Hindawi
Advances in Civil Engineering
Volume 2021, Article ID 6641496, 11 pages
https://doi.org/10.1155/2021/6641496

Research Article

Study on the Mechanism of Stabilizing Loess with Lime: Analysis of Mineral and Microstructure Evolution

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Received 10 December 2020; Revised 13 April 2021; Accepted 26 April 2021; Published 12 May 2021

Academic Editor: Jian Xu

X-ray diffraction (XRD) technique was adopted to test the mineral composition of quicklime-solidified loess with different lime-adding rates at different curing periods. Scanning electron microscopy (SEM) and nitrogen adsorption were used to analyze the microporous structure of the solidified loess. The unconfined compressive strength and limit moisture content of solidified loess were combined to analyze the evolution mechanism of mineral composition and microstructure of solidified loess with the change of curing period and clarify the mechanism of quicklime-solidified loess. The results showed reduced content of clay minerals and decrease in the number of large pores due to increase of hydrates and pozzolanic products during extended curing period. The solidified soil fabric transformed from a compact structure into a mesh structure composing of acicular crystal and cementation. The main reasons for strength increase and change of liquid and plastic limits with the lime-solidified loess after extended curing are the change of the substance and the microstructure.

1. Introduction

Loess is widely distributed in the midlatitude arid and semiarid regions of the northern hemisphere. Of the loess regions worldwide, China is the country with the most extensive loess distribution. The area of loess regions in five provinces of Shaanxi, Gansu, Qinghai, Ningxia, and Shanxi amounts to 640,000 square kilometers, and provinces such as Shaanxi, Gansu, and Qinghai are typical loess regions [1]. Loess, due to its large porosity and loose structure, is highly sensitive to water. Therefore, the loess foundations and roadbeds should be solidified for safe civil construction in loess regions. Two methods are mainly applied to solidify loess: physical and chemical solidifications. For chemical solidification, curing agents are mainly added in the foundation soil. The agents will have a series of physical and chemical reactions with the loess to change its structure. There are a variety of curing agents for different soils, including lime [2], sodium silicate [3], and ion curing agents [4]. These agents have been widely used because of easy operation. Among them, lime is widely used in various projects for easy accessibility, low price, and recyclability [5].

When lime is added to loess, a physicochemical reaction occurs under a certain water content at a given temperature, which changes the mineral composition [6], particulate composition, and connection mode [7] of the particles, improves the plasticity [8], strength [9], compressibility, and water impermeability [10] of loess, and makes the soil more stable, thus changing the microstructure and physical and mechanical properties of loess [11, 12]. Bell et al. [13] found that the types of clay mineral, curing time, and temperature had an important influence on the physical and mechanical properties of lime-solidified clay. Marshall et al. [14] believed that lime curing significantly improved the shear strength and elastic modulus of solidified soil. The increase in shear strength was mainly due to the obvious improvement in cohesion, while extended curing period increased the shear strength and elastic modulus of the solidified soil. Phanikumar [15] conducted tests on lime and fly ash solidified expansive soil, and the results showed that they had a significant influence on the expansion, solidification, and compression characteristics of solidified expansive soil. With the increase of lime content, the degree of expansion and expansion pressure decreased, accompanied by improved characteristics of solidification and secondary solidification. Harichane et al. [16] studied the influence of natural volcanic ash and lime as well as their combined additives with different contents on the compression and shear strength of two kinds of soil. The results showed that the maximum dry density of the soil increased due to the combined effect of volcanic ash and lime, but the moisture content of the soil decreased. Over time, the cohesion and internal friction angle of lime-solidified soil increased. The combination of volcanic ash and lime had a greater impact on improving the cohesion and internal friction angle of solidified soil. The addition of both lime and natural volcanic ash improved the parameters of shear strength more evidently than addition of lime or natural volcanic ash. Bessaim et al. [17] adopted quicklime with different contents to solidify cohesive soil and studied the influence of quicklime on its physical and chemical properties. The results showed that quicklime reduced the plasticity of clay, increased the soil's pH value, and catalyzed the pozzolanic reaction. The pH value could be a good parameter for understanding the reaction of soil and lime. Metelkovad [6] explained the pore distribution of loess solidified with lime for 360 days from the perspective of mineral formation. He believed that when the lime-adding rate was lower than 2%, the decrease of macropores was mainly due to the formation of calcium hydroxide and calcite. When the lime-adding rate was higher than 2%, the reduction of macropores of lime-solidified loess was caused by the generation of new pozzolanic reaction products. Stoltz et al. [18] studied the effect of clay minerals on the process of pozzolanic reaction. The results showed that, during the curing period of 28 days, kaolin mainly underwent flocculation and ion-exchange reaction, while bentonite had ion-exchange reaction and volcanic ash reaction in a short period.

Lime has been used primarily in solidifying problematic soils for thousands of years. Limited by regional soil conditions, many studies focus on expansive soils and clays. However, the application of lime-solidified loess is also extensive, and some studies mainly highlight the mechanical and physical properties of solidified soil [6, 19–21]. However, loess has restricted regional characteristics and is quite different from expansive soil in terms of engineering characteristics. Although some literatures have dealt with mechanical properties and physicochemical indexes of lime-solidified loess, little attention has been paid to the effect of the mechanism of solidification to lime-solidified loess [20, 22], and the solidification mechanism is the fundamental reason for the change of macroscopic physical, chemical, and mechanical properties of loess. The main purpose of this study is to analyze the mineral composition and microstructure of lime-solidified loess with different mass ratios over time. The mechanical properties of loess before and after solidifying with lime were analyzed using liquid and plastic limits and unconfined compressive strength tests (UCS). The solidified loess was tested by means of X-ray diffraction (XRD), scanning electron microscopy (SEM), and nitrogen adsorption, in order to further analyze the mechanism of lime-solidified loess at different time intervals for mineralogical and morphological analysis.

2. Test Materials

2.1. Materials and Sampling Methods. The loess samples were taken from a construction site in Xining City, Qinghai Province (N36°40′E101°44′, 2286ma.s.l.). The basic physical parameters are shown in Table 1, and the distribution curve of the particles is shown in Figure 1. Xining region loess is dominated by silt, with sand, silt, and clay content accounting for 26.6%, 55.24%, and 18.16%, respectively. The loess is low-plasticity silt ML (USCS; ASTM 2011) with a plasticity index of 9.06. The mineral analysis showed that it was mainly composed of quartz, plagioclase, and calcite, with a small amount of hornblende, anhydrite, and mirrorstone. The powders of undisturbed loess samples were tested using X-ray diffraction (XRD), and the relative mineral contents of unearthed samples were analyzed using X'Pearson software. The relative content of clay minerals obtained is 31.9%, mainly composed of illite, mirrorstone, and chlorite, as shown in Table 2.

