Abstract: With the construction of expressways in eastern Henan, silt has been widely used as a filling material. However, the silt in this area is lacking clay, the content of active oxides in the soil is low, and the soil particles are bonded together. The property is poor, the erosion resistance is not strong, and the direct filling of the roadbed is prone to engineering problems. Due to the obvious regionality of silt in eastern Henan, this paper firstly analyzes the basic physical properties of silt in eastern Henan using compaction, compression, direct shear and particle gradation tests. The research displays that with the increase of the dosage of cement or lime, the optimal water content increases, while the maximum dry density decreases. The compressibility decreases linearly with the increase of the content. The improved soil has a significant increase in large particles. When the dosage of lime is 2%–6%, the improved soil has a good gradation, and the improved soil has a significant increase in large particles. When the dosage is 2%–6%, the improved soil has a good gradation, and the improvement effect on the cohesion is much greater than that on the internal friction angle. The comprehensive analysis of cement lime shows that the dosage of cement should be 4%–6%. In the early stage, the improvement effect of cement on silt is better than that of lime.

Keywords: silt in eastern Henan Province; improvement; compaction characteristics; compression characteristics; shear strength

1. Introduction

The eastern Henan area belongs to the alluvial plain in the middle and lower reaches of the Yellow River, and the silt is widely distributed. In recent years, expressways in eastern Henan have been rapidly built, but due to the lack of local sand and gravel materials with stable engineering properties, silt is widely used as a filling material. The silt in eastern Henan mainly lacks clay, and has a small specific surface area, which makes it have a low ion exchange capacity, a low activity and low plastic index and a small content of active oxides in the soil. The cohesiveness, erosion resistance and stability between soil particles are poor. After filling the embankment, the soil particles are easily lost with the erosion of rainwater, and it is very easy to cause the road surface and road shoulder to collapse. The lost silt accumulates in the side ditches and culverts, blocking the side ditches and culverts, resulting in poor drainage and endangering the safety of the embankment. Therefore, it is of great practical significance to study the physical and mechanical properties of the silt in eastern Henan and to improve its unfavorable properties so as to provide a certain basis for the design and construction of subsequent projects.

Silt is widely distributed in China. Scholars at home and abroad have done a lot meaningful research on the characteristics of silt itself and its improvement. Jiang et al. [1] conducted an indoor improvement test on the low liquid limit silt in the Taizhou area through a water glass with a different modulus and concluded that the maximum dry
density and optimal moisture content of the water glass modified soil are greater than the optimal moisture content and California bearing ratio (CBR) value of the plain soil. Xiao Yu [2] made a comprehensive study on road distress and prevention in silt areas. Jiang Tong [3] studied the influence of the unconfined compressive strength of silt on the drying and wetting cycles and pointed out that the unconfined compressive strength of silt was increased with the number of drying and wetting cycles. Wu et al. [4] pointed out that the reason that silt is relatively loose is that the particle size of silt is large and uniform, and the effect of silt filling pores is not good during the compaction process. Li et al. [5] studied the performance changes of silt after freeze-thaw cycles and pointed out that the strength of remodeled silt first decreased and then stabilized with the increase of the number of cycles. Zhang et al. [6] carried out an indoor compaction test and CBR test on the improved silt. Zhang et al. and others conducted an experimental study on the characteristics of the improved silt with lime fly ash in combination with the electrification reconstruction project of the Zheng Railway on the Long et al. [7]. Some scholars have conducted research on engineering properties or improvement schemes for silt in different regions [8–11], and other scholars have given the evolution mechanism of engineering characteristics of lime- and cement-improved silt based on firm scientific grounds [12–15]. However, because silt has great variability, shrinkage, easy cracking and poor water stability [16,17], the engineering properties of silt in different regions are significantly different, and the improvement effects of different modifiers are also significantly different. However, there are few studies on the characteristics of silt in the eastern Henan plain and the physical and mechanical indicators after cement-lime improvement. Therefore, this paper studies the physical indicators, impact test properties, compression properties, strength properties and particle gradation of improved silt in the eastern Henan plain, comprehensively evaluates the indicators based on the test data, and combines the improvement mechanism to deeply analyze the change law of improving the silt in eastern Henan, screening reasonable improvement plans and providing data reference for the design and construction of highway subgrade filling in the eastern Henan plain.

2. Basic Physical Properties and Test Preparations of Silt in Eastern Henan

2.1. Basic Physical Properties of Silt in Eastern Henan

The test point is the embankment filling site of the Kaifeng-Weishi section of Kaigang Avenue, Henan Province. The soil sampling depth is about 2–4 m. The soil is loose and has a clear powdery texture when kneaded by hand. According to the relevant provisions of the “Geotechnical Test Method Standard” (GBT50123-1999) [18] and other relevant regulations, density, moisture content and liquid-plastic limit experiments were carried out on the undisturbed soil. The particle gradation curve is shown in Figure 1, the basic physical properties of the undisturbed soil are shown in Table 1, and you can find the mineral composition of the silt in [19].

