



Study on the Effect of Carbonation on the Mechanical Properties of Lime Modified Waste Clay

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ABSTRACT

A large amount of waste clay is generated in shield tunnel engineering. Although the physical properties such as the unconfined compressive strength of the clay have been improved through lime modification, some still fail to meet the specifications for road embankment materials. In this study, an indoor carbonation device was used to carbonize lime-modified clay samples with different lime contents. The changes in water content (ω), plasticity index (I_p), undrained compressive strength (q_u), and softening coefficient (Kr) of the samples were analyzed. Microscopic mechanisms were investigated through tests such as Scanning electron microscope (SEM) and Diffraction of x-rays (XRD). The results showed that with increasing carbonation period, the ω and I_p of soil samples with different lime contents gradually decreased and stabilized. After 2 hours of carbonation, the q_u , elastic modulus (E_{50}), and Kr of the soil samples significantly increased. After 1 hour of carbonation and 7 days of curing, the modified clay with lime content greater than 7% met the subgrade strength standards for secondary and lower-grade highways ($I_p \leq 26$; $q_u \geq 500$ kPa). The carbonation reaction resulted in the formation of CaCO_3 crystals on the surface of soil particles and $\text{Ca}(\text{OH})_2$. With carbonation further developed, a CaCO_3 — $\text{Ca}(\text{OH})_2$ —C-S-H hybrid material was generated, which filled the pore space in clay reinforcing the structure and improving the strength of lime-modified clay.

1. Introduction

In the construction of shield tunnels, a large amount of waste mud and sludge is generated with high water content (here after referred to as “waste clay”), which cannot be directly reused due to its low strength and complex nature (Zhang et al., 2022). In engineering practice, lime is usually mixed into the waste clay to reduce its moisture content and increase its unconfined compressive strength (UCS) in order to meet the engineering requirements and make it to be used as a filler or other engineering materials (Al-Mukhtar et al., 2012). However, due to the high moisture content of the waste clay generated by the shield, a high lime

dose (e.g., over 10%) is generally required to make it satisfactory. Moreover, lime production is characterized by high energy consumption and serious dust pollution (Shan et al., 2016). Therefore, higher lime dosage may cause the problems of high costs, high energy consumption and potential environmental pollution. In the case of waste clay ($\omega = 71.43\%$) generated by a mud and water shield tunnel project after centrifugal dewatering, over 15% lime is required to treat the clay to meet the requirements of the specifications for road fill (Li et al., 2023). Therefore, how to reuse these waste clay in a more economical and environmentally friendly way is currently a major engineering concern.

In the context of carbon neutrality and carbon peaking,

carbonation technique has been applied to soil reinforcement recently. At the same time, the study of the sorption and sequestration capacity of alkaline solids for CO₂ is of great importance for achieving carbon neutrality (Padmaraj and Arnepalli, 2021). In the early days, lime was generally used for consolidation of soils with low water content. A good improvement was obtained by simply mixing. Due to the low CO₂ content in the air (only 0.03% by volume) (Chang et al., 2018), the reinforcing effect of carbonation on lime cured soils was neglected in its natural state. However, in the field of ancient architecture and heritage restoration, the long-term carbonation of lime treated soils has been a constant concern (Silva et al., 2014; Xu et al., 2020; Tamassoki et al., 2022). In order to make better use of carbonation, accelerated carbonation techniques have been developed. It reduces the time of carbonation to less than a few hours by changing carbonation pressure, time, humidity and temperature (Lim et al., 2010). Zhang et al. (2018) found that accelerated carbonation significantly improved the mechanical properties of water-hardened lime mortars. The strength of specimens that have experienced accelerated carbonation for 72h is 7.5 times that strength of specimens under natural conservation conditions.

There are also some works that have been conducted on the carbonation of weak soils. Exploratory carbonation tests on different soil types found that sandy soils and silty soils experience significant strength growth after 3 hours of carbonation under a pressure of 200 kPa (Yi et al., 2013). Liu et al. (2020) found that the main products of magnesia-stabilized soil after carbonation are magnesite trihydrate, hydromagnesite, and nesquehonite. The strength of the stabilized soil is generally increased with increase in amount of carbonation products. After carbonation and subsequent sulfate erosion, the pore structure of the soil does not undergo significant changes, and the soil's resistance to sulfate erosion is significantly improved (Liu et al., 2016). Cai et al. (2020a) applied the technology of magnesia stabilization-carbonation treatment to a construction site and found that the maximum ventilation radius for magnesia carbonation treatment should be around 60 cm, and the spacing of air ducts should be between 1 and 1.2 m. The bearing capacity of the sludge field after carbonation treatment reached above 140 kPa, and the dynamic rebound modulus reached 20 MPa, meeting the requirements for highway subgrade.

The research of domestic and foreign scholars has mostly focused on the changes in the physical and chemical properties and microscopic mechanisms of magnesia-stabilized soil after carbonation reinforcement (Liu et al., 2016; Liu et al., 2020; Cai et al., 2020a; Wang et al., 2021; Liu et al., 2021; Cai et al., 2020b). Lime, as a commonly used reinforcement material, has the advantages of low cost and strong calcium ion exchange

capacity, which enables lime to have a short curing time and strong physical bonding capability of hydration products. However, there are few studies on the mechanical property and microscopic mechanisms of lime-modified clay after carbonation.

This study aims to use accelerated carbonation technology to investigate the changes in ω , I_b , q_u and K_r (the softening coefficient, which is the ratio of the unconfined compressive strength in the fully saturated state to that in the dry state) of lime-modified clay with different lime contents after different carbonation periods. The microscopic structure of lime-modified clay after carbonation was observed, and the influencing mechanisms of carbonation were analyzed. The research findings can provide references for the application of carbonized lime-modified clay technology in engineering practice.

