Effect of electrode material on electro-osmotic consolidation of bentonite

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ABSTRACT

Electrode material has significant influence on the behavior of soil during electro-osmotic consolidation. Four electro-osmotic consolidation experiments on a sodium bentonite were conducted with copper, iron, graphite and stainless steel electrodes. The result indicated that the copper electrodes achieved the best drainage performance. The change in drainage rate, current and voltage loss near the anode was similar for the four electrodes, with a rapid change stage in the first 2 hours followed by a slow change stage in the next 6–8 hours and finally a stable stage. The rapid voltage loss in stage 1 was mainly caused by the formation of vertical and horizontal cracks, while in stage 2, the relative less voltage loss was due to the corrosion of electrode and the development of cracks. The electro-osmosis conductivity decreased along with the drainage of water and varied in the range of 1×10^{-4} to 1×10^{-5} cm^2/(V·s). The average electro-osmosis conductivity and the average energy consumption per milliliter water discharge were independent of electrode material.

Keywords: electro-osmotic consolidation, electrode material, voltage loss, crack, electro-osmosis conductivity, energy consumption instruction

1 INTRODUCTION

Electro-osmosis is an electro-kinetic phenomenon in which the pore water is dragged from the anode to cathode by the cations in the clay-water system under an applied electrical field. In civil engineering, electro-osmosis has been employed successfully to 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; Cameselle and Reddy, 2012; Hu et al., 2012; Wu and Hu, 2013; Hu and Wu, 2014).

Prior studies showed that the contact of the anode and soil had important effect on the electro-osmosis process. Voltage loss at the soil-anode interface was remarkable when an imperfect contact was encountered, and the drainage efficiency was greatly reduced (Bjerrum et al., 1967; Lo et al., 1991; Lefebvre and Burnotte, 2002). Therefore, electrode material is of great importance to the performance of electro-osmotic consolidation. Different electrode material including metallic electrodes (copper, iron, steel, aluminium) and non-metallic electrodes (graphite) have been used for electro-osmotic consolidation (Lockhart, 1983; Mohamad et al., 2011; Tao et al., 2013). Lockhart (1983) conducted electro-osmotic dewatering tests on sodium kaolinite and copper kaolinite using steel, copper and carbon electrodes. The results indicated that for the copper kaolinite, copper electrode was the best performers and carbon electrode was the worst performers, while no such variation was found for the sodium kaolinite. Mohamad et al. (2011) compared the voltage loss of copper and carbon electrodes during the electro-osmosis tests performed on a remolded marine sediment recovered from the seabed. The results indicated that the voltage loss was less for the copper electrode than the carbon one. Mohamad et al. (2011) concluded that from the result of cumulative water discharge, the copper, iron and aluminium electrodes had almost the same effect during the electro-osmotic consolidation tests on kahang clay. Tao et al. (2013) reported that the performance of iron electrode was better than the copper electrode during the electro-osmosis experiments on the clay in Zhejiang, China.

Summarizing the previous studies, there is no consistent conclusion about which electrode can achieve the best drainage effect. Experiments on different kinds of soil may lead to different or even contradictory conclusions. The clay mineral category

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and content have considerable influence on the soil behavior during electro-osmotic consolidation. Most of the existing experiments were conducted on kaolinite or local clay soil, while the study on bentonite, a swelling, low-permeability clay which usually contains large amount of smectite, was rarely reported.

The main objective of this paper was to study the effect of electrode material on the consolidation characteristics of a sodium bentonite during electro-osmotic consolidation. A one dimensional column apparatus was developed to perform the experiments and four types of electrodes (copper, iron, graphite and stainless steel) were used. During the electro-osmosis process, the water discharge, current and voltage distribution along the soil profile were monitored. A camera was used to observe the behavior of the soil-anode interface. Based on these results, the drainage rate, voltage loss, electro-osmosis conductivity and energy consumption were calculated. The effect of the four electrodes was then discussed by comparing the above measured and calculated values.

2 MATERIALS AND EXPERIMENTS

2.1 Material

A sodium bentonite from Zhangjiakou, Hebei Province, China, was used in the electro-osmotic consolidation experiments. Its geotechnical properties were displayed in Table 1. The sodium bentonite presents a plasticity index as high as 124% and a free swelling ratio as high as 540%, indicating that the sodium bentonite possess remarkable swell and shrinkage characteristics. The value of the specific surface area (33.89 m²/g) and the cation exchange capacity (40.03 meq/100g) implies that the sodium bentonite contains a large amount of clay minerals.

