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Model tests for corrosion influence of electrode surface on electroosmosis in marine sludge

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Abstract. The corrosion of metal electrodes is inevitable on electroosmosis in soil. Surface corrosion of electrodes is also one of the reasons for increasing energy consumption in electroosmosis treatment. A series of laboratory tests were conducted employing three kinds of materials, aluminium, steel, and brass. To explore the impact of surface corrosion degree on electroosmosis, metal electrodes were pretreated with durations 0 h, 12 h, 24 h, and 36 h. After the pretreatment, corroded electrodes are used as anodes on electroosmosis. Water discharge, current, voltage potential were measured during the tests; water content was also tested at three points after the electroosmosis. The results showed that aluminium was better than steel in electroosmotic drainage while brass provided the worst dewatering performance. Surface corrosion did not influence the aluminium and steel on electroosmosis in marine sludge, but brass did. In the pretreatment of brass electrodes, corrosion rate had started to slow down at later periods, with the deterioration rate of dewatering reduced afterwards. As the results showed, it is not recommended to employ those easily deteriorated electrode materials from surface corrosion in practical engineering, such as brass; electrode material with higher electroosmosis exchange rate is recommended, such as aluminium.

1. Introduction

In the early 19th century, Russian scientist Reuss, firstly discovered the phenomenon of electroosmosis and electrophoresis in lab. With the practice of electroosmosis in foundation treatment by Casagrande[1], continuous studies emerged in the fields of electroosmosis mechanism and application. The electroosmosis method (EOM) can even effectively accelerate drainage consolidation for fine grained clay with low hydraulic permeability while conventional methods decreased significantly in efficiency; so EOM has certain prospect in foundation treatment application. The fundamental principle of EOM is transport of pore water with the direct current, contributing to the soil settlement and enhancement. Electroosmosis treatment for clay has coupled multi-fields including electric field, stress field, seepage field, thermal field, etc.

In theoretical research aspect, Esrig^[2] raised the one-dimensional electroosmosis consolidation theory and its analytical solution, using the superposition method of electrokinetic flow and hydraulic flow. Wan and Mitchell^[3] further extended Esrig's theory and determined the validity in theory when adopting polarity reversal on electroosmosis. Su and Wang^[4] theoretically analyzed varying drainage conditions on electroosmosis by partition method; the excess pore water pressure induced by electroosmosis could be positive or negative. Chang and Sheen^[5] deduced the three-dimensional electroosmosis consolidation equations, further, performed an electroosmosis experiment supplied by



solar energy. The conventional electroosmosis theory actually does not contain the changing parameters in the real process. Yuan and Hicks^[6] considered nonlinear permeability under finite strain condition to explore the soil deformation characteristics and dissipation of excess pore water pressure with time; the results of calculations and tests showed good agreement. The overwhelming majority of theoretical research left electrode factor out of consideration, although it is one of the main influencing factors since the electrochemical nature of electroosmosis.

In experimental research aspect, the comparison of different electrodes appeals to researchers, due to the varied electroosmosis treatment efficiency. Mohamedelhassan and Shang^[7] found that steel electrode and cuprum electrode had lower loss of potential than carbon electrode in electroosmosis process. Tao et al.^[8] conducted a series of laboratory tests to investigate the different effects of electrodes on electroosmosis; the results showed anode material acted a leading role in electroosmosis rather than cathode material; better dewatering performance was achieved by ferrum electrodes than cuprum electrodes. Li et al.^[9] studied the effect on electroosmotic drainage through laboratory model tests by aluminium electrodes, with three different arrangements of the electrodes, namely rectangular array, hexagonal array, as well as parallel and transposition array. The loss voltage potential at the interface between electrode and soil body could reach up to 50 %, the corrosion quantity of anodes could reach up to 37 % after electroosmosis treatment, reported from an engineering project case^[10].

Corrosion of metals is an electrochemical oxidation process, and it occurs in electroosmosis treatment, in which the metal transfers electrons to the environment and the valence changes from zero to a positive value. However, corrosion of anodes was generally displayed as a result of treatment rather than analyzed as an initial condition or a process. Marine sludge nearby the coastal area has some special properties such as high water content, high salinity content, and low permeability. Compared to other soils, marine sludge has higher apparent current during the electroosmotic treatment which accelerates the surface corrosion of anodes. In this paper, we adopted three electrode materials for model tests namely aluminium, steel, and brass; these electrodes (anodes only) were pretreated with varying surface corrosion degrees correspond to different stages in electroosmotic process. Further, the pretreated electrodes were applied for formal electroosmosis tests.

