buildings

Essay

Experimental Study on the Effects of Freeze–Thaw Cycles on Strength and Microstructure of Xining Region Loess in China

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Abstract: Loess, a collapsible soil, is widely distributed in the Qinghai–Tibet Plateau in China. In the meantime, loess is a sustainable and green building material that is widely used in traditional residential buildings. However, previous studies have focused on the properties of loess itself, ignoring the influence of climatic conditions on loess buildings, as well as a series of engineering problems such as soil spalling caused by freezing and thawing, cold cracks in walls, and settlement deformation of foundation. This research presents a series of laboratory tests on both undisturbed and remolded loess. The tests investigated changes in the unconfined compressive strength (UCS) of both types of loess after different freeze–thaw cycles. The freeze–thaw-induced changes to the internal structures of the loess were also investigated using a scanning electron microscope (SEM) and X-ray diffraction test (XRD). The test results showed that: (1) with increasing freeze–thaw cycles, the UCS of both the undisturbed and remolded loess appeared to first increase and then decrease, and the stress–strain curves showed a stronger strain-softening tendency. (2) The compressive strength of undisturbed loess is higher than remolded loess. (3) SEM analysis showed that the large particles inside the loess sample were gradually broken down into small particles, which led to an accumulative increase in fine particles and a decrease in the porosity. With the increase in the number of freeze–thaw cycles, the particles inside the soil become denser, and the strength increases. (4) Freezing and thawing have less effect on loess minerals. (5) The conclusion can provide a reference value for the protection of loess buildings in Qinghai and the management of freeze–thaw disasters.

Keywords: freeze–thaw cycle; undisturbed loess; remolded loess; unconfined compressive strength; micro-test

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1. Introduction

Qinghai Province, located in the Qinghai–Tibet Plateau of China (as shown in Figure 1), has unique climatic characteristics and geological conditions, which have a key impact on the construction and development of Qinghai Province. In Qinghai Province, the area of loess accounts for 3.9% of the area of loess in China, so loess is widely distributed in this area [1,2], and the loess has fine particles, high viscosity, high compressive strength, and shear strength. It has good integrity, stability, and moderate plasticity [3,4]. As a sustainable and green building material, loess has local materials, environmental friendliness and renewability, and a series of advantages [3], so loess has a wide range of applications in traditional green residential buildings.

For example, building loess cave hotels and museums, the unique architectural forms of residential buildings may attract many artists or tourists and, at the same time, may increase the income of residents [3]. It can also be made into a masonry kiln. The loess in the wall as filling material is an important part of its envelope to maintain its thermal performance [5]. There are also portable houses composed of loess as the main building material, which can improve the thermal performance of manufactured houses supplied after disasters [6]. More and more loess buildings are being refurbished and used to reduce the waste of resources. Loess can also be used as an alternative resource to replace cement to reduce carbon dioxide emissions [7].

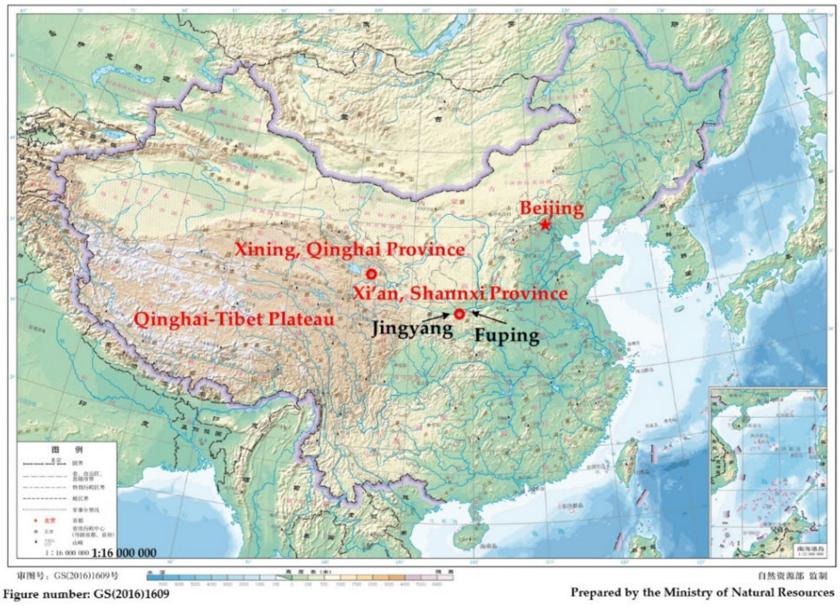


Figure 1. Topography map of China.

At the same time, the unique local climatic characteristics make loess affected by freeze–thaw cycles and affect the stability of loess buildings. Therefore, it is of great practical significance to explore the physical and mechanical properties of undisturbed and remolded loess under freeze–thaw cycles.

The freeze–thaw cycle has an important influence on the physical and mechanical properties of soil [8–12]. Previous studies have found that the freeze–thaw cycle weakens the strength of the soil. Zhao et al. [13] compared the change in the shear strength of undisturbed loess before and after freeze–thaw cycles under closed conditions. They concluded that the soil moisture content decreased, the soil structure weakened, and the shear strength decreased after repeated freeze–thaw cycles. According to Ye et al. [14] and Zhou et al. [15], the cohesion and internal friction angle of remolded loess also deteriorated with an increasing number of freeze–thaw cycles. Studies have also found that after the freeze–thaw cycle, the unconfined compressive strength of the loess decreases significantly, and it has been suggested that the strength decreases with an increasing number of freeze–thaw cycles [16,17]. Zhang et al. [18] and Liu et al. [19] measured the improved soil using a uniaxial compressive test after the freeze–thaw cycle, which showed that the uniaxial compressive strength of the improved soil decreased with an increasing number of freeze–thaw cycles. Thus, the freeze–thaw cycle has a great influence on the mechanical properties of loess.

