The Curing and Strength Properties of Highly Moist Waste Mud from Slurry Shield Tunnel Construction

Ziyu Ding 1, Tao Liu 1,2,*, Yan Zhang 3, Xiuting Su 1,4 and Jianguo Zheng 1,*

1 College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, China; dingziyu@163.com (Z.D.); sxting0920@163.com (X.S.)
2 Laboratory for Marine Geology, Pilot National Laboratory for Marine Science and Technology, Qingdao 266061, China
3 College of Marine Geosciences, Ocean University of China, Qingdao 266100, China; zhangyan4850@ouc.edu.cn
4 SGIDI Engineering Consulting (Group) Co., Ltd. Qingdao Branch, Qingdao 266100, China
* Correspondence: ltmilan@ouc.edu.cn (T.L.); jianguozh@126.com (J.Z.)

Abstract: The waste mud from slurry shield tunnel construction can easily cause environmental pollution. Thus, the RCSLP curing agent is developed to reutilize the waste mud produced in the Jinan Yellow River tunnel. The strength properties of the soils solidified with cement or RCSLP were tested, and their microstructures were studied by scanning electron microscopy. The results show that for the RCSLP curing agent, an optimum cement content of 15% and an optimum additive content of 12% improved the early compressive strength of the solidified soil. The mechanical properties of the RCSLP solidified soil were improved due to the significantly increased hydration products. The findings of this research could help achieve the utilization of waste mud from slurry shield tunnel construction.

Keywords: waste mud; curing agent; solidified soil; strength properties

1. Introduction

In recent years, the progressive utilization of underground space has gradually become a new trend in energy conservation worldwide. Due to urban development, many underwater tunnels crossing rivers, lakes, and seas have been constructed in major cities. The slurry shield method has become the first choice for underwater tunnel construction due to its high efficiency and security [1,2]. During slurry shield tunnel construction, the sludge-water separation equipment separates the large mud particles but not the small particles promptly, resulting in increased mud gravity and viscosity. As part of the waste mud meets the construction requirements, a proper amount of water or additive is added to produce a lot of waste mud with high specific gravity and high viscosity. The waste mud contains much cellulose, sodium carbonate, bentonite, and other auxiliary additives and chemical substances, which could cause environmental pollution and land occupation [3].

Currently, engineering mud generally refers to the treatment methods of oil drilling, i.e., adding specific curing agents and water to the mud to initiate the hydration reaction and reduce the moisture of the mud. Additionally, hydration reaction products can improve the strength of the solidified soil, which is conducive to waste mud recycling [4,5]. Sewage sludge ash for manufacturing building materials has been investigated, such as bricks and tiles, raw materials for cement production, aggregates for concrete and mortar, and substitutes for sand and cement in cement solidified bases, subbases, and subgrades in road constructions [6]. Based on the highly moist waste mud from a tunnel project in Wenzhou, Wu et al. [7] performed a vacuum preloading model test to investigate the effect of different inorganic reagents on the vacuum
preloading of waste mud with high moisture content. Their results indicated that the reagent treatment could cause the small mud particles to aggregate into larger particles, thus improving mud permeability and accelerating drainage. The time required to reach the same water discharge was reduced to nearly half of that without adding the reagents. Liu et al. [8] used steel slag, cement, and metakaolin (SCM) as composite curing agents to solidify the soft marine soil of Lianyungang and studied the effects of moisture content, plasticity index, and age on the strength of the solidified soil. The results showed that SCM could effectively solidify the soft marine soil. Cuisinier et al. [9] discussed the effects of nitrate, phosphate, and chloride on the mechanical properties of lime solidified soil. Compound concentration, soil properties, cement, and curing conditions could reduce the mechanical strength of the solidified soil as the added compounds delayed the hydration of the curing agent. Shi et al. [10] suggested that the chemical additives improved the permeability of the mud and accelerated its consolidation. Shirazi et al. [11] studied the changes in physical and mechanical properties of cement solidified soil as a flexible subgrade material after adding lime and fly ash. Sariosseiri et al. [12] studied the effect of Portland cement on soil stability and measured soil moisture content, maximum dry density and pore pressure, and other characteristic parameters under different cement content. Mukhtar et al. [13] analyzed the effect of curing age, lime content, and periodic freezing–thawing cycles on the mechanical properties of lime solidified soil. Moreover, the liquid limit, plastic limit, and strength of the soil could be significantly enhanced. With the increase in fly ash and slag contents, the moisture content of solidified sludge first decreased and then increased, whereas the shear strength first increased and then decreased, thus enabling an optimal combination of curing agents [14,15]. The research on curing agents mainly focuses on the curing mechanism of soft soil, such as drilling mud and mud soil, while few scientists have studied the curing mechanism of waste mud.

Based on the Yellow River Tunnel Project of Jiluo Road in Jinan, the mechanical properties of the solidified mud from slurry shield tunnels are improved through different curing agents. The effectiveness of curing agents is assessed in terms of moisture content, compressive strength, and shear strength. Furthermore, the correlation analyses of additive content, the various mechanical properties, and SEM tests are also analyzed and discussed.

2. Materials and Methods

2.1. Materials

2.1.1. Waste Mud from Slurry Shield Tunnels

The Yellow River Tunnel of Jiluo Road in Jinan is 4760 m in length, and the tunnel section is 3700 m in length and 15.74 m in diameter. The tunnel mainly crosses the hard-plastic silty clay strata, multi-sand strata, and calcareous nodule strata (Figure 1). On average, the sand content in the strata is only 14.83%, while the mud particle content is as high as 85.17%. During excavation, the mud weight increased due to the inability of the sludge-water separation equipment to separate the smaller clay particles. To address this issue, only part of the mud can be discarded during construction. There are also calcareous nodules in the strata, and a large number of calcareous nodules are over 10 cm in diameter, which increases the difficulty of waste mud treatment. Therefore, a large amount of waste mud cannot be treated effectively in time, which is inconducive for waste mud utilization.