| Property                     | Value   |
|------------------------------|---------|
| Specific gravity, Gs         | 2.625   |
| Initial water content, w (%) | 1.33    |
| Liquid limit, wL (%)         | 155     |
| Plastic limit, wp (%)        | 31      |
| Plasticity index, I_p (%)    | 124     |
| Free swelling ratio, FSR (%) | 540     |
| Cation exchange capacity, CEC (meq/100g) | 40.03 |
| Zeta potential, ζ (mv)       | -36.05  |

2.2 Experiment apparatus

Fig. 1 displayed the size and details of the 1D electro-osmotic consolidation apparatus made of 5 mm thick plexiglass. The testing cell was 90 mm in diameter and a soil sample with a height of 200 mm can be placed into it. Two pipes were equipped on the wall of the testing cell for inflow and outflow of water. The upper pipe was used for the outflow of drainage water due to electro-osmosis. The lower pipe was used for the inflow of deionized water during the saturation period and was sealed with glass cement before the test began. Six voltage probes with a distance of 10 mm, 46 mm, 82 mm, 118 mm, 154 mm, 190 mm to the cathode (marked as V1, V2, V3, V4, V5, V6) were inserted into the bentonite sample through the small holes on the testing cell (these small holes were also sealed with glass cement before the experiment began). V1 and V6 were placed in the vicinity of the electrodes so that the voltage loss at the soil-anode interface could be calculated. In addition, in order to observe the formation and development of cracks near the anode, a camera was applied to take pictures about the soil-anode interface during the experiments.

Four types of electrodes made of copper, iron, graphite and stainless steel respectively were used.

2.3 Sample preparation

After the placement of a porous stone on the bottom of the cell, the anode was put into the testing cell. The porous stone was used to prevent the bentonite sample from being squeezed out from the water pipe. The bentonite was then filled into the testing cell in 5 layers and compacted according to the predesigned saturated water content, which was determined to be 150%. A filter paper and the cathode were put upon the bentonite sample respectively. The filter paper was used to prevent the clay from dragging out by the pore water. The bentonite sample was then saturated with deionized water by vacuum method.

2.4 Experiment programme

After the bentonite sample was fully saturated, the water pipe in the bottom was sealed with glass cement to achieve an impervious boundary and the anode and cathode were connected to the power supply. An ammeter was also series connected in the circuit. A constant voltage of 20 V was applied. The experiment lasted about 30 hours until the electro-osmosis stopped.

3 RESULTS AND DISCUSSION

3.1 Water discharge and current

The water discharge and drainage rate of the four electro-osmotic consolidation experiments were
displayed in Fig. 2 and 3. The total drainage volume was 69 ml, 47.5 ml, 30 ml, and 26 ml respectively for copper, iron, graphite and stainless steel experiments. The performance of copper electrode was the best during the electro-osmotic consolidation on bentonite while the stainless steel electrode presents the worst performance.

The drainage rate of the four experiments was almost the same with a value of about 34 ml/h at the beginning. During the electro-osmotic consolidation process, the change of the drainage rate was similar in the four experiments. In the first 2 hours, the drainage rate decreased rapidly to less than 5 ml/h. In the following 6–8 hours, the drainage rate decreased slowly and finally became stable. Fig. 4 showed the real time electric current through the bentonite samples. In the first half hour, the current increased slightly. Afterwards, the change in the current was similar to that of the drainage rate, with a rapid decrease from about 0.3–0.35 A to 0.12, 0.08, 0.03, and 0.03 A for the copper, iron, graphite, and stainless steel electrodes respectively, and a slow decrease in which the current further decreased to 0.05, 0.02, 0.01, and 0.01 A, and finally became stable.

### 3.3 Voltage loss

The measured voltage distribution along the soil column illustrated that the effective voltage applied on the soil samples encountered significant reduction near the anode. The change in voltage loss was similar to that in the drainage rate and current (Fig. 5). About 58% (copper), 72% (iron), 79% (graphite) and 77% (stainless steel) of the applied voltage was lost in the first 2 hours. In the next 6–8 hours, a relative smaller voltage loss occurred, and the value was about 22%, 13%, 10% and 10% respectively for the copper, iron, graphite and stainless steel experiments. After the experiments, totally 84%, 89%, 89%, 88% of the applied voltage was lost for the copper, iron, graphite and stainless steel experiments. Since the decrease of the drainage ratio and current was mainly resulted from the increase of voltage loss near the anode, their changes were similar to each other.

Most of the previous studies analyzed the voltage loss near the anode both in laboratory tests and field experiments (Bjerrum et al., 1967; Lo et al., 1991; Mohamedelhassan and Shang, 2001; Tao et al., 2013). Table 2 summarized the voltage loss in some of the
previous studies conducted with different electrode materials on different soils. The values obtained from this research were also added in the table. The voltage loss from different experiments was quite different from each other, indicating that the electro-osmotic consolidation performance was relevant to the electrode material, soil type, and the applied voltage. Table 2 demonstrated that most of the voltage losses near the anode were lower than 50%, while the voltage losses measured in this study exceeded 80% no matter what kind of electrode material was used.

