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Effects of Lime Content on Road Performance of Low Liquid Limit Clay

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Abstract: Low liquid limit clay has a low plastic index, displays poor strength, and is sensitive to water, and its mechanical qualities decline as the water content changes, making it difficult to employ directly in the construction process. Adding lime is a fantastic way to improve it. The influence of lime concentration on the road performance of low liquid limit clay is investigated in this research using a limit water content test, compaction test, and California bearing ratio test. The results show that the original plain soil does not meet the requirements of highway subgrade filling, and the basic properties of subgrade soil are improved to varying degrees after adding lime, resolving the problem regarding the original well-cultivated soil's inability to meet the requirements of construction. The plastic limit of the improved soil increased by roughly 3% as the lime content increased, but the maximum dry density decreased dramatically by 9.03%, 5.71%, and 5.98%, respectively. With an increase of 57.3% in lime content and compaction times, the California bearing ratio increases dramatically. The ideal moisture content rises as the lime content rises. The optimal dosage is 6%, according to a rigorous study of several performance metrics.

Keywords: low liquid limit clay; lime improvement; CBR; compaction; liquid plastic limit

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1. Introduction

The Yellow and Yangtze River basins in China include a considerable number of low liquid limit clays. The use of low liquid limit clay as roadbed filler in the construction of expressways in this area is unavoidable. However, because of the low liquid limit, poor plasticity index, low strength, and water sensitivity, the mechanical properties of low liquid limit clay deteriorate with water changes [1,2], making it difficult to compact in roadbed construction. Because of its water sensitivity, water migration is common as the environment changes, affecting road performance [3]. The elastic modulus is significantly influenced by the stress state and water content of compacted clay. This directly affects road service [4]. In addition, it is simple to create roadbed collapse and pavement cracking if it is employed during the active period of a highway, which will directly impact the safety of traffic operation. To meet the performance requirements for the road, it is crucial to improve the low liquid limit clay.

Presently, bad soil is typically improved using physical (soil compaction, etc.) and chemical approaches. The three primary additions utilized in chemical stability are lime, cement, and fly ash [5–9]. Due to its low cost, positive effects, and practical construction, lime has drawn the interest of several researchers and produced many research-related findings. In Yan'an City, Gao et al.'s [10] research looked at the impact of dry density and lime content on the hydraulic conductivity and microstructure of loess. Due to the negative logarithmic correlation between hydraulic conductivity and dry density, adding lime will make loess less hydraulically conductive at the same dry density. However, lime addition causes a decrease in dry density at a specific level of compaction because of increased flocculation and aggregation. Al-Mukhtar et al.'s study of the main geotechnical properties of untreated and lime-treated compacted FoCa clay samples used X-ray diffraction, thermogravimetric analysis, scanning electron microscopy (SEM), and transmission electron microscopy (TEM) [11]. The findings demonstrate that lime-treated clay has additional layers of accumulation, altered clay particles, and a higher calcium content at the particle border. By conducting studies on lime-stabilized loess with various moisture levels and temperatures, Bao Weixing [12] looked at the features of lime stability and internal mineral changes at high temperatures. The pozzolanic reaction, crystallization reaction, and lime ripening reaction all contribute to the strength improvement of lime-stabilized loess. The response rate of these processes can be accelerated by high temperatures. Eades and Grim [13] claim that the lime stabilization process consists mostly of two steps. It may take several hours or days to finish the first stage of alteration. According to the soil's mineralogical makeup, cation exchange, flocculation, carbonization, and various short-term pozzolanic reactions take place at this stage. The pozzolanic process can also increase strength and durability, which is the second stage. In order to assess the effects of compaction delay and ambient temperature on the physical, mechanical, and hydraulic properties of lime-treated expansive clay, Hatim Ali [14] conducted a number of tests. Al-Mukhtar et al.'s [15] research examined the effects of a 10% lime treatment on several clay minerals. The consumption of lime on the curing time was assessed using an atomic absorption device, revealing the mechanism underlying the mineral reaction and the short- and long-term curing of lime soil subgrade. Malkathi [16] conducted studies to lower the clay and silt content in CSEB manufacturing and discovered the stability of lime and lime-cement combinations as stabilizers. According to the test results, lime-stabilized blocks can be utilized for single-layer construction, and lime combined with cement stabilizer results in blocks with greater compressive strength than lime alone. Noorzad [17] conducted triaxial tests, including the Atterberg limit, standard invigilation compaction, unconfined compressive strength, and unconsolidated undrained strength, to assess the impacts of the stabilizer type, variable curing duration, and different lime-sludge ratio. The results of the tests indicate that sludge and lime can improve the maximum strength. The fundamental interactions between lime and clay during the stabilization process have also been extensively researched and elucidated. They contend that the four reactions listed below—cation exchange, flocculation and agglomeration, lime carbonization, and finally, volcanic ash reaction—are responsible for the improved performance of lime-stabilized soil [18–26]. The strength of lime soil is produced through a pozzolanic reaction, which is the most important process. There are only a few studies on low liquid limit clay, and the majority of them are about new roadbeds, while a small number of them are about road reconstruction and expansion. The aforementioned studies primarily concentrate on the mechanism of the lime improvement of poor soil, and the research objects are primarily expansive soil and saline soil, etc.