Through ion exchange between cations of lime and soil particles, the carbonization reaction occurs with carbon dioxide in the air, and pozzolanic reaction occurs with active silica and alumina in soil; as a result, lime-solidified loess changed soil particles, formed crystal transformation, and shortened the distance between particles, thus solidifying the loess [23]. The dissolved silica and alumina react with calcium ions during pozzolanic reaction, producing new cementitious compounds—hydrated calcium silicates (CSH), aluminates (CAH), and/or aluminosilicates (CASH) [6]. It was found that the quicklime caused effective stabilization of the loess [24, 25]. Both unconfined compressive strength and load-bearing ratio of the loess were improved by quicklime, while the swelling ratio was decreased. Given its characteristics, quicklime was selected as the curing agent in this study. Quicklime adopted is a commercial bottled quicklime powder produced by Tianjin Guangfu Fine Chemical Research Institute. The content of quicklime (after burning) is more than 98%.

2.2. Preparation of Samples. The quicklime-dry soil mass ratio was defined as lime-adding rate, and the water-lime soil mass ratio was defined as moisture content. Samples were prepared in batches and the designed curing periods of the solidified loess were 7 days, 28 days, and 60 days, respectively. The target moisture content of the solidified loess was set to be 15%, the dry density was set to be 1.6 g/cm^3, and the lime-adding rate was designed to be 5%, 15%, 20%, and 25%, respectively. To carry out the comparative analysis, compacted loess samples were prepared at the same time, with the same curing condition and solidified soil.

Preparation of quicklime-solidified loess samples: loess was screened through a 1 mm sieve after drying at 105°C for 24 h. Quicklime was added to loess in the form of dry powder

Table 1: Basic physical properties of the soil samples.

Soil sample	Water content (%)	Density (g/cm^3)	Specific gravity (g/cm^3)	Porosity (%)	Liquid limit (%)	Plastic limit (%)
Undisturbed loess	10.3	1.61	2.68	53.4	28.3	19.3

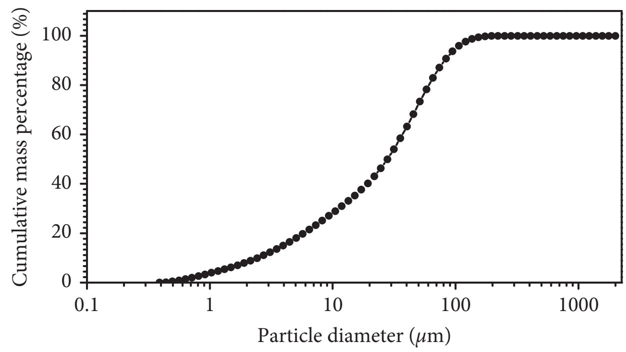


Figure 1: Grain-size distribution curve of loess.

Table 2: Mineral composition of loess samples.

Mineral name	Hornblende	Clay mineral	Anhydrite	Quartz	Potassium feldspar	Anorthose	Calcite	Dolomite
Relative content (%)	1.4	31.9	1.2	36.3	2.1	8.8	16.5	1.8

at the preset mass percentage. The mixture was sprayed with distilled water, depending on the target moisture content. To avoid excessive moisture evaporation, we stirred the mixture quickly and evenly. Then, we put it in a polyethylene bag, sealed the bag, cured for 24 h in the humidor, and let the water mixing evenly with water film transfer. The sample was consolidated by two-way compaction, and the mold was a cube of $7.07 \times 7.07 \times 7.07 cm^3$. We sealed the consolidated cubic sample in the humidor and cured the sample to a specified period (see Figure 2). We prepared samples in three batches according to the designed curing periods and tested them at one time. Meanwhile, the compacted loess samples were prepared by drying, sieving, adding water, curing, and finally testing in the same way.

Figure 2: The samples of quicklime-solidified loess under curing conditions.

3. Test Methods

To analyze the effect of lime content and curing period on the microstructure evolution and solidifying mechanism of solidified loess, we evaluated the physical properties using limit moisture content, estimated the strength of solidified loess using unconfined compressive strength, analyzed soil microstructure using scanning electron microscopy(SEM) and nitrogen adsorption aperture, and analyzed soil mineral composition using X-ray diffraction (XRD), based on which, we further expounded the mechanism of lime-stabilized loess. The lime-stabilized loess samples were tested for unconfined compressive strength, and then the damaged samples were taken for liquid and plastic limit tests, X-ray diffraction test, BET nitrogen adsorption pore distribution test, and scanning electron microscopy (SEM) test, respectively. Two identical samples were tested unconfined compressive strength and liquid and plastic limits, and the average value was used in the result analysis. The average value and error bars were illustrated. All these errors for the results of unconfined compressive strength test were less than 8% and errors for liquid and plastic limit tests were less than 5%, indicating reproductivity of the test results.

The unconfined compressive strength test (UCS) was carried out with an automatic compression method by CSS-WAW300DL universal testing machine, with a loading rate of 1 mm/min. The test was operated in strict accordance with Standard for Geotechnical Soil Test Method of the People's Republic of China (GB/T 50123-2019), and the maximum pressure at the time of failure of each specimen was taken as the unconfined compressive strength. The liquid and plastic limits were tested with a conical LL&PL combined tester following the procedures established according to the Standard for Soil Test Method (GB/T 50123-2019). We have defined the liquid limit (LL) and plastic limit (PL) for penetration depths of 17 mm and 2 mm, respectively. In addition, the plasticity index (PI) was defined as the difference between LL and PL. The fall cone apparatus used has a cone penetrometer with a cone angle at 30° and a cone mass of 76 g.

Powder X-ray diffraction analysis (XRD) was adopted for mineral composition analysis. The test instrument was Philips PW3710 with the diffraction angle of 4° to 45°. During the test, we took 10 g of the designed dry sample to grind with agate mortar till no visible aggregate, put the powder through 0.053 mm sieve, and placed it on a glass slide before mineral analysis. The diffraction patterns were determined using $Cu-K\alpha$ radiation at a rate of 0.05°/sec. The original data of XRD pattern was calculated and analyzed using X'Pert High Score software.

To analyze the change of particle morphology and connection mode in loess samples, a low-vacuum scanning electron microscope (JSM-5600LV) was used to qualitatively analyze the microstructure of unsolidified loess and quicklime-solidified loess in different states. The samples were taken from the inside of the test block damaged by an unconfined compressive strength test. After being air-dried, they were treated with metal spraying. Before scanning electron microscopic (SEM) examination, the loess sample was applied with $100\dot{A}$ gold-palladium coating for 38 sec using a sputter coater, polaron E_5100 at 10^{-3} Torr Vacuum. The test pictures with a magnification of 2000 times were taken for analysis.

Tristar II 3020 analyzer and BET nitrogen adsorption method were used for soil pore distribution analysis. The test sample was 5 g dry loess taken from the middle of the test block. The pore distribution was calculated by nitrogen adsorption process according to Kelvin pore filling model Barrett-Joyner-Halenda (BJH) [22] with the aperture analysis range of 1.0~300 nm. The instrument was controlled with a microprocessor and communicated via dedicated data processing software which makes it ideal for physisorption analysis.

