Experimental Study on The Effect of Cement-Lime Double Admixture on Dewatering and Strength of Sludge

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Abstract. Cement and lime are mixed into the sludge in different ratios to analyze the effect of curing agent on sludge dewatering and the dehydration rate, improve the strength of sludge, and promote the application of sludge in water conservancy and geotechnical engineering. The solidified sludge was subjected to test of moisture content and direct shear test to study the dewatering effect and strength characteristics of the improved soil. It was found that the precipitation and dehydration rate of solidified sludge were related to the ratio of curing agent incorporation. The higher the incorporation ratio is, the more obvious the dehydration effect is, and the maximum reduction value of dehydration is 13%. The sample’s dehydration rate is from the large to the small, and the average precipitation rate of 0-12h is 2-6 times than that of 12-72h. With the increase of the dosage of curing agent, the cohesion of solidified soil increases obviously, and its range of variation is between 32 and 77kPa. The internal friction angle of the sample increases with the increase of cement content, but fluctuates slightly under the action of lime. After comprehensive consideration of dehydration effect, shearing strength parameters and economic benefits, the optimal ratio of cement and lime to modified sludge soil can be controlled at 10% and 10%, respectively.

1. Introduction

The problem of dredged sludge and urban sludge disposal needs to be resolved. According to statistics, in the Yangtze River basin, the sedimentation amount reached 4.2×10⁸ m³, and the dredging amount reached 3.2×10⁸ m³, which seriously affected the river bed height and navigation capacity. The annual silt dredging volume in the Pearl River Delta region was 8×10⁷m³, which has a serious impact on the alluvial fan landform and shipping capacity. The annual clearing amount in rivers and lakes was as high as 8×10⁷t, and the waste sludge in urban sewers could discharge more than 100 million tons of sludge in China[1]. According to the data published in the "2014 Marine Environmental Quality Bulletin" that the dredged mud dumped in the ocean in 2014 reached 189.5 million m³. In addition, silt soil carried a variety of pollution impurities. If effective measures are not taken to treat these wastes, it will inevitably occupy land, pollute water sources and cause serious environmental pollution.

At present, the chemical curing method is more advanced sludge treatment way at home and abroad, which is specifically converted into a good geotechnical material or a building material by incorporating a chemically solidified material into a dredged sludge to be recycled. The method overcomes the problems of low efficiency and heavy pollution of traditional methods such as ocean dumping and land dumping, and effectively realizes the resource utilization of sludge. Many scholars at home and abroad have carried out a series of in-depth studies on sludge solidification[2-6]. They conducted a large number of experiments on the mechanical properties, shrinkage deformation law and the failure mode of
solidified sludge, and analyzed the growth mechanism and the influence law of non-lateral compressive strength. They also learned about the consolidation compression and control measures and consolidation soil water stability and brittle ductile failure modes. Some scholars have also given the predicted formula of the strength of solidified soil. For example, Lee et al.[7] introduced the soil-ash ratio parameter to obtain the empirical formula for the strength prediction of cement-solidified silt, and the strength is considered to a power function that varies with the water to cement ratio. Ding, J.W. et al.[8] believed that the compressive strength of solidified sludge not only increases linearly with the increase of cement content, but also has a linear decreasing relationship with the ratio of initial moisture content and liquid limit of $\omega_0/\omega_1$. Exploration of curing agents, except for traditional cementitious materials such as lime, cement, fly ash, slag and coal gangue[9-12]; Ren, W.W.[13] also tried to use polymer materials and bio-enzymes as new solidification materials of sludge.

In view of the above, a systematic study was conducted for the dehydration principle and the precipitation law of solidified sludge based on geotechnical test in this paper. The strength characteristics of solidified sludge under different proportions of curing agent were analyzed. The cohesion and internal friction angle change trends were clarified. The optimum ratio of cement and lime mixed to improve the sludge was explored.

2. Test introduction

2.1. Test materials

| $\omega_0$/% | $\gamma$/kN·m$^{-3}$ | $c$ | $d$ | $w_f$/% | $w_p$/% |
|----------|-----------------|-----|-----|---------|---------|
| 73       | 15.3            | 2.23| 2.7 | 40      | 19      |

The soil used in the test was a sludge obtained locally in Chongqing. Its initial moisture content is as high as 90% ~ 110%. During sampling, it has been drained and dried in the landfill for a certain time. The soil sample was taken from the direction of 40cm below the surface, and its water content is $\omega_0=73\%$. Immediately after the soil was removed, it was placed in a pre-packed bag and sealed to maintain moisture content and other physical properties. According to the data of the plastic index, this silt is cohesive soil, and the specific physical properties are shown in table 1.

