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Experimental Study on Strength and Microstructure of Loess Improved by CG-2 Curing Agent and Cement

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Abstract: In order to study the improvement effect of the CG-2 curing agent and cement on loess, a series of physical and mechanical property tests and microstructure tests were carried out on loess improved with different dosages of curing agent and cement to study the physical and mechanical properties, durability and microscopic pore characteristics of the CG-2 curing agent and cement-improved loess. The results show that the unconfined compressive strength of improved loess increases gradually with the increase in curing agent and cement dosage, and the higher the compaction degree and the longer the curing age, the higher the unconfined compressive strength. In the case of the same cement content, the higher the dosage of curing agent, the more the unconfined compressive strength of improved loess increases. Under the condition of reaching the same unconfined compressive strength, the addition of curing agent can significantly reduce the amount of cement. The more the content of cement and curing agent, the less the unconfined compressive strength decreases after a certain number of freeze–thaw cycles, and the higher the dry-wet cycles index after a certain number of dry-wet cycles, indicating that the addition of curing agent can significantly improve the ability of the sample to resist freeze–thaw cycles and dry–wet cycles. According to the microscopic test results, it is found that the addition of curing agent can reduce the porosity of soil particles, change the contact and arrangement mode between soil particles, and enhance the agglomeration and cementation characteristics between soil particles, and obviously improve the physical and mechanical properties of soil. The research results can provide new ideas and methods for the improvement technology of loess.

Keywords: improved loess; CG-2 curing agent; cement; physical and mechanical properties; microstructure

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1. Introduction

Loess is widely distributed and thick in China, especially in the northwest regions such as Shaanxi, Gansu, and Ningxia. Loess has two major engineering problems: water sensitivity and structural characteristics [1–4]. The loess structure can be regarded as a spatial structure system formed by skeleton units such as single grain, aggregate, or clot. The unit shape determines the transmission performance of the force, the connection mode determines the structural strength of the soil, and the arrangement mode determines the stability of the soil. Once the loess under naturally low humidity encounters water or humidity increases, it will undergo a sudden drop in strength and a sudden increase in deformation. Therefore, loess is prone to many diseases such as water softening and roadbed settlement when used as roadbed filler. Cement or lime is often used to improve loess in engineering. If high-quality soil curing agent is used to reinforce loess instead of cement stabilized gravel for pavement base, it cannot only improve its physical and

mechanical properties, but also reduce the use of sand and cement materials. It can save resources, reduce material mining and transportation costs, and is of great significance for reducing carbon emissions.

At present, the application of cement and lime to improve loess is very extensive [5–8], but the engineering examples of using high-quality curing agent to improve loess are relatively few. Zhang et al. [9] studied the reinforcement of Yangling loess by EN-1 curing agent through compaction test, direct shear test and penetration test. The results showed that EN-1 curing agent can significantly increase the dry density of the soil, and improve its shear strength and permeability. Zhang et al. [10] analyzed the strength formation mechanism and advantages of Xi'an loess reinforced by composite BTS curing agent, and compared the unconfined compressive strength (UCS) and California bearing ratio (CBR) value of plain loess, lime reinforced loess, and composite BTS-reinforced loess. It was found that the composite BTS curing agent-reinforced soil has a higher strength, water stability, and CBR value than plain soil and lime soil. Zhang et al. [11] carried out chemical modification tests on loess in the Qingyang and Lanzhou area of Gansu Province using an anti-sparsity soil curing agent. It was found that the liquid limit, plastic limit, plastic index, and compressive strength of the modified loess increased and the maximum dry density decreased after adding anti-sparsity curing agent. Wang et al. [12] used a new type of polymer material SH curing agent to solidify Taiyuan loess in Shanxi. The results showed that, with the increase in SH dosage, the scour resistance was significantly enhanced. Wang et al. [13] carried out a nano-indentation test and scanning electron microscope test on plain loess and loess modified by anti-hydrophobic curing agent with different dosages. Based on the test results, the micro-mechanical properties, structural characteristics, and modification mechanism of modified loess were analyzed, and the optimal dosage of anti-hydrophobic curing agent modified loess was proposed. Wu et al. [14] investigated the effect of cement and trace curing agents on the strength and water stability of the loess roadbase, and combined with the microscopic morphology diagrams of the loess specimens with the addition of the four trace curing agents, respectively, analyzed the mechanism of curing agents to improve the stabilization of cemented loess. Liu et al. [15] used an indoor simulation test to study the water holding, water supply, water conductivity and evaporation properties of EN-1 type ionic curing agent cured loess, taking the typical soil of the loess region, yellow main soil, as the research object. Amin et al. [16] used a mixture of lime and rice husk ash (LRHA) to modify the loess in the Golestan province of Iran. At different curing ages, the UCS increased with the increase in LRHA content, and the UCS of the modified loess at the curing age of 28 d increased by about five times. The effects of cement dosage, compaction coefficient, molding method (vertical vibration method and static pressure method), and dry–wet and freeze–thaw cycles on the mechanical strength of cement-improved loess (CIL) were studied by Jiang et al. [17] to reveal its strength degradation law under dry–wet and freeze–thaw cycles. The use of cement–EVA stabilized loess as a roadbed soil was evaluated by Jiang et al. [18] from the point of view of chemically stabilized soils with the addition of cement and EVA (Ethylene Vinyl Acetate Copolymer) as a soil curing agent. The performance of cement–EVA-cured loess was evaluated by analyzing the mechanical properties, damage resistance, water stability, frost resistance, dry shrinkage analysis, and micromorphology of cement stabilized soil (CSS) and cement-EVA stabilized soil (CESS) specimens.

