

# Electro-Osmosis Treatment of Lead-Contaminated Soil with Carbon Fiber-Based Geotextile Electrodes

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The application of electro-osmosis (EO) can rapidly improve the strength of soft soil by EO consolidation; at the same time, heavy metal migration in the soil can be induced. Traditional metal electrodes have many shortcomings and need to be improved. This paper investigates the effects of carbon fiber-based geotextiles (CFBGs) as electrodes on the characteristics of EO for the treatment of lead-contaminated soil. The experimental results show that the CFBG material leads to a lower electric current and energy consumption coefficient than stainless steel (SS) electrodes at similar drainage volumes, thus expending less energy than the SS electrodes. The treatment effect of CFBGs on lead migration is better than that of SS, which is due to the inert electrochemical properties of the CFBGs. In addition, the presence of lead results in an irregular distribution of the bearing capacity of the soil after EO. Finally, the EO treatment mainly reduces the contents of the exchangeable and carbonate-bound lead fractions, which is due to the strong mobility of exchangeable lead and the acidic environment generated at the anode.

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**Keywords:** Electro-osmosis; Carbon fiber-based geotextiles; Lead; Migration; Exchangeable.

## 1. INTRODUCTION

The soft soils in coastal areas are mostly fine, soft clays with high water content and porosity [1, 2], and traditional drainage consolidation methods such as preloading and vacuum preloading require a relatively long construction period [3, 4]. The electro-osmosis (EO) drainage reinforcement method has many advantages compared to traditional methods, such as high drainage efficiency and short construction periods [5-7], and this method can rapidly consolidate soft soil to improve the bearing capacity of foundations [8, 9]. However, several problems with EO treatments exist, e.g., the high cost

of electrodes, corrosion phenomena [9, 10], electric potential losses and high energy consumption [11, 12].

To solve these problems, researchers have conducted many experiments. Electrically conductive geotextiles have been developed to create inexpensive and corrosion-resistant electrodes, such as electrokinetic geosynthetics (EKGs) [13, 14]. EKGs are similar to the current common geosynthetic material and provide electrical conductivity while reinforcing the soil and enhancing the soil shear strength [11, 13]; thus, they can be applied in practical EO treatments. Compared with traditional electrode materials such as stainless steel (SS) and copper, EKG has advantages such as low cost, corrosion resistance and a lack of secondary pollution [14-16]. The conductive materials used in EKG mainly include carbon black, carbon fiber, conductive filler polymers, and corrosion-resistant metal wire [14, 16, 17]. Carbon fiber-based geotextiles (CFBGs) are studied in this paper. Carbon fiber materials have good electrical conductivity, chemical durability and almost no loss of themselves during EO [16, 18, 19].

During the process of rapid consolidation caused by EO, heavy metal migration in the soil can be induced, which reduces the concentration of heavy metals in the soil [20, 21]. The migration mechanisms include EO flow, electromigration and electrophoresis [22, 23]. Metal cations can be effectively driven to the cathode under the action of the seepage field and concentration field. With the rapid increase in human industrial activities, soil lead pollution has become increasingly serious (e.g., 1.5% of the land in China exceeds the lead standard values) [24]. In 1993, Lageman [25] conducted EO experiments on outdoor fields that were seriously contaminated with Cu and Pb. The results showed that the removal rate of Pb reached 70% after 43 days of applying EO for 10 hours per day. Probst et al. [26] found that EO treatment costs approximately \$20-30 per ton of soil, which is significantly less than the \$150 per ton required for conventional treatments. However, when metal is used as an electrode material, the heavy metals from the electrode materials, such as copper, chromium and nickel, will migrate to the soil due to electrode corrosion and other reasons [11], resulting in secondary pollution. Therefore, the adoption of a stable electrode material will reduce the risk of secondary pollution during the treatment process.

Therefore, the use of electrically conductive geotextiles in the treatment of lead-contaminated soft soil can not only rapidly EO consolidate the soil via EO but also improve the strength of the soil and reduce the concentration of lead in the soil. In this study, model experiments were conducted to explore the characteristics of EO for treating lead-contaminated soil with different electric potential gradients, different electrode materials (SS, CFBGs) and different lead concentrations. The EO drainage, electric current, and bearing capacity of the soil samples were recorded to study the EO characteristics. Lead concentration and speciation were tested to explore lead migration during EO. In addition, the migration of chromium and nickel through the SS electrode material during EO was analyzed.

## **2. MATERIALS AND EXPERIMENTAL METHODS**

### *2.1. Material preparation*

The soil used for the experiments was river silt dredged from the Yong River, Ningbo, China. The properties shown in Table 1 were obtained following the “Standard for Soil Test Method” [27].

