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Influence of the electric voltage gradient, electrode spacing and electrode radius on slurry dewatering by vertical electro-osmosis

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Electro-osmosis technology is an effective method for slurry dewatering, and the voltage gradient, electrode spacing and electrode radius have a large effect on electro-osmosis dewatering. In this paper, a series of tests are conducted to study the effects of those factors on slurry dewatering. The results indicate that a higher voltage gradient can improve electro-osmosis dewatering. Under the same voltage gradient, a smaller electrode spacing leads to a lower discharge rate and less energy consumption, but the water content is also smaller than that with a larger electrode spacing. A larger electrode radius has a good effect on electro-osmosis dewatering, but its energy consumption is also increased. When the slurry is dewatered by electro-osmosis, the water content will be maldistributed after dewatering, with the lowest water content in the anode and the highest in the cathode, and the factors that affect electro-osmosis are also analyzed theoretically. In engineering applications, the voltage gradient and electrode radius should be increased appropriately, and the electrode spacing should be reduced to obtain a lower water content.

Keywords: Electro-osmosis dewatering; Voltage gradient; Electrode spacing; Electrode radius;

1. INTRODUCTION

In tunnel construction, large volumes of high water content slurries are usually produced [1]. It is difficult to transport these slurries to a spoil ground because they very easily spill out to roads, and they may cause traffic accidents. Even if those slurries are placed in a spoil ground, they will also cause many problems; for example, they take a long time for their water content to decrease under natural drying conditions and occupy valuable land resources [2, 3], and they may also cause geological disasters. Therefore, the key to slurry treatment is to separate the water from the slurry to reduce the slurry volume, and a lower water content slurry can be reused in many other engineering fields. Thus, determining how to obtain a low water content slurry is a technical problem for its ultimate disposal or reuse.

When a voltage is applied to both ends of the slurry, a current loop is formed inside the slurry, the cations move towards the cathode and the anions move towards the anode, and the water is discharged from the cathode [1]; this is electro-osmosis dewatering technology. Electro-osmosis was first discovered by Russe in 1809 [4]; since then, electro-osmosis technology has been widely used in foundation treatment [5-7], slurry dewatering [8] and other engineering fields [9], and it has achieved great success in those fields. Many researchers find that the efficiency of electro-osmotic dewatering has been restricted by its complicated process and many influencing factors [10]; therefore, it is very important to study the influencing factors to improve the electro-osmosis dewatering efficiency. Generally, those factors can be divided into two categories: external factors and internal factors. External factors include voltage, electrode materials, electric stage spacing, electrode layout, and so on, and the internal factors include soil mineral composition, pH and so on. Many scholars have studied those factors to improve the efficiency of electro-osmosis dewatering. Xue et al. [11] conducted a series of tests to explore the effects of voltage and temperature on the electro-osmosis properties of marine clay and concluded that high temperature and high voltage are beneficial to reduce the water content and improve the soil strength. Zhou et al. [12] performed many experiments to study different electrode materials and concluded that electro-osmosis relies on ions in the original soils instead of those generated by electrode reactions. Tao et al. [13] reported that the electro-osmotic effects were better when the electrodes were arranged in a hexagonal array than when using rectangular and staggered arrays, and the properties of drainage volume, water content, and shear strength of treated soil were improved. Some scholars have also studied electro-osmosis from the perspective of electrolyte addition, and the most commonly used electrolytes include $CaCl_2$, KCl, NaCl, and so on [14, 15]. Further, some scholars have explored combinations of electro-osmosis with other methods, including vacuum electro-osmosis [16-18], pressure filtration electro-osmosis and so on [19, 20]. These methods all have a positive effect on electro-osmosis.

Higher voltages have been confirmed to effectively improve electro-osmosis dewatering [11, 21], and the electrode spacing [1, 22] and electrode area also affect electro-osmosis dewatering [23]. These factors are the most basic influencing factors in electro-osmosis applications, and it is necessary to understand how these basic factors affect dewatering. The present study explores the effects of the potential gradient, electrode spacing, and electrode radius on electro-osmosis dewatering, and basic evaluation indexes were measured, including drainage volumes and drainage rates, current and energy consumptions, and so on. This research can provide a reference for engineering.

2. MATERIALS AND METHODS

2.1 Slurry properties

The slurry materials were collected from a tunnel construction site in Suzhou, Jiangsu Province, China. For more reasonable and accurate analysis of the experiment, the slurry sample was air-dried under natural conditions, crushed and then reconfigured to a slurry with a moisture content of 60%. The slurry properties are summarized in Table 1.

