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Utilization of Novel Electrokinetic Geosynthetics for Stabilization of Ultra-fine Tailings

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Abstract

Dewatering by means of electroosmosis involves placing a series of electrodes into the ground and applying a potential difference between the electrodes to induce water molecules to move towards the negative electrode from the positive electrode. Despite well documented applications of this technique for improving fine and ultra-fine sediments, the mining industry has yet to embrace this technology at field scale. One of the main impediments is the rapid electrode corrosion of conventional metal electrodes. Severe corrosion of electrodes can hinder the efficiency of this technique over time, which leads to increased energy consumption. The advancement of electrically conductive geosynthetics, also known as electrokinetic geosynthetics (EKGs), presents a significant opportunity to improve the industrial uptake of this technique by replacing conventional metallic electrodes, owing to EKGs vastly superior anti-corrosive properties. The current study investigated the performance of novel EKG electrodes in dewatering ultra-fine tailings using a laboratory-scale experimental approach. The dewatering efficiencies using EKG electrodes were compared with that of conventional metal electrodes (mild steel) by assessing the volume of water expelled, strength gain, end-of-test water content, and energy consumption. The results showed that for dewatering fine, slurried tailings, the novel EKG electrodes proved to be just as effective as their traditional metal counterparts, and usually better, since corrosion effects did not hinder the electroosmosis process. Although the variation in water content between the tests conducted with the two types of electrodes under the same voltage gradients was marginal, the use of EKGs has led to a significant enhancement in undrained shear strength. This constitutes one of the main advantages of utilizing EKGs for treating ultra-fine tailings.

Introduction

Stabilizing slurried, ultra-fine tailings is one of the significant challenges faced by the owners and operators of tailings storage facilities, particularly when it comes to closure and rehabilitation. While there are several conventional practices in the industry to enhance consolidation, these techniques are sometimes only moderately effective or impractical. Consolidation by means of electroosmosis offers a promising approach for treating slurried tailings. This technique involves placing a series of electrodes into the ground and applying an electrical potential difference between the electrodes to induce water molecules to move toward the negatively charged electrode from the vicinity of the positively charged electrode. When drainage is facilitated at the cathode, consolidation of material takes place in an amount equal to the quantity of water extracted.

One of the abiding factors that has impeded the widespread use of electroosmosis dewatering technique at the field scale is the severe corrosion of metal electrodes. Previous studies have demonstrated that metallic electrodes such as steel, copper, and aluminum are highly prone to corrosion, which negatively impacts efficiency and power consumption, which in turn impacts achieving the required degree of consolidation (Xue et al., 2015). Studies conducted with titanium and gold electrodes have shown little or no corrosion due to the corrosion-resistive properties, but the extremely high cost of these materials makes their usage in large-scale field applications not viable (Loch et al., 2010). In addition, non-metallic electrode types such as graphite have solved the corrosion issue to a considerable extent, although the disadvantages of these include: (1) lesser efficiency and (2) high brittleness (Malekzadeh et al., 2016).

The advancement of electrically conductive geosynthetics, also known as electrokinetic geosynthetics (EKGs), presents a significant opportunity to improve the industrial uptake of this technique by replacing conventional metallic electrodes, owing to EKGs' vastly superior anti-corrosive properties. The current study investigated the performance of novel EKG electrodes in dewatering ultra-fine tailings using a laboratory-scale experimental approach. The dewatering efficiencies using EKG electrodes were compared with those of conventional metal electrodes (mild steel) by assessing the volume of water expelled, strength gain, end-of-test water content, electrochemical changes and energy consumption.

Experimental methodology

Test materials

Commercially available kaolin clay was used to prepare the slurry specimens required for the testing. The basic physicochemical properties of kaolin are summarized in Table 1.

Table 1: Basic physicochemical properties of kaolin

Specific gravity	Liquid limit (%)	Plastic limit (%)	Clay content (%)	Silt content (%)	pH	Conductivity (mS/cm)
2.6	73.7	44.4	74.6	25.4	4.98	0.65

Experimental setup

The experiments were carried out using 20 L capacity (380 x 280 x 200 mm) tubs, as shown schematically in Figure 1. The electrodes utilized in the experiments were composed of either mild steel or EKGs. Both types of electrodes had the same nominal dimensions of 180 × 83 × 3 mm, whereas the weights of mild steel and EKG electrodes were approximately 226 g and 46 g, respectively. While there are various types of EKGs, the specific EKG electrodes used in the study are identical in size to a conventional prefabricated vertical drain but manufactured from electrically conductive polymer. A perforated polyvinyl chloride (PVC) tube encased in nonwoven geotextile facilitated drainage through a small hole at the bottom of the PVC tube, and the drained water was subsequently collected into a measuring cylinder.