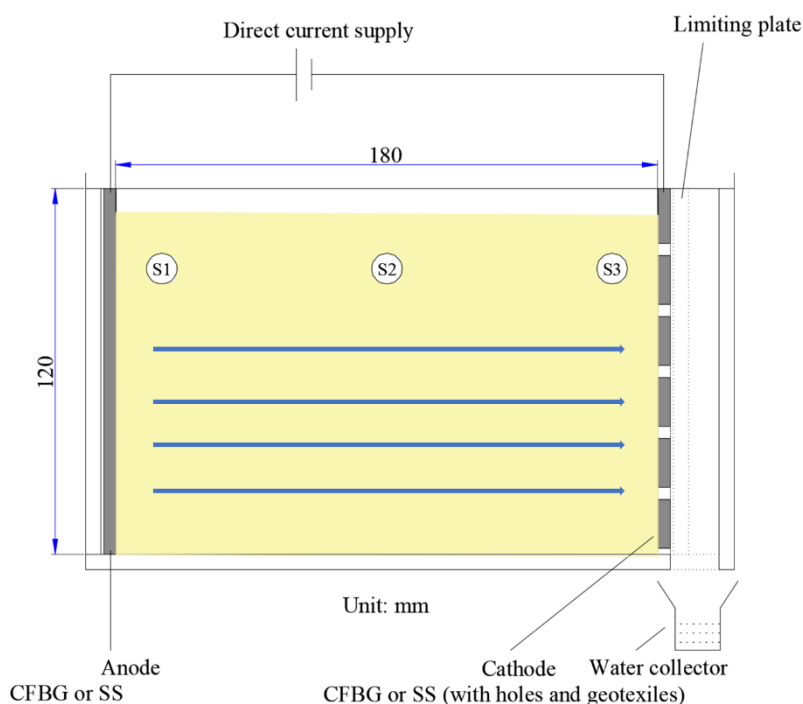
**Table 1.** Properties of the river silt

Water content (%)	Unit weight (kN m <sup>-3</sup> )	Plastic limit (%)	Liquid limit (%)	Specific gravity
39.4	18.6	20.2	42.6	2.72

2.2. Testing apparatus and method

As shown in Fig. 1, the testing apparatus was mainly composed of acrylic boxes, a direct current power apparatus, anodes (CFBG or SS plates), cathodes (CFBG or SS plates with holes and gauze (to prevent the loss of soil particles)), cathode drainage outlets, and water collectors. The internal size of the acrylic box was 180 mm × 120 mm × 120 mm. The direct current power apparatus was produced by Beijing HSPY Technology Co., Ltd., China.

The carbon fiber used in this study was based on a 3k carbon fiber precursor that was obliquely woven, which belongs to the PYROFIL series provided by the Mitsubishi Chemical Corporation, Japan. The carbon fiber is composed of PAN-based materials manufactured from acrylic fibers carbonized at a high temperature. We modified the weave form of the carbon fiber to make it more suitable for EO treatment, thus forming electrically conductive geotextiles (CFBGs). One side of the carbon fiber was specifically combined with geotechnical press-cloth (to prevent soil particle loss), and the other side was not treated (for contact with soil). The CFBG material has both electrical conductivity and a certain strength, as well as the function of reverse filtration.



**Figure 1.** Schematic diagram of the testing apparatus in this study (profile view)

A pocket penetrometer (XGR-3.0/4.0) was adopted to test the bearing capacity after treatment at the S1–S3 positions. The content and speciation of lead from the soil was sampled at the S1–S3 positions.

The S1 position represents the soil in the anode area, the S2 position represents the soil in the middle area, and the S3 position represents the soil in the cathode area. To avoid the influences of soil contraction and boundary effects on the test results, the soil sampling positions in the anode and cathode areas were 15 mm away from the respective electrode. During the test, the surface of the soil sample was scraped to create a flat surface, the penetrometer was pressed into the soil at a constant speed, and the data were recorded when the indicator was stable. Each position was sampled and tested three times, and the results were averaged. The sampling positions are shown in Fig. 1.

To determine the content of lead in soil, 0.1 g of soil was weighed and transferred to a 40 mL polytetrafluoroethylene crucible. Five milliliters of hydrofluoric acid, 3 mL of nitric acid and 1 mL of perchloric acid were added to the crucible and covered with a lid. Then, the mixture was heated at 120 °C for 3 hours. After that, the lid was moved, and the mixture was heated at 180 °C to evaporate the acid. Finally, 5 mL of 20% nitric acid was added to the crucible, heated to a slight boil, and then transferred to a 50 mL volumetric flask to ensure a constant volume. The lead concentration was tested by the ICP-AES method with an Optima 7000DV instrument (PE, US). The test method for chromium and nickel content in soil is the same as above, which is aimed at detecting the contamination of the SS electrode during the EO process.

To study the mobility and transformation of lead during the EO process, the speciation of lead was determined by the Tessier sequential extraction procedure [28] using the samples before and after the EO treatment. Through the five steps, the proportions of exchangeable lead, lead bound to carbonates, lead bound to Fe-Mn oxides, lead bound to organic matter and residual lead were determined. In each step, the lead concentration in the supernatant was measured in the same way as described in the previous paragraph.