The effectiveness of lime as a stabilizer has also been thoroughly researched by academics. Raheem et al. [27] stabilized lime with 5–25% lime content utilizing laterite as the test object. Compressed stabilized earth blocks (CSEB) were stabilized with lime by Ramirez et al. [28], and the ideal lime concentration was 28%. Lime was employed as a stabilizer by Guettala et al. [29] to alter the proportion of clay to sand, and they found that 8% was the best dosage. Lime is another stabilizer used by Ngowi [30], and the ideal dosage is 15%. Lime is used by Akpokodje [31] as a stabilizer to provide the best lime content in various material proportions. According to a review of earlier studies by Bogas et al. [32], the optimal lime level is between 6% and 12%. The findings of the pertinent research that the aforementioned academics conducted on lime as a stabilizer are displayed in Table 1. The ideal lime content range is often between 6% and 15%, however there is no precise and optimum value of lime content for diverse uses and types of improved soil.

Table 1. The best dosage of lime under different coating [28–32].

	Application	Optimum Content
Literature [28]	CSEB	28%
Literature [29]	Sand and clay	8%
Literature [30]	CSEB	15%
Literature [31]	Clay and silt	6–12%
Literature [32]		6–12%

In conclusion, lime has a wide variety of applications and has a good application effect in improving expansive soil, red clay, and other soils. Relevant studies have also produced fruitful outcomes, but there are still some limitations. For example, the studies mentioned above mostly concentrate on the research mechanism, while there is a dearth of study on low liquid limit clay, new roadbeds, and rehabilitation and expansion. In order to identify the representative low liquid limit clay, this paper analyzes its natural moisture content, particle gradation composition, boundary moisture content, compaction test results, and California bearing ratio (CBR value) as specific research indicators. It then modifies this clay by adding digestion lime to study its basic performance indicators. The optimum lime content of subgrade filling provides a reference and guidance for construction. It provides a feasible disposal idea for road construction.

2. Testing Program

2.1. Basic Properties of Low Liquid Limit Clay

The soil samples used in this paper are from the Hefei-Dagudian section of the Shanghai-Shanxi Expressway reconstruction and expansion project; the soil samples of three different project soil fields are chosen for research. The three soil samples returned from different project soil fields are marked as soil sample A, soil sample B, and soil sample C, respectively. Figure 1 depicts the soil sampling site and some soil samples that have been classified.

(**a**) Soil field to take soil (**b**) Soil samples

Figure 1. Soil field and Soil samples.

(1) Natural moisture content

After the return of the undisturbed soil samples from the soil field, the natural moisture content was tested by the drying method. The test is conducted strictly in line with Highway Soil Test Specification JTG3430-2020. Five samples are taken for each soil sample in order to confirm the validity of the test results, and the average value is used to represent the natural water content of the undisturbed soil. Table 2 displays the test results.

Table 2. Natural moisture content of soil sample.

Sample	Sample Moisture Content (%)					
	1	2	3	4	5	Average
A	24.8	23.3	25.2	28.1	29.1	26.1
B	25.7	25.4	25.5	22.7	24.2	24.7
C	20.6	21.9	20.2	20.3	24.0	21.4

(2) Particle grading

In order to analyze the gradation composition of soil samples with a particle size range of 0.075~60 mm, a particle screening test was carried out by Highway Geotechnical Test Procedure JTG3430-2020. The test steps are as follows: Firstly, the samples were weighed according to the regulations, and the samples were passed through a 2 mm sieve in batches. Samples larger than 2 mm were passed through coarse sieves at all levels larger than 2 mm from a large to small order. The soil left on the sieve is weighed separately. If the amount of soil under the 2 mm sieve is too much, it can be reduced to 100~800 g by quartering. Samples less than 2 mm were passed through a fine sieve at all levels from a large to small order. Shaking can be carried out by a shaker. The shaking time is generally 10~15 min. Starting from the sieve with the largest pore size, each sieve is taken down in sequence, and shaken with the hand on the white paper until the number of sieves per minute is no more than 1% of the residual mass of the sieve. The leaking soil particles should be put into the next sieve, and the soil samples left on each sieve should be brushed with a soft brush and weighed separately. The difference between the total mass of the soil under the sieve and the total mass of the sample before the sieve should not be greater than 1% of the total mass of the sample before the sieve. Finally, three soil sample gradations are obtained through experiments, as shown in Figure 2. Figure 2 shows that the mass percentage of soil sample A (less than 0.075 mm) is 93.2%, the mass percentage of soil sample B (less than 0.075 mm) is 61.8%, and the mass percentage of soil sample C (less than 0.075 mm) is 93.5%.