2. Corrosion pretreatment of anodes

2.1. Experimental materials

The laboratory tests were conducted with plate-shaped electrodes made of aluminium, steel, and brass; each size of electrodes was 130 mm×120 mm×4 mm. Besides, the plate-shaped cathodes were provided with boreholes and covered with gauze for drainage. According to the practical situation and the electrochemical corrosion law, anodes show much greater corrosion than cathodes. So we just pretreated the plate-shaped anodes for the subsequent electroosmosis formal tests. Since the rugged contact between electrode and soft soil, while the contact area would be changing during the electroosmosis due to the shrinkage of the soil sample, seawater was adopted as the continuous medium for corrosion pretreatments; and a pH of 7.8. Constituent of seawater collected from Huchen harbor (Ningbo, China) are shown in table 1.

Table 1. Ion concentration of seawater.

Ion	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SO ₄ ²⁻	Cl ⁻	HCO ₃ ⁻
Concentration (mg/L)	300.4	993.4	9000	294.6	2216.2	16000	118.9

2.2. Scheme and analysis of pretreatment

To investigate the effect of anode surface corrosion on electroosmosis, anode weight reduction (i.e. corrosion quantity) in pretreatment should be close to the situation in formal tests. The durations of treatment were 0 h (i.e. untreated), 12 h, 24 h, and 36 h, respectively, for graded corrosion of anodes; the output current remains 1 A unchanged. Treatment durations represented different surface corrosion

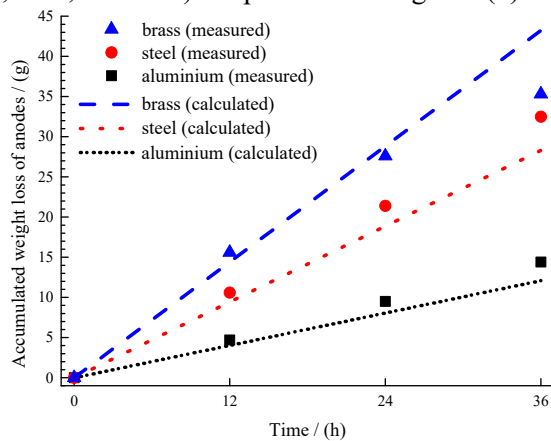
degrees of the plate-shaped electrodes.

Three electrode materials, aluminium, steel (approximately 72 % ferrum, 18 % chromium, and 10 % nickel), and brass (approximately 62 % cuprum and 38 % zinc), were pretreated. Through Faraday's law^[11], we could convert the current flow to the mass of consumed metal:

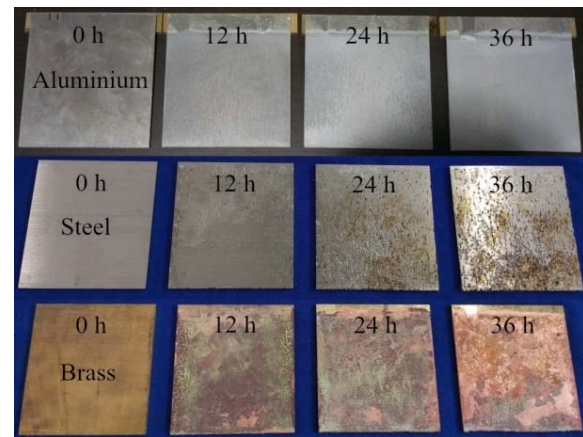
$$W = \frac{MIt}{nF} \quad (1)$$

where W is the mass of consumed metal (g); M the atomic weight of metal (g/mol); I the output current (A); t the time duration (s); n the ionic charge; F the Faraday's constant (96485 C/mol).

Figure 1(a) shows the accumulated weight loss of electrodes (anodes) with time in pretreatment experiments. Weight loss curves calculated by Faraday's law is also provided with dotted and broken lines. Measured points of values indicate the aluminium and steel nearly keep a constant corrosion rate in electrochemical corrosion process when the output current keeps 1 A unchanged. However, the corrosion rate of brass had been slowed down with time, especially between 24 h to 36 h. Generally this phenomenon can be attributed to the passivation occurred in the surface of brass anodes. The variations of surface topography of three plate-shaped metal anodes for graded treatment time (0 h, 12 h, 24 h, and 36 h) are presented in figure 1(b).



