ISSN: 2414-1895 | DOI: 10.6919/ICJE.202508_11(8).0011

Experimental Study on the Influence of pH on Drainage of Soft Soil by Anode Following Electro-Osmosis Method

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Abstract

Using a self-made electro-osmosis device, electro-osmosis experiments were conducted on soft clay under different electrification conditions. The drainage volume, drainage rate, electro-osmotic coefficient, water content, and shear strength were comparatively analyzed. The research results indicate that the soil pH has a significant impact on the electro-osmosis effect. Specifically, the electro-osmosis effect increases with the rise in pH, and the soil in an alkaline environment exhibits a higher electro-osmotic coefficient. Under the same conditions, the soil strength at the cathode of the anode following group is significantly higher than that of the non-anode following group, where the soil at the cathode exhibits almost no shear strength. The advantage of intermittent electrification becomes apparent only in the later stages of electro-osmosis, but its energy consumption coefficient is lower than that of the continuous electrification group.

Keywords

Electro-osmotic Drainage Consolidation; Anode Following; The Coefficient of Electro-osmosis; Intermittent Electrification; Soil pH.

1. Introduction

Reinforcement of soft soil foundations is a crucial and complex field, especially in areas with soft soil characterized by high water content and high compressibility. The effectiveness of foundation treatment directly impacts the safety and economy of engineering projects. Traditional methods for treating soft soil foundations, such as surcharge preloading and vacuum preloading, can improve foundation performance to a certain extent. However, for silts and clays with extremely high water content or in a fluid plastic mud state, these methods are relatively inefficient and difficult to achieve the desired results.

In recent years, electro-osmotic drainage and consolidation has emerged as a novel ground treatment technology, gradually gaining attention due to its unique advantages. The electro-osmotic method involves inserting electrodes into the soil and applying an electric field to utilize electro-osmotic flow to promote the migration of water within the soil, thereby achieving rapid drainage and consolidation. Unlike traditional drainage and consolidation methods, electro-osmosis is not limited by the soil's hydraulic conductivity coefficient. It offers advantages such as fast consolidation speed and high safety, demonstrating broad application prospects in the reinforcement of soft soil foundations.

Since Cassagrande[1] successfully applied the electro-osmotic method to a railway excavation project in Germany in 1939, the technique has gradually been utilized in various engineering projects. Currently, numerous scholars worldwide have conducted laboratory simulations or field tests to investigate the impact of electrode type, arrangement, power supply mode, and soil chemical environment on the effectiveness of electro-osmotic drainage. Research by Mohamedelhassan[2] and others has shown that iron electrodes perform better than graphite electrodes in electro-osmotic drainage tests. Glendining[3-5] and others have studied electrokinetic geosynthetics (EKG) and

ISSN: 2414-1895 DOI: 10.6919/ICJE.202508_11(8).0011

expanded their use. Many domestic scholars[6-7] have also researched EKG, finding that it not only facilitates electrode polarity switching but also addresses issues of anode corrosion and cathode clogging. Zhang Lei[8] and his team developed a new composite material that, compared to metal electrodes, exhibits less corrosion, lower voltage loss, and superior electro-osmotic performance. In addition to electrode materials, the power supply mode also significantly affects electro-osmotic performance. Yang Kejun[9] and others conducted electro-osmotic tests using four different power supply modes, revealing that increasing voltage during current decay resulted in the most soil drainage and the highest shear strength. Yang Kaixiang[10] and others proposed a staggered power supply mode to address the problems of severe corrosion at the bottom of electrodes and uneven reinforcement effects in traditional electro-osmotic methods. Gong Xiaonan[11] and others' research on intermittent power supply showed that it improves soil strength uniformity and water content distribution. Zeng Fangjin and others[12-13] combined intermittent power supply and electrode movement methods in electro-osmotic tests on tidal flat mud, which mitigated the decline in current and improved soil reinforcement. Li Ying and others[14] studied voltage, finding that higher voltages result in faster drainage rates but also faster increases in anode contact resistance. Chen Xiongfeng[15] and others conducted drying studies on environmentally friendly dredged sediment, showing that linear electrodes outperform circular electrodes in terms of electro-osmotic performance. Wang Junbo[16] and others investigated the electro-osmotic effect of hydraulic fill mud through laboratory tests, finding that electro-osmosis was effective on the tested hydraulic fill mud and that relatively higher temperatures enhanced drainage volume and rate. Wang Jun and others[16] studied the combination of vacuum preloading and electro-osmosis, finding that electro-osmosis can alleviate drainage board clogging in vacuum preloading, while vacuum preloading can mitigate soil cracking and rapid temperature increases in electro-osmosis.