The main reason for the weakening of the soil during the freeze–thaw cycle is the change in the physical shape of the water inside the soil, which changes the soil pore structure and the cementation force between the soil particles [8,20,21]. Using an electron microscope, observed undisturbed and remolded loess in Xi'an after the freeze–thaw cycle reported that both the undisturbed and remolded loess microstructures changed significantly. Meanwhile, the strength of the soil cementation force decreased, and the soil particles were more loosely packed, increasing the porosity ratio. Ye et al. [14], Zhang et al. [22], Yang et al. [23], and Zhao et al. [24] studied the microstructure of loess using a scanning electron microscope. These investigations observed that with increasing freeze–thaw cycles, the large particles inside the soil were decomposed into several small particles, and the internal micro and small pores were continuously transformed into medium and large pores. Ning et al. [25] also used scanning electron microscopy and found that the large pores of the sample decreased, the small voids increased, and the overall porosity increased. Zhang et al. [26] examined the pore characteristics of the reshaped soil samples under different freeze–thaw cycles using mercury injection and found that with increasing freeze–thaw cycles, the porosity of the sample first increased and then decreased.

In conclusion, as a sustainable and green building material, loess is widely used in traditional residential buildings. However, previous studies have focused on the properties of loess itself, ignoring the influence of climatic conditions on loess buildings. Although research on the changes in the physical and mechanical properties of loess by freeze–thaw cycles has been relatively common, the research on the loess in Xining, Qinghai Province, mostly focuses on the microscopic and mechanical properties of the compacted loess before and after the triaxial shear test [27], as well as the microscopic properties of loess at different moisture contents, different confining pressures, different depths, and different temperatures [19,28,29]. The research on the influence law of freeze–thaw cycles in this region is insufficient. Therefore, the present study investigated the changes in the unconfined compressive strength of undisturbed loess and remolded loess under different freeze–thaw cycles. The soil microstructure was observed by SEM and XRD at different freeze–thaw cycles. The research results will provide a reference value for the protection of loess buildings in Qinghai and the management of freeze–thaw disasters, which have certain engineering significance.

2. Materials and Methods

2.1. Sample Preparation

The loess samples were prepared for testing following the Professional Standards of the People's Republic of China, the Standard of Geotechnical Testing Methods (GB/T 50123-2019) [30]. Briefly, the undisturbed loess was cut into small aliquots of the required specifications for the test, and the cylindrical specimens that were used in the unconfined compressive strength tests were prepared from loess, with a height of 80.0 mm and diameter of 39.1 mm.

Remolded loess samples were first air-dried, then crushed through a sieve (hole diameter of 2 mm). A sample aliquot was then heated for 24 h at 108 °C in an oven. Distilled water was then used to restore the remolded loess sample to its natural water content. The remolded sample preparation method used was layered and dense and was divided into 3 layers.

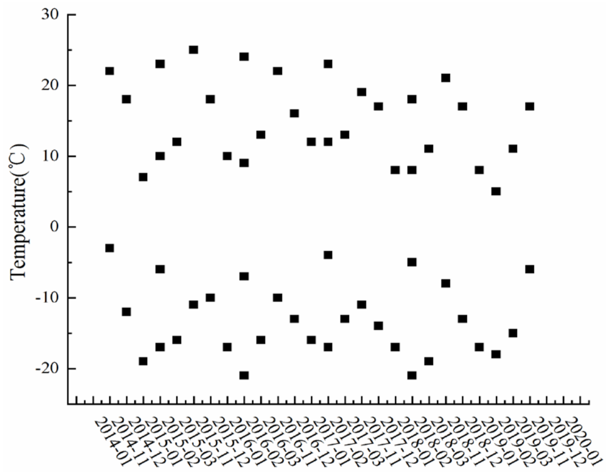
During sample preparation, to minimize sample variability, each experiment was undertaken using two parallel groups. In addition, it was observed that the dry density of the undisturbed loess sample and the remolded loess sample showed little difference with the variation in the water content being <0.1%.

2.2. Experimental Design

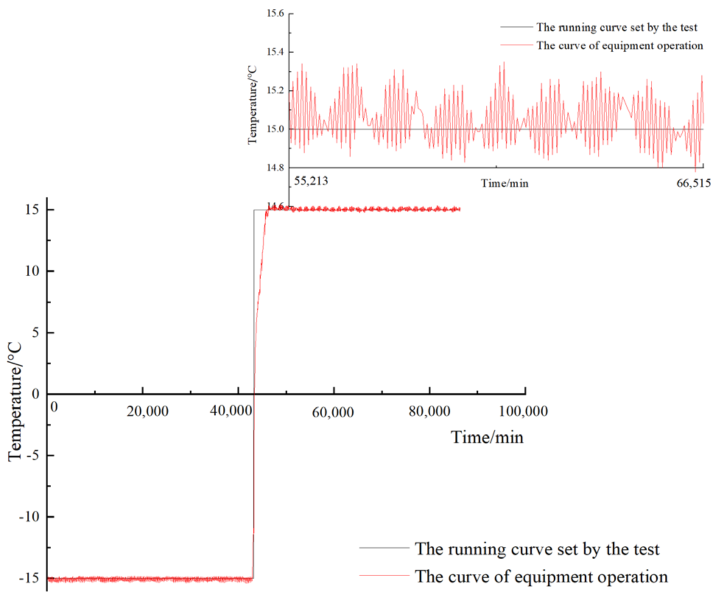
Before testing, the prepared sample aliquots were wrapped in plastic and then placed in a sealed bag to ensure that the sample was clarified and its water content remained unchanged. The sample was then placed in the freeze–thaw cycle test box (TMS 9018-500) to start the freeze–thaw cycle test (Figure 2). To simulate the climate in Qinghai, the curve for a single freeze–thaw cycle was set as a rectangular curve, as shown in Figure 3. In the set curve, the initial temperature starts from −15 °C and lasts for 12 h. After the preset time is reached, the curve temperature is set from −15 °C to 15 °C, and the temperature also lasts for 12 h. Due to the delay in equipment conversion to the set temperature, there are fluctuations in the curve. Each freeze–thaw cycle was carried out over 24 h, including 12 h for freezing and 12 h for thawing. The number of progressive freeze–thaw cycles was 0, 2, 4, 6, 8, 10, 15, and 20.

(**a**) (**b**) (**c**) (**d**)

Figure 2. Sample preparation flow chart. (**a**) Wrapped in plastic; (**b**) marked sample; (**c**) sealed sample; (**d**) freeze–thaw cycle test box.



(**a**)



(**b**)

Figure 3. Temperature curve. (**a**) Winter temperature change curve in Xining (in recent years); (**b**) sine curve set during the test.