4. Test Results and Analysis

4.1. Influence of Quicklime on the Physical and Mechanical Properties of Loess. The liquid and plastic limits are the basic hydraulic property parameters of soil, which comprehensively reflect the connection strength between soil particles or the relative activity of soil particles. They can be used to study the change of mineral composition of soil to predict the mechanical behavior of soil. Figure 3 shows the relationship with different lime-adding rates and curing periods. The results revealed that the liquid and plastic limits of the solidified loess increased with the increase of lime content after adding quicklime, while the plasticity index remained almost unchanged. However, with extended curing period, the liquid limit increased slightly while the plastic limit decreased. Therefore, the plasticity index increased slightly. When quicklime was added to the loess, due to flocculation in the short term, the total pore space increased with the increase of lime content, and the intergranular pores increased as well. Warkentin [26] suggested that interaction volume between soil particles has significant impact on the liquid limit and plastic limits of the soil. Divalent calcium ions and high-concentration electrolyte solutions will become more compact due to the flocculation of the particles, leading to increase in both liquid limit and plastic limit. Locat [11] believed that the agglomeration and flocculation of soil particles cause the formation of a new microstructure for lime clay with increased liquid limit and plastic limit. Bell [9] observed that different clay minerals behave differently when lime is added. The plasticity of montmorillonite decreases, while that of quartz and kaolin increases. It was also found that the addition of lime caused concurrent increase in liquid limit and plastic limit, with plasticity index of the gravel soil almost unchanged. Metelkova et al. [6] found that the liquid limit is related to the large pores between soil particles or aggregates. The larger the pores, the bigger the liquid limit. Our study found that the strength of lime-solidified loess increases with the increase of lime content. Therefore, it can be observed that the liquid limit increases with the addition of more lime. The plastic limit of lime-solidified loess is related to the size of the particles. Generally, the plastic limit of lime-solidified loess increases with the particles in bigger size. Research has found that, with the increase of the volume of lime added, the aggregates of the lime-solidified loess increase, which leads to the increase of the plastic limit. Zhang [21] has similar findings and mechanism analysis on the liquid and plastic limits of lime-solidified loess. So, it is the change of the microstructure of the lime-solidified loess that caused the change of the liquid and plastic limits, which can also be verified from the subsequent SEM analysis.

Figure 4 shows the change of compressive strength with lime content at different curing periods. As can be seen from Figure 4, the unconfined compressive strength of the quicklime-solidified loess at different curing periods increased nonlinearly with the increase of lime-adding rates. According to the data analysis, for lime-solidified loess with the lime-adding rate of 25%, the unconfined compressive strength at curing periods of 7, 28, and 60 days reached 460, 550, and 790 kPa, respectively, which was about 7, 8, and 11 times higher than those of the loess not solidified with lime, indicating significant increases. The effect of the curing period on the strength of solidified loess was related to the lime-adding rate. For lime-solidified loess with the lime-adding rate of 5%, when the amount of lime added was small, the strength of lime-solidified loess was almost unchanged during the curing period of 7–28 days, while the strength had increased significantly during the curing period of 28–60 days. This indicates that when small amount of lime is added, the strength of lime-solidified loess is increased as a result of full and quick reaction. When the lime-adding rate reaches a maximum of 25%, the strength increases continuously during the curing period of 60 days. The results showed that the strength of solidified loess increased with the increase of lime-adding rate and curing period, and it was strongly affected by the lime-adding rate. This result is consistent with the research results of Russo [27] and Rogers [28].

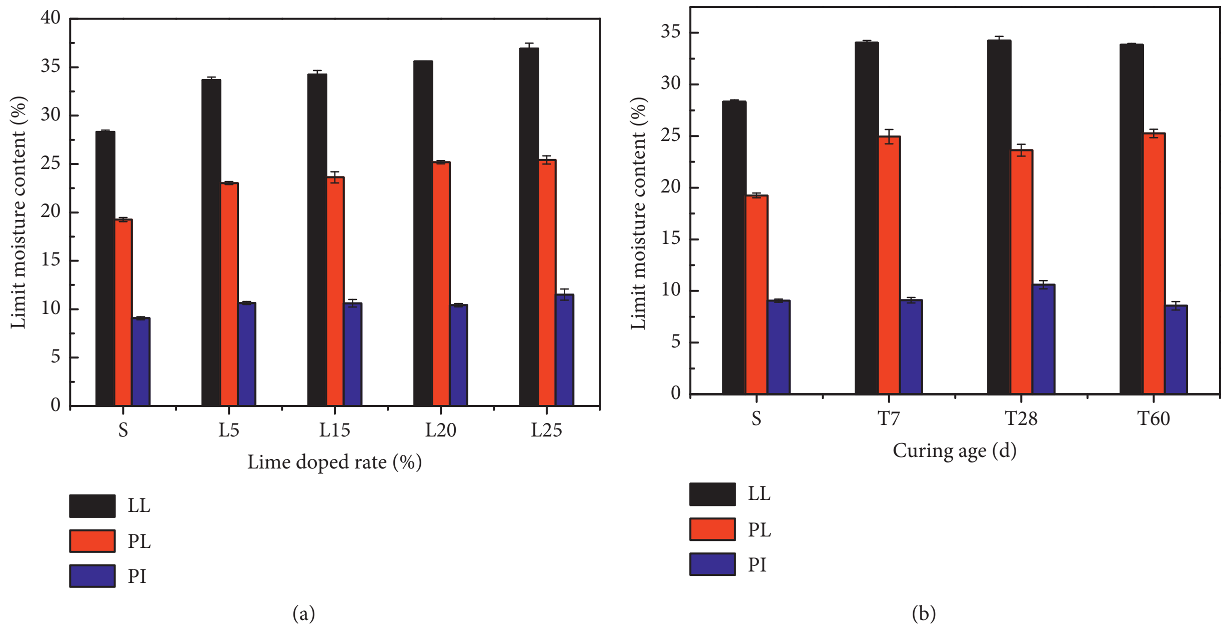


Figure 3: The relationship between limit-water content of lime-solidified loess and its admixture ratio and curing periods. (a) The relationship between limit-water content and lime admixture ratio (curing for 28d). (b) The relationship between limit-water content and curing period (L15) (S = loess, L = lime, and the following numbers represent the incorporation ratio of quicklime; T = curing time, followed by the number of curing days; LL = liquid limit, PL = plastic limit, and PI = plastic index.).

The above results are due to the fact that when the lime-adding rate was low (<5%), quicklime underwent quick carbonization with water and carbonate in the loess, which led to the flocculation of soil particles and the increase of the contact surface between large particles, thus improving the bonding force and compressive strength between soil particles. With extended curing period, there were not enough OH^- ions to dissolve silicon and aluminum ions due to their reduction, which resulted in less crystal connection between the generated particles. Therefore, the strength did not change much with the extension of the curing period. When the lime-adding rate increased, the pH value of the pore fluid increased, which dissolved silicon and aluminum ions of minerals in the loess. The pozzolanic reaction continued to intensify, and loess particles increased due to flocculation. At the same time, the gelatinization and filling effect of pozzolanic reaction improved the strength, and the increase of lime-adding rate played an important role in the strength increase.