The mud used in this test is from the bottom of the sedimentation tank at the construction site. The obtained mud is yellow and odorless with high clay content, high moisture content, and difficulty in dehydration. Table 1 shows the basic properties of the mud. The particle size distribution curve is shown in Figure 2. The mud particles are composed of clay, silt, and fine sand, where the clay content is about 37%.
2.1.2. RCSLP Curing Agent

Ordinary Portland cement (P.O. cement) is used in the test. The P.O. 42.5 grade of cement curing agent and the developed RCSLP solidified soil are selected for comparative analyses. The RCSLP curing agent is based on P.O. 42.5 cement, mixed with gypsum, quicklime, silica powder, and absorbent resin. Gypsum is the dihydrate of CaSO\(_4\) \(3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot3\text{CaSO}_4\cdot32\text{H}_2\text{O}\) with micro-expansion characteristics is generated by adding gypsum to the waste mud from slurry shield tunneling, which can fill all pores of different sizes in the solidified soil, thus enhancing its strength. Quicklime, whose main component is calcium oxide (CaO), is added to the waste mud so that the active substance on the surface of mud particles reacts with Ca(OH)\(_2\) to generate CaSiO\(_3\) and Ca(AlO\(_2\))\(_2\). As a result, the strength of the solidified soil is enhanced. The silicon powder particles have...
small sizes and smooth surfaces, which can fill the pores between the soil particles and improve the microstructure of the solidified soil. As the silica powder has a high volcanic ash activity, it can be added to the waste mud to promote the hydration reaction, resulting in improved density and strength of solidified soil. The compositions of the chemical materials are shown in Tables 2–5.

**Table 2.** Main chemical composition of cement.

| Chemical Component (%) | SiO₂ | CaO | Al₂O₃ | Fe₂O₃ | MgO | Na₂O | K₂O | Loss on Ignition |
|------------------------|------|-----|-------|-------|-----|------|-----|-----------------|
| Content                | 21.95| 57.83| 5.41  | 4.29  | 2.37| 0.12 | 0.59| 5.28            |

**Table 3.** Main chemical composition of gypsum.

| Chemical Component (%) | CaSO₄·2H₂O | CaSO₃·1/2H₂O | CaSO₃ | MgO | H₂O | SiO₂ | Al₂O₃ | Fe₂O₃ | Cl |
|------------------------|------------|-------------|-------|-----|-----|------|-------|-------|----|
| Content                | 71.34      | 0.52        | 3.60  | 3.79| 10.55| 3.49 | 5.04  | 1.30  | 0.01|

**Table 4.** Main chemical composition of quicklime.

| Chemical Component (%) | CaO | MgO | SiO₂ | Fe₂O₃ | Al₂O₃ |
|------------------------|-----|-----|------|-------|-------|
| Content                | 90.47| 2.61| 4.77 | 0.37  | 0.74  |

**Table 5.** Main chemical composition of silica powder.

| Chemical Component (%) | SiO₂ | Al₂O₃ | CaO | K₂O | Fe₂O₃ | MgO | H₂O | Na₂O | Loss on Ignition |
|------------------------|------|-------|-----|-----|-------|-----|-----|------|-----------------|
| Content                | 90.36| 0.11  | 0.25| 2.0 | 0.36  | 1.09| 1.21| 0.30 | 4.14            |

2.2. Sample Preparation

Construction waste mud is prepared with the mud samples obtained during the indoor mud solidification test. \( m_1 \) kg of mud samples obtained on-site and \( m_2 \) kg of water are added to prepare \( m \) kg of the required mud, which satisfy the equations as follows:

\[
m_1 = \frac{m(1 + \omega_1)}{1 + \omega}
\]

\[
m_2 = \frac{m(\omega - \omega_1)}{1 + \omega}
\]

where \( \omega \) is the moisture content of fresh mud, and \( \omega_1 \) is the moisture content of mud at the sampling point.

2.3. Methods

2.3.1. Unconfined Compressive Strength Test

In order to study the compressive strength characteristics of solidified soil under different conditions, a series of unconfined compressive strength tests are conducted. The effect on cement solidified soil is analyzed in this study to compare with the solidified soil. The test schemes are shown in Tables 6 and 7. The effects of cement content and additive content on the solidified soil are analyzed through testing.

**Table 6.** Test scheme for compressive strength properties of cement solidified soil.

| Test Number | Factor                  | Level       |
|-------------|-------------------------|-------------|
| A1          | Cement content (%)      | 10, 12, 15, 18, 20 |
| A2          | Curing time (d)         | 3, 7, 14, 28, 60 |

Basis of the mix-ratio: cement content 15%; moisture content 100%; curing time 7 days.
Table 7. Test scheme for compressive strength properties of RCELP solidified soil.

| Test Number | Factor               | Level              |
|-------------|----------------------|--------------------|
| B1          | Cement content (%)   | 10, 12, 15, 18, 20|
| B2          | Additive content (%) | 7, 10, 12, 15, 18 |
| B3          | Curing time (d)      | 3, 7, 14, 28, 60  |

Basis of the mix-ratio: cement content 15%; additive content 12%; moisture content 100%; curing time 7 days.