2. Material and Method

2.1 Material

The soil sample was obtained from centrifugally dewatered waste clay from a slurry shield tunneling project crossing the Yellow River. The project is located at Jihe Road, Jinan City, Shandong Province, China. The physical properties of the soil were tested in accordance with the “Technical Specifications for Geotechnical Testing of Highways” (JTG3430-2020) and the “Standard Test Methods for Geotechnical Testing” (GB/T50123-2019). As shown in Table 1, the waste clay had a moisture content of 71%, a plastic limit of 26%, a liquid limit of 69%, a plasticity index of 43, and a fines content exceeding 50%. It is classified as high liquid limit fat clay (CH) according to the USCS classification system. The mineralogical analysis of the waste clay is presented

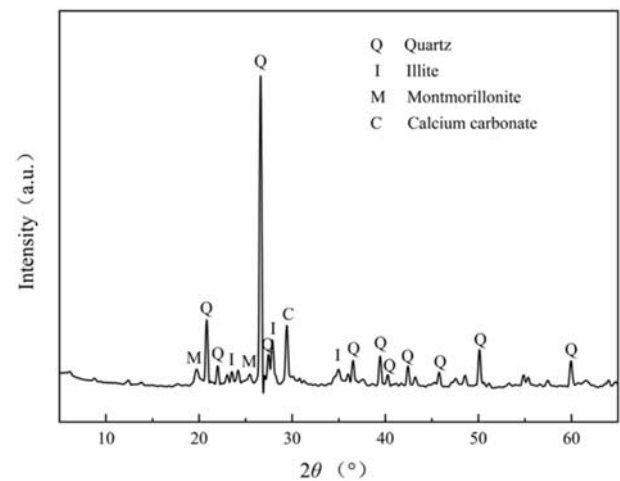


Fig. 1. XRD Patterns of Waste Clay

Table 1. Basic Physical Properties of Waste Clay

ω (%)	Gs	pH	Soil particle size content (%)			ω_p (%)	ω_L (%)	I_p
			< 0.005 mm	0.005 – 0.075 mm	0.075 – 2 mm			
71%	2.68	7.5	36	58	6	26	69	43

in Fig. 1. Quartz is the predominant mineral, with minor amounts of calcite. The clay minerals are principally composed of illite and montmorillonite.

The lime used in the experiments was “Taiyang Brand” analytical grade calcium oxide ($\geq 98.0\%$), produced by Tianjin Zhiyuan Chemical Reagent Co., Ltd. The chemical composition of the lime was well-defined, and it exhibited high purity with minimal impurity content.

2.2 Test Method

In this experiment, carbonation reinforcement was conducted on modified clay with five different lime contents: 3%, 5%, 7%, 9%, and 12%. The lime content, denoted as “ a_c ” is defined as the ratio of the mass of lime to the mass of dry soil.

After adding lime to the waste soil according to the above-mentioned lime contents, a B10 mixer was used for thorough mixing to ensure uniformity of the sample. The samples were prepared using the Standard Proctor Compaction Test method. Table 2 presents the optimal moisture content (ω_{op}) and maximum dry density (ρ_{dmax}) of the modified clay at each lime content. As the lime content (a_c) increased, ω_{op} gradually increased while ρ_{dmax} decreased. According to the maximum dry density of

Table 2. Maximum Dry Density of Modified Soils at Different Lime Content

a_c	ω_{op} (%)	ρ_{dmax} ($g \cdot cm^{-3}$)
0%	24.9	1.67
3%	25.8	1.64
5%	28.2	1.62
7%	28.7	1.59
9%	31.6	1.57
12%	33.5	1.56

modified soil at different a_c in Table 2, the mass of the required soil sample was measured to achieve a volume of 96 cm^3 . The mixed modified clay was then layered and filled into a stainless-steel compaction mold with an inner diameter of 39.1 mm and a height of 80 mm. After the mold was filled with soil, a hydraulic jack was used for static compaction to compact the modified clay.

After compaction, the top and bottom surfaces were leveled, and the molds were removed to demold the specimens. Three specimens were prepared for each lime content. The cylindrical specimens were sealed with plastic and placed in a curing chamber at a temperature of $20 \pm 2^\circ\text{C}$ and a humidity level above 90% for a curing period of 7 days. The compaction degree of all specimens in the study was set at $94\% \pm 2\%$ and controlled based on the mass of the mixture.

Figure 2 shows the accelerated carbonation apparatus used in the laboratory experiment. The design and fabrication of this apparatus were based on previous experiments conducted by researchers (Liu et al., 2020). It consists of a carbon dioxide pressurized bottle and a carbonation barrel. The carbonation barrel is composed of an acrylic column, a flange plate, an inlet port, and an exhaust valve. Specimens with different lime contents were placed in the carbonation barrel and CO_2 gas was introduced. Based on previous carbonation test studies, including alkaline modifiers such as lime, a carbonation pressure of 200 kPa has been found to achieve favorable carbonation effects on modified soil, while excessively high carbonation pressure may damage the structure of lime-modified clay (Cai, 2018). Therefore, the CO_2 gas pressure was set at 200 kPa, and carbonation periods of 0.5 h, 1 h, 2 h, 4 h, and 8 h were selected.