Table 2. Comparison of the voltage loss near the anode in this study and previous results.

| Authors           | Test soil       | Electrode | Voltage loss |
|-------------------|-----------------|-----------|--------------|
| Bjerrum et al.,   | soft sensitive  | reinforcing| 52%          |
| 1967              | clay            | bar       |              |
| Lo et al., 1991   | soft sensitive  | copper    | 25%          |
| Mohamedelhassan   | remolded marine | carbon    | 24%          |
| and Shang, 2001   | sediment        | steel     | 9%           |
| Tao et al., 2013  | Zhejiang clay   | copper    | 10%          |
|                   | sodium bentonite| iron      | 23%          |
|                   |                 | copper    | 84%          |
|                   |                 | iron      | 89%          |
|                   |                 | graphite  | 89%          |
|                   |                 | stainless steel | 88%   |

A series of images about the soil-anode interface during the electro-osmotic consolidation process were taken and displayed in Fig. 6. For the copper and iron electrodes, the voltage loss was about 4% and 12% after 40 minutes. However, it increased to 56% and 70% after 1.8 hours. The rapid voltage loss between 40 minutes and 1.8 hours was accompanied by the formation of vertical cracks at the soil-anode interface. The formation of the cracks induced an imperfect contact between the anode and the bentonite and the effective voltage applied on the bentonite sample was therefore greatly reduced. For the graphite and stainless steel electrodes, the voltage loss was about 4.8% and 5.3% after 20 minutes and increased to about 77% and 76% after 1.8 hours. Different from that for the copper and iron electrodes, a horizontal crack with several small vertical cracks formed at the soil-anode interface for the graphite and stainless steel electrodes. Due to the horizontal crack, the anode was almost separated from the bentonite samples and the voltage loss caused by the horizontal crack was much larger than that caused by the vertical cracks.

Fig. 7 showed the voltage loss in different periods during the electro-osmotic consolidation process. Most of the voltage loss occurred the first 2 hours due to the formation of the cracks, especially for the graphite and stainless steel electrodes. After 2 hours, the voltage loss became slow and the corrosion of electrodes was the main reason for the decrease in this period, which was smaller for the graphite and stainless steel electrodes than that the copper and iron electrodes.

The formation of the cracks was caused by the severe volume shrinkage of the sodium bentonite, and the increasing gas pressure at the anode due to water electrolysis. Therefore, the voltage loss was much higher for the sodium bentonite than other kinds of soils. Other methods should applied together with electro-osmotic consolidation to improve its effect on expansive soil that contained substantial bentonite or smectite.

3.3 Electro-osmotic conductivity

The calculated electro-osmosis conductivity of the sodium bentonite in the four experiments were displayed in Fig. 8. As the water discharge stopped within 10 hours for the graphite and stainless steel electrodes, the data after that was not obtained. The electro-osmosis conductivity decreased with time and finally reached a stable value which was about \(5 \times 10^{-3}\), \(1 \times 10^{-5}\), \(8 \times 10^{-3}\) and \(2 \times 10^{-5}\) cm²/(V·s) respectively for the
copper, iron, graphite and stainless steel electrodes. During the electro-osmosis process, the porosity decreased with the consolidation of the soil mass and caused the decrease of electro-osmosis conductivity. Mitchell and Soga (2005) summarized the electro-osmosis conductivity of different soil including sand, kaolin, sodium montmorillonite and other clay soils, and concluded that the electro-osmosis conductivity of soil was generally in the range of $1 \times 10^{-4}$ to $1 \times 10^{-5}$ cm²/(V·s). Fig. 8 also illustrated that the $\kappa_e$ of the sodium bentonite was varied in this range during the experiment.

![Calculated electro-osmosis conductivity in the four experiments](image)

### 3.4 Energy consumption

Energy consumption is an important consideration for engineering application of ground improvement techniques. The high energy consumption of electro-osmotic consolidation was one major constraint that limited the development and application of this method. Fig. 9 (a) showed the total energy consumption during the experiments, which was 29, 20, 10.4 and 10.5 w·h respectively for the copper, iron, graphite and stainless steel electrodes. Therefore, the energy consumption per milliliter water discharge was 0.42, 0.42, 0.35, 0.4 w·h, indicating that the required electric energy for a unit water discharge was almost the same for the four electrodes.

Fig. 9 (b) illustrated that the average energy consumption per milliliter water discharge gradually increased during the electro-osmotic consolidation process. At the beginning of the experiments, the energy consumption per milliliter water was about 0.2 w·h/ml and increased to about 0.5 w·h/ml at the end of the process for the four electrodes.

