Effects of the pore water's pH value on the shear strength of the Loess

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Received 04 January 2017; revised 05 June 2017

Pore water plays an important part in the shear strength of the soils. A series of shear tests involved remolded loess which mixed with different chemical solutions were performed to investigate the effects of the pH values of the solution on the shear strength of the Loess. The results show that the pore water’s pH value has strong effects on the cohesive force of the loess, even on the grain size, while it has non-remarkable affection on the internal friction angle. When the loess is soaked in strong acid solutions, the cohesive force of the remolded soils will increase following the equilibrium time, while when the loess soaked in alkaline solutions, the cohesive force of the remolded soils will decrease.

[Keywords: Loess, pH value, cohesion, internal friction angle, pore water]

Introduction

Due to human activities and climate changes, the component and concentration of the interstitial water in the soils void are easily altered. Thus, the balance of the water and soil is broken by the variation of the pore water, and then the soil’s physical, chemical and mechanical properties are changed from the initial state. In that case, the pore water’s component and pH value are substantially affected by the external water’s infiltration. Previous research on the pore water’s transformation found that if the pore water’s pH value or the components influenced by the acid rain or the industrial pollution, the soils’ strength, compression, permeability even the stability change correspondingly. In previous works, acid solutions in the soil pore void improve the red clays’ shear strength and on the contrary the alkaline solutions make the red clay’s shear strength decreased. While in another study, the result is that the higher pH values the lower shear strength. Spagnol finds that when the solutions’ pH value changes, the kaolin and montmorillonite mixed clay’s undrained shear strength increases. Thus, it can be noted that the pore water’s chemical property is the important factor to the soil’s shear strength. Present study consists the variation of the loess’s internal friction angle and cohesive forces are tested in different infiltration time when the pore water’s pH value altered.

Materials and Methods

Loess, is a very typical silt in north of China, which is famous for its macro void and collapsibility. In the direct shear test, the loess is derived from the southern edge of the Loess Plateau, which is generated in the quaternary period. The powdery loess is brownish-yellow, and uniform texture. Specific gravity of the Loess is 2.70, and the undisturbed soil’s moisture content is 13.1%. In addition, the dry density of the natural Loess is 1.36g/cm³, and the void ratio is 0.98. The mine chemical composition of the loess is SiO₂, Al₂O₃, CaO, and Fe₂O₃. Other parameters of the Loess are shown in Table 1 & 2.

When the Loess is collected from the sampling site, the natural soils are ground to be powdered, and sieved by the 2 mm griddle. From the moisture-density test, the loess’s maximum dry density is 1.68g/cm³, and the optimum moisture content is 17.9%.

Five different pH value solutions are utilized to infiltrate the powdery loess. All the solutions are mixed by the chemical solution of the hydrochloric acid and sodium hydroxide. The distilled water is considered to be the standard solution, with a pH value of 7. And the pH value of 3 and 5 solutions are resulting from the hydrochloric acid and the pH value of 9 and 11 solutions are prepared by the sodium hydroxide.

All the farinose loess is drying by the oven under 105°C for more than 10h, and then incorporate with the 5 different solutions in order to attain the optimum
Table 1 — The physical and chemical parameters of the loess

<table>
<thead>
<tr>
<th>parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.70</td>
</tr>
<tr>
<td>Liquid limit, %</td>
<td>37.3</td>
</tr>
<tr>
<td>Plastic limit, %</td>
<td>20.5</td>
</tr>
<tr>
<td>Plastic index</td>
<td>16.8</td>
</tr>
<tr>
<td>Cohesion, kPa</td>
<td>41.5</td>
</tr>
<tr>
<td>Internal friction angle, °</td>
<td>18.0</td>
</tr>
<tr>
<td>Grain size composition</td>
<td></td>
</tr>
<tr>
<td>Sand, %</td>
<td>0.52</td>
</tr>
<tr>
<td>silt, %</td>
<td>69.41</td>
</tr>
<tr>
<td>clay, %</td>
<td>30.07</td>
</tr>
<tr>
<td>pH</td>
<td>8.19</td>
</tr>
<tr>
<td>Soluble salt, g/kg</td>
<td>0.54</td>
</tr>
<tr>
<td>Moderate soluble salt, g/kg</td>
<td>0.37</td>
</tr>
<tr>
<td>Insoluble salt, g/kg</td>
<td>125.4</td>
</tr>
<tr>
<td>Organic matter, g/kg</td>
<td>3.88</td>
</tr>
</tbody>
</table>