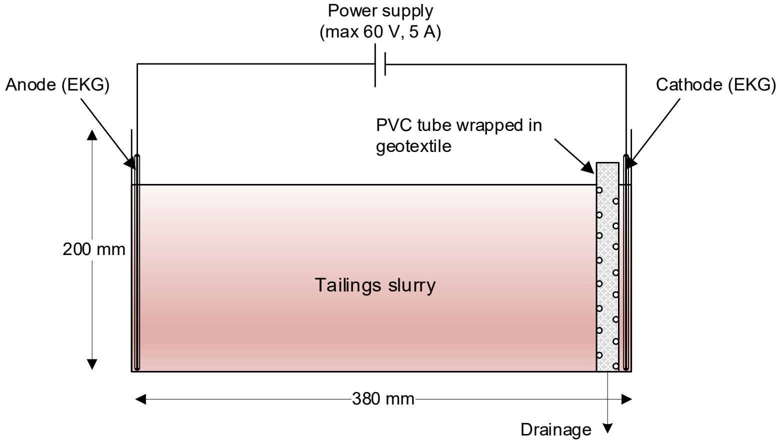

Figure 1: Schematic of the test setup

Test program

The kaolin slurry was prepared by mixing kaolin with deionized water to a water content of 150%. After 24 hours, the slurry was carefully poured into the tub to an initial height of approximately 160 mm. To prevent any moisture loss due to evaporation, the top surface of the tub was covered with clear plastic wrap. The volume of drained water and current were monitored at one-hour intervals, and the tests were terminated once the discharge rate fell below a threshold of 10 ml/hour. Once a test was completed, post-treatment moisture content and undrained shear strength were measured between the electrodes. Details of the test program are provided in Table 2.

Table 2: Details of the testing program

Test designation	Electrode material	Voltage gradient (V/m)	Voltage (V)
SE1	Mild steel	50	19
SE2	Mild steel	100	38
SE3	Mild steel	150	57
EK1	EKG	50	19
EK2	EKG	100	38
EK3	EKG	150	57

Results and discussion

Variation of drainage volume

The temporal variation of cumulative drainage volume for both types of electrode material is depicted in Figure 2a. As can be seen, the final cumulative discharges for tests conducted with EKGs under 150 and 100 V/m voltage gradients were 5.9% and 8.1% higher than those carried out with metal electrodes, respectively. In contrast, when the experiment was carried out at a relatively low voltage gradient (50 V/m), the test with the EKGs (EK1) resulted in an 11.5% lower discharge volume compared to the test with mild steel electrodes. Given that the electrode degradation rate is a function of the amount of electric charge according to Faraday's law, the reason for this behavior could be mainly attributed to the low corrosion rate occurring in the metal electrodes at lower voltage gradients. However, the corrosion effects may start to govern in metal electrodes even at low voltage gradients under field conditions since the dewatering usually extends for prolonged periods (Lockhart and Stickland, 1984).