4.2. Mineral Evolution Characteristics of Quicklime-Solidified Loess. Al-Mukhtar [29] suggested the changes in the main geotechnical properties associated with the microtexture and microstructure of lime-treated compacted clay samples are due to the lime-clay reactions, mainly a pozzolanic reaction. Maubec [30] suggested that lime addition led to improvements of engineering properties of two different clays. These improvements are linked to the development of secondary hydrate phases. Chemeda [31] suggested the modification in the mechanical properties of the kaolinite with varying amount of lime was attributed to the aggregation microstructure of kaolinite particles. Yong [32] studied the change of engineering properties of lime-solidified marl soil which can be detected by X-ray diffraction test. Modoni [33] suggested that the fabric in quicklime-stabilized samples of alluvial silty soil changed with curing time. In summary, lime mainly reacts with clay minerals. What the authors want to express here is that the X-ray diffraction test can be used to characterize the mineral evolution of lime-solidified loess.

Table 3 shows the relative content of loess samples through XRD analysis of various minerals. It is found from comparative analysis that the relative content of calcite increased within 7 days of curing, and it grew with the increase of lime-adding rate, indicating carbonation reaction of calcium hydroxide and carbon dioxide in the loess. The relative content of original minerals in the loess, especially the clay minerals, decreased, indicating that the chemical reaction between lime and loess consumed the primary minerals. In addition, the cemented substance adsorbed on the surface of the original minerals, while its crystallinity was relatively low, which reduced the relative content. New cemented materials (hematite and pyrite) had been formed, and the relative content increased with the increase of lime-adding rate. From curing of 28 days onward, the relative content of calcite did not increase, which may be due to the limited content of carbon dioxide in the loess. The relative content of the generated substance increased with the increase of lime-adding rate. During the curing period of 60 days, the relative content of calcite did not increase much, while the total relative content of the generated substance increased compared with that of the curing period of 28 days. It increased with the increase of

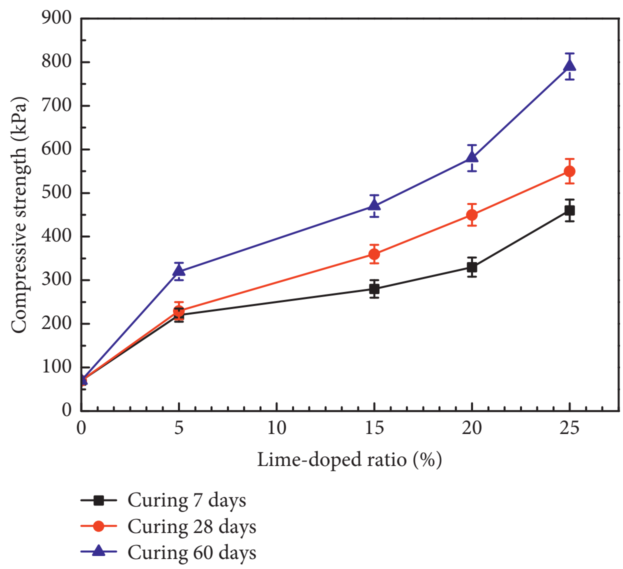


FIGURE 4: The relationship between the unconfined compressive strength and the ratio of quicklime-solidified loess under different curing periods.

TABLE 3: Mineral composition of unsolidified loess and solidified loess.

Sample no.	Hornblende	Clay mineral	Anhydrite	Quartz	Potash feldspar	Anorthose	Calcite	Dolomite	Augite	Hematite	Pyrite	Siderite
S	1.4	31.9	1.2	36.3	2.1	8.8	16.5	1.8	—	—	—	—
L5 (T7)	4.2	27.9	—	27.6	1.7	14.1	18.6	2.0	3.9	—	—	—
L15 (T7)	2.7	23.3	2.3	34.5	1.7	5.4	23.6	2.2	3.8	0.4	—	—
L20 (T7)	2.3	23.6	3.2	36	1.8	11.4	18.2	2.4	—	—	1.1	—
L25 (T7)	1.8	25.9	2	30	1.1	7.9	23.3	3.4	3.4	—	—	—
L5 (T28)	4.1	25.2	0.5	35.5	2.3	10.9	16.4	2.2	2.8	—	—	—
L15 (T28)	2.2	23.9	—	33.9	2.6	9.8	23.2	0.8	3.1	—	—	0.6
L20 (T28)	2.4	23.3	0.7	31.9	1.4	7.0	25.3	2.0	3.4	—	—	0.3
L25 (T28)	2.9	19.8	4.7	26.4	0.7	6.9	32.0	2.2	3.5	—	—	0.9
L5 (T60)	2.4	22.1	2.3	36.7	2.7	9.9	18.0	1.7	2.5	0.9	—	0.7
L15 (T60)	3.4	17.7	0.6	26.7	2.5	14.8	27.7	2.0	2.1	0.9	—	—
L20 (T60)	5.3	25.6	0.6	33.7	3.6	10.2	18.6	1.1	—	—	1.3	—
L25 (T60)	4.5	21.5	2.7	22.6	1.2	6.9	18.4	12.9	—	—	—	—

the lime-adding rate. It was also noted that the relative content of clay minerals decreased significantly during the curing period of 60 days.

To further analyze the influence of clay minerals on the evolution process of pozzolanic reaction, the clay minerals were treated with glycol saturated solution for XRD analysis. The diffraction angle range was 3°–30°, and the diffraction pattern is shown in Figure 5. As shown in Figure 5, for limed loess with the lime-adding rate of 5%, the peak value of clay minerals declined as a whole, mainly because the pozzolanic reaction consumed clay minerals. Among the three clay minerals, the peak value of illite decreased the most. For the loess with the lime-adding rate of 15%, new weak wave peaks appeared in clay mineral analysis and the peaks of clay mineral continued to decline. For the loess with the lime-adding rates of 20% and 25%, the new peaks of CASH and CAH occurred at the diffraction angles of 17.8° and 27.65° during curing for 28 days and 60 days, and a new peak of CSH also occurred at 3.5°. Therefore, it can be assumed that the crystallites of the pozzolanic reaction do not appear until the lime and loess are cured for 28 days with the lime-adding rate greater than 5%, and the quantity and mass of calcium hydrate increased with the increase of lime-adding rate and extended curing period. Bell [13], Rao [34], and Almukhtar et al. [35] confirmed the existence of CSAH in lime-solidified clay and believed that the appearance of new materials