### 2.3 Experimental process

**Table 2.** Experimental conditions for the samples

Group	Electrode material	Potential gradient (V cm <sup>-1</sup> )	Lead concentration (mg kg <sup>-1</sup> )
T0	SS	1.5	0
T1	CFBGs	0.5	0
T2	CFBGs	1.0	0
T3	CFBGs	1.5	0
T4	SS	0.5	5000
T5	SS	1.0	5000
T6	SS	1.5	5000
T7	CFBGs	0.5	5000
T8	CFBGs	1.0	5000
T9	CFBGs	1.5	5000

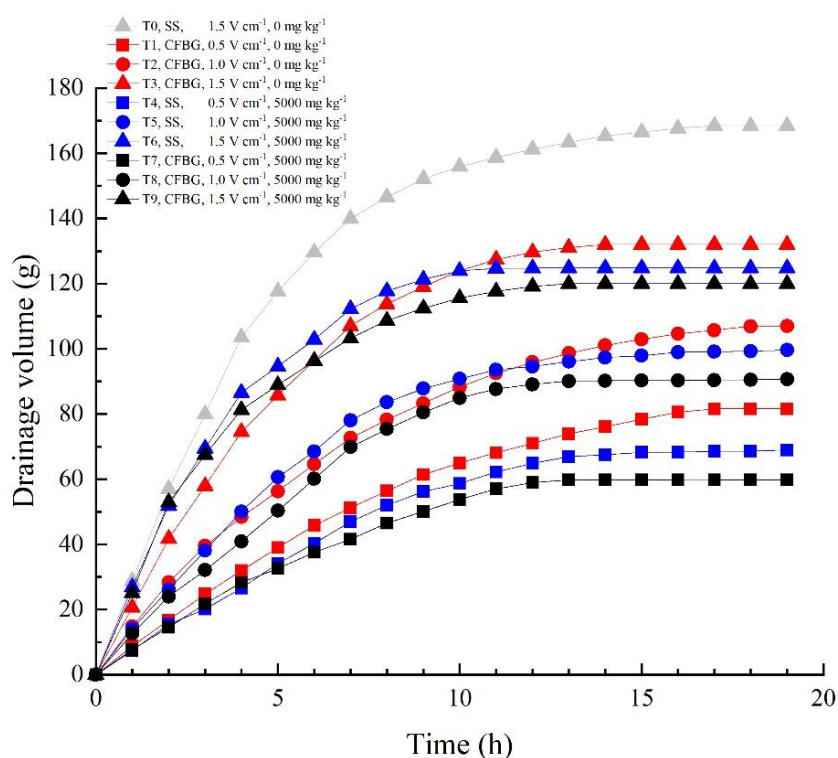
Before the test, the soil was dried, broken and ground into a powder. First, artificially lead-contaminated soil was prepared. Lead nitrate powder, dry soil powder and deionized water were mixed, and the target water content was controlled at 50%. The lead-contaminated soil was sealed for 10 days

to achieve stability between the soil and lead to ensure that the experimental conditions of the artificially lead-contaminated soil were close to the actual conditions. The content of lead nitrate relative to dry soil was  $5000 \text{ mg kg}^{-1}$ .

Before the application of EO, the cathode and anode were installed, and the soil was placed into the acrylic boxes in layers. The boxes were sealed on top with plastic film to reduce evaporation. Under the action of direct current, the pore water in the soil moved from the anode to the cathode and flowed into a water collector below the cathode. The details of the experimental conditions in the different groups are shown in Table 2. The electric current and the volume of drained water were recorded during the EO process. The energy consumption coefficient was calculated to represent the electrical energy consumed for EO drainage in unit mass. The soil bearing capacity, concentration of lead, chromium and nickel, and lead speciation were tested after EO.

### 3. RESULTS AND DISCUSSION

#### 3.1. EO drainage



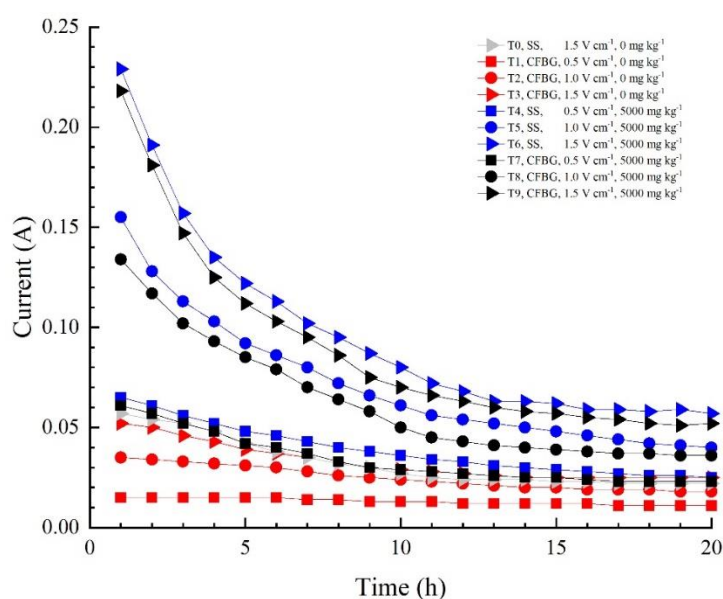
**Figure 2.** Variations in the EO drainage volume with time for different electrode materials (SS or CFBG), electric potential gradients ( $0.5$ ,  $1.0$  or  $1.5 \text{ V cm}^{-1}$ ) and lead concentrations ( $0$  or  $5000 \text{ mg kg}^{-1}$ )