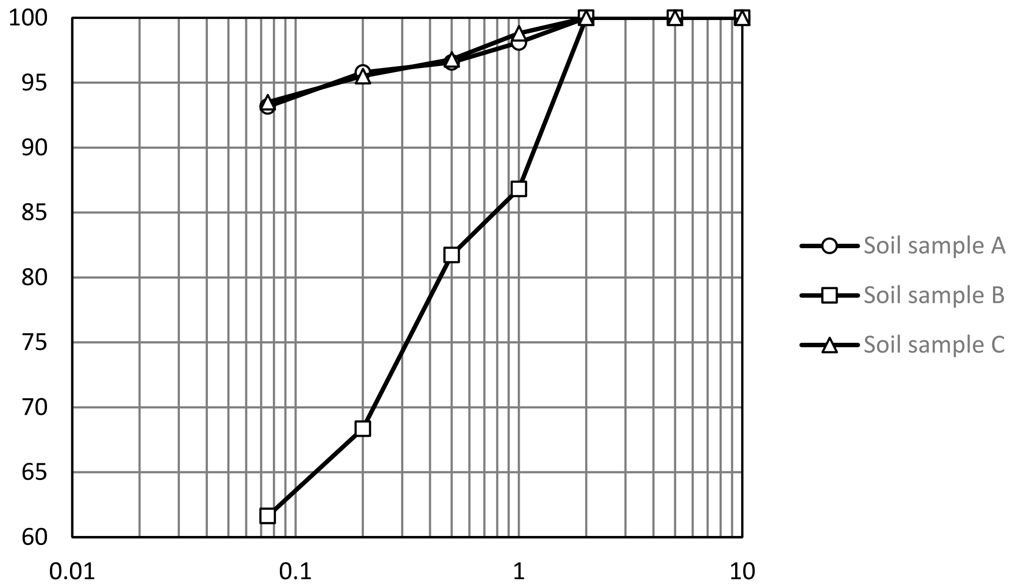


Figure 2. Soil sample gradation.

2.2. Preparation of Digestion Lime

The digestion lime that was collected from the lime digestion site is the lime digestion lime that was used in this article. Since the digestion lime retrieved from the site contains some water, it cannot be used to directly prepare the test soil for this paper's purposes. Before being utilized for the test, it needs to be processed. The following are the precise therapy steps: The site's recovered digestion lime samples were dried for 24 h in an oven at

105 °C. A 0.5 mm sieve was used for screening, and a lime that was less than 0.5 mm thick was used for this test. Figure 3 depicts the particular test procedures.

(**a**) lime digestion site

(**b**) slaked lime drying

(**c**) sifting

(**d**) slaked lime after 0.5 mm sifting

Figure 3. Lime preparation for test.

2.3. Test Scheme

The following three experiments were conducted in this experiment to examine the changing rule of the boundary moisture content of subgrade filling with varying lime contents: California bearing ratio test (CBR), compaction test, and boundary moisture content test. The design documentation was consulted for the engineering filler's required lime content in the test lime soil configuration. The lime content in the areas where the degree of compaction is 93% and 94% is 4%, and the lime content in the 96% area is 6%. Therefore, the test involved in this paper is sets up six lime contents of 0%, 1%, 2%, 4%, 6%, 8%, and the corresponding lime content is mixed with the test soil to prepare the lime soil used in the test. After the preparation of the test soil samples, the road performance tests, such as the limit water content, compaction test, and CBR value test, were carried out according to the test procedures. The specific test plan is shown in Table 3. Each group of experiments was repeated three times, and the average value was removed for subsequent analysis.

Table 3. Test schedule.

	Lime Content of Soil Sample A	Lime Content of Soil Sample B	Lime Content of Soil Sample C
Water ratio limit test	0%, 1%, 2%, 4%, 6%, 8%	0%, 1%, 2%, 4%, 6%, 8%	0%, 1%, 2%, 4%, 6%, 8%
compaction test	0%, 1%, 2%, 4%, 6%, 8%	0%, 1%, 2%, 4%, 6%, 8%	0%, 1%, 2%, 4%, 6%, 8%
CBR	0%, 1%, 2%, 4%, 6%, 8%	0%, 1%, 2%, 4%, 6%, 8%	0%, 1%, 2%, 4%, 6%, 8%

2.4. Test Method

The liquid-plastic limit of soil is determined by a combined liquid-plastic limit tester, which reflects the interaction between soil particles and water, and can indirectly reflect the engineering properties of soil. These are the test steps: In order to ensure that the water content of the soil samples was controlled within the liquid limit (point a), and slightly larger than the plastic limit (point c) and the intermediate state (point b), of the two, 200 g of treated soil samples were taken and separately put into three soil containers. A soil cutter was used to mix the soil, which was then sealed for over 18 h. After scraping the surface and setting it on the lifting seat, the lifting knob was steadily turned clockwise while the adjusted soil sample was inserted into the test cup. The indicator light turned on instantly, stopped rotating, and pressed the "measurement" button to wait for the test to finish the reading when the soil sample made contact with the cone tip. The previous steps were repeated until the test was over. A portion of the sample must be taken after the test has finished in order to determine the water content. The weight of the cone is 100 g.