In this test, cement and lime were used as curing agents, and their Physical properties are shown in table 2 and table 3, respectively.

| Fineness/mm | Initial setting/min | Final setting/min | $f_f$/MPa | $f_c$/MPa |
|-------------|---------------------|------------------|-----------|-----------|
| $\leq 0.08=2.5\%$ | $\geq 45$ | $\geq 60$ | $3d\geq 4.0$ | $28d\geq 6.5$ | $3d\geq 22.0$ | $28d\geq 42.5$ |

2.2. Test plan

2.2.1. Sample preparation. The blending ratio of cement and lime is defined respectively as:

$$\omega_c = \frac{m_c}{m}$$
\[ \omega_l = \frac{m_l}{m} \]

Where: \( m_c \) is the quality of cement, \( m_l \) is the quality of lime, \( m \) is the quality of test sludge.

According to the relevant research results, considering the curing effect and cost budget, the cement content of this paper is: \( m_c=0\% \), \( m_c=5\% \), \( m_c=10\% \). Lime has better water absorption effect and can effectively reduce the microbial content in the sludge soil, so the lime content is controlled as: \( m_l=0\% \), \( m_l=10\% \), \( m_l=20\% \). The two curing agents are combined and mixed into the sludge soil for solidification treatment to form 9 groups of solidified sludge soil samples, as shown in table 4.

Cement and lime were added to the sludge according to the mass ratio of the curing agent, and mixed well to prepare the soil sample of test. Each group of soil samples is taken 600g, and 12 parts are placed in a 2cm\( \times \)2cm\( \times \)2cm grid. It is placed in constant temperature and humidity chamber with a temperature of 20 \( \pm \) 2 \(^\circ\)C and a humidity of more than 95\% for dehydration test. Each group of soil samples was placed in three 6.18 \( \times \)2.0 cm steel ring cutters as direct shear test specimens. During the loading process, the mold was continuously vibrated to discharge the air bubbles to make the solidified soil dense. The sample prepared after the soil sample was placed in a polyethylene storage bag, placed in a standard curing box for maintenance, and subjected to a direct shear test at 28 days of age.

| Curing agent dosage | mass ratio |
|---------------------|------------|
| \( m_c \)\(/\%\)     | 0          | 5         | 10        |
| \( m_l \)\(/\%\)     | 0          | 10        | 20        |

2.2.2. Test methods. The dewatering performance of solid stasis soil was measured under constant temperature and humidity, in which the soil sample of the lattice plate was tested, and the concrete process was as follows: firstly, the moisture content of the soil samples was measured every two hours and continuously tested for 12 hours, and then it was measured once every 12 hours and continuously tested for 60 hours. The change regularity of water content of modified soil sample with time was analyzed. The sample was tested by quick shearing test. The test adopts a variable-control type direct shearing instrument, and the shear rate is 2.4mm/min, when the shear strain to the 5mm automatically stops shearing, the data recorder was used to collect the experimental data automatically.

2.3. Curing reaction mechanism

Mixing the sludge with different cement and lime, the material and moisture in the soil will be in a series of chemical reactions with the minerals in the cement and lime, and the water in the reaction soil and the solid skeleton can be dehydrated to achieve the effect of curing the improved soil. The reaction process of cement and sludge is presented in the following:

- \( 3\text{CaO} \cdot \text{SiO}_2 + 6\text{H}_2\text{O} = 3\text{CaO} \cdot \text{SiO}_2 \cdot 3\text{H}_2\text{O} + \text{Ca(OH)}_2 \)
- \( 2(2\text{CaO} \cdot \text{SiO}_2) + 4\text{H}_2\text{O} = 3\text{CaO} \cdot \text{SiO}_2 \cdot 3\text{H}_2\text{O} + \text{Ca(OH)}_2 \)
- \( 3\text{CaO} \cdot \text{Al}_2\text{O}_3 + 6\text{H}_2\text{O} = 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} \)

The reaction process of lime and sludge is presented in the following:

- \( \text{CaO} + \text{H}_2\text{O} = \text{Ca(OH)}_2 \)
- \( \text{CO}_2 + \text{Ca(OH)}_2 = \text{CaCO}_3 \downarrow + \text{H}_2\text{O} \)

The specific solidification and dehydration of soil samples under the lime-cement admixture are as follows:

- The elements in curing agent and sludge exchanged with each other to cause the soil particles to solidify. Various ions involved in the reaction adsorb each other, causing the soil particles to gather together through cohesive force, resulting in a larger structure of soil particles. Because the calcium ion of the combined product can adsorb the soil particles together, the soil particle group will gradually be
gathered to, and a chain structure will be formed inside the soil body. Gaps between the particles of soil will be filled by the chain structure, and a stable structure will be formed in each group[14].