![Figure 1. Improvement steps of silt specimen. (a) silt screening. (b) adding lime. (c) adding cement. (d) specimen maintenance.](image-url)
Table 1. Basic physical and mechanical properties of silt in eastern Henan.

<table>
<thead>
<tr>
<th>Moisture (%)</th>
<th>Gravity (g/cm³)</th>
<th>Void Ratio</th>
<th>Plastic Limit</th>
<th>Liquid Limit</th>
<th>Plasticity</th>
<th>Exponential Inhomogeneity Number Cu</th>
<th>Curvature System Count Cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2</td>
<td>18.6</td>
<td>0.687</td>
<td>16.6</td>
<td>23.5</td>
<td>6.9</td>
<td>4.2</td>
<td>0.95</td>
</tr>
</tbody>
</table>

It can be seen from the table that the natural silt is in a plastic state, and through the analysis of the gradation curve, the silt is mainly silt, containing a certain amount of sand. The clay content is extremely low, and the non-uniformity coefficient Cu = 3.877 < 5; the curvature coefficient is Cc = 0.21. The soil is poorly graded and lacks clay particles. Therefore, the soil is not easy to compact, the dry strength is not high, and it is easy to compress. Although it has a certain bearing capacity, it has strong permeability, and the liquid limit is only 23.5. In the rainy season, the soil can easily reach the liquid limit, and the water retention capacity of the subgrade is poor. Therefore, the subgrade of the soil construction can very easily cause water and soil loss, resulting in secondary road disasters.

2.2. Preparation of Improved Soil Test

The study proposes to use cement lime to improve the poor filling characteristics of silt in eastern Henan. In this experiment, the content of cement or lime was 2%, 4%, 6% and 8%, respectively. Both the cement and lime were bags produced in Zhengzhou City. We took the silt to the laboratory, passed it through a 2 mm sieve first, removed the sundries and dried it. We added lime or cement in the corresponding proportion and mixed it evenly. After that, according to the plastic limit of the plain silt, different amounts of water were adjusted into modified soils with different water contents. After mixing evenly again, the materials were stuffed for 7 days, and then, the compaction, consolidation, direct shearing and particle analysis tests were carried out with the stuffed modified soils, respectively (Figure 1).

3. Mechanism Analysis of Cement-Lime Improvement of Silt in Eastern Henan

The lime soil formed using silt modified with cement or lime has the characteristics of high strength, large bearing capacity and good water stability, so the engineering properties are generally better than the original soil. However, the mechanism of improving the silt is different. The reason for the increase in soil strength of the cement-soil formed via cement-modified silt is that after the minerals in the cement are hydrated, the wrapped soil particles form a solid core and form a hydrated cement skeleton in the soil pores to constrain the soil. Herzog [12] pointed out that the stress-strain characteristics of low-dose cement show that the cement first forms the core in the soil, and when the cement content increases, the cement becomes a skeleton structure and forms a continuous skeleton structure at 2.5% dosage.

Lime-modified silt is a process in which lime first forms calcium hydroxide with water and then further reacts with the mineral components in the silt. The main mineral components of silt in eastern Henan are quartz, feldspar, kaolin, etc. Among them, the sum of quartz and feldspar exceeds 70%, and a certain amount of lime is added to the silt and mixed into lime soil. After rolling, Ca(OH)₂ is in close contact with the silicate minerals in the soil, and the silicate minerals are in lime dissociates under the excitation of alkalinity and chemically react with Ca(OH)₂ with the participation of water:

Chemical reaction with quartz: SiO₂ + Ca(OH)₂ = CaSiO₃ + H₂O;
Chemical reaction with feldspar: Ca(Al₂Si₂O₈) + 2Ca(OH)₂ = 2CaSiO₃ + CaAl₂O₄ + 2H₂O.
After lime reacts with minerals such as quartz and feldspar on the surface of silt particles, calcium silicate and aluminum silicate are formed. The granules are wrapped and combined with the adjacent soil granules to form a whole, which is the main reason for the formation of the strength of lime soil.
4. Physical and Mechanical Analysis of Cement-Lime-Modified Silt

4.1. Analysis of Compaction Characteristics

In order to measure the optimal moisture content and maximum dry density of the modified silt with different contents, based on the plastic limit of the plain silt, cement-lime modified soil with different moisture contents was configured. The optimum moisture content and maximum dry density of cement- and lime-modified soil are shown in Figure 2 when different dosages are measured.

