Research Article

Mechanical Properties and Microstructure Characteristics of the Loess Modified by the Consolid System

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The soil stabilizer of the Consolid system (content: 0%–2.46%) was used for the modification of collapsible loess. The consolidation test, compression test, collapsibility test, and strength test of modified loess were conducted. In addition, X-ray diffraction (XRD), scanning electron microscopy (SEM), and mercury injection tests were carried out to study the loess before and after modification. The results indicated that with an increase in the content of the stabilizers, the optimal water content of the modified loess increased, whereas the dry density decreased. Furthermore, as the content of the stabilizers increased, the compressibility and collapsibility of the modified loess decreased. When the stabilizer content was 0.86%, the modified loess exhibited almost no collapsibility. The unconfined compressive strength of the modified loess demonstrated an exponential relationship with the content of the stabilizers. The shear strength increased with the increase in the content of the stabilizers. When the stabilizer content reached 1.66%, the friction angle started to decrease. The microstructure analysis indicated that the cumulative pore volume of the modified loess decreased with the increase in the content of the stabilizers, which could facilitate the formation of a more stable soil structure and improve the impermeability and strength.

1. Introduction

Loess and materials similar to loess cover approximately 10% of the Earth’s surface and are widely distributed in Central Asia, Central Europe, and North America [1, 2]. The loess deposits found in China contain more than 60 known minerals, including quartz (about 50% of the total mass), feldspar (about 20% of the total mass), carbonate minerals (about 10% of the total mass), and clay minerals (illite, kaolinite, chlorite, etc.) [3–5]. Loess has a porous structure; therefore, when the water content of the loess increases, sliding and collapsibility are likely to occur, resulting in various engineering problems.

In China, systematic research and engineering advances were initiated by the Road and Railway Departments in the 1950s and 1960s to improve the properties of soil. Recently, with the increase in engineering projects in Northwest China, research on loess modification has gradually increased. Traditional materials such as lime, cement, fly ash, and sodium silicate are widely used in loess modification. Researchers have evaluated the modified effect of traditional materials on the optimal content, modified age, and strength of modified loess [6–10]. With the increase in environmental awareness, researchers have started to investigate new types of stabilizers, especially environmentally friendly stabilizers for soil. The mechanical properties of the loess sample modified with the SH stabilizer were better than those of cement and lime-modified loess samples. Different mixing contents of the stabilizers resulted in different strengths of the modified loess [11–14]. Fu et al. [15] conducted experimental research on the engineering properties of soil modified with the EN-1 ionic stabilizer. The results indicated that this could significantly reduce the deflection of the loess roadbed, improve the resilience modulus and compactness.
of the roadbed, improve the bearing capacity of the roadbed, and considerably increase the water stability of the roadbed. Huang et al. [16] combined the use of a polymer composite soil stabilizer named the aqua-dispersing-nano-binder (ADNB), with biological approaches, and applied this environmentally friendly method for the treatment of the silty slope of clay rock.

The soil stabilizers of the Consolid system have been widely used throughout the world with considerable effectiveness, but to a lesser extent in the loess areas of China. During the study on the improvement of clay in northern Spain, Seco et al. [17] found that the soil sample modified with stabilizers exhibited high early strength. Moreover, they found that the results obtained by using a large number of other reinforcement stabilizers could be obtained by using only a small number of the Consolid stabilizers. In the study on the improvement of Italian clay with stabilizers, Eren et al. [18] found that the addition of a small amount of stabilizers could increase the optimal moisture content and California bearing ratio (CBR) value of the soil and reduce the maximum dry density, expansion rate, liquid and plastic limits, and relative density of the soil. Zhang et al. [19] modified remolded Q3 loess using the Consolid stabilizer. They carried out the water drop penetration time test, flexible wall permeability test, shrinkage test, and dehydration test using a pressure membrane apparatus test to explore the stabilizer influence of the content on the water infiltration and the water loss capacity of the loess. The results indicated that compared with the 5% cement-modified soil, the optimal content of the stabilizers was 2%–2.5%.

In the loess slope treatment with the traditional soil stabilizer, if the rainfall is too concentrated or continuous, the slope surface is easy to be washed away, resulting in a poor slope protection effect, as shown in Figure 1. In addition, for some traditional slope protection materials, the amount added to the slope protection is about 2%–10% [20–22], while the Consolid soil stabilizer can achieve the purpose of elimination of loess collapsibility, water erosion prevention, and slope protection when the amount is relatively small, which is beneficial to environmental protection. According to the characteristics of the fragile ecological environment, serious water and soil loss, and prone to geological disasters in this area, it is proposed to apply the Consolid stabilizer to ecological slope protection. Therefore, the mechanical characteristic and microstructure of the stabilizer were studied in this study. The compressibility, collapsibility, and strength of the modified loess by the Consolid system were analyzed, and the hydrated reaction products were examined by X-ray diffraction. The changes in the pore structure of the modified samples were studied by scanning electron microscopy and mercury injection tests. It can provide theoretical support for the application of the ecological curing agent in the protection engineering of the slope.

