The stress-strain properties of the cement stabilized/solidified chromium contaminated soils eroded by sodium chloride

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ABSTRACT

The groundwater always rich in corrosive ions such as sulfate and chloride in coastal or industry developed regions. Exposing to the corrosive groundwater environment could cause the secondary contamination of the cement solidified/stabilized heavy metal contaminated soils. Corrosive ions may change the deformation behaviors of the solidified soils by binding into the cement binders. To investigate the stress-strain properties of the cement stabilized/solidified chromium contaminated soils that had been soaked in the sodium chloride solution, a series of triaxial stress-strain tests were performed. The results showed that the stress-strain curve of the specimens included three phases: ① Elastic deformation; ② Plastic yield deformation; ③ failure-deformation. Both the failure stress and failure strain increased with the confining pressure increased. The presence of corrosive caused the failure stress decrease and the slope of the stress-strain curve in failure-deformation stage decline. Compared with the short-time soaking specimens, the failure stress increased and the failure strain decreased of the long-time soaking specimens. Generally, the stress-strain curves of the specimens presented strain softening, and belonged to brittle failure.

Keywords: chloride, solidified/stabilized, heavy metal contaminated soil, stress-strain properties

1 INTRODUCTION

Stabilization/solidification is one of the most widely used methods for remediation of heavy metal contaminated soils[1,2]. It can not only enhance the strength of soils but lower the mobility of the heavy metals[3,4]. While the solidified soils are exposed to the groundwater that involves sulfate and chloride, secondary contamination would take place. The presence of corrosive ions may attack the cement hydration products, and lead to a strength loss as well. Deformation behaviors of the solidified soils can be influenced by binding saline ions into the cement binders.

Theoretical and experimental studies on the mechanical properties of cement solidified soils and concrete attacked by inorganic salt have been carried out by many researchers[5,7]. Fan et al. [8] reported that as the chloride concentration increased, unconfined compressive strength of soil-cement decreased and stress-strain curves convert into plastic failure from fragile failure. Xing et al.[9] concluded that failure yield stress and failure strain decreased with the increase of chlorides concentration as well as the unconfined compressive strength of the cement solidified soils. Korkmaz et al.[10] investigated the effect of magnesium sulfate on the concrete and found that both magnesium ions and sulfate ions significantly influenced the concrete engineering properties. Chen et al.[6,11] argued that sulfate attack could damage the concrete structures by converting cement hydration products to gypsum, and so on. Zhang et al.[12] studied the expansion of concrete under attack of sulfate and sulfate-chloride ions. The results indicated that specimens eroded by sulfate appeared macro-cracking, while the phenomenon was diminished with the addition of chloride ions. Aye et al.[13] proved that surface hardness of Portland cement mortar decreased with the number of cycles increased by drying and wetting test based on sulfate solution. After 28 cycles, cracking or spalling occurred on the Portland cement mortar. Zhang et al.[14]...
deemed that the negative effect of salt on the cement soils directly refers to the salt concentration and cement content. Currently, most of the studies are focused on the effects of corrosive ions on the properties of concrete or cement solidified soils, while the stabilized/solidified heavy metal contaminated soils under attack of corrosive ions are scarcely studied. Therefore it is necessary to investigate the properties of it for improving the stability of the solidified soils.

In the present paper, the deformation behaviors of the solidified trivalent chromium contaminated soils immersed in pure water, chloride solutions with different chloride concentrations were investigated. Based on the experimental obtained results, the effects of the confining pressure, chloride concentrations and soaking time on the deformation behaviors were proposed.

2 MATERIALS AND METHODS

2.1 Materials

The soil sample was collected from a construction site in Hefei, China at 3-5 depth, which is cohesive clay. The basic physics parameters and the compositions of the clay specimen are listed in Table 1 and 2 respectively. The other materials include slag Portland cement, trivalent chromium and sodium chloride. Table 2 also presents the compositions of slag Portland cement.