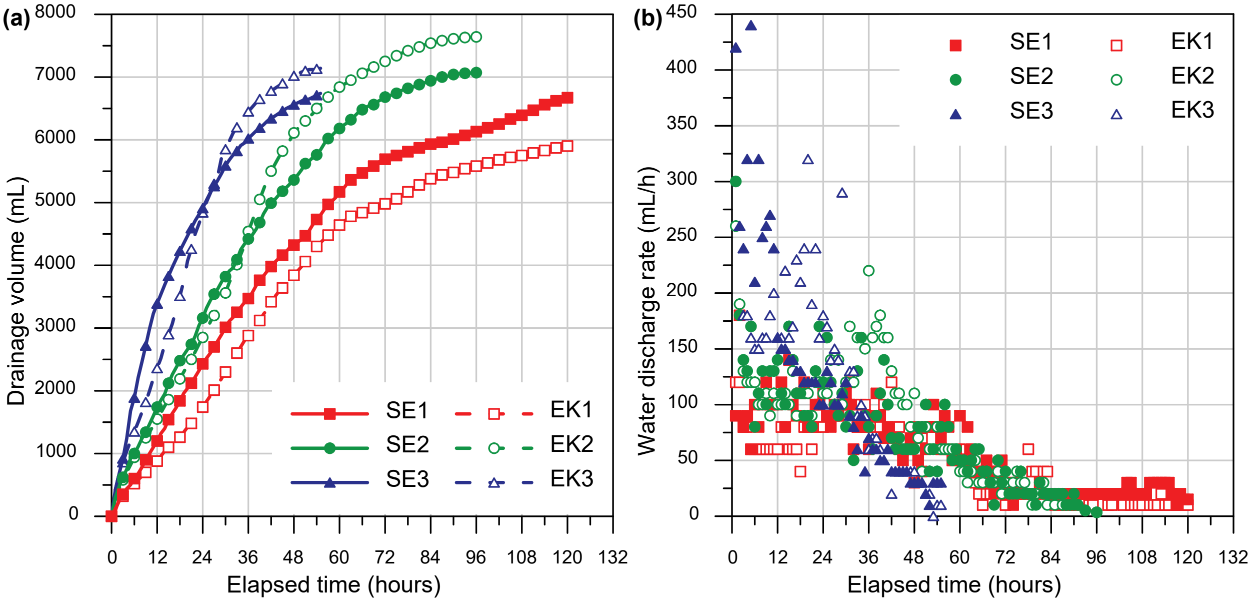

Figure 2: (a) Variation of drainage volume with time; (b) variation of drainage rate with time

It is apparent that the highest voltage gradient resulted in a lower discharge volume than that of the intermediate voltage gradient, regardless of the electrode type. This is predominantly due to the rapid desaturation of material in the vicinity of the anode, with other reasons being (1) loss of contact area between the electrode and soil, (2) electrochemical changes and (3) loss of applied voltage at the electrode interface.

According to Figure 2b, the water discharge rate was relatively constant for a longer time period in tests conducted with EKGs. Although the drainage rate was higher within the first few hours of the experiments with metal electrodes, a progressive declining rate over time can be seen since the early stages of the tests, particularly for SE2 and SE3. This ever-declining rate is an indication of corrosion occurring at the metal electrodes, which is also reflected by the electric current drawn during the tests, depicted in Figure 3a.

Power consumption

Figure 3a shows that the amount of current drawn was relatively constant for a longer period in tests with EKG at higher voltage gradients, whereas the current tends to drop earlier for the experiments with metal electrodes. Particularly in the case of SE3, the amount of electric current drawn dramatically reduced within the first 12 hours after the commencement of the test, hindering the water discharge rate. This behavior is closely related to the corrosion effects and subsequent voltage loss at the electrode-material interface, which is discussed in the forthcoming sections. Another noteworthy observation pertaining to test EK2 is that after fluctuating around 0.08 A for more than 24 hours, there is a sudden increase in the current drawn, peaking at around 0.16 A. While the prime factor that triggered this spike is not clear, previous studies have shown that changes in ionic concentrations, formation of additional conductive pathways for ion movement within the treated material, and pore structure changes of the material could alter the amount of current drawn during electroosmosis treatment (Liu et al., 2024; Pandey et al., 2024).

The electric current was then used to determine power consumption during the electrically assisted dewatering, and to facilitate comparisons between the tests, the power consumption was interpreted in terms of kWh/dry tonnes of treated material:

$$P = \int_0^t VIdt/W_s$$

where, P is the power consumption, V is the average voltage, I is the average current, t is the treatment time and W_s is the dry weight of the material calculated from the initial solids content.

As depicted in Figure 3b, dewatering with EKG electrodes under 50, 100, and 150 V/m consumed approximately 7.6%, 31.6% and 18.9% more power, respectively, compared to mild steel electrodes under the same voltage gradients. This is mainly because the amount of current drawn during the dewatering process is generally high (resulting from lesser corrosion effects) when EKGs are utilized. Although the power consumption is only marginally higher at the lowest voltage gradient (50 V/m), a noticeable increase in the power consumption can be seen at higher voltage gradients (100 and 150 V/m). However, this can be justified by the higher volume of water extracted using EKGs under 100 and 150 V/m voltage gradients. The currently available power consumption evaluation methods do not account for the degree of treatment achieved. This highlights the necessity for a better measure of power consumption, i.e., an approach that includes changes in material characteristics.