Fig. 2 shows the drainage volume over time. With the increasing potential gradient, the total volume of drained water and the drainage rate also increased in each group with the same electrode material and lead concentration. This change occurred because the pore water in the soil moved towards the cathode more rapidly under the action of a strong electric field, which is consistent with the

experimental results of Estabragh et al. [6] and Zheng et al. [12]. In the CFBG group without lead contamination (T1, T2, T3), the drainage volume improved by 31.1% and 23.4% when the electric potential gradient was  $0.5\text{--}1.0\text{ V cm}^{-1}$  and  $1.0\text{--}1.5\text{ V cm}^{-1}$ , respectively. In the CFBG group with lead contamination (T7, T8, T9), the drainage volume improved by 51.8% and 32.2% when the electric potential gradient was  $0.5\text{--}1.0\text{ V cm}^{-1}$  and  $1.0\text{--}1.5\text{ V cm}^{-1}$ , respectively. In the SS group (T4, T5, T6), the drainage volume improved by approximately 44.5% and 25.2% under the same variations in the electric potential gradient. As the electric potential gradient increased, the increment of the drainage volume increased first and then decreased. An optimal electric potential gradient appeared during the EO process. The drainage effect did not increase significantly when the electric potential gradient exceeded this optimal value. In addition, the addition of lead improved the drainage volume.

The comparison of the drainage volume of lead-contaminated soil with the different electrode materials (T4–T6; T7–T9) indicated that the drainage volume of the CFBG group was 13.3%, 8.9% and 3.9% lower than that of the SS group at electric potential gradients of  $0.5\text{ V cm}^{-1}$ ,  $1.0\text{ V cm}^{-1}$  and  $1.5\text{ V cm}^{-1}$ , respectively. The results showed that the drainage volume with the SS electrode was slightly larger than that with the CFBG electrode under the same electric potential gradient, with an average difference of approximately 8.7%. This difference may have occurred because the SS electrode has a smaller electric potential loss and a larger effective electric potential for soil than the CFBG electrode. A larger electric field exists in the SS group, leading to stronger EO drainage effects. The gap gradually decreases as the electric potential gradient increases, which may be because the SS electrode is not stable at a high electric potential gradient. Electrode corrosion results in an increase in the interface resistance at the anode of SS materials [10].

### 3.2. Electric current

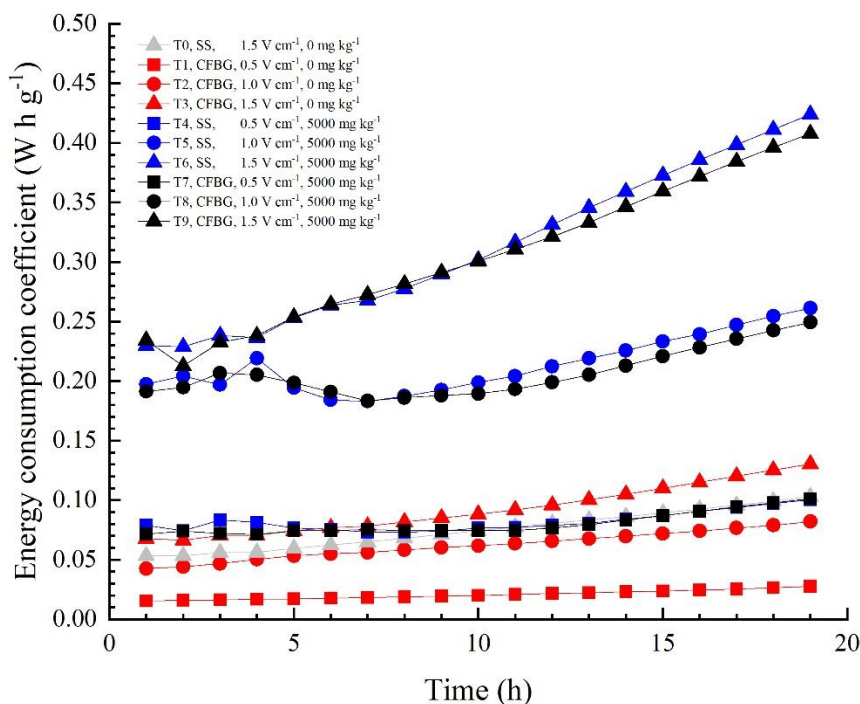


**Figure 3.** Variations in the electric current with time for different electrode materials (SS or CFBG), electric potential gradients ( $0.5, 1.0$  or  $1.5\text{ V cm}^{-1}$ ) and lead concentrations ( $0$  or  $5000\text{ mg kg}^{-1}$ )