The chemical environmental conditions of soil are significant factors in the process of electro-osmotic drainage. Zhang Lin and others[17] studied the impact of pH and salinity on electro-osmotic effectiveness, finding that alkaline and low-salinity environments yield better electro-osmotic drainage results. As an important indicator of the chemical environment, the pH value of soil not only affects the physicochemical properties of the soil but also directly influences key parameters such as the electro-osmotic coefficient and zeta potential during the electro-osmotic process, thereby affecting the effectiveness of electro-osmotic drainage. Therefore, conducting in-depth research on the mechanism of how soil pH affects the electro-osmotic drainage process is of great significance for optimizing electro-osmotic drainage techniques and enhancing the reinforcement effect of soft soil foundations.

2. Introduction to Electro-Osmotic Drainage Experiments

2.1 Experimental Materials

The soil used in this experiment is soft soil from a construction site in Jingzhou. The various physical property indicators of the soil are shown in Table 1. The collected soil was dried, crushed, and sieved.Each group of soil samples was prepared with 1400g of dry soil and a water content of 80%. After adjusting to the preset pH and ensuring uniform mixing, 1120g of this treated soil was weighed and mixed with dry soil to produce the final soil sample.

Table 1. Basic Physical Properties Indices of Undisturbed Soil.

Water Content/%	Particle Specific Gravity	Void Ratio	Saturation/%	Liquid Limit/%	Plastic Limit/%
80	2.75	1.53	99.6	54.67	21.97

As shown in Figure 1, the experimental container is a custom-made organic glass model box, divided into a soil chamber and a drainage chamber. The dimensions of the soil chamber are

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20cm×10cm×10cm. A partition with evenly spaced holes is placed between the soil chamber and the drainage chamber. During the electro-osmotic process, the water discharged flows from the soil chamber into the drainage chamber through the holes in the partition, and then into a measuring cylinder through holes in the bottom plate of the drainage chamber to measure the amount of drainage.

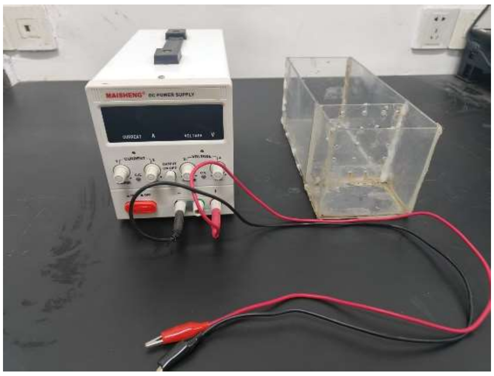

Figure 1. The experimental device is integrated.

As shown in Figure 2, brass plates are used as electrodes. To facilitate the smooth drainage of pore water in the soil, the cathode brass plate is perforated with 81 holes, each having a diameter of 5mm and a center-to-center distance of 10mm. A layer of geotextile is wrapped around the cathode surface to prevent the loss of soil particles. When advancing the anode, a new brass plate is inserted at the preset position, which avoids the problem of increased electrode resistance and contact resistance due to anode corrosion, thereby preventing a decrease in current.

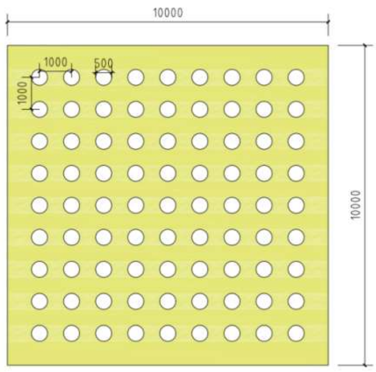

Figure 2. Schematic Diagram of a Cathode Copper Plate.