Table 1. Physical properties of the slurry

Water content (%)	Liquid limit (%)	Plastic limit (%)	Soil particle composition (%)		
			<0.005 mm	0.005 mm-0.075 mm	0.075 mm<
60	36.9	17.5	34.6	61.5	3.9

2.2 Experimental apparatus

The device for the experiments is shown schematically in Fig. 1. The experimental apparatus (100 mm in diameter and 160 mm in height) was made of acrylic with an opening at the top, and the test device included a slurry box, electrodes, DC power supply, etc. In this study, a porous aluminum plate with a thickness of 1.5 mm was connected to the cathode at the bottom, and an aluminum plate was connected to the anode at the top. To improve the contact between the electrodes and the slurry, a pressure of 0.15 kPa was applied on the top of the slurry. The drainage channels were at the bottom of the slurry box, and the cathode was covered by geotextile in order to prevent slurry particles from blocking the channels. The cathode and anode were connected to a DC power supply, and the currents were monitored by a digital multimeter during the dewatering process. A beaker and an electronic balance were placed under the device to record the mass of discharged water.

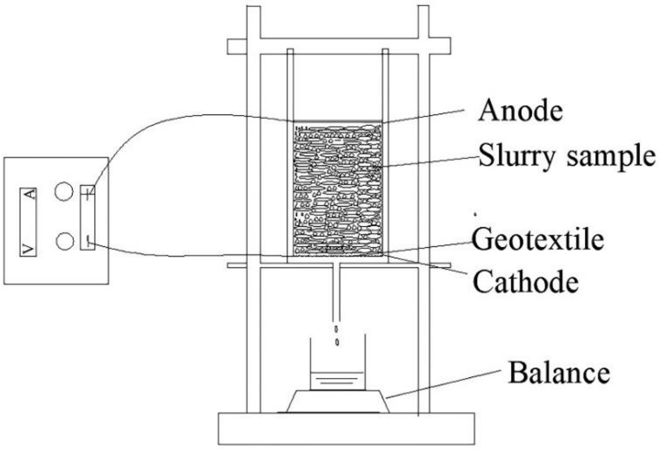

Figure 1. Laboratory-scale of electro-osmosis dewatering apparatus

2.3 Experimental procedures

The test procedures are shown in Table 2. In this study, we performed several tests to analyze the influences on electro-osmosis dewatering. We adjusted the electric field intensity to carry out slurry dewatering with voltage gradients of 6 V/cm, 4 V/cm and 2 V/cm to study the effect of dewatering on TS 1, TS 2 and TS 3, respectively. We also performed tests to study the effect of the electrode spacing on electro-osmosis dewatering by adjusting the thickness to 5 cm, 7.5 cm and 10 cm in TS 2, TS 5 and TS 4, respectively, under a constant potential gradient of 4 V/cm. The contact between electrodes and the slurry will also have an impact on electro-osmosis dewatering. We used the radius of the electrode to indicate the area of the electrode, and we used electrode radii of 3 cm, 4 cm and 5 cm to represent electrode surfaces of 28.3 cm^2, 50.2 cm^2 and 78.5 cm^2 in TS 7, TS 6 and TS 2, respectively, the reason is that the electrodes are round.

Table 2. The experimental procedures in this study

Test number	Electric potential gradient (V/cm）	Electrode spacing (cm)	Electrode radius (cm)	Electrode surface area (cm^2)
TS1	6	5	5	78.5
TS2	4	5	5	78.5
TS3	2	5	5	78.5
TS4	4	10	5	78.5
TS5	4	7.5	5	78.5
TS6	4	5	4	50.2
TS7	4	5	3	28.3

3. RESULTS AND DISCUSSION

3.1 Effect of voltage gradient on dewatering

3.11 Drainage volume and drainage rate

Fig. 2 shows the water volume that was discharged by electro-osmosis under different voltage gradients. In each test, the electrode spacing was 5 cm, and the electrode surface area was 78.5 cm^2, i.e., the electrode radius was 5 cm. The drainage volume was 59 ml, 66.8 ml and 72.6 ml when the voltage gradient was 2 V/cm, 4 V/cm and 6 V/cm, respectively. The drainage rate at the initial dewatering stage was high and then started to decrease during each test. The reason is that in the early stage of the tests, there is much free water in the slurry, and the water was dewatered by gravity and electro-osmotic force. Then, the slurry water content was decreased, the dewatering resistance increased, and the drainage rate started to decrease. The drainage rate decreased in the later stage with a higher voltage gradient because the slurry electric resistance and the electrode contact interface resistance increased due to water released, but from the whole dewatering process, a higher voltage gradient was applied, which had a greater effect on slurry dewatering. We can also know from this figure that the drainage rate was also larger at a higher voltage gradient during the initial stage of the process, and the dewatering volume almost reached the dewatering limit with 4 V/cm and 6 V/cm, but not when the voltage gradient was 2 V/cm; a larger voltage gradient can enhance the slurry dewatering effect by electro-osmosis because the larger voltage gradient can remove more water in the slurry and shorten the dewatering time [24].