Table 2 — The chemical composition of the Loess, %

<table>
<thead>
<tr>
<th>parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>48.90</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.62</td>
</tr>
<tr>
<td>CaO</td>
<td>9.08</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>4.71</td>
</tr>
<tr>
<td>MgO</td>
<td>2.41</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.50</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.22</td>
</tr>
</tbody>
</table>

moisture content. Then all the remolded soils are retained in the corrosion-resistant plastic jars, which are sealed by the lid. When the soils are stored in the jars for a period of 1d, 5d, 10d, 20d, 30d, some of the soils are took from the jars to compact the shear samples. All the samples are made in the same size of 2 cm high and 6.18 cm diameters. The density of the wet samples is 1.9g/cm³. And the natural loess samples are also tested by the shear test.

Results and Discussion

Grain size components of the different soils are tested for the grain analysis when all the samples are soaked in different solutions for 30 days (Fig. 1). As shows in Fig. 1, the soil’s component changes obviously. The sand fraction has a distinct diminishment which is from 0.52% to 0.10% in the mean; on the contrary, the clay fraction has an evident augment from 30.07% to 32.06% in average. When the soils are infiltrated by acid or saline solutions, some of the colloid, free oxide and soluble salts, which are consisted of the natural soil, are easily dissolved in the water, and the ions on the particle surface hydrated, thus the original aggregates came to be decomposed. At the same time, if the soils are influenced by the alkaline solution, the hydroxyl in the alkaline solution would react with the cations, which speed up the particle decomposition. The increase of the Na⁺ ions in the solution would improve the diffusion layer thickness between the soil particles, and then the repulsive force would be greater than the attractive force, which is leading to the soil disperse. While in the acid solution, the carbonate in the loess would respond to the hydrochloric which is forming the soluble salts. As a result of the above reasons, the clay fraction increases while the sand fraction decreased.

Compared with the standard solution (pH=7), remolded soils in the acid solution has the smaller sand fraction and clay fraction, huge silt fraction nevertheless. When the pH value varies from 7 to 3, it means that pore water’s acidity fortify, the soils clay fraction decreases and the silts fraction increases. However, in the alkaline solution, the silt fraction is diminishing with the enhancement of the solutions alkalinity.

For the change of the pore water, the remolded soil’s shear strength parameters had been changed obviously. The internal friction angle and cohesion force of the remolded soil are presented in Fig. 2 & 3.

Compared with the undisturbed loess, the remolded soil’s shear strength, internal friction angle and cohesion, changed obviously for the variation of the pore water. After 30 days’ reaction, the internal friction angle and cohesive force of almost all the remolded soil samples are less than those of the untreated soil.

When the loess powder was soaked in the water, the soluble salts will first dissolve, and then the
cement between the particles would dissolve also. As a result of the dissolution, the surface of the soil particle is smoothed, and the pore voids between particles become bigger and bigger, which leads to reduced cohesion and internal friction angles. When the soils are soaked in the acid or alkaline solutions, the intergranular cementation material corroded, and a series of chemical reactions, such as hydration, dissolution and precipitation, were created, in that case the structural connection becomes weakened.

When immersed by the hydrochloric acid solution, the loess’s minerals, especially the calcareous cement will react with the HCl in the following equation:

\[
\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{H}_2\text{O} + \text{CO}_2 \uparrow \quad \ldots (1)
\]

\[
\text{CaO} + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{H}_2\text{O} \quad \ldots (2)
\]

The smaller pH value of the soaking solution means the higher quantity of the H\(^+\), the more fully dissolved in the soil, and the abundant particles in the sample were gradually reduced. At the same time, the Ca\(^{2+}\) cations precipitated from the aggregates, and a new electrolyte of CaCl\(_2\) is created in the solution. As a catalyst of the reinforcing loess, CaCl\(_2\) has the effect of rapid cementing. Therefore, when the low pH value hydrochloric acid solution react with the minerals in the loess, a large amount of CaCl\(_2\) will be produced. In that case, parts of particles are connected into aggregates, which lead to the soil internal friction angle bigger than the higher pH value of the acid solution.