The sample used in the test was cylindrical with a diameter of 100 mm and a height of 50 mm. The specific sample preparation method is as follows: First, the mold was cleaned and dried, and its base and inner walls were coated with a layer of vaseline. Thoroughly stirred solidified soil was added to the mold layer (generally 5 to 8 layers) through the hammering method so that the solidified soil had a certain degree of density. For subsequent addition of soil, the surface of the previous layer needed to be shaved. When all soil treatment was completed, the samples were kept level. Next, the samples were cured in the curing box at a temperature of (20 ± 2) °C and relative humidity above 90%. Three samples were prepared for each group, and the unconfined compressive strength was obtained through averaging.

2.3.2. Shear Strength Test

Shear strength tests on the cement solidified and RCSLP solidified soils are conducted to analyze the effect of additives on the shear strength. The cement content of cement solidified soil was 15%, as was the RCSLP curing agent content of RCSLP solidified soil. The basic moisture content of mud was 100%, and the curing time was 7 days and 28 days. Four samples were prepared for each group. The vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa were applied.

An electronic scale was adopted to weigh the curing agents mixed with the waste mud. After mixing evenly for 10 min with a blender, the cured soil was placed under a ring knife by the static pressure method to produce direct shear samples with a diameter of 6.18 cm and a height of 2 cm. Due to the necessity of the direct shear test, 4 samples were made for each group. After preparation, the samples were put into the curing box for curing.

2.3.3. Microstructure Analysis

After the unconfined compressive strength test, the central area of the solidified soil samples was selected for microstructure analysis. The soil samples needed to be dried and cut to a thickness below 3 mm, with one side being the fresh section. The magnifications were set to 500 times, 2500 times, and 5000 times to observe the microstructures, including soil particles and pores.

3. Results

3.1. Strength Properties Analysis

3.1.1. Curing Effect of Curing Agent

The effect of the RCSLP curing agent was evaluated based on the visible changes and the moisture content. The visible changes of the mud solidified with cement after different curing times are shown in Figure 3, and the visual changes of the mud solidified with the RCSLP curing agent after different curing times are shown in Figure 4.

According to the visual results, the RCSLP curing agent was more likely to cause the mud samples to lose their fluidity than cement. The waste mud solidified by the RCSLP curing agent lost fluidity in a short time, which was more effective compared to the traditional method. One of the most important reasons was that absorbent resin was added to the RCSLP curing agent. After incorporating the RCSLP curing agent, the free water in mud is bound to the three-dimensional space grid structure through the different internal and external ion concentrations. Therefore, a large amount of the pore water in the waste mud is converted into bound water. While adding the RCSLP curing agent to the waste mud, the cement, lime, silica powder, and gypsum in the curing agent react with the water
in the pores, thus consuming the free water and causing the solidified soil to quickly loses its fluidity.

Figure 3. Curing effect of cement solidified soil: (a) After 0.5 h; (b) After 1 h; (c) After 3 h; (d) After 6 h.

Figure 4. Curing effect of RCSLP solidified soil: (a) After 0.5 h; (b) After 1 h; (c) After 3 h; (d) After 6 h.

The moisture content of the waste mud was measured by taking samples at 0.5 h, 1 h, 3 h, and 6 h after adding the curing agent. The results are shown in Figure 5. The moisture content of waste mud solidified in the two ways shows relatively small decreases within a short period. The moisture content of cement solidified soil decreased by 3.3%, and that of the RCSLP solidified soil decreased by 5.6%, i.e., the RCSLP curing agent performs better. In general, the moisture content of the waste mud varies in a small range within a short period. Considering the intuitive effect of adding curing agents, the curing effect of the RCSLP curing agent is more significant than that of the cement curing agent.

Figure 5. Moisture content variation of the solidified soil with curing time.
The reason is that the free water in the waste mud reacts with the materials in the RCSLP curing agent to form bound water. At the same time, part of the free water in the RCSLP curing agent is bound by the absorbent resin structure due to its electrical neutrality and becomes bound water. However, during moisture content measurement, the temperature is between 105 °C and 110 °C, and the drying time is over 8 h, which vaporizes the strong binding water, weak binding water, bound water, and free water in the RCSLP solidified soil. Therefore, the moisture content of the RCSLP solidified soil has not changed significantly in the short term.

3.1.2. Compressive Strength Properties of Solidified Soil

(1) Effect of cement content

The variation of compressive strength with cement content is shown in Figure 6. The compressive strength of cement solidified and RCSLP solidified soils increases in the form of a power function. The relationship between the compressive strength of cement solidified soil $R_1$ and cement content $\omega_{\text{cement}}$ can be expressed as:

$$R_1 = 5.053 (\omega_{\text{cement}})^{1.444}$$

(3)

The variation of compressive strength with cement content is shown in Figure 6. Compressive strength variation of solidified soil with cement content.