The test power supply adopts the MS-365D controlled stabilized DC power supply, with an output voltage range of 0~5A. It can maintain a stable voltage output for extended periods and can display both voltage and real-time current.

2.2 Experimental Protocol

During the experiment, a voltage of 36V was applied, resulting in a potential gradient of 1.8V/cm, and the duration of electrification was 13.5 hours for all cases. The experimental scheme is shown in Table 2. The experiment was divided into three groups, with three different pH levels set for each group, primarily to investigate the influence of soil pH on electro-osmotic drainage. Groups C1 to C3 served as control groups. The impact of anode advancement on electro-osmotic drainage was studied by comparing Group A with Group C. The effect of electrification mode on electro-osmotic drainage was examined by comparing Group B with Group C.

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Table 2. Experimental Scheme.

Experiment Number	A1	A2	A3	B1	B2	B3	C1	C2	C3
pH	3.5	5.5	8.5	3.5	5.5	8.5	3.5	5.5	8.5
Type of Electro-Osmosis Electrification (on/off)	Continuous Electrification	Continuous Electrification	Continuous Electrification	2h/1h	2h/1h	2h/1h	Continuous Electrification	Continuous Electrification	Continuous Electrification
Whether Anode Advancement is Applied	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

First, the electrodes are placed inside the experimental tank. After mixing the prepared soil sample evenly, it is filled into the model box in layers. Subsequently, potential measuring probes are inserted at preset intervals. The power supply and electrodes are connected using wires. Finally, the upper surface of the soil chamber is covered with plastic wrap to prevent water loss from the soil. Once the assembly is complete, the power supply is turned on to begin the experiment. During the experiment, the potential, current, and drainage volume are recorded every 0.5 hours.

3. Experimental Results and Analysis

3.1 pH at Different Locations in the Soil Mass

Figure 3 presents the pH values at various locations in the soil mass after electroosmosis for Group C. Overall, after the three groups of experiments, the soil pH gradually decreases with increasing distance from the cathode for all groups. Regarding the soil pH near the cathode, Group C3 has the highest value, while Group C1 has the lowest. Conversely, for the soil pH near the anode, Group C3 has the lowest value, and Group C1 has the highest.

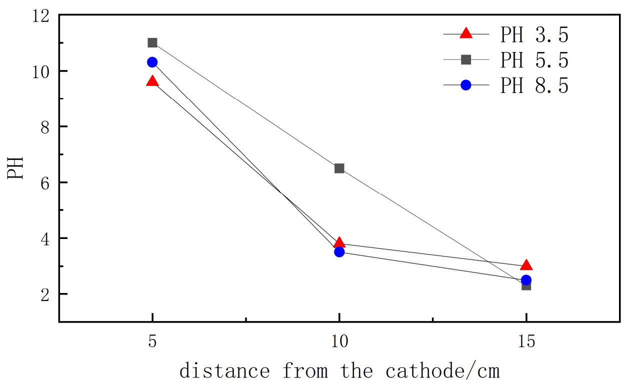

Figure 3. pH of Soil After Electro-Osmotic Treatment.

The relationship between soil current values and time for Group C experiments is shown in Figure 4. Overall, as water in the soil is gradually drained out during the experiment, the soil resistance gradually increases, leading to a decreasing trend in voltage. In the early stages of the experiment, the current intensity of Group C1 was higher than that of Groups C2 and C3, but its current intensity decayed at the fastest rate, while Group C3 had the slowest decay rate. After 9 hours, Group C3 had the highest current intensity, while Group C1 had the lowest.

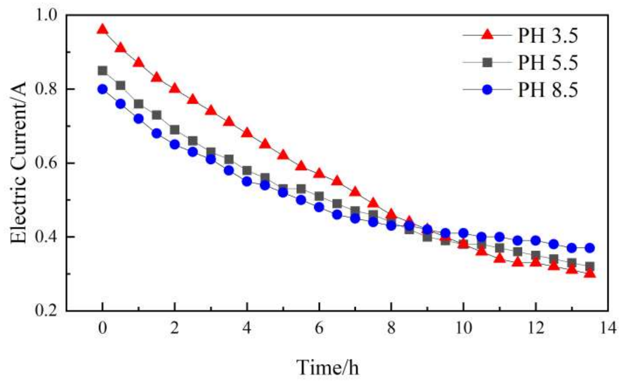

Figure 4. Current Variation Curve.

