Research Article

Effect of Chromium Ion on the Strength Characteristics and Damage Law of Red Clay

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As heavy metals invade the soil, they will continue to corrode the internal structure of the soil, expand the pores of the internal soil, and destroy the internal skeleton structure of the soil. The shear strength of the soil is reduced and the structure is damaged, causing the building to crack and deform. This research is aimed at analyzing the mechanical strength characteristics and damage discipline of red clay polluted by chromium ions. Taking Guilin red clay as the research object, the chromium pollution concentrations of 0%, 0.01%, 0.05%, and 0.1% contaminated soil were artificially configured indoors to conduct unconsolidated and undrained triaxial tests. The results reveal that chromium ions can destroy the original structure of the red clay. With the increase of chromium ion concentration, the deviatoric stress of red clay decreases. The downward trend is in the form of an exponential function. The deviator stress of red clay contaminated by a low concentration of chromium ions has a significantly decreasing trend. With the increase of the concentration, the deviator stress of red clay tends to decrease. Compared with unpolluted red clay, the contaminated red clay requires less axial pressure to produce the same deformation. The chromium ions in the polluted red clay increase the concentration of ions in the electrical double-layer structure of the soil particles and reduce the stiffness of the soil.

1. Introduction

Various studies in the field of geotechnical engineering in China are relatively complete, and many experts and scholars have achieved great results in this field [1–10]. Red clay is a kind of brown-red high-plastic clay, which is formed by a strong breeze based on carbonate rocks in subtropical warm and humid regions. Its liquid limit is equal to or greater than 50%. Sun et al. [11] and Wang et al. [12] stated the theory of acid-soluble residue accumulation and weathering in situ and believed that the difference of acid insolubles in bedrock is caused by the weathering of underlying carbonate rocks and the accumulation of acid insolubles in situ.

Anirudhan et al. [13] explored the adsorption and desorption mechanisms of heavy metal ions by clay through a large number of laboratory experiments. Chen et al. [14] found that the main factors affecting the migration of heavy metal ions are the pH value and the organic matter content in the soil. Rubin et al. [15] considered that the soil was polluted by heavy metal ions undergoing varying degrees of abnormality due to the mineral components in the soil under the action of heavy metals, which led to different degrees of swelling of the soil. Ratnaweera and Meegoda [16] observed that the shear strength of fine-grained soil is proportional to the concentration of heavy-metal pollution. Nayak et al. [17] simulated the impact of municipal solid waste landfill leachate on the compaction characteristics and hydraulic conductivity of red soil through indoor experiments. The results showed that the microscopic effective pore structure space and porosity of the soil increased after being contaminated. Huang et al. [18] reported that the first shear failure of red clay under triaxial stress was on the weak structural surface with the help of the CT technology. It can be seen from the stress-strain curve that the strength of red
clay increased with the increase of axial strain. Tan [19] assessed the strength index changes greatly before and after the intake value in the triaxial shear test with different confining pressures and different matrix suctions by the unsaturated triaxial system. When the matrix suction is greater than the intake value, there will be a trend of nonlinear changes. Wu et al. [20] observed that the sample had a tendency of brittle failure when the dry density of red clay continued to increase in the triaxial shear test using an unsaturated soil triaxial instrument. They indicated that the effective cohesion, effective internal friction angle, and suction friction angle increased with the increasing dry density. Wang et al. [21] indicated that the failure first occurred on the weak structural surface and then penetrated to form a shear failure surface under greater compressive stress. Nie et al. [22] observed that the maximum dry density of remolded soil is larger than that of undisturbed soil, while the optimal moisture content of remolded soil is lower than that of undisturbed soil. Ou et al. [23] observed that the shear strength indexes of red clay and expansive soil varied with different thermal conditions and the cohesion of red clay and the internal friction angle of expansive soil had smaller values in the room test. Ye et al. [24] reported that the ability of montmorillonite to adsorb chromium chelate was better than that of Cr$^{3+}$ because the adsorption of chelate was caused by electrostatic attraction, hydrogen bond, and van der Waals force. Lin et al. [25] observed that the pH value of the leaching solution had a greater impact on the number of heavy metals leached and the high pH values

<table>
<thead>
<tr>
<th>Physical properties of red clay.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural moisture content (%)</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>31.2</td>
</tr>
</tbody>
</table>

**Figure 1:** Dry density and moisture content curve of Guilin red clay.

**Table 1: Triaxial test plan.**

<table>
<thead>
<tr>
<th>Heavy metal ion</th>
<th>Concentration</th>
<th>Confining pressure (kPa)</th>
<th>Dry density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr$^{3+}$</td>
<td>0%</td>
<td>100, 200, 300, 400</td>
<td>1.35, 1.40, 1.45</td>
</tr>
<tr>
<td></td>
<td>0.01%</td>
<td>100, 200, 300, 400</td>
<td>1.35, 1.40, 1.45</td>
</tr>
<tr>
<td></td>
<td>0.05%</td>
<td>100, 200, 300, 400</td>
<td>1.35, 1.40, 1.45</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
<td>100, 200, 300, 400</td>
<td>1.35, 1.40, 1.45</td>
</tr>
</tbody>
</table>

**Figure 2:** TKA-TTS-1 triaxial instrument.
Table 3: The deviatoric stress of chromium-polluted red clay under different conditions.