(a) Accumulated weight loss of anodes



(b) Surface topography of anodes

Figure 1. Electrochemical pretreatment results of different metals with time.

3. Test apparatus and design

The marine sludge used for model tests was obtained from the mud flat located in Huchen harbor in Ningbo, China. The physical parameters of intact soil are given in table 2.

Table 2. Physical parameters of intact soil.

Property	Unit weight γ / (kN/m ³)	Specific gravity d_s	Void ratio e	Water content w / (%)	Saturation ratio / (%)	Liquid limit (LL) / (%)	Plastic limit (PL) / (%)
Value	14.7	2.76	2.52	91.2	99.9	59	32

Considered the flowability of soil in the backfill process and actual drainage effect, the intact soil was crushed and stirred with water, remoulded to the target water content of soil at 94 %. Vaseline was smeared evenly on the inner wall of the chamber to avoid the impact on the shrinkage deviation induced by the friction of the soil-wall interface. Further, remoulded soil was rained down into 12 test chambers by layers, with the dimension of 180 mm × 120 mm × 120 mm. Transparent coverings had been taken to avoid water evaporation in the 12 h self-weight consolidation process (to form a good contact between soil and electrode) and the whole electroosmosis consolidation process. The test chambers were assembled by polymethyl methacrylate (PMMA) plates with the thickness of 5 mm. The internal space available for the soil was 180 mm × 120 mm × 120 mm in each chamber. The metal

plate-shaped anodes and cathodes with 4 mm thicknesses for each group of laboratory tests. Initially moistened gauze plays a role in preventing soil loss and borehole clogging. Two steel probes had a 2 mm diameters were inserted into the soil body along the direction of gravity in each test chamber for measurement of effective potential changes during the electroosmosis treatment. Finally, the tests could be conducted by connecting anodes and cathodes to the DC power sources.

In this series, we had conducted 12 formal tests each lasting 20 hours. The purposes of this research are to study the effects of electrode materials and their surface corrosion on electroosmosis; all the other working conditions were equal. Test design and test results of water content before and after the formal tests are shown in table 3.

Table 3. Test design and water content test results.

Electrode material	Test number	Corrosion time / (h)	Initial water content / (%)	Final water content at w_a / (%)	Final water content at w_b / (%)	Final water content at w_c / (%)
Aluminium	T1	0	93.4	47.9	40.6	70.3
	T2	12	92.4	46.9	42.9	70.2
	T3	24	92.9	49.6	39.2	73.8
	T4	36	92.7	47.7	42.5	74.4
Steel	T5	0	94.4	54.6	45.7	88.3
	T6	12	93.4	53.6	45.5	85.7
	T7	24	95.2	51.7	39.7	83.2
	T8	36	94.4	51.0	46.2	85.3
Brass	T9	0	95.9	71.3	83.7	84.6
	T10	12	93.7	66.1	84.9	83.1
	T11	24	95.1	71.2	85.0	79.9
	T12	36	95.1	73.2	88.3	83.2

Figure 2 shows the layout of the model test and measuring points in the laboratory tests. Each test chamber comprised a soil sample, an anode and a cathode coated with nylon gauze. Actually, in the electroosmosis process, the moisture transported from anode to cathode and drained through the boreholes in plate-shaped cathodes. According to the above design, lateral seepage rate was quite low, the electroosmosis test was considered to be a one-dimensional problem.

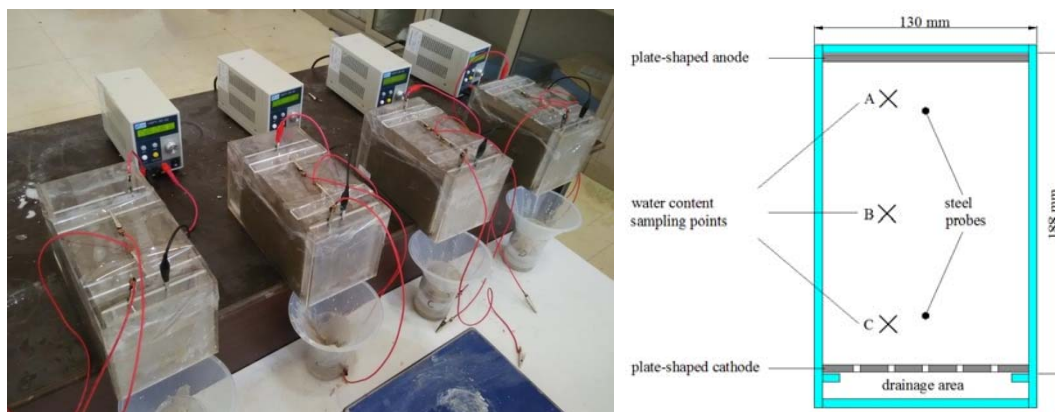


Figure 2. Layout of model tests and measuring points.

