Experimental study of the electrode material for electro-osmosis in mudflat sludge

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Abstract: In order to study the performance of electro-osmosis, several tests including indoor electro-osmosis experiments using copper, aluminum as the anode and cathode electrode materials, and Mercury Intrusion Porosimenter (MIP) were conducted. The results indicate that the drainage ratio using aluminum is faster than that of copper while the energy consumption per unit is lower, the effectiveness is better than that of copper. After electro-osmosis, the percentage of pore with large diameter shows a remarkable decrease comparing with the remolded soil which result in the increase of pore with small diameter. The reasons were discussed in this paper.

1. Introduction
Electro-osmosis (EO) in soils is a newly developed geotechnical technology, and it has already been proven to be an effective way in ground improvement and practice projects, especially for those soils with high water content and poor hydraulic conductivity. Acar [1] found out that the electro-osmosis flow rates are several orders magnitude higher than that driven by hydraulic head difference. Casagrande first applied the electro-osmosis into the reinforcement for a railway embankment in 1939 [2] which resulted in a remarkable result, then EO was used in more and more geotechnical and foundation projects including disposals of industrial sludge, mine tailings dewatering, pile foundations, etc.[3,4] In general, there are several vital factors—including soil salinity, electric potential, initial water content, and so on—that affect the performance of the EO treatment, one of which is the material of electrodes. Researchers have done plentiful experiments or theoretical studies in order to explore the mechanism of the process.

Based on the former work, this paper aims to investigate the one of the factors that influence the EO process—suitable electrode material for one kind of soils through indoor experiments. The details of the test program and results are presented below.

2. Experimental details
2.1 Experiment apparatus
The major equipment for this test are the EO box, DC power supply and multimeter. Fig 1 shows the basic profile of the EO box. The box is consisted of plexiglass and the internal geometry is 200 mm in length, 130mm in width and 100 mm in height. The maximum output voltage and current of the DC power is 60V/2A. Two plate electrodes, 5 mm in length, 130 mm in width and 200 mm in height, one of which had been punctured and covered by geotechnical cloth was placed at cathode and another at anode. The holes on the plate electrode allow the drainage water to pass freely while the geotechnical
cloth forbidden the soil particles moving through. Several steel needle were put 10 mm away from the electrode at both ends in order to measure the voltage loss at the electrode-soil interfaces. Measuring cups with a plastic membrane were put beneath the cathode so that the drainage water could be collected and counted. The soils’ physical properties are listed below in table 1.

**Table 1. Physical parameters of original sludge in Ninghai**

|                | Water content (%) | Specific gravity | Bulk density (kg/m³) | Liquid limit (%) | Plastic limit (%) | Void ratio |
|----------------|-------------------|------------------|----------------------|------------------|------------------|------------|
| Mudflat        | 71.2              | 2.68             | 14.7                 | 59               | 32               | 2.52       |

The mudflat sludge is widely distributed in the Southeast coastal area of China. Its hydraulic conductivity is quite low and shear strength is close to zero. The sludge used in the tests was extracted from Ninghai, located about 20 km Southeast of Ningbo, China. The samples were taken from the offshore area at a depth of 0.5~1 m.

2.2 Test program

The original mudflat sludge was first dried and grinded into fine particles soils. After this procedure, a quantitative amount of water was poured into the soils and mixed in order to obtain the remolded soils sample with 100% water content. Then the remolded soils were filled into the plexiglass box for three times and tapped to eliminate air bubbles generated during the filling process. After 24 hours until the sample reached stabilization (no drainage water due to gravity), the EO tests could be conducted. The voltage gradient is 0.9V/cm and the duration lasts for 48 hours.

Immediately after the EO tests, MIP samples, each about 0.5cm³ in volume (see Fig 1), were taken from the treated soils at middle depth for each box. The MIP tests give the information about the pore diameters’ distribution in soils thus reflecting the soils microstructure properties enhancement and it was conducted in the State Key Laboratory of Chemical Engineering in Zhejiang University. The MIP tests require the soil samples to be absolutely dried so that the data obtained through the tests could be accurate. However, due to the high water content and poor strength, soft soil shows the feature that the volume will decrease largely and microstructure will change during the drying process. Chai[5] explored the shrinkage ratio in volume and in length by air-drying and freeze drying for soft soils extracted from Shanghai, the data shows a 5.6~84.5% change in length and 14.8~98.5% in volume change for air-drying while only 0.4~2.1% in length and 1.1~4.7% in volume for freeze-drying. Researchers [6] concluded that freeze-drying does not induce the break inner the soil and maintains the soil’s original geometry characteristic. Out of this consideration, freeze drying with vacuum pump technology was adopted. The details of the test program are listed in table 2.
Table 2. Details of the Tests Program

|                        | EO tests | MIP tests |
|------------------------|----------|-----------|
|                        | Distance to anode 1cm | 9cm | 17cm |
| Electrode Voltage Duration | EA Copper 16.2V 48h | EA | M1 | M2 | M3 |
|                        | EB Aluminum 16.2V 48h | EB | M4 | M5 | M6 |

3. Results and Discussion

3.1 EO tests

Drainage water and Energy consumption

The total drainage amount for EO tests are shown in Fig 2. The total drainage amount after 48 hours treatment for both tests are 509.1 mL for copper and 779.7 mL for aluminum. At the first 10 hours, more than half of the drainage water discharged from the soil, 261.9 mL for copper test and 484.1 mL for aluminum respectively. The drainage amount from 20 hour to the end only cover 26.1% for copper and 14.5% for aluminum. This phenomena indicate that most Electro-osmosis dewatering occurs at the first a few hours. The drainage rate increased rapidly at the first 4 hours and reached its maximum in 5 hour, 38.6 mL/h for copper and 62.5 mL/h for aluminum. A slow decrease in drainage rate was observed after the maximum value. After 18 hours, both rates floated around 3-10 mL/h until the tests were stopped. The current in the soils was highly consistent with the drainage rate, as shown in Fig 3 and Fig 4.