In summary, scholars at home and abroad have carried out a large number of studies on the improvement of loess by the soil curing agent. The improvement of loess by the soil curing agent has certain advantages in improving the physical properties of loess and increasing its shear strength and UCS. However, there is a lack of systematic research on the anti-freeze–thaw cycle and anti-dry–wet cycle of improved loess, and the increment value of UCS after improvement is very limited, which is not enough to meet the requirements of the subgrade base on its compressive strength. In view of this, this paper combines the secondary highway reconstruction project in the Pengyang area of Ningxia, and uses the CG-2 curing agent and cement to improve the loess. Through a series of physical and

mechanical properties tests and microstructure tests [19–22], the UCS freeze–thaw cycle resistance, dry–wet cycle resistance, and micro-pore structure change characteristics of the improved loess were studied, which can provide technical support for the improvement of the loess subgrade base filler in this area.

2. Materials and Methods

2.1. Materials

The test loess was taken from the soil field of Caohe highway in Pengyang County. It is mainly composed of loess-like silt (Q4al+pl), which has a grayish-brown to grayish-yellow color, with developed pores and obvious joints. The soil–rock engineering is classified grade II ordinary soil, and its physical properties and particle size distribution are shown in Table 1. Table 2 provides the performance parameters of Ningxia Yinghai ordinary 42.5 grade Portland cement.

Table 1. Physical parameters and particle size distribution of loess.

Liquid Limit WL/%	Plastic Limit WP/%	Optimum Moisture Content/%	Maximum Dry Density/g·cm^{-3}	Particle Size Distribution/%					
				<0.005	0.005–0.05	0.05–0.075	0.075–0.1	0.1–0.25	>0.25
28.8	18.2	12.1	1.88	9.28	63.11	18.02	6.56	3.03	0

Table 2. Performance parameters of cement.

Break Off Strength/MPa		Compressive Strength/MPa		Setting Time/min		Specific Surface Area (m^2/kg)
3 d	28 d	3 d	28 d	initial set	final set	338
4.8	8.6	24.6	44.3	205	255	

A new type of curing agent CG-2 is selected as the curing agent. It is an admixture composed of a variety of organic or inorganic materials. It is a colorless and odorless transparent solution. It has stable physical and chemical properties at room temperature and can be completely dissolved in water. The density is 1.303 g/cm^3. The aqueous solution is non-toxic, harmless, and pollution-free, and can be stored and transported safely for a long time. The contents of lead, cadmium, mercury, arsenic, and chromium in the curing agent are less than the standard values.

2.2. Test Mix Ratio

During the pre-test period, the relevant tests were carried out on the loess improved by the CG-2 curing agent. The results showed that only the curing agent was added to the loess, which had little effect on its physical and mechanical indexes and could be ignored. Therefore, this paper no longer discusses the case of only adding curing agents, and mainly compares and analyzes the case of adding cement, curing agent, and cement in loess. The cement content of improved loess was 4%, 6%, and 8%, respectively, the curing agent content was 0.015%, 0.020%, and 0.025%, respectively, the compaction degree was 96%, and the curing age was 7 d, 14 d, and 28 d.

2.3. Testing Methods

2.3.1. Compaction Test

According to the relevant provisions of the "Test Methods of Materials Stabilized with Inorganic binders for Highway Engineering" [23], the compaction test was carried out on the improved loess with different curing agents and cement content. The weight of the hammer is 4.5 kg, the cylinder volume is 997 cm^3, the compacting work is 2659 kJ/m^3, and it is compacted in 5 layers with 27 blows per layer. Set 5 water content, respectively, 9%, 11%, 13%, 15%, and 17%. Figure 1 shows the compaction test process.



Figure 1. Compaction test.

2.3.2. Unconfined Compressive Strength Test

In order to explore the influence of the different curing agent (0.015%, 0.020%, 0.025%) and cement (4%, 6%, 8%) contents, compaction degrees (92%, 94%, 96%), and curing ages (7 d, 14 d, 28 d) on the UCS of improved loess, according to the test specification [23], the UCS test of improved loess was carried out, and the influence law of each factor on the UCS was obtained, which provides a theoretical basis for the engineering application of improved loess. Figure 2 shows the unconfined compressive strength test process.



Figure 2. Unconfined compressive strength test.

2.3.3. Triaxial Test

In order to study the stress–strain relationship of improved loess, triaxial unconsolidated undrained shear tests were carried out on compacted loess, 6% cement-improved loess and 0.020% curing agent plus 6% cement-improved loess. The sample was compacted by pressing method, the size was φ39.1 mm × h80 mm, the degree of compaction was 96%, and the curing age was 7 d. Figure 3 shows the triaxial test process.



Figure 3. Triaxial test.

2.3.4. Freeze–Thaw Cycle Test

In order to study the effect of adding curing agent and cement on the freeze–thaw resistance of improved loess (an important index to evaluate the durability of solidified soil), according to the "Test Methods of Materials Stabilized with Inorganic binders for Highway Engineering" [23], the improved loess samples with a different curing agent and cement content, curing age of 28 d and compaction degree of 96% were subjected to 0, 3,

5 and 10 freeze–thaw cycle tests, respectively (one freeze–thaw cycle includes two stages, that is, freezing in a low temperature box at −18 °C for 16 h, and then immediately melting in a 20 °C water tank for 8 h). The influence of the freeze–thaw cycles on the UCS of the improved loess was discussed. Figure 4 shows the freeze–thaw cycle test process.