During the experiment, water electrolysis occurs at the electrodes, generating H+ ions at the anode and OH- ions at the cathode. These ions enter the soil, resulting in a gradual decrease in soil pH near the anode and a gradual increase in soil pH near the cathode. After the experiment, compared to the other two groups, Group C3 had the lowest soil pH near the anode and the highest soil pH near the cathode. The reason for this phenomenon is that Group C3 generated more H+ and OH- ions during the experiment than the other two groups. This is because the current intensity of Group C3 remained higher than that of the other two groups after 9 hours of experimentation, leading to a stronger water electrolysis reaction in the soil of Group C3.

3.2 Changes in Drainage Volume and Drainage Rate

Figure 5 illustrates the relationship between cumulative drainage volume and time during the electro-osmosis process for Groups C1 to C3. The drainage volume continuously increases with time, but the rate of increase gradually diminishes. The final drainage volumes for the three groups are 408.6 mL, 435.3 mL, and 444.4 mL, respectively, indicating an increase in final drainage volume with increasing pH. The reason for the insignificant difference in final drainage volume between Group C2 and Group C3 is that Group C2 had a higher content of pH adjuster added, and the drainage volume was influenced by salinity.

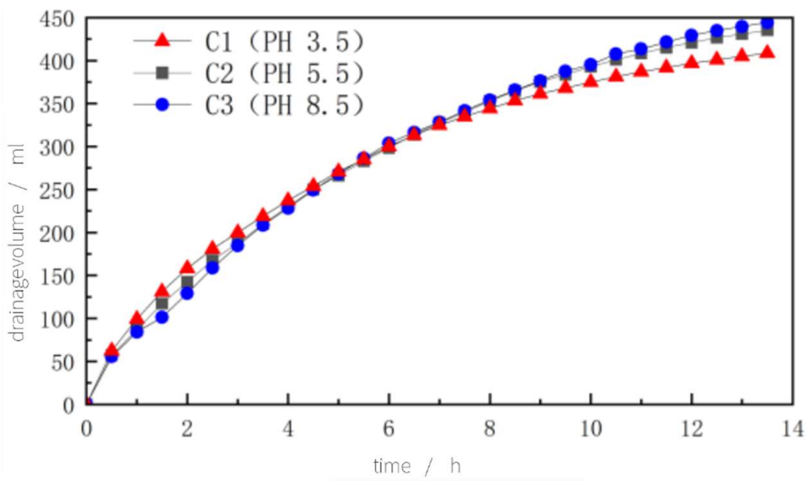

Figure 5. Variation Curve of Electro-Osmotic Dewatering Volume for Group C.

Figure 6 shows the drainage volume variation curves during the experiments for Groups A and B. Since the power supply for Group B was interrupted for 1 hour every 2 hours of electro-osmosis, for the purpose of comparison, the total duration of power-on is defined as effective electro-osmosis time. At the beginning of the experiment, there was little difference in drainage volume among the six test soil samples. After 2 hours, the electro-osmosis drainage volume of Group B3 was significantly higher than that of the other groups. After 6 hours, the drainage volume of Group B2 was lower than that of Group B3 but much higher than the other four groups, among which there was little difference in drainage volume. After 10 hours, the gap in drainage volume between Groups B2 and B3 gradually narrowed over time. The final drainage volumes for Groups B1, B2, and B3 were 386.33 mL, 434.82 mL, and 439.53 mL, respectively. For Group A, the final drainage volumes were 363.14 mL, 372.63 mL, and 395.73 mL, respectively. Similar to Group C, a higher initial soil pH resulted in a higher final drainage volume. Comparing Groups A and B, the final drainage volumes of Groups A2 and A3 were significantly higher than those of Group B, and the final drainage volume of Group B1 was only lower than that of Group A3 in Group A. Additionally, the rate of increase in drainage volume for Groups B2 and B3 suddenly accelerated immediately after power was restored following the 1-hour interruption, indicating that the rate of electro-osmosis drainage in the soil was higher after the power interruption than before.