![Figure 6. Compressive strength variation of solidified soil with cement content.](image)

The relationship between the compressive strength of RCSLP solidified soil $R_2$ and cement content $\omega_{\text{cement}}$ can be expressed as:

$$R_2 = 20.784 (\omega_{\text{cement}})^{1.383}$$

(4)

As the cement content increases from 10% to 20%, the compressive strength of the cement solidified soil increases from 135 kPa to 376 kPa, and the compressive strength of the RCSLP solidified soil increases from 492 kPa to 1291 kPa. Compared with the cement solidified soil, the compressive strength of the RCSLP solidified soil increased by 3.64 times and 3.42 times, respectively. Therefore, the compressive strength growth rate of the RCSLP solidified soil is much higher than that of the cement solidified soil, and the RCSLP curing agent can significantly enhance the compressive strength of the solidified soil.
The compressive strength ratio variation of the solidified soil with cement content is shown in Figure 7. The compressive strength ratio of the solidified soil also increases in the form of a power function. The fitting curve correlation coefficient of the strength ratio of cement solidified soil is 0.996, and that of the RCSLP solidified soil is 0.993. Compared with the cement solidified soil, the strength ratio of the RCSLP solidified soil is relatively smaller, and the compressive strength growth rate is also lower. The reason is that the additive has a great effect at the early stage, and the overall strength of the solidified soil can be improved by changing its early strength. With the additive and cement content of 10%, the compressive strength of the RCSLP solidified soil reaches 492 kPa after 7 days. With the increase in the curing time, cement plays an increasingly important role in strengthening the RCSLP solidified soil. When the cement content exceeds 15%, the compressive strength ratio of the cement solidified soil is higher than that of the RCSLP solidified soil. Therefore, the cement content should be 15%.

The compressive strength variation of the RCSLP solidified soil with additive content is shown in Figure 8. With the increase in additive content, the compressive strength $R_3$ of the RCSLP solidified soil increases in the form of a logarithmic function, as shown in Figure 8. The relationship between the compressive strength of the RCSLP solidified soil $R_3$ and additive content $\omega_{\text{additive}}$ is expressed as Equation (5). The correlation coefficient of the fitting curve is 0.995. When the additive content is 7%, the compressive strength of the RCSLP solidified soil is 477 kPa. When the additive content is 18%, the compressive strength of the RCSLP solidified soil is 1234 kPa, increasing by 2.58 times. Therefore, the additive can significantly improve the compressive strength of the solidified soil. From the economic point of view, the optimal mixing ratio of the additive is 12%.

$$R_3 = 405.708 \ln(\omega_{\text{addmixture}} - 5.049) + 203.989$$

(2) Effect of additive content

Figure 7. Compressive strength ratio variation of solidified soil with cement content.

Figure 8. Compressive strength variation of the solidified soil with additive content.

$$y = 0.037x^{1.444} \quad R^2 = 0.996$$

$$y = 0.042x^{1.383} \quad R^2 = 0.993$$
strengthening the RCSLP solidified soil. When the cement content exceeds 15%, the compressive strength ratio of the cement solidified soil is higher than that of the RCSLP solidified soil. Therefore, the cement content should be 15%.

**Figure 7.** Compressive strength ratio variation of solidified soil with cement content.

**Effect of additive content**

The compressive strength variation of the RCSLP solidified soil with additive content is shown in Figure 8. With the increase in additive content, the compressive strength of the RCSLP solidified soil increases in the form of a logarithmic function, as shown in Figure 8. The relationship between the compressive strength of the RCSLP solidified soil $R_3$ and additive content $\omega_{\text{additive}}$ is expressed as Equation (5). The correlation coefficient of the fitting curve is 0.995. When the additive content is 7%, the compressive strength of the RCSLP solidified soil is 477 kPa. When the additive content is 18%, the compressive strength of the RCSLP solidified soil is 1234 kPa, increasing by 2.58 times. Therefore, the additive can significantly improve the compressive strength of the solidified soil. From the economic point of view, the optimal mixing ratio of the additive is 12%.

$$R_3 = 405.708 \ln(5.049) - 203.989$$

**Figure 8.** Compressive strength variation of the solidified soil with additive content.

**Effect of curing time**

The compressive strength variation of the solidified soil with the curing time is shown in Figure 9. With curing time increasing, the compressive strength of the cement solidified soil and the RCSLP solidified soil increases in the form of a logarithmic function. The fitting relationship between the compressive strength and curing time of the cement solidified soil is expressed in Equation (6), and the fitting relationship between the compressive strength and curing time of the RCSLP solidified soil is shown in Equation (7).

$$R_4 = 32.311 \ln(T - 1.496) + 213.607$$

$$R_5 = 136.162 \ln(T + 0.355) + 658.328$$

As the curing time increases from 3 days to 60 days, the compressive strength of the cement solidified soil increases from 228 kPa to 358 kPa. For the RCSLP solidified soil with additive, the compressive strength increases from 828 kPa to 1203 kPa. Therefore, the additive significantly affects the early strength of solidified soil.

**Figure 9.** Compressive strength variation of the solidified soil with curing time.

(3) Effect of curing time

The compressive strength variation of the solidified soil with the curing time is shown in Figure 9. With curing time increasing, the compressive strength of the cement solidified soil and the RCSLP solidified soil increases in the form of a logarithmic function. The fitting relationship between the compressive strength and curing time of the cement solidified soil is expressed in Equation (6), and the fitting relationship between the compressive strength and curing time of the RCSLP solidified soil is shown in Equation (7).

$$R_4 = 32.311 \ln(T - 1.496) + 213.607$$

$$R_5 = 136.162 \ln(T + 0.355) + 658.328$$

**Figure 10.** Compressive strength ratio variation of the solidified soil with curing time.

As the curing time elapses, the compressive strength ratio of the RCSLP solidified soil is always lower than that of the cement solidified soil, indicating that the compressive strength growth rate of the RCSLP solidified soil is lower than that of the cement solidified soil. The reason is that the additive mainly enhances the early-stage strength of the solidified soil before improving its overall strength. As the curing time increases, the effect of cement on the strength of the solidified soil becomes more important, which is consistent with the results obtained in Figure 9.
As the curing time increases from 3 days to 60 days, the compressive strength of the cement solidified soil increases from 228 kPa to 358 kPa. For the RCSLP solidified soil with additive, the compressive strength increases from 828 kPa to 1203 kPa. Therefore, the additive significantly affects the early strength of solidified soil.