Figure 4. Freeze–thaw cycle test.

2.3.5. Dry–Wet Cycle Test

The dry–wet cycle process caused by the change of environmental factors will lead to the deterioration of the density, structure, and strength characteristics of the subgrade fill, which will lead to the deformation and instability of the subgrade [24]. Therefore, it is of great significance to study the influence of dry–wet cycles on the strength characteristics of improved loess. In order to evaluate the stability of the improved loess against dry–wet cycles, the dry–wet cycle index Qs is defined. The index Qs = qu_1/qu_2, where qu_1 is the UCS of the sample after a certain number of dry–wet cycles, and qu_2 is the UCS of the sample without dry–wet cycles.

The dry–wet cycle test sample preparation process is the same as the UCS test. After the sample is prepared, it undergoes standard curing for 7 days, before being soaked in distilled water for one day, and then air-dried at 28 °C room temperature for one day, as a complete dry–wet cycle process. After a certain number of dry–wet cycles, the UCS test was carried out.

2.3.6. SEM Test

In order to study the changes in the pore structure of the improved loess, the compacted loess samples, 6% cement-amended loess samples, and 0.020% curing agent + 6% cement-amended loess samples were scanned by scanning electron microscope technique [25,26] using GeminiSEM 500 (Carl Zeiss AG, Oberkochen, Germany) electron microscope. Figure 5 shows the freeze–thaw cycle test process.



Figure 5. GeminiSEM 500 electron microscope.

2.3.7. NMR Test

Nuclear Magnetic Resonance (NMR) [27,28] is a technique in which nuclear spins undergo a low-energy state transition to a high-energy state by absorbing the energy provided by the RF field, and use the energy change of the nucleus in the magnetic field to obtain information about the nucleus. In porous media such as soil and rock, the transverse relaxation T_2 of pores and surface fluids can be expressed as:

$$\frac{1}{T_2} \approx \rho_2 \frac{S}{V}, \tag{1}$$

where ρ_2 is the lateral relaxation rate, which is related to the physical and chemical properties of the soil. S and V are the surface area and volume of the particle pores, respectively.

When the pore shape is spherical, if the pore radius is R, Equation (1) becomes:

$$\frac{1}{T_2} \approx \rho_2 \frac{3}{R}, \tag{2}$$

When the pore shape is columnar, Equation (1) becomes:

$$\frac{1}{T_2} \approx \rho_2 \frac{2}{R}, \tag{3}$$

From the above two equations, it can be seen that T_2 is approximately proportional to R. The larger R is, the larger T_2 is, i.e., the distribution of T_2 in soil samples can reflect the situation of pore aperture size.

The saturated water samples of the cement-modified loess with a 6% cement content and modified loess with different curing agent contents were tested using the Rock Core NMR Analyzer and MRI System, Benchtop NMR (MacroMR12-150 H-I type, Suzhou Niumag Corporation, Suzhou, China) is shown in Figure 6, and the change characteristics of the micro-pores of cement-modified loess with the addition of curing agent were analyzed. Figure 6 Rock Core NMR Analyzer and MRI System, Benchtop NMR.

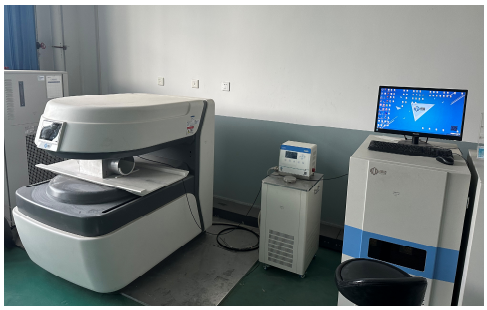


Figure 6. MacroMR12-150 H-I type.

3. Results

3.1. Compaction Test

Table 3 shows the results of the compaction test of improved loess. it can be seen from the table that, under the same dosage of curing agent, the ρ_{dmax} and wop of the improved loess increase first and then decrease with the increase in cement content, and reach the maximum when the cement content is 6%. When the cement content is the same, the ρ_{dmax} and wop of the improved loess also increase first and then decrease with the increase in the curing agent content, and reach the maximum when the curing agent content is 0.020%, but the difference with the other content is small.

Table 3. Compaction test results of improved loess with different curing agent and cement content.

Dosage of Curing Agent /%	Cement Content /%	Optimum Moisture Content /%	Maximum Dry Density /g·cm^{-3}
0	4	12.85	1.93
	6	13.35	1.98
	8	12.85	1.91
0.015	4	12.25	1.90
	6	12.55	1.91
	8	12.41	1.89
0.020	4	12.62	1.91
	6	12.78	1.93
	8	12.50	1.90
0.025	4	12.35	1.90
	6	12.55	1.91
	8	12.40	1.86

3.2. UCS Test

3.2.1. Effect of Cement and Curing Agent Content

The compaction degree is set to 96%, and the curing age is 7 d. The influence of the different content of curing agent and cement on the UCS of the improved loess is shown in Figure 7. It can be seen from the figure that, with the increase in the curing agent content, the UCS of the improved loess shows an apparent growth trend. When the cement content is 6%, the UCS of the improved loess with 0.015% curing agent is 1.14 times higher than that without curing agent, while the UCS of the improved loess with 0.025% curing agent is 1.29 times compared with that without curing agent. In addition, when 0.015% curing agent and 4% cement are added, the UCS of the improved loess is equivalent to that of cement-improved loess with a content of 6%. When 0.020% curing agent and 6% cement are added, the UCS of the improved loess is the same as that of cement-improved loess with a content of 8%.