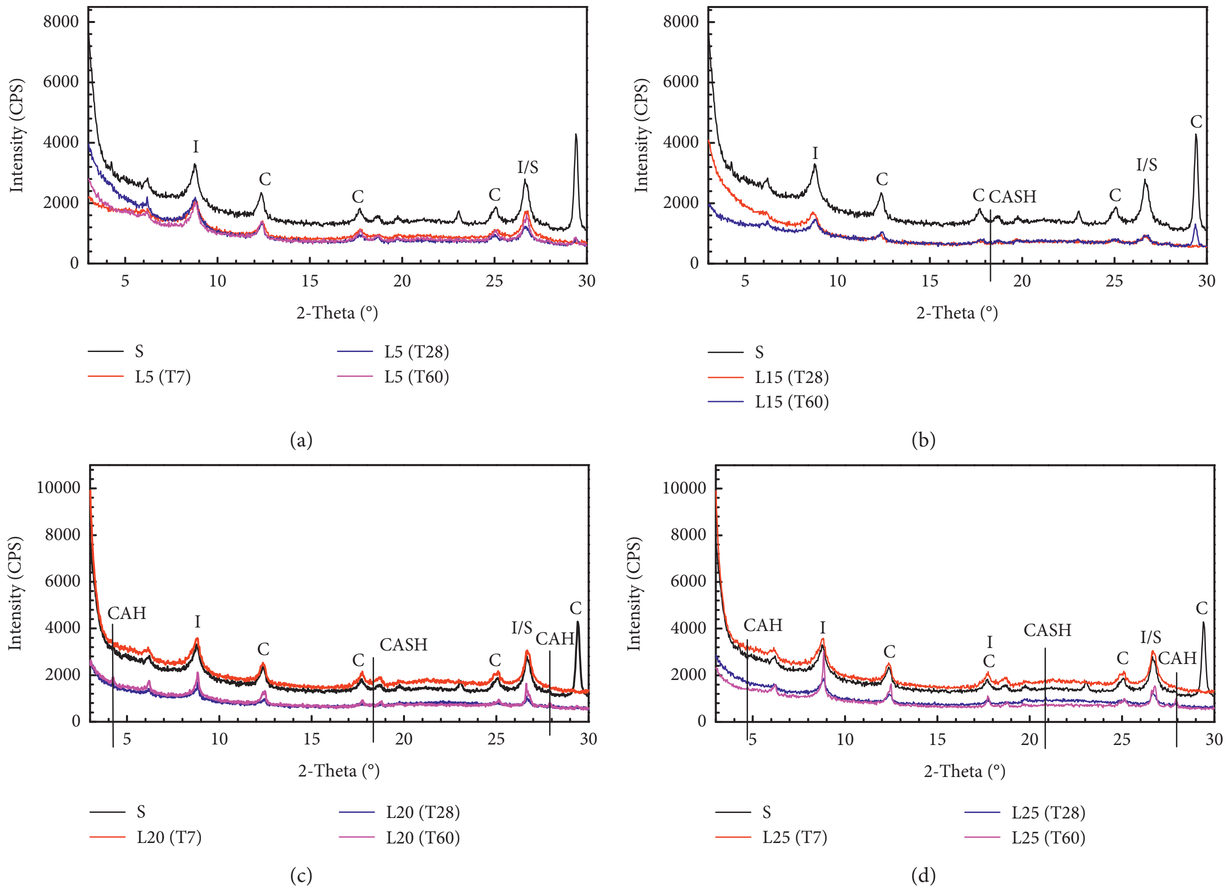


FIGURE 5: XRD patterns of clay mineral analysis of unsolidified loess and lime-solidified loess under different curing conditions. (a) Loess solidified with 5% quicklime. (b) Loess solidified with 15% quicklime. (c) Loess solidified with 20% quicklime. (d) Loess solidified with 25% quicklime. Key: I (illite), C (chlorite), I/S (illite + smectite), CAH (calcium aluminate hydrate), CSH (calcium silicate hydrate), and CASH (calcium silicoaluminate hydrate).

changed the soil structure and thus improved its geotechnical property. It is also noted that the peaks were not apparent from the diffraction pattern, because those phases were poorly crystallized and/or spread over a small (nanoscale) range, hardly to be distinguished by X-ray diffraction. To study these new microfacies, electron microscopy was adopted for further observations.

4.3. Characteristic Analysis of the Microstructure of Quicklime-Solidified Loess. The external behavior of the soil is controlled by its internal microstructure. The addition of quicklime changed the connection mode of loess particles and the structure of the grain skeleton, and the microstructure analysis of solidified loess can explain the macroscopic physical and mechanical characteristics of solidified loess to some extent. SEM pictures of lime-solidified loess with the different lime-adding rates at different curing periods are shown in Figure 6.

As can be seen from Figure 6, with extended curing period, the new products gradually increased. When cured for 7 days, there were a small number of attachments on the surface of the solidified loess, which might be crystals of calcium carbonate and calcium hydroxide [36, 37]. While cured for 28 days, new products were clearly generated on the surface and at the edge of the solidified loess particles, and needle-shaped substances appeared to connect each other among the loess particles. When cured for 60 days, new materials were further formed, which were similar to needle-shaped particles in much bigger size, and formed by a chain network composed of needle-shaped and flaky structure. The form of this microstructure was akin to the substance produced in cement hydration [38–41] and very similar to calcium silicate hydrate. However, the X-ray powder diffraction results from the sample cured for 28 days showed that the new product did not form significantly, which confirmed that the crystallinity of the newly formed substances was very low. For solidified loess with different lime-adding rates, with the increase of lime-adding rate, the crystal products continued to increase on the surface, and at the edge of lime-solidified loess, the pore space was filled with cemented substance, and the macropores decreased. The cemented substance even formed flaky condensate between the pores when the lime-adding rate was 25%. However, the pore morphology generally did not change. With the increase of lime-adding rate, the number of cemented substances generated on the surface and at the edge of loess particles increased, which could explain why