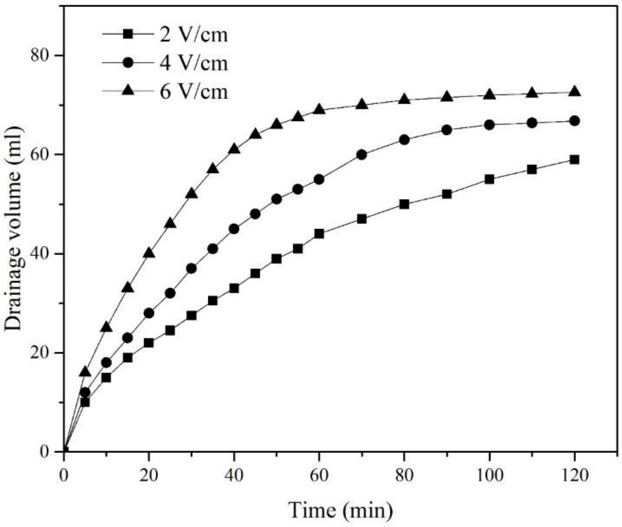

Figure 2. The drainage volume verse time by electro-osmosis under different voltage gradients

3.12 Current and energy consumption

Fig. 3 shows the various currents of the tests under different voltage gradients. The current was 0.119 A, 0.205 A and 0.32 A at the start of each test and ended at 0.063 A, 0.059 A and 0.061 A when the voltage gradient was 2 V/cm, 4 V/cm and 6 V/cm, respectively. A higher voltage gradient will lead to a higher current in the initial stage of the test, but it also decreases faster in the later stage. When each test was completed, the current dropped to nearly half of the original value at the voltage gradient of 2 V/cm, and the current dropped to nearly 1/3 of the original value at the voltage gradient of 4 V/cm. When the voltage gradient was 6 V/cm, the current was stabilized at 1/5 of the original current; the greater the voltage gradient was, the larger the current attenuation was. The reason is that the amount of water in the slurry decreased and the pore ratio of the slurry also decreased, so the conductivity decreased, and the electric conductivity decreased more dramatically with a higher voltage gradient [11]. All the currents decreased with time, and there was an intersection of the currents during the dewatering process. Fig. 4 shows that the greater the voltage gradient was, the greater the energy consumption coefficient was, and the energy consumption coefficient was 0.037 W·h/ml, 0.063 W·h/ml and 0.092 W·h/ml when the voltage gradient was 2 V/cm, 4 V/cm and 6 V/cm, respectively. This is because the slurry of the current system during electro-osmosis can be used as a power-consuming load; the greater the voltage is, the higher the power load that will be consumed, and the energy also promotes Joule heating and other electrochemical reactions, which is not good for electro-osmosis dewatering.

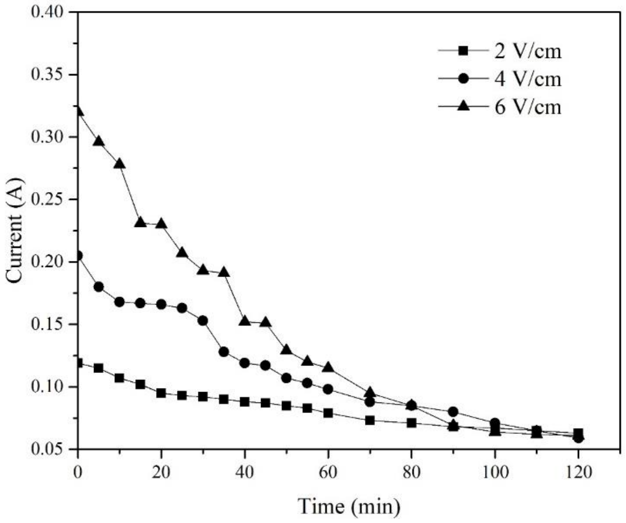

Figure 3. The current verse time during by electro-osmosis under different voltage gradients