After the sample had undergone the set number of freeze–thaw cycles, it was removed from the test box for the unconfined compressive strength test (UCS test). This test used a YYW-2 stress-controlled unconfined pressure instrument. The variation law of unconfined compressive strength of loess under different freeze–thaw cycles was discussed.

The preparation of microstructure samples is to place the samples into the oven to be dried after reaching the predetermined number of freeze–thaw cycles. The central section of the sample is used as the standard to prepare the microstructure samples. The size of the microscopic sample is length × width × height = 2 cm × 1 cm × 1 cm, and the middle position is carved with a fine groove so that the natural section of the sample can be broken as the scanning section for scanning electron microscopy (SEM) test. In this research, SEM images 500 times were selected for analysis.

At the same time, the soil samples in the test process were selected; 20~30 g soil samples were taken, the samples were dried or dried, ground, and screened, and the sample powder was taken for X-ray diffraction (XRD) test and X-ray fluorescence (XRF) test. The test list is shown in Table 1.

Table 1. Test list.

Type of Soil	Freeze–Thaw Cycle Test	UCS Test	SEM Test	XRD and XRF Test
Undisturbed loess Remolded loess	(1) Freeze–thaw cycles were 0, 2, 4, 6, 8, 10, 15, 20 (2) The freezing and thawing temperature was set as ±15 °C (3) 12 h for freezing and 12 h for thawing as a cycle	Each group has 3 samples, a totalof 48 samples	Each group has 2 samples, a totalof 32 samples	Each group has 2 samples, a totalof 32 samples

2.3. Basic Physical Properties of Loess

The loess used in the unconfined compressive strength test was taken from a site in Xining City, Qinghai Province, China. The sampling depth was approximately 2 m from the surface because the depth of the surface frozen layer in the seasonal frozen land area of Qinghai Province is about 2 m. The Atterberg limits test, grain size analysis test, and compaction test were all conducted according to the Professional Standards of the People's Republic of China, the Standard of Geotechnical Testing Methods (GB/T 50123-2019) [30]. Table 2 details the basic physical and mechanical properties of the loess sample. The grain size distribution curve and compaction curve of Xining loess are also shown in Figure 4.

Table 2. Basic physical and mechanical properties of loess.

Specific Gravity of Soil Solids (Gs)	Natural Water Content (%)	Dry Density (g/cm^3)	Liquid Limit (%)	Plastic Limit (%)
2.71	13.40	1.72	25.30	13.95

From the XRD diffraction pattern of loess (Figure 5), it was found that there were many characteristic diffraction peaks in loess, with quartz, albite, and illite as the main mineral components. The internal mineral composition of loess was complex, but the material was relatively stable. At the same time, the internal particle distribution of undisturbed loess was uneven, and there were soil particles of different particle sizes (from the microstructure of loess (Figure 6)). Due to the original structure of undisturbed loess, the internal soil particles were closely connected, and the surface-to-surface contact between soil particles and soil particles was dominant. There were few pores in the undisturbed loess, the formed soil skeleton had a certain strength, and the undisturbed loess had a certain initial strength.

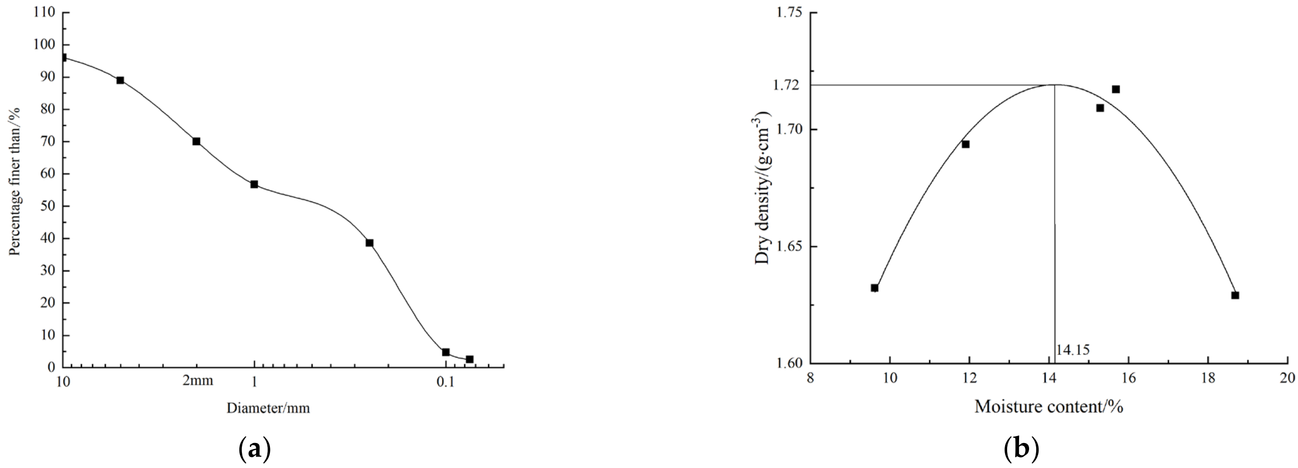


Figure 4. Physical property curve of Xining loess. (**a**) Grain size distribution of Xining loess; (**b**) compaction curve of Xining loess.

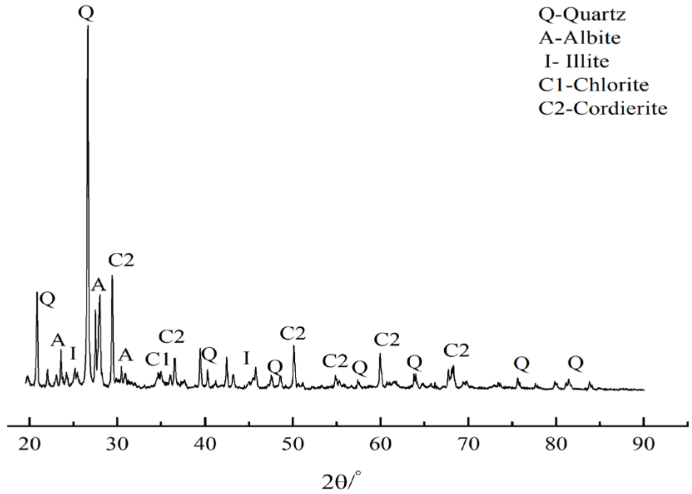


Figure 5. XRD diffraction pattern of loess.