2. Methods and Materials

2.1. Research Materials

2.1.1. Loess. The study area is located in the hinterland of the Loess Plateau, at an altitude of 976–1459 meters above the sea level. The testing area is located in Qingyang, China, between 106° 20′ to 108° 45′ east longitude and 35° 15′ to 37° 10′ north latitude, as shown in Figure 2. The loess for testing is obtained in the area. The selected slope is located at the edge of the Loess Plateau, and the top of the slope is farmland. The upper part of the slope has been cut, and the lower part of the slope is filling slope. The sampling point is located at the bottom of the slope, as is shown in Figure 3. The values of the physical properties of the unmodified loess are given in Table 1. The loess sample was mainly composed of silt particles, with a silt content of 79%, a soil proportion of 2.71, a liquid limit of 30.5%, a plastic limit of 18.5%, a maximum dry density of 1.82 g·cm⁻³, and an optimal water content of 15.05%. The particle size distribution curve obtained by the sieving method is shown in Figure 4. The loess is collapsible.

2.1.2. Soil Stabilizers of the Consolid System. The soil stabilizers of the Consolid system were used in this study. The soil stabilizers of the Consolid system are composed of two materials: a water agent named Consolid 444 (C444) and a powder agent named Consolid Solidry (SD). C444 is a semiviscous liquid, which is composed of monomers and polymers mixed with an accelerated penetration catalyst. It is a slightly acidic organic chemical (pH = 6). It can break the water layer around the soil particles, resulting in irreversible agglomeration of the small particles and promotes the natural binding of the fine particles in the soil. In addition, it causes irreversible agglomeration of the powder by shifting the electrochemical load on the soil particles. SD is a dry inorganic compound. It prevents the treated loess from soaking in water by closing the capillaries. It can also help compact the soil sample, reduce the pores of the soil, significantly reduce the water absorption capacity of the modified loess, and prevent the collapsibility of the loess.

The PH values as well as the values for total Cu, total Zn, total As, total Hg, total Pb, Cr, Fe, Mn, and Al elements of the leaching solution of the soil sample modified with 2.46% stabilizers were measured (Table 2). The PH value is 8.07. It
can be seen from Table 2 that the leaching solution satisfies the requirements listed in the standards for irrigation water quality (GB5084–2021) [23]. Therefore, it can be concluded that the stabilizers are environmentally friendly, with a PH value of 8.07 of the leaching solution.

2.2. Test Method

(1) Preparation of modified soil samples: according to the standard for geotechnical testing method (GB/T 50123–2019) [24], the ground-dried loess sample was passed through a 2 mm sieve; water was evenly sprayed on the sample and it was laid aside for one night. The sample was then evenly mixed with SD and then this mixture was added to the solution that consisted of C444 and water (in optimal water content). After thorough mixing, the modified loess by the Consolid system was obtained. According to the experimental design, different weights of SD were used: 0%, 0.40%, 0.80%, 1.20%, 1.60%, 2.00%, and 2.40% of the loess weight; the weight of the C444 was equal to 0.06% of the weight of the loess.

(2) Optimal water content and dry density tests: through the standard compaction test of the loess samples modified with different contents of the stabilizers. The striking times of the compaction test was determined 24 times, and the weight of the drop hammer was 2.5 kg and the height was 305 mm. According to the liquid limit and the plastic limit of undisturbed loess, five groups of samples with different contents are established for the solidified soil with different proportions for testing. After compaction, the samples before demoulding, the water content of the middle soil of the sample was determined. Finally, the optimum water content and dry density were deduced from the fitting curve of the water content and dry density.

(3) Soil mechanical properties: according to the standard for geotechnical testing method (GB/T 50123–2019), the modified loess was subjected to the shear
Table 1: Physical Properties of the unmodified loess.