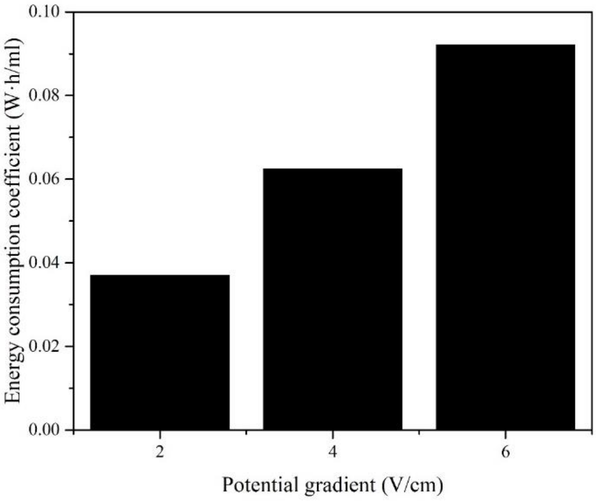

Figure 4. The energy consumption coefficient of each test under different voltage gradients

3.13 Water content

The ultimate purpose of electro-osmotic dewatering is to discharge water out the slurry and reduce the slurry moisture content to facilitate transportation and other reasonable utilization. Therefore, the final moisture content after the electro-osmosis dewatering test is an important criterion to evaluate the electro-osmosis effect. The water content after each test in different locations under different voltage gradients is shown in Fig. 5. When the slurry was dewatered by electro-osmosis, the different locations had different water contents. For the tests, the cathode had the highest water content, the second highest was the middle location, and the last was the anode because the water flows from the anode to the cathode. A higher voltage gradient would result in a lower water content, and the higher voltage gradient can improve the dewatering ability of the electro-osmosis process because the higher voltage can help remove more water and produce more Joule heat to evaporate more water [25, 26].

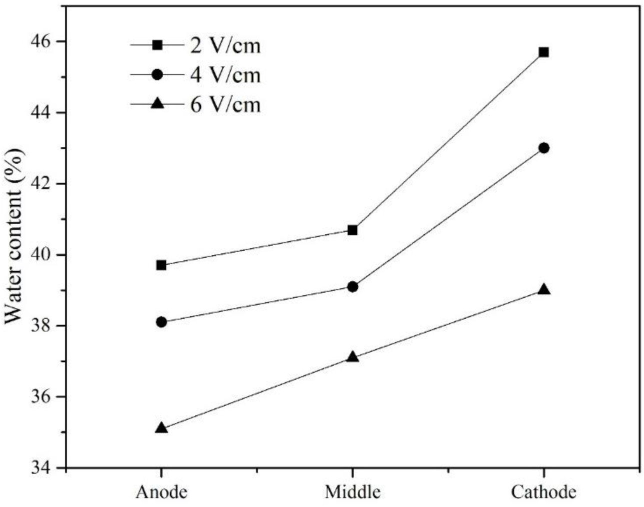

Figure 5. The water content of each test under different voltage gradients in different locations

3.2 Effect of electrode spacing on dewatering

3.2.1 Drainage volume and drainage rate

The drainage volume and drainage rate versus treatment time are shown in Fig. 6 and Fig. 7. The electrode spacing had a large important effect on these parameters, and we also know that the drainage volume was 66.8 ml, 105.5 ml and 125 ml when the electrode spacing was 5 cm, 7.5 cm and 10 cm, respectively. The drainage rate was related to the electrode spacing, and when the electrode spacing was larger, the drainage volume and the drainage rate were larger; this was the same as in previous studies [1, 22]. The drainage trend under different electrode spacings was similar to that under the different voltage gradients.

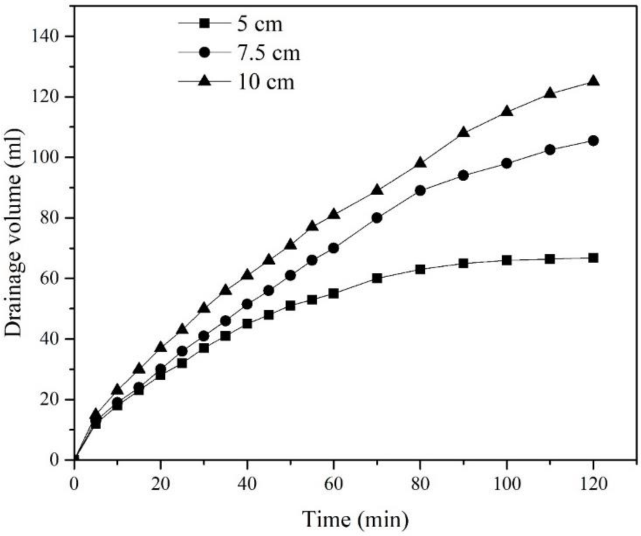

Figure 6. The drainage volume verse time during by electro-osmosis in different electrode spacings