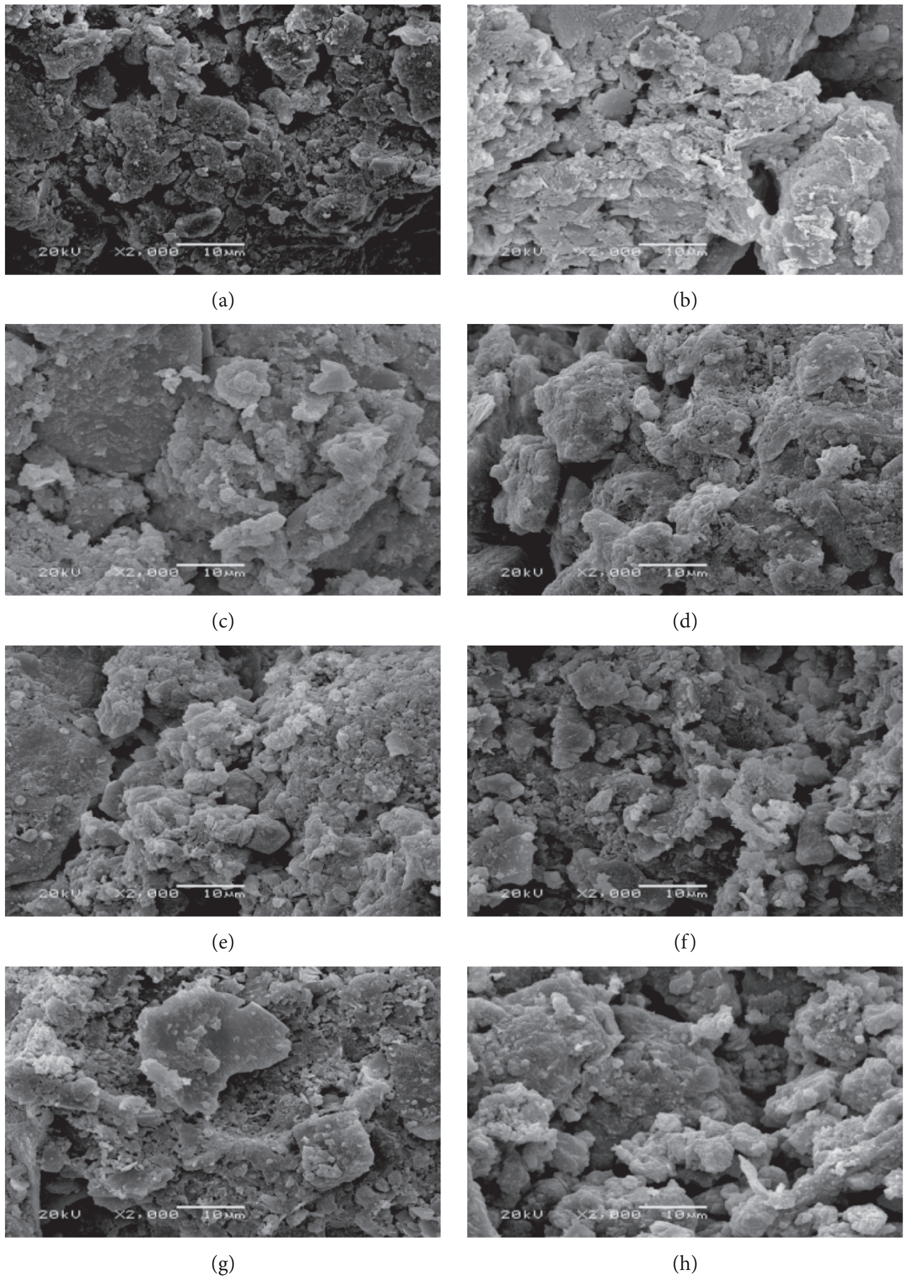
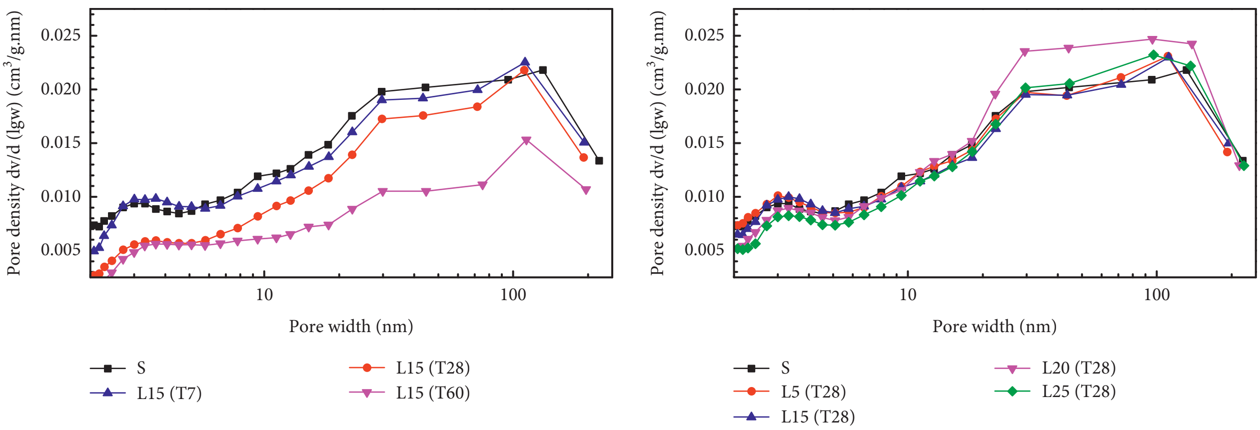


Figure 6: SEM diagrams of unsolidified loess and lime-solidified loess under different curing conditions. (a) SEM image of loess. (b) SEM image of compacted loess. (c) SEM image of L15 (T7) solidified loess. (d) SEM image of L5 (T28) solidified loess. (e) SEM image of L15 (T28) solidified loess. (f) SEM image of L20 (T28) solidified loess. (g) SEM image of L15 (T60) solidified loess. (h) SEM image of L25 (T28) solidified loess.

the mechanical properties were improved with the increase of lime-adding rate.

The pore size distribution of lime-solidified loess calculated by BJH method is shown in Figure 7. The pore distribution curve of the loess sample was a typical bimodal curve, showing three types of pores: 1~5 nm, 5~50 nm, and 50~200 nm. For these three types of pores, quicklime was added without changing the pore morphology of the loess; however, the density of the three types of pores changed with curing time. During extended curing period, the maximum pores decreased significantly, especially after curing for more than 28 days. However, the pores ranging from 5 nm to 50 nm were slightly less during curing time; the minimum pores hardly changed or even enlarged slightly after curing for 7 days. After curing for 28 days, it decreased significantly and then remained almost unchanged. This is mainly because, during the solidifying process, new products resulting from carbonization and pozzolanic reactions filled intraparticle pores, which made the change of overall distribution of pores. However, during the curing period of 28 days, the lime content had little effect on the distribution of pores. Therefore, it is believed that the change of pore distribution



(a) (b)

Figure 7: Pore size distribution of unsolidified loess and lime-solidified loess. (a) Solidified loess at different curing periods with the proportion of lime increased by 15%. (b) Solidified loess with different ratio of adding lime at 28 d curing period.

was mainly affected by the curing period (set 28 d curing as the critical point).

Bozbey's [40] studied the microstructure of lime-solidified clay, which showed that the lime content and curing time have significant effects on the resulting microstructure. The main type of pores is intragranular ones. The dominant porosity is usually below 100 nm. The porosity decreases as the curing time increases, mainly because the intraparticle pores are partially or completely filled and/or the pore entry is partially or completely blocked during the extended curing period. Cuisinier [41] studied the microstructure and hydraulic conductivity of lime-solidified silt, and the results showed reduced porosity of lime-solidified soil. Russo [27] studied the microstructure of lime-solidified alluvial silt, and the results showed that the microstructure of the lime-solidified soil changed with the curing time, and water compounds were formed in the range of smaller pore size. Our analysis of the pore size of lime-solidified loess is mainly in the range of 1~200 nm. Our results showed that the pore size was significantly reduced in the range of 50~200 nm during the curing period of 28~60 days, indicating that the pozzolanic reaction mainly fills and blocks this part of the micropores.