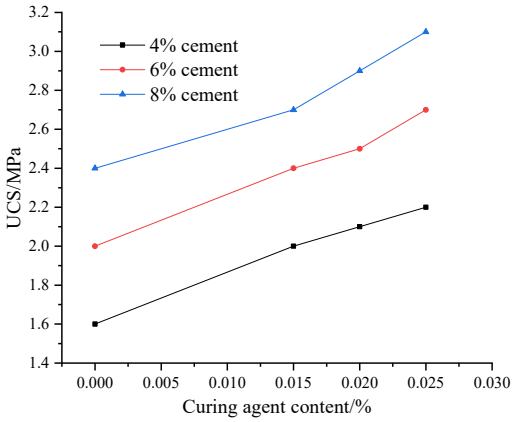


Figure 7. Effect of curing agent and cement content on the UCS of the improved loess.

3.2.2. Effect of Compaction Degree

The cement content is set to 6% and the curing age is 28 d. The effect of the sample compaction degree on the UCS of the improved loess with a different curing agent and cement content is shown in Figure 8. It can be seen from the figure that with the increase in compaction degree, the UCS of the improved loess shows a significant increasing trend. When the compaction degree increases from 92% to 94%, the UCS of the improved loess with a different curing agent content increases by about 6.9%~8.3%. When the compaction degree increases from 94% to 96%, the UCS of the improved loess with a different curing

agent content increases by about 11.5%~14.8%. Under the condition of the same compaction degree, the improvement of UCS is especially significant when the content of the curing agent increases from 0.020% to 0.025%.

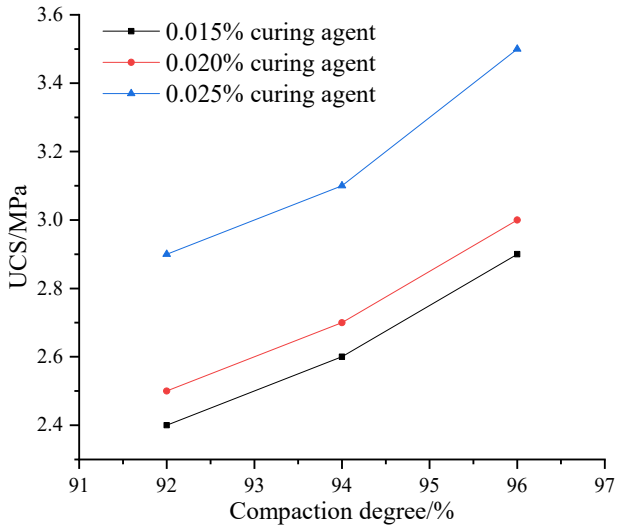


Figure 8. Effect of the sample compaction degree on the UCS of the improved loess.

3.2.3. Effect of Curing Age

The cement content is set to 6%, and the compaction degree is 96%. Figure 9 shows the effect of curing age on the UCS of the improved loess under different curing agent contents. It can be seen from the figure that, with the increase in curing age, the UCS of the improved loess with a different curing agent content gradually increases. In the early stage of curing (7 d~14 d), the UCS increases rapidly, while in the later stage of curing (14 d~28 d), the UCS increase gradually slows down. In addition, under the same curing age, the UCS will increase with the increase in curing agent content. When the curing agent content is 0.020%, the UCS of 7 d is about 84% of that of 28 d, and the UCS of 14 d has reached 91% of that of 28 d.

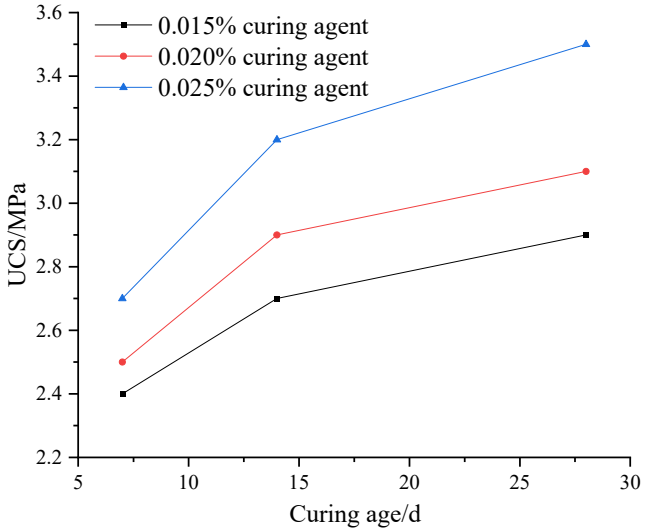


Figure 9. Effect of curing age on UCS of improved loess.

3.3. Triaxial Test

The stress–strain curve obtained from the triaxial test is shown in Figure 10. From Figure 10a, it can be seen that with the increase in confining pressure, the stress–strain curve of the compacted loess gradually changes from strain softening to strain hardening. This is

because, under low confining pressure, the interaction between loess particles is weak, and relative slip and deformation can easily occur, resulting in a gradual increase in strain but a slow increase in stress. With the increase in confining pressure, the interaction between loess particles is enhanced. It can be seen from Figure 10b that the stress–strain curves of cement-improved loess under different confining pressures are all strain-softening, and the peak strength under different confining pressures is much larger than that of compacted loess, and there is also a high residual strength. When the peak strength is reached, the corresponding strain value becomes smaller, indicating that the cement-modified loess can better resist deformation and maintain higher strength when subjected to external forces. It can be seen from Figure 10c that the stress–strain curve of the curing agent and cement modified loess is similar to that of cement modified loess, but the peak strength and residual strength under different confining pressures are improved to varying degrees.

