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A comparative study on the performance of electroosmotic consolidation of fluid fine tailings under constant voltage and constant current configurations

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Abstract

Accelerating the consolidation of fluid fine tailings plays a key role when it comes to mine closure, particularly due to the challenges associated with placing the capping layers. 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 (EO) offers a promising approach for the treatment of slurried tailings in the context of safely closing tailings storage facilities. 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 towards the negatively-charged electrode from the vicinity of the positively-charged electrode. Here, the electroosmotic force which drives the water flow through soils can be generated by either applying constant voltage with a variable current or a constant current with variable voltage. Although numerous studies have been conducted using both aforementioned approaches, to the authors' knowledge a comparison of these approaches focusing on dewatering and the strength gain aspects of fluid fine tailings has not been carried out. In this study a series of laboratory-scale experiments were carried out to evaluate the performance of EO consolidation of fluid fine tailings under constant voltage and constant current configurations. The results show that in contrast to the constant voltage approach, the constant current mode produces superior outcomes in terms of dewatering at a higher and more sustained rate, but at the expense of higher power consumption. The outcomes of the study also suggest that dewatering under constant voltage configuration maintains a constant dewatering rate for the majority of the test period owing to the high initial moisture content and high conductivity characteristics of fluid fine tailings. The implications of these findings in improving the economic viability of EO treatment of tailings prior to final cover placement are discussed.

Keywords: *consolidation, electroosmosis treatment, tailings dewatering, mine closure, fluid fine tailings*

1 Introduction

It is important to acknowledge that the mine decommissioning and closure phase is just as important as the initial (from exploration to construction) and operational phases of the life of mine. Failure to address proper mine closure and rehabilitation could pose significant impacts on the reputation and sustainable future of the mineral resources industry. In most regulatory standards, as a part of the mine decommissioning and closure plan, there is often a legislated requirement to rehabilitate the land and return it to the community (Bennett & Lacy 2012) for post-mining land uses. In general, tailings storage facilities (TSFs) occupy 10–40% of the mining operations area (McKenna & Van Zyl 2020), which makes them a salient element of the final landform design. The International Commission on Large Dams (ICOLD) Bulletin on Sustainable Design and Post-Closure Performance of Tailings Dams outlines that sustainable closure should be achieved by reclaiming the land and making it suitable for the benefit of stakeholders by ensuring its long-term physical,

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chemical, social and ecological stability (ICOLD 2013). It should be emphasised that none of the aforementioned stability aspects could be fulfilled without ensuring the stability of the tailings deposit itself; hence stabilisation of TSFs is of paramount importance when it comes to mine closure (Bjelkevik 2011).

Unlike coarse tailings, fluid fine tailings poses significant challenges to the closure works, particularly when it comes to the placement of the capping layers. The term 'fluid fine tailings' adopted in this study is not necessarily focused on fluid fine tailings generated in oil sands mining (where the term 'fluid, fine tailings' is common) but rather a generic term that covers any type of fine tailings (i.e. clay size particles or a combination of clay and silt size particles) with high water contents. Owing to the extremely low permeability of the finer fraction, these types of tailings deposits will take extended periods of time to consolidate and transform into a ready-to-reclaim state; sometimes in the order of decades under natural in situ conditions (Jeeravipoolvarn et al. 2009; Miller & Range 1989). While there are several conventional practices in the industry to enhance consolidation, these techniques are sometimes only moderately effective, or are impractical, due to the very nature of the fluid fine tailings. For instance, the use of prefabricated vertical drains (wick drains) is one of the most attractive methods to enhance the shear strength of soft soil deposits (Indraratna 2008). However, the extremely weak, compressible nature of fluid fine tailings constrains the placement of the surcharge to a limited height, which subsequently compromises the efficacy of this technique and increases the time required to achieve the desired level of ground improvement or necessitates the placement of the drains at close centres to reduce the drainage path length.

Consolidation by means of electroosmosis (EO) offers a promising approach to the treatment of soft tailings deposits (Araruna et al. 2022; Fourie et al. 2007; Fourie & Jones 2010; Shang et al. 2009). The process of EO treatment involves placing a series of electrodes into the tailings (or the ground) and applying an electrical potential between the electrodes. The potential difference causes the water molecules to move towards the negatively-charged electrode (cathode) from the vicinity of the positively-charged electrode (anode). While EO drives water towards the cathode from the vicinity of the anode and drainage is facilitated at the cathode, consolidation of tailings occurs corresponding to the amount of water removed, provided that water is not permitted to enter the system (Mitchell & Soga 2005). According to the analogy with Darcy's law, the electroosmotic flow through soils under the influence of a voltage gradient can be represented by:

$$q_e = k_e i_e A \tag{1}$$

where:

- q_e = electroosmotic flow
- k_e = coefficient of electroosmotic conductivity
- i_e = electrical gradient
- A = cross-sectional area perpendicular to the flow.

The electrical gradient that causes the movement of water can be provided by means of a direct current (DC) field, either by applying a constant voltage with variable current or constant current with variable voltage, with the concepts of both operating conditions having been successfully demonstrated (Bjerrum et al. 1967; Yukawa et al. 1976).

The current literature offers significant insights into the factors that influence the effectiveness of the electroosmotic dewatering (EOD) technique. Outcomes from previous studies suggest that the effectiveness of this technique is governed by a number of factors including the type of electrodes (Bergado et al. 2003; Mohamedelhassan & Shang 2001; Xiao et al. 2021), the configuration of electrodes (Glendinning et al. 2008; Karunaratne 2011), the electrical gradient (Fourie & Jones 2010; Hamir et al. 2001), soil type (Jayasekera & Hall 2007; Kaniraj & Yee 2011) and pore fluid chemistry (Mohamedelhassan & Shang 2002). However, despite it being a fundamental aspect, research investigating the influence of applying a constant voltage or a constant current on the effectiveness of EOD is scarce, with only a very limited number of studies available (Glendinning et al. 2010; Zheng et al. 2019). More notably, to the authors' knowledge, a comparison of these approaches focusing on dewatering and the strength gain aspects of fluid fine tailings has not been carried out. The objective of the present research is to better understand the performance of EOD with the constant voltage mode and constant current approach. Laboratory-scale tank tests were utilised to compare the dewatering efficiencies in both electrical configurations and assess the post-treatment strength gain. The implications of these findings in improving the economic viability of EO treatment of fluid fine tailings prior to final cover placement are also discussed.

2 Experimental methodology

2.1 Test materials

Commercially available kaolin powder was used to prepare the slurry specimens required for the testing. The use of standard soils allows achievement of the required target water content of the slurry and enables easy replication of the tests. The geotechnical properties of kaolin, determined in accordance with the standard test methods, are summarised in Table 1.