<table>
<thead>
<tr>
<th>Unmodified density (g·cm⁻³)</th>
<th>Dry density (g·cm⁻³)</th>
<th>Water content (%)</th>
<th>Saturated water content (%)</th>
<th>Specific gravity</th>
<th>Porosity ratio</th>
<th>Plastic limit (%)</th>
<th>Liquid limit (%)</th>
<th>Coefficient of compressibility (MPa)</th>
<th>Collapsibility coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.61</td>
<td>1.44</td>
<td>11.32</td>
<td>50.39</td>
<td>2.71</td>
<td>0.84</td>
<td>18.5</td>
<td>30.5</td>
<td>0.43</td>
<td>0.078</td>
</tr>
</tbody>
</table>

Figure 4: Particle size distribution curve of the loess sample.

test and unconfined compressive strength test (curing for 7 days). Strain-controlled direct shear tests were conducted using a standard shear testing procedure. The modified loess samples were placed in a shear testing device (Nanjing Soil Machine, DZJ-1, Nanjing, China). And, the vertical pressure acting on the sample was 50 kPa, 100 kPa, 150 kPa, and 200 kPa, with three replications for each species. Horizontal displacement was applied at a speed of 1.2 mm/min until species failure. The maximum shear force was noted. Then, the cohesion and internal friction angle of the modified soil were calculated by the Mohr–Coulomb failure envelope. The sample size of the nonconfined compressive strength is 3.91 cm × 8 cm. The samples were placed in the strain-controlled triaxial apparatus (TSZ-1A, China). The vertical displacement was applied at a speed of 0.5 mm/min until species failure, and the peak values of the stress were noted.

(4) Loess collapsibility test: according to the method specified in the collapsibility coefficient test of the loess collapsibility test in Chinese specification GB/T 50123-2019, the pressurization levels are 50 kPa, 100 kPa, 150 kPa, and 200 kPa. After applying each level of pressure, read once per hour until the deformation is stable. When the sample stabilizes at the pressure of 200 kPa, distilled water is injected into the consolidation container and the surface of the water is higher than that of the top surface of the sample. During the sample test, the water surface shall be kept stable by water injection and the deformation shall be measured per hour until the deformation of the sample is stable.

(5) Microstructure characteristics of loess modified by the consolidation system: the mineral composition of the modified loess samples was analyzed by X-ray diffraction. The sample contents of the analyzed samples were 0% and 2.46%, respectively. The microstructure of the modified loess with different contents (0%, 0.86%, 1.66%, and 2.46%) was studied using the in-lens probe of a Gemini 300 scanning electron microscope (SEM). The pore diameter and pore distribution of the modified sample were determined by using an Autopore IV 9500 mercury porosimeter produced by the Micrometrics Instrument Corporation. The maximum pressure can reach 415 MPa, and the aperture measurement range is 3 nm–360 μm. The test was conducted in two stages. First, manually apply the low pressure from 0.003 MPa to 0.21 MPa, and then automatically apply high pressure from 0.21 MPa to 242 MPa. After the low pressure is applied, take out the sample from the low-pressure chamber and determine its mass. Then, conduct the high-pressure test. The contact angle set in the experiment was 130°, and the balance time was 30 s.

3. Conclusions and Analysis

3.1. Effect of the Stabilizer Content on the Optimal Water Content. Table 3 shows the optimal water content and the maximum dry density of the loess samples modified with different contents of the stabilizers measured by using the standard compaction test. It can be seen from the table that after adding the stabilizers, the optimal water content increased from 15.05% (0% stabilizer content) to 17.78% (2.46% stabilizers content). It presents an increase of 2.73%. The maximum dry density decreased from 1.82 g/cm³ to 1.77 g/cm³ and presents a decrease of 2.75%. When the water content reaches the optimal water content, the free water in the pores of soil particles gradually increases. Because the stabilizer is slightly hydrophilic, some physical-chemical reactions that occurred will absorb part of the free water which will lead to an increase in the optimal water content and a decrease in the maximum dry density due to the relative reduction of soil particles.

3.2. Effect of the Stabilizer Content on Soil Compressibility and Collapsibility. Figure 5 shows the compressibility relationship between the coefficient of compressibility (a₁₋₂) and the different contents of the stabilizers. It can be seen from the figure that when the content of the stabilizer content increases from 0% to 2.46%, the coefficient of compressibility decreases from 0.32 MPa to 0.08 MPa, respectively. Through curve fitting, it was observed that the compressibility
coefficient and the content of the stabilizers followed an exponential relationship ($R^2 = 0.98$). This suggested that the stabilizers could effectively reduce the compressibility of the loess, but this effect decreased with increasing the stabilizer content.

Figure 6 shows the curve of the collapsibility coefficient of the modified loess samples with different stabilizer content. It can be seen from the figure that when the content of the stabilizer content increases from 0% to 2.46%, the collapsibility coefficient decreases from 0.052 to 0.001, respectively. When the stabilizer content increased to 0.86%, the collapsibility coefficient decreased to 0.02; in this case, the modified loess samples exhibited almost no collapsibility. By further increasing the content of the stabilizers, the collapsibility coefficient value was less than 0.015, and the modified loess samples exhibited no collapsibility.