Table 1 Basic physics properties of tested soil

| Water content/% | Density / (g/cm³) | Specific gravity | Liquid limit /% | Plastic limit/% | Optimum moisture content /% | Maximum dry density / (g/cm³) |
|----------------|------------------|------------------|-----------------|----------------|-----------------------------|-----------------------------|
| 22.0           | 1.952            | 2.706            | 48.6            | 25.1           | 18.28                       | 1.752                       |

Table 2 The chemical composition of tested soil and cement (%)

| Compositions | CaO   | SiO₂  | Al₂O₃ | SO₃  | Fe₂O₃ | MgO  | TiO₂  | Na₂O  | others |
|--------------|-------|-------|-------|------|-------|------|-------|-------|--------|
| soil         | 1.425 | 69.378| 16.00 | 0    | 7.100 | 1.752| 0.590 | 1.347 | 2.405  |
| cement       | 58.014| 22.267| 8.878 | 1.047| 3.794 | 3.633| 1.304 | 0.205 | /      |

2.2 Methods

(1) Proportion

The specimens were obtained artificially by mixing with cement to attain cement content of 10% and 15% dry weight of soil, and subsequently mixing with 0.1% Cr(NO₃)₃·9H₂O. Four different solutions contained 0, 5, 10 and 15% sodium chlorides were used in the tests.

(2) Specimens preparation

The soil and slag Portland cement were oven-dried at 105℃ for 24 hours, and then pulverized. The soil was screened with a 2mm sieve, and cement was screened with a 0.5mm sieve. Preparing chromic nitrate solution by blending the predetermined mass of chromium(III) into pure water that calculated based on the optimum moisture content. According to the proportion, mixing the soil and cement uniformly, then the chromic nitrate solution was added to the mixture. Pressing the mixture into a cylinder molds based on maximum dry density. The samples were cured in a laboratory, where temperature and humidity were kept at about 22℃ and 97%, respectively for 28 days.

(3) Test procedure

The cured specimens were immersed vertically in the prepared sodium chloride solutions for 0, 7, 28 and 90 days. After that the triaxial compression tests were conducted on the specimens.

3 RESULTS AND DISCUSSIONS

3.1 Effects of confining pressure on the stress-strain curves characteristics

Fig.1 presents the influence of confining pressure on the triaxial stress-strain curves characteristics of the cement solidified soils Cr(III)-contaminated. The specimens were immersed in the 15 %-sodium chloride solution for 28 days.

![Fig.1 Effects of confining pressure on the stress-strain curves](image_url)

It can be seen that the deformation process can divide into three stages: ① elastic deformation; ② plastic yield deformation; ③ failure deformation. In the
first stage, the stress development with strain can be approximately expressed as linear variation. The slope of the linear segment increases with the confining pressure increases. The deformation can recover if the pressure is removed. In the second stage, the stress continues to increase as the strain increases, but appears as non-linear variation. The deformation cannot recover any more. When the stress exceeds the failure stress, the deformation enters into the last stage, failure deformation. Both of failure stress and failure strain increase as the confining pressure increases, while the stress obviously reduces with the strain increases after the specimens destroyed. The type of failure of the specimens is brittle failure.

### 3.2 Effects of NaCl concentration on the stress-strain curves characteristics

The triaxial compression test was conducted on the cement solidified contaminated soils under 300kPa confining pressure, which were immersed in the solutions with different NaCl concentrations for 28 days. The stress-strain curves are shown in Fig.2.

![Stress-strain curves](image)

**Fig.2** Effects of NaCl concentration on the stress-strain curves

It can be seen that the stress increases significantly with the strain increases. Before the strain attain to about 1.2% for specimens with 10% cement and 1.5% for specimens with 15% cement, the relationship between strain and stress can be expressed as linear variation. The slope of the linear segment decreases as the NaCl concentration increases. While the strain exceeds 1.2% (or 1.5% for specimens contained 15% cement), cracks emerge in the specimens. The deformation turns into the plastic yield stage. The sustaining increased strain causes cut-through of the cracks and slows down the growth rate of stress until achieves the failure stress. And the failure stress decreases as the concentration increases. After the specimens destroy, the gradient of the failure curves decreases with the NaCl concentration increases.