![Figure 2](image-url)

**Figure 2.** Variation curve of optimum water content and maximum dry density of modified soil with different dosages. (a) optimum water content, (b) maximum dry density.

It can be seen from Figure 2 that the optimum moisture content and maximum dry density of the improved soil change with the dosage are:

1. The optimal water content of cement- and lime-improved soil is higher than that of silt in eastern Henan. The optimal water content of lime-improved soil shows a trend of first rapid increase and then slow increase with the increase of the content of lime. When the dosage is 2%, the growth rate is the largest, and the growth rate reaches 16.8%. When the dosage increases from 2% to 8%, the growth rate is only 1.7%. The growth trend of cement-improved soil is similar to that of lime-improved soil, reaching the maximum at 6% and slightly decreasing at 8%. Under the same content, the optimum moisture content of cement-improved soil is lower than that of lime-improved soil earth.

2. The maximum dry density of cement-lime improved soil is smaller than that of undisturbed silt. The maximum dry density of lime-improved soil decreases with the increase of dosage, while the maximum dry density of cement-lime improved soil increases with dosage. The increase of \( \alpha \) first decreased, reaching the minimum value at 6%, and then increased slightly. Under the same dosage, the dry density of cement-modified soil was lower than that of lime-modified soil.
The reasons for the above results may be related to the changes in the composition of the modified soil particles, the water absorption capacity of the particles, the clay content in the silt and the characteristics of the newly formed chemical substances. First of all, due to the small particle size of cement and lime particles, the specific surface area, the water absorption capacity of the particles and the thickening of the surface water film gradually increase.

Secondly, from the perspective of the improvement mechanism, the change in the performance of cement-modified soil is mainly the cementitious substances formed after cement hydration, while the lime-modified soil, in addition to the reaction of lime and water to form calcium hydroxide, will also interact with the active substances in the clay particles of the soil. Silica and feldspar react to form cement materials with good water stability such as silicate and ettringite, which can wrap unreacted soil particles and form a whole with adjacent soil particles, thereby making soil particles larger. At the same time, in addition to requiring water to form crystal water, this type of cementitious material will also have a certain volume expansion. Therefore, after the improvement of Henan silt with cement and lime, the particles become larger, and the combined water film on the surface of the particles becomes thicker, resulting in the reduction of the largest dry density. For cement-modified soil, with the increase of the content, the number of unhydrated cement particles wrapped by hydrated particles increases, and the influence on the optimum water content and maximum dry density decreases. For lime-improved soil, the clay content in the silt is insufficient. When the content is large, the active substances in the clay are exhausted, resulting in the presence of a certain amount of incompletely reacted lime in the improved soil.

To sum up, the optimal water content of cement-lime-modified soil basically increases with the increase of the content, while the maximum dry density decreases with the increase of the content. The optimum moisture content and maximum dry density were higher than those of cement-modified soil. The reasons for the above results are related to the changes in the composition of the modified soil particles, the water absorption capacity of the particles, the clay content in the silt and the characteristics of the newly formed chemical substances.

4.2. Analysis of Compression Characteristics

After the compaction test was completed, we selected improved soil with a compaction degree of 95%, used a bulldozer to withdraw it from the soil, and took samples with a ring knife to conduct a consolidation test. The compressibility coefficient of the cement-lime-improved soil under different dosages is shown in Figure 3 for when the compaction degree is 95%.

![Figure 3](image_url)
It can be seen from Figure 3 that the compression coefficients of the cement-lime-modified soils gradually decrease with the increase of the dosage, that is, the compressive properties of the two modified soils continue to improve with the increase of the dosage. When the dosage is 2%, the compression coefficient of cement-lime-improved soil decreases by about 3.6% and 5.0%, respectively. When the content increases to 8%, the compression coefficient decreases by about 20.9% and 13.7%, respectively, indicating that the compressive characteristics of lime-improved soil are more uniform. The improvement effect is better when the dosage is larger. Through the linear fitting of the two modified soil curves, the relationship between the compression coefficient of the cement-lime-modified soil and the dosage is $a_{1-2(\text{cement})} = -0.375x + 0.139$ with a correlation coefficient of 0.981 and $a_{1-2(\text{lime})} = -0.24x + 0.138$ with the correlation coefficient of 0.971. The correlation coefficients of the two improved soils are both greater than 0.97. It can be considered that the compression coefficient decreases linearly with the increase of the content, and the cement-improved soil is better than the lime-improved soil in terms of compression characteristics.

The silicates formed by the two improved soils cemented a large number of soil particles together, and the larger soil particles were connected to each other to form a soil skeleton in the soil mass. The soil skeleton has high strength and low compression. With the increase of the dosage, the strength of the particles forming the soil skeleton increases, the integrity of the skeleton increases, and the compression decreases. In addition, due to the fast hydration speed of cement and high strength, the reaction speed of lime is slow, and it needs to interact with the activity of the soil. The clay particles further react, so the compression performance of the cement-modified soil is better than that of the lime-modified soil in the early stage, but the strength of the lime-modified soil will increase over time.