As shown in Fig. 3, the electric current gradually decreased with the increase in the duration of the EO treatment. The electric current increased with increasing electric potential gradient, and the electric current in the SS group was higher than that in the CFBG group. The comparison of the lead-contaminated groups (T7–T9) to the normal soil groups (T1–T3) with the same electrode material indicated that the presence of lead nitrate significantly improved the electric current. More salt existed in the pore water in the lead-contaminated soil than in the normal soil, leading to stronger electrical conductivity than that in the groups with no additional lead. The electric current attenuation in the groups with a large electric potential gradient (T3, T6, T9) was also faster than that in the groups with a small gradient, especially when lead (T6 and T9) was added to the soil. The main reason for this difference is that a high electric potential gradient results in a high drainage rate, and the presence of lead leads to improved electrical conductivity. Under these conditions, more water is transferred to the cathode and drained per unit time. As a result, the soil resistance increases, and the electric current curve falls faster.

In the lead-contaminated groups (T4–T9) with SS or CFBG as the electrode material, when the electric potential gradient increased from 0.5 to 1.5 V cm<sup>-1</sup>, the difference in the electric current between the SS electrode and CFBG electrode under the same electric potential gradient showed a trend of increasing first and then decreasing, especially in the later period of EO. This result occurred because the corrosion rate of the SS electrode is fast under a high electric potential gradient, which leads to a low electric current [10, 29]. In contrast, the electrical properties of CFBGs are relatively stable under high voltage, while electrode corrosion and changes in interface resistance do not occur.

### 3.3. Analysis of energy consumption



**Figure 4.** Energy consumption coefficient for different electrode materials (SS or CFBG), electric potential gradients (0.5, 1.0 or 1.5 V cm<sup>-1</sup>) and lead concentrations (0 or 5000 mg kg<sup>-1</sup>)

The energy consumption coefficient is an important parameter of EO treatment and represents the electrical energy consumed for drainage in unit mass. The formula is as follows:

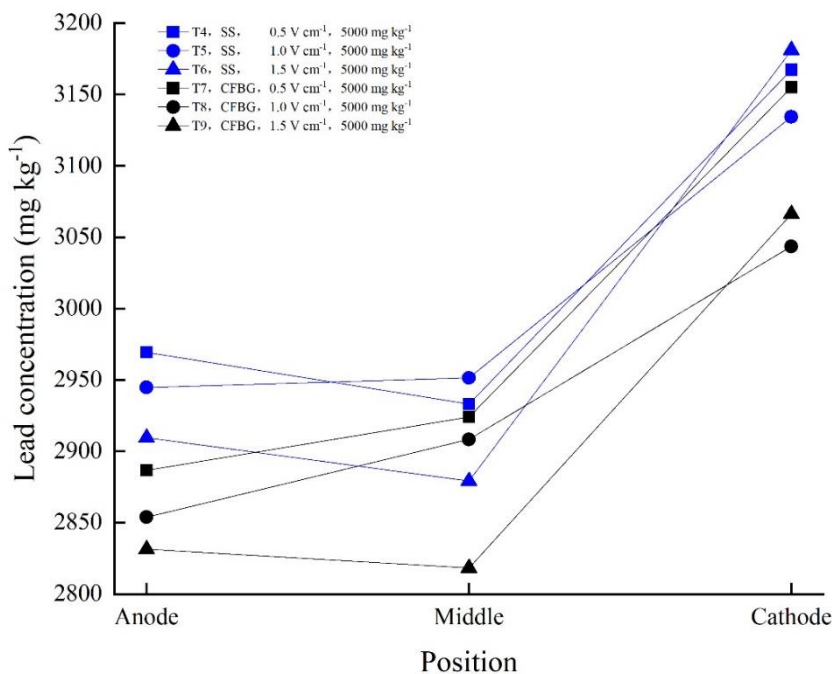
$$C = \frac{\int_{t_1}^{t_2} U(t)I(t)dt}{\int_{t_1}^{t_2} q_e(t)dt} \tag{1}$$

where  $C$  is the energy consumption coefficient at time  $t_1$  to  $t_2$  ( $W h g^{-1}$ ) and  $q_e(t)$  is the drainage rate ( $g h^{-1}$ ) at time  $t$ .

As shown in Fig. 4, over time, the energy consumption coefficient in each group increased. As EO continued, the water content decreased, and the electricity required for the drainage of each unit of water mass continued to increase; thus, the energy consumption coefficient of each group increased with time, which is similar to the findings of studies by Xue et al. [10] and Zheng et al. [12].