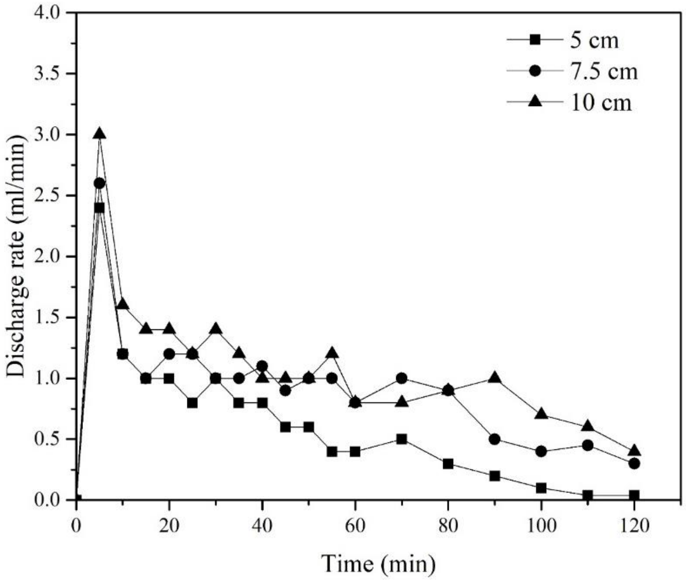

Figure 7. The drainage rate verse time by electro-osmosis in different electrode spacings

3.2.2 Current and energy consumption

Fig. 8 shows the current versus treatment time during each test under different electrode spacings. The current during each test was almost the same at the start of the experiments, but as the tests continued, changes in the current gradually appeared, and the current under the larger electrode spacing decreased slower than that of the smaller spacing; the reason is that the water was discharged and the water content decreased faster with the smaller electrode spacing, even if the drainage volume with the larger electrode spacing was bigger than that of the smaller, which resulted in the electric conductivity decreasing rapidly with a smaller electrode spacing. Fig. 9 shows the electric permeability coefficient of each test; the electric permeability coefficient was not constant for the slurry during the electro-osmosis process, and the various trends of the electric permeability coefficient were similar to those of the drainage rate under different electrode spacings as shown in Fig. 7.

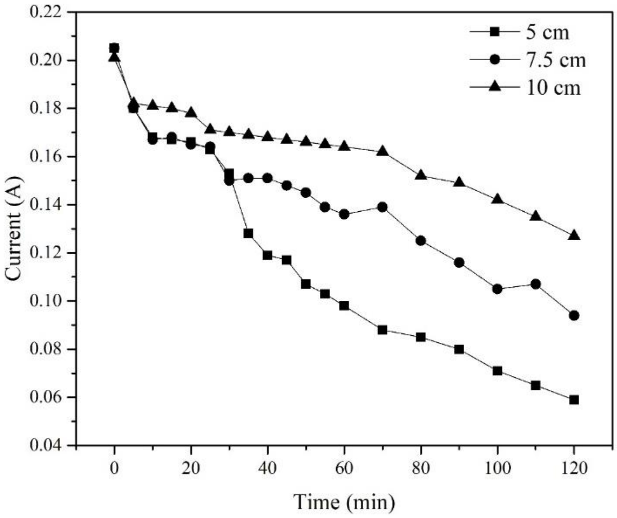

Figure 8. The various currents with time in electro-osmosis test in different slurry electrode spacings

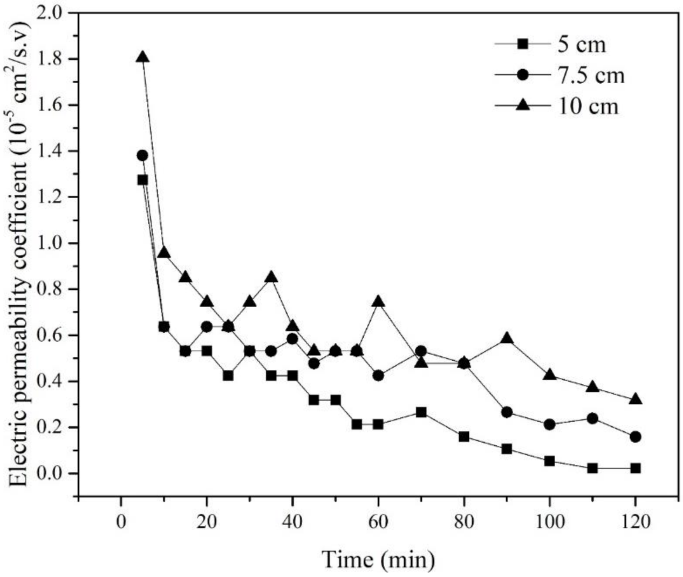

Figure 9. The electric permeability coefficient of each test in different slurry electrode spacings

3.2.3 Water content

The water content after each test with different electrode spacings and in different locations is shown in Fig. 10. When the electrode spacing was 5 cm, the water content in the anode location, middle location and cathode location was 38.1%, 39.1% and 43%, respectively; when the electrode spacing was 7.5 cm, the water content in those locations was 39.4.1%, 42.0% and 45.5%; and when the electrode spacing was 10 cm, the water content in those locations was 40.9%, 44.0% and 46.3%. The smaller the electrode spacing was, the lower the water content of the treated slurry would be, and the water content was highest in the cathode, second highest in the middle, and lowest in the anode.