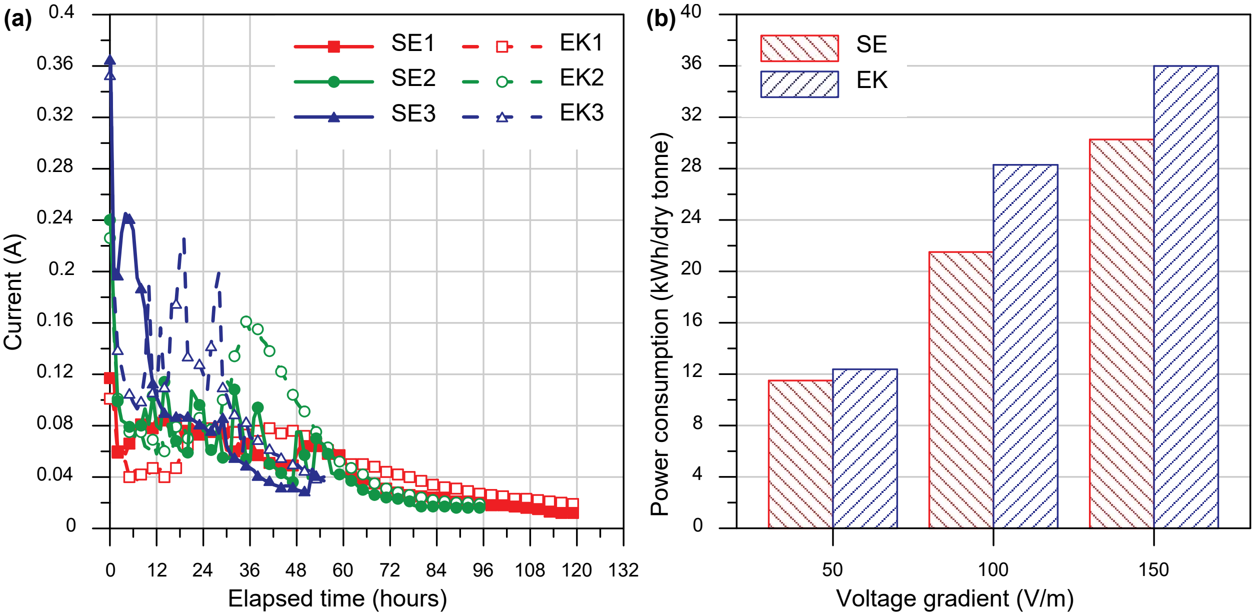

Figure 3: (a) Variation of current drawn with time; (b) power consumption in terms of kWh/dry tonnes of treated material

Electrochemical and corrosion effects

As dewatering progressed using the metal electrodes, the color of the surficial material adjacent to the anode was changed from its initial white to a yellow-brown color. Further investigation at the completion of the tests revealed that similar discoloration was present throughout the material stratum, irrespective of the applied voltage. This is a consequence of anode corrosion and subsequent accumulation of degraded substances in kaolin adjacent to the anode. Application of DC current between the electrodes not only induces the electroosmosis process, but also causes electrochemical reactions to occur adjacent to the electrodes (Mitchell and Soga, 2005). Oxidation will take place at the anode, generating oxygen gas and creating an acid front (due to the reduction in pH) in the vicinity of the anode. If the anode material is reactive (e.g., metal such as mild steel), it could oxidize and release ions into the adjacent soil matrix, causing anode corrosion, as observed in Figure 4a. Similarly, hydrolysis will occur at the cathode, generating hydrogen gas and creating a basic front (due to the increase in pH) in the vicinity of the cathode.

At the end of each test, the weight of the electrodes was recorded to determine the degree of electrode degradation based on the loss of weight during the electroosmosis dewatering. The degrees of anode degradation for the tests with steel electrodes under 50, 100, and 150 V/m voltage gradients were 3.27%, 2.91%, and 2.64%, respectively, whereas for the tests with EKGs, the anode degradation under the same voltage gradients were 0.51%, 0.13%, and 0%, respectively. It is clear that steel anodes undergo corrosion and subsequent degradation due to electrochemical reactions, whereas the EKG-type anodes demonstrated better corrosion resistance. Although the EKG electrodes exhibited minimal signs of corrosion in terms of the degree of degradation, upon close examination of the electrodes at the conclusion of the tests, some had formed bubbles (smaller than 1 mm in size) on the surfaces of the EKG. Unlike steel electrodes, where corrosion only occurred in areas where the electrode was in contact with the material, the bubbling effect in EKGs was observed beyond those areas, for instance, the section above the material surface horizon. Hence, it is unclear whether the "bubbling" effect is solely due to electrochemical reactions or rather a ramification of applying DC current. Although the polymers do not technically "corrode" as a metallic material (Schweitzer, 2009), it is nevertheless important to further investigate the root cause for this effect as it could compromise the durability of EKGs in long-term field applications.

Regardless of the electrode material, the degree of cathode degradation under all voltage gradients was less than 0.1%, indicating no signs of corrosion as explained by electrochemical theories (Micic et al., 2001). Another noteworthy observation regarding the steel electrodes is the formation of a thin, dark layer in the sections where the electrode is in contact with the material. This is believed to be oxide precipitates resulting from electrochemical reactions. According to Xue et al. (2015), X-ray diffraction tests have revealed that these types of substances present extremely low conductive characteristics. The formation of precipitate films adjacent to electrodes could result in significant potential loss at the soil-electrode interfaces and subsequently lead to a sharp increase in resistivity. No such behavior was observed in EKG electrodes, which may be the reason for the relatively steady water extraction rate during the dewatering process (Figure 2b).