Table 1 Geotechnical properties of kaolin

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

2.2 Experimental set-up

The experiments were carried out in 20 L capacity (380 × 280 × 200 mm) plastic tubs, as shown schematically in Figure 1. The electrodes utilised in the experiments are composed of electrically conductive geosynthetics, also called electrokinetic geosynthetics (EKGs). Compared to conventional metal electrodes, these types of electrodes offer better corrosion-resistance against electrochemical reactions (Fourie et al. 2007; Jayasiri et al. 2024). The specific EKG electrodes used in the study, each having dimensions of 190 × 83 × 3 mm, are identical to a conventional prefabricated vertical drain but are manufactured from electrically conductive polymer. The EKG electrodes were placed at both ends of the tank, close to the sides, in such a way that almost all the material in the tub would be under the influence of the electrical field.

A perforated polyvinyl chloride (PVC) tube encased in non-woven geotextile was placed adjacent to the cathode electrode. While the geotextile layer prevented the inrush of kaolin slurry, the water was freely drained into the PVC tube. Drainage was facilitated through a small hole at the bottom of the PVC tube and the drained water was subsequently collected in a measuring cylinder. This system enabled a continuous flow of drained water, eliminating the need to extract water manually at regular intervals. A DC power supply (max 60 V and 5 A), which is capable of operating in both constant voltage and constant current modes,was used as the power source. Moreover, a temperature sensor was placed in the vicinity of the anode to measure changes in the slurry temperature.

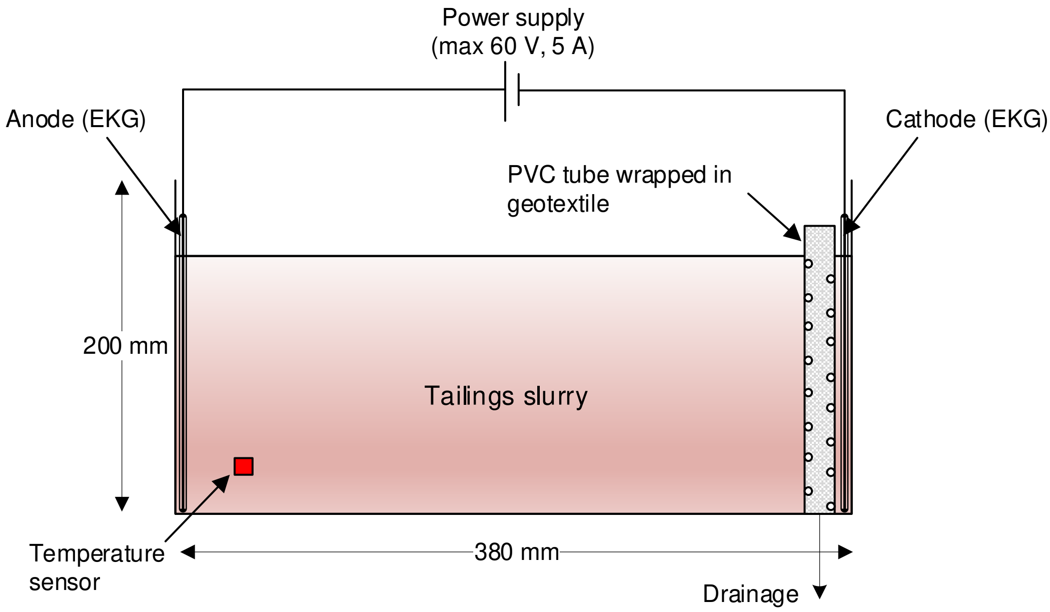

Figure 1 Schematic of the test set-up

2.3 Test program

The slurry was prepared by mixing powdered kaolin with deionised water to a gravimetric water content of 150% (approximately two times the liquid limit), ensuring a uniform slurry without any lumps. Batches to be used for the EOD testing were then stored in airtight storage containers for at least 24 hours to reach moisture equilibrium. Afterwards, the slurry was carefully poured into the tub in stages while the body of the tub was gently tapped, forcing any entrapped air bubbles to escape. Once the slurry thickness reached about 60 mm the temperature sensor was placed near the anode and the pouring of slurry continued until about 160 mm. In order to prevent any loss of moisture due to evaporation, the top surface of the tub was covered with clear plastic wrap. The EOD tests were commenced by connecting the power supply to the respective electrodes. The initial weight of the slurry to be treated was kept constant among the tests in order to make direct comparisons of the EOD performance. Details of the tests carried out in constant voltage and constant current modes are provided in Table 2.

Table 2 Details of the electroosmotic dewatering tests

Test designation	Electrical configuration	Applied voltage (V)	Initial current reading (A)	Applied current (A)	Initial voltage reading (V)
CV1	Constant voltage	10	0.040		
CV2	Constant voltage	19	0.101		
CV3	Constant voltage	38	0.226		
CC1	Constant current			0.040	9.95
CC2	Constant current			0.101	19.42
CC3	Constant current			0.226	38.43

The tests with constant voltage mode (CV1–CV3) were carried out first, and the initial current readings from those tests were used in the tests with constant current configuration (CC1–CC3). This approach ensures the power consumption in the initial stages of the tests is approximately equal in each coupled set of tests (e.g. the initial power consumption of tests CV1 and CC1 is approximately 0.4 W) (Zheng et al. 2019). The volume of drained water, current and voltage were monitored at one-hour intervals. In most cases the tests were terminated once the discharge rate fell below a threshold of 10 ml/hour to avoid any misinterpretation of power consumption calculations; particularly for tests with higher voltage/current. However, this criterion was not applied for the tests with lower voltage/current as conducting the tests for a longer period until the discharge ceases does not significantly affect the power consumption calculations.

Once a test was completed, five purpose-built Shelby tube type samplers were driven into the improved kaolin bed at approximately 0.1, 0.3, 0.5, 0.7 and 0.9 normalised distances from the anode. The extracted samples were then used to determine undrained shear strength using a handheld shear vane device at three different depths (i.e. top, mid-depth and bottom). Similarly, samples were retrieved for post-treatment moisture content determination.

3 Results and discussion

3.1 Variation of drainage volume

Figure 2 illustrates the variation of water discharge during the EOD under constant voltage and constant current configurations. While tests CV2 and CV3 continued to dewater until the flow rate became virtually zero, CV1 was terminated at day no. 10 (240 hours), although the water was still being extracted at an acceptable rate (about 15 mL/h), and there were no indications of the water flow ceasing. On the other hand, tests CC1, CC2 and CC3 were terminated as a result of voltage approaching the maximum allowable limit (i.e. 60 V). Continuing to apply power beyond the 60 V point would have transformed the electrical configuration from EOD under constant current to constant voltage mode. In CC1, the test was conducted only for about an hour as the voltage reached the 60 V threshold at an exponential rate within an extremely short time. Apart from CV3 and CV1, which are extreme cases, the final cumulative discharges were fairly similar in the remaining testing scenarios. However, comparison of cumulative discharge levels at initial stages (for instance, 48 hours from the commencement of the tests) suggests that the discharge volumes of CV2 and CV3 are 200% and 377% higher, respectively, than that of the test with the lowest applied voltage (CV1). Similarly, in constant current scenarios, the test with relatively higher applied current (CC2) had an approximately 115% higher amount of water collected than the test with lower applied current (CC1) at the same time frame (t = 48 hours). Overall, in both electrical configurations, an increasing trend can be observed with the applied voltage/current in the context of short-term water extraction. Moreover, as can be seen in Figure 2, the discharge tends to terminate sooner for the tests with higher voltage/current than the tests with lower voltage/current.