After carbonation, the dimensions and mass of the specimens were measured, followed by testing the ω (ASTM D2216-71), I_p (ASTM D4318-10^{e1}), q_u (ASTM D2166-00), E_{50} and K_r of the modified soils with different a_c after different carbonation

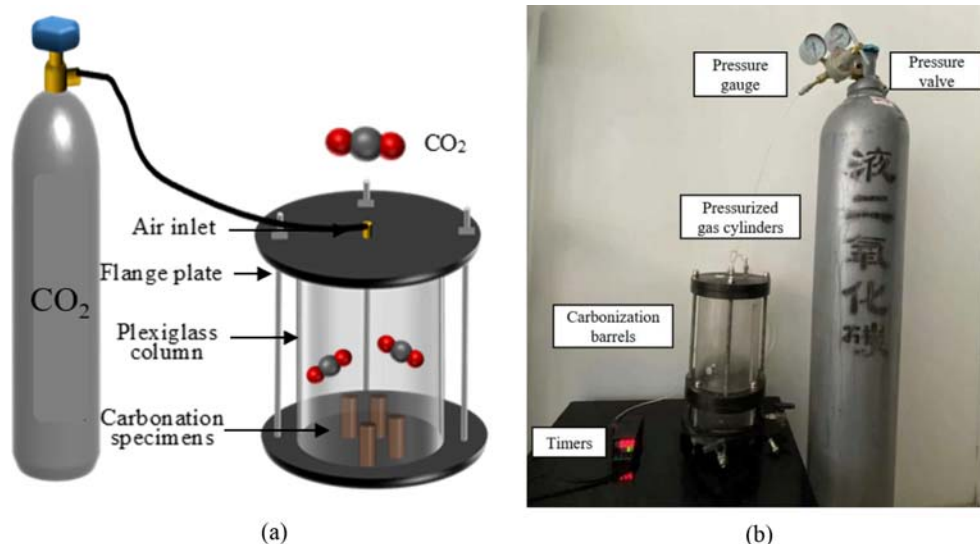


Fig. 2. Apparatus for Carbonation Reinforcement Test: (a) Schematic of the Carbonation Reinforcement Device, (b) Physical View of the Carbonation Reinforcement Device

periods. The GYS-2 liquid and plastic limit combined tester was used to determine the plastic limit, which was used to calculate the plasticity index of the specimens. The unconfined compressive strength tests were conducted using the YSH-3 unconfined compressive strength testing apparatus produced by Nanjing Soil Instrument Factory.

X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests were further conducted to investigate the effects of a_c and carbonation duration on carbonation effectiveness and further elucidate the microscopic mechanisms of accelerated carbonation. The XRD test was performed using a Rigaku Ultima IV X-ray diffractometer from Japan. The specific parameters for the test were as follows: rated output power of 3 kW, Cu target, step size of 0.02° , scanning speed of $5^\circ/\text{min}$, and scanning range of 5° to 65° . The SEM test was conducted using a Zeiss Sigma 300 scanning electron microscope.

3. Results

3.1 Water Content and Malleability

Figure 3 presents the relationship between carbonation period and water content (ω) of lime-modified clay. It can be observed that with increasing carbonation period, the ω of the modified soil initially decreases rapidly and then tends to be varied slightly after 8 hours. Taking the $a_c = 3\%$ soil sample as an example, after 0.5 hours of carbonation, ω decreases from 62% to 58.5%, accounting for a 60% change. However, from 6 to 8 hours of carbonation, ω remains almost unchanged.

Moreover, the rate of decrease in ω varies with different a_c values. For the $a_c = 3\%$ soil sample, it only takes 0.5 hours of carbonation to achieve a 60% reduction in ω . When a_c increases to 5% to 7%, the soil sample requires 1 hour to achieve a 60% to 65% reduction in ω . On the other hand, for the 9% to 12% lime content, ω decreases from 48.75% to 46.25% (a 65% reduction) and requires 2 hours of carbonation. Lower a_c values result in

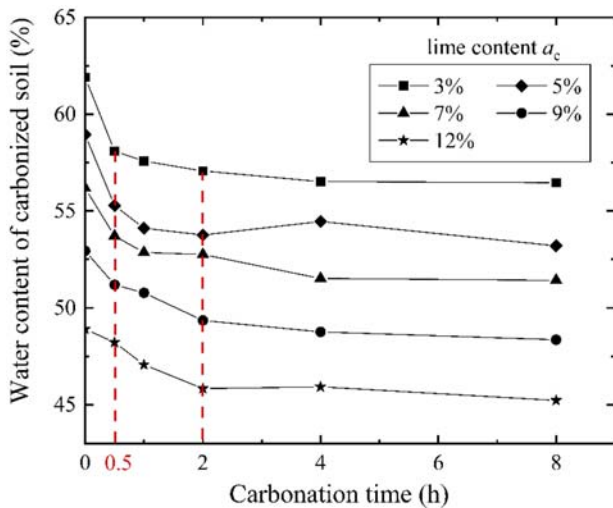


Fig. 3. Effect of Carbonation Period on the Water Content of Lime Modified Soils

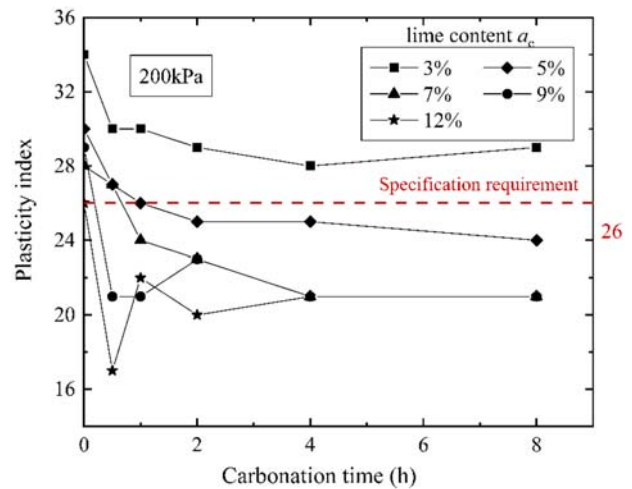


Fig. 4. Effect of Carbonation Period on Plasticity Index of Modified Soils

shorter carbonation periods to achieve the same reduction in ω .