### Table 2: Contents of elements in the leaching solution of the modified loess.

<table>
<thead>
<tr>
<th>Element</th>
<th>Content (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.001</td>
</tr>
<tr>
<td>Zn</td>
<td>0.02</td>
</tr>
<tr>
<td>As</td>
<td>0.0015</td>
</tr>
<tr>
<td>Hg</td>
<td>0.00009</td>
</tr>
<tr>
<td>Pb</td>
<td>0.002</td>
</tr>
<tr>
<td>Cr</td>
<td>0.012</td>
</tr>
<tr>
<td>Fe</td>
<td>0.03</td>
</tr>
<tr>
<td>Mn</td>
<td>0.01</td>
</tr>
<tr>
<td>Al</td>
<td>0.008</td>
</tr>
</tbody>
</table>

### Table 3: Optimal water content and maximum dry density at different stabilizers contents.

<table>
<thead>
<tr>
<th>Number</th>
<th>Stabilizers’ content (%)</th>
<th>Optimal water content (%)</th>
<th>Maximum dry density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>15.05</td>
<td>1.82</td>
</tr>
<tr>
<td>2</td>
<td>0.46</td>
<td>15.46</td>
<td>1.81</td>
</tr>
<tr>
<td>3</td>
<td>0.86</td>
<td>15.50</td>
<td>1.80</td>
</tr>
<tr>
<td>4</td>
<td>1.26</td>
<td>15.70</td>
<td>1.80</td>
</tr>
<tr>
<td>5</td>
<td>1.66</td>
<td>16.58</td>
<td>1.79</td>
</tr>
<tr>
<td>6</td>
<td>2.06</td>
<td>17.01</td>
<td>1.78</td>
</tr>
<tr>
<td>7</td>
<td>2.46</td>
<td>17.78</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Figure 5: Testing data

\[ y = A_1 \times \exp \left(\frac{-x}{t_1}\right) + y_0 \]

- \( A_1 = 0.500 \)
- \( t_1 = 3.543 \)
- \( y_0 = -0.17 \)

\( R^2 = 0.96 \)

Figure 6: Collapsibility coefficient for different stabilizer contents.

### 3.3. Effect of the Stabilizer Content on Strength Measurements.

The shear strength of a material is described by a straight line called the failure envelope: \( \tau = c + \sigma \tan \theta \) (here, \( c \) and \( \theta \) are the cohesive force and internal friction angle, respectively). The relationship between the strength parameters and the content of the stabilizers is shown in Figure 7. It could be seen that the cohesion force, \( c \), increased with the increase in the content of the stabilizers. As the stabilizer content increased from 0% to 2.46%, the cohesion force \( c \), increased from 22.36 kPa to 42.14 kPa, respectively. The internal friction angle \( \theta \) increased rapidly in the early stage and gradually tended to be stable in the later stage; however, a decreasing trend was observed at 1.66%. In general, the shear strength of loess can be improved by adding stabilizers, but the effects tend to decrease with the increase in the content of the stabilizers.

The relationship between the unconfined compressive strength (UCS) of the samples and the different contents of the stabilizers is plotted in Figure 8. The results indicated that the unconfined compressive strength of the modified loess increased with the increase in the content of the stabilizers, and the greater the content of the
stabilizers, the higher the unconfined compressive strength. It was observed that the content of the stabilizers and UCS generally followed an exponential relationship ($R^2 = 0.96$), where $a$, $b$, and $k$ are the parameters obtained from the tests.

### 3.4. Determination of Mineral Composition

In Table 4, we have reported the specific mineral content determined by XRD. It was inferred that both the content of both SiO$_2$ and Al$_2$O$_3$ decreased, while the content of CaO increased after the soil of the loess was modified with the stabilizers. The SiO$_2$ content decreased from 40.31% to 37.71%, presenting a decrease of 2.60%. The powder and liquid components of the stabilizers formed hydrates with SiO$_2$ and Al$_2$O$_3$ in the loess, which in turn strengthened the loess. The strengthening mechanism in terms of the chemical reaction was similar to that observed for cement-modified loess. However, because the mineral compositions of the loess and modified soil are similar, the stabilizers have little impact on the mineral composition of the loess after strengthening.