- Hard coagulation reaction. Mixed solution will produce a large number of carbon ore, so that the soil hardening, CAO-A1O3-H2O and CAO-SiO2-H2O, and the two types of hydrate are insoluble in water, and their nature is more stable[15].
- Carbonation effect. The Ca(OH)2 generated by the reaction of cement and lime to saturated silt soils reacts with the carbon dioxide in the air to produce calcium carbonate in contact with the gas, improving and enhancing the resistance shear property and strength of the solidified soil[16].

3. Results and Discussion

3.1. Dewatering performance of solidified sludge soil

3.1.1. Effect of single curing agent on moisture content of sludge. Both cement and lime can reduce the water content of lake mud and have a certain dehydration effect. As shown in figure 1, the moisture content of the sample decreases with the increase of cement content. For example, when the cement content is 5%, the moisture content of the sample is decreased by 8%; when the cement content is 10%, the moisture content of the sample is drops by 14%. With the increase of cement incorporation, the moisture content of the sample changes linearly. Mainly because the CaO·SiO2 in the cement reacts with H2O, which reduces the moisture content of the sample, and the moisture content of the cement is low, and there is a certain water absorption.

![Figure 1. Effect of cement on moisture content of sludge](image1)

![Figure 2. Effect of lime on moisture content of sludge](image2)

Figure 1 shows the change of moisture content of solidified sludge with cement content. It can be obtained from the figure that the lime content is 10%, the moisture content of the sludge with an initial water content of 73% drops to 62%; the lime content is 20%, the moisture content of the sample drops to 58%. Therefore, the lime can effectively reduce the water in the sludge. It is because CaO in lime reacts with H2O and CO2, causing carbonation. Moreover, the moisture content of the sludge soil is larger than that of the lime, and the dry lime absorbs some water in the sludge. However, the moisture content of the sample did not decrease linearly, mainly due to the formation of agglomerate structure during the precipitation of calcium carbonate, which caused partial lime to fail to fully react.

3.1.2. Effect of cement-lime mixed curing agent on moisture content of silt. Figure 3 shows the change of water content of soil sample under cement - lime mixture. Adding different amounts of lime to the sludge with 5% and 10% cement content, the water content of samples showed a downward trend. When the cement content was 5%, lime content increased from 10% to 20%, and water content of samples decreased by 4%. When the cement content was 5%, 10% lime was added, the water content of samples decreased by 3%, and 20% lime was added, the moisture content of samples decreased by 4%, slightly increasing. Mainly because the cement hydration reaction to generate solid particles can fill soil sample
space, and change the charged state of soil. The consolidation with the decrease of the repulsive force among particles, and then squeezes out water. Then dry lime carbonate reaction and itself will reaction and free moisture absorption, further reduce the moisture content of soil sample, change of soil properties.

![Figure 3. Effect of cement and lime on moisture content of sludge](image1)

![Figure 4. The moisture content of cement-solidified sludge varies with time](image2)

3.1.3. Effect of curing time on water content of solidified sludge.

![Figure 5. The water content of lime solidified sludge varies with time](image3)

![Figure 6. The moisture content of cement-lime hybrid solidified sludge varies with time](image4)

Figure 4-6 show the variation of water content of solidified soil over time. The moisture content of the sample gradually decreased with time. After 72 hours, the minimum value could be reduced to 19%, which was a large drop. According to figure 4-6 and table 5, the sample’s dehydration rate is from the large to the small. More important, the rate of decline and the value of precipitation are related to the amount of curing agent. The larger the content of curing agent, the larger the precipitation, \( V_{0-12}/V_{12-72} \) the smaller the ratio. This is because the sample is carbonated to form a chain structure, which has a good structure and is favorable for surface drainage. The reaction between curing agent and sludge continues with time. As time prolongs, the reaction material is relatively sufficient, and the water consumption is large. Under the condition of constant temperature and humidity, the water on the surface of the soil will evaporate and the water content will be lowered. The degree of reaction in 12-72h is reduced. The moisture inside the soil forms a pellet structure due to the reaction between the curing agent and the soil, and the moisture inside the sample is difficult to discharge. Therefore, the average dehydration rate of 0-12h is 2-6 times than that of 12-72h.

According to the relevant specifications, the moisture content of the silt soil improved by
solidification can meet the needs of engineering fill, and can be used for foundation filling after a certain period of maintenance, to achieve engineering utilization.