Although the total energy consumption was different in the four experiments, the average energy consumption per milliliter water discharge was almost the same during the electro-osmosis process and changed in the range as shown in Fig. 9 (b).

![Energy consumption during the electro-osmotic consolidation experiments](image)

### 4 CONCLUSIONS

Four experiments on a sodium bentonite were conducted with copper, iron, graphite and stainless steel electrodes to study the effect of electrode material on the drainage and consolidation characteristics during electro-osmotic consolidation. The results are compared from different aspects including the water discharge, current, voltage loss, electro-osmosis conductivity and energy consumption. The behavior of the interface between the anode and soil is also discussed.

The result of water discharge indicated that the copper electrode has the best performance while the stainless steel presents the worst performance. The reactive electrodes (copper and iron) achieve better drainage effect than the inert electrodes (graphite and stainless steel).

The drainage rate, current and voltage loss near the anode exhibited similar change pattern with a rapid change stage in the first 2 hours followed by a slow change stage in the next 6–8 hours and finally a stable stage. Different from other soil types, the sodium
bentonite encountered significant voltage loss (especially when inert electrodes were used) during electro-osmotic consolidation caused by soil cracking near the anode due to severe volume shrinkage and high gas pressure.

During the experiment, the electro-osmosis conductivity decreased along with the drainage of water and changed in the range of $1 \times 10^{-4}$ to $1 \times 10^{-5}$ cm$^2$/ V·s.

The average energy consumption per milliliter water discharge increased during the electro-osmotic consolidation process. Although the total energy consumption was different, the average energy consumption per milliliter water discharge was almost the same for the copper, iron, graphite and stainless steel electrodes.

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REFERENCES

1) Bjerrum, L., Moun, J., and Eide, O. (1967). Application of electroosmosis to a foundation problem in Norwegian quick clay. Géotechnique 17(3), 214-235.
2) Cameselle, C., Reddy, K. R. (2012). Development and Enhancement of Electro-osmotic Flow for the Removal of Contaminants from Soils. Electrochimica Acta. 86, 10-22.
3) Casagrande, L. (1948). Electroosmosis in soils. Géotechnique 1(3), 159-177.
4) Casagrande, L. (1983). Stabilization of soils by means of electroosmotic state-of-art. Journal of Boston Society of Civil Engineering, ASCE 69(3), 255-302.
5) Glendinning, S., Jones, Lamont-Black, J., Jones, C. J. F. P. (2007). Treatment of sewage sludge using electrokinetic geosynthetics. Journal of Hazardous Materials A139, 491-499.
6) Hu, L. M., Wu, H. (2014). Mathematical mode of electro-osmotic consolidation for soft ground improvement. Géotechnique 64(2), 155-164.
7) Hu, L. M., Wu, W. L., and Wu, H. (2012). Numerical model of electro-osmotic consolidation in clay. Géotechnique 62(6), 537-541.
8) Lefebvre, G., Burnotte, F. (2002). Improvement of electroosmosic consolidation of soft clay by minimizing power loss at electrodes. Canadian Geotechnical Journal 39, 399-408.
9) Lo, K. Y., Ho, K. S. (1991). The effects of electroosmotic field treatment on the soil properties of a soft sensitive clay. Canadian Geotechnical Journal 28, 763-770.
10) Lockhart, N. C. (1983). Electroosmotic dewatering of clays. III. Influence of clay type, exchangeable cations, and electrode materials. Colloids and Surface 6, 253-269.
11) Mitchell, J. K., and Soga K. (2005). Fundamentals of soil behavior. The 3rd Edition, John Wiley & Sons, Inc, USA.
12) Mohamad, E. T., Othman, M. Z., Adnan, S. S., Gofar, N., Saad, R. (2011). The Effectiveness of Electrodes Types on Electro-Osmosis of Malaysian Soil. The Electronic Journal of Geotechnical Engineering 16, 887-898.
13) Mohamedellhassan, E., Shang, J. Q. (2001). Effects of electrode materials and current intermittence in electro-osmosis. Ground Improvement 5, 3-11.
14) Reddy, K. R., Saichek, R. E. (2002). Effect of Soil Type on Electrokinetic Removal of Phenanthrene Using Surfactants and Cosolvents. Journal of Environmental Engineering 129(4), 336-346.
15) Tao, Y. L., Zhou, J., Gong, X. N., Chen, Z., Li, Y. W. (2013). Comparative experiment on influence of ferrum and cuprum electrodes on electroosmotic effects. Chinese Journal of Geotechnical Engineering 35(2), 388-394.
16) Wu, H., Hu, L. M. (2013). Analytical solution for axisymmetric electro-osmotic consolidation. Géotechnique 63(12), 1074-1079.