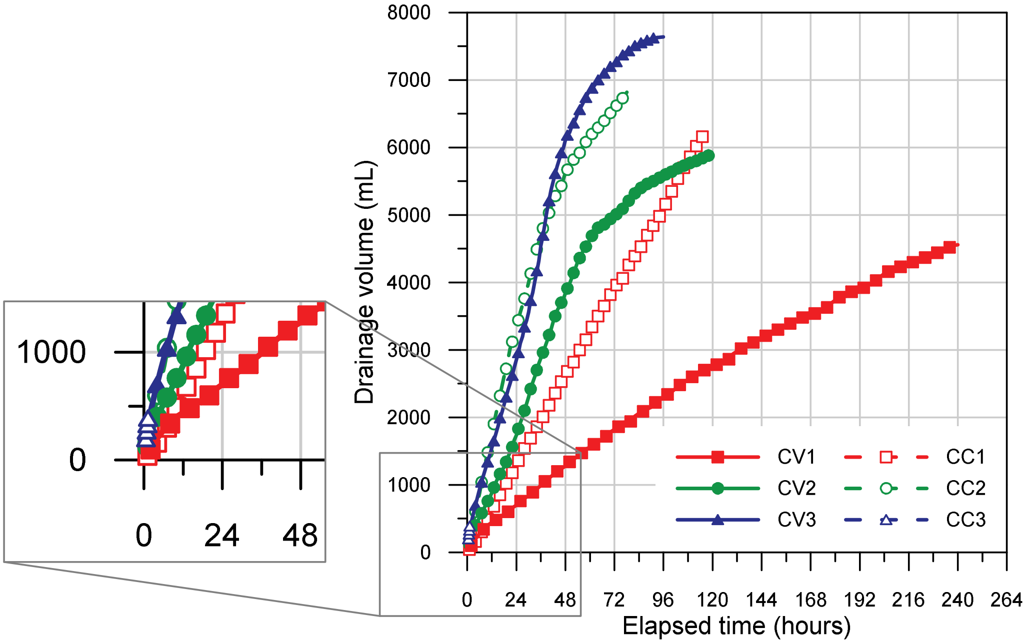

Figure 2 Variation of drainage volume with time

3.2 Variation of drainage rate and electrical parameters

According to Equation (1), the electroosmotic flow rate is governed by the coefficient of electroosmotic conductivity, electrical gradient and cross-sectional area. When the EOD process is carried out in a constant voltage setting, the voltage remains constant over the test period and the current varies. The current is highest at the start of a test since this is when the material contains the highest amount of moisture. As EOD progresses, the moisture content starts to decrease and electrochemical reactions may occur. This causes the material to become less conductive (hence the resistance to increase) and, in accordance with Ohm's law, the current starts to decrease, which subsequently affects the efficiency of EOD. Conversely, in the constant current approach, the voltage is the variable parameter. In this case, even though the material starts to become less conductive and resistance increases as EOD progresses, the voltage will start to increase to maintain a constant current. Since a constant current is maintained by compensating the voltage as required, the EOD rate is expected to remain fairly constant over time.

Arguments of the above theoretical analogy can be validated by the outcomes of previous experimental work (Glendinning et al. 2010; Zheng et al. 2019). Figure 3 illustrates idealised relationships for discharge versus time and voltage/current versus time for both EOD under constant current and constant voltage modes at the same initial power. As can be seen in Figures 3a and 3c, discharge volume and voltage have linear and exponential relationships with time, respectively, for EOD under constant current mode. In contrast, the drainage volume in constant voltage mode tends to increase but with a gradual decreasing rate, while the current decreases exponentially (Figures 3a and 3b).

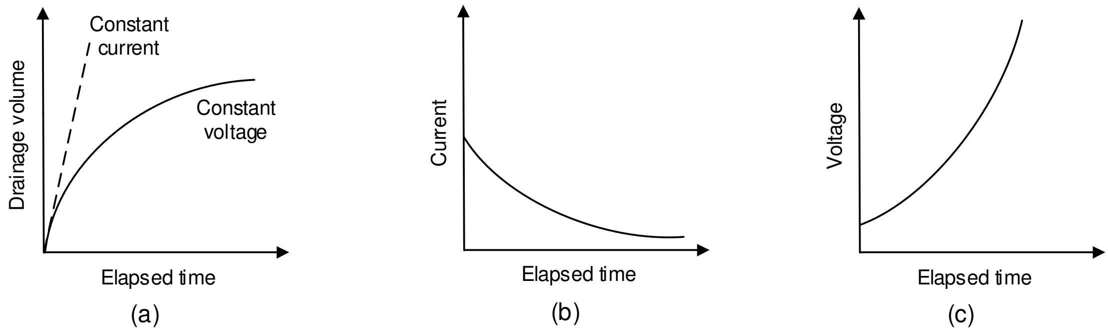

Figure 3 Idealised relationship of: (a) Drainage volume and time for electroosmotic dewatering under constant voltage and constant current configurations; (b) Current and time for EOD under constant voltage setting; (c) Voltage and time for EOD under constant current mode

Although the above electrical parameter behaviour and dewatering response may be valid for a typical saturated fine-grained material, the results of the present research, which was conducted using kaolin slurry that mimics fluid fine tailings with a moisture content of approximately 150%, suggests a slightly different relationship, particularly for the tests with constant voltage configuration. Figure 4 shows the variation of current and voltage over the test period for tests with both constant voltage and constant current modes.