3.4. Freeze–Thaw Cycle Test

Figure 11 shows the effect of the number of freeze–thaw cycles on the UCS of improved loess samples under different curing agent contents. It can be seen from the figure that the UCS of improved loess gradually decreases with the increase in the number of freeze–thaw cycles. In the first three freeze–thaw cycles, the reduction in the UCS was small, and the UCS rapidly decreased from the third to the fifth freeze–thaw cycles. From the fifth to the tenth freeze–thaw cycles, the rate of reduction in UCS slowed down. In the case of the same amount of curing agent, the more the cement content, the less the UCS reduction after a certain number of freeze–thaw cycles. In the case of the same amount of cement, the greater the amount of curing agent, the less the UCS decreases after the same number of freeze–thaw cycles. When the cement content is 6%, the UCS of the sample with 0.015% curing agent is reduced by about 14% after 10 freeze–thaw cycles, while the UCS of the sample with 0.020% and 0.025% curing agent is reduced by about 10% and 8.6%.

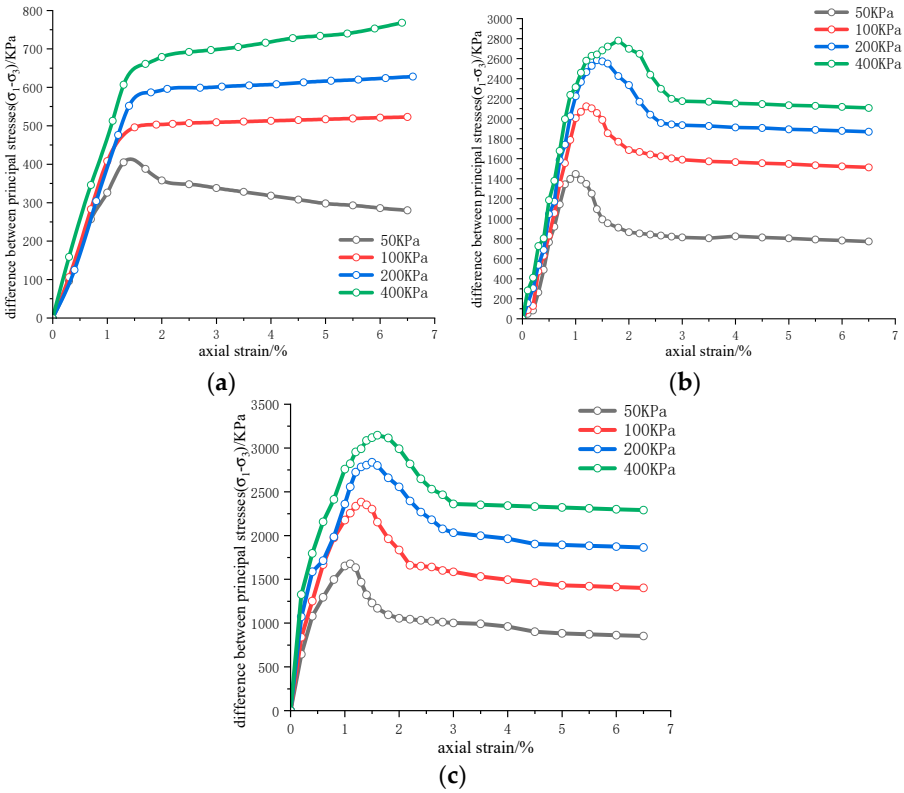


Figure 10. Stress–strain curve: (**a**) compacted loess; (**b**) 6% cement-improved loess; (**c**) 0.020% curing agent and 6% cement to improve loess.

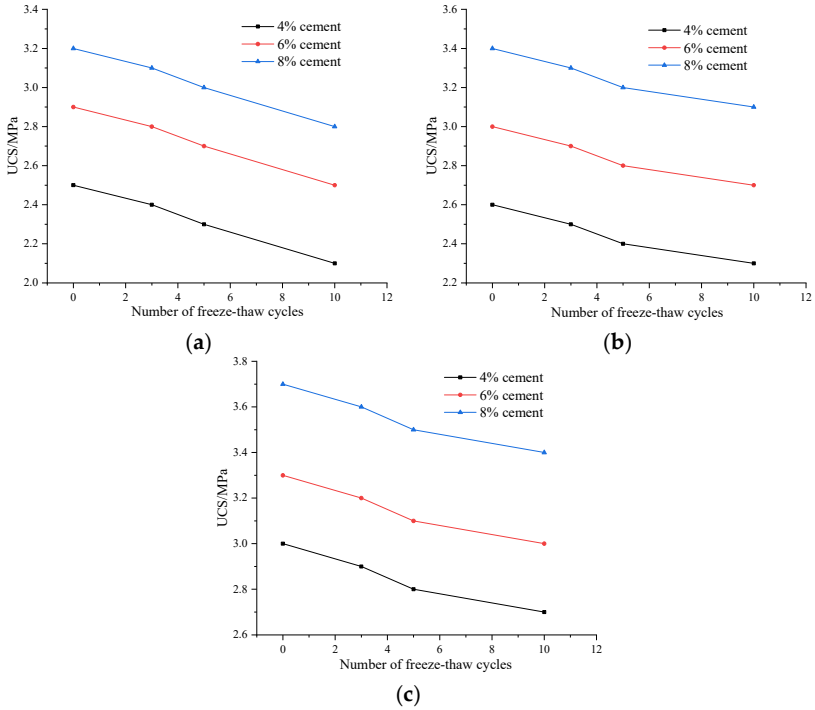


Figure 11. Effect of freeze–thaw cycles on UCS of the improved loess: (**a**) 0.015% curing agent dosage; (**b**) 0.020% curing agent dosage; and (**c**) 0.025% curing agent dosage.