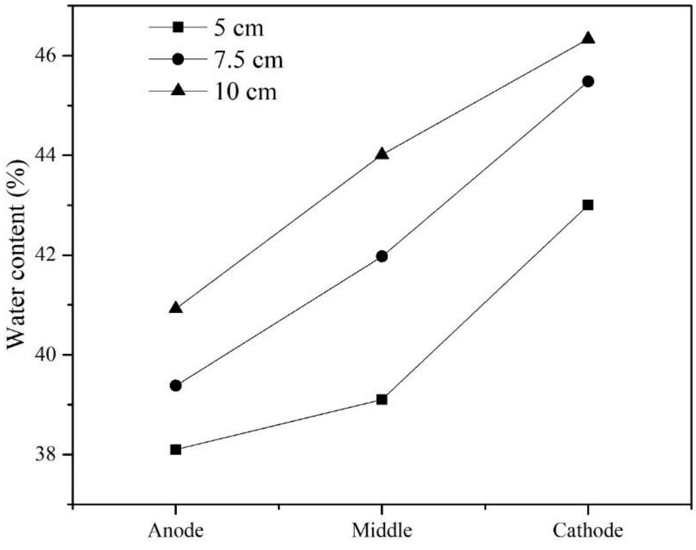

Figure 10. The water content of each test in different electrode spacings and different locations

3.3 Effect of electrode radius on dewatering

3.3.1 Current

Fig. 11 shows the current with different electrode radii. When the electrode radius was 5 cm, 4 cm and 3 cm, the current was 0.205 A, 0.168 A and 0.154 A, respectively, at the start of the test and ended at 0.059 A, 0.073 A and 0.086 A at the end of each test. Therefore, the larger the electrode radius was, the larger the initial current was, but the more rapidly the current decreased because a larger electrode radius which means a larger electrode area, and the larger electrode surface removed more water than the smaller, and the electric conductivity became smaller and the interface resistance became larger, so that the current decreased faster with larger electrode radius.

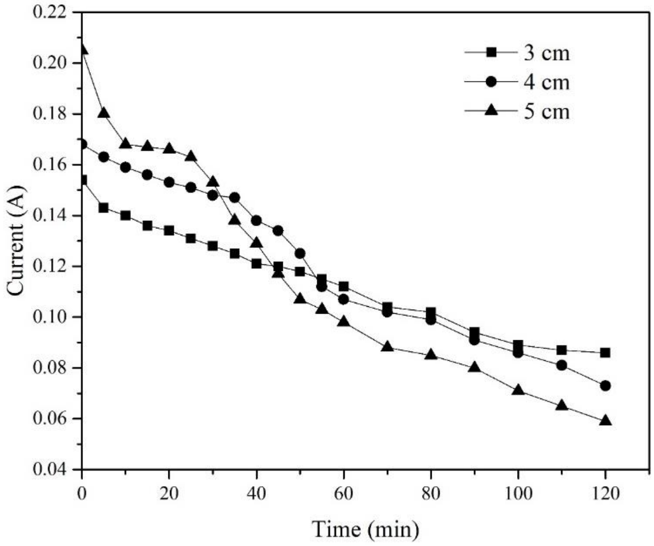

Figure 11. The current verse time during by electro-osmosis under different electrode radii

3.3.2 Drainage volume and drainage rate

Fig. 12 shows the drainage volume versus time during electro-osmotic dewatering with different electrode radii. The larger electrode radius can increase the contact area between the electrodes and the slurry surface. The drainage volume was 58.8 ml, 62 ml and 66.8 ml when the electrode radius was 3 cm, 4 cm and 5 cm, respectively. The electro-osmosis rate can be expressed as [1]:

$$v_e = k_i i_e A \tag{1}$$

where v_e is the electro – osmosis dewatering rate; k_i is the electro-osmosis permeability coefficient; i_e is the voltage gradient; and A is the cross-sectional area.