A compaction test is a technique that involves hammering soil samples to determine the soil's propensity for compaction. This technique involves hammering soil samples with varying water contents using various compaction techniques to produce the maximum dry bulk density and ideal water content, which serves as the foundation for the design and construction of filling engineering. Samples were made with varying amounts of lime content, including 0%, 1%, 2%, 4%, 6%, and 8%. Dry heavy compaction was used in the compaction test, with 3 compaction layers and 98 compaction times for each layer. After compaction was completed, the sample in the cylinder was pushed out with the demolding instrument to determine the wet density of the sample, and then the representative soil sample was taken from the center of the sample to measure its water content, which was calculated as 0.1%.

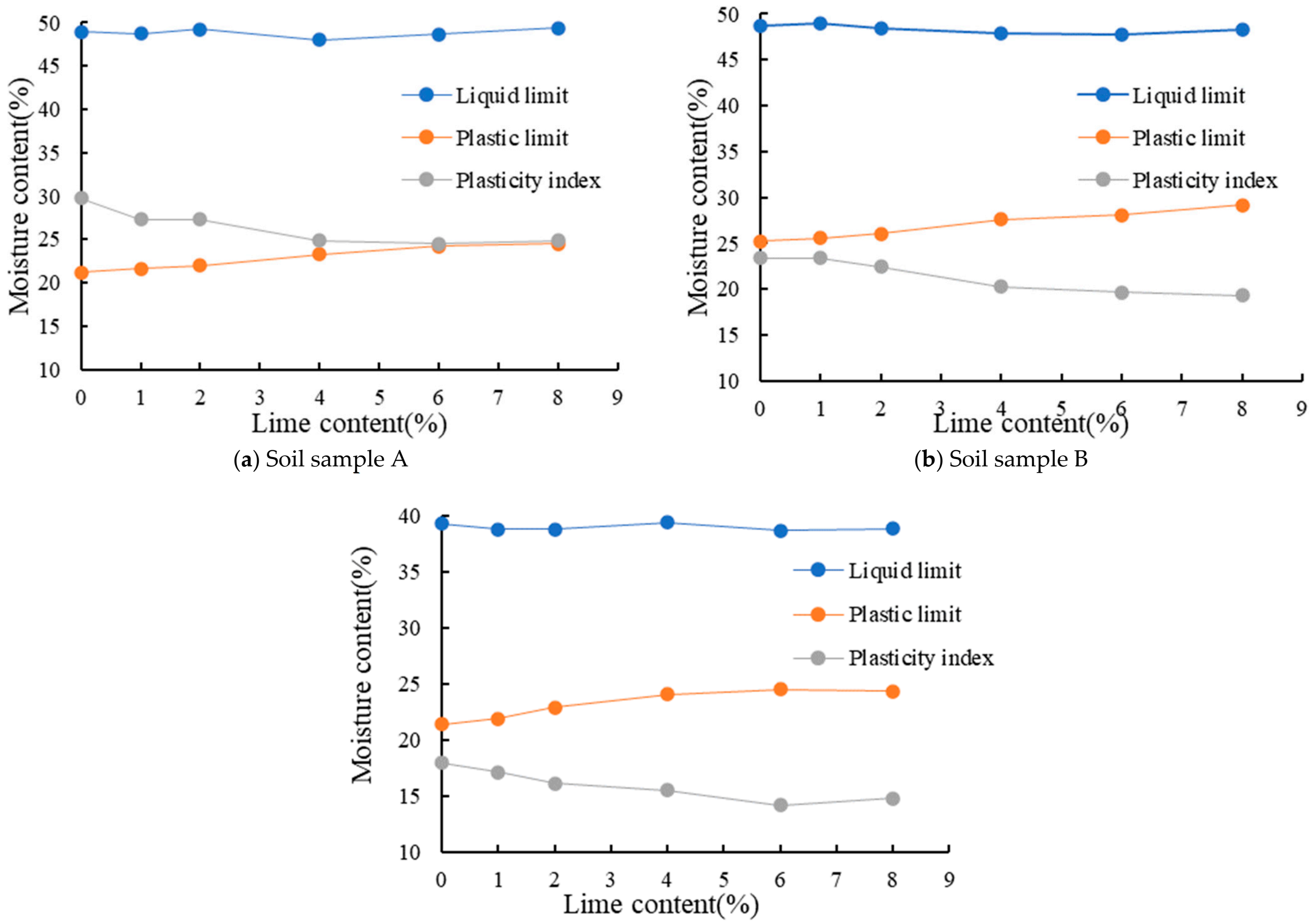
3. Test Results and Analysis

3.1. Limit Moisture Content

The measured result was mapped, and the horizontal coordinate was lime content and the vertical coordinate was moisture. The test results are shown in Figure 4.

Figure 4 shows that while the plastic limit of the three soil samples increases to some degree with an increase in lime content, the liquid limit of the three soil samples does not become more obvious. For soil sample A (plain soil), the respective liquid limit, plastic limit, and plastic index values were 48.9%, 21.2%, and 27.7%. For soil sample B (plain soil), the liquid limit, plastic limit, and plastic index were 48.6%, 25.2%, and 23.3%, respectively. The plain soil type C has a liquid limit, plastic limit, and plastic index of 39.2%, 21.4%, and 17.8%, respectively.