<table>
<thead>
<tr>
<th>Sample state</th>
<th>Chromium ion concentration (%)</th>
<th>Initial dry density (g/cm³)</th>
<th>Deviator stress σ₁−σ₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.35</td>
<td>137</td>
<td>100 kPa</td>
</tr>
<tr>
<td></td>
<td>1.40</td>
<td>204</td>
<td>200 kPa</td>
</tr>
<tr>
<td></td>
<td>1.45</td>
<td>238</td>
<td>300 kPa</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>125</td>
<td>400 kPa</td>
</tr>
<tr>
<td>0.01</td>
<td>1.40</td>
<td>176</td>
<td>100 kPa</td>
</tr>
<tr>
<td></td>
<td>1.45</td>
<td>218</td>
<td>200 kPa</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>63</td>
<td>300 kPa</td>
</tr>
<tr>
<td>0.05</td>
<td>1.45</td>
<td>180</td>
<td>400 kPa</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>62</td>
<td>100 kPa</td>
</tr>
<tr>
<td>0.1</td>
<td>1.45</td>
<td>83</td>
<td>200 kPa</td>
</tr>
<tr>
<td></td>
<td>1.35</td>
<td>98</td>
<td>300 kPa</td>
</tr>
<tr>
<td></td>
<td>1.45</td>
<td>121</td>
<td>400 kPa</td>
</tr>
</tbody>
</table>

caused heavy metal precipitation to be adsorbed on the surface of the waste rock. Chu et al. [26] reported that the plasticity index of contaminated soil increased as the concentration of zinc ions increased. The compressibility increased and the shear strength of contaminated soil decreased with the increase of zinc ion concentration. Cha et al. [27] found that the content of soluble salt in the soil decreased with the increase of the concentration of heavy metals. After heavy metals invaded the soil, the cation exchange capacity decreased and it showed a downward trend as the concentration of heavy metals increased. Rao et al. [28] assessed that the strength index of contaminated soil was significantly lower than the shear strength index of remodeled pure soil. Chen et al. [29] indicated that the soil cohesion increased with the increase of pollutant concentration but the internal friction angle decreased with the increase of concentration. Tang et al. [30] found that as the content of adsorbed K⁺ and Cu²⁺ ions increased, the permeability coefficient of silty clay and modified soil increased. However, the impact on the permeability of modified soil was less than that of silty clay. Liu et al. [31] carried out a one-dimensional compression test and found that the void ratio and compression index of bentonite decreased as the Zn²⁺ concentration increased under the same pressure when the vertical pressure was lower than a certain critical value. Zhang et al. [32] reported that with the increase of Cu²⁺ concentration, the soil permeability coefficient firstly decreased and then increased. Cheng et al. [33] investigated that the deviator stress-strain curve and the strength of specimens with the same damage area but different damage locations were the same; the damaged area and variance can be used as damage variable characterization parameters. Chen et al. [34] established the linear relationship between the damage variable and the shear stress ratio and the elastic damage model by determining the method of damage variables and parameters based on the mean value of the CT number. Wang et al. [35] found that the overall damage variable evolution curve of the soil sample was linear and the damage development of each shear zone became faster and faster as the longitudinal strain increased. Zhao et al. [36] propose a dual-medium seepage damage model and noted that damage evolution is driven by the initiation and propagation of intermittent rock cracks. Song et al. [37] reported that the variables related to the initial elastic modulus and secant modulus can be used as damage variables through laboratory experiments.

Based on the previous research results, this study mainly investigates the influence of heavy-metal chromium pollution on the strength characteristics and stress-strain curve damage of red clay. Then, the effect of chromium ions on the damage of red clay is analyzed by the damage variable. This study provides a theoretical basis and technical support for future engineering practice.

2. Materials and Methods

2.1. Materials. Soil samples were collected from the upper 1-3 m surface at the s site located in the Yanshan district of Guilin city, Guangxi, China. The soil sample was air dried, crushed, and sieved through a 2 mm square sieve. The screened soil samples are prepared into soil samples with different moisture contents, and the soil is simmered for 24 hours, and then, the compaction test is carried out. Table 1 shows that the optimal moisture content is 30.2%, and Figure 1 shows that the maximum dry density is 1.57 g/cm³.

2.2. Test Instruments. The test is mainly based on the unconsolidated and undrained triaxial test of chromium-contaminated red clay. The TKA-TTS-1 triaxial instrument (TEKEAO Company, Nanjing) is used and can perform triaxial tests with different pore water pressures and different consolidation stress conditions. The test equipment is shown in Figure 2.

2.3. Test Program and Methods. The size of the standard triaxial test is φ 39.1 mm × 80 mm. The braised soil was taken out and divided into 6 layers according to the steps of the compaction method to prepare kinds of triaxial soil samples with different dry densities: 1.35 g/cm³, 1.40 g/cm³, and 1.45 g/cm³. Before the triaxial sample was loaded into the
Figure 3: Continued.
triaxial instrument, the soil sample was placed in a vacuum cylinder for 2 hours, and then, water was pumped into the cylinder by the air extraction saturation method and it was left to stand for 24 hours to fully saturate. In this triaxial test, the contaminated red clay samples under the same chromium ion concentration and the same dry density were tested under different confining pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa and the triaxial shear rate was taken as 0.8 mm/min. The test plan is shown in Table 2.