The compressive strength ratio variation of the solidified soil with curing time is shown in Figure 10. As the curing time elapses, the compressive strength ratio of the RCSLP solidified soil is always lower than that of the cement solidified soil, indicating that the compressive strength growth rate of the RCSLP solidified soil is lower than that of the cement solidified soil. The reason is that the additive mainly enhances the early-stage strength of the solidified soil before improving its overall strength. As the curing time increases, the effect of cement on the strength of the solidified soil becomes more important, which is consistent with the results obtained in Figure 9.

![Figure 10. Compressive strength ratio variation of the solidified soil with curing time.](image)

3.1.3. Shear Strength Properties of the Solidified Soil

The shear strength of the cement solidified soil and the RCSLP solidified soil after 7 days with vertical pressure is shown in Figure 11. The shear strength of the cement solidified soil and the RCSLP solidified soil after 7 days can be obtained via the following equation:

\[
\tau_1 = 0.368\sigma + 67.367 \quad (8)
\]

\[
\tau_2 = 0.394\sigma + 78.833 \quad (9)
\]

where \(\tau_1\) is the shear strength of the cement solidified soil after 7 days, \(\tau_2\) is the shear strength of the RCSLP solidified soil after 7 days, and \(\sigma\) is the vertical pressure.

Under the condition of reference content, the cohesion of the cement solidified soil is 67.367 kPa, and the internal friction angle is 20.2°. In contrast, the cohesion of the RCSLP solidified soil is 78.833 kPa, and the internal friction angle is 21.5°. Therefore, the additives can enhance the shear strength of the solidified soil because the components of the additives promote the formation of gel products, thus enhancing the cementation of the solidified soil. However, the promoting effect of the additives on the shear strength is significantly lower than the effect on the compressive strength.
Coalescence is a process in which dispersed particles combine into larger particles, i.e., viscoplastic fluid particle coalescence. According to the different mechanisms, particle coalescence can be divided into four types: thermal coalescence, Coulomb coalescence, Brownian coalescence, and turbulent coalescence. The coalescence of charged particles is mainly Coulomb coalescence.

### 3.2. Properties of Slurry Fluid

#### 3.2.1. Particle Concentration Theory of Viscoplastic Fluids

The shear strength of the cement solidified soil and the RCSLP solidified soil after 28 days with vertical pressure is shown in Figure 12. The shear strength of the cement solidified soil and the RCSLP solidified soil was obtained using the following equation:

\[
\tau_3 = 0.374\sigma + 120.5
\]

(10)

\[
\tau_4 = 0.425\sigma + 154
\]

(11)

where \(\tau_3\) is the shear strength of the cement solidified soil after 28 days, \(\tau_4\) is the shear strength of the RCSLP solidified soil after 28 days, and \(\sigma\) is the vertical pressure.

**Figure 11.** Shear strength of the solidified soil after 7 days.

**Figure 12.** Shear strength of the solidified soil after 28 days.

Under the condition of reference content, the cohesion of the cement solidified soil is 120.5 kPa, and the internal friction angle is 20.5°. In contrast, the cohesion of the RCSLP solidified soil is 154 kPa, and the internal friction angle is 23.0°. The cohesion of the two solidified soils after 28 days is much better than the cohesion after 7 days as the chemical reaction in the soil progresses gradually over time. At the same time, the cohesion of the RCSLP solidified soil is higher than that of the cement solidified soil, indicating that the additive has a significant promoting effect on cohesion.

Therefore, the RCSLP curing agent can significantly promote the strength of the solidified soil from the waste mud of slurry shield tunneling mainly by improving its
early-stage strength. The compressive strength after 3 days can reach 828 kPa. The effect of the RCSLP curing agent on the shear strength is less predominant.

3.2. Properties of Slurry Fluid
3.2.1. Particle Concentration Theory of Viscoplastic Fluids

Coalescence is a process in which dispersed particles combine into larger particles through chemical or physical actions [16]. According to the different mechanisms, particle coalescence can be divided into four types: thermal coalescence, Coulomb coalescence, Brownian coalescence, and turbulent coalescence [17]. The coalescence of charged particles is mainly Coulomb coalescence.

The mud particles in this test mainly include silt (particle size d between 75 and 5 µm), clay (d between 5 and 2 µm), and colloidal particles (d < 2 µm). When d < 0.1 µm, the particles easily form a gel system, and when ≥0.1 µm, the particles easily form a suspension system. Therefore, the original mud is a colloid-suspension mixture classified as viscoplastic fluid. After adding the curing agent, the fine particles coalesce to produce larger particles. Generally, the smaller the particle size, the easier the coalescence into larger particles, i.e., viscoplastic fluid particle coalescence.

When quicklime is added, the waste mud is strongly alkaline, generating Ca(OH)_2 and less Ca^{2+}, producing ion exchange and compressing the electric double layer. The Ca(OH)_2 colloid in the RCSLP solidified soil is positively charged and will neutralize with the negatively charged particles. Therefore, Ca^{2+} and Ca(OH)_2 aggregate in the RCSLP solidified soil.