The drainage rate was related to the contact area, so the larger electrode radius could improve the drainage volume because the larger the electrode area was, the larger the drainage rate was. From Fig. 13, we know that the discharge rate was higher when the larger electrode radius was used at the early stage of the test, but as the tests went on, the drainage rate of the larger electrode radius decreased, and there was an intersection of the three tests.

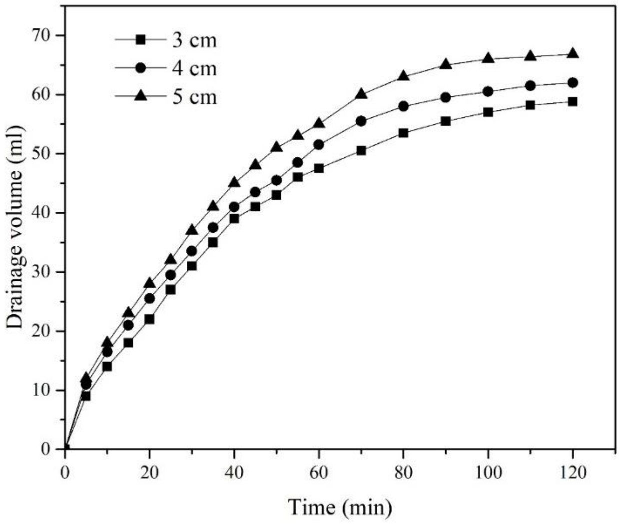

Figure 12. The drainage volume verse over treatment time during by electro-osmosis under different electrode radius

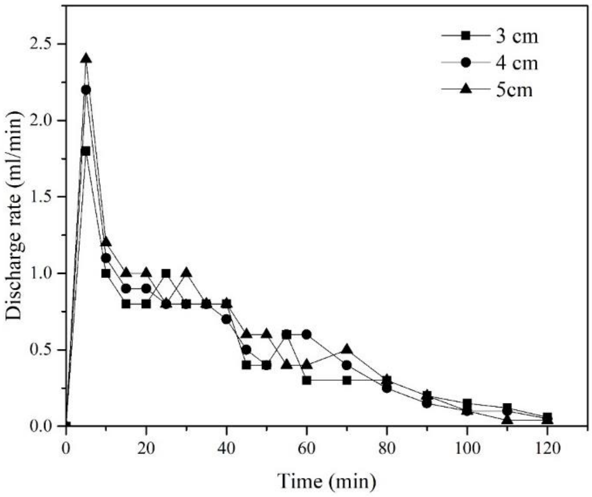

Figure 13. The drainage rate verse over treatment time during by electro-osmosis under different electrode radius

3.33 Water content

The water contents in different locations of the treated slurry by electro-osmosis using different electrode radii are shown in Fig. 14. When the electrode radius was 5 cm, 4 cm and 3 cm, the water content was 38.1%, 39.6% and 41.0% at the anode location, respectively, that of the middle location was 39.1%, 42.3% and 44.4%, and that of the cathode location was 43.0%, 45.3% and 46.5%. The larger electrode area is beneficial to electro-osmosis dewatering. From the above analysis, we know that there is a larger current and a larger discharge rate when the electrode radius is larger, and those factors result in a lower water content.

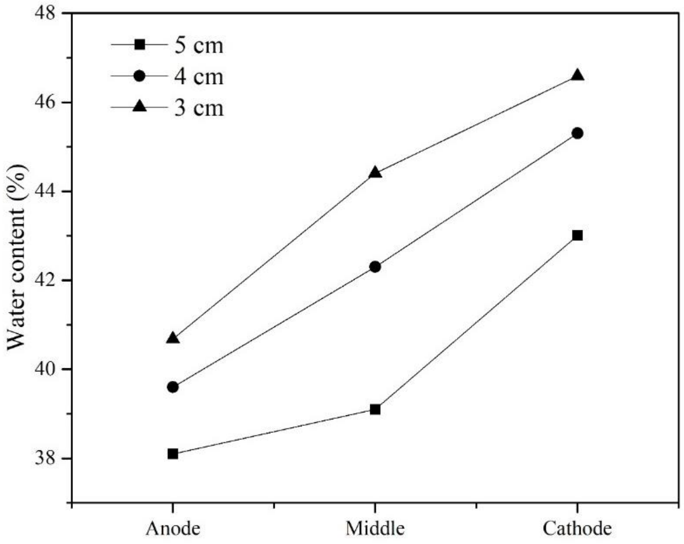

Figure 14. The water content after electro-osmotic dewatering by different electrode radii in different locations

3.4 Current analysis under different influencing factors

From the experiment results, we know that the initial current of the slurry was linearly correlated with the electric potential gradient, and the initial current of the slurry changed little as the electrode spacing was increased when the voltage gradient was constant. The reason is that when the slurry is dewatered by electro-osmosis, the slurry can act as an electrical load, assuming that the slurry is homogeneous, the electric conductivity inside each part of the slurry was the same. When increasing the electrode spacing of the slurry, the circuit diagram of the slurry, power supply and electrodes is as follows in Fig. 15.