The materials and methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail, while well-established methods can be briefly described and appropriately cited.

Research manuscripts reporting large datasets that are deposited in a publicly available database should specify where the data have been deposited and provide the relevant accession numbers. If the accession numbers have not yet been obtained at the time of submission, please state that they will be provided during review. They must be provided before publication.

Interventional studies involving animals or humans and other studies that require ethical approval must list the authority that provides approval and the corresponding ethical approval code.

3. Strength Change Characteristics of Chromium-Polluted Red Clay

3.1. Effect of Chromium Pollution on Deviator Stress of Red Clay. The value of the deviator stress in the triaxial test can reflect the change in the mechanical strength of the soil. This paper selects the deviatoric stress ($\sigma_1 - \sigma_3$) corresponding to 20% soil strain in the unconsolidated and undrained triaxial test results as the peak deviatoric stress of the soil. Table 3 shows the peak deviatoric stress of the chromium-contaminated red clay under different initial dry densities, different chromium ion concentrations, and different confining pressures without consolidation and undrained triaxial shear tests.

3.2. Effect of Confining Pressure on Deviatoric Stress of Chromium-Contaminated Red Clay. Unconsolidated and undrained tests of 100 kPa, 200 kPa, 300 kPa, and 400 kPa
Figure 4: Continued.
confining pressure were carried out on red clay with the same initial dry density and the same chromium pollution concentration to study the deviatoric stress variation of chromium-polluted red clay under different confining pressures. The variation of deviatoric stress of chromium-contaminated red clay under different confining pressures is shown in Figure 3.

It can be seen that the deviatoric stress of red clay increased as the confining pressure increased under the same initial dry density and chromium pollution concentration, because insufficient radial restraint force leads to insufficient compaction of the soil, larger volume deformation, and Poisson’s ratio and less work was needed for the axial stress to overcome soil dilatancy, resulting in a decrease in deviatoric stress under low confining pressure. As the confining pressure increased, the red clay was compacted by the surrounding liquid (simulating the surrounding soil), the volume deformation and Poisson’s ratio became smaller, and the axial pressure becomes larger. As an elastoplastic material, the strength of soil is closely related to the pressure exerted by the surrounding soil. On the one hand, as the radial pressure increases, the soil needs to do more work to overcome the dilatancy and the normal stress of the shear surface also increases, causing the friction of the soil particles on both sides of the shear surface to increase. The increase in radial pressure will compact the soil, squeeze the pores of the soil particles, convert the adsorbed water between the soil particles into free water, reduce the thickness of the adsorbed water film, and improve the cohesive force. On the other hand, according to the generalized Hooke’s law, the increase of radial pressure will inevitably cause the decrease of Poisson’s ratio and soil volume deformation. To achieve shear failure of the soil, the axial pressure will increase accordingly.

3.3. Effect of Chromium Ion Concentration on Deviator Stress of Red Clay. The undrained and undrained triaxial test of red clay with different chromium ion concentrations under the same initial dry density and confining pressure was carried out to study the strength change of the red clay under different chromium pollution concentrations. It can be seen in Figure 4 that the fitting function of deviator stress with dry density is $y = a + b \times \exp(-c \times x)$.

With the increase of chromium ion concentration, the deviator stress of red clay decreases. Its downward trend takes the form of an exponential function. In the curve of an initial dry density of 1.45 g/cm³ and confining pressure of 300 kPa and 400 kPa, the deviator stress of red clay contaminated with a low concentration of chromium ion decreases significantly. With the increase of concentration, the deviator stress of red clay tends to decrease. It shows that a small number of chromium ions can have a great influence on the strength of red clay. Under high dry density and high consolidation stress, the effect of chromium ions on the mechanical properties of red clay is more significant than that of dry density and consolidation stress. After chromium ions invade the red clay, it increases the ion concentration of the red clay soil, destroys the electric double-layer structure of the soil particles, increases the thickness of the public absorption water film, and reduces the cohesive force of the soil particles of the red clay. On the other hand, the ion exchange capacity of chromium ions is greater than that
of aluminum ions and silicon ions in clay minerals and will undergo substitution reactions with clay minerals and soluble salt cementing substances, destroying the soil skeleton structure and soluble salt cementing structure and making the red clay sticky. Cohesion and friction are reduced.

3.4. Effect of Initial Dry Density on Deviator Stress of Red Clay. According to Table 3, the relationship curve between initial dry density and deviatoric stress is shown in Figure 5. The deviator stress of red clay under the same confining pressure and chromium pollution concentration increases with the increase of the initial dry density. With the increase of the initial dry density, the deviatoric stress curve becomes smoother and smoother under the same confining pressure and the downward trend of the curve segment after 0.01% concentration becomes less and less obvious, especially in the case of high confining pressure. Obviously, this shows that the higher the dry density of the red clay, the ability to resist chromium ion damage is stronger than that of the low-density red clay.