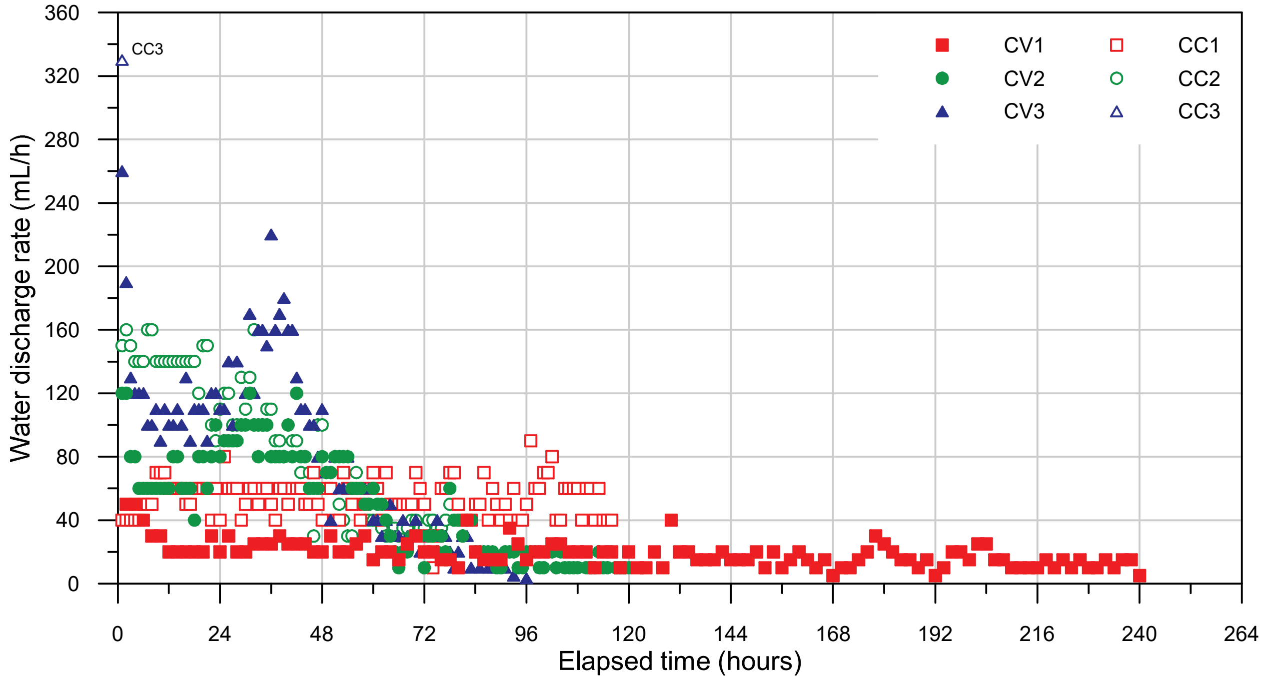

Figure 4 Variation of drainage rate with time

According to Figures 2 and 4, it is evident that the drainage rate is generally consistent for more than 48 hours after the commencement of the tests with constant voltage mode (CV2 and CV3), which is counter-intuitive to the typical relationship discussed earlier. The observed steady dewatering rate can be explained by the readings of current drawn during the testing period, depicted in Figure 5. The measurements indicate that the amount of current drawn fluctuated around 0.08 A without showing signs of rapid decrease within the first 48 hours, which is in line with the EOD phase with the constant rate. Although the tests were conducted in constant voltage mode, it is likely that the constant current maintained during the period of interest may have promoted a constant flow, which agrees with the theoretical principles. Once the current starts to decay after 48 hours it is apparent that the flow rate gradually decreases until it becomes virtually zero. One of the potential reasons for this behaviour could be that the amount of water drained within the first 48 hours may not be up to the threshold where it is significant enough to develop resistance, which usually causes the current to decay. By the time the drainage rate starts to decrease, the majority of the water that can be extracted by EOD with the respective applied voltage has been withdrawn, i.e. more than 80% for both CV2 and CV3. Unlike in a material with relatively low water content (e.g. soft clay), which most of the previously published experimental work is based on, the results of the present work suggest that the EOD with constant voltage configuration maintains a constant dewatering rate when dewatering is carried out on materials with high initial moisture content (e.g. fluid fine tailings, dredged sludge). However, it is important to note that the applied voltage should also be high enough to drive water molecules consistently from the anode vicinity and maintain a steady flow rate. If the voltage is too low, the flow rate can be affected over time, although a constant current is maintained in the system; thus the behaviour observed in test CV1.

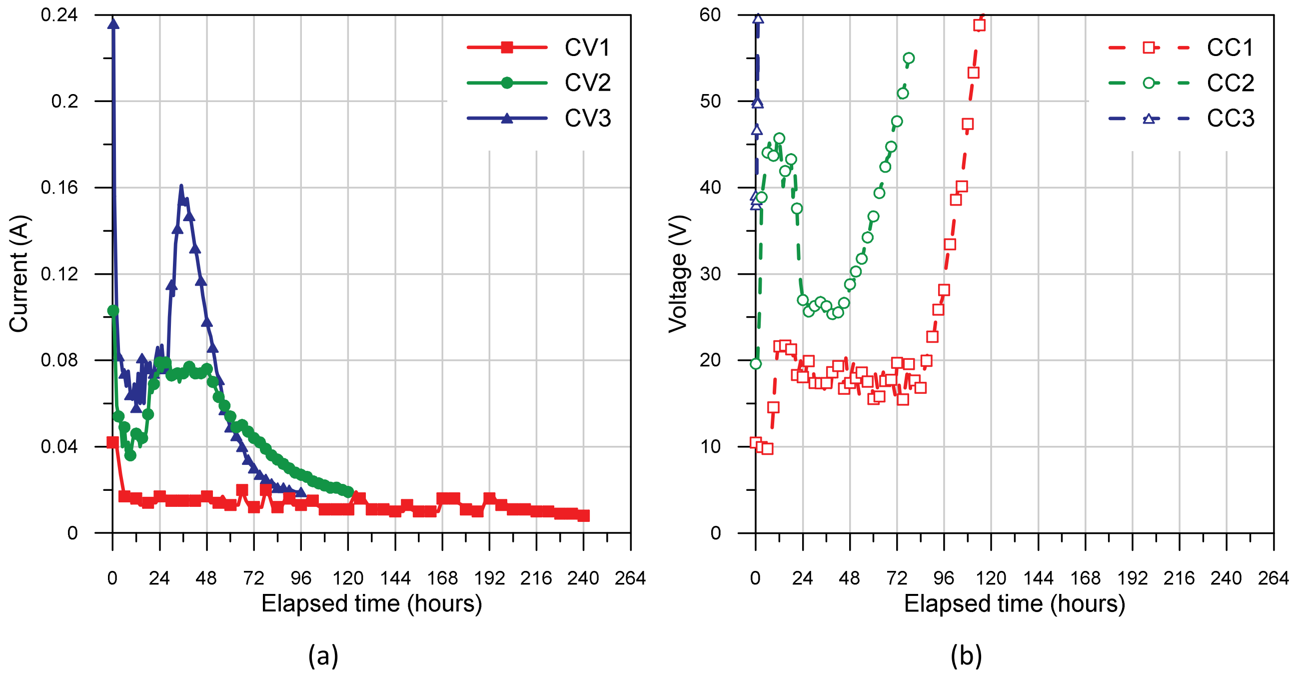

Figure 5 Variation of: (a) Current with time for tests with constant voltage mode; (b) Voltage with time for tests with constant current configuration