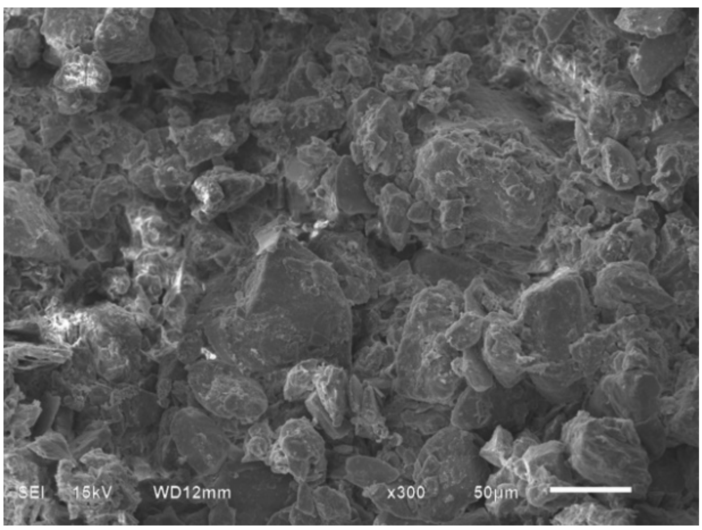


Figure 6. Microscopic image of loess.

3. Analysis of Micro-Test Results

3.1. SEM Test

Figure 7 presents the SEM images of the undisturbed loess at different freeze–thaw cycles at a magnification of 500 times. It is found that the original structure of the undisturbed loess sample is gradually destroyed due to the frost heave and thawing of water, and the original cracks and original pores inside the sample are gradually decomposed.

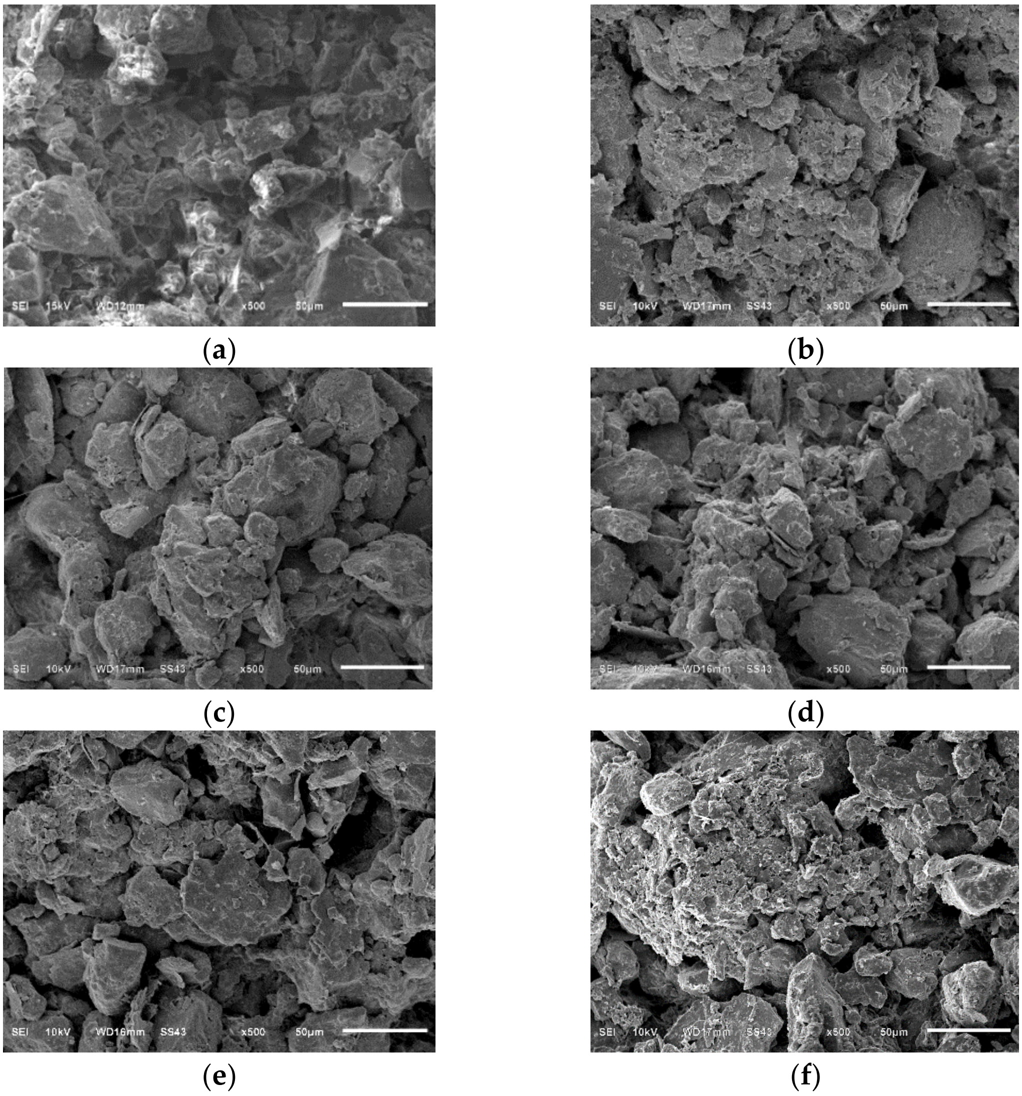


Figure 7. SEM images of undisturbed loess at different freeze–thaw cycles (500 times). (**a**) The number of freeze–thaw cycles is 0. (**b**) The number of freeze–thaw cycles is 2. (**c**) The number of freeze–thaw cycles is 6. (**d**) The number of freeze–thaw cycles is 10. (**e**) The number of freeze–thaw cycles is 15. (**f**) The number of freeze–thaw cycles is 20.

When the undisturbed loess is frozen and thawed for 0–6 (as shown in Figure 7b,c), the soil particles are gradually decomposed into small particles, and the number of fine particles increases with the number of cycles. The large pores inside the sample are gradually filled into small pores. The contact mode between them gradually changes from point-to-point contact to surface-to-surface contact. Compared with the SEM images after 8–20 freeze–thaw cycles and the SEM images, after the 0–6 freeze–thaw cycles, the pores inside the sample after 8–20 freeze–thaw cycles are mainly small pores, the number of pores is less, and the soil particles are mainly fine particles (Figure 7d,f). Therefore, under the action of water gravity, the fine particles will fill the pores inside the sample, the structure becomes relatively dense, and the compressive strength of the sample is improved. Long et al. [31] found that freezing and thawing cause the structure of loess to be broken, and the reorganization and arrangement of particles occur, which leads to the improvement of soil strength. This is similar to the analysis of the results of the freeze–thaw cycles of 0 to 6 times in this paper.