The reason for the limited effect of chromium ions on the high-dry density red clay: for the undisturbed red clay, after chromium ions invade the red clay, due to the high compactness, the specific surface area of the framework structure formed by the soil particles is small and the area where the chromium ions can contact the soil particles is...
small; the chromium ions can only damage the surface of the framework and some framework structures with fragile structures and larger pores. For the remodeled red clay, the intrusion of chromium ions increases the thickness of the adsorbed water film, which converts free water into adsorbed water. After mixing with the red clay, it attracts the surrounding soil particles to form aggregates with low cohesive force and fragile structure. The free water surrounding the particles is encased in the pellets. The high-density red clay needs to undergo stronger compaction, which makes the aggregate structure formed by chromium ions and soil particles compressed, and the absorbed water wrapped inside the aggregate is squeezed out so that the soil particles on the outer layer of the aggregate absorb the thickness of the water film. The soil particle cohesive force and friction bite force are recovered.

In summary, the confining pressure, chromium ion concentration, and initial dry density will affect the strength of red clay. With the increase of chromium ion concentration, the decrease in the strength of red clay is obvious. With the increase of the initial dry density, the downward trend of the deviatoric stress curve of chromium-contaminated red clay slows down. In high density and high confining pressure, the influence of chromium ions on the strength of red clay is smaller than that of low density and low confining pressure. It can also be seen that the deviatoric stress of the red clay with a single influencing factor changes clearly, but under the interactive influence of multiple factors, the law becomes complicated. To further study the influence of chromium ion concentration, dry density, confining pressure, and their interaction on deviatoric stress, a multifactor analysis of variance was carried out.

3.5. Variance Analysis of the Influence of Various Factors on the Deviator Stress of Chromium-Contaminated Red Clay

To further study the influence of chromium ion concentration, dry density, confining pressure, and their interaction on the deviator stress of chromium-contaminated red clay, a multifactor analysis of variance was carried out to quantify the influence of the interaction effects of various factors and factors on the deviator stress degree. A multifactor analysis is used to analyze the influence of various influencing factors on the peak deviator stress by SPSS22.0. Without considering the influence of interaction effects, the peak deviator stress data in Table 4 was calculated. It is stipulated that the significance level is less than E-8 as strong (impact level I), significance greater than E-8 and less than 0.001 (impact level II), and significance greater than or equal to 0.001 weak (impact level III). The variance analysis table of the degree of influence of the influencing factors on the peak deviator stress is shown in Table 5.

It can be seen that the influence of chromium ion concentration and initial dry density on the peak deviator stress is level I and the influence of confining pressure on the peak deviator stress is level II without considering the influence of the interaction effect. It shows that the influence of chromium ion concentration and initial dry density on the change of peak deviator stress is greater than that of confining pressure.

<table>
<thead>
<tr>
<th>Initial dry density (g/cm³)</th>
<th>Confining pressure (kPa)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kPa</td>
<td>54.78</td>
<td>86.79</td>
<td>33.67</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>200 kPa</td>
<td>46.44</td>
<td>109.90</td>
<td>19.76</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>300 kPa</td>
<td>57.27</td>
<td>108.57</td>
<td>20.74</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>400 kPa</td>
<td>102.83</td>
<td>67.15</td>
<td>43.96</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>100 kPa</td>
<td>75.16</td>
<td>131.58</td>
<td>31.54</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>200 kPa</td>
<td>102.84</td>
<td>183.58</td>
<td>65.89</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>300 kPa</td>
<td>126.68</td>
<td>187.07</td>
<td>60.81</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>400 kPa</td>
<td>116.92</td>
<td>187.15</td>
<td>27.56</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>100 kPa</td>
<td>137.53</td>
<td>98.91</td>
<td>17.60</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>200 kPa</td>
<td>73.91</td>
<td>210.16</td>
<td>8.39</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>300 kPa</td>
<td>251.98</td>
<td>80.01</td>
<td>181.41</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>400 kPa</td>
<td>284.50</td>
<td>121.50</td>
<td>235.69</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

If the interaction effect is considered, the variance analysis table of the influence degree of each influencing factor and the interaction effect between the factors on the peak deviator stress is shown in Table 6. It can be seen that level II is the significance of the interaction effect between the chromium ion concentration and the initial dry density level I is the significance of the interaction effect between chromium ion concentration and the confining pressure c and the interaction effect between the initial dry density b and the confining pressure c. The interaction effect between the chromium ion concentration and the initial dry density has a higher degree of influence on the peak deviator stress than the other two interaction effects. It can be known that the influence of chromium ion concentration, initial dry density, confining pressure, and the interaction between them on the deviator stress is as follows: chromium ion concentration, initial dry density > confining pressure, chromium ion concentration, initial dry density interaction effect chromium interaction effect ion concentration and confining pressure, and the interaction effect of initial dry density and confining pressure.

4. Investigation on the Mechanics’ Damage Law of Chromium-Contaminated Red Clay

4.1. Determination and Analysis of Initial Deformation Modulus

The deformation modulus is an important index to evaluate the ability of soil to resist elastic deformation. There are many methods for selecting the initial deformation modulus. In this paper, the Duncan-Chang nonlinear elastic hyperbolic model is used to fit the stress-strain curve of chromium-contaminated red clay and its parameters are used as the initial deformation modulus. The hyperbolic fitting formula is as follows:

\[ \sigma_1 - \sigma_3 = \frac{e_a}{a + be_a}. \]

Only hyperbolic fitting is performed on the typical stress-strain curve in the triaxial test. The data of different
dry densities and corresponding confining pressures which is 100 kPa or 300 kPa were selected to do a treatment. The $\varepsilon_1/(\sigma_1 - \sigma_3) - \varepsilon_u$ curve of chromium-contaminated red clay under different dry density conditions is obtained and shown in Figure 6. Table 7 shows the hyperbolic fitting parameter table under different dry densities and confining pressure of 300 kPa.