Figure 4 is the change curve of plasticity index (I_p) of lime-modified clay with carbonation period. It can be observed that the I_p curve generally exhibits a decreasing trend and varied slightly after being carbonized for 8h. Different a_c values show a significant change in I_p after 0.5 hours of carbonation. Higher a_c values result in a more pronounced decrease in I_p , and also a lower I_p values. When the a_c increases from 3% to 5% to 9% to 12%, the decrease in I_p after 0.5 hours of carbonation increases from 3 – 4 to 6 – 7, and the stabilized I_p decreases from 29 to 21.

Referring to the “Highway Subgrade Design Code” (JTG D30-2015), when $a_c \geq 7\%$, even with only 1 hour of accelerated carbonation, the I_p is lower than 26, meeting the requirements for the use of embankment fill materials.

3.2 Unconfined Compressive Strength

Lime modified soils undergo accelerated carbonation reactions at a carbonation pressure of 200 kPa and the resulting carbonation

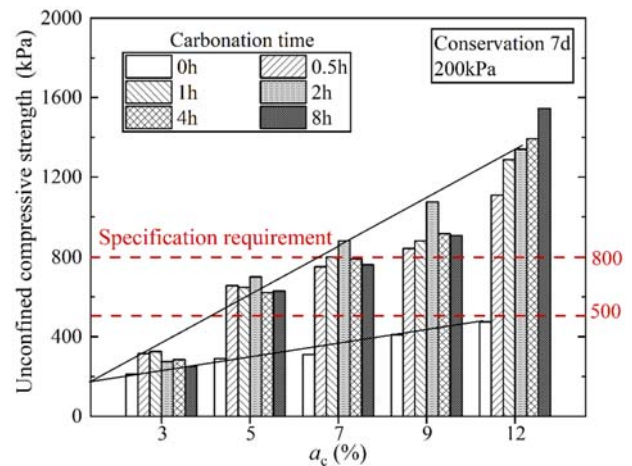


Fig. 5. Effect of Carbonation Period on Unconfined Compressive Strength of Modified Soil

products affect the UCS strength of the soil. Fig. 5 depicts the effect of carbonation duration on the q_u of different a_c lime-modified clay.

It can be observed that q_u exhibits a significant increase for different a_c values with the increase of carbonation period. The increment ranges from 30% to 225% with increasing carbonation period. However, the effect of carbonation varies with a_c values. When a_c is 3%, compared with clay uncarbonated, the strength increments after carbonation ranges from 20% to 50%. As a_c increases to 5% to 7%, the strength increments for the modified soil after carbonation ranges from 130% to 200%. When a_c is 12%, the strength increment can reach 133% to 225%. The soil strength shows a nearly linear increase with the increase in a_c . After carbonation, the $\text{Ca}(\text{OH})_2$ in the modified soil undergoes a carbonation reaction to form CaCO_3 , which fills the pores of the soil and increases its strength. The reasons for the strength increase will be further analyzed and explained in the microscopic experiments below.

Furthermore, the modified soil exhibits a peak strength with varying durations of appearance as carbonation period increases. When a_c is 3%, the peak strength appears after 0.5 hours of carbonation, while for 5%, 7%, and 9% a_c values, the peak strength occurs after 2 hours of carbonation, followed by a subsequent decrease in strength, and for $a_c = 12\%$, UCS is monotonically increased with carbonation period.

Figure 6 illustrates the effect of carbonation duration on the E_{50} of lime-modified clay. It can be observed that carbonation leads to a significant overall improvement in E_{50} for different a_c values, with an increment ranging from 20% to 215%. The increment in E_{50} after carbonation becomes more pronounced as a_c increases. When a_c increases from 3% to 7%, the increment in E_{50} after carbonation increases from 20% – 30% to 200%.

Similar to the trend observed in the unconfined compressive strength, E_{50} also exhibits a peak value as carbonation period increases, especially pronounced at a_c values of 7% and 9%, with

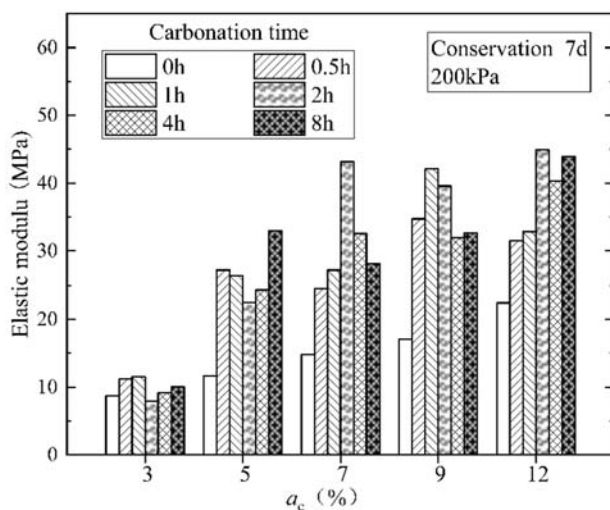


Fig. 6. Effect of Carbonation Period on Elastic Modulus of Modified Soil

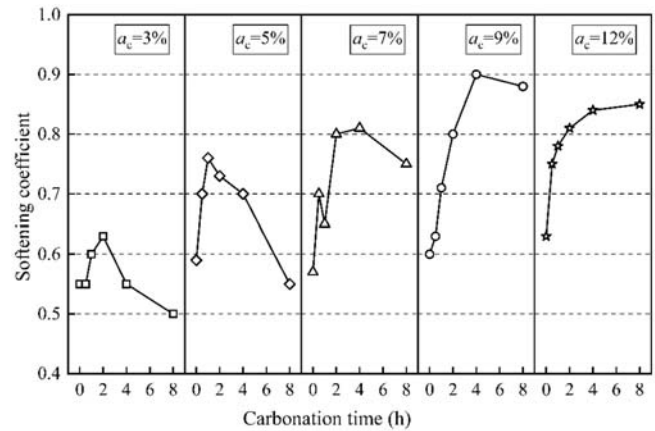


Fig. 7. Effect of Carbonation Period on Softening Coefficient of Modified Soil

peak values occurring at 2 hours and 1 hour, respectively.

