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Research paper

# Electro-osmotic enhancement of bentonite with reactive and inert electrodes

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Electro-osmosis can be a potential improvement technique for expansive soils. One-dimensional column experiments were conducted to comprehend the impact of electro-osmosis on the consolidation behavior and the geotechnical properties of a sodium bentonite with different electrode materials, including two reactive electrodes (copper and iron) and two inert electrodes (graphite and stainless steel). The change in drainage rate, electric current and voltage loss close to the anode were similar for the four electrodes, with a rapid change stage in the first 2 h followed by a slow change stage in the next 6 to 8 h and finally a stable stage. The rapid voltage loss in the first stage was caused by soil cracking near the anode due to severe volume shrinkage and gas generation. Soil properties, including plasticity, swelling potential, zeta potential, and cation exchange capacity decreased emarkably in the vicinity of the anode. During electro-osmosis, the reactive electrodes caused more significant change in soil properties than the inert ones. Electro-osmosis technique can reduce the swelling potential of the bentonite, however, the zone of influence is restrained.



## 1. Introduction

Electro-osmosis is an electrically induced process in which pore water is driven from the anode to the cathode with the dissolved electrolytes, leading to dewatering and consolidation of soil or other porous media. Casagrande (1948) made use of this phenomenon to consolidate soft soil and enhance the geotechnical properties for engineering purposes. Since then, electro-osmosis has been successfully employed for soft ground improvement, slope stabilization, dewatering of tailings and sludge, pile foundation and soil remediation (Casagrande, 1983; Lo and Ho, 1991; Reddy and Saichek, 2002; Glendinning et al., 2007; Jones et al., 2008; Chien et al., 2009; Lamont-Black and Weltman, 2010; Cameselle and Reddy, 2012; Hu et al., 2012; Wu and Hu, 2013; Hu and Wu, 2014).

The strength of soil is enhanced as a result of two processes: the discharge of pore water and the complex chemical reactions including water electrolysis, electrode corrosion, cation exchange and cementation under the influence of an electric field. These chemical reactions are expected to alter the geotechnical properties of the soils. Previous studies reported the change in Atterberg limits for different soils after electro-osmosis (Bjerrum et al., 1967; Esrig and Gemeinhardt, 1967; Casagrande, 1983; Lo and Ho, 1991; Bergado et al., 2000; Micic et al., 2001; Asavadorndeja and Glawe, 2005; Ou et al., 2009; Abdullah and Al-Abadi, 2010). However, their conclusions were different or even contradictory when different kinds of soils were tested. The results on illitic clay and soft Bangkok clay indicated that both the liquid limit and the plastic limit increased, while marine clay exhibited no change in neither the liquid limit nor the plastic limit during electro-osmosis (Bjerrum et al., 1967; Esrig and Gemeinhardt, 1967; Lo and Ho, 1991; Bergado et al., 2000; Micic et al., 2001). Both the clay mineral category and the content have considerable influences on soil behavior during electro-osmosis. Most of the previous electro-osmosis experiments were conducted on kaolinite or local soft clay, while studies on expansive soils that usually contain large amounts of expansive clay minerals (especially smectite) were rarely reported. Expansive soils are characterized by severe swelling and shrinkage due to change in water content, which may lead to significant volume change and result in deformation of overlying buildings or pavements. Electro-osmosis may be a potential technique to improve expansive soils since the soil plasticity is changed during this process.

The main objective of this paper was to study the impact of electro-osmosis on the consolidation behavior and the geotechnical properties of a sodium bentonite, which has similar characteristics (high swelling and low permeability) and components (smectite) as expansive soil. One-dimensional column experiments were conducted on the sodium bentonite with reactive (copper and iron) and inert (graphite and stainless steel) electrodes in order to analyze the effect of different electrode materials. During the experiments, water discharge, electric current and voltage distribution along the soil column were monitored. A camera was used to observe the behavior of the soil–anode interface.

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After the experiments, soil samples taken from different positions of the soil column were prepared for geotechnical property tests, including plasticity index, free swelling ratio, zeta potential, and cation exchange capacity.

## 2. Materials and experiments

### 2.1. Materials

A sodium bentonite from the city of Zhangjiakou in Hebei Province of China was used for electro-osmosis experiments. The geotechnical properties and the chemical composition of the material are summarized in Table 1. The high plasticity index (124%) and free swelling ratio (540%) indicate that the sodium bentonite possesses remarkable swelling and shrinkage characteristics. The dominant $Na^+$ cation, as reflected by the 2.9 wt.% $Na_2O$, is the main reason for the high swelling potential. The specific surface area is 33.89 $m^2$/g, and the cation exchange capacity is 40.03 meq/100 g.