The initial deformation modulus ($E_i$) is the reciprocal of the intercept ($a$), and $(\sigma_1 - \sigma_3)_{ult}$ is the reciprocal of slope ($b$). It can be seen in Figure 6 that as the chromium ion concentration increases, the slope and the intercept gradually increase. It can be seen in Table 7 that the $E_i$ and $(\sigma_1 - \sigma_3)_{ult}$ are on an opposite trend with the increase of chromium ion concentration. It shows that the intrusion of chromium ions has an impact on the elastic modulus of the soil. After chromium ions invade the red clay, it increases the ion concentration of the electric double-layer structure of the red clay particles. The $\text{Ce}^{3+}$ ion exchange capacity is greater than $\text{Al}^{3+}$, so the common absorption water film between the soil particles becomes thicker and the aluminum ions are replaced by the chromium ions in the clay minerals, destroying the cemented structure in the soil, resulting in its strength being lower than uncontaminated red clay under the same load, and the deformation modulus decreases.

### Table 5: Variance analysis table of the degree of influence of each influencing factor on the peak deviator stress (without considering the interaction effect).

<table>
<thead>
<tr>
<th>Origin</th>
<th>Type 3 sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>The value of $F$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium ion concentration $a$</td>
<td>105118.73</td>
<td>3</td>
<td>35039.58</td>
<td>36.40</td>
<td>Level I</td>
</tr>
<tr>
<td>Initial dry density $b$</td>
<td>158814.29</td>
<td>2</td>
<td>79407.15</td>
<td>105.15</td>
<td>Level I</td>
</tr>
<tr>
<td>Confining pressure $c$</td>
<td>40270.56</td>
<td>3</td>
<td>13423.52</td>
<td>17.78</td>
<td>Level II</td>
</tr>
<tr>
<td>Error</td>
<td>29452.40</td>
<td>39</td>
<td>755.19</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sum</td>
<td>1967219.00</td>
<td>48</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

### Table 6: Variance analysis table of the degree of influence of each influencing factor on the peak deviator stress (taking into account the interaction effect).

<table>
<thead>
<tr>
<th>Origin</th>
<th>Type 3 sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>The value of $F$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium ion concentration $a$</td>
<td>105118.73</td>
<td>3</td>
<td>35039.58</td>
<td>150.64</td>
<td>Level I</td>
</tr>
<tr>
<td>Initial dry density $b$</td>
<td>158814.29</td>
<td>2</td>
<td>79407.15</td>
<td>341.38</td>
<td>Level I</td>
</tr>
<tr>
<td>Confining pressure $c$</td>
<td>40270.56</td>
<td>3</td>
<td>13423.52</td>
<td>57.71</td>
<td>Level II</td>
</tr>
<tr>
<td>$a \times b$</td>
<td>13096.71</td>
<td>6</td>
<td>2182.79</td>
<td>9.38</td>
<td>Level II</td>
</tr>
<tr>
<td>$a \times c$</td>
<td>3521.35</td>
<td>9</td>
<td>391.26</td>
<td>1.68</td>
<td>Level III</td>
</tr>
<tr>
<td>$b \times c$</td>
<td>8647.38</td>
<td>6</td>
<td>1441.23</td>
<td>6.20</td>
<td>Level III</td>
</tr>
<tr>
<td>Error</td>
<td>4186.96</td>
<td>18</td>
<td>232.61</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sum</td>
<td>1967219.00</td>
<td>48</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

4.2. Determination and Analysis of Strain Threshold and Secant Modulus. In the stress-strain curve, the turning point of the curve indicates the beginning of damage, that is, the initial damage point and the corresponding strain is the strain threshold. For chromium-contaminated red clay, the strain turning point is generally about 2% of the axial strain. This paper selects the three-axis test data of 100 kPa and 300 kPa at different dry densities to process the corresponding strain thresholds, as shown in Table 8.

It can be seen in Table 8 that after the addition of chromium ions, the strain thresholds of different dry densities show different situations. At a dry density of 1.35 g/cm$^3$, the strain threshold of red clay added with chromium ions is reduced but the increase of chromium ion concentration in the contaminated soil does not affect the strain threshold. At a dry density of 1.40 g/cm$^3$, the threshold of uncontaminated red clay is the same as that of contaminated red clay and there is no change. At a dry density of 1.45 g/cm$^3$, the strain threshold shows a downward trend with the increase of chromium ion concentration. From the perspective of the overall threshold change, the addition of chromium ions cannot provide sufficient bite force and friction between particles, resulting in its strength being lower than uncontaminated red clay under the same load, and the deformation modulus decreases.