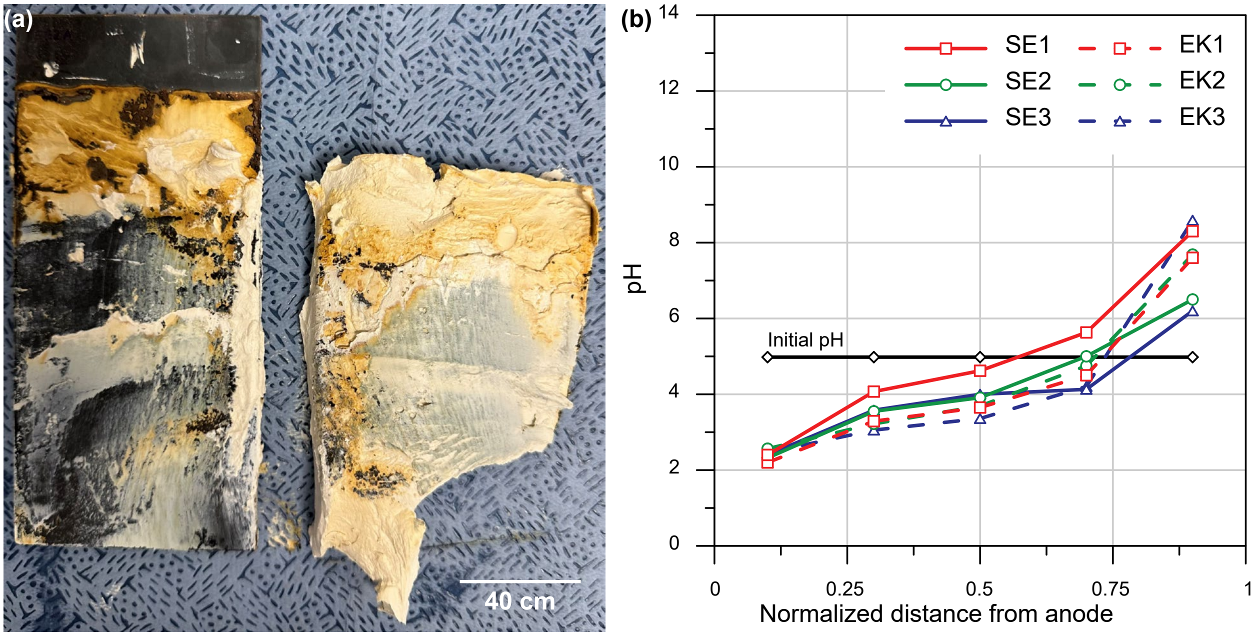

Figure 4: (a) Corrosion observed in anode and adjacent soil at test SE2; (b) variation of pH between the electrodes

Figure 4b shows the pH variation between the electrodes with respect to the normalized distance from the anode (distance to the sampling point from the anode normalized by the distance between electrodes). As expected, the material near the anode exhibited acidic conditions due to hydrogen ion (H^+) release. The pH value of the anodic zone was generally about 2.4, irrespective of the electrode type and the voltage gradient, indicating a twofold decrease from the initial state. In contrast, the pH in the vicinity of the cathode increased due to the release of hydroxide ions (OH^-); nonetheless, the pH values demonstrated considerable variability. The post-treatment pH value of the material near the cathode ranged from 6.2 to 8.6, which is approximately a 50% average increase from the pre-treatment pH. As depicted in Figure 4b, the material away from the electrodes (0.3 – 0.5 normalized distance from the anode) experienced a lesser change in pH. Interestingly, the posttreatment pH of the tailings treated with EKGs was comparable to that of metal electrodes, despite the EKGs being manufactured from non-metallic polymer material.

Variation of water content

The distribution of water content between the anode and cathode is presented in Figure 5. On average, the water content of the slurry reduced approximately 70% from the initial value of 150% due to the electroosmosis treatment. As expected, EK1 has the lowest average reduction in water content (88%) and is 7% higher than the water content obtained from the test with metal electrodes under the same voltage gradient. In contrast, the post-treatment average water contents for tests conducted with EKGs under 150 and 100 V/m voltage gradients are 4.2% and 8.8% lower than those carried out with metal electrodes, respectively. The obtained water content values are generally in line with the extracted water volumes presented in Figure 2. Overall, the results of water content measurements further showed that the EKGs performed slightly better in dewatering compared to metal electrodes at high voltage gradients.