Therefore, the compression coefficient of cement-lime-modified soil basically decreases linearly with the increase of the content, that is, with the increase of the content, the compressive properties of the two modified soils continue to improve. With regards to the hydration rate, the strength of the cemented particles, the integrity of the soil skeleton, etc., the compression performance of cement-modified soil is better than that of lime-modified soil in the early stage.

4.3. Strength Characteristic Analysis

Through the direct shear test, the internal friction angle and cohesion of the cement-lime modified soil under different dosages were measured for a compaction degree of 95%, and the variation curve of shear strength parameters with the dosage of cement-lime is shown in Figure 4.

![Figure 4](image-url)
As can be seen from Figure 4, for the cement-modified silt, the internal friction angle and cohesion show similar variation laws, and they both increase rapidly with the increase of the content and then slow down. When the dosage changes from 0% to 4%, the internal friction angle and cohesion increase from 29.6° and 14.1 kPa to 31.8° and 23.4 kPa, which is an increase of 7.4% and 66.0%, respectively. When the dosage increases from 4% to 8%, the internal friction angle and cohesion increases from 31.8° and 23.4 kPa to 32.6° and 27.2 kPa, only increasing by 2.5% and 16.2%, respectively. From the above data analysis, the improvement of cement on Henan silt has a far greater impact on the cohesion than on the internal friction angle.

The internal friction angle and cohesion of the improved soil are related to the particle gradation and cementation strength of the soil. Whether it is cement or lime, the cementation strength between soil particles can be greatly enhanced. Therefore, the two kinds of improved soil cohesion strength are greatly improved. The change of the internal friction angle may be related to the particle gradation of the improved soil. In order to verify the conjecture, a particle analysis test is carried out on the lime-improved soil with a stuffy material for 7 days, and the particle gradation curve is drawn as shown in Figure 5.

![Figure 5. Particle gradation curve of lime-modified soil with different dosages.](image)

From the particle gradation curve of soil, in the soil improved by lime, the large particles increase significantly, the curve moves to the left as a whole, and the curve is gentler. The non-uniformity coefficient, Cu, of lime-improved soil is 4.2, 8.3, 12.5, 18.3 and 15.4, respectively, and the curvature coefficient, Cc, is 0.95, 1.02, 1.03, 1.02 and 0.39, respectively. The non-uniformity coefficient increases with the increase of the content, and the curvature coefficient is also relatively close, so the increase of the internal friction angle of the lime-improved soil is related to the good particle gradation of the soil. When the content is 8%, the curvature coefficient is 0.39, and the fine particles increase more, indicating that the soil contains some lime in the form of powder at this time, so the strength parameters of the lime-improved soil are reduced at this time.

To sum up, the shear strength parameters of cement-modified silt first increase rapidly and then slow down with the increase of the content, while for the silt improved by lime, they first increase and then decrease with the increase of the content. The maximum value is reached at 6%. The improvement effect of cement and lime on cohesion is much greater than that of the internal friction angle. Under the same dosage, the improvement effect of cement on the shear strength parameters is better than that of lime. This is mainly related to the change of soil particle gradation after improvement, the cementation strength between soil particles and the presence of unreacted lime powder in the soil. Based on the results of the direct shear test, for the improvement of silt in eastern Henan, the content of cement and lime should be 4%–6%. Below this range, the improvement effect is not obvious.
improvement is recommended for those with high early strength requirements, while lime has a better long-term effect on silt improvement.

5. Conclusions

(1) The optimal water content of the cement-lime-improved soil increases with the increase of the dosage, while the maximum dry density and compression coefficient decreases with the increase of the dosage.

(2) For the soil modified by lime, the coarse particles increase greatly, the curve moves to the left side and becomes gentler, and the coefficient of unevenness increases with the increase of the dosage. When the dosage reaches 6%, the gradation of the improved soil is the best.

(3) The shear strength of cement-modified silt continues to increase with the increase of the dosage, and the growth rate of the shear strength obviously slows down when the dosage surpasses 6%. For the lime-improved silt, the shear strength of the soil increases first and then decreases with the increase of the dosage and reaches the maximum value when the dosage reaches 6%.

(4) The improvement effect of cement and lime on cohesion is much greater than that of the internal friction angle under an identical dosage, the improvement effect of cement on shear strength is better than that of lime.

(5) Through comprehensive analysis, the results of compaction tests, compression tests, direct shear tests and particle compositions, the best dosage to improve the silt can be determined, and the corresponding value is 6%.

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