3.2.2. Rheological Property

The solidification process of waste mud can be divided into two stages: particle coalescence-solidification and consolidation. As shown in Figure 13, the solidification effect of the waste mud is limited shortly after adding the additive, and the RCSLP solidified soil is still a viscoplastic fluid, which means that the particle coalescence and solidification effect coexist. As time goes by, the hydration becomes more prominent, CaSiO_3 and Ca(AlO_2)_2 contents increase, and the moisture content of the RCSLP solidified soil gradually decreases until the RCSLP solidified soil shifts into an elastic-plastic state.

As shown in Figure 14, fluids are mainly divided into Bingham fluid, pseudoplastic fluid, Newtonian fluid, and dilatant fluid [18]. As a viscoplastic fluid, mud is a typical Bingham fluid but not an ideal one because it has a curve at low shear rates, while the ideal Bingham fluid is straight at low shear rates. The relationship between shear stress \( \tau \) and shear rate \( du/\text{dy} \) is as follows:

\[
\tau = \eta \frac{du}{dy} + \tau_s
\]

(12)
where $\eta_p$ is plastic viscosity, and $\tau_s$ is ultimate static shear stress. With the shear stress below the ultimate static shear stress, Bingham fluid behaves as an ordinary elastomer. For mud, rheological parameters $\tau_s$ and $\eta_p$ are related to moisture content and particle composition [7].

![Figure 14. Flow curves of fluids.](image)

When the additive is added to the waste mud, a series of physical and chemical reactions will occur, mainly including coalescence and solidification. As the reaction progresses, the moisture content of the RCSLP solidified soil gradually decreases, the density and the ultimate static shear stress continue to increase, and the rheological properties gradually transition from a viscoplastic fluid state to an elastic-plastic state. The rheological state of the whole is from part to whole. At this time, the RCSLP solidified soil should be analyzed by the theory of elastic-plastic consolidation in soil mechanics.

3.3. Microstructure Evaluation and Analysis

The SEM images of the waste mud before and after adding the cement curing agent and the RCSLP curing agent are taken to observe the differences in the microstructure of the two solidified soils, as shown in Figures 15–17. The original mud, cement solidified soil, and RCSLP solidified soil are selected for analysis under 500, 2500, and 5000 times magnification.

![Figure 15. Microstructure of waste mud from slurry shield tunneling.](image)
With cement serving as a single curing agent, the spatial structure of the cement solidified soil is improved (Figure 16a), and the pores of the solidified soil are less numerous compared with the original mud. The soil particles are also filled with hydration products (Figure 16b), but their total amount is small. The morphology of soil particles is improved after adding cement, and then some acicular hydration products are generated. However, acicular hydration products cannot fill the larger pores and only develop in the smaller pores (Figure 16c). Therefore, the apparent strength of the solidified soil is still low after adding the cement curing agent.

Figure 16. Microstructure of conventional cement solidified soil.

With the addition of the RCSLP curing agent, the RCSLP solidified soil undergoes strong hydration reactions, and the soil particles in the original mud are wrapped into aggregates by the generated hydration products (Figure 17a). Due to the hydration reaction, the soil particle surface changes from smooth to rough, and new substances are generated. Among them, the elongated flaky particles in cotton pellets are Ca(AlO₂)₂, while the flocculent substances are CaSiO₃ (Figure 17b). The hydration products change the spatial structure of soil particles and improve the overall skeleton stability of the RCSLP solidified soil.

After the mud is solidified with the RCSLP curing agent, the amount of hydration products increase, and the pore area decrease again (Figure 17c). The main reason is that the lime dissolves in water to generate Ca(OH)₂ and reacts with the active substance to form CaSiO₃ and Ca(AlO₂)₂. Gypsum can form ettringite with hydrated Ca(AlO₂)₂, and the silica powder can also promote the hydration reaction of cement. Therefore, the strength of the RCSLP solidified soil is improved.

Figure 17. Microstructure of RCSLP solidified soil.

3.3.2. Pore Characteristics

The corresponding pore data can be extracted through image binarization processing of the SEM images. SEM images at 2500 times magnification were selected for qualitative comparison analysis (Figure 18).

According to the pore classification method of Gao [19], the surface porosity and porosity abundance of the solidified soil are statistically analyzed (Figure 19). After using the cement curing agent to solidify waste mud, the pores in the cement solidified soil are mainly macropores, which account for 87.05%, and the other three types of pores are relatively small. However, the pores in the RCSLP solidified soil are mainly medium pores, accounting for 40.45%. In addition, the proportion of large pores and small pores in the RCSLP solidified soil is 37.53% and 12.97%.

Compared with the cement solidified soil, the proportion of large pores in the RCSLP solidified soil decreases significantly, mainly because the addition of additive greatly promotes the hydration reaction of the cement and produces more hydration products and gel substances to fill the pores, which is consistent with the SEM images. The strength of the RCSLP solidified soil is greatly improved due to the filled pore structure.

The pore abundance of the solidified soil is shown in Figure 20. The pore abundance proportion of the cement solidified soil is mostly in the ranges of 0.8 to 1.0 and 0.4 to 0.6; the ranges of 0.6 to 0.8 and 0.2 to 0.4 are less; and the range of 0 to 0.2 is the least. Nearly elliptic cement solidified soil accounts for 60.81%, and the nearly round 38.66%. However, the pore abundance proportion of the RCSLP solidified soil is mostly in the ranges of 0.4 to 0.6 and 0.8 to 1.0; the ranges of 0.6 to 0.8 and 0.2 to 0.4 are less; and the range of 0 to 0.2 is the least. Nearly elliptic RCSLP solidified soil accounts for 68.62% and the nearly round 30.84%. The results show that the soil pores are mainly near elliptic, but some could be near round and near elliptic.