It should be noted that the occurrence of peak values followed by a decrease in q_u and E_{50} may be related to the adoption of unconfined tests as evaluation methods. In practice, there may not be an optimal carbonation period, or peak strength may not exist under relatively short carbonation durations. However, excessively long carbonation durations are not economical and may affect the soil structure (Cai et al., 2020b).

In conclusion, for various lime content levels, the lime-modified clay can achieve favorable carbonation effects within 2 hours of carbonation. Additionally, carbonation can reduce the lime content required. For instance, the strength and elastic modulus of $a_c = 5\%$ modified soil after 0.5 hours of carbonation are significantly higher than those of non-carbonated $a_c = 12\%$ modified soil. The reasons for this phenomenon will be further analyzed and explained in detail in the following microscopic experiments.

3.3 Water Stability

The K_r curves of carbonated lime-modified clay after 24 hours of saturation are shown in Fig. 7. It can be observed that with increasing carbonation period, the K_r of the modified soil initially increases and then decreases. The occurrence time of the peak of K_r varies with the lime content. For soil samples with $a_c = 3\%$, 5% and 7% 9%, the K_r starts to decrease after 2 hours and 4 hours of carbonation. The K_r of $a_c = 12\%$ modified soil exhibits a rapid increase followed by a relatively slight change. A higher lime content leads to a larger increase in K_r , indicating a more pronounced carbonation effect and improved soil reinforcement. Each modified soil with various lime doses has an optimal carbonation duration, and exceeding it can result in more significant softening phenomena and decreased water stability.

4. Discussion on Micromorphology and Mechanism

4.1 XRD Test Analysis

The XRD experiment primarily focuses on two aspects: 1) the influence of different lime contents on carbonation effect. 2) the

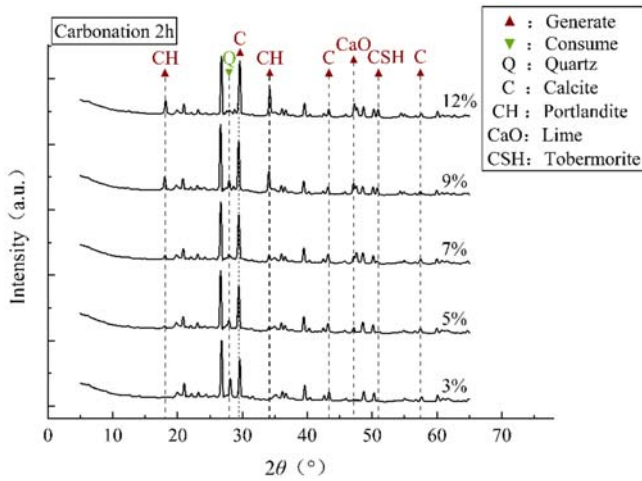


Fig. 8. XRD Patterns of Modified Soils with Different Lime Content after 2h Carbonation

influence of different carbonation periods on carbonation effect.

Based on the previous experimental results, the strength and water stability of the modified soil exhibit the most significant growth after 2 hours of carbonation. Therefore, to address issue (1), XRD tests were conducted on the different a_c modified soils with a carbonation duration of 2 hours and a carbonation pressure of 200 kPa. The XRD patterns are presented in Fig. 8.

From Fig. 8, it can be observed that as the carbonation reaction progresses, carbonation products CaCO_3 are generated within the lime-modified clay. This indicates that, after 2 hours of carbonation, regardless of the value of a_c , the $\text{Ca}(\text{OH})_2$ in the soil participates in the accelerated carbonation reaction, leading to the formation of new mineral crystals and changing the soil's structure, therefore affecting its physical properties.

When $a_c \leq 5\%$, the characteristic peaks representing CaO and $\text{Ca}(\text{OH})_2$ are barely detectable, suggesting that lime in the soil has undergone complete hydration reaction, and the generated hydrated product $\text{Ca}(\text{OH})_2$ has been consumed by the accelerated carbonation reaction, resulting in the formation of CaCO_3 crystals.

However, when $a_c \geq 9\%$, the characteristic peak of CaO gradually becomes prominent, and the characteristic peak of $\text{Ca}(\text{OH})_2$ increases significantly. This indicates that the $\text{Ca}(\text{OH})_2$ generated by the hydration reaction reaches a saturation state, and $\text{Ca}(\text{OH})_2$ precipitates in crystal form. It also means the reaction is not fully developed within 2 hours of carbonation.

This also explains the phenomenon observed in Fig. 5, where a larger a_c value leads to a greater increase in q_u after carbonation. It implies that the carbonation effect of the modified soil depends on the lime and its hydrated product content within the soil. The higher the effective content in the soil, the more CO_2 can combine with $\text{Ca}(\text{OH})_2$, resulting in a higher degree of reaction and more significant changes in soil structure.