The electroosmosis process causes the water molecules to move toward the cathode from the vicinity of the anode and as a result, the water content at the anode is generally lower than that at the cathode. However, no such variation was found in the present study. According to Figure 5, the water content is generally low at the closest sampling point to the anode, but as the sampling location moves towards the cathode, it starts to increase before starting to decrease again, indicating the highest water content at the section before the halfway point between the electrodes (0.3 – 0.5 normalized distance from the anode). The reason for this behavior could be mainly attributed to the formation of shrinkage cracks perpendicular to the flow path (Figure 6), which subsequently resulted in disrupting the conductivity and electroosmotic flow (Jayasiri et al., 2024). It appears that the shrinkage cracks may have acted as a barrier up to a certain degree, preventing water molecules from passing from the anode section to the cathode. Besides the above, loss of contact area between the electrode and soil cluster due to electrode detachment could also contribute to this peculiar behavior.

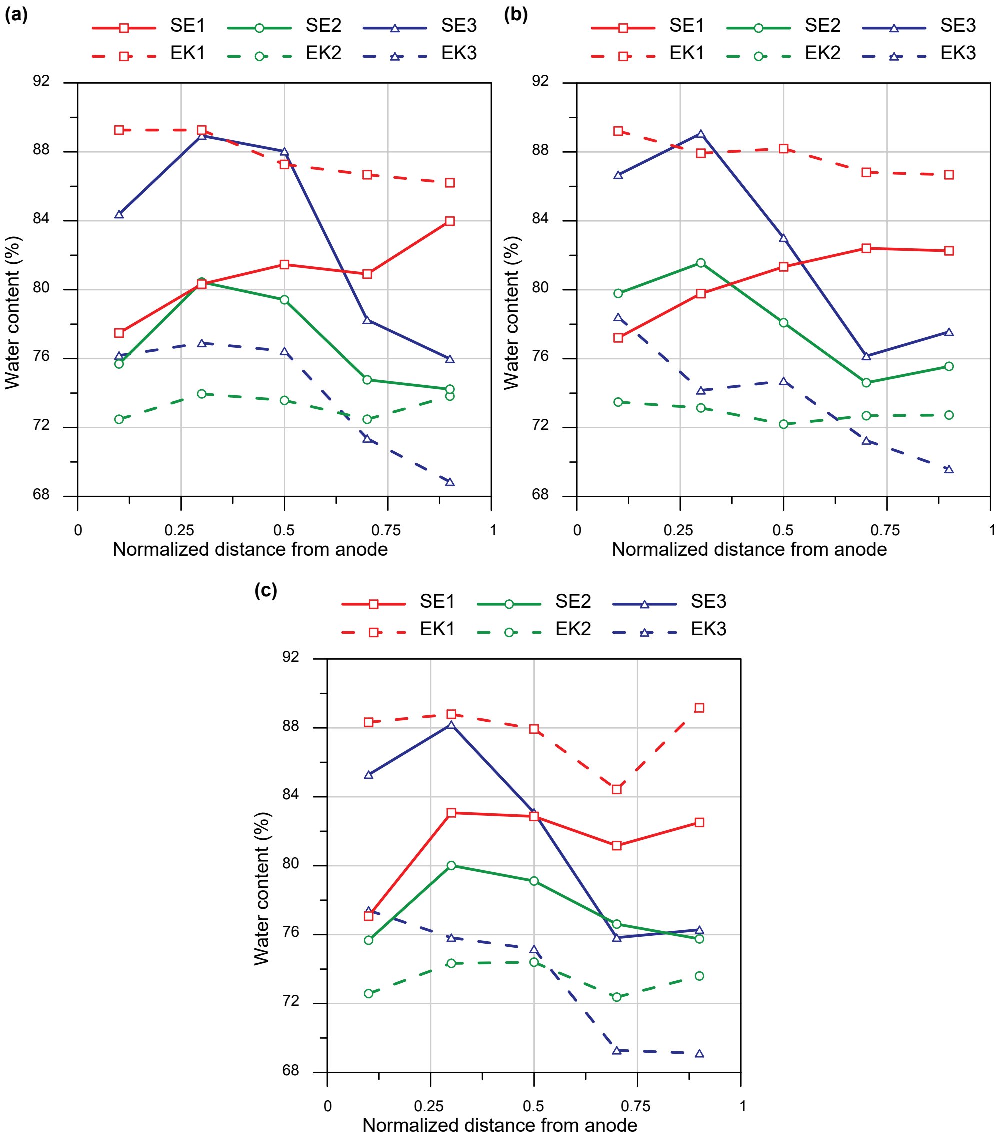

Figure 5: Variation of water content in (a) top layer; (b) mid-depth layer; (c) bottom layer