Figure 18. Pore comparison analysis of solidified soil.

Figure 19. Statistical analysis of pore characteristics.

Figure 20. Pore abundance of solidified soil.
3.3.1. Surface Morphology of the Solidified Soil

The original waste mud is mainly composed of clay particles and clay flocs, and the skeleton structure surface of the soil particles is smooth in the SEM images (Figure 15). Therefore, the waste mud is more delicate from a macroscopic view. Due to the high content of clay particles, a large amount of free water is absorbed around the clay particles after long-term immersion, resulting in the reduction in the soil strength, which is also the main reason for the difficult waste mud dehydration. Apparent pores are also observed in adjacent soil particles, as well as between soil particles and minerals in the waste mud. The pore diameter is about 5 to 10 µm, most of which are round, long, and irregular (Figure 15a). The pore distribution is not regular (Figure 15b), and the shape and size are different. Therefore, the strength of waste mud is low after natural drying (Figure 15c).

With cement serving as a single curing agent, the spatial structure of the cement solidified soil is improved (Figure 16a), and the pores of the solidified soil are less numerous compared with the original mud. The soil particles are also filled with hydration products (Figure 16b), but their total amount is small. The morphology of soil particles is improved after adding cement, and then some acicular hydration products are generated. However, acicular hydration products cannot fill the larger pores and only develop in the smaller pores (Figure 16c). Therefore, the apparent strength of the solidified soil is still low after adding the cement curing agent.

With the addition of the RCSLP curing agent, the RCSLP solidified soil undergoes strong hydration reactions, and the soil particles in the original mud are wrapped into aggregates by the generated hydration products (Figure 17a). Due to the hydration reaction, the soil particle surface changes from smooth to rough, and new substances are generated. Among them, the elongated flaky particles in cotton pellets are Ca(AlO₂)₂, while the flocculent substances are CaSiO₃ (Figure 17b). The hydration products change the spatial structure of soil particles and improve the overall skeleton stability of the RCSLP solidified soil.

After the mud is solidified with the RCSLP curing agent, the amount of hydration products increase, and the pore area decrease again (Figure 17c). The main reason is that the lime dissolves in water to generate Ca(OH)₂ and reacts with the active substance to form CaSiO₃ and Ca(AlO₂)₂. Gypsum can form ettringite with hydrated Ca(AlO₂)₂, and the silica powder can also promote the hydration reaction of cement. Therefore, the strength of the RCSLP solidified soil is improved.

3.3.2. Pore Characteristics

The corresponding pore data can be extracted through image binarization processing of the SEM images. SEM images at 2500 times magnification were selected for qualitative comparison analysis (Figure 18).

According to the pore classification method of Gao [19], the surface porosity and porosity abundance of the solidified soil are statistically analyzed (Figure 19). After using the cement curing agent to solidify waste mud, the pores in the cement solidified soil are mainly macropores, which account for 87.05%, and the other three types of pores are relatively small. However, the pores in the RCSLP solidified soil are mainly medium pores, accounting for 40.45%. In addition, the proportion of large pores and small pores in the RCSLP solidified soil is 37.53% and 12.97%.

Compared with the cement solidified soil, the proportion of large pores in the RCSLP solidified soil decreases significantly, mainly because the addition of additive greatly promotes the hydration reaction of the cement and produces more hydration products and gel substances to fill the pores, which is consistent with the SEM images. The strength of the RCSLP solidified soil is greatly improved due to the filled pore structure.
Figure 18. SEM binarization process. (a,b) SEM images at 2500 times magnification were selected for qualitative comparison analysis.

Figure 19. Surface porosity of the solidified soil.

The pore abundance of the solidified soil is shown in Figure 20. The pore abundance proportion of the cement solidified soil is mostly in the ranges of 0.8 to 1.0 and 0.4 to 0.6; the ranges of 0.6 to 0.8 and 0.2 to 0.4 are less; and the range of 0 to 0.2 is the least. Nearly elliptic cement solidified soil accounts for 60.81%, and the nearly round 38.66%. However, the pore abundance proportion of the RCSLP solidified soil is mostly in the ranges of 0.4 to 0.6 and 0.8 to 1.0; the ranges of 0.6 to 0.8 and 0.2 to 0.4 are less; and the range of 0 to 0.2 is the least. Nearly elliptic RCSLP solidified soil accounts for 68.62% and the nearly round 30.84%. The results show that the soil pores are mainly near elliptic, but some could be near round and near elliptic.
Figure 18. SEM binarization process.

Figure 19. Surface porosity of the solidified soil.

Figure 20. Pore abundance of the solidified soil.

4. Discussion

The compressive strength of waste mud cured with the CERSM curing agent increases with age and reaches 1.5 MPa after 28 days [10]. Compared with the RCELP solidified soil, the CERSM solidified soil has higher strength after 28 days. Therefore, the RCSSLP curing agent is not outstanding in improving the ultimate strength. However, the strength of the RCELP solidified soil is higher after 7 days, indicating that the RCELP curing agent mainly improved the early strength instead of the ultimate strength.

The next step is to modify the RCSSLP curing agent and increase the ultimate strength while increasing the early strength to meet the resource utilization requirements.