Figure 8 is a microscopic image of the remolded loess at a magnification of 500 times. Compared with the undisturbed loess, the soil particle size of the remolded loess is the same. Since the remolded loess has no obvious structure, the particles inside the unfrozen and thawed samples are clear. The internal pores are mainly large pores, which are connected, and the cementation ability between soil particles is poor. The unconfined compressive strength of the specimen is small. With the increase in the number of freeze–thaw cycles, soil particles are gradually decomposed into small particles, the particles tend to be smooth, and the large pores turn into small pores.

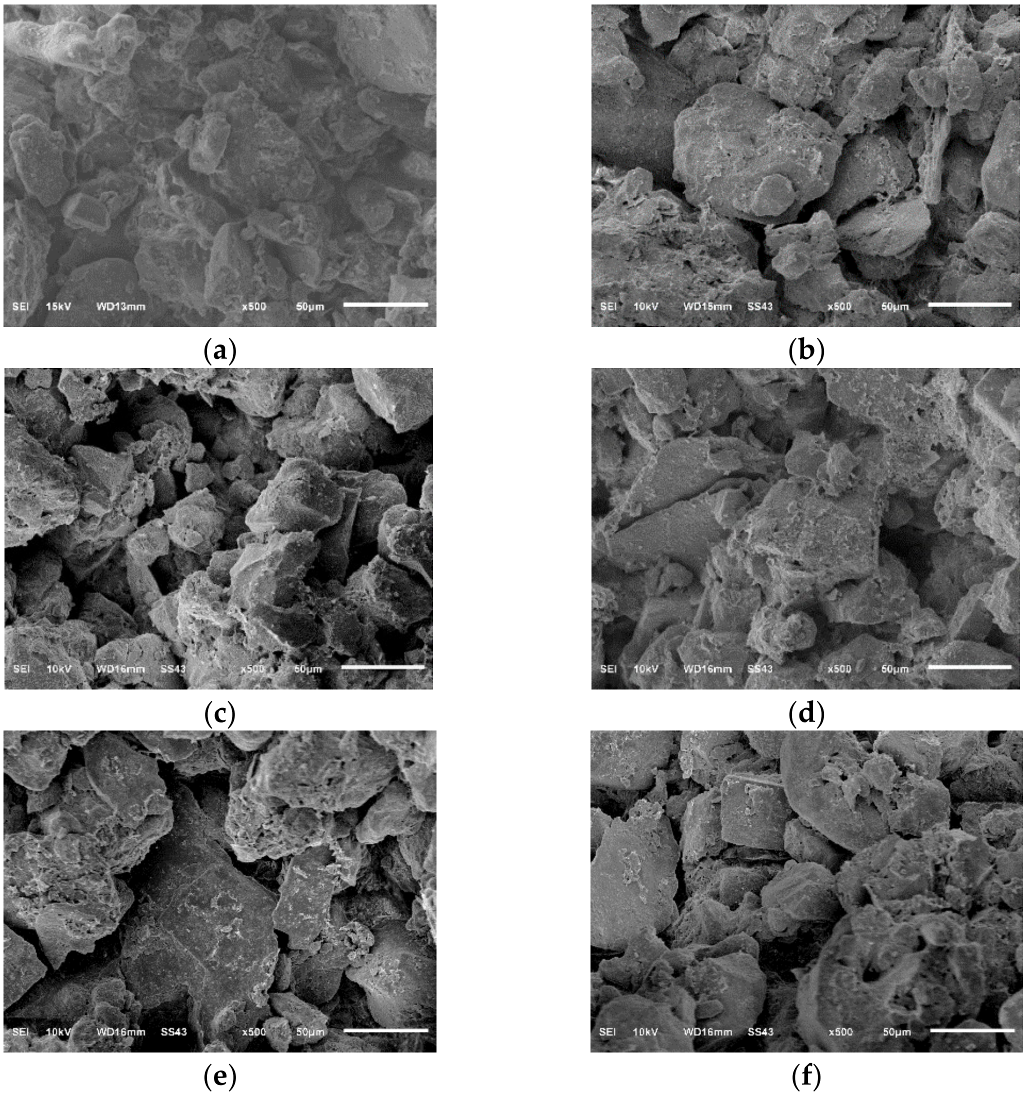


Figure 8. SEM images of remolded loess at different freeze–thaw cycles (500 times). (**a**) The number of freeze–thaw cycles is 0. (**b**) The number of freeze–thaw cycles is 2. (**c**) The number of freeze–thaw cycles is 6. (**d**) The number of freeze–thaw cycles is 10. (**e**) The number of freeze–thaw cycles is 15. (**f**) The number of freeze–thaw cycles is 20.

Due to the few freeze–thaw cycles in the early stage, the cementing ability between soil particles is poor under the action of gravity, and the external load that can be endured is small. When the number of freeze–thaw cycles is 8 to 20, the interior of the sample is dominated by small particles and small pores. The gravity and melting of water lead to the increase in the contact area between soil particles and the enhancement of cementing ability, which leads to the increase in the compactness of the sample, so the compressive strength of the sample increases gradually.

Because the undisturbed loess has an original structure, the cementing ability between the internal particles of the undisturbed loess sample is stronger than that of the remolded loess sample after the same number of freeze–thaw cycles. After the number of freeze–thaw cycles is 20, the connection between soil particles is mainly surface-to-surface contact, while the connection mode of soil particles in the remodeled loess part is point-to-point contact. At the same time, the soil particles in the original loess are decomposed into small particles, and the soil particles are smooth and regularly arranged, while there are still large soil particles in the remodeled loess samples. Fu et al. [32] researched Fuping loess (as shown in Figure 1) and found that with the increase in the number of freeze–thaw cycles, the contact mode between particles gradually evolved from surface cementation to point contact and finally returned to surface cementation, which was similar to the changing trend found in this paper, but some scholars have also found that the contact mode between particles is mainly from surface-to-surface contact to point-to-surface and point-to-point contact [33].