Table 5 Average precipitation rate of the sample

| ω_c/1% | ω_l/1% | V_0-12/ %·h^1 | V_12-72/ %·h^1 | V_0-12/V_12-72 |
|--------|--------|----------------|----------------|-----------------|
| 0      | 0      | 1.33           | 0.20           | 6.67            |
| 0      | 10     | 0.92           | 0.27           | 3.44            |
| 0      | 20     | 0.67           | 0.27           | 2.50            |
| 5      | 0      | 0.92           | 0.22           | 4.23            |
| 5      | 10     | 0.67           | 0.23           | 2.86            |
| 5      | 20     | 0.58           | 0.27           | 2.19            |
| 10     | 0      | 0.92           | 0.27           | 3.44            |
| 10     | 10     | 1.08           | 0.32           | 3.42            |
| 10     | 20     | 1.25           | 0.30           | 4.17            |

3.2. The strength characteristic of solidified sludge

After the soil samples were cured, the direct shear test was carried out to obtain the shear strength and shear strength parameters of the samples under different curing agent dosages. Then measure the improvement effect and evaluate whether the improved soil can be effectively used in actual engineering.

3.2.1. The effect of cement on the strength of sludge.

Figure 7 shows the shear strength envelope of the sample under different cement content. It can be seen from the figure that the shear strength increases with the increasing of the plumb force. Figure 8 shows the shear strength parameter c, φ value with the change of cement content. It can be concluded from the figure that the cohesive force and internal friction angle of the sample increase with the increase of the cement content, and the change rate are from the larger to the smaller. The change in the force is more pronounced than the change in the internal friction angle. Mainly because cement can react with water in sludge to form hydration products. The product can bind the soil particles and enhance the cohesion of the sample. Moreover, the particle size and shape change after the curing reaction, so that the particles are sharp and angular, which increases the friction between the soil particles. Therefore, the shear strength of the sample is enhanced.

3.2.2. The effect of lime on the strength of sludge. The envelope of shearing strength of samples with different lime content is shown in figure 9. It can be concluded from the figure that with the increase of lime content, the strength of sludge increases significantly, which is mainly reflected in the cohesive force of solidified soil. Figure 10 shows the change of shearing strength parameters c and φ with the content of lime. It can be seen from the figure that lime has a significant influence on the cohesion of...
sludge soil, and the rate of change of cohesive force decreases with the increase of lime content. For example, the lime content is increased from 0% to 10%, the sample cohesion is increased by 48.7 kPa, the lime content is increased from 10% to 20%, and the sample cohesion is increased by 10.07 kPa. The internal friction Angle of sludge soil remains unchanged with lime content. This is mainly due to the hydration reaction of lime, which increases the cementing force of the soil and enhances the cohesive ability between the soil particles. The lime particles are very fine and do not contribute to the increase of the internal friction angle. In addition, some moisture is filled in the pores of the solidified sludge that the internal friction angle of the solidified soil sample slightly decreases.

3.2.3. Effect of mixed admixture on the strength of sludge. Figure 11 shows the shear strength envelope of the sample under the mixing contents of cement and lime. It can be seen from the figure that the shear strength of sludge under the mixing amount of cement and lime is relatively large, and the intercept of the strength envelope gradually increases with the increasing amount of cement and lime, and the slope does not change significantly. The variation of the shear strength parameters \( c \) and \( \phi \) with the blending amount is shown in figure 12. It can be concluded from the figure that the cohesive force and internal friction angle of solidified soil increase with the increase of the blending amount, which is mainly reflected in the cohesion. The internal friction angle of the sample is change greatly by the amount of cement, and remains basically unchanged under the action of lime. The shearing strength parameters and dehydration effect of the solidified soil were analyzed, and when the mixing ratio of cement and lime was 10% and 10%, respectively, the improvement effect of the solidified soil was better and economical.
Note: in the figure, S1 represents the mixing ratio ($\omega_c=5\%$, $\omega_l=10\%$), S2 represents the mixing ratio ($\omega_c=5\%$, $\omega_l=20\%$), S3 represents the mixing ratio ($\omega_c=10\%$, $\omega_l=10\%$), S4 represents the mixing ratio ($\omega_c=10\%$, $\omega_l=20\%$).

4. Conclusion
The lake sludge was improved by the curing agent of cement and lime. The dehydration effect, the dehydration rate and shear strength parameters of solidified sludge were studied by means of dehydration test and direct shear test, and the following conclusions were obtained:

- After the cement and lime were mixed into the sludge, the moisture content of the sample decreased, and the highest reduction of the moisture content of the sample was 13%. The rate of water content reduction of the sample is from high to low. The average precipitation rate of 0-12h is 2-6 times than that of 12-72h. After 72 hours, the moisture content of the solidified sludge can be reduced to 18%.
- With the increase of cement and lime content, the cohesive force of solidified sludge soil is greatly improved; the internal friction angle increases with the increase of cement content, but fluctuates slightly under the action of lime content.
- The optimal ratio of cement and lime modified sludge is 10% and 10%, respectively, after comprehensive consideration of dehydration effect, shear strength parameters and economic benefits.

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