As expected, the tests with constant current mode maintained a relatively steady flow throughout the dewatering process, resulting in a higher water extraction rate than the tests conducted with the same initial power under constant voltage mode. The average dewatering rates of CC1 and CC2 were 53.5 mL/h and 87.4 mL/h, respectively, which shows that the applied current has resulted in a higher dewatering rate. Despite the applied current in CC2 being 2.5 times higher than that of CC1, the dewatering rate has not increased proportionally. Further research is required to investigate the relationship between the discharge rate and the magnitude of applied current. It is important to note that at the very end of test CC2 a slight decrease in dewatering rate can be seen. This may be due to the electrochemical reactions at the anode and cathode, and the subsequent reduction in the coefficient of electroosmotic conductivity (Zheng et al. 2019). Moreover, in both tests CC1 and CC2, the voltage starts to increase at an exponential rate, at approximately 84 and 48 hours, respectively, into the dewatering process. The higher dewatering rate in CC2 may have caused the resistance to increase at a higher rate than that of CC1, which may have caused the voltage to rise sharply at an earlier stage.

3.3 Power consumption

By combining the measurements of current/voltage drawn and applied current/voltage, it was possible to calculate average power usage over the treatment period for each test as shown in Figure 6a. It is evident that the power usage in tests with constant current mode continues to increase over time, owing to the exponential increase in voltage, which could possibly lead to an increase in the end-of-treatment power consumption. In contrast, a gradual decrease in the power usage in tests with constant voltage configuration can be seen to result from the decrease in the current drawn as dewatering progresses.

To make direct comparisons between the tests the power consumption was interpreted in terms of kWh/dry tonne of treated material:

$$P = \int_0^t VIdt / W_s \quad (2)$$

where:

P = power consumption

V = average voltage

I = average current

t = treatment time

W_s = dry weight of the material calculated from the initial solids content.

The results presented in Figure 6b demonstrate that there is a substantial difference among the power consumption values obtained from the two approaches. As can be seen, EOD using constant current mode consumes more than double the power used in the constant voltage approach. Even though the tests carried out in the present study were limited to laboratory scale, the power consumption rates presented in Figure 6b can be used to improve the economic viability of EO treatment of tailings at field scale.

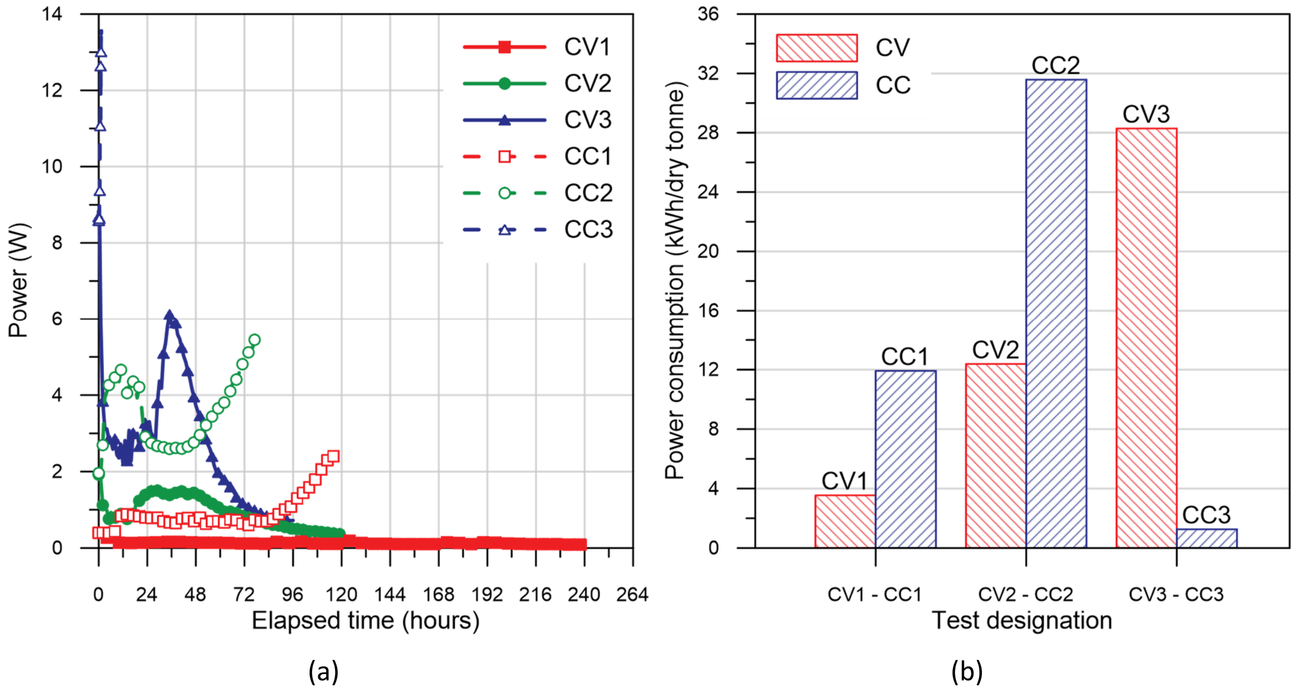

Figure 6 (a) Variation of power usage; (b) Power consumption in terms of kWh/dry tonne of treated material, categorised by each coupled set of tests with the same initial power

Although it is not possible to make direct comparisons, power consumption values from previous attempts that utilised the EOD technique to dewater mine tailings have ranged between 0.6 and 880 kWh/dry tonne (Fourie et al. 2007). The work by Lockhart & Stickland (1984) showed that EOD of coal tailings can be achieved at a rate of 20–30 kWh/dry tonne. Results from large outdoor tank tests by Fourie et al. (2007) demonstrate that the water content of mineral sand tailings was reduced from 158 to 75% at an energy consumption rate of only 0.9 kWh/dry tonne. Despite numerous encouraging works, large-scale field applications are still lacking to date. One of the major reasons for the limited real-world applications is the high operational costs involved, with electricity cost constituting one fourth of the overall project cost according to the work done by Bjerrum et al. (1967). Given that this technique demands a significant amount of capital cost (electrodes, wires, power supply units, pumps) as well, it will invariably be the last resort to employ in the field when all other methods are infeasible. Hence it is of paramount importance to minimise costs and achieve the required amount of ground improvement with optimum operating conditions. Although EOD with constant current configuration provides superior outcomes in terms of dewatering at a higher and constant rate, this is at the expense of higher power consumption. Hence, if time is not a limiting factor, dewatering under constant voltage mode with a lower voltage gradient may represent the key to achieving the required ground improvement with minimum energy consumption. One of the major advantages of the EOD technique is that it offers the flexibility to adjust variables according to the project requirements (e.g. a higher dewatering rate or lower energy consumption) even as the project progresses. This can be achieved without any major logistical efforts by simply changing the operational parameters. As discussed in Section 3.2, EOD with constant voltage configuration offers a steady dewatering rate at the initial phases of the dewatering process, particularly for material with higher initial water content. With the dewatering rate being the only significant distinction between the two approaches it is questionable whether dewatering of fluid fine tailings using constant current mode will accrue any financial benefit.