5. Discussion

The macroscopic properties of soil (such as compressive strength and liquid and plastic limits) are the external manifestations of its microstructure. Xu et al. [42, 43] explained the loss of strength mechanism with saline loess under dry-wet and freeze-thaw cycles. XRD mineral composition analysis can indicate the change of soil material, SEM image analysis can visually demonstrate the change of soil particles and pore morphology, and nitrogen adsorption technology can demonstrate the distribution characteristics of pores in the soil. These three methods, when combined, can effectively explain the physical and mechanical behavior of the soil.

The above test results show that, by adding quicklime, the physical and mechanical properties of lime-solidified loess can be significantly modified. The compressive strength of lime-solidified loess increases with the increase of lime content and also with the increase of curing time (see Figure 4). SEM image and pores distribution results show that the microstructure of lime-solidified soil caused by more aggregates and smaller pores has undergone significant changes (see Figures 6 and 7). After curing for 28 days, denser packing and smaller holes appeared. Mineral analysis indicated that, after curing for 28 days, traces of new minerals appeared in the lime-solidified loess with a large amount of lime admixture (15%) (see Figure 5), which suggests that, during short-term curing (<28 days), the lime-solidified loess accumulates, mainly as a result of ion-exchange reaction and flocculation, and its strength increases due to the change of its microstructure; in case of extended curing, however, the strength of lime-solidified soil increases under the combined actions of material change and change of microstructure from pozzolanic reaction. Previous studies have found that loess with aggregates and smaller pores has relatively high strength.

The changes of liquid and plastic limits of lime-solidified loess are also closely related to the change of microstructure. At curing for 28 days, the lime deposits and the macropores increase with the increase of lime content (see Figures 6 and 7), with increase in liquid limit and plastic limit of quicklime-solidified loess (see Figure 4(a)). Under different curing periods, liquid and plastic limits fluctuate (see Figure 4(b)), mainly because the microstructure of lime-solidified loess changes to porous structure after curing for 60 days, also indicating that the microstructure of lime-solidified loess gradually changes, which is also the main reason for the later strength increase of lime-solidified loess. Therefore, for lime-solidified loess with a sufficient content of lime admixture, sufficient curing time is an important guarantee for strength, and 28 days is an important time control point.

6. Conclusions

The quicklime-solidified loess taken from Xining area of Qinghai Province is used as the research object of this paper, which has been analyzed through laboratory tests in order to study the basic physical and mechanical properties of the soil, analyze its minerals and microstructures, investigate the influence of lime-adding rate and curing time upon lime-solidified loess, and explain the mechanism of quicklime-solidified loess, from which the following conclusions are drawn:

(1) The unconfined compressive strength test shows that the compressive strength of quicklime-solidified loess gradually increases with the increase of lime content and curing time. The increase in compressive strength at the initial curing period can be attributed to compacter structure and smaller pores in the quicklime-solidified loess. These changes in microscopic characteristics can be proved by SEM and BET evidence; the increase in the compressive strength of lime-solidified loess after extended curing is attributed to changes in mineral properties and the formation of compacter porous structures. Changes in mineral characteristics can be affirmed from the reduction of clay minerals and the formation of new minerals in the XRD test results. SEM images and nitrogen adsorption test results also confirmed that, after curing for 60 days, the lime-solidified loess formed into a smaller porous structure. The change of the liquid and plastic limits of lime-solidified loess can also be explained by the change of microstructure, which further proves that the microstructure of lime-solidified loess changes gradually during extended curing.

(2) The long-term physical and mechanical properties of lime-solidified loess are related to its mineral composition and microstructure, which could be the reason for the increase in the later strength of lime-solidified loess. From the perspective of engineering construction, long-term maintenance is an important guarantee for the strength of lime-solidified loess with sufficient adding volume and under certain curing conditions.

Data Availability

The figures and table data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors hereby declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was partially supported by the Natural Key Basic Research Development Plan of China (973 Program no. 2014CB744701). The authors would like to express their heartfelt gratitude to all members who helped and cooperated with them.

References

[1] E. Derbyshire, "Geological hazards in loess terrain, with particular reference to the loess regions of China," *Earth-Science Reviews*, vol. 4, no. 54, pp. 231–260, 2001.

[2] I. Bozbey, M. Demir, S. Saglik, and A. Mert, "Importance of soil pulverization level in lime stabilized soil performance," *Procedia Engineering*, vol. 143, no. 5, pp. 642–649, 2016.

[3] N. Comez, A. A. Eisazadeh, and A. Marto, "Strength behavior and microstructural characteristics of tropical laterite soil treated with sodium silicate-based liquid stabilizer," *Environmental Earth Sciences*, vol. 72, no. 1, pp. 91–98, 2014.

[4] A. F. Rauch, L. E. J. S. Harmon, and H. M. Liljestrand, "Measured effects of liquid soil stabilizers on engineering properties of clay," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1787, no. 1, pp. 33–41, 2002.

[5] H. Zhao, L. Ge, T. M. Petry, and Y.-Z. Sun, "Effects of chemical stabilizers on an expansive clay," *KSCE Journal of Civil Engineering*, vol. 18, no. 4, pp. 1009–1017, 2014.

[6] Z. Metelková, J. Boháč, R. Přikryl, and I. Sedlářová, "Maturation of loess treated with variable lime admixture: pore space textural evolution and related phase changes," *Applied Clay Science*, vol. 61, no. 61, pp. 37–43, 2012.

[7] X. Han and Z. Guo, "Research on the principal factors in strength of the lime-loess," *Chinese Journal of Geotechnical Engineering*, vol. 24, no. 5, pp. 667–669, 2002.

[8] H. Zhang, H. Gao, and C. Hu, "Test study on compression characteristics of compacted lime stabilized loess," *Central South Highway Engineering*, vol. 30, no. 2, pp. 45–47, 2005.

[9] H. Fan, J. Gao, P. Wu et al., "Analysis of influence factors for solidified soil strength based on change of physicochemical properties of loess," *Rock and Soil Mechanics*, vol. 32, no. 7, pp. 1996–2000, 2011.

[10] Z. Hu, L. Ding, H. Wang et al., "Test study on the permeability and strength variation of lime loess bedding under wetting and drying cycles," *Journal of Xi'an University of Architecture & Technology*, vol. 31, no. 1, pp. 39–45, 2011.

[11] J. Locat, H. Trembaly, and S. Leroueil, "Mechanical and hydraulic behaviour of a soft inorganic clay treated with lime," *Canadian Geotechnical Journal*, vol. 33, no. 4, pp. 654–669, 1996.

[12] M. Al-Mukhtar, S. Khattab, and J.-F. Alcover, "Microstructure and geotechnical properties of lime-treated expansive clayey soil," *Engineering Geology*, vol. 139-140, no. 1, pp. 17–27, 2012.