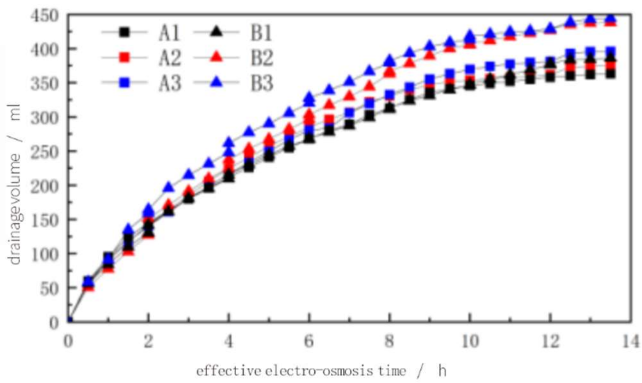

Figure 6. The variation curves of electro-osmotic drainage volume for Group A and Group B.

Figure 7 displays the changes in drainage rate for Group C, showing an overall downward trend in the drainage rate across the three experimental groups. This is attributed to several factors. Firstly, as water in the soil gradually drains out under the combined effects of gravity and the electric field, the soil resistance increases, causing a corresponding decrease in current and subsequently the drainage rate. Secondly, as the soil moisture content decreases, the double-layer cushion becomes thinner, leading to an increase in the interaction force between water molecules and soil particles. This requires more energy for drainage, yet the output voltage of the power supply remained constant at 36V during the experiment, resulting in a reduced drainage rate.

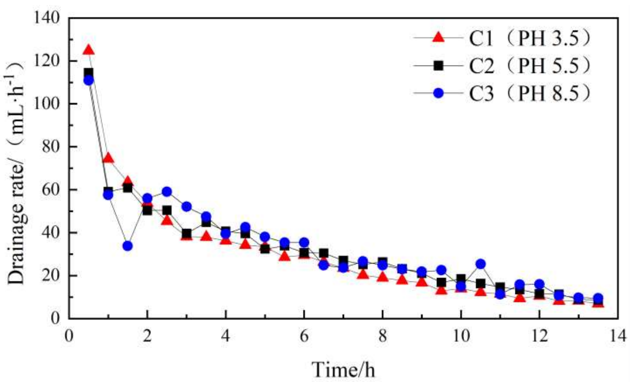

Figure 7. Variation Curve of Dewatering Rate for Group C.

In the variation of drainage rate displayed in Figure 8 for Group B, there are significant increases in drainage rate at the time points of 3h, 6h, 9h, 12h, 15h, and 18h. These time points correspond exactly to the moments when power was restored after a 1-hour interruption. This indicates that the intermittent power supply mode with a ratio of on-to-off time of 2:1 and an off time of 1 hour can significantly enhance the electro-osmosis drainage rate.

While the time points of 2h, 5h, 8h, 11h, 14h, and 17h correspond to the moments when the power was off, it can be observed from the following figure that the drainage rate exhibited a significant downward trend at these time points, indicating that under the action of the electric field, water within the soil can be drained out more quickly.

Under the effect of anode advancement, there were slight increases in the drainage rate at 10h and 16.5h. This was because anode advancement was implemented at these two time points, which shortened the distance between electrodes and increased the electric field intensity, resulting in a faster drainage rate. Additionally, new copper plates were used for each anode advancement, leading to better results.