3.5. Dry–Wet Cycle Test

The compaction degree of the sample was set to 96%, the cement contents were 4%, 6%, and 8%, and the curing agent content was 0.020%. Table 4 shows the UCS of the cement-improved loess and curing agent and the cement-improved loess samples under different dry–wet cycles. Figure 12 shows the relationship between the dry–wet cycle index and the dry–wet cycle times of improved loess.

Table 4. The UCS of sample with different numbers of wet and dry cycles (MPa).

Number of Wet and Dry Cycles	Without Curing Agent			0.020% Curing Agent Content		
	Cement Content			CEMENT Content		
	4%	6%	8%	4%	6%	8%
0	1.6	2.1	2.5	2.1	2.5	2.9
3	1.2	1.8	2.2	1.8	2.3	2.7
5	0.9	1.6	2.0	1.6	2.1	2.5

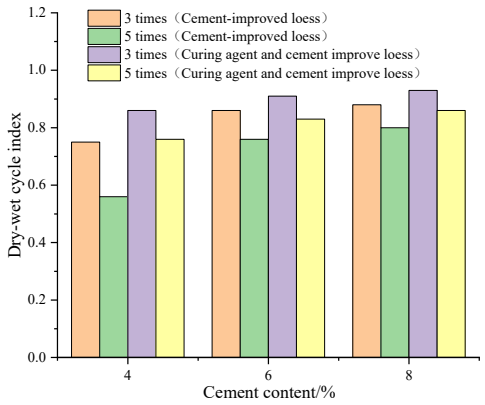


Figure 12. Effect of dry–wet cycle times on the dry–wet cycle index of improved loess.

From Table 4 and Figure 12, it can be seen that with the increase in the number of dry–wet cycles, the UCS of the improved loess shows a gradual downward trend. However, with the increase in cement content, the dry–wet cycle index increases accordingly, that is, the sample with a higher cement content has a stronger performance in resisting the influence of dry–wet cycle. When the number of dry–wet cycles of cement-improved loess increased from 3 to 5, the dry–wet cycle index decreased significantly. After adding 0.020% curing agent, although the dry–wet cycle index gradually decreased with the increase in dry–wet cycles, the value of decrease was relatively small. This shows that after adding the curing agent, the ability of the improved loess to resist dry–wet cycles has been significantly improved. When the number of wet and dry cycles is five times, the dry–wet cycle index of 4% cement-improved loess is 0.56, while that of 8% cement-improved loess is 0.80. After adding 0.020% curing agent, the dry–wet cycle index of the 4% cement-improved loess is 0.76, while that of the 8% cement-improved loess is 0.86.

In summary, it can be seen from the analysis that after a certain number of dry–wet cycles, the microstructure of the cement-improved loess sample changes due to the influence of dry shrinkage and wet expansion deformation, and micro-cracks are formed inside it. With the increase in the number of dry–wet cycles, the micro-cracks continue to expand and connect, which eventually leads to the damage and even destruction of the sample structure, which is manifested by the gradual decrease in the strength of the sample. After adding the curing agent, the cement hydration is more sufficient, the pores between the particles are greatly reduced, the mutual connection between the particles is enhanced, and the ability to resist external force deformation is greatly improved. Therefore, under the same number of dry–wet cycles, the UCS of the cement-improved loess sample mixed with the curing agent is higher.

3.6. Qualitative Analysis of the Microstructure of Modified Loess

The micro-pore analysis software IPP6.0 was used to process the scanning electron micro-scope photos. As shown in Figure 13, in which the red color represents the particle pore, and the gray color represents the soil skeleton.