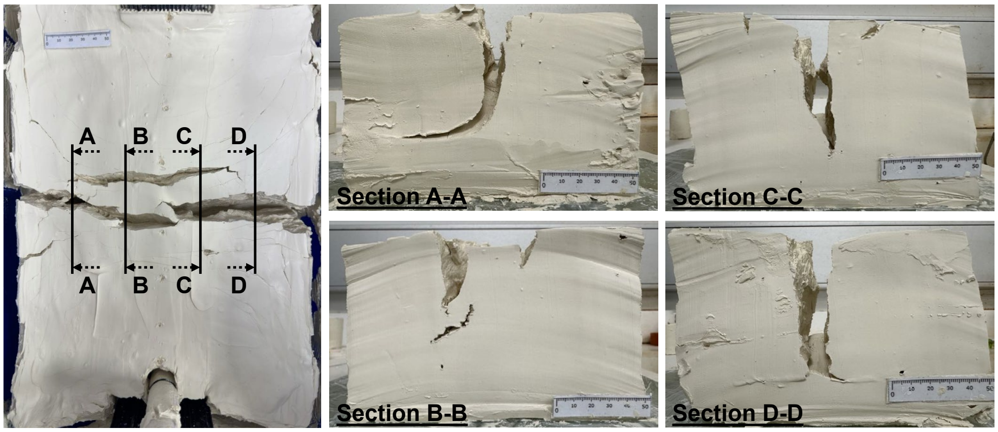

Figure 6: Cross-sections showing the formation of shrinkage cracks in test EK2

Variation of undrained shear strength

Figure 7 depicts the distribution of approximate undrained shear strength between the electrodes. The measured undrained shear strength variation generally agrees with the observed water content trend presented in Figure 5. On average, the electroosmosis treatment enhanced the undrained shear strength of the material by 24 times compared to the pretreatment shear strength of 0.3 kPa. Under the low voltage gradient (50 V/m), the test conducted with mild steel electrodes indicated a marginal 16.3% increase in shear strength compared with the test conducted with EKG.