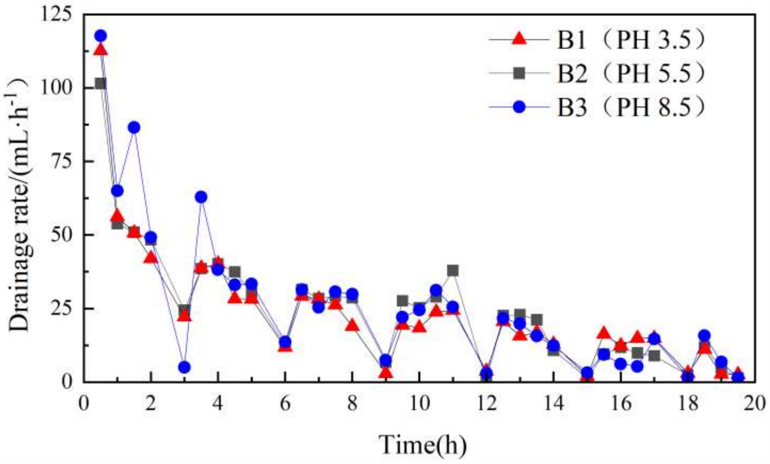

Figure 8. Variation Curve of Dewatering Rate for Group B.

3.3 Changes in Soil Electro-Osmosis Coefficient

The electro-osmosis coefficient of soil is calculated using Equation 1, where represents the electro-osmosis drainage rate, which in this experiment is obtained by dividing the drainage volume every half hour by the corresponding time period; E is the effective electric potential, assumed to remain constant over each 0.5-hour interval and considered as a uniform electric field in the experiment. The effective electric potential is the ratio of voltage to the length in the direction of the electric field. Since the voltage remains constant throughout the experiment, the effective electric potential is a fixed value; A is the cross-sectional area through which water or current flows in the soil. Since the interval between two recording points remains constant at 0.5 hours, the magnitude of the electro-osmosis coefficient is only related to the drainage volume recorded each time. Figure 9 shows the variation of the electro-osmosis coefficient during the experiment for Group C. From the figure, it can be seen that the electro-osmosis coefficient generally shows a downward trend, with a faster decline before 2 hours and a slower decline thereafter. Although Group C1 has a higher electro-osmosis coefficient in the early stages of the experiment due to the higher salinity of the soil, after 2.5 hours, the experimental group with an initial soil pH of 8.5 has an electro-osmosis coefficient that is almost consistently slightly higher than the other two groups.

$$K_e = \frac{V_e}{EA} \tag{1}$$

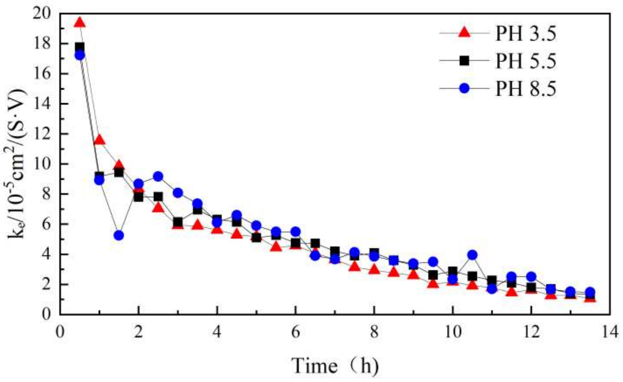

Figure 9. Variation Curve of Electro-Osmotic Coefficient.

3.4 Water Content at Different Locations in the Soil Mass

Figure 10 shows the water content distribution measured after the experiment for each experimental group. In Group C, the soil water content at the cathode was higher than that at other locations. This is because during the electro-osmosis drainage experiment, water in the soil continuously moves towards the cathode when power is on. Initially, the rate of water accumulation at the cathode is greater than the rate of water drainage from the cathode, leading to water accumulation in the middle of the soil. However, as the experiment progresses, the accumulated water is eventually drained out. In Groups A and B, the soil water content at the anode was not only higher than that at other locations within the same group but also higher than that at the anode in Group C. This is due to the fact that the copper plates used for anode advancement were not perforated, preventing water from the non-electrified part of the soil from migrating to the cathode. Additionally, the electrification time for Groups A and B was shorter than that for Group C.

Secondly, under the same pH conditions, the water content of the soil in the middle section was highest in Group C and lowest in Group B. Moreover, the electrification time for the middle section of the soil in Groups B and A was shorter than that in Group C. This further confirms that the methods of anode advancement and intermittent power supply are beneficial for electro-osmosis drainage.