5. Conclusions

The waste mud from the slurry shield tunnel in the Jiluolu Yellow River Tunnel Project in Jinan was selected as the research object. For resource utilization, the RCSSLP curing agent was developed to improve the strength of the solidified soil. The main conclusions can be summarized as follows:

(1) For the RCSSLP curing agent, an optimum cement content of 15% and an optimum additive content of 12% improved the early compressive strength of the solidified soil;

(2) The RCSSLP curing agent caused the mud samples to lose their fluidity in a short time and improved their shear strength, but the increase was smaller than that of the compressive strength;

(3) As viscoplastic Bingham fluid, the waste mud was gradually transformed into elastic-plastic fluid due to the complex coalescence and solidification caused by the RCSSLP curing agent;

(4) From the microscopic perspective, the hydration products in the RCSSLP solidified soil increased significantly, which filled part of the pores between the soil particles and formed a good skeleton structure to improve the mechanical properties of the RCSSLP solidified soil.

Author Contributions: Methodology, T.L., Y.Z. and J.Z.; validation, Z.D. and X.S.; formal analysis, Z.D.; writing original draft preparation, Z.D.; writing review and editing, X.S.; supervision, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of China (Nos. U2006213, U1806230), the Fundamental Research Funds for the Central Universities (201962011), and the Open Foundation of Key Laboratory of Marine Environment and Ecology, Ministry of Education (MGQNLM-KF201804).
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. Hong, K.R. Development and Thinking of Tunnels and Underground Engineering in China in Recent 2 Years (From 2017 to 2018). *Tunn. Constr.* 2019, 39, 710–723. (In Chinese)
2. Xiao, M.Q. Representative Projects and Development Trend of Underwater Shield Tunnels in China. *Tunn. Constr.* 2018, 38, 360–367. (In Chinese)
3. Guo, W.S.; Wang, B.Q.; Li, Y.Z.; Mo, S. Status Quo and Prospect of Harmless Disposal and Reclamation of Shield Muck in China. *Tunn. Constr.* 2020, 40, 1101–1112. (In Chinese)
4. Shi, Q.T.; Wu, W.Q.; Lu, Y. Mixing Proportion and Working Mechanism of Inorganic Binder-Waste Slurry Composite Cementing Materials. *Tunn. Constr.* 2020, 40, 629–635. (In Chinese)
5. Yang, A.W.; Wang, T.; Xu, Z.L. Experimental Study on Lime and its Additional Agent to Cure Tianjin Marine Soft Soil. *J. Eng. Geol.* 2015, 23, 996–1004. (In Chinese)
6. Smol, M.; Kulczycka, J.; Henclik, A.; Gorazda, K.; Wzorek, Z. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *J. Clean. Prod.* 2015, 95, 45–54. [CrossRef]
7. Wu, Y.J.; Gu, S.S.; Luo, J.C.; Qiang, X.B.; Lu, L.H.; Tang, J. Effect of inorganic chemicals on vacuum preloading with flocculation of construction waste slurry. *China J. Highw. Transp.* 2018, 31, 34–42. (In Chinese)
8. Liu, S.J. Application of Flocculation Belt Filtering Technology in Treatment of Slurry Shield Tunnel Waste Material. *Railw. Constr. Technol.* 2019, 6, 118–123. (In Chinese)
9. Cuisinier, O.; Borgne, T.L.; Deneele, D. Quantification of the effects of nitrates, phosphates and chlorides on soil stabilization with lime and cement. *Eng. Geol.* 2011, 117, 229–235. [CrossRef]
10. Shi, Z.M.; Xue, D.X.; Peng, M.; Chen, Y.J. Experiment on Modified-curing and Strength Properties of Waste Slurry from Slurry Shield Tunnel. *J. Eng. Geol.* 2018, 26, 103–111. (In Chinese)
11. Shirazi, H. Field and Laboratory Evaluation of the Use of Lime Fly Ash to Replace Soil Cement as a Base Course. *Transp. Res. Rec. J. Transp. Res. Board* 1999, 1652, 270–275. [CrossRef]
12. Sariosseiri, F.; Muhunthan, B. Effect of cement treatment on geotechnical properties of some Washington State soils. *Eng. Geol.* 2009, 104, 119–125. [CrossRef]
13. Hotinranu, A.; Bouasker, M.; Aldaood, A.; Al-Mukhtar, M. Effect of freeze-thaw cycling on the mechanical properties of lime-stabilized expansive clays. *Cold Reg. Sci. Technol.* 2015, 119, 151–157. [CrossRef]
14. Liu, F.Y.; Zhu, C.G.; Yang, K.J.; Ni, J.F.; Hai, J.; Gao, S.H. Effects of fly ash and slag content on the solidification of river-dredged sludge. *Mar. Georesources Geotechnol.* 2021, 39, 65–73. [CrossRef]
15. Asavapisit, S.; Naksrichum, S.; Hamwajanawong, N. Strength, leachability and microstructure characteristics of cement-based solidified plating sludge. *Cem. Concr. Res.* 2005, 35, 1042–1049. [CrossRef]
16. Siqueira, I.R.; de Souza Mendes, P.R. On the pressure-driven flow of suspensions: Particle migration in apparent yield-stress fluids. *J. Non-Newton. Fluid Mech.* 2019, 265, 92–98. [CrossRef]
17. Liu, Z.; Liu, H.X.; Feng, X.X.; Li, H.L.; Xing, Z.Z. Comparative study on the different coalescence models of ultrafine particles. *J. Combust. Sci. Technol.* 2012, 18, 212–216. (In Chinese)
18. Zuo, D.Q. *China Water Resources Encyclopedia of Hydraulics. Volume of Hydraulics, River and Coastal Dynamics; China Water Conservancy and Hydropower Press: Beijing, China, 2004.* (In Chinese)
19. Gao, G.R. *Neoteric Soil Geotechnology, 2nd ed.; Science Press: Beijing, China, 2012.* (In Chinese)