The initial deformation modulus ($E_i$) is the reciprocal of the intercept ($a$), and $(\sigma_1 - \sigma_3)_{ult}$ is the reciprocal of slope ($b$). It can be seen in Figure 6 that as the chromium ion concentration increases, the slope and the intercept gradually increase. It can be seen in Table 7 that the $E_i$ and $(\sigma_1 - \sigma_3)_{ult}$ are on an opposite trend with the increase of chromium ion concentration. It shows that the intrusion of chromium ions has an impact on the elastic modulus of the soil. After chromium ions invade the red clay, it increases the ion concentration of the electric double-layer structure of the red clay particles. The $\text{Ce}^{3+}$ ion exchange capacity is greater than $\text{Al}^{3+}$, so the common absorption water film between the soil particles becomes thicker and the aluminum ions are replaced by the chromium ions in the clay minerals, destroying the cemented structure in the soil, resulting in its strength being lower than uncontaminated red clay under the same load, and the deformation modulus decreases.
Figure 6: Continued.
Figure 6: Continued.
Figure 6: The $\varepsilon_a/(\sigma_1 - \sigma_3) - \varepsilon_a$ curve of different dry densities. (a) The initial dry density is 1.35 g/cm$^3$, 100 kPa. (b) The initial dry density is 1.35 g/cm$^3$, 300 kPa. (c) The initial dry density is 1.40 g/cm$^3$, 100 kPa. (d) The initial dry density is 1.40 g/cm$^3$, 300 kPa. (e) The initial dry density is 1.45 g/cm$^3$, 100 kPa. (f) The initial dry density is 1.45 g/cm$^3$, 300 kPa.
which causes the pores of the soil to increase and the pore ratio to increase.

The secant modulus is the ratio of stress to strain on the stress-strain curve. The secant modulus is calculated by the ratio of the stress and strain after the strain threshold of the chromium-contaminated red clay with a confining pressure of 100 kPa and 300 kPa at different dry densities. The axial strain-secant modulus curve is obtained, as shown in Figure 7. Then, the secant modulus curves are fitted by the fitting curve \( y = a - b \times \exp(-x/c) \). The fitting parameter is shown in Table 9.

It can be seen in Figure 8 that the secant modulus decreases with the increase of axial strain and the slope of the secant modulus tends to be gentle with the increase of deformation. In the initial stage of compression of red clay, there are macroscopic and microscopic pores in the soil. The application of load destroys the bite force and cohesive force between the particles, forcing the particles to rotate horizontally or downwards around the surrounding soil particles. The pores are beginning to be filled with particles, and a small axial pressure causes large deformation of the soil. As the pores are filled and become denser, the secant modulus of the red clay becomes smaller and smaller. Compared with the initial stage, the same pressure causes less deformation.

The analysis of Figure 8 shows that as the chromium ion concentration increases, the secant modulus under the same deformation gradually decreases. It means that the contaminated red clay requires less axial pressure than uncontaminated red clay to produce the same deformation. The ion concentration of the electric double-layer structure of the soil particles and the thickness of the adsorbed water film is increased by the chromium ions in the red-stained clay. The cemented structure is destroyed, and the bonding force and frictional bite force between the particles are weakened. The soil particles form fragile aggregates with high-ion concentration clusters as the core, and the secant modulus decreases. It can also be seen in Figure 8 that as the concentration of chromium ion increases, the slope of the secant modulus becomes smaller and smaller and the secant modulus becomes increasingly prone to "weakness.”

4.3. Determination and Analysis of Damage Variables. The damage variables can be used to analyze the damage pattern of unpolluted red clay and polluted red clay. The decline of soil stiffness is usually caused by damage. Therefore, the damage state can be described by the change in modulus. In this paper, the damage variables of chromium-contaminated red clay under confining pressure of 100 kPa and 300 kPa at different dry densities were calculated using the conventional triaxial damage variable calculation formula: \( D = 1 - (E_1/E_0) \) and deformation modulus, secant modulus, and strain threshold calculated in the previous section. The relationship curve between the damage variable and axial strain is shown in Figure 8.

It can be seen in Figure 9 that the damage variable increases with the increase of the axial strain and the damage variable curve gradually tends to be flat, showing exponential growth. The damage variables can reflect changes in soil stiffness. When the red clay is compressed, the friction and bite force between the particles are destroyed by the axial pressure. The particles in the middle of the soil sample rotate