Another constraint with EOD in constant current mode is that it requires a power supply unit with an extremely high capacity to keep up with the increasing voltage demand during the dewatering process. Exposure to extreme voltage levels could cause electrical hazards and thereby increase health and safety risks (Wang et al. 2018).

3.4 Variation of water content

Figure 7 shows the distribution of water content between the electrodes with respect to the normalised distance from the anode (distance to the sampling point from the anode normalised by the distance between electrodes). On average, the water content of the slurry reduced approximately 60% from the initial value of 150%. As expected, CV1 had the lowest reduction in water content while CV3 had the highest, which is reflected by the lowest and highest drainage volumes provided in Section 3.1. While there is an approximately 15% difference between the water content values of the tests with constant voltage, the average post-treatment water content of tests with constant current (CC1 and CC2) are about the same. This may be because the loss of water in both tests CC1 and CC2 are in the same range, as depicted in Figure 2.

It is well-documented that EOD results in an uneven moisture content distribution wherein the moisture content in the vicinity of the anode is less than that of the cathode, owing to the movement of water molecules in the slurry towards the cathode. Interestingly, a substantial difference among the water content values of the two regions cannot be observed in the tests in the current study. The reason for this behaviour could be mainly attributed to the formation of cracks perpendicular to the flow path which subsequently resulted in disrupting the conductivity and electroosmotic flow (Figure 8). It is important to note that these cracks are not due to the heating and desaturation of the material near the anode but rather the result of high shrinkage caused by dewatering; hence the crack formation occurred at the centre of the tested sample. As can be seen, the water content profile of CV1 followed the typical expected profile after EOD treatment, where, in this case, the water content was 6% lower in the anode region than that of the cathode. Owing to the lowest dewatering rate (hence shrinkage rate) among the tests conducted, the crack formation in CV1 occurred at a slower rate, allowing the water to pass from the anode region to the cathode. It appears that in every other case 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. Similar observations have been reported by Xue et al. (2015). Besides the above, factors such as loss of contact area between the electrode and soil cluster due to electrode detachment, electrochemical changes and loss of applied current/voltage at the soil-electrode interfaces may affect the efficiency of EOD (Mohamedelhassan & Shang 2001; Xiao et al. 2021; Zheng et al. 2019).

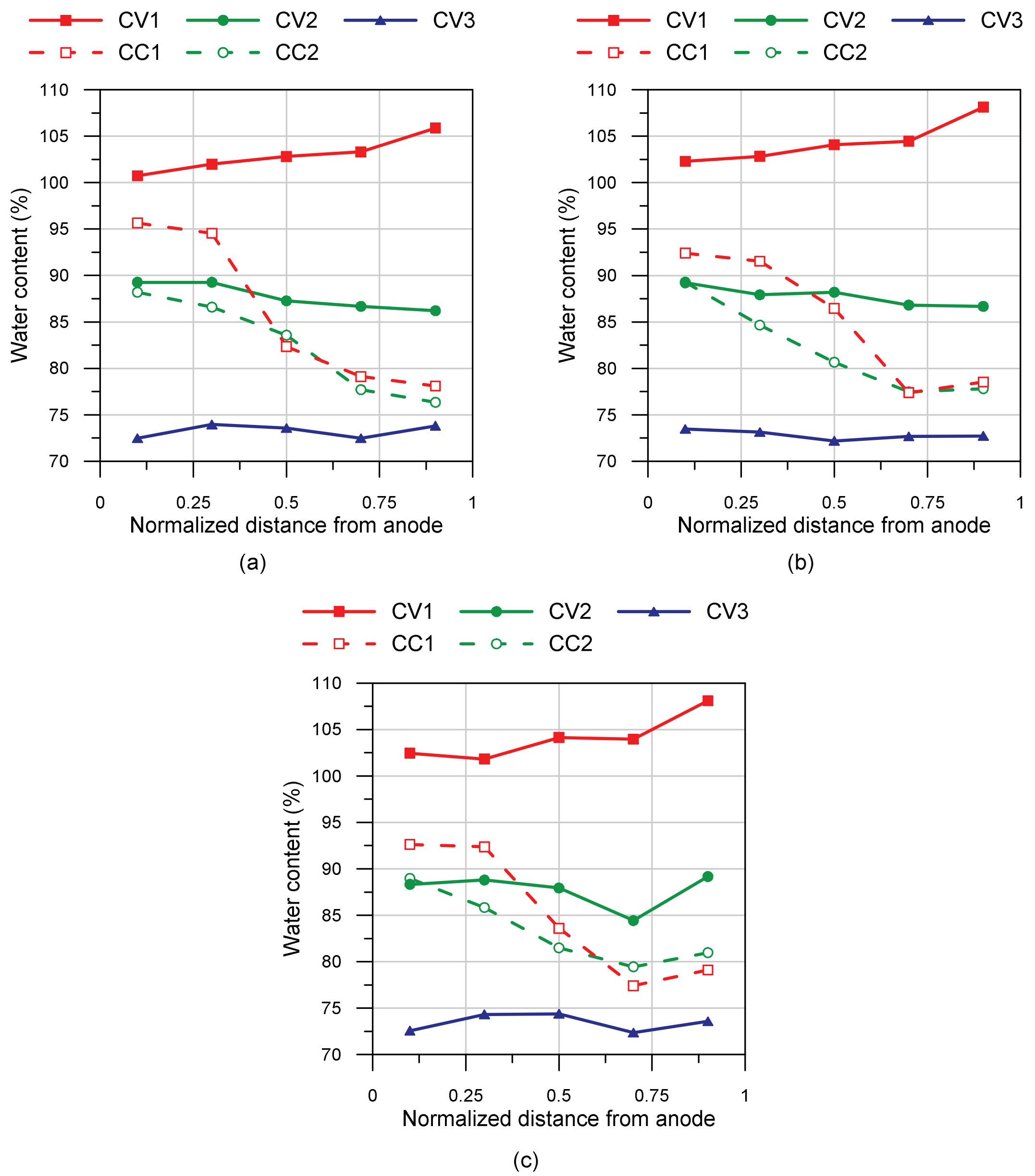

Figure 7 Variation of water content in: (a) Top layer; (b) Mid-depth layer; (c) Bottom layer