Soil sample A's liquid limit, plastic limit, and plastic index were 48.6%, 24.2%, and 24.5% when the lime level exceeded 6%. Soil sample B had a plastic index of 19.6%, a plastic limit of 47.7%, and a plastic limit of 28.1%. Soil sample C had a liquid limit, plastic limit, and plastic index of 38.6%, 24.5%, and 14.1%, respectively. The three different types of soil samples all had their plastic limits raised by 3%, 2.9%, and 3.1%, respectively. Soil sample A's plastic limit had a propensity towards stability. The deplasticity index reduces with an increase in the plastic limit to some extent when the liquid limit does not increase evidently. This is because certain ion exchanges, carbonation, crystallization, and pozzolanic actions exist in lime-improved soil, which leads to the plastic limit of each soil sample increasing with the increase in lime content, while the plastic index decreases correspondingly.



(**a**) Soil sample A (**b**) Soil sample B

(**c**) Soil sample C

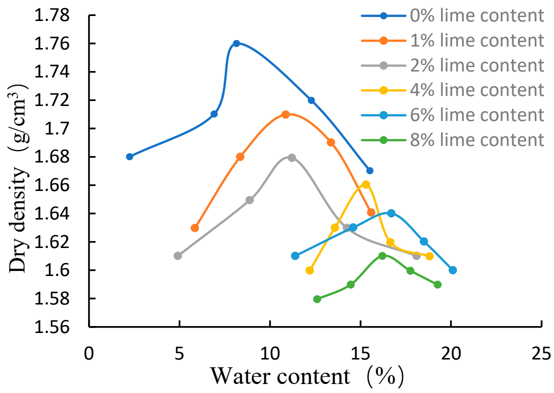
Figure 4. Boundary moisture content test results.

Combined with the undisturbed soil particle grading obtained above, it can be seen from Highway Geotechnical Test Procedure JTG3430-2020 that the mass percentage of the fine grain groups of all soil samples is greater than 50%, the liquid limit of all soil samples is less than 50%, and the plasticity index is greater than 7%, indicating that these three soil samples are all low liquid limit clays (CL).

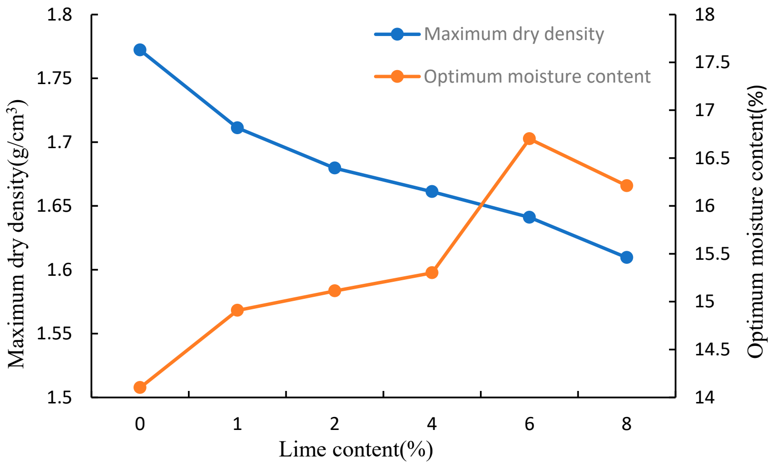
3.2. Compaction Test

The relationship curve between dry density and water content is drawn. The horizontal coordinate represents water content and the vertical coordinate represents dry density. The test results are shown in Figures 5–7.

It can be seen from the figure that the maximum dry density of lime-stabilized soil reaches its peak as the ash content of soil samples A and B increases from 0% to 8%, and reaches its peak when the ash content of soil sample B reaches 6%. Soil sample A decreased from 1.77 g/cm^3 to 1.61 g/cm^3 by 9.03%; soil sample B decreased from 1.75 g/cm^3 to 1.65 g/cm^3 by 5.71%; soil sample C decreased from 1.84 g/cm^3 to 1.73 g/cm^3 by 5.98%; and when lime content exceeded 6%, the maximum dry density decreased less. At the same time, with the increase in the ash mixing rate from 0% to 6%, the optimal water content has basically reached the maximum. Sample A increased from 14.7% to 16.7% (13.6%), sample B increased from 14.5% to 17.2% (18.6%), and sample C increased from 15.1% to 17.4% (15.2%). However, when the ash content increased from 6% to 8%, the improvement effect of increased lime dosage on low liquid limit clay was no longer obvious. The decrease in dry density is small, and the optimal water content is basically unchanged. On the one hand, the water consumption of the improved soil is due to the exchange of Ca^{2+} in the lime with other cations on the soil surface. On the other hand, as lime dissolves and hydrates in the soil, the soil is pressed in real time, requiring more water to reduce the friction between particles for optimal compaction. Therefore, with different lime dosage, water consumption is also different, so the change in optimal water content is also different. Therefore, it can be concluded that 6% ash content is a reasonable dosage of improved low liquid limit clay in this area.