[13] F. G. Bell, "Lime stabilization of clay minerals and soils," *Engineering Geology*, vol. 42, no. 4, pp. 223–237, 1996.

[14] M. R. Thompson, "Shear strength and elastic properties of lime-soil mixtures," *Poper Sponsored by Committee on Lime and Lime-Fly Ash Stabilization and Presented at the 45th Annual Meeting*, vol. 1, no. 1, pp. 1–11, 1966.

[15] B. R. Phanikumar, "Effect of lime and fly ash on swell, consolidation and shear strength characteristics of expansive clays: a comparative study," *Geomechanics and Geoengineering*, vol. 4, no. 2, pp. 175–181, 2009.

[16] K. Harichane, M. Ghrici, and H. Missoum, "Influence of natural pozzolana and lime additives on the temporal variation of soil compaction and shear strength," *Frontiers of Earth Science*, vol. 5, no. 2, pp. 162–169, 2011.

[17] A. Amadi and A. Okeiyi, "Use of quick and hydrated lime in stabilization of lateritic soil: comparative analysis of laboratory data," *Geo-Engineering*, vol. 8, no. 3, pp. 3–13, 2017.

[18] X. Pei, W. F. Zhang, and S. Liang, "Physicochemical and index properties of loess stabilized with lime and fly ash piles," *Applied Clay Science*, vol. 114, no. 9, pp. 77–84, 2015.

[19] M. M. Bessaim, A. Bessaim, H. Missoum et al., "Effect of quick lime on physicochemical properties of clay soil," *MATEC Web of Conferences*, vol. 149, no. 4, pp. 1–5, 2018.

[20] G. Stoltz, O. Cuisinier, and F. Masrouri, "Multi-scale analysis of the swelling and shrinkage of a lime-treated expansive clayey soil," *Applied Clay Science*, vol. 61, no. 1, pp. 44–51, 2012.

[21] X. L. Han, B. Zhi, and Z. Y. Guo, "Research on the principal factors in strength of the lime-loess," *Chinese Journal of Geotechnical Engineering*, vol. 24, no. 5, pp. 77–84, 2002.

[22] A. A. Al-Rawas, A. W. Hago, and H. Al-Sarmi, "Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman," *Building and Environment*, vol. 40, no. 5, pp. 681–687, 2005.

[23] W. H. Zhang, W. Y. Xi, B. T. Wang, and B. N. Hong, "Test study of high liquid limit clay modified by quick lime used as sub-grade material," *Journal of Central South University of Technology*, vol. 15, no. 2, pp. 126–130, 2008.

[24] E. P. Barrett, L. G. Joyner, and P. P. Halenda, "The determination of pore volume and area distributions in porous substances. I. Computations from nitrogen isotherms," *Journal of the American Chemical Society*, vol. 73, no. 1, pp. 373–380, 1951.

[25] B. P. Warkentin, "Interpretation of the upper plastic limit of clays," *Nature*, vol. 190, no. 4772, pp. 287-288, 1961.

[26] F. Zhang, X. Pei, and X. Yan, "Physicochemical and mechanical properties of lime-treated loess," *Geotechnical and Geological Engineering*, vol. 36, no. 4, pp. 685–696, 2018.

[27] G. Russo and M. Cecconi, "Microstructural features of lime-stabilised pyroclastic soils," *Geotechnique Letters*, vol. 3, no. 1, pp. 124–129, 2013.

[28] C. D. F. Rogers, S. Glendinning, and T. E. J. Roff, "Lime modification of clay soils for construction expediency," *Geotechnical Engineering*, vol. 149, no. 3, pp. 201-202, 2015.

[29] M. Al-Mukhtar, A. Lasledj, and J.-F. Alcover, "Behaviour and mineralogy changes in lime-treated expansive soil at 20°C," *Applied Clay Science*, vol. 50, no. 2, pp. 191–198, 2010.

[30] G. Modoni and G. Russo, "Fabric changes induced by lime addition on a compacted alluvial soil," *Geotechnique Letters*, vol. 3, no. 4, pp. 93–97, 2013.

[31] R. Yong and V. Ouhadi, "Experimental study on instability of bases on natural and lime/cement-stabilized clayey soils," *Applied Clay Science*, vol. 35, no. 3-4, pp. 238–249, 2007.

[32] Y. C. Chemeda, D. Deneele, G. E. Christidis, and G. Ouvrard, "Influence of hydrated lime on the surface properties and interaction of kaolinite particles," *Applied Clay Science*, vol. 107, no. 1, pp. 1–13, 2015.

[33] N. Maubec, D. Deneele, and G. Ouvrard, "Influence of the clay type on the strength evolution of lime treated material," *Applied Clay Science*, vol. 137, no. 1, pp. 107–114, 2017.

[34] S. M. Rao and P. Shivananda, "Compressibility behaviour of lime-stabilized clay," *Geotechnical and Geological Engineering*, vol. 23, no. 3, pp. 309–319, 2005.

[35] M. Arabi and S. Wild, "Microstructural development in cured soil-lime composites," *Journal of Materials Science*, vol. 21, no. 2, pp. 497–503, 1986.

[36] G. Lees, M. O. Abdelkader, and S. K. Hamdani, "Effect of the clay fraction on some mechanical properties of lime-soil mixtures," *Highway Engineer*, vol. 29, no. 11, pp. 3–9, 1982.

[37] E. S. A. Seif, "Efficiency of quicklime in reducing the swelling potential of pulverized expansive shale, Northern Jeddah, Saudi Arabia," *Bulletin of Engineering Geology & the Environment*, vol. 74, no. 2, pp. 637–650, 2015.

[38] S. K. Antiohos, A. Papageorgiou, V. G. Papadakis, and S. Tsimas, "Influence of quicklime addition on the mechanical properties and hydration degree of blended cements containing different fly ashes," *Construction and Building Materials*, vol. 22, no. 6, pp. 1191–1200, 2008.

[39] J. L. Eades and R. E. Grim, "A quick test to determine lime requirements for lime stabilization," *Highway*, vol. 139, no. 1, pp. 61–72, 1996.

[40] L. Bozbey, "Microfabric evaluation of lime-treated clays by mercury intrusion porosimetry and environment scanning electron microscopy," *International Journal of Civil Engineering*, vol. 16, no. 3, pp. 443–456, 2018.

[41] O. Cuisinier, J.-C. Auriol, T. Le Borgne, and D. Deneele, "Microstructure and hydraulic conductivity of a compacted lime-treated soil," *Engineering Geology*, vol. 123, no. 3, pp. 187–193, 2011.

[42] J. Xu, Y. Li, W. Lan et al., "Shear strength and damage mechanism of saline intact loess after freeze-thaw cycling," *Cold Regions Science and Technology*, vol. 164, pp. 1–13, 2019.

[43] J. Xu, Y. Li, C. Ren et al., "Damage of saline intact loess after dry-wet and its interpretation based on SEM and NMR," *Soils and Foundations-Tokyo*, vol. 60, no. 6, pp. 911–928, 2020.