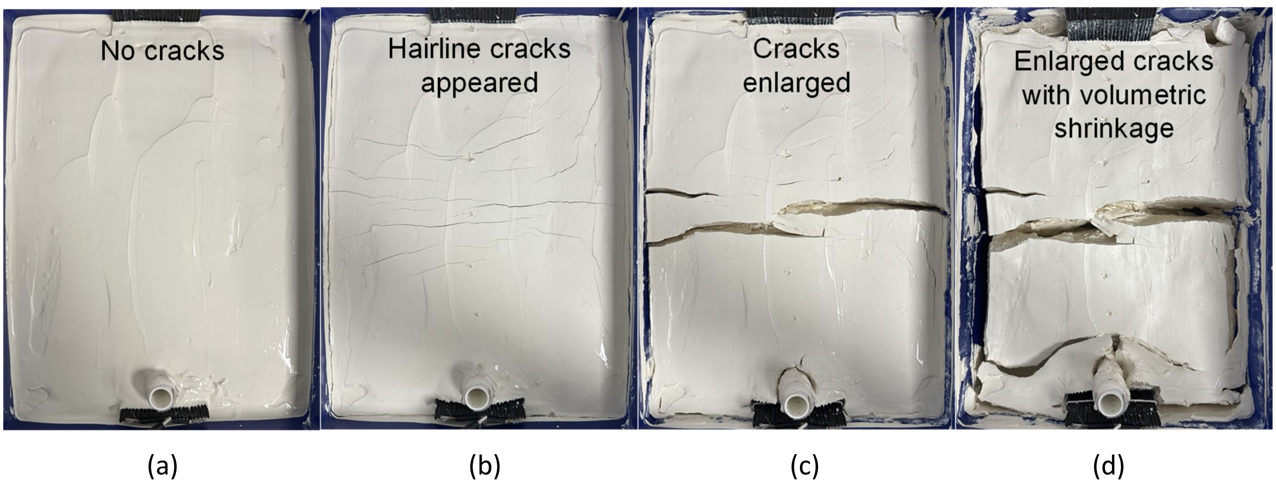

Figure 8 Progressive crack development as seen from above: (a) Pretreatment condition; (b) Five hours into the treatment; (c) 24 hours into the treatment; (d) Post-treatment condition observed in test CV2

3.5 Variation of undrained shear strength

The distribution of approximate undrained shear strength between the electrodes is shown in Figure 9. The measured undrained shear strength variation generally agreed with the observed water content trend presented in the previous section, except for CV3. It is unclear what caused the abrupt increase in the undrained shear strength profile of CV3, which is not in line with the water content profile. As can be seen, CV3 shows the highest increase, in contrast to CV1, which indicates the lowest increase in average shear strength. The average post-treatment strengths for tests CV1, CV2 and CV3 are 3, 14 and 36 times higher than the pretreatment shear strength of 0.3 kPa, indicating a positive correlation between the applied voltage and post-treatment shear strength. On the other hand, tests conducted under the constant current mode demonstrated approximately similar strength gain despite the level of applied current.

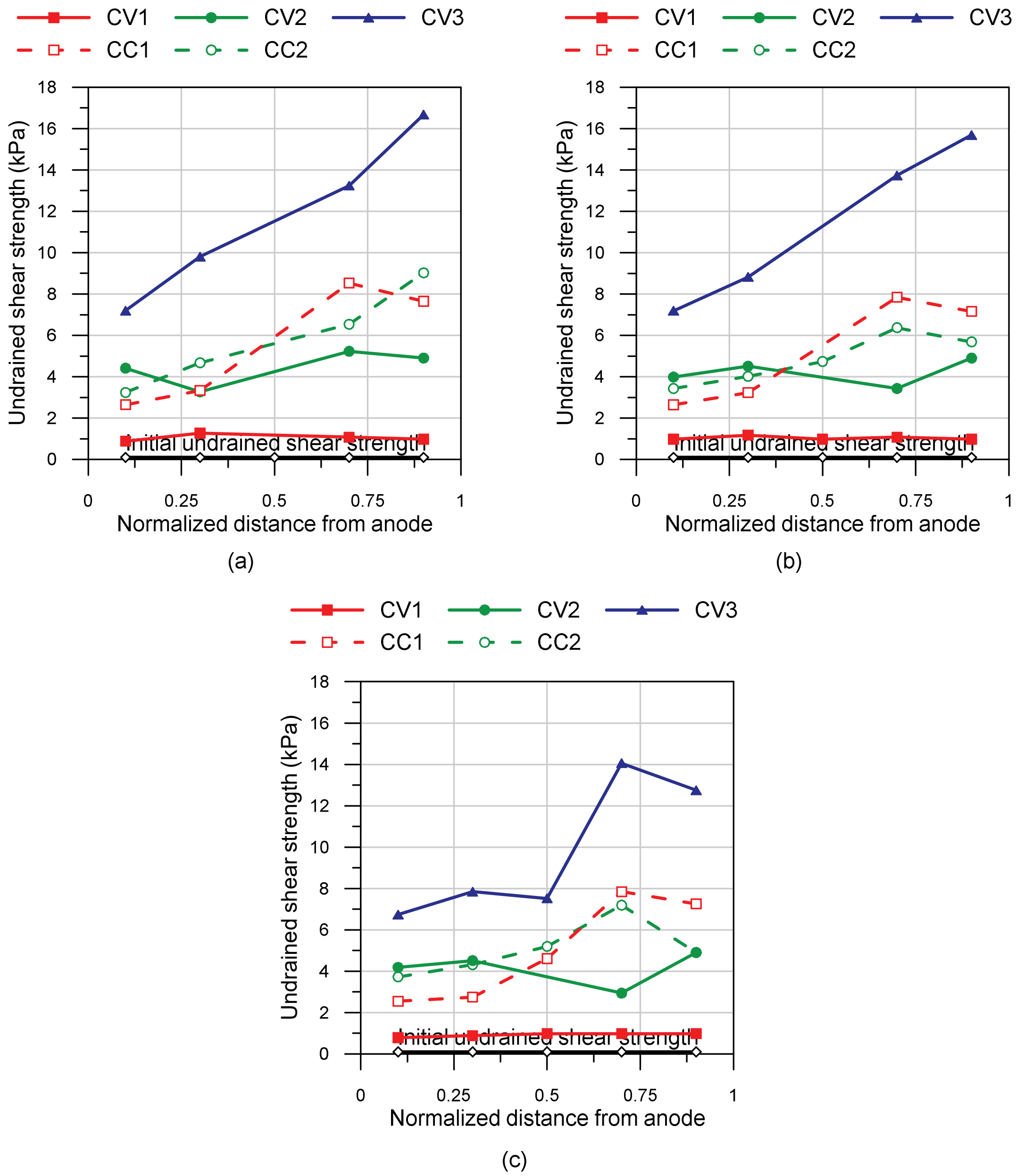

Figure 9 Variation of undrained shear strength in the: (a) Top layer; (b) Mid-depth layer; (c) Bottom layer

3.6 Change in slurry temperature

A portion of the applied energy is transformed into heat due to the resistance of the material. This phenomenon is known as Ohmic heating, and depends on the amount of power applied to the system. Temperatures as high as 100°C after 41 days of extensive EOD treatment have been recorded in the field demonstrations carried out by Burnotte et al. (2004). While elevated temperatures in fine-grained soil could enhance the hydromechanical properties such as shear strength and hydraulic conductivity (Abuel-Naga et al. 2006), excessive temperatures could also cause adverse effects in terms of electrode degradation, increased power consumption and increased applied current/voltage loss at the soil-electrode interfaces. Despite being an important aspect, temperature effects due to EOD are not well-documented. Hence, attempts were made to examine the thermal response of soil under both constant voltage and constant current modes.