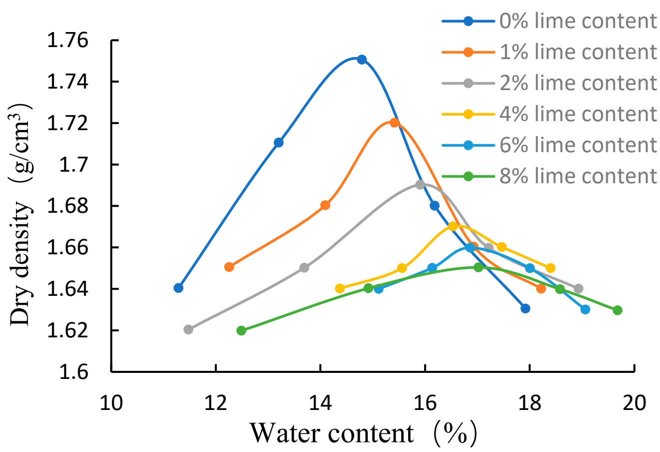


(**a**) Compaction curve under different lime content



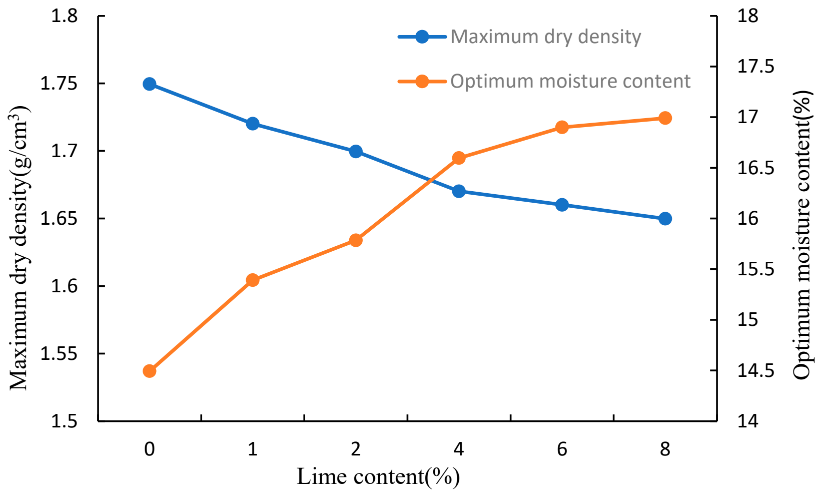
(**b**) Variation of compaction results under different lime content

Figure 5. Compaction test results of soil sample A.



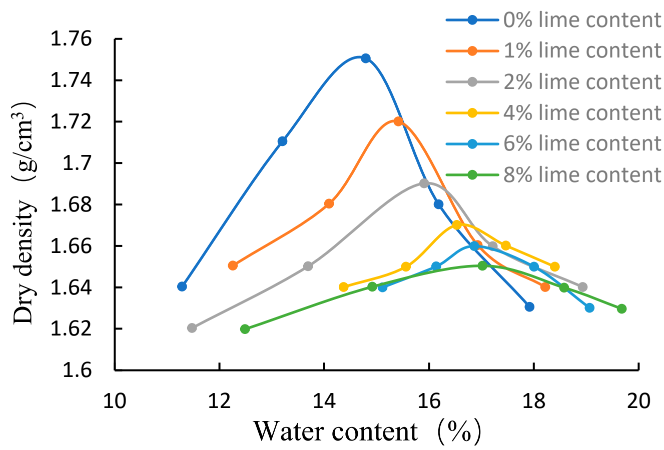
(**a**) Compaction curve under different lime content

Figure 6. *Cont.*

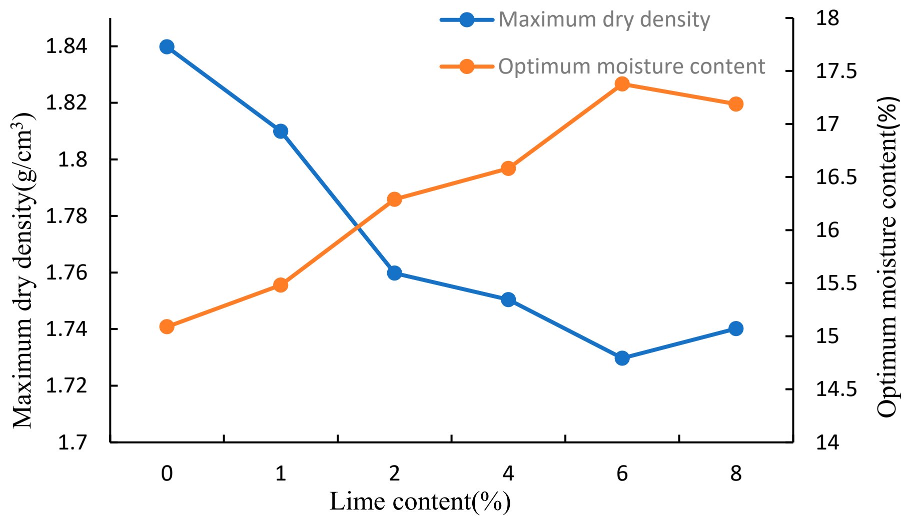


(**b**) Variation of compaction results under different lime content

Figure 6. Compaction test results of soil sample B.



