Dewatering of mine tailings using electrokinetic geosynthetics

A.B Fourie, D.G. Johns, and C.J.F.P. Jones

Abstract: Many mining operations produce tailings that dewater very slowly under self-weight consolidation. One way of reducing the water content of such tailings is by electroosmotic dewatering. Although the technique has been used with some success in civil engineering applications, it is still largely seen as a solution of last resort. This is probably due to the high energy costs reported in the literature, as well as problems of very rapid corrosion of metal electrodes. This paper describes a study using newly developed electrokinetic geosynthetics (EKGs) as electrodes for the in situ dewatering of mine tailings. Laboratory tests were undertaken on mineral sands tailings in both a purpose-built testing cell and a laboratory testing tank using EKGs, followed by an outdoor experiment in a tank containing approximately 9 m^3 of the tailings. This test was run for over 2 months. Energy consumption in the outdoor test was less than 1 kWh per dry tonne of material dewatered and there was no sign of electrode deterioration even after 2 months of usage. The results point to a potentially powerful technique for reducing the water content of tailings ponds in situ, thus increasing storage space, improving stability, and facilitating closure of these facilities.

Key words: tailings, dewatering, electroosmosis, electrokinetic geotextiles, consolidation.

Résumé : Plusieurs opérations minières produisent des stériles qui se drainent très lentement par consolidation sous leur poids propre. Une façon de réduire la teneur en eau de tels stériles est par assèchement électroosmotique. Quoique la technique ait été utilisée avec un certain succès dans des applications de génie civil, elle est toujours considérée comme une solution de dernier recours. Ceci est probablement dû aux coûts élevés d'énergie dont la littérature fait état, de même qu'à des problèmes de corrosion très rapide des électrodes métalliques. Cet article décrit une étude dans laquelle on utilise des géosynthétiques électrocinétiques « EKGs » comme électrodes pour l'assèchement in situ de stériles miniers. On a réalisé des essais en laboratoire sur des stériles sableux de minéraux tant dans une cellule triaxiale conçue à cette fin que dans un réservoir d'essai en laboratoire utilisant un EFGs, suivis par une expérience à l'extérieur dans un réservoir contenant environ 9 m^3 de stériles. Cet essai a été réalisé durant plus de 2 mois. La consommation d'énergie dans l'essai extérieur était de moins de 1 kWh par tonne sèche de matériau desséché et il n'y avait pas de signe de détérioration d'électrode même après 2 mois d'utilisation. Les résultats indiquent une technique potentiellement puissante pour réduire la teneur en eau de bassins de stériles in situ, accroissant ainsi l'espace d'entreposage, améliorant la stabilité et facilitant la fermeture de ces installations.

Mots-clés : stériles, drainage, électroosmose, géotextiles électrocinétiques, consolidation.

[Traduit par la Rédaction]

Introduction

Extremely large volumes of mine waste are produced annually around the world. Recently Davies (2001) estimated that there are at least 3500 active tailings storage facilities (TSFs) worldwide. This is likely an underestimate, as in many countries not all facilities are documented. In some of these TSFs, very wet tailings with low solids content, have been deposited. Many years after placement, the water content remains relatively high, resulting in high risks of instability and extremely difficult rehabilitation. Examples include the fine tailings fraction derived from mining of oil sands (Morgenstern and Scott 1995; Liu et al. 1996) and from phosphate mining (Bromwell and Oxford 1977; Martin et al. 1977).

In situ dewatering of such problem material is highly desirable. The most likely technique to achieve this dewatering would traditionally include the installation of prefabricated vertical drains. In order for these drains to work it is necessary to create a flow gradient in the tailings, which is usually achieved by the application of a surcharge load (e.g., by constructing a surcharge of imported fill). The drawbacks of this approach include the cost of importing and placing the fill, potential instability of the fill because of the low shear strength of the in situ material, and the fact that in some instances continuing and ongoing deposition of tailings is required and this would not be possible if fill were imported and placed within the tailings impoundment.

Electroosmotic dewatering provides a potentially attractive alternative technique for in situ dewatering. The tech-

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nique, which involves the application of a potential difference between electrodes and causes the flow of water to the negatively charged cathode, has seen some limited use in civil engineering applications. These include the stabilization of slopes, excavations, and embankments (Chappel and Burton 1975), increasing pile capacity (Soderman and Milligan 1961), and increasing the strength of clays (Bjerrum et al. 1967; Casagrande 1983; Shang and Dunlap 1996).