Xing et al. [9] analyzed based on the laboratory tests that the quantity of cement hydration products would reduce with the content of chloride increased. Because of chloride could react with tricalcium aluminate, and produced $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot3\text{CaCl}_2\cdot3\text{H}_2\text{O}$ that without gelatification. The reactions are shown as follows,

$$\text{Ca(OH)}_2 + 2\text{NaCl} \rightarrow \text{CaCl}_2 + 2\text{Na}^+ + 2\text{OH}^-$$

$$3\text{CaO} \cdot \text{Al}_2\text{O}_3 + 3\text{CaCl}_2 + 3\text{H}_2\text{O} \rightarrow 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCl}_2 \cdot 3\text{H}_2\text{O}$$

Some calcium ions and aluminium hydroxide participate in the process, therefore the formation of $\text{C-S-H}$ and $\text{Ca}_6\text{Al}((\text{SO}_4)_2(\text{OH})_2\cdot26\text{H}_2\text{O}$ are curried. Aggrandizing the NaCl concentration could accelerate the reaction, reduce the quantity of hydration products, and weaken the cementation among the soil particles. As a result, the compactness of soil structure declines and offering space for the movement of soil particles. Therefore, the soil particle gathered gradually under the action of axial stress. Due to the compact structure, when the stress reaches to the failure stress, particles have to bypass the nearby soil particles of them would move. Result in the destruction of the soil structure. So the stress decreases obviously after the soil failure.

Fig.2 also shows that the failure strain increases slightly with the NaCl concentration increases. It can be attributed to the erosion effects of chloridion on solidified soils. Chloridion could react with cement matrix by penetrating to the solidified soils. Consequently, the formation of $\text{Ca}_3\text{Al}((\text{OH})_6\text{Cl}(\text{H}_2\text{O})_2$ which structure is loose reduces the density of specimens. Otherwise, this matter can reduce the cementation of hydration products and prevents solidified soils particles from closing up by enveloping $\text{C-S-H}$, $\text{C-A-H}$ and sheeting clay mineral [9]. Thus deformation resistance of the specimens immersed in the 15% NaCl solutions is worse than the specimens immersed in the lower concentration solutions.

### 3.3 Effects of soaking time on the stress-strain curves

After the cement solidified soils were immersed in the 15% NaCl solutions for 0, 7, 28 and 90 days, the triaxial stress-strain curves were obtained as presented in Fig.3.

Fig.3 shows that the slope of stress-strain curves in the elastic deformation stage and the failure stress of the specimens eroded both increase and the failure strain decreases with the soaking time increases, besides the specimens immersed for 7 days. It is well known that cement generally requires 24 hours to hydrolyze. In the process of hydration, some cement particles might be enveloped by the hydration products. In a short term (immersed for 7 days), the progress of
hydration reaction is restrained, because the enveloped cement particles are difficult to contact with pore water. Otherwise, some hydration products such as CSH and CAH may be dissolved due to the corrosion of chloride. As a result, the degree of density of the solidified soils structure would reduce. Furthermore, the sodium ions in the soaking solutions can penetrate into the pore water of the specimens, so that the sodium ions concentration in the pore water increases. It hinders calcium ions from exchanging with sodium or potassium ions according to enhance the thickness of double electrode layer. The pozzolanic reaction is deferred. 

As the soaking time exceeds 7 days, the corrosion of chloride is still sustaining. The hydration products cover on the surface of the cement particles are dissolved gradually based on the corrosion of chloride. Some cement particles enveloped are released, and take part in the hydration reaction and gelation reaction. A mass of hydraulic and cementitious materials are generated, which contribute to improving strength and density of the contaminated soils.

Fig. 3 Effects of soaking time on the stress-strain curves

**4 CONCLUSIONS**

The effect of sodium chloride solutions on the deformation behaviors of the Cr(III)-contaminated soils solidified with cement were investigated by the triaxial stress-strain tests. The main results are shown as follows:

The stress-strain curves of the specimens include three phases: ① Elastic deformation; ② Plastic yield deformation; ③ Failure-deformation.

Both the failure stress and failure strain increase with the confining pressure increases. The slope of the linear segment increases as the confining pressure increases.

Increasing chloride concentration causes decrease of the slope of the linear segment and the failure stress. After the specimens destroyed, the gradient of the failure curves decreases with the NaCl concentration increases.

Comparing with the short-time soaking specimens, the failure stress increases and the failure strain decreases for the long-time soaking specimens.

The stress-strain curves of the specimens are strain softening, and belongs to brittle failure.

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