When the soils were immersed by the alkaline solutions, the loess’s minerals, especially the calcareous cement will react with the NaOH in the following equation:

\[
2\text{NaOH} + \text{Ca}^{2+} \rightarrow 2\text{Na}^+ + \text{Ca(OH)}_2 \downarrow \quad \ldots (3)
\]

With a gradual increase of the pH value of the alkaline solution, the concentration of NaOH in the soil gradually increased, a large amount of Na\(^+\) ions entered into the particles’ fixed layer and the diffusion layers, weakened the soil’s original cohesive force, so that the particles adhered and swelled. In addition, some of the calcium bicarbonate formed in the soils.

Fig. 4 & 5 show the remolded loess’ internal friction angle and cohesive force in the different soaking time with the acid or alkaline solution.

Fig. 4 shows that there is no distinct difference in the internal friction angle for all the remolded soils. They all varied from 12.5\(^\circ\) to 18.7\(^\circ\). At the end of the 30 days’ equilibrium time all the soil’s friction angle is average.
14.6°, which is a little smaller than that of the natural soil. These observations suggest that the pH value of the solution in the pore water has unremarkable effects on the loess’ internal friction angle.

Compared with the internal friction angle of the soil, as showed in Fig. 3, the remolded soil’s cohesion is smaller than the natural soil which has the cohesive force of 41.5 kPa. At the end of the equilibrium time, all the samples’ cohesion was very close to 22.7 kPa, which was less than that of the natural soil.

When the immersed solution was the distilled water (Fig. 5), the soil’s cohesive force was very low at the first 10 days, with about 5 kPa. Then in the remaining equilibrium time, it increased quickly to be close to that of the other soils. When the soils were immersed with the alkaline solutions, in the first 10 days, the cohesion was more than 30 kPa, followed by a decrease with the increment of the equilibrium time. By contrast, when immersed by the strong acid solution, the soils’ cohesion was increased with the equilibrium time.

This can be explained in two ways. First, the undisturbed soil’s water content is 13.1%, while the remolded soil’s water content is 18.9%, higher than that of the natural soil. The shear strength of soil with high water content is lower than that of soil with low water content. Second, the chemical reaction between the minerals and solutions is the primary factor. As the calcareous cement dissolves in the acid solutions quickly, the cohesion decreases from 41.5 kPa to 8.39 kPa in the first day, and with more and more CaCl₂ appeared in the soil, which connected the soil particles, more aggregates formed. And then, the silt fraction increased, followed by an increment of the cohesive force. On the contrary, Na⁺ has the dispersion effect by changing the thickness of the electric double layer. The connection between particles disappeared, as showed in the result of the particle size analysis, the clay fraction are increased when the loess infiltrated in the alkaline solutions. Therefore, the remolded loess’ cohesive force would be reduced.

The results suggest that the cohesion and the friction angle of the loess are both affected by the pore water’s pH values. Moreover, with the chemical solution’s infiltration, the strength of all the remolded soils is reduced. The results show that there is no direct linear relationship between the strength and the pore water’s pH value in the long soaking possess. It is different from the observations in other works. We speculate that minerals difference between different soils may explain the difference. The reasons for these phenomena would be studied in future work.

Conclusions

This study investigated the effects of the acid and alkaline solutions on the loess’s shear strength. Soaking and direct shear tests were conducted and factors affecting the characteristics of the shear strength were discussed. The observations are summarized as follows:

1) Grain analysis test results show that all the acid and alkaline solutions lead decreased sand fraction, while for the fine fraction, acid solutions decrease the percentage of the fine fraction and the alkaline solutions increase the percentage of the fine fraction.

2) The results of direct shear tests show that the loess’s cohesion is significantly affected by the pore water’s pH value while the effect on the internal friction angle is not remarkable.

3) The reaction time of the loess and the chemical solution are important factors to the loess’s strength.

Acknowledgement

This research is financially supported by Yangling Science and technology project (2018NY-28) and National Natural Science Foundation of China (51409217), the Fundamental Research Funds for the Central Universities (2014YB047, Z109021538), and the Foundation of the China Scholarship Council.
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