However, as noted by Lo et al. (1991), despite the successful case histories, the process was considered economically impractical (primarily because of the high operating costs) and usually only entertained as a last resort. As an example, in the project described by Bjerrum et al. (1967), the cost of electricity was 25% of the total project cost, which is prohibitively high. At this level of cost, the technique would most certainly only be used as a last resort and when the alternative to no treatment is failure of some sort. Other impediments to the widespread adoption of electrokinetic dewatering techniques are the corrosion of electrodes (particularly the anode) and the lack of proven practical implementations.

Although most of the better known instances of electrokinetic dewatering are in traditional civil engineering applications (such as slope stabilization), applications to mining operations have also been attempted, as discussed in the next section.

Use of electrokinetic dewatering in mining applications

Much of the early work on the use of electroosmosis for the dewatering of mine tailings was carried out by the United States Bureau of Mines (USBM) on tailings placed underground as backfill. The results were not reported to be economically attractive and the work never implemented at an operational level.

Although the electrokinetic dewatering of mine backfill was perhaps not as successful as hoped, the USBM experiences still provide some very valuable lessons. As is now widely accepted, they inadvertently proved there is little benefit to be gained in trying to dewater material that is not fine grained. Considering their experiments with the benefit of hindsight, it is also clear that they tended to use voltage gradients that were too large, resulting in poor energy-use efficiencies. Their experiences also showed the importance of enveloping the free draining cathode with an appropriate material. The use of burlap seemed to be particularly unsuccessful.

The USBM team also considered the possibilities of dewatering surface deposits of tailings in situ. The main benefits of dewatering an existing tailings deposit are improved stability, an increase in storage capacity, and the facilitation of closure and rehabilitation. Water recovery is unlikely to be a major factor because the recovered volumes are relatively low. Although dewatering of soft clays has been reported on a number of occasions (Bjerrum et al. 1967; Fetzer 1967; Eggestad and Føyn 1983), the application to dewatering of mine tailings is more recent. Once again, the efforts of the USBM in the United States, as well as the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia resulted in significant advances in this field of application.

Sprute and Kelsh (1982) carried out a large (450 m^3) field test in a pond filled to an initial depth of about 1 m with fine coal sludge from a preparation plant thickener. Horizontal electrodes were used and the applied voltage varied between about 70 and 10 V. Very good results were reported for the material, which had an initial solids content of 17%, with final solids contents being between 31% and 35%. Using the data provided by Sprute and Kelsh (1982), it is estimated that the power consumption was about 64 kWh/dry tonne. In this same document the authors present a proposed design to dewater an existing sludge disposal pond containing approximately 750 m^3 of sludge using vertical electrodes. This included a full costing exercise, but for reasons that are not explained, it appears that the project was never carried out.

The USBM work showed that electrokinetic in situ dewatering of mine waste was feasible, but it was the CSIRO that took the concept further. Two ponds, each filled with 500 t of coal washery tailings, were treated with horizontal electrodes, the applied voltage being between 33 and 40 V (Lockhart and Stickland 1984). Dewatering from an initial solids content of 45% to a final solids content of 75% was achieved with an energy use of between 20 and 30 kWh/dry tonne. The reported metal loss at the anode was 1.1 kg/dry tonne. Even better results were reported by Lockhart (1992) for the dewatering of sand washery tailings, with vertical electrodes placed from a pontoon, where dewatering was achieved using only 1 kWh/dry tonne. Veal et al. (2000) reported successful dewatering of tailings from a sand mine with as little as 0.6 kWh/dry tonne being required for dewatering from an initial solids content (S_c) of 45%–67%. Shang and Lo (1997) dewatered extremely fine (>30% finer than 2 μm) phosphatic clay waste in laboratory tests where the solids content was increased from 13% to 34%, although the majority of this improvement was attributed to sedimentation with a smaller proportion owing to electroosmotic consolidation. In addition, energy consumption was about 96 kWh/dry tonne. This extremely high energy consumption is somewhat unexpected, since as shown by Gray and Mitchell (1967), the rate of electroosmotic dewatering increases as the initial solids content decreases, and S_c in the tests of Shang and Lo (1997) was extremely low.

Even higher energy consumption was reported by Wilmans and van Deventer (1987), who carried out electroosmotic tests on ultra-fine (80% <1 μm) kimberlite tailings. Dewatering of the 8.1% solids content material was carried out at between 16 and 46 V, with the energy consumption varying from 144 to 880 kWh/dry tonne.