The energy consumption of the SS groups was higher than that of the CFBG groups, especially under electric potential gradients of  $1.0 V cm^{-1}$  and  $1.5 V cm^{-1}$ . This difference was related to the high electric current in the SS groups, as mentioned in section 3.2. The use of the CFBG electrode material expends less energy than SS electrodes to achieve the same drainage.

### 3.4. The concentrations of lead, chromium and nickel in soil after EO



**Figure 5.** Distribution of the lead concentration (T4–T9 groups after EO)

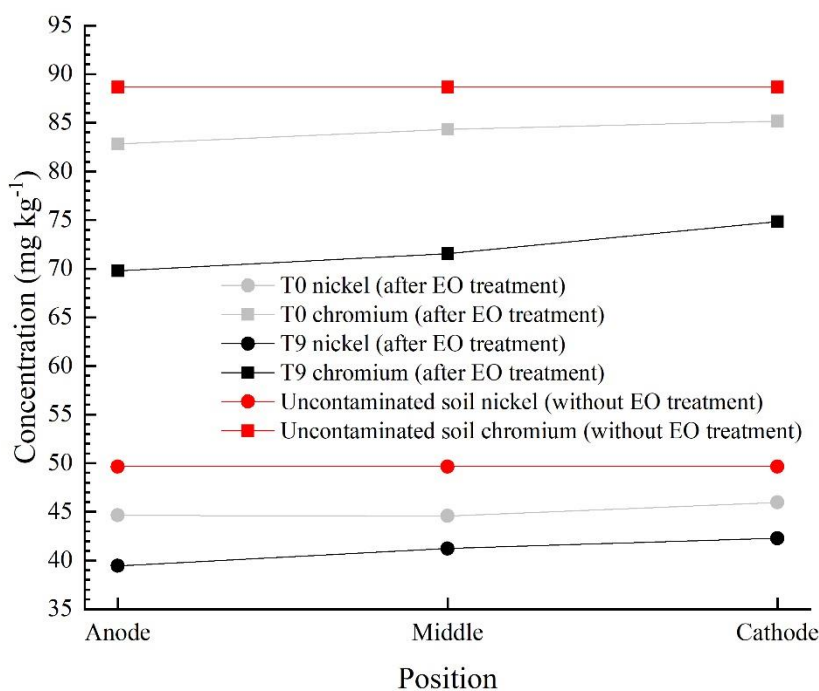
Fig. 5 shows the distribution of the lead content in different groups and positions. After the EO treatment, the lead concentrations in the anode and the middle area of the soil were similar but were significantly lower than that in the cathode, which was related to the migration and enrichment of lead caused by EO. In the cathode area, more  $OH^-$  is generated during the process of EO hydrolysis, and the



alkalinity of the cathode area increases. The lead that is transported to the cathode by EO flow is precipitated due to the alkaline environment and attaches to the soil particles, which causes lead accumulation over time. After the EO treatment, the overall concentration of lead in the soil was 3000 mg kg<sup>-1</sup> (approximately 40% of lead was discharged). Only a part of the free lead is in the pore water that can move freely, while the other part of the lead is adsorbed by the soil particles. In addition, as the EO treatment continues, the electric current and effective electric potential gradually decrease, and an excessively low electric current can no longer drive lead migration and discharge with water flow [30]. In addition, the relatively high pH in the cathode contributes to the desorption and dissolution of heavy metals from soil particles [31]; thus, more free lead can migrate from the soil with EO flow during the initial process of EO.

The comparison of the lead concentrations after the use of different electrodes indicated that CFBGs are more effective than SS for lead removal. This result may be because the SS electrode is more active in the EO treatment than the CFBGs; the SS electrode continuously corrodes and dissolves to participate in the electrochemical reaction, which leads to different metal ions from the SS migrating into the soil and interfering with the migration of lead.