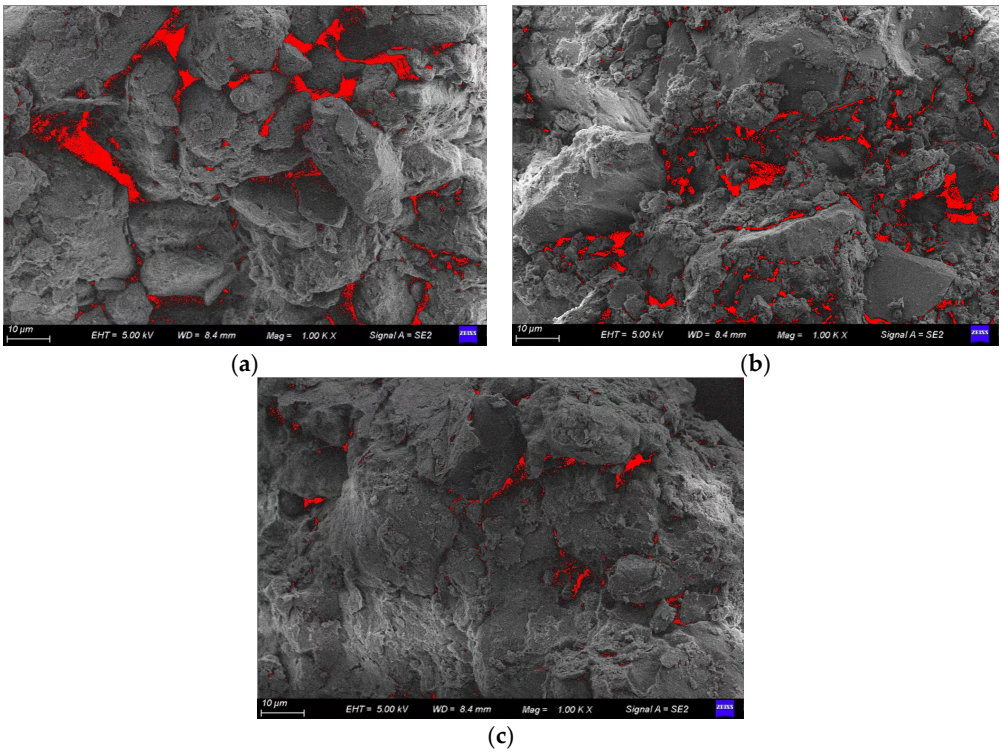


Figure 13. SEM images of microstructure of improved loess (1000×): (**a**) compacted loess; (**b**) 6% cement; and (**c**) 0.020% curing agent + 6% cement.

It can be seen from Figure 13a that the pores of compacted loess particles are large, and the connection between particles is mainly point-to-point and point-to-surface contact. From Figure 13b, compared with compacted loess, the large pores of cement-improved loess basically disappear, the small pores are denser, and the connection between soil particles gradually becomes surface contact. This is because the cement hydration reaction continues to occur, and the cement hydration products increase rapidly. Among them, hydrated calcium silicate ($CaO{\cdot}SiO_2{\cdot}H_2O$), hydrated calcium aluminate ($CaO{\cdot}Al_2O_3{\cdot}H_2O$), and hydrated calcium ferrite ($CaO{\cdot}Fe_2O_3{\cdot}H_2O$) and other cementitious materials will encapsulate soil particles, agglomerate soil particles, and fill the original soil skeleton. It can be seen from Figure 13c that, after adding the curing agent, the pores of the improved loess are significantly reduced, the aggregates are further increased, they are combined with each other, and the overall cementation characteristics are enhanced.

In addition, the IPP software can also extract the equivalent perimeter and equivalent area of the microscopic pores of the improved loess sample, which can be used to calculate the fractal dimension [29,30] of the soil pores, and at the same time, it can be used to plot log *P*-log *A* double logarithmic plots. The fractal dimension *D* reflects the complexity of the microscopic pore structure of the soil, and its value is in the range of 1~2. The larger the pore structure is, the more complex the pore structure is, and the farther the spatial morphology of the pore deviates from the smooth surface. Its calculation formula is:

$$\log P = \frac{D}{2}\log A + C \tag{4}$$

where P is the equivalent perimeter of the polygon (μm); A is the corresponding polygon area (μm^2); C is a constant; and D is the fractal dimension.

Figure 14 shows the fractal dimension of micro-pores in soil samples. It can be seen from the figure that the fractal dimension of the compacted loess is 1.552, the fractal dimension of the 6% cement-improved loess is reduced to 1.434, and the fractal dimension of 0.020% curing agent +6% cement-improved loess is reduced to 1.392 again. It can be seen that the addition of curing agent can significantly reduce the total number and total area of soil pores, and the arrangement of soil structure is more compact, the pores become more uniform, the shape tends to be isotropic, the loess particles become more regular, the structural complexity of the soil decreases, and the whole is denser.

3.7. Quantitative Analysis of Curing Agent Content on the Microstructure of Improved Loess

The microscopic pores of the soil determined by NMR tests are divided into four categories according to the pore size (d) [27]: micropores (d < 0.01 μm), small pores (0.01 μm < d < 0.4 μm), medium pores (0.4 μm < d < 4 μm), and large pores (d > 4 μm). Figure 15 shows the pore size distribution curve of improved loess obtained by the NMR test. From the figure, it can be seen that the pore size distribution of compacted loess is more comprehensive, and the percentage of the pore size is larger, while the pore size distribution of cement-improved loess is mainly concentrated in the range of 0.003~0.5 μm, which is dominated by a small pore space, microporosity, and a large-pore and medium-pore space accounting for a smaller percentage. After adding the curing agent, the peak value of the test curve gradually decreases and slightly moves to the left, indicating that the addition of the curing agent can reduce the pore size distribution range of the improved loess, and the proportion of the pore size is significantly reduced.