Based on the results of the unconfined compressive strength tests and XRD pattern analysis, it is known that when $a_c > 9\%$, the $\text{Ca}(\text{OH})_2$ in the modified soil will reach saturation within two hours or less of carbonation. From a more economical and

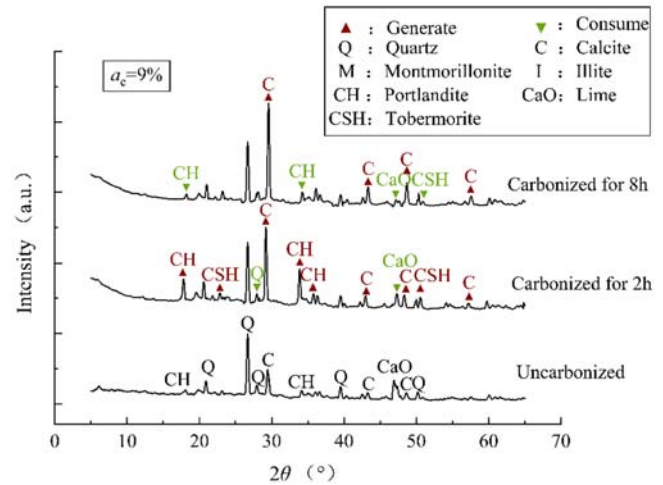


Fig. 9. XRD Pattern of $a_c = 9\%$ Modified Soil after Carbonation

environmentally friendly perspective, using $a_c = 7\%$ and $a_c = 9\%$, the modified soil can achieve relatively good strength improvement after carbonation. Compared to $a_c = 7\%$, the XRD pattern of the modified soil at $a_c = 9\%$ shows more distinct characteristic peaks and more pronounced changes in microstructure, making it easier to analyze the changes in properties of the modified soil over the duration of carbonation. Additionally, the carbonation reaction process and the reaction products of the modified soils at $a_c = 9\%$ and $a_c = 7\%$ are not significantly different. Therefore, in response to question (2), the modified soil at $a_c = 9\%$ is selected as an example, XRD patterns of uncarbonated soil, soil carbonated for 2 hours, and soil carbonated for 8 hours are shown in Fig. 9.

From the figure, it can be observed that as the carbonation period increases, the mineral composition of the soil undergoes significant changes. After 2 hours of carbonation, the characteristic peaks of CaCO_3 , C-S-H, and $\text{Ca}(\text{OH})_2$ in the soil increase significantly, while the characteristic peaks of CaO and SiO_2 decrease. This indicates that not only carbonation occurs generating CaCO_3 crystals, but also hydration reactions occur with CaO as a raw material and volcanic ash reactions occur with free SiO_2 as a raw material, facilitating the generation of gel-like hydrated product C-S-H and crystalline hydrated product $\text{Ca}(\text{OH})_2$.

With further carbonation for 8 hours, the mineral composition of the soil undergoes additional changes. The characteristic peak of CaCO_3 in the soil rises again, while the characteristic peaks of $\text{Ca}(\text{OH})_2$, CaO , and C-S-H decrease. This indicates that prolonged carbonation continuously consumes $\text{Ca}(\text{OH})_2$ and CaO in the soil, while decalcification reactions occur (Li et al., 2017), further consuming C-S-H and disrupting the gel structure of the soil, which is the fundamental reason behind the peak values observed in the soil's strength and water stability in the previous experiment results.

4.2 SEM Test Analysis

To further investigate the micro-mechanisms of accelerated carbonation experiments, SEM tests were conducted on 9% lime-modified clay, and SEM images showing the changes of