Twelve formal tests were performed after the pretreatment of anodes under the same potential

gradient, 1 V/cm. We did the chamber tests by adopting aluminium electrodes first and confirmed the equal duration for three kinds of metal in electroosmosis tests was 20 hours. The duration of 20 hours was sufficient for aluminium electrodes to finish the electroosmosis treatment, as a reference, consistent duration was adopted for other metal electrodes for contrast. Anode and cathode were fixed at both ends of each test chamber. During the electroosmosis process, test data were monitored and recorded once an hour, namely apparent current, volume of water discharge, voltage potential. At the end of electroosmosis tests, we sampled from three preselected positions (anode area, cathode area, and the area between them), 10 mm below the soil surface then tested the water content of soil samples.

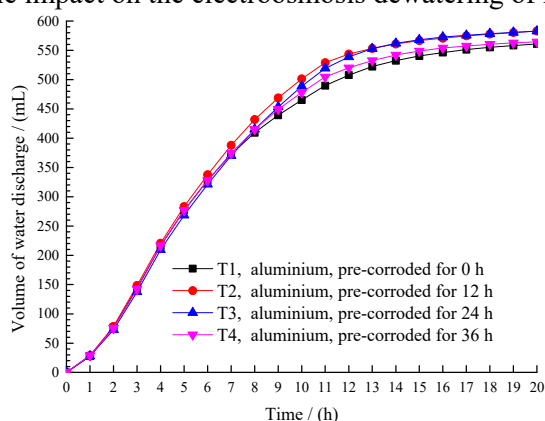
4. Model test result and analysis

4.1. Water discharge and dewatering curves

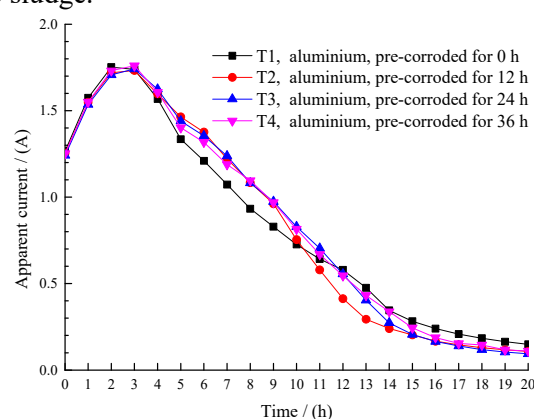
At the standing stage for 12 hours, the volumes of water discharge in tests were also measured, which ranged from 16 to 20 mL, much less than the quantity in electroosmosis process and could be neglected. Furthermore, the water discharge volume instantly stopped increasing when disconnected the power supply. The accumulated volumes of water discharge with time were shown in figure 3(a), (b), and (c), for aluminium, steel, and brass, respectively.

There were differences among 3 electrode materials in dewatering results as figure 3 showed. It should be pointed out that aluminium electrode had the best drainage performance on electroosmosis, which also firstly reached the plateau of drainage; the dewatering result of steel electrode was a little bit poor than aluminium. The abnormal dewatering curves of brass also indicate brass has the most poor performance in electroosmosis treatment. The drainage velocity and the accumulated volume of water discharge depended on the interface resistance of electrode-soil and corrosion generated on the electrode surface. In fact, the initial water content values of soil in 12 test chambers are pretty close. However, different drainage velocities led to discrepancies in dewatering curves.