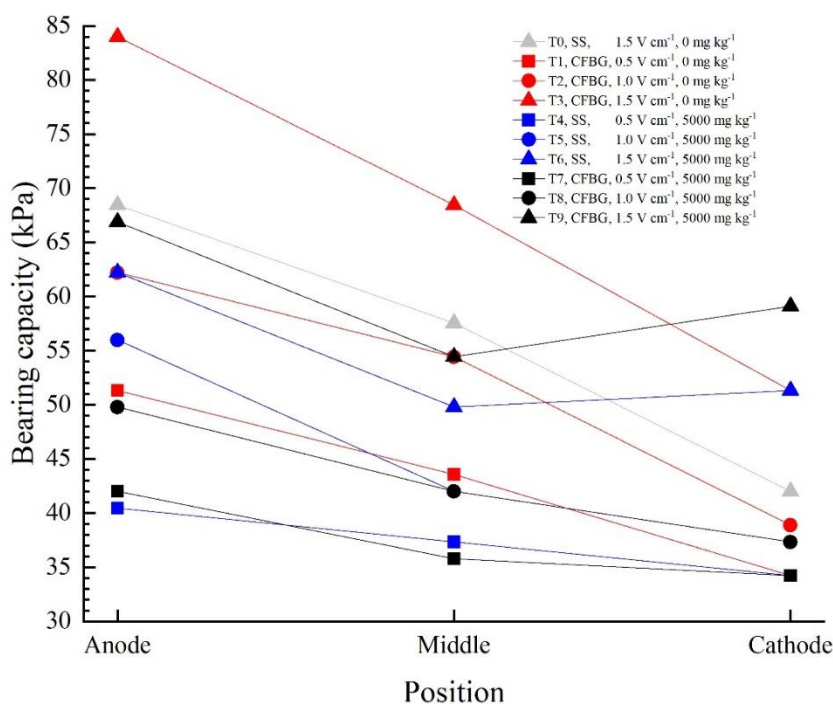
With an increase in the electric potential gradient, the lead concentration in the soil decreased gradually. When the voltage gradient was 0.5 V cm<sup>-1</sup>, the electric current was relatively low, resulting in the migration velocity of heavy metal ions being reduced [30]. Under the action of a strong electric field, heavy metal ion exchange and adsorption properties become more active [32, 33]. In addition, a high electric potential gradient leads to a decreased pH value near the anode, which results in more carbonate-bound lead near the anode being dissolved [34] and subsequently transported with EO flow.



**Figure 6.** Distribution of chromium and nickel concentrations (artificially contaminated in T0 group, T9 group with EO treatment or uncontaminated without EO treatment)

The distributions of the chromium and nickel concentrations are shown in Fig. 6. The comparison of the T9 group to the uncontaminated group indicated that chromium and nickel in the uncontaminated soil were 16.6 mg kg<sup>-1</sup> and 8.7 mg kg<sup>-1</sup> lower in the T9 group, respectively, and these amounts accounted for approximately 20% of the original concentration in the uncontaminated soil. The comparison of the T9 group to the T0 group indicated that ionized chromium and nickel from the SS electrode were produced constantly during the EO process. Compared to the T9 groups, the concentrations of chromium and nickel in the T0 group increased by 12.0 mg kg<sup>-1</sup> and 4.1 mg kg<sup>-1</sup>, respectively, accounting for 13.6% and 8.2% of the original concentrations in the uncontaminated soil. If the electricity period is long (more than 20 hours in this study), due to the oxidation reactions and interface resistance increase in the SS electrode materials, together with the low pH near the anode, severe corrosion of the SS electrode will occur [11]. Heavy metals can migrate into the soil with EO flow, causing unnecessary pollution. CFBG electrodes do not create this problem, avoiding additional pollution to the environment.

### 3.5 Bearing capacity distribution

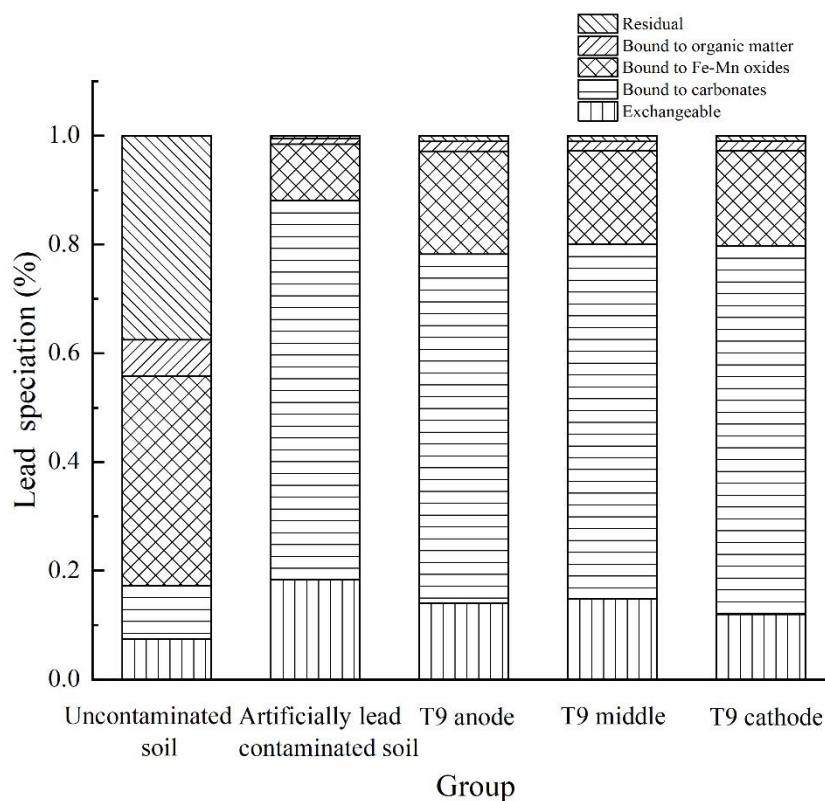


**Figure 7.** Soil bearing capacity for different electrode materials (SS or CFBG), electric potential gradients (0.5, 1.0 or 1.5 V cm<sup>-1</sup>) and lead concentrations (0 or 5000 mg kg<sup>-1</sup>)

The distribution of the soil bearing capacity after EO treatment is shown in Fig. 7. The bearing capacity of the soil increases with the increase in the electric potential gradient under the same electrode material and lead concentration conditions, which corresponds to the trends in the drainage volume in section 3.1. At a high electric potential gradient, more pore water in the soil is driven towards the cathode and discharged, the soil porosity is reduced and the bearing capacity is increased.