3.2. XRD and XRF Test

From the SEM image of the soil, it is found that there are many fine particles in the sample attached to the surface of the soil particles or filling the internal pores. Therefore, the XRD test was performed on the sample powder after the test, and the internal mineral composition was analyzed.

Figure 9 shows the internal mineral composition of loess when it undergoes different freeze–thaw cycles. It was found that with the increase in the number of freeze–thaw cycles, the characteristic diffraction peaks inside the loess did not change significantly. After different freeze–thaw cycles, the interior of loess is mainly composed of minerals such as quartz, albite, potassium feldspar, and illite, and there is no obvious change in mineral composition. Thus, it is found that the effect of freeze–thaw cycles on the internal mineral composition of loess is weak.

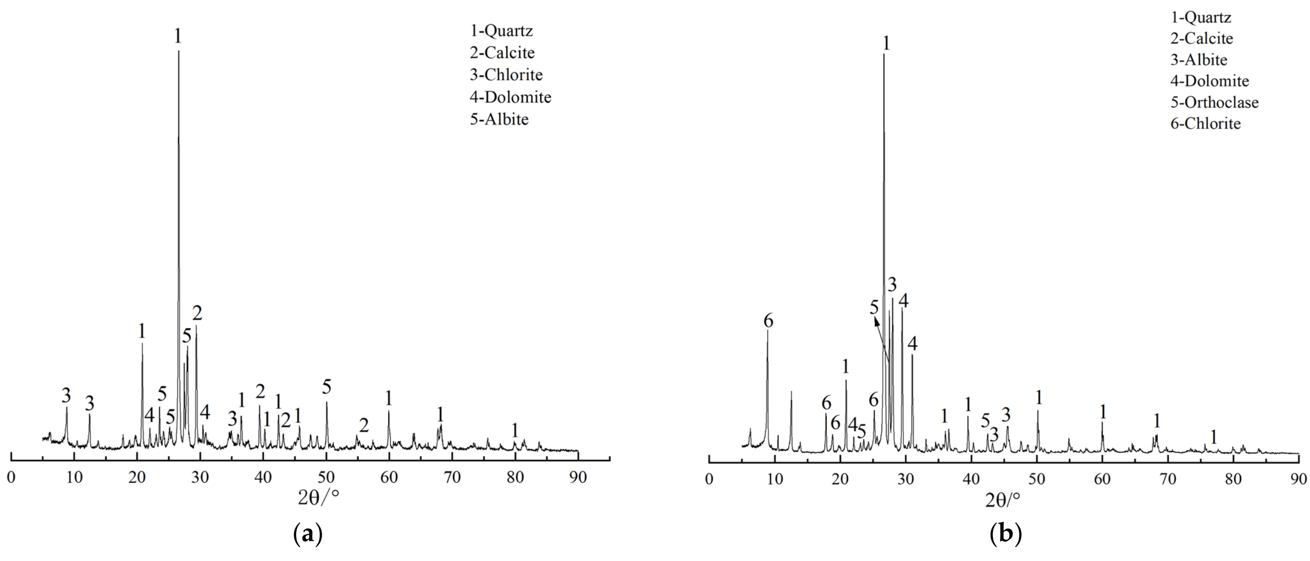
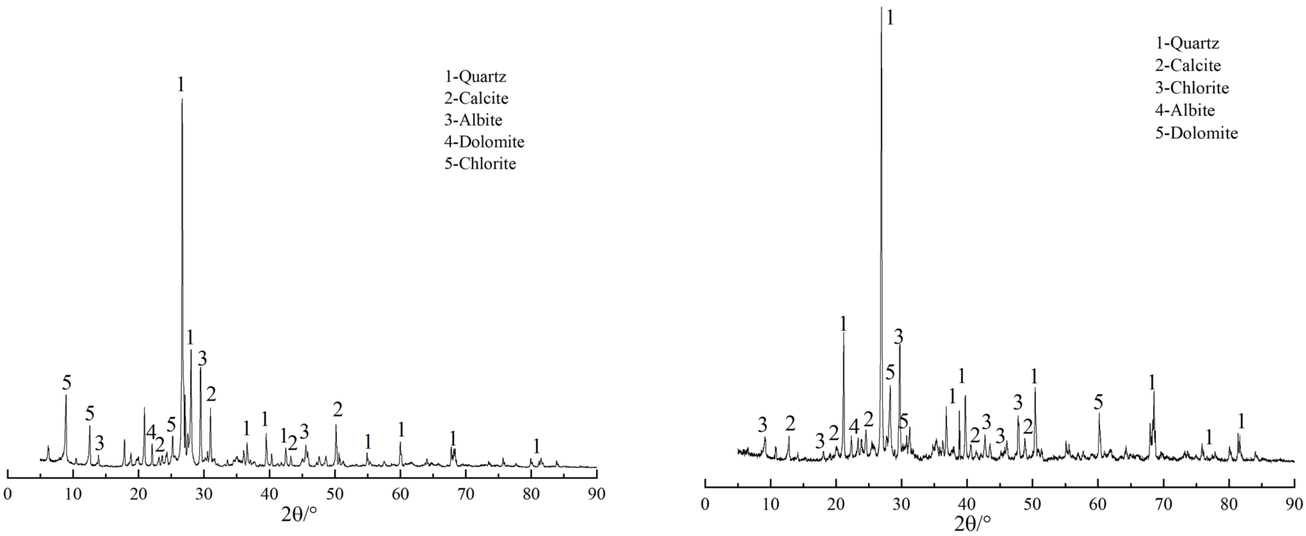


Figure 9. *Cont.*



(**c**) (**d**)

Figure 9. XRD patterns of loess under different freeze–thaw cycles. (**a**) The number of freeze–thaw cycles is 0. (**b**) The number of freeze–thaw cycles is 2. (**c**) The number of freeze–thaw cycles is 6. (**d**) The number of freeze–thaw cycles is 20.

The principal elements of loess under different freeze–thaw cycles are analyzed. It can be seen from Table 3 that with the increase in the number of freeze–thaw cycles, the contents of Si, Al, Ca, Mg, and other major elements in the loess are the same, and no new elements are found. Combined with the XRD test results, it can be found that the freeze–thaw cycle has little effect on the mineral composition of loess. Li [34] studied the mineral composition of Jingyang loess (as shown in Figure 1) and found that the content of quartz minerals in undisturbed loess and remodeled loess is relatively stable, and carbonate minerals are easily affected by the environment. Therefore, it is found that the freeze–thaw cycle has little effect on the mineral composition of loess.