Figure 10 depicts the variation of temperature change, with fluctuations caused by the change in room temperature. Two distinct trends can be seen between the tests with constant voltage and constant current modes. It is important to note that temperature changes in the tests conducted with the lowest initial power (CV1 and CC2) do not follow a similar trend, which may be due to the relatively low resistance (due to a low dewatering rate) and applied power. The temperatures in the tests with constant voltage mode (CV2 and CV3) tended to increase at the initial stages before starting to gradually decrease over time. This behaviour was in line with the variation in power consumption, whereas the power consumption peaked and then started to gradually decrease as shown in Figure 6a. In the context of EOD with constant current, temperature in test CC2 showed an increasing trend over time which may be a result of the continuous power increase as discussed in Section 3.3.

The limited results demonstrate that the temperature of the slurry continued to increase as dewatering progressed in the constant current mode. The measured temperatures were not as extreme as previously reported due to (i) a shorter testing period and (ii) excessive heat dissipation from the sample boundaries (Burnotte et al. 2004), which are limitations of the present study.

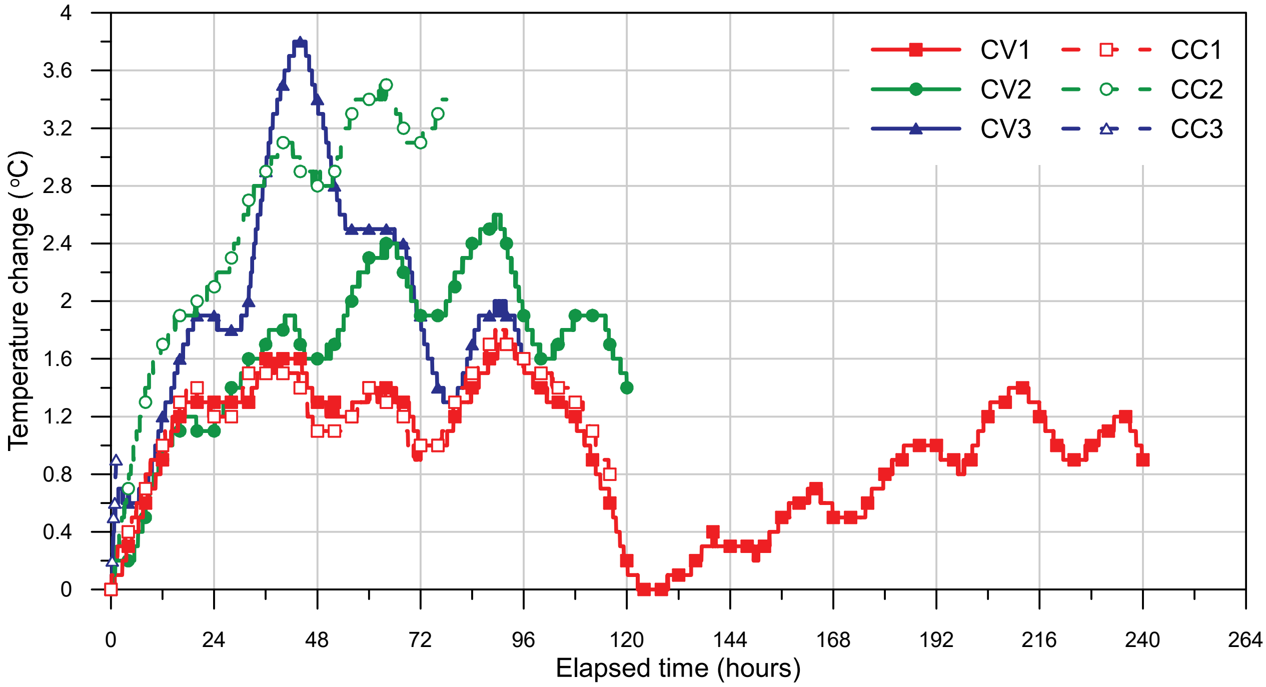

Figure 10 Variation of temperature change with time

4 Conclusion

This paper compared the performance of EOD of fluid fine tailings under two different electrical configurations, i.e. constant voltage with variable current and constant current with variable voltage, utilising laboratory-scale tank tests. The performance of each configuration was assessed by comparing the drainage volume, power consumption, distribution of water content and undrained shear strength from tests with three initial power levels. Based on the outcomes of this study, the following conclusions can be drawn.

EOD under constant current configuration tends to maintain a steady dewatering rate while the dewatering rate under constant voltage mode is considered to decrease as dewatering progresses. While the results of the present work confirm that EOD with constant current mode extracts water at a constant rate, it also suggests that the EOD with constant voltage configuration maintains a constant dewatering rate for the majority of the test period owing to the high initial moisture content and high conductivity characteristics of fluid fine tailings.

Power usage in tests with constant current mode continues to increase over time, owing to the exponential increase in voltage, which could possibly lead to an increase in the end-of-treatment power consumption. In contrast, a gradual decrease in power usage in tests with constant voltage configuration can be seen as a result of the decrease in the current drawn as dewatering progresses.

EOD using constant voltage mode consumes less than half of the power, in terms of kWh/dry tonne, of the constant current approach. Given that the cost of electricity constitutes a significant portion of the overall cost in larger-scale applications, dewatering under constant voltage mode with a lower voltage gradient is the key to achieving the required ground improvement with minimum energy consumption.

On average, the water content of the slurry reduced to approximately 90% from the initial value of 150%, indicating a 40% reduction in soil moisture. Furthermore, EO treatment resulted in up to an approximately 17-fold increase in undrained shear strength.

Attempts were made to examine the thermal response of soil under EOD but the recorded temperature changes were lower compared to previous studies. The obtained results were sufficient, however, to demonstrate that the temperature of the slurry continues to increase as dewatering progresses in the constant current mode.

In essence, the findings of the current study suggest that although EOD with constant current configuration provides superior outcomes in terms of the dewatering rate, increased power consumption is required. The study further implies that EOD under constant voltage mode is not only an effective approach but also an efficient technique which certainly has the potential for use in the treatment of fluid fine tailings prior to final cover placement.

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