This is reasonable, because the drainage water molecules are moving along with the hydraulic cations under external electric force in the soils. When the cations reach the cathode, water clusters are released once the cations are neutralized by the negative electric charge at the cathode. The current-time curve only has one peak appeared at 5 hour which is similar to the drainage water. The peak value are 1.203 A for copper, 1.451 A for aluminum, respectively. After 20 hours, the current maintained from
0.05~0.20A. The EO treatment has the advantage of draining water in poor hydraulic conductivity soils [7]. When the DC power supply was cut, soil samples (see Fig 1) were extracted at middle depth in order to obtain the water content at different area after the EO tests. Results showed an uneven distribution of water content. The biggest water content drop happened at the middle of the soil and the value is 33.98% and 21.72% while there were only little change near the cathode, 87.38% and 80.03% for copper and aluminum, respectively. Energy consumption is another vital index evaluating the EO treatment efficiency. The total energy consumption and average consumption are listed in Table 3.

|                | Total Energy(kWh/L) | Average Energy(kWh/L) |
|----------------|---------------------|-----------------------|
| EA(Copper)     | 2.599E-1            | 5.104E-1              |
| EB(Aluminum)   | 3.039E-1            | 3.898E-1              |

Overall, aluminum electrodes consumed more energy because of the higher current resulting in more draining water, but the average energy consumption was lower than Copper (76.4% of the Copper electrodes). The experiments results indicated that aluminum is a better material which is contrary to some conclusions from other articles [8]. This will be discussed in the next part.

3.2 MIP tests

Liquid mercury usually doesn’t infiltrate the solid surface when contacting with soil particles. An external force has to be loaded to counteract the surface tension between the mercury and the soil particles. According to Washburn [9], this force can be written as follow:

\[ p = \frac{2\sigma \cos \theta}{r} \]  

(1)

\( p \) stands for the infiltration pressure; \( r \) is the radius of the pore; \( \theta \) is the contacting angle between liquid and solid (130 degree in this article); \( \sigma \) is the surface tension, 0.484 N/m. Fig 5 illustrates the pore distribution for all samples. Mitchell [10] put forward the standards for the pores in soils:

- Type A: 0.1~1μm, pore between aggregates;
- Type B: 0.01~0.1μm, pore superimposed by the clay particles;
- Type C: <0.1μm, pore between clay platelet.
- Type D: >10μm, macro size pore.

Taken the soil samples extracted from copper box as examples (M1, M2, M3) and similar rule can be found in aluminum box, we can conclude from Fig 5 and Table 4 that anode and middle area have the best EO treatment effect. The majority pores in these area have a diameters from 0.1~1μm (about 63%), while macro size pores only occupy a small part for all samples. All the samples’ curves only have one major peak. For samples M1 and M2, although the difference between the volume percentage of 0.01μm pore is tiny (1.152% vs 0.748%), the number of these pores may be of several orders of magnitude. Because one single type C pores only occupies very little volume. In the cathode area (M3), the dominated pore is type A (69.176%) indicating that cathode area have a poor treatment effect due to the high water content after EO treatment.
Table 4. Percentage of pores with different diameters (μm)

| Diameter Range | M1  | M2  | M3  | M4  | M5  |
|----------------|-----|-----|-----|-----|-----|
| <0.01          | 1.512 | 0.748 | 0.029 | 2.106 | 1.127 |
| 0.01-0.1       | 21.072 | 16.951 | 7.069 | 27.204 | 30.034 |
| 0.1-1          | 63.631 | 63.326 | 15.217 | 60.562 | 58.848 |
| 1-10           | 7.442 | 9.748 | 69.176 | 2.759 | 1.499 |
| >10            | 6.343 | 9.497 | 8.510 | 7.369 | 7.492 |

Fig 6 illustrates the curve between cumulative intrusion and intrusion pressure for anode and middle area samples. The cumulative intrusion can be treated as the total volume of the pores and the pressure’s unit is psia, 1psia = 6.8948kPa.. At the first section (0~100psia), curves rise slowly owing to the good treatment effect after 48 hours electro-osmosis. Then the curves’ slopes increase rapidly at 100~1000psia because the diameters in this range occupy the majority of the soils. After this point, the curve rise fast until the pressure reach about 10000psia. Over the whole procedure, the total volume of copper test is larger than the aluminum test from the beginning to the end. Hence, we can conclude that the void ratios in copper test soils are larger than that of aluminum test.

From the point of microstructure, aluminum is a better material for EO treatment when EO is applied on mudflat sludge.

4. Discussion and Conclusion
Tao [8] conducted indoor experiments and discovered that aluminum electrode turns out to show the worst performance than ferrum and copper electrodes. The reason leads to the difference between this paper and Tao’s work mainly is the difference between the soils. The soil used in paper [8] was soft soils from a foundation pit in Hangzhou. The soft soils’ original salinity is relatively low compared with mudflat sludge used in this paper which was extracted from offshore area in Ninghai.

This paper conducted several indoor tests including electro-osmosis draining tests and MIP tests, aiming to find out the best material for EO treatment in sludge. Compared with copper electrodes, aluminum electrodes have a faster drainage rate and more drainage water amount. Meanwhile, the average energy consumption is lower which is quite economical efficient. It is noticeable that the most suitable electrode may change with soil properties.

Acknowledgements
The author thanks the financial support from Chinese National Natural Scientific Foundation (No.51378469) for this paper’s study.
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