<table>
<thead>
<tr>
<th>Dry density (g/cm³)</th>
<th>Chromium ion concentration (%)</th>
<th>( a )</th>
<th>( b )</th>
<th>( E_t )</th>
<th>( (\sigma_1 - \sigma_3)_{ult} )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
<td>1.410</td>
<td>0.550</td>
<td>70.922</td>
<td>181.818</td>
<td>0.989</td>
</tr>
<tr>
<td>0.05</td>
<td>0.1</td>
<td>2.814</td>
<td>0.890</td>
<td>35.534</td>
<td>25.252</td>
<td>0.969</td>
</tr>
<tr>
<td>0</td>
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<td>1.270</td>
<td>25.024</td>
<td>21.978</td>
<td>0.973</td>
</tr>
<tr>
<td>0</td>
<td>0.05</td>
<td>0.655</td>
<td>0.280</td>
<td>152.74</td>
<td>357.143</td>
<td>0.981</td>
</tr>
<tr>
<td>0</td>
<td>0.1</td>
<td>0.889</td>
<td>0.410</td>
<td>112.465</td>
<td>243.902</td>
<td>0.985</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>1.322</td>
<td>0.620</td>
<td>75.645</td>
<td>161.29</td>
<td>0.976</td>
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<tr>
<td>0</td>
<td>0.05</td>
<td>2.707</td>
<td>0.820</td>
<td>36.942</td>
<td>121.951</td>
<td>0.977</td>
</tr>
<tr>
<td>0</td>
<td>0.1</td>
<td>0.430</td>
<td>0.290</td>
<td>232.558</td>
<td>344.828</td>
<td>0.993</td>
</tr>
<tr>
<td>0.01</td>
<td>0.05</td>
<td>0.698</td>
<td>0.340</td>
<td>143.21</td>
<td>294.118</td>
<td>0.985</td>
</tr>
<tr>
<td>0.01</td>
<td>0.1</td>
<td>0.890</td>
<td>0.350</td>
<td>112.36</td>
<td>285.714</td>
<td>0.991</td>
</tr>
<tr>
<td>0.01</td>
<td>0.05</td>
<td>1.076</td>
<td>0.410</td>
<td>92.923</td>
<td>243.902</td>
<td>0.981</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial dry density (g/cm³)</th>
<th>Chromium ion concentration (%)</th>
<th>100 kPa threshold</th>
<th>300 kPa threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
<td>1.830</td>
<td>1.774</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>1.830</td>
<td>1.774</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>1.834</td>
<td>2.134</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>1.834</td>
<td>2.021</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>1.834</td>
<td>2.134</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>2.113</td>
<td>2.334</td>
</tr>
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<td>0.01</td>
<td>0.05</td>
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<td>1.83</td>
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<tr>
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<td>0.05</td>
<td>1.771</td>
<td>2.137</td>
</tr>
<tr>
<td>0.1</td>
<td>0.01</td>
<td>1.609</td>
<td>1.666</td>
</tr>
</tbody>
</table>

Table 7: Hyperbolic fitting parameter table of different dry densities and confining pressures of 300 kPa (\( a \times 10^{-2}, b \times 10^{-2} \)).

Table 8: Strain threshold of chromium-contaminated red clay under different conditions (%).
Figure 7: Continued.
Figure 7: Continued.
horizontally or downwards around the surrounding particles, so that the volumetric strain of the red clay grows negatively, resulting in dilatancy. The soil has become denser, and the stiffness and deformation modulus of the soil has become bigger.

It shows that chromium ions have a reduced effect on the damage variables of red clay. As the chromium ion concentration increases, the damage variable gradually decreases. It can be seen from the foregoing that for uncontaminated red clay, its initial deformation modulus is higher than that of contaminated red clay. At the same time, the secant modulus during the shear test is also higher than that of the contaminated red clay. According to the formula $D = 1 - (E_t/E_0)$, it can be seen that when the ratio of the secant modulus to the initial deformation modulus increases, the damage variable will decrease. It shows that the ratio of the secant modulus to the initial deformation modulus of the uncontaminated red clay is lower than that of the contaminated red clay. The intrusion of chromium ions into the red clay increases the ion concentration of the soil, increases the thickness of the absorbed water film, and destroys the cemented structure of the soil. The initial deformation modulus and the secant modulus after the strain threshold are not only reduced but the gap between the initial deformation modulus and the secant modulus becomes larger and larger and the damage variable becomes smaller and smaller. It can also be seen in Figure 9 that expecting the chromium ion concentration, dry density, and confining pressure will also affect the damage of chromium-contaminated red clay.

4.4. Effect of Dry Density and Confining Pressure on the Damage of Red Clay Contaminated by Chromium. Using the formula $D = 1 - (E_t/E_0)$ and the previously calculated deformation modulus, secant modulus, and strain threshold, the damage variable value of the chromium-contaminated red clay can be calculated. The final damage variable parameter table of the confining pressure 300 kPa at the dry densities of 1.40 g/cm$^3$ and 1.45 g/cm$^3$ and the damage variable curve under different confining pressures at 1.45 g/cm$^3$ are shown in Figure 9 and Table 10. The damage variable of uncontaminated red clay increased significantly with dry density, and the damage variable of contaminated red clay increased with a dry density as much as that of unpolluted red clay.

It can be seen in Table 10 that the damage variables of uncontaminated red clay and contaminated red clay both increase with the increase of dry density. Because as the dry density of the soil increases, the red clay becomes increasingly dense, the pores in the soil become less and less, the cementation of soluble salt and the adhesion between particles increase, and the initial soil rigidity is strengthened.