In general, the bearing capacity of soil after EO followed the rule of anode > middle > cathode, which was due to the water content increasing from the anode to the cathode. However, in this experiment, the bearing capacity in the T6 and T9 groups showed cathode > middle. During the EO treatment, the alkaline environment in the cathode can generate  $Pb(OH)_2$ ,  $PbCO_3$ , etc. precipitates, and the drainage path becomes blocked. At the same time, it is difficult for pore water in the middle part of the soil to transfer to the cathode, leading to water accumulation in the middle; thus, the bearing capacity in the middle parts is lower than that in the cathode region. In addition, as detected in section 3.4, the lead concentration near the cathode is lower than that in the middle area. Resmi et al. [35] found that the addition of lead decreased the strength of soil. The concentration of lead in the soil will lead to changes in the soil microstructure and increase the soil porosity and permeability [36]. In addition, the higher bearing capacity of the T0 and T3 groups (not contaminated by lead) than the other groups is due to their higher drainage volume, as noted in section 3.1.

### 3.6 Variations in lead speciation before/after EO



**Figure 8.** Variations in lead (uncontaminated soil, artificially lead-contaminated soil and T9 test group in anode, middle and cathode positions)

As shown in Fig. 8, the speciation of lead in the uncontaminated soil ( $24.63 \text{ mg kg}^{-1}$  in the natural environment) is much different from that in the artificially lead-contaminated soil ( $5000 \text{ mg kg}^{-1}$ ). In artificially lead-contaminated soil, more lead exists in the exchangeable and carbonate-bound forms. The different chemical forms of lead have different properties. Exchangeable lead has the highest solubility,

while residual lead is the most stable. Lead that is bound to carbonates can also be easily released into solution under conditions such as an acidic environment [34], and it has relatively strong mobility [37]. The fractions bound to Fe-Mn oxides and bound to organic matter are also referred to as the reducible and oxidizable fractions, respectively, and their mobility is relatively low [38].

The fractions of exchangeable lead and carbonate-bound lead were reduced after the EO treatment. The proportions of the fractions bound to Fe-Mn oxides and bound to organic matter increased, but their total concentrations did not change. The main reason for this difference is that this experiment is only a single EO treatment of lead-contaminated soil and does not involve an electrokinetic leaching treatment. Therefore, there are relatively few processes of desorption and chemical reactions. Most of the exchangeable lead is induced to migrate and is removed by EO flow (pore water). Therefore, the amount of exchangeable lead in each group decreases substantially after EO. At the same time, the acidic environment at the anode (caused by anodic hydrolysis) can also dissolve some of the lead that is bound to carbonates. The carbonate-bound fraction at the anode of the T9 group was the lowest of that in all groups and positions.

#### 4. CONCLUSION

(1) When the electric potential gradient varies from 0.5–1.0 V cm<sup>-1</sup>, there is an optimal electric potential gradient that leads to a high drainage volume. The drainage volume with the SS electrode is slightly higher than that with the CFBG electrode under the same electric potential gradient, with an average of approximately 8.7%. The CFBG material leads to a decreased electric current and energy consumption coefficient and thus expends less energy than the SS electrodes.

(2) After the EO treatment, approximately 40% of the lead in the soil was discharged, and the overall concentration of lead in the soil was 3000 mg kg<sup>-1</sup>. The treatment effect of CFBGs was better than that of SS, which is due to the inert electrochemical properties of CFBGs. In addition, ionized chromium and nickel from the SS electrode were produced constantly during the EO process. Substantial amounts of chromium were transferred to the soil from the SS electrodes (accounting for approximately 13.6% of the amount in the uncontaminated soil). CFBG electrodes do not cause additional pollution to the environment.

(3) The presence of lead resulted in an irregular distribution of the bearing capacity of soil after EO because the highly alkaline environment in the cathode can generate Pb(OH)<sub>2</sub>, PbCO<sub>3</sub>, etc. precipitates, and the drainage path becomes blocked; in addition, the high concentration of lead changes the physical and mechanical properties of the soil.

(4) Through the Tessier sequential extraction procedure for lead, it was found that the EO treatment mainly reduced the amount of exchangeable and carbonate-bound lead, which was due to the strong mobility of exchangeable lead and the acidic environment generated at the anode.

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