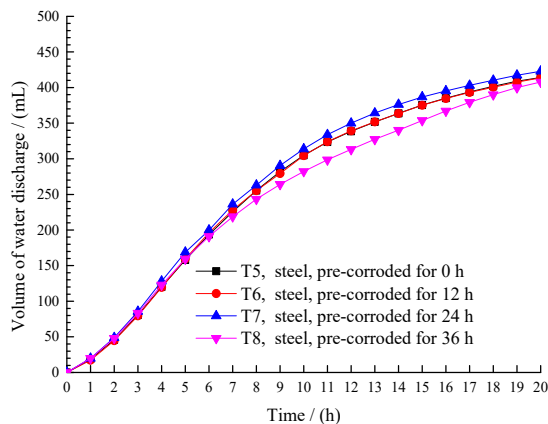
The corrosion of electrodes, especially anodes, was often considered as one of the major influencing factors on electroosmosis performance since the drainage deterioration was always associated with it. The differences between aluminium and steel in dewatering curves on electroosmosis were small, while the initial corrosion degrees of electrode material were different, e.g. aluminium. This phenomenon indicated that electrodes made of aluminium or steel were insensitive to the initial surface corrosion or the increasing corrosion during the electroosmosis, even though the surface corrosion situations of anodes were impressive; surface corrosion of aluminium and steel had little impact on the electroosmosis dewatering of marine sludge.



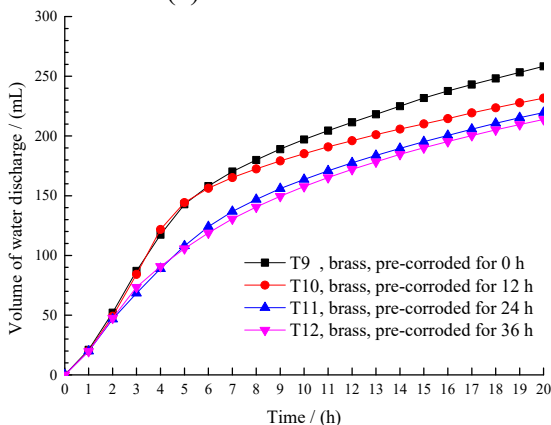
(a) Aluminium electrodes



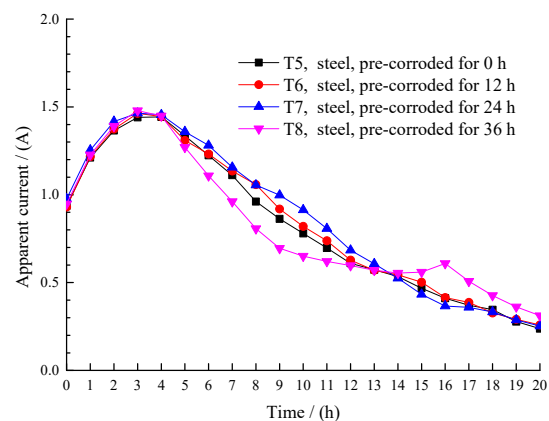
(a) Aluminium electrodes



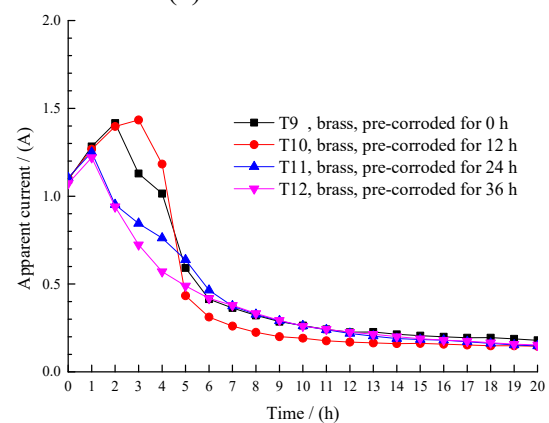
(b) Steel electrodes



(c) Brass electrodes

Figure 3. Dewatering curves for three electrode materials on electroosmosis.

(b) Steel electrodes



(c) Brass electrodes

Figure 4. Apparent current curves for three electrode materials on electroosmosis.

The dewatering curves of brass were in sharp contrast to aluminium or steel. The sequence of final volume of water discharge was $T9 > T10 > T11 > T12$ (high to low). Surface corrosion on brass anodes increased the interface resistance of electrode-soil, and decreased discharged water volume of T12 by 17.2 % compared to T9. T9 and T10 differed quite a bit in dewatering curves, rather than T11 and T12. So there was a consistency between the pretreatment experiments and formal tests in surface corrosion. Since the passivation of the electrode surface occurred at a later stage by electrochemical treatment, the weight loss of anodes in T10 was much greater than in T9, but weight loss of anodes in T11 and T12 had small discrepancy. Final water discharge volumes were closely related to the corrosion degree of anodes in electroosmosis process, and passivation mechanism was also used to explain this phenomenon. The passivation coating on the surface of brass brought more disadvantages than other two metals and decelerated the electroosmosis. We could also see that drainage deterioration rate would also decrease with the corrosion rate slow down (because of the passivation coating) when adopting brass as electrodes.