The results of the various tests discussed in the preceding paragraphs as well as some additional data are summarized in Table 1. The results are difficult to compare because of the range of voltage gradients used, differences in initial and final water contents, and differences in the types of electrodes used and their orientation. Assuming that in all cases the final solids content represented a consistency that satisfied a criterion set by the authors (e.g., referred to as "spadeable" by Lockhart and Stickland 1984), the factor that provides the most telling comparison is the energy consumption. As can be seen from Table 1, this varies enormously (from 0.6 to 880 kWh/dry tonne).

Table 1. Examples of dewatering of mine tailings using electroosmosis.

Tailings	Particle size characteristic	Sc_i (%)	$Scf.$ (%)	CEC (mequiv. per 100 g)	Mineralogy
Metal mine	D_{50} = 0.08–0.01 (28% <20 µm)			0.4–1.0	
Metal mine	D_{50} ≈ 0.1 mm (4% <20 µm)	72	83	1.0	
Sand mine washery	70% <10 µm	45	67		Kaolinite, illite
Kimberlite	80% <1 µm	8		27	
Molybdenum	60% <20 µm	23	44–65	7.3	
Coal	44% <20 µm	17	45	54	Illite, kaolinite
Coal	D_{50} = 0.04 mm			3.5	
Phosphate	>30% <2 µm	13	34	33	Kaolinite, smectite, illite
Gold	100% <150 µm	60–67	69		
Gold	100% <600 µm	60–67	69		
Coal washery	70% <53 µm	45	75		
Sand mining					
Sand mining	34% <10 µm	27	44		Kaolinite
Ilmenite, zircon	69% <10 µm	27	56		Kaolinite

It is unlikely that electroosmotic dewatering of tailings in situ would be deemed economically viable at anything but the lower end of this range. In trying to achieve the ideal of maximum dewatering at lowest cost, optimizing operational conditions is obviously crucial. In addition, the very rapid corrosion rates experienced at the anodes in the reported studies would render the technique of limited applicability in all but the most short-term dewatering projects. As discussed in this paper, the use of electrokinetic geosynthetics (EKGs) appears to hold some promise in dealing with both of these potential problems.

Optimization of operational conditions

The results summarized in Table 1 indicate certain characteristics that render a material amenable to electrokinetic dewatering. Much of the early testing done by the USBM was on relatively coarse material ($d_{50} \geq 40$–100 µm), and the resulting energy consumption tended to be greater than 50 kWh/dry tonne. As is now widely recognised, in general, the finer the material the better the electrokinetic dewatering potential. The material for which the lowest energy consumption was found was the sand mining washery overflow, which had 70% less than 10 µm. However, it is not only the fineness that is important, since Wilmans and van Deventer (1987) found extremely high energy consumption rates (>100 kWh/dry tonne) for dewatering of tailings with 80% <1 µm. It is also the nature of the clay minerals that are important, as shown by Gray and Mitchell (1967).

A property that appears to be a very useful indicator of likely success, although it is seldom reported, is the zeta (ζ) potential. As reported by Chen et al. (1996), the percentage of water removed during dewatering of fine gold tailings was directly proportional to the ζ potential. This was confirmed by West and Stewart (1995), who argued that electrokinetic dewatering was unlikely to be of benefit in highly saline soils because of the drop in ζ potential that results. Shang (1997) showed that the low ζ potential of marine sediments was consistent with the low electrokinetic dewatering rate of these soils. Segall and Bruell (1992) found that an increase in salinity caused an increase in the energy consumption rate during dewatering, and Mitchell (1991) suggested that above a material conductivity of 2.5 mS/cm, electrokinetic dewatering would not be viable. Although a high salinity (and thus lower ζ potential) is detrimental to the process, Lockhart (1992) suggested that up to a salinity corresponding to 10^{-2} mol/L there was an accelerated dewatering rate (compared with distilled water), although beyond a concentration of 0.1 mol/L the efficiency dropped off. Mohamedelhassan and Shang (2002) also found that there was an optimum salinity, which in their tests corresponded to about 8 g/L of NaCl.