Table 3. Total elemental analysis of loess.

Chemical Constituent (Mass%) Freeze–Thaw Cycles	SiO_2	Al_2O_3	$CaCO_3$	MgO	K_2O	Na_2O	Fe_2O_3	Others
0 times	48.0	13.5	25.9	3.15	2.74	1.26	4.17	1.28
2 times	48.8	14.0	24.4	3.25	2.84	1.32	4.28	1.11
6 times	49.4	13.7	24.1	3.27	2.82	1.35	4.28	1.08
10 times	49.1	13.5	24.8	3.13	2.70	1.30	4.28	1.19
20 times	48.8	13.5	24.4	3.06	2.85	1.29	4.80	1.30

4. Analysis of Mechanical Test Results

4.1. Unconfined Compressive Strength

Figure 10 shows the relationship between the compressive strength of undisturbed loess and remolded loess and the number of freeze–thaw cycles. It is found that there are differences in the strength law of undisturbed loess and remolded loess. With the increase in the number of freeze–thaw cycles, the external force generated by the freeze–thaw cycle will destroy the original structure of the soil during the transformation of the free water form, which makes the compressive strength of the undisturbed loess increase with the number of freeze–thaw cycles, then the compressive strength gradually decreases. For remolded loess, there is no original structure in the soil, so the initial strength of remolded loess is low. After two freeze–thaw cycles, the free water in the soil migrated under the action of freeze–thaw cycles. The arrangement of soil particles in the remolded loess changed, and the small soil particles gradually filled the large pores in the remolded loess.

The strength of the sample is about 16% higher than that of the unfreeze–thawed sample. With the increase in the number of freeze–thaw cycles, the external force generated during the freeze–thaw cycle caused secondary damage to the soil structure, and the compressive strength of the remolded loess gradually decreased. The change law in this stage is similar to the change law of strength of undisturbed loess after the freeze–thaw cycle.

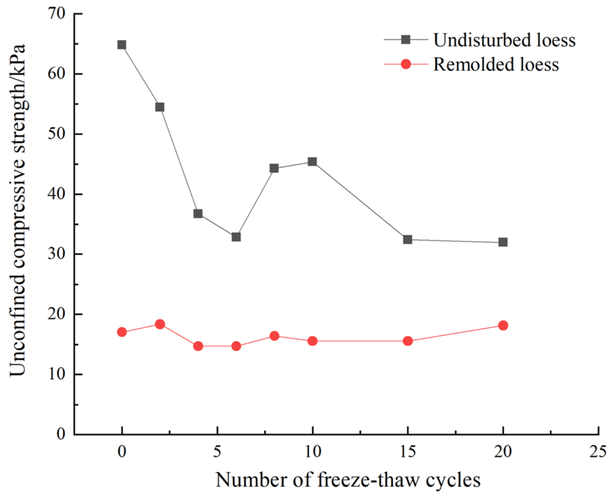


Figure 10. Relationship between the compressive strength of loess and the number of freeze–thaw cycles at different freeze–thaw cycles.

When the freeze–thaw cycles were 0–6, the compressive strength of undisturbed loess and remolded loess gradually decreased. When the number of freeze–thaw cycles is 8–20, the compressive strength of loess is relatively improved (Figure 10). The reason is that in the early freeze–thaw cycle when the internal structure of the soil is destroyed, the large pores increase. However, with the increase in the number of cycles, the large pores transform into small pores, and the water fills the fine soil particles into the large pores under the action of its weight. This increases the compactness of the sample, and its compressive strength also shows a secondary increase compared to the previous period.

4.2. Stress–Strain Curve

The undisturbed loess sample has strong structural properties, and the stress–strain curves of undisturbed loess after different freeze–thaw cycles show strain-softening characteristics (Figure 11a). The main reason is that when the undisturbed loess is subjected to vertical loads, the external loads cause damage to the original structure, the original cracks are continuously compacted, and the arrangement of soil particles inside the soil body is continuously denser. In the initial stage of loading, the external load is not enough to destroy the original structure of the sample, the arrangement of soil particles is relatively stable, the stress–strain curve belongs to the linear stage, and the original structure is not destroyed at this stage. With the continuous increase in the load, when the original structure cannot resist the external load, the original structure of the soil is damaged, and part of the deformation can be recovered. The arrangement between primary cracks and soil particles reaches the densest state, cracks begin to appear on the surface of the sample, and the compressive strength of the sample reaches the maximum, which belongs to the elastic–plastic stage. When the peak strength is reached, the cracks on the surface of the sample continue to develop, and the sample's compressive strength begins to decrease. When the soil structure cannot resist the external load, cracks penetrate the surface of the sample, dislocation occurs between soil particles, and the sample is fractured.

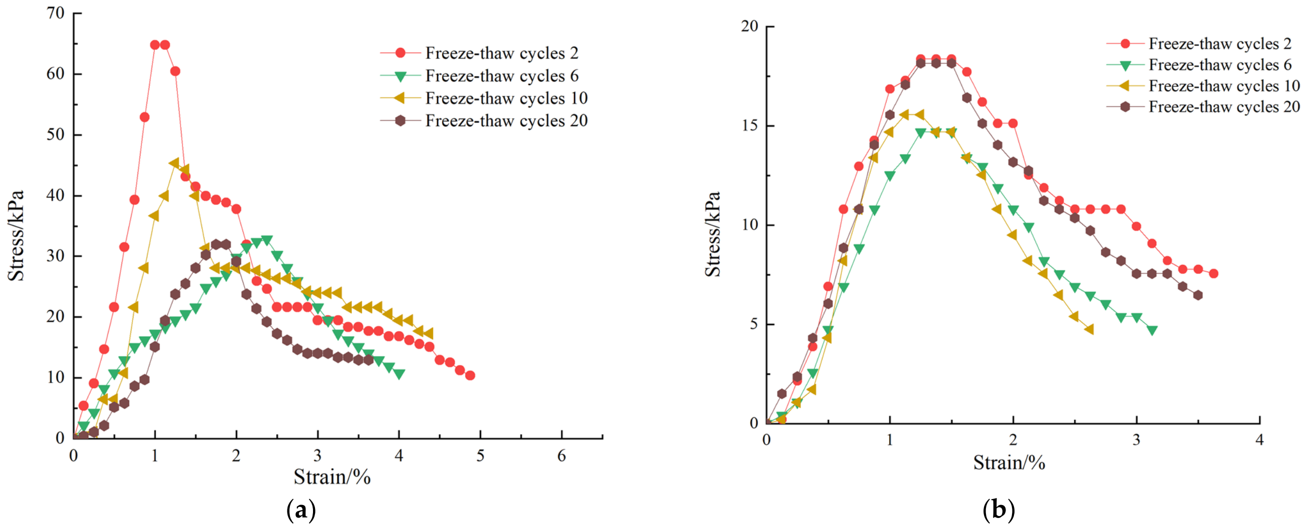


Figure 11. Stress–strain curves of loess with different freeze–thaw cycles. (**a**) Undisturbed loess. (**b**) Remolded loess.