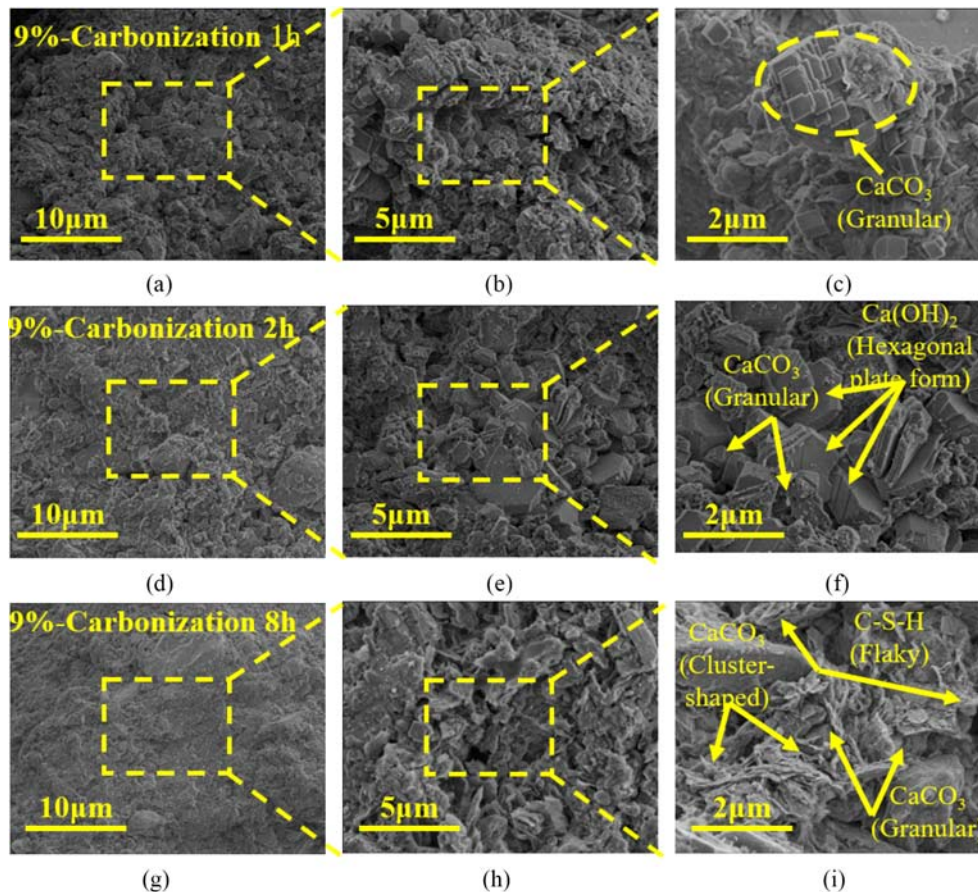


Fig. 10. SEM Images of Different Carbonation Times at $a_c = 9\%$: (a) SEM Image of $a_c = 9\%$ Modified Soil after 1 Hour of Carbonation at $10\ \mu\text{m}$ Scale, (b) SEM Image of $a_c = 9\%$ Modified Soil after 1 Hour of Carbonation at $5\ \mu\text{m}$ Scale, (c) SEM Image of $a_c = 9\%$ Modified Soil after 1 Hour of Carbonation at $2\ \mu\text{m}$ Scale, (d) SEM Image of $a_c = 9\%$ Modified Soil after 2 Hours of Carbonation at $10\ \mu\text{m}$ Scale, (e) SEM Image of $a_c = 9\%$ Modified Soil after 2 Hours of Carbonation at $5\ \mu\text{m}$ Scale, (f) SEM Image of $a_c = 9\%$ Modified Soil after 2 Hours of Carbonation at $2\ \mu\text{m}$ Scale, (g) SEM Image of $a_c = 9\%$ Modified Soil after 8 Hours of Carbonation at $10\ \mu\text{m}$ Scale, (h) SEM Image of $a_c = 9\%$ Modified Soil after 8 Hours of Carbonation at $5\ \mu\text{m}$ Scale, (i) SEM Image of $a_c = 9\%$ Modified Soil after 8 Hours of Carbonation at $2\ \mu\text{m}$ Scale

micromorphology after 1 hour, 2 hours, and 8 hours of carbonation are shown in Fig. 10.

From Figs. 10(a), 10(d), and 10(g), it can be observed that the surface of the modified soil becomes smoother with increasing carbonation period, indicating that the mechanism that carbonation products CaCO_3 influence the soil strength is similar with crystalline hydrated products (Adeleke et al., 2022). They strengthen the soil structure by filling the pores.

From Figs. 10(b), 10(e), and 10(h), various forms of products are present within the soil samples at different carbonation periods. The reaction products reinforce soil structure by filling the pores and wrapping and cementing among soil particles. With prolonged carbonation period, smaller products within the soil become more evident, and pore space among soil particles decreases. This corresponds to the growth of characteristic peaks of CaCO_3 , C-S-H, and Ca(OH)_2 in the XRD patterns, indicating that carbonation products can synergistically interact with various types of products, collectively filling the micropores.

Figures 10(c), 10(f), and 10(i) illustrate the specific products and their structures within the soil samples at different carbonation

durations are different: after 1 hour of carbonation, granular carbonation products CaCO_3 appear on the surfaces of the soil and Ca(OH)_2 crystals, indicating that within a relatively short carbonation period, carbonation products mainly originate from Ca(OH)_2 .

After 2 hours of carbonation, a large amount of Ca(OH)_2 - CaCO_3 hybrid structure appears in the soil, primarily due to the attachment of CaCO_3 to the surfaces of Ca(OH)_2 crystals under high-purity CO_2 , continuously increasing the volume through stacking and filling the micropores between particles. This also explains the presence of a certain amount of Ca(OH)_2 in fully carbonated soil (Lawrence et al., 2007).

After 8 hours of carbonation, a more complex CaCO_3 - Ca(OH)_2 -C-S-H mixture appears within the soil, formed by the deep penetration of CO_2 into the pores at a pressure of 200 kPa and its carbonation reaction with Ca(OH)_2 and C-S-H. Under natural conditions, it usually takes several years or decades to form such a mixed structure. The solidified microstructure generated by accelerated carbonation tests is denser than natural carbonation, but excessively long carbonation period can affect the cementing