### 2.2. Experiment apparatus

Fig. 1 displayed the details of the 1-D column apparatus used in this study. The testing cell was made of 5 mm thick plexiglass, and had an inside diameter of 90 mm and a height of 250 mm. The wall was equipped with two pipes for inflow and outflow of water. The upper pipe was used for outflow of discharged water due to electro-osmosis. The lower pipe was used for inflow of deionized water during the sample saturation period and was sealed with glass cement to achieve an impervious bottom boundary before the test began. The anode platen was placed on the bottom of the soil column, while the porous cathode platen was placed on the top. The thickness of the electrode was 3 mm and more details about the cathode were illustrated in Fig. 1. Small holes with a radius of 0.5 mm were drilled on the cathode platen so that the discharged water could pass through. Particularly 8 circular grooves, 0.5 mm in depth and 2 mm in width, and a vertical groove, 2 mm in width, were slotted on the cathode to lead the discharged water to the drainage pipe. The depth of the vertical groove was designed to be gradational and increased from 0.5 mm on the left side to 1.5 mm on the right side. The discharged water can flow because of gravity to the right side of the vertical groove, which was aimed at the drainage pipe.

Six voltage probes were inserted into the bentonite column through the small holes on the testing cell. The probes were marked as V1, V2, V3, V4, V5, and V6, which had a distance of 10 mm, 46 mm, 82 mm, 118 mm, 154 mm, and 190 mm to the cathode, respectively. V1 and V6 were placed in the vicinity of electrodes so that the voltage loss close to the electrodes could be measured. In addition, a camera was applied during the experiments in order to investigate the behavior of soil–anode interface.

Previous studies indicated that the drainage and consolidation behavior was different when different electrode materials were used during electro-osmosis (Lockhart, 1983; Bergado et al., 2000; Mohamedelhassan and Shang, 2001). In order to study the effect of electrode materials on the electro-osmotic enhancement of bentonite, four types of electrodes were used including two reactive electrodes (copper and iron) and two inert electrodes (graphite and stainless steel).

**Table 1**
Geotechnical properties and chemical composition of the sodium bentonite.

| Properties | Values |
|---|---|
| Geotechnical properties | |
| Specific gravity, *Gs* | 2.625 |
| Initial water content, *w* (%) | 1.33 |
| Liquid limit, $w_L$ (%) | 155 |
| Plastic limit, $w_P$ (%) | 31 |
| Plasticity index, $I_p$ (%) | 124 |
| Free swelling ratio, *FSR* (%) | 540 |
| Cation exchange capacity, *CEC* (meq/100 g) | 40.03 |
| Zeta potential, $\zeta$ (mv) | −36.05 |
| Chemical composition (weight proportion, %) | |
| $SiO_2$ | 68.2 |
| $Al_2O_3$ | 15.1 |
| CaO | 4.2 |
| MgO | 3.8 |
| $Fe_2O_3$ | 3.1 |
| $Na_2O$ | 2.9 |
| $K_2O$ | 1.6 |
| $SO_3$ | 0.4 |
| $TiO_2$ | 0.4 |
| Cl | 0.08 |

### 2.3. Sample preparation

A porous stone was placed on the bottom of the testing cell to prevent the bentonite from being pressed out. The anode platen was then placed upon the porous stone. The bentonite powder was first mixed with deionized water at a pre-determined water content of 10 wt.% before compacted in the column by five layers. After that, the compacted bentonite was saturated by vacuum method to achieve an initial water content of 150 wt.%. The cathode platen, along with a filter paper, was placed upon the bentonite sample.

### 2.4. Experiment program

A constant voltage gradient of 100 V/m was applied to the bentonite samples for 24 h. After the experiments, soil samples from different locations of the bentonite column were prepared for subsequent physical and chemical analysis, including the determination of Atterberg limits, free swelling ratio, and cation exchange capacity (Chinese Specifications of Soil Testing, SL237-1999). The zeta potential was measured with a Beckman DelsaNano C zeta potential instrument at a constant pH of 6.5.

## 3. Results and discussion

### 3.1. Water discharge and electric current

The water discharge and drainage rate for the four electrodes were displayed in Figs. 2 and 3. The total volume of the discharged water was 69 ml, 47.5 ml, 30 ml, and 26 ml for the copper, iron, graphite, and stainless steel electrodes respectively. The copper electrodes accounted for the best drainage performance while the stainless steel electrodes accounted for the worst.

The initial drainage rate for the four electrodes was approximately 34 ml/h, and three stages afterwards for water drainage were observed (Fig. 3). In the first 2 h (Stage 1), the drainage rate decreased rapidly to less than 5 ml/h. This was followed by a slow decrease stage (Stage 2) in the next 6 to 8 h and afterwards a stable stage (Stage 3). Fig. 4 showed the real time electric current through the bentonite columns during the experiments. In the first half hour, the electric current increased slightly due to the presence of salt precipitates that went into the solution, as well as the desorption and mobilization of ions in the soil matrix (Mitchell and Soga, 2005; Yukselen-Aksoy and Reddy, 2012; Cameselle and Reddy, 2013). Afterwards, the change in electric current was similar to that in drainage rate, with a rapid decrease stage (Stage 1) where the initial values of around 0.3 to 0.35 A were decreased to 0.12, 0.08, 0.03, and 0.03 A for the copper, iron, graphite, and stainless steel electrodes respectively. There after a slow decrease stage (Stage 2) followed in which the electric current further decreased to 0.05, 0.02, 0.01, and 0.01 A and finally a stable stage (Stage 3) was reached. Figs. 3 and 4 indicated that the copper electrodes had the largest drainage rate and electric current. The reactive electrodes exhibited a larger electric current and therefore a better drainage effect than the inert electrodes.