For the remolded loess sample (Figure 11b), the sample does not have the original structure and other characteristics of the undisturbed loess, but the stress–strain curve of the remolded loess also exhibits strain-softening characteristics. Due to the recombination and arrangement of the soil particles of the remolded loess, the fluctuation of the compressive strength is small, and the compressive strength of the remolded loess is lower than that of the undisturbed loess. The ability of the remolded loess to resist external loads is weak. However, the failure mechanism of remolded loess is similar to that of undisturbed loess, both of which are the continuous development of vertical cracks in the sample, resulting in the loss of soil strength.

4.3. Elastic Modulus

The elastic modulus is one of the engineering parameters related to strength. Therefore, according to the interpretation of the initial elastic modulus by Chen et al. [35] and Xie et al. [36], the initial elastic modulus of the soil is obtained based on the curve in the initial deformation stage in the stress–strain curve showing a linear change stage.

Figure 12 shows the relationship between the initial elastic modulus of undisturbed loess and remolded loess and the number of freeze–thaw cycles. The elastic modulus of the undisturbed loess is higher, because the original structure of the undisturbed loess makes the soil stiffness larger, while the remolded loess has no structure, so the initial elastic modulus is smaller. Therefore, the elastic modulus of the loess without freezing and thawing is not included in the analysis. Through the fitting relationship, it is found that there is an exponential relationship between the elastic modulus of loess and the number of freeze–thaw cycles. The fitting degree of undisturbed loess is relatively high (R^2 = 0.80172), which indicates that the elastic modulus of undisturbed loess shows an exponentially decreasing trend with the increase in freeze–thaw cycles. With the void increases, the compressive strength of the undisturbed loess decreases, and its strength tends to be stable with the increase in freeze–thaw cycles. For the remolded loess, with the increase in the number of freeze–thaw cycles, its elastic modulus changes gradually, and the fitting degree between the values is low. This may be due to the low strength of the remolded loess itself and the high compressibility between soil particles. The effects of freeze–thaw cycles on soil elastic modulus are roughly the same, so the fitting curve is relatively smooth, and the fitting degree is poor.

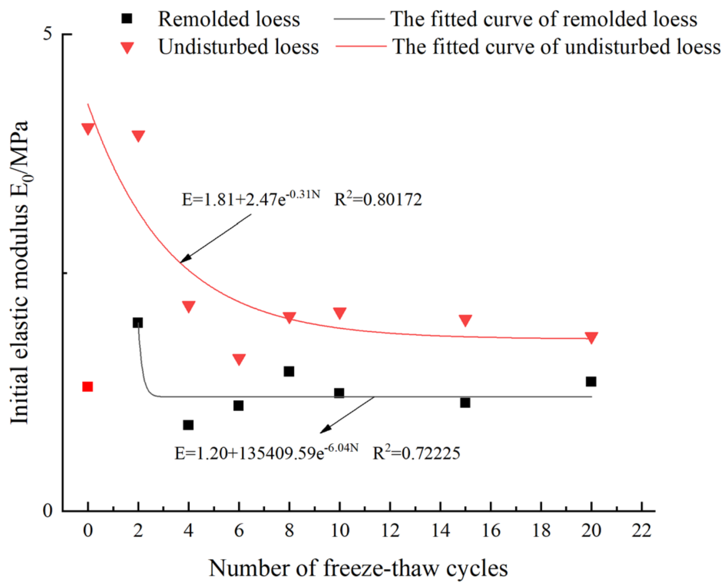


Figure 12. Relationship between the initial elastic modulus of loess and the number of freeze–thaw cycles.

5. Conclusions

In this paper, taking loess as the test material, the mechanical properties and microscopic mechanism of soil under the freeze–thaw cycle were analyzed by unconfined compressive strength test and microscopic test, and the change law of original loess and remolded loess was compared. The main conclusions are as follows:

1. With an increasing number of freeze–thaw cycles, the unconfined compressive strength of undisturbed loess and remolded loess first increases and then decreases as the strain increases, and the stress–strain curve exhibits strain-softening characteristics. During the freeze–thaw cycle, through the mutual conversion of free water to ice water inside the sample, the structure of the loess is destroyed. At the same time, due to the influence of the primary structure, the unconfined compressive strength of the undisturbed loess is higher than remolded loess.
2. The unconfined compressive strength of undisturbed loess and remolded loess decreases after 6 freeze–thaw cycles, and the strength increases after 8 to 20 freeze–thaw cycles.
3. It can be seen from the SEM images that with increasing freeze–thaw cycles, the large particles inside the sample gradually decompose into small particles, increasing the fine particles inside the sample. At the same time, the larger pores inside the sample gradually reduce in size. With the increase in the number of freeze–thaw cycles, the particles inside the soil become denser, and the strength increases.
4. The mineral composition of loess after freeze–thaw cycles are studied, and it is found that the internal composition of loess did not change significantly, and the mineral content is stable. Therefore, the effect of freeze–thaw cycles on the mineral composition of loess can be ignored in engineering.

The soil used in the whole experiment came from the seasonal frozen soil area in Qinghai, China. Due to the regional nature of the loess, more detailed research and analysis need to be carried out over a longer period. Based on this study, it was found that undisturbed loess had better mechanical properties when used as a building material, but the freeze–thaw effect had a great influence on the structure of undisturbed loess. To ensure the safety of the loess building structure, the loess can go through two to four freeze–thaw cycles during the project. At the same time, the research results present a reference value for loess construction projects.

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