of the Seventh Academic Annual Conference of China Cultural Relics Protection Technology Association, Zhenjiang, China, 11–15 September 2012; pp. 247–256.
11. Han, W.; Li, Y.; Tan, X. The performance and mechanism of methyl silicate inhibiting clay hydration. Prospect. Eng. 2018, 45, 19–23.
12. Jiang, G.; Wang, J. Performance evaluation and action mechanism of potassium methyl silicate shale inhibitor. Sci. Technol. Eng. 2014, 14, 6–10.
13. Yang, H.; Yu, J. Research on the effect of active components on concrete properties. N. Build. Mater. 2019, 46, 131–133.
14. Guo, Z.; Zhu, Q.; Liu, C.; Xing, Z. Preparation of Ca–Al–Fe deicing salt and modified with sodium methyl silicate for reducing the influence of concrete structure. *Constr. Build. Mater.* **2018**, *172*, 263–271. [CrossRef]

15. Yuan, Y.; Jia, M.; Li, W. Experimental study on sodium methylsilicate stabilizing silt soil in yellowing area. *Chin. Sci. Technol. Pap.* **2017**, *12*, 831–833+844.

16. Chen, L.; Jiang, Y.; Zhang, X.; Chen, L. Methyltriethoxysilane modified silica sol and its hydrophobic properties. *Paint Ind.* **2012**, *42*, 26–28+32.

17. Huang, Y.; Wu, C.; Yang, H.; Que, Y.; Pan, C. Effects of methyltriethoxysilane on the structure and properties of porous silica reflective films (English). *Chin. J. Silic.* **2015**, *43*, 705–708.

18. JTGE40-2007; Highway Geotechnical Test Regulations. People’s Communications Press: Beijing, China, 2007.

19. Ahmed, A. Recycled bassanite for enhancing the stability of poor subgrades clay soil in road construction projects. *Constr. Build. Mater.* **2013**, *48*, 151–159. [CrossRef]

20. Ahmed, A.; Ugai, K.; Kamei, T. Investigation of recycled gypsum in conjunction with waste plastic trays for ground improvement. *Constr. Build. Mater.* **2011**, *25*, 208–217. [CrossRef]

21. Shear, D.; Olsen, H.; Nelson, K. *Effects of Desiccation on the Hydraulic Conductivity Versus Void Ratio Relationship for a Natural Clay*; Transportation Research Record; National Academy Press: Washington, DC, USA, 1993; pp. 1365–1370.

22. Wu, S.; Yang, J.; Yang, R.; Zhu, J.; Liu, S.; Wang, C. Investigation of microscopic air void structure of anti-freezing asphalt pavement with X-ray CT and MIP. *Constr. Build. Mater.* **2018**, *178*, 473–483. [CrossRef]