<table>
<thead>
<tr>
<th>Initial dry density (g/cm$^3$)</th>
<th>Chromium ion concentration (%)</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.35 0 0%</td>
<td>0.84618 1.48798 2.86753 0.98512</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01 0.01%</td>
<td>0.85456 1.57224 2.64597 0.99179</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05 0.05%</td>
<td>0.84951 1.36064 2.89306 0.98316</td>
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<td></td>
</tr>
<tr>
<td>0.1 0.1%</td>
<td>0.84441 1.32597 3.00917 0.98937</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 0%</td>
<td>0.85554 1.25288 3.12261 0.98821</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.40 0 0%</td>
<td>0.84773 1.44205 2.83284 0.9903</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01 0.01%</td>
<td>0.86551 1.52642 2.66317 0.99127</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.05 0.05%</td>
<td>0.81775 1.7455 2.16494 0.98624</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 0.1%</td>
<td>0.85129 1.51821 2.87628 0.99247</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01 0.01%</td>
<td>0.83059 1.05911 3.6175 0.99408</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0.05 0.05%</td>
<td>0.82304 1.53438 2.58447 0.99304</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 0.1%</td>
<td>0.78967 1.46989 2.47203 0.99275</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: The relationship between secant modulus and axial strain at different dry densities. (a) The initial dry density is 1.35 g/cm$^3$, 100kPa. (b) The initial dry density is 1.35 g/cm$^3$, 300 kPa. (c) The initial dry density is 1.40 g/cm$^3$, 100 kPa. (d) The initial dry density is 1.40 g/cm$^3$, 300 kPa. (e) The initial dry density is 1.45 g/cm$^3$, 100 kPa. (f) The initial dry density is 1.45 g/cm$^3$, 300 kPa.
However, during the shearing process of red clay, as the adhesion and friction between particles are destroyed by pressure, the soil gradually loses its structural properties. Although the secant modulus has been improved with the increase of dry density, compared with the initial deformation modulus, its growth is not as significant as the initial deformation modulus. The ratio of the initial deformation modulus becomes larger and larger, and the damage variable becomes larger. As the ratio to the initial deformation modulus becomes larger and larger, the damage variable becomes

![Figure 8: Comparison curves of damage variables under different chromium ion concentrations. (a) The initial dry density is 1.45 g/cm³, 100 kPa. (b) The initial dry density is 1.45 g/cm³, 300 kPa.](image)
smaller and smaller. On the other hand, the ion concentration of the soil, the thickness of the absorbed water film, and the adhesion between the particles are increased and irreversibly destroy the soluble salt cementation of the red clay because of the intrusion of chromium ions. Although the increased dry density improves the stiffness of the red clay macroscopically, the adhesion and occlusion between the particles in the soil have not been effectively improved, resulting in the change of the damage variable of the polluted red clay under the change of dry density and no unpol-luted red. The clay is remarkable.

It can be seen in Figure 9 that the damage variable increases with the increase of the confining pressure under the same axial deformation of the contaminated red clay and the uncontaminated red clay. In the conventional triaxial test, the increase of confining pressure makes the red clay become compacter, the volume deformation and Poisson’s ratio are reduced, and the bulk modulus is improved. To
overcome the dilatancy, more work needs to be done. The axial pressure becomes larger, the axial deformation modulus is improved, and the overall stiffness of the red clay rises. However, the increase in pressure destroys the cohesive force and bite force between soil particles, the plastic deformation of the red clay becomes larger and larger, and the structure gradually loses. The increase of the confining pressure can make the initial deformation modulus increase, but the increase of the secant modulus after the corresponding threshold is not as significant as the initial deformation modulus, which makes the damage variable larger.

5. Conclusions

(1) Chromium ion has an obvious destructive effect on red clay. With the increase in the concentration of chromium ions, the deviator stress of red clay reduces. The downward trend takes the form of an exponential function. The low concentration of chromium in polluted red clay has a significant downward trend. As the concentration increases, the deviator stress of red clay tends to decrease. A small number of chromium ions can have a great influence on the strength of red clay, but the effect of chromium ions on the mechanical properties of red clay is more significant than those of the dry density and consolidation stress of the red clay under higher dry density and consolidation stress. Through the variance analysis of the influence of chromium ion concentration, dry density, and confining pressure on the deviatoric stress, it is concluded that the influence of chromium ion concentration and initial dry density on the change of deviatoric stress is greater than the confining pressure.

(2) The Duncan-Chang nonlinear elastic hyperbolic model is used to fit the stress-strain curve to obtain its initial deformation modulus. It is found that with the increase of chromium ions, the initial deformation modulus $E_i$ of red clay shows a decreasing trend. After the chromium ions invade the red clay, the cemented structure in the soil is destroyed and the thickness of the adsorbed water film is increased, which reduces the bonding force between the soil particles, and the particles gather around the chromium ions to form fragile aggregates. When the soil is under load, its fragile aggregate structure cannot provide sufficient bite force and friction between particles, resulting in its strength being lower than that of uncontaminated red clay under the same load, and the initial deformation modulus decreases.

(3) With the increase of chromium ion concentration, the damage variable of red clay gradually decreased. The intrusion of chromium ions made the initial deformation modulus and the secant modulus reduce after the strain threshold, and the gap between the initial deformation modulus and the secant modulus became larger and smaller, and the damage variable became smaller and smaller. The damage variables of uncontaminated red clay and contaminated red clay increased with the increase of dry density. Under the same axial deformation of contaminated red clay and uncontaminated red clay, the damage variable increased with the increase of confining pressure. The increase of the confining pressure can increase the initial deformation modulus, but the increase of the secant modulus after the corresponding threshold was not as significant as the initial deformation modulus, which made the damage variable larger and larger.

Data Availability

Data supporting the results of our study are in the article.

Conflicts of Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgments

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