Under different initial pH conditions, all Groups A, B, and C exhibited a trend where the final water content of soil with a higher initial pH was lower than that of soil with a lower initial pH. This indicates that environmental conditions with a higher initial pH can enhance the effectiveness of electro-osmosis drainage.

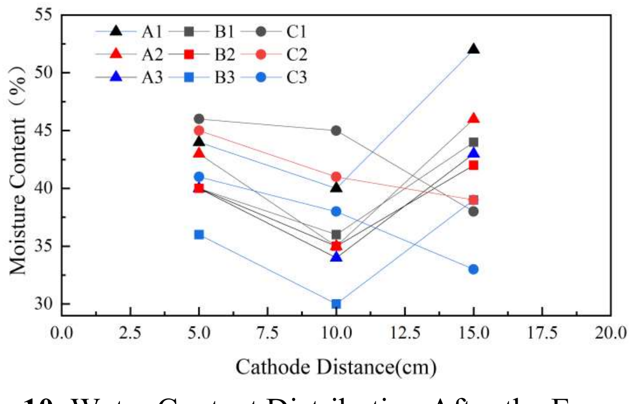

Figure 10. Water Content Distribution After the Experiment.

3.5 Changes in the Average Energy Consumption Coefficient

The issue of energy consumption has always held significant reference value in electro-osmosis research. Within the time t after the initiation of electro-osmosis power supply, the ratio of the total energy consumed by electro-osmosis to the total volume of water displaced represents the average electrical energy consumed per unit volume of water displaced. The average energy consumption coefficient C can be defined to compare the energy consumption levels of different experiments, with the unit being kW·h/L. The calculation formula is as follows:

$$C = \frac{\int_{t_1}^{t_2} U_t I_t dt}{Q} \tag{2}$$

In the formula, and are respectively the voltage applied to the soil and the current generated at time t, with the unit being amperes (A); Q represents the amount of water drained between time t1 and t2, with the unit being milliliters (mL).

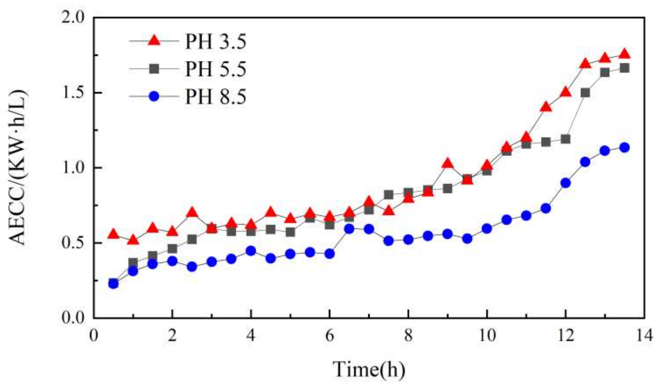

Figure 11. Variation of Average Energy Consumption Coefficient.

The relationship between the average energy consumption coefficient calculated based on the test results and the electrification time is shown in Figure 11. As the test progressed, the soil moisture content gradually decreased, leading to a reduction in the drainage rate. The average energy consumption coefficient exhibited a slow increasing trend and then rapidly increased after 10 hours. Additionally, the average energy consumption coefficient for the experimental group with an initial soil pH of 8.5 was consistently lower than that of the other two groups.

4. Conclusion

The impact of pH on the drainage of soft soil using the anode following electro-osmosis method was studied through indoor one-dimensional electro-osmosis experiments. Comparative analyses were conducted in terms of drainage volume, drainage rate, electro-osmosis coefficient, and energy consumption. The main conclusions drawn are as follows:

1) The initial pH value of the soil has a significant impact on the electro-osmosis effect. As the initial pH value of the soil increases, the final drainage volume of the soil also increases, and the electro-osmosis efficiency improves. The advantage of a high pH value becomes apparent after 6 hours.

2) The overall drainage rate of the soil tends to decline, but there is a significant increase in the soil drainage rate after intermittent electrification with the anode following and a ratio of 2:1 for electrification and de-electrification, with the de-electrification duration being 1 hour.

3) NThe experimental group with a higher initial soil pH had slightly lower energy consumption compared to the group with a lower initial soil pH.

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