Figure 3(c) indicates the drainage velocity was not affected at the incipient stage of electroosmosis when adopting brass electrodes. In the early stage of corrosion, passivation had little negative influence on electroosmosis or just not obvious. The deterioration rate of electroosmosis drainage for brass anodes showed a strikingly similarity with corrosion rate in pretreatment; particularly in mid-late stage, the two rates both reduced. So the corrosion-induced passivation was the fundamental reason for the drainage deterioration of electroosmosis indeed.

We tested the final water content of marine sludge after the whole electroosmosis finished, point A

for water content w_A , B for w_B , and C for w_C , as is shown in figure 2. Test data are also listed in table 3. The water content distribution showed a coincident pattern between tests for aluminium and steel; sequence of water content test result is $w_C > w_A > w_B$ (high to low). However, tests for brass had the lowest water content in point A after the electroosmosis, i.e. the treatment effect at the vicinity of anode was best.

4.2. Current and exchange rate analysis

Electroosmosis exchange rate is defined as the water discharge volume of unit charge ratio. It shows the migration efficiency of ions and pore water in the soil, which also reflects the utilization of electrical energy[12]. Also, it can be calculated from equation (2):

$$E = \frac{q}{I_{\text{ave}}} \quad (2)$$

where E is the electroosmosis exchange rate and q is the drainage velocity. In addition, the average current I_{ave} can be calculated by taking an average of the current at each interval.

The measured exchange rate in electroosmosis can be inferred from the relationships between drainage rate and current with different electrode materials and corrosion degrees, as well as the fitting curves and formulas, were presented in figure 5. Aluminium electrode showed powerful exchange ability and efficiency as the E value reached up to 38 mL/Ah. However, there was little difference between steel and brass in electroosmosis exchange rate, although brass electrodes had the dewatering deterioration and passivation effect. It means the energy consumption of unit water discharge is essentially constant for a certain electrode material under this condition, even if the drainage velocity is varying in the electrokinetic process.

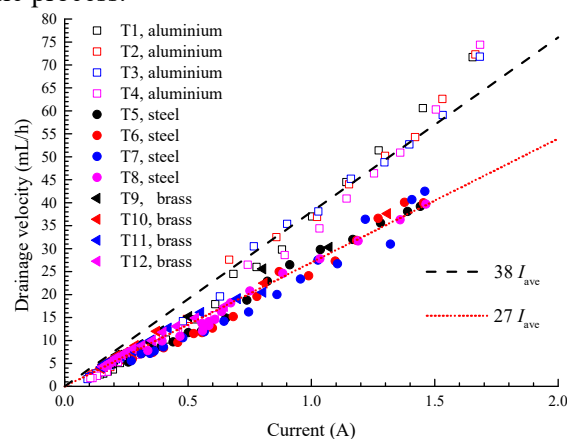


Figure 5. Relationships between drainage velocity and current with different electrodes.

5. Conclusions

The electroosmosis drainage effect on marine sludge would be gradually decreased with increasing surface corrosion of anodes in electrokinetic process. The conclusions are the following:

(1) Constant current flow contributed to constant electrochemical corrosion rate for aluminium and steel. The surface corrosion rate of brass at the incipient stage was basically unchanged and showed little impact on electroosmosis drainage. However, electrochemical corrosion rate decreased rapidly in the later period due to the corrosion-induced surface passivation of brass anodes and further influenced the electroosmosis drainage performance.

(2) Brass had differences in surface corrosion properties and deterioration influences on electrokinetic drainage as electrodes. For instance, surface corrosion of aluminium and steel had less impact on electroosmosis; it was not the main reason for reduction of electroosmosis efficiency. However, the electrokinetic water discharge of brass had decreased nearly 17.2 %, which was due to

the surface corrosion and passivation effect, when used brass as electrodes on electroosmosis. It is not recommended to use easily passivated metal (e.g. brass) as electrodes on electroosmosis in practical engineering.

(3) Aluminium showed higher electroosmosis exchange rate in marine sludge treatment; the average energy consumption will be lower when using aluminium as electrodes. When potential gradient 1 V/cm was applied for marine sludge on electroosmosis, the order of drainage efficiency from the highest to lowest is aluminium, steel and brass.

Acknowledgements

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