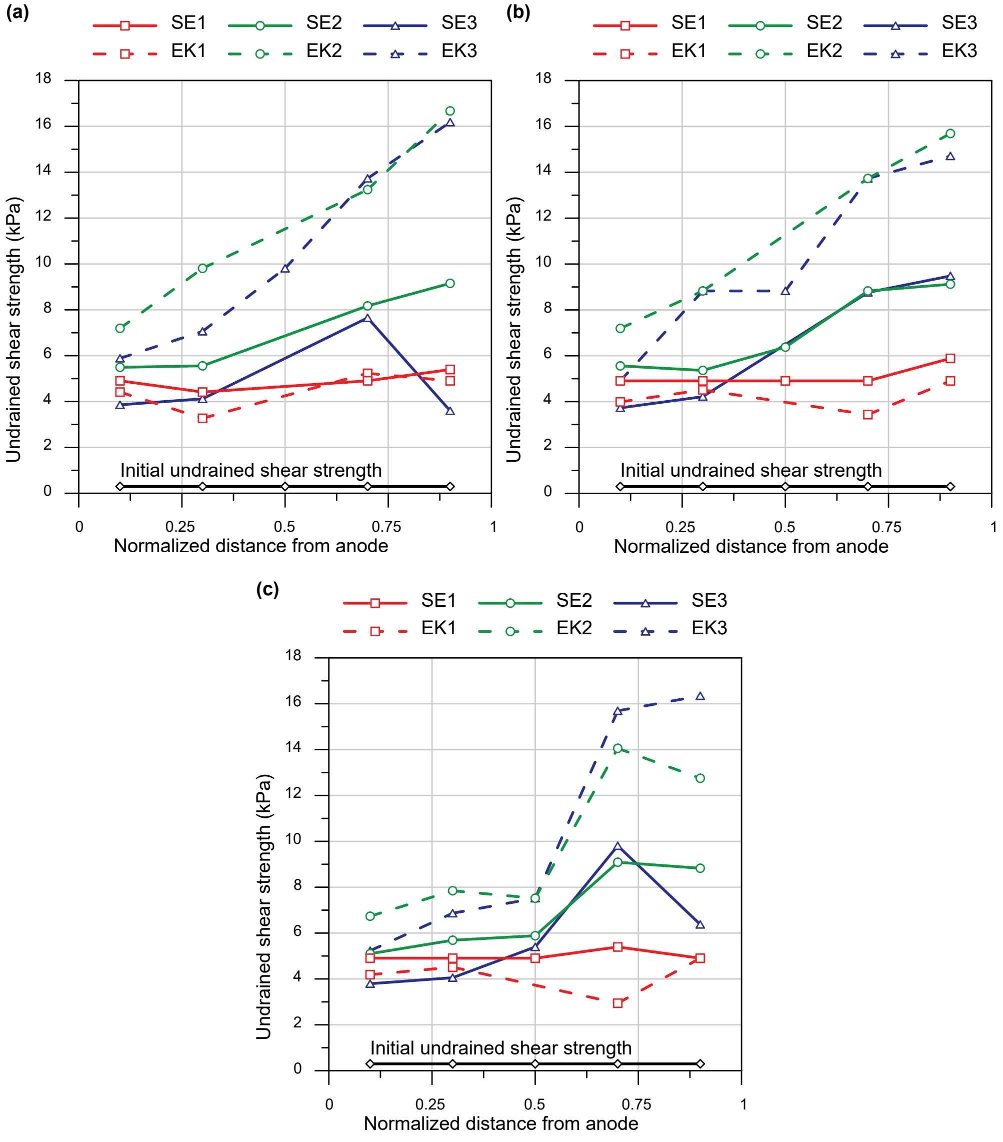

Figure 7: Variation of undrained shear strength in (a) top layer; (b) mid-depth layer; (c) bottom layer

At 150 and 100 V/m voltage gradients, the average post-treatment strengths of the tests that utilized EKGs were 79.3% and 55% higher than those conducted with mild steel electrodes, respectively. In contrast, the post-treatment average water contents for tests performed with EKGs under the same voltage gradients were only 4.2% and 8.8% lower than those carried out with metal electrodes. Although the change in water content between the tests conducted with the two types of electrodes is marginal, the use of EKGs has led to a significant enhancement in undrained shear strength. This constitutes one of the main advantages of utilizing EKGs for treating ultra-fine tailings. However, further research is required to investigate the factors contributing to this effect and to quantify the enhancement not reflected by the change in water content.

Conclusion

Severe corrosion of metal electrodes is one of the major barriers that impede the widespread use of the electroosmotic dewatering technique in stabilizing ultra-fine tailings. The current study investigated the performance of novel electrokinetic geosynthetic (EKG) electrodes, which are manufactured from electrically conductive polymer in dewatering ultra-fine tailings, compared to conventional metallic electrodes. Based on the outcomes of this study, the following key conclusions can be drawn:

- EKGs performed well at higher voltage gradients (150 and 100 V/m) compared to conventional metal electrodes, whereas under a lower voltage gradient (50 V/m) metal electrodes resulted in a relatively better discharge volume.
- The better performance at lower gradient and the poor performance under higher voltage gradients could be mainly attributed to the lower corrosion rate in the metal electrodes at lower voltage gradients. However, the corrosion effects may start to govern in metal electrodes even at low voltage gradients under field conditions since the dewatering usually extends for prolonged periods.
- Dewatering with EKG electrodes under 100 and 150 V/m consumed approximately 31.6% and 18.9% more power, respectively, compared to mild steel electrodes under the same voltage gradients. This is mainly because the amount of current drawn during the dewatering process (resulting from lesser corrosion effects) is generally higher when EKGs are utilized.
- Dewatering with EKG electrodes under 100 and 150 V/m consumed approximately 31.6% and 18.9% more power, respectively, compared to mild steel electrodes under the same voltage gradients. This is mainly because the amount of current drawn during the dewatering process (resulting from lesser corrosion effects) is generally higher when EKGs are utilized.
- Post-treatment water content and undrained shear strength assessments showed that although the change in water content between the tests conducted with the two types of electrodes under the same voltage gradients is marginal, the use of EKGs has led to a significant enhancement in undrained shear strength. This constitutes one of the main advantages of utilizing EKGs for treating ultra-fine tailings.

In summary, the results showed that for dewatering fine, slurried tailings, the novel EKG electrodes proved to be just as effective as their traditional metal counterparts, and usually better, as corrosion effects did not hinder the electroosmosis process. While the present work only focused on the corrosion issue of conventional metal electrodes and investigating the viability of replacing them with EKGs at laboratory scale, other aspects such as long-term performance under field conditions, scale effects, capital and operational costs and logistics, etc., should be broadly investigated to promote the application of electroosmosis dewatering technique in large scale field applications.

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