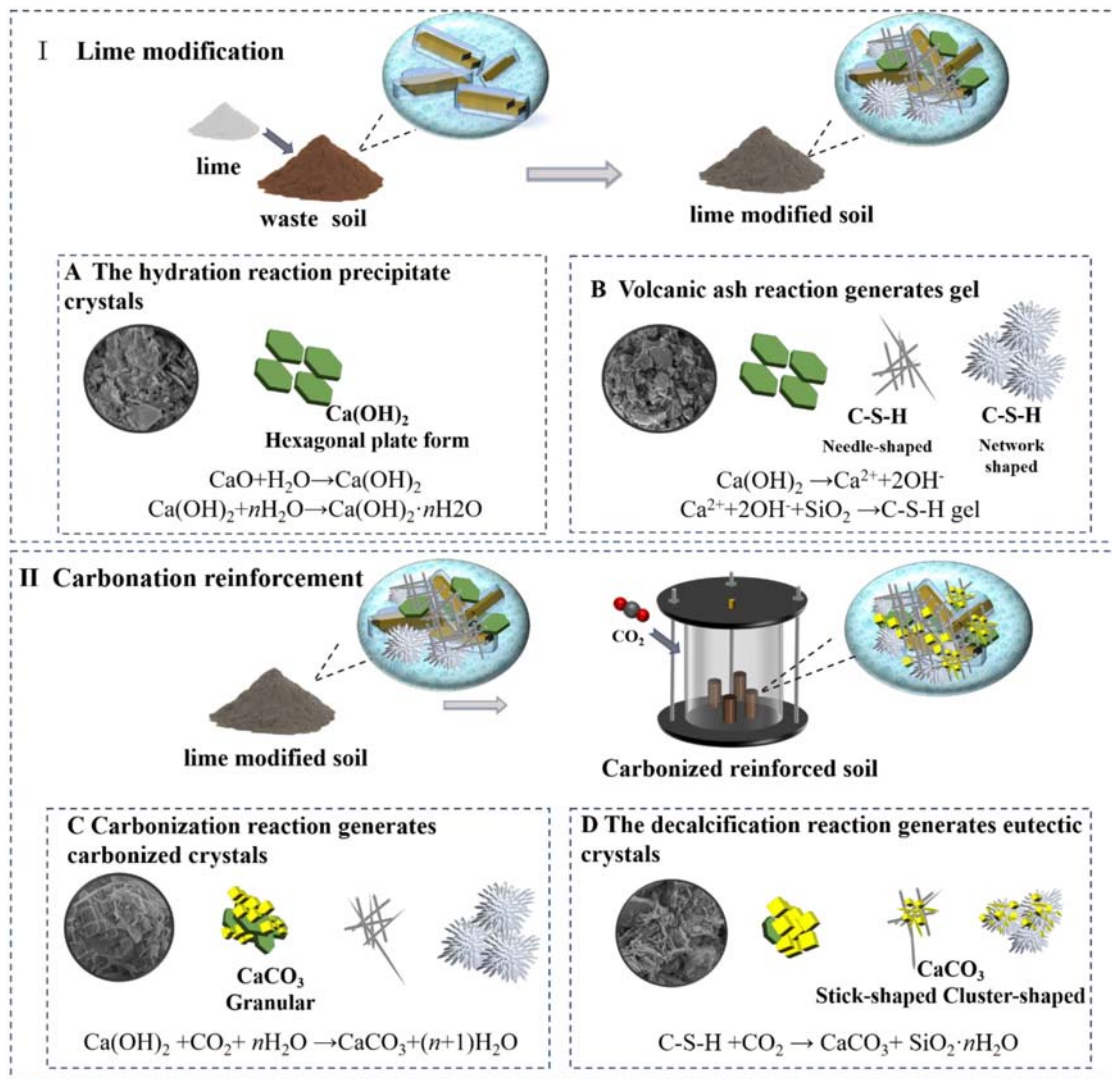


Fig. 11. Enhancing Mechanism of Lime Modified Soil Properties by Carbonation Reinforcement

action of gelatinous hydrated products such as C-S-H (Ahmad et al., 2017).

4.3 Mechanism of Carbonation and Discussion

Figure 11 illustrates the improvement mechanisms of the mechanical properties of lime-modified clay after carbonation reinforcement, mainly including two stages: lime modification and carbonation reinforcement.

During the lime modification stage, hydration reactions occur, generating plate crystals $\text{Ca}(\text{OH})_2$, and volcanic ash reactions generate gelatinous hydrated product C-S-H. During the carbonation reinforcement stage, under a carbonation pressure of 200 kPa, high-concentration CO_2 immediately dissolves in the free water of lime-modified clay. It undergoes carbonation reaction with $\text{Ca}(\text{OH})_2$, and forms fine carbonation crystals of CaCO_3 on the surfaces of $\text{Ca}(\text{OH})_2$ crystals. Meanwhile, due to the consumption of hydrated products, unreacted CaO in the soil undergoes secondary hydration, facilitating the generation of hydrated products. With

the continuous extension of carbonation period, the carbonation products continue to develop and grow, further filling the pore space in soil. Some C-S-H gel combines with CO_2 , undergoes decalcification, and forms more complex products in the soil, reinforcing and filling the voids, thereby strengthening the soil structure and improving its mechanical properties. During carbonation, it ought to avoid excessively long carbonation period, as it can affect the content of C-S-H gel in the soil, leading to a decrease in the water content, disruption of the network gel structure, and weakening of the cementing action between soil particles.

It can be concluded that accelerated carbonation of lime-modified clay can save curing time. After 0.5 hours of accelerated carbonation, the strength of the modified soil cured for 7 days is approximately 1.2 – 1.6 times that of the naturally cured soil for 28 days. Required lime content is reduced due to the carbonation effects. The strength and water stability of soil with a lime content of 5% after 0.5 hours of carbonation are significantly higher than those

of uncarbonated soil with a lime content of 12%.

Taking the experimental materials of this study as an example, modified soil with a lime content of 7% cured for 7 days and carbonated for 1 hour can achieve good physical properties: $I_p \leq 26$ and $q_u \geq 500$ kPa, meeting the requirements of specifications. The specific required lime content and carbonation period in engineering applications need to be further studied and then determined based on the physical properties of the soil sample.

5. Conclusions

Effect of carbonation on mechanical properties of lime-treated waste clay is investigated through a series of laboratory experiments, such as water content test, undrained compressive strength test, SEM test and XRD test etc. The conclusions can be drawn below.

1. With the increase of carbonation period, the ω of lime modified soils showed a decreasing trend, and the rate of decrease of ω gradually slowed down with the increase of a_c . When $a_c \geq 7\%$, after 1h of accelerated carbonation, the I_p can meet the requirements of the specification for use.
2. The q_u and E50 of lime-modified clay are significantly increased after 1 hour of accelerated carbonation. The q_u can meet the specified usage standards after 1 hour of carbonation for lime-modified clay with $a_c \geq 7\%$.
3. The K_r of various lime-modified clay samples is increased significantly after 1 to 2 hours of carbonation. The increase range of K_r improves with increasing a_c . Modified soils with different a_c have an optimal carbonation duration for water stability. Beyond this optimal duration, structural damage and softening occur, resulting in a decrease in water stability.
4. By using carbonation, required curing time of modified soil can be reduced, as the carbonation period increases, required lime content can also be reduced. Low lime content modified soil can achieve satisfactory mechanical properties after short-term carbonation. $a_c = 7\%$ modified soil of 7 days curing can satisfy the specifications in terms of I_p and q_u after 1 hour of carbonation.
5. The carbonation effect depends on the content of lime and its hydrated products. The higher the effective content, the more CO_2 can combine with $\text{Ca}(\text{OH})_2$ to form CaCO_3 and further generate CaCO_3 - $\text{Ca}(\text{OH})_2$ -C-S-H mixtures, reinforcing soil structure and improving strength of lime-treated clay.

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