### 3.5. Microstructure Characteristics of Modified Loess

The modified soil samples with different stabilizer contents were observed under the magnification of 2000 times by using a scanning electron microscope (SEM). From the overall observation of the image, the masked soil with 0% content has a relatively loose particle arrangement. From a structural point of view, it is relatively fragmented. There are uneven distributions, holes, and obvious cracks in the pattern, and there is no good cementation between the particles, as shown in Figure 9(a). Compared to the 0% modified soil sample, the number of holes and the width of the 0.86% modified soil sample are significantly reduced and the integrity of the sample is improved as shown in Figure 9(b). For the modified soil sample with the content of stabilizer of 1.66%, the number and width of holes and fissures are significantly reduced, cluster flake crystals appear in the sample, and only a few holes exist with high integrity as shown in Figure 9(c). In the modified soil sample with 2.46% curing agent content, the soil particles are arranged well, the number of holes and cracks is small, and the number of flake crystals are more uniform than that of the modified soil with 1.66% content as shown in Figure 9(d). In general, with the increase in the stabilizer content, the structural integrity of the modified loess increased, the porosity decreased, the attraction between particles became stronger, and the corresponding macro-compressive strength increased. The microstructure characteristics were consistent with the micromechanical...
Furthermore, it could be inferred from the microstructure of the loess sample that the stabilizers could enhance the microstructure of the soil, achieve uniform dispersion, and improve the impermeability and strength of loess.

3.6. Mercury Content, Pore Size Distribution, and Density of Different Stabilizer Contents. Figure 10 shows the cumulative mercury content (mg/L) of the loess samples modified with different stabilizer contents. It can be observed that the curve is well graded and the boundary is smooth, indicating that all pore sizes were within the detectable range. The cumulative pore volume of the modified loess decreased with the increase in the content of the stabilizers. This was mainly because the density of the modified loess was higher than that of the unmodified loess. After the loess was stabilized, a more stable loess structure was formed, which was in accordance with the SEM results discussed previously. This suggested that the increase in the content of the stabilizers resulted in a decrease in the pore volume and densification of the structure at the microscopic level, as well as an increase in the strength and an improvement in the mechanical properties at the macroscopic level.

Figure 11 shows the differential distribution of the pore sizes of the samples modified with different stabilizer contents. Three porosity groups were observed for the unmodified loess samples, whereas two groups were observed for the other samples. No intragranular pores could be found in the modified or unmodified loess samples ($d < 0.0054 \mu m$). The main porosity group comprised intergranular pores ($0.009–1.20 \mu m$) and agglomerated pores ($1.80–9.0 \mu m$). With the increase in the stabilizer content, the pore diameter of the aggregates decreased from 3.4 $\mu m$ (the

Table 4: Mineral composition.

<table>
<thead>
<tr>
<th>Stabilizer’s content (%)</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>Fe$_2$O$_3$</th>
<th>MgO</th>
<th>K$_2$O</th>
<th>Na$_2$O</th>
<th>Ti$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40.31</td>
<td>19.03</td>
<td>17.36</td>
<td>7.52</td>
<td>6.73</td>
<td>4.50</td>
<td>2.05</td>
<td>1.96</td>
</tr>
<tr>
<td>2.46</td>
<td>37.71</td>
<td>18.40</td>
<td>18.66</td>
<td>7.76</td>
<td>6.46</td>
<td>4.35</td>
<td>1.93</td>
<td>4.28</td>
</tr>
</tbody>
</table>

Figure 9: Microstructure characteristics of the modified loess (a) 0% (b) 0.86% (c) 1.66% and (d) 2.46%.
content of the modified loess was 0.86%) to 1.7 µm (the content of the modified loess was 2.46%), and the peak value also decreased from 0.14 to 0.08.

4. Conclusions

(1) The soil stabilizer of the Consolid system is an environmentally friendly material that can be used for the modification of the soil. After treatment, the optimal water content of the loess increased with increasing the stabilizer content, and the dry density decreased with increasing the stabilizer content. With the increase in the content of the stabilizers, both the coefficient of compressibility and the collapsibility coefficient of the loess decreased, and UCS exhibited an exponential relationship with the content of the stabilizers. The shear strength of the loess was enhanced. The friction angle started to decrease when the content of the stabilizers reached 1.66%.

(2) According to XRD analysis, the contents of SiO₂ and Al₂O₃ in the loess treated with the stabilizers decreased. The cumulative pore volume of the modified loess decreased with the increase in the content of the stabilizers, and a more stable soil structure could be formed after treatment.

(3) When the stabilizer content reached 0.86%, the modified loess exhibited almost no collapsibility. Furthermore, since this modified material is environmentally friendly, it can be applied for the treatment of loess slopes, where the use of the stabilizer-modified loess can be combined with biological measures.

Data Availability

The data used to support the findings of this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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