(**a**) Compaction curve under different lime content



(**b**) Variation of compaction results under different lime content

Figure 7. Compaction test results of soil sample C.

3.3. CBR

The carrying capacity of soil foundation materials and the soil foundation's resistance to deformation are measured using the CBR value. It is an important signal while constructing a roadbed. The bearing capacity of a material is defined as its ability to endure deformation under a local load, and standard gravel is used as the benchmark. This capacity is denoted by their relative ratio CBR value. Prior to the experiment, the specimen that has been prepared in accordance with the test guidelines must be immersed in water. In order to calculate the change in the humidity density of the specimen, the specimen is weighed after being removed from the solution and allowed to drain for 15 min. Following the results of the last compaction test, the sample for this test was prepared using 30, 50, and 98 compaction times. During sample preparation, the lime content was still 0%, 1%, 2%, 4%, 6%, and 8%, and the ideal moisture content was chosen. The results of the CBR test are displayed in Figures 8–10.

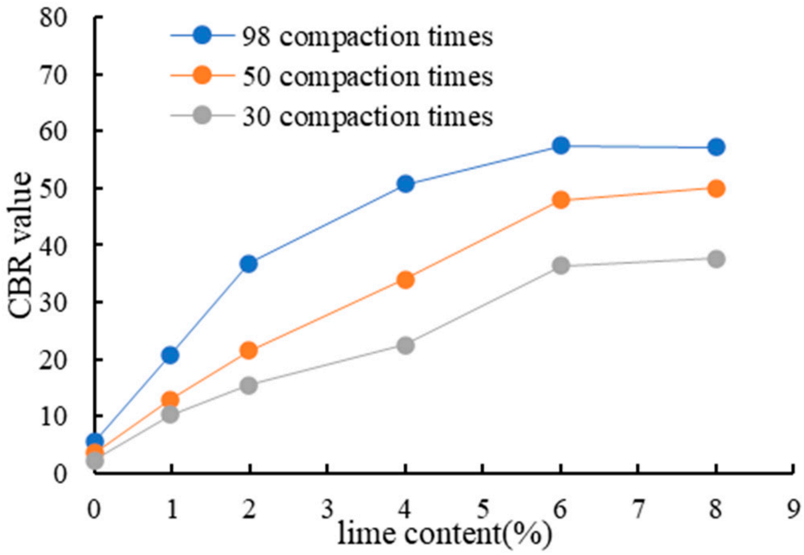


Figure 8. CBR test results of soil sample A.

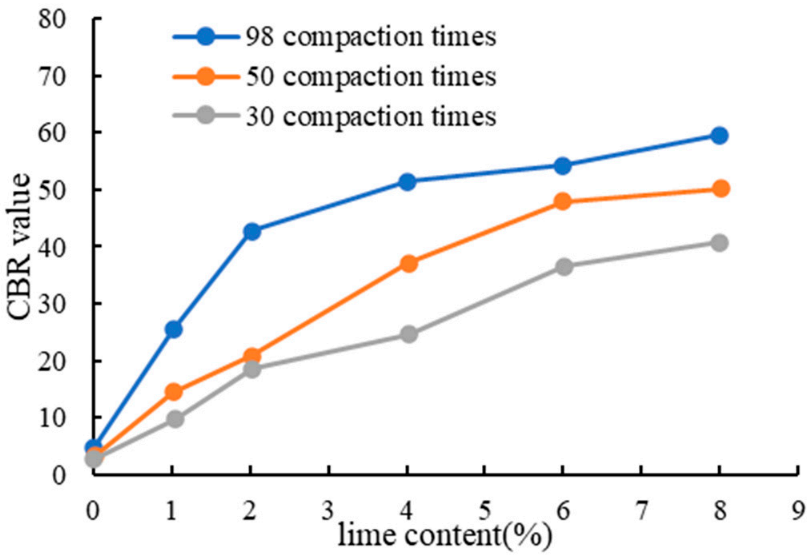


Figure 9. CBR test results of soil sample B.

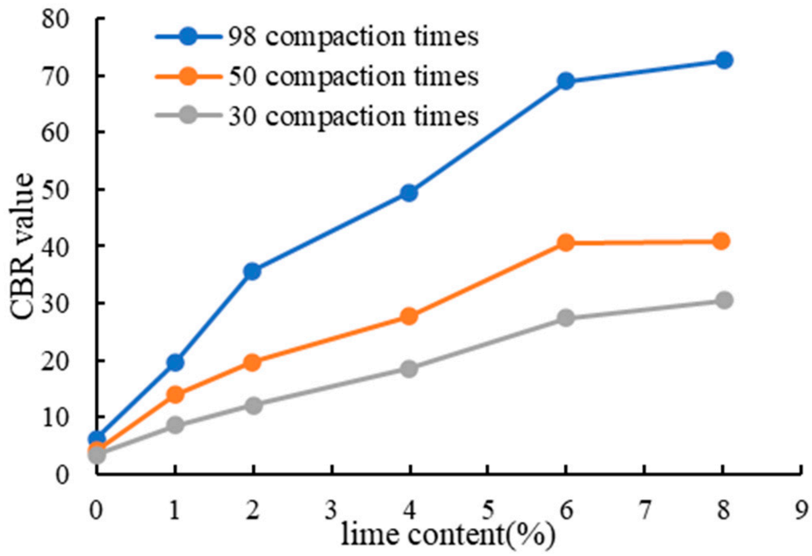


Figure 10. CBR test results of soil sample C.

