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Microfabric change of electro-osmotic stabilized bentonite

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ABSTRACT

Electro-osmotic stabilization has long been studied as a soft soil improvement technique, while the influence of an applied electrical field on the soil microfabric and minerals is always ignored. In this study, three laboratory experiments were conducted on sodium bentonite using copper, iron and graphite electrodes to investigate the microfabric and chemical composition change before and after electro-osmotic stabilization. The soil samples near the anode were identified using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). The microfabric of the sodium bentonite changed from flocculated fabric to aggregated fabric after electro-osmotic stabilization. Regular calcium sulfate tubes were generated near the copper and iron anodes. EDX tests showed that the content of sodium near the anode decreased, while the copper, iron and calcium presented substantial increase, indicating that the sodium ions were substituted by copper, iron, and calcium ions in copper, iron and graphite experiments respectively. The change of microfabric and the ion exchange reactions between sodium, copper, iron and calcium ions are the main reasons for the significant decrease of the plasticity index and free swelling ratio.

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1. Introduction

Electro-osmotic stabilization is a widely studied method for soft soil improvement (Casagrande, 1948; Bjerrum et al., 1967; Esrig, 1968; Casagrande, 1983; Shang and Lo, 1997; Hu et al., 2012; Wu and Hu, 2013; Hu and Wu, 2014). The pore water is dragged from anode to cathode by the mobilizable cations under electrical field. Numerous laboratory tests and field experiments have been conducted to investigate the stabilization effect on soil mass in terms of water discharge, voltage distribution, current, pore water pressure, settlement and shear strength (Lo and Ho, 1991a; Micic et al., 2001; Lefebvre and Burnotte, 2002; Cherepy and Wildenschild, 2003; Burnotte et al., 2004; Reddy et al., 2011; Hu et al., 2013). The drainage and consolidation process were the major concerns in the above studies. Both the laboratory tests and field experiments illustrated the change of geotechnical properties, including Atterberg limit, swelling potential, and cation exchange capacity, after electro-osmotic stabilization (Bjerrum et al., 1967; Esrig and Gemeinhardt, 1967; Casagrande, 1983; Lo and Ho, 1991b; Bergado et al., 2000; Micic et al., 2001; Asavadorndeja and Glawe, 2005; Ou et al., 2009; Abdullah and Al-Abadi, 2010). Most of the previous studies simply attributed the change of soil properties to the increase of salinity. During the electro-osmotic stabilization process, complex chemical reactions occurred near the anode and cathode, including electrolysis of pore water, electrode corrosion, ion exchange and transport, and

cementation (Acar and Alshawabkeh, 1993; Chien et al., 2009). Therefore, the microfabric and chemical compositions changed and induced the change of soil properties (Zimmie and Almaleh, 1976; Du et al., 1999; Santamarina et al., 2001; Dananaj et al., 2005; Mitchell and Soga, 2005; Al-Hamdan and Reddy, 2008; Yong et al., 2009; Karakaya et al., 2011; Zhang et al., 2012; Du et al., 2014). Dananaj et al. (2005) studied the influence of sodium and calcium contents on the coefficient of permeability and swelling parameters of bentonite. Du et al. (2014) reported the microfabric characteristics of cement-stabilized zinc-contaminated kaolin, which showed that the change of soil microfabric and zinc concentration had significant influence on soil properties including Atterberg limits and stress–strain characteristics.

The purpose of this paper is to study the change of soil microfabric and chemistry before and after electro-osmotic stabilization, accounting for the micro-mechanism of geotechnical property change. Scanning Electron Microscopy (SEM) was used to identify soil microfabric, and Energy Dispersive X-ray Spectroscopy (EDX) test was performed to analyze the change of chemical composition during the electro-osmotic stabilization process.

2. Material and experiments

Sodium bentonite with Na⁺ as predominant exchangeable cation was used for the electro-osmotic stabilization experiments. The bentonite was obtained from Zhangjiakou, Hebei Province, China. The basic geotechnical properties and chemical composition of the sodium bentonite was summarized in Table 1. The Atterberg limits, free swelling ratio and cation exchange capacity of the sodium bentonite were

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Table 1
Basic geotechnical properties and chemical composition of the sodium bentonite.

Properties	Values
Geotechnical properties	
Specific gravity, G_s	2.625
Initial water content, w (%)	1.33
Liquid limit, LL (%)	155
Plastic limit, PL (%)	31
Plasticity index, PI (%)	124
Specific surface area, S (m^2/g)	33.89
Free swelling ratio, FSR (%)	540
Cation exchange capacity, CEC (meq/100 g soil)	40.03
pH (after saturated with deionized water)	9.4
Chemical composition (weight proportion, %)	
SiO ₂	68.2
Al ₂ O ₃	15.1
CaO	4.2
MgO	3.8
Fe ₂ O ₃	3.1
Na ₂ O	2.9
K ₂ O	1.6
SO ₃	0.4
TiO ₂	0.4
Cl	0.08

detected according to the Chinese Standard for Specification of Soils (SL237-1999), and the specific surface area was measured according to the ISO 9277-1995. The high values of plasticity index (124%) and free swelling ratio (540%) of the sodium bentonite indicate particularly high content of smectite. The presence of K₂O indicates the existence of illite. The sodium bentonite contains 2.9% of Na₂O and 1.6% of K₂O and this implies that the bentonite possesses a great water adsorption capacity (Al-Mukhtar et al., 2010). This is also confirmed from the high plasticity index and free swelling ratio. A small amount of SO₃ is identified in the bentonite. The cation exchange capacity was 40 meq/100 g, which means that strong ion exchange reaction may occur during the experiment.