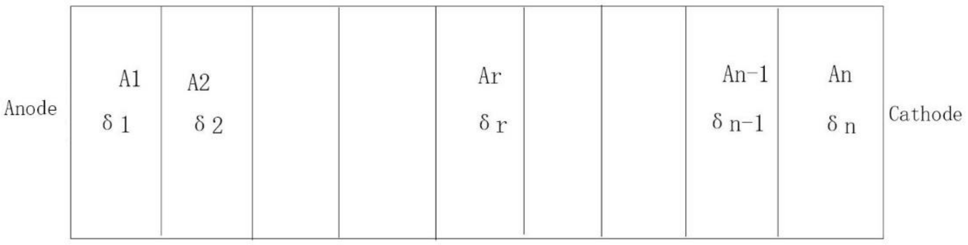

Figure 15. Schematic diagram of the slurry circuit model

Assuming the current in different units is I_1, $I_2 \cdots I_n$, the cross-sectional area in different units is A_1, $A_2 \cdots A_n$, the electric conductivity in different units is σ_1, $\sigma_2 \cdots \sigma_n$, the equations are:

$$I_1 = E_1 \sigma_1 A_1 \tag{2}$$

$$I_2 = E_2 \sigma_2 A_2 \tag{3}$$

$$\cdots$$

$$I_n = E_n\sigma_n A_n \quad (4)$$

$$\sigma = \sigma_1 = \sigma_1 = \cdots\cdots = \sigma_n \quad (5)$$

$$A = A_1 = A_2 = \cdots \ldots = A_n \quad (6)$$

$$E = E_1 = E_2 = \cdots \ldots = E_n \quad (7)$$

so that:

$$I = I_2 = I_3 \ldots \ldots = I_n \quad (8)$$

$$I = E\sigma A \quad (9)$$

Therefore, the current in the slurry is related to the voltage gradient; the greater the voltage gradient is, the greater the current in the slurry. Increasing the electrode spacing is equivalent to increasing the slurry thickness, and the increased slurry forms a series resistance with the original slurry under the same potential gradient.

However, when the contact area between the slurry and the electrode increases, the initial current of the slurry increases because the anions inside the slurry move to the anode and the cations move to the cathode by the electric field. When the electrode area increases, ion movement inside the slurry is promoted, and the current of the slurry increases. This effect can be analyzed from the contact resistance between the electrode and the slurry [27].

$$I = \frac{U}{R_t + R_m + R_s} \quad (10)$$

where

R_t is the slurry resistance, R_m is the velamen resistance, and R_s is the contraction resistance.

Additionally,

$$R_s = \frac{(\rho_1 + \rho_{2)} * L^2}{4 * A * a} \quad (11)$$

$$R_m = \frac{L^2\sigma}{A\pi a^2} \quad (12)$$

where ρ_1 and ρ_2 are the electric resistivity of contact materials; a is the radius of the conductive spot; L is the distance between two conducting spots; and A is the electrode surface area.

Therefore,

$$I = \frac{U}{R_t + \frac{L^2\sigma}{A\pi a^2} + \frac{(\rho_1 + \rho_{2)} * L^2}{4 * A * a}} \quad (13)$$

It can be seen that with increasing electrode surface area, the current presents an increasing trend. If the current needs to be increased, the electric resistivity of the electrode plate can be decreased, or the number of conductive spots increases; that is, the electrode plate needs to be treated to increase the contact degree between the electrode plate and the slurry surface.

4.CONCLUSION

In this paper, a series of electro-osmosis dewatering tests were conducted, and the results are summarized as follows:

(1) A higher voltage gradient can improve the dewatering rate, and a higher voltage gradient also produces higher current and higher energy consumption, resulting in an uneven water content distribution after electro-osmosis. The electrode spacing is in direct proportion to the volume discharged by electro-osmosis dewatering, and the smaller the electrode spacing is, the lower the water content will

be after electro-osmosis dewatering. The electrode radius is related to the volume discharged by electro-osmosis dewatering; the larger the electrode radius is, the larger the discharge volume will be.

(2) Increasing the voltage gradient can increase the initial current, but increasing the electrode spacing causes the initial current to change little under a constant voltage gradient due to its series risistance characteristics, and the bigger electrode radius can increase the initial current by electro-osmosis. The velamen resistance and contraction resistance have an adverse effect on the current, and decreasing them can increase the current.

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