It can be seen from the figure that with the increase in compaction times, the CBR values of stabilized soil with different ash content increase. In the case of the same compaction times, the CBR value increased by a large margin before 6%. When the ash content increased again, the increase was not obvious, and the curve tended to be stable. Taking the test with 98 times of compaction as an example, when the ash content increases from 0 to 6%, the CBR value increases from 5.4% to 57.3%. When the ash content increases again, the CBR value does not increase significantly or even decrease to 56.9. It shows that the increase in ash content can significantly improve the water stability of low liquid limit clay. It can be concluded that the ash content of 6% is a reasonable dose for improving low liquid limit clay in this area.

Longer compaction times improve the CBR value of stabilized soil with varied lime levels, mostly for the following two reasons: When lime first absorbs water from the soil, a lot of heat is emitted as the volume expands, which evaporates the water and improves the soil's quality. Second, some lime reacts with carbon dioxide in the atmosphere to form calcium carbonate, a weakly-bonding material that increases the soil's CBR value and strength to some level.

4. Discussions

In view of the problem mentioned above that the original engineering soil does not meet the filling requirements, this paper improved the original soil by mixing ash. At the same time, the improvement effect is judged by comparing the basic properties of undisturbed soil and lime-doped soil before and after mixing.

The addition of lime has little effect on the liquid plastic limit, and the plastic limit of the three soil samples is about 3%. This shows that the addition of lime does not change the plastic limit property of soil liquid considerably, but the addition of lime has a great effect on dry density and water content. As can be seen from Figures 5–7, the curve of water content and dry density presents the following rules with the increase in lime content: First, with the increase in lime content, the maximum dry density corresponding to the curve gradually decreases, while the optimal water content gradually increases. Moreover, the effect of lime improvement on the CBR value is also obvious. With the increase in compaction times, the CBR value of the soil sample will be increased to a certain extent. With the increase in lime content, the CBR value gradually increases, and basically stabilizes when the lime content reaches 6%. Following the addition of lime, the basic physical characteristics of the original soil, such as the liquid-plastic limit, CBR, and optimal water content, can be enhanced due to the aforementioned interaction between lime and bad soil, allowing the bad soil that did not initially meet the filling requirements to do so.

Ion exchange, carbonation, and crystallization will occur throughout the process of enhancing low liquid limit clay with lime mixing, resulting in an increase in the plastic limit of each soil sample with an increase in lime concentration and a corresponding decrease in the plastic index. On the one hand, the interchange of $Ca2^+$ in the lime with other cations on the surface of the soil particle is what causes the water loss of the improved soil. On the other hand, more water is required to produce the best compaction effect because the dissolution and hydration of lime in the soil causes soil to be compressed in real time [18].

Compared with other treatment methods, such as replacement, lime improvement has the following advantages: first, lime improvement is convenient in construction, as it does not need to be transported back and forth to shorten the construction period and save costs; second, the price of lime is low, and the improvement of 1 m3 bad soil only needs about 60 rmb; finally, the technology of lime improved soil is mature, mixing is simple, and there is no complicated process.

5. Conclusions

In this research, the CBR test, compaction test, and limit water content test are used to assess and compare the differences between lime-improved soil and an untouched soil sample. The results of this inquiry were as follows:

1. After lime digestion improves the initial low liquid limit clay, the liquid limit essentially stays the same, the plastic limit increases as the lime content rises, and the plastic index gradually declines. After lime is introduced to the soil, ions from the lime and the soil exchange, causing the clay particles to form a granular structure. The rise in the plastic limit often remains steady once the lime content reaches 6%. It is also shown that a low liquid limit clay mixture with lime has a reasonable ash concentration of about 6%. When the lime content is 6%, the maximum dry densities are 1.61 g/cm^3, 1.65 g/cm^3, and 1.73 g/cm^3, respectively. The optimal water content was 16.7%, 17.2%, and 17.4%, respectively.
2. The CBR value of the soil samples under various compaction durations considerably rose with an increase in ash content, showing that ash mixing had improved the water stability of low liquid limit clay containing sand. The acceptable ash content is 6% at the same time. When the lime content is 6% and the compaction times are 98, the CBR values are 57.4%, 54.2%, and 68.9%, respectively.
3. The ideal water content and CBR value of the clay with low liquid limit are clearly impacted by the amount of dissolved lime added. The ideal water content falls as the incorporation amount increases, while the CBR value rises.
4. Plain soil does not meet the filling requirements of subgrade in areas 93, 94, and 96 of expressways. The performance of the improved soil has been improved to varying degrees after the ash mixing improvement, and it can meet the filling requirements of subgrade in areas 93, 94, and 96. According to the test, the most reasonable ash mixing amount of the improved soil is determined to be 6%.

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Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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

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