Three soil column tests for electro-osmotic stabilization were conducted using copper, iron and graphite as anode respectively. The diameter and height of the bentonite samples are 90 mm and 200 mm, respectively. The anode was placed on the bottom, and the cathode was placed on the top of the bentonite sample, to induce an electro-osmotic flow from the bottom upwards. The bottom boundary was impervious and the top boundary was permeable for the drainage of pore water. After the fill and compaction of bentonite, the samples were saturated by deionized water with vacuum saturation method and the initial water content was 150%. A voltage of 20 V was applied to the soil samples and lasted for about 24 h.

Before and after the electro-osmosis treatment, the soil near the anode was carefully taken out and desiccated by freeze-drying method to maintain the microfabric. The SEM and EDX tests were then performed using the field emission scanning electron microscope (JSM 6301F, JEOL, Japan).

3. Results and discussion

3.1. Change of the microfabric

The results of SEM and EDX tests before and after electro-osmotic stabilization were presented in Fig. 1. Fig. 1(a) showed the SEM image of bentonite before electro-osmotic stabilization. The microfabric was characterized by large amounts of flocculus formed after the sample was immersed into the deionized water during the saturation period. These flocculi greatly increased the interaction between the soil and water. After electro-osmotic stabilization, the flocculated fabric changed

to aggregated fabric, and the soil aggregates were clearly visible in Fig. 1(b), Fig. 1(c) and Fig. 1(d). This phenomenon has also been observed by adding sodium nitrate electrolyte to bentonite (Stawinski et al., 1990). Compared to the flocculated fabric, the aggregated fabric is denser and possesses smaller void ratio (Mitchell and Soga, 2005), which is easier for water to enter into the clay with flocculated fabric than the clay with aggregated fabric. As a result, the water adsorption capacity of the bentonite with aggregated fabric is smaller than the bentonite with flocculated fabric.

Some well-formed regular tubes were found in the bentonite near the anode in the copper and iron experiments as shown in Fig. 2, while in the graphite experiment, a similar phenomenon was not observed. The chemical composition and formation of the tube was analyzed in the next section.

3.2. Change of chemical composition

Table 1 illustrated that the main elements in the bentonite were silicon, aluminium, oxygen with relatively less calcium, magnesium, iron, sodium, potassium, sulfur, titanium and chlorine. During the electro-osmotic stabilization process, complex oxidation reactions occur at the copper and iron anodes and induce the release of copper and iron ions from the anode into the bentonite. Therefore, EDX tests were performed to measure the content of elements that originally existed in the bentonite as well as elements that released from the anode. Fig. 1 displayed the full scale EDX results on the corresponding SEM images. The comparison of the element content before and after electro-osmotic stabilization was demonstrated in Fig. 1(e). The content of the predominant exchangeable cation, Na⁺, almost decreased to 0 in the copper and iron experiments and another cation, Ca²⁺, increased about 4 times near the copper anode and 1.5 times near the iron anode. In the graphite experiment, the content of Na⁺ only decreased about 15% while the Ca²⁺ content increased about 8.5 times. The content of other elements, such as Mg, Al, Si, and K, decreased while the content of S and Cl increased. The significant change of chemical elements was also reported by Acar and Alshawabkeh (1993), indicating that significant species transport processes under electric field consisted of mass fluxes generated by diffusion, electromigration and electro-osmosis, among which the ionic migration was the most significant component. Therefore the change of the content of Na, Mg, K, S and Cl was mainly induced by electromigration under the applied electric field.

Fig. 1(e) also illustrated that the content of copper increased from 0 to about 32.7% near the copper anode and the content of iron increased from 3.3% to about 22.4% near the iron anode. The significant increase of the copper and iron contents is due to the oxidation reaction near the anode, leading to the release of metal ions from the anode into the soil. The iron content in graphite experiment, nevertheless, decreased about 52% under the effect of electromigration.

Clay minerals have the characteristic of adsorbing cations and retaining them in an exchangeable state (Bradl, 2004). Replacement of cation may occur between different cations and the ease of the replacement depends mainly on the valence, hydrated radius of cation and relative abundance (Mitchell and Soga, 2005). Mitchell and Soga (2005) also reported that if other things were equal, divalent cations were held more tightly than monovalent cations and they showed a typical exchange series as Na⁺ < Li⁺ < K⁺ < Rb⁺ < Cs⁺ < Mg²⁺ < Ca²⁺ < Ba²⁺ < Cu²⁺ < Al³⁺ < Fe³⁺ < Th⁴⁺. According to the exchange abilities of different cations, the sodium ion in the double layer has the priority to be exchanged by the entering copper and iron ions and original calcium ion. The change of the element content in Fig. 1(e) revealed that the original sodium ions in the bentonite were replaced by the copper and iron ions in the

Fig. 1. SEM images and chemical composition of the bentonite before and after electro-osmotic stabilization: (a) before electro-osmotic stabilization (magnification $\times 2000$), (b) after electro-osmotic stabilization by copper electrode (magnification $\times 2000$), (c) after electro-osmotic stabilization by iron electrode (magnification $\times 2000$), (d) after electro-osmotic stabilization by graphite electrode (magnification $\times 1000$), and (e) comparison of element content in the bentonite before and after electro-osmotic stabilization.

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