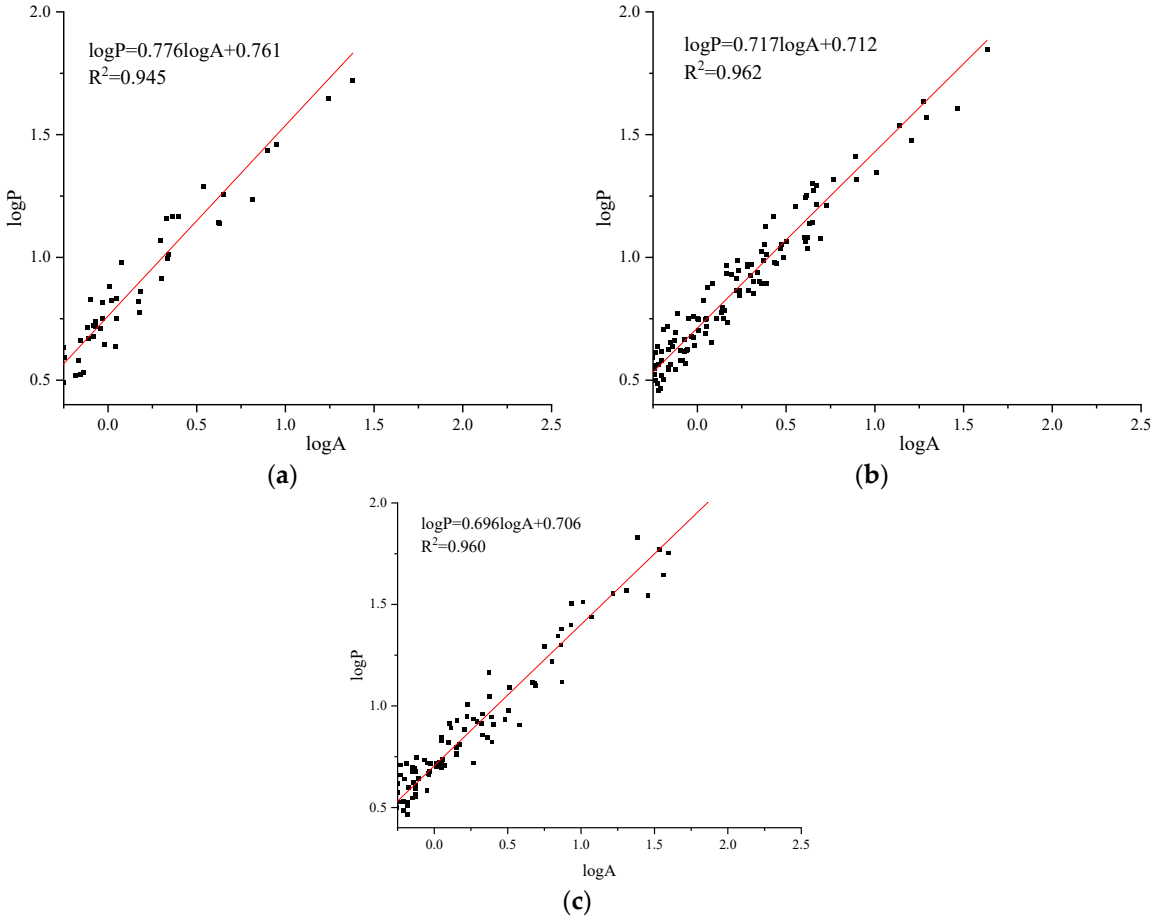


Figure 14. Fractal dimension of the microscopic pores of soil samples: (**a**) compacted loess; (**b**) 6% cement; and (**c**) 0.020% curing agent + 6% cement.

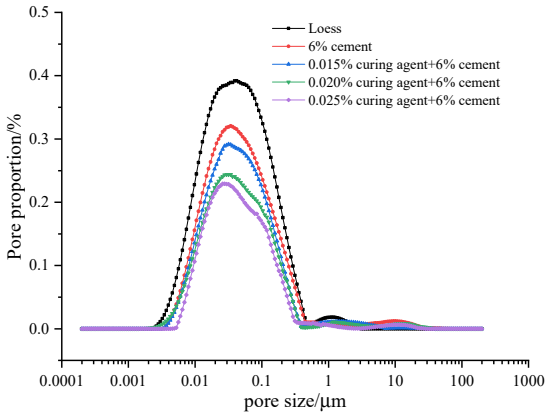


Figure 15. Pore size distribution curve of the improved loess.

4. Discussion

The test results show that the UCS of the improved loess increases with the increase in curing agent and cement content, and the larger the content of both is, the more obvious the UCS increases. Under the condition of the same strength, the addition of curing agent can reduce the amount of cement. The stress–strain relationship of the improved loess is also affected by the curing agent and cement. After adding the curing agent and cement, the peak strength and residual strength of the stress–strain curve of the improved loess are significantly improved, and the strain value corresponding to the peak strength is also slightly smaller. With the increase in curing agent and cement content, the strength

attenuation of improved loess after freeze–thaw cycle decreases, and the durability index after dry–wet cycle increases. In addition, the compaction degree and curing age are also effective means of improving the strength of improved loess. However, when the compaction degree is lower than 94%, the UCS of the improved loess increases slowly. When the curing age is 7 d~14 d, the UCS of the improved loess increases rapidly. Therefore, considering the economic benefits and strength requirements of engineering applications, it is recommended that the optimum blending ratio of the cement and curing agent is 6% and 0.020%. The degree of compaction is not less than 94%, and the curing age is not less than 14 days. In engineering design, the content of different curing materials can be reasonably adjusted to meet the corresponding design goals.

5. Conclusions

(1) Cement and curing agent are the main factors affecting the strength and stability of the improved loess. Increasing the content of curing agent and cement can significantly enhance the unconfined compressive strength of the improved loess. And, under the same strength conditions, the incorporation of curing agent can effectively reduce the amount of cement. The incorporation of curing agent and cement will also increase the peak strength and residual strength of the stress–strain curve of the improved loess.
(2) Curing agent and cement can significantly improve the freeze–thaw resistance and dry–wet cycle resistance of the improved loess. Compaction and curing age are also convenient and effective means of improving the strength of the improved loess.
(3) Considering the economic benefit and the strength index of the engineering application, the optimum mixing ratio of cement and curing agent is 6% and 0.020%. The compaction degree is at least 94%, and the curing age is at least 14 days.
(4) In the qualitative and quantitative analysis of the microstructure of the improved loess, it was found that the reaction products of the curing agent and cement with the loess will wrap and agglomerate the soil particles, and its unit form develops from single particle to aggregate and agglomerate. These aggregates further fill the skeleton of soil particles, and their connection mode develops from a large number of point contacts to surface contacts, which eventually changes the arrangement of soil particles from the dominance of large pores and overhead pores to the dominance of intergranular pores, so the strength and stability of the soil are greatly improved.

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