In summary, optimum conditions seem to be a fine-grained material with a high ζ potential and a moderate salinity. The tailings tested in the study reported in this paper fulfilled these criteria to a significant extent, as discussed later. It is interesting to note that the characteristics that are beneficial to electrokinetic dewatering are consistent with the suggestions of Gray and Mitchell (1967). In particular, soils with low exchange capacities (such as the sand washery waste in Table 1) have much greater electroosmotic flow rates than those with high exchange capacities.

Effect of electrodes used

Much of the early work, in both civil and mining engineering applications concentrated on metal electrodes operating at high voltages. For example, Bjerrum et al. (1967) used metal electrodes operating at 50 V to dewater a soft, quick marine clay. Common problems reported included high corrosion rates at the anode (2.5 g/A/day (Bjerrum et al. 1967), 26 g/A/day (Sprute and Kelsh 1982), and 1.1 kg/dry tonne (Lockhart and Stickland 1984)), and significant voltage losses at the electrodes (reported as 25%–50% by Bjerrum et al. (1967)). According to Lockhart (1983*b*), the type of metal used had little effect on the energy required to achieve a particular solids content.

Alternative materials have also been tried, e.g., Mohamedelhassan and Shang (2001) used carbon-coated metal anodes, but found that they resulted in the largest voltage drop at the electrodes. Abiera et al. (1999) and Bergado et al. (2003) both reported on the use of metal or carbon rods inserted into prefabricated vertical drains (PVDs). The

Zeta potential (mV)	Electrodes	Voltage (V)	Energy (kWh/dry tonne)	Reference
	Metal, horizontal	300–475	20	Sprute and Kelsh (1975*b*).
	Iron, horizontal		25–30	Sprute and Kelsh (1975*a*)
	Steel, vertical	18	0.6	Veal et al. (2000)
–45	Stainless steel	16–46	144–880	Wilmans and van Deventer (1987)
–16	Metal	65–70	17–68	Sprute and Kelsh (1980)
–30	Metal, horizontal	2–46	64	Sprute and Kelsh (1982)
	Steel mesh, horizontal	30–60	14–36	Lockhart and Stickland (1984)
	Copper and steel, horizontal	3–20	96	Shang and Lo (1997)
–27	Carbon graphite, horizontal	20		Chen et al. (1996)
–20	Carbon graphite, horizontal	20		Chen et al. (1996)
	Horizontal	30–60	20	Lockhart (1992)
	Vertical		1	Lockhart (1992)
	Steel, vertical	22–50	94	Veal et al. (2000)
	Steel, vertical	20	33	Veal et al. (2000)

carbon electrodes performed better initially but disintegrated with time, and the metal anodes still experienced corrosion problems. In short, dewatering of large volumes of mine tailings would not seem to be feasible using conventional electrodes. A significant improvement in technology was required and it appears that it may be possible with the new generation electrokinetic geosynthetics (Hamir et al. 2001). These developments are discussed in more detail later in this paper, but before doing so there are other operational features that should be considered.

Voltage gradient and current density

A topic of debate in the literature is whether voltage gradient or current density is a better indicator of the achievable rate of electrokinetic dewatering. The debate was somewhat clouded by the extremely high voltages used in much of the early work, e.g., 330 V/m (Esrig 1968) and 140 V/m (Arnold 1973), plus many others quoted by Shang et al. (1995), and current densities of up to 7.3 A/m^2 (Bjerrum et al. 1967). As discussed by Bjerrum et al. (1967), excessive current density tends to dry out the soil around the anode very rapidly, thereby disguising the true potential benefit of electrokinetic dewatering. As shown by Nicholls and Herbst (1967) and Lockhart (1983*a*), electrokinetic dewatering is much more energy efficient at lower voltage gradients. In addition to this benefit, a lower voltage gradient also resulted in a lower pH rise of the drainage water at the cathode (Veal et al. 2000; Lockhart 1983*a*). A lower voltage gradient (or lower current density) has the obvious disadvantage that the rate of dewatering is lower than at a high voltage gradient, although the energy efficiency is better. Conditions can be further optimized by starting at a low voltage gradient and gradually increasing it as dewatering proceeds (Lockhart 1983*a*). The debate over voltage gradient versus current density is not fully resolved, although intuitively current density seems more appropriate, which is supported by the observations of Shang et al. (1995). Despite this, voltage gradient remains a valuable parameter that is easy to control, e.g., power at a remote site may be supplied by a 12 V car battery. What seems clear from the published case histories is the desirability of using as low a voltage gradient as possible if energy efficiency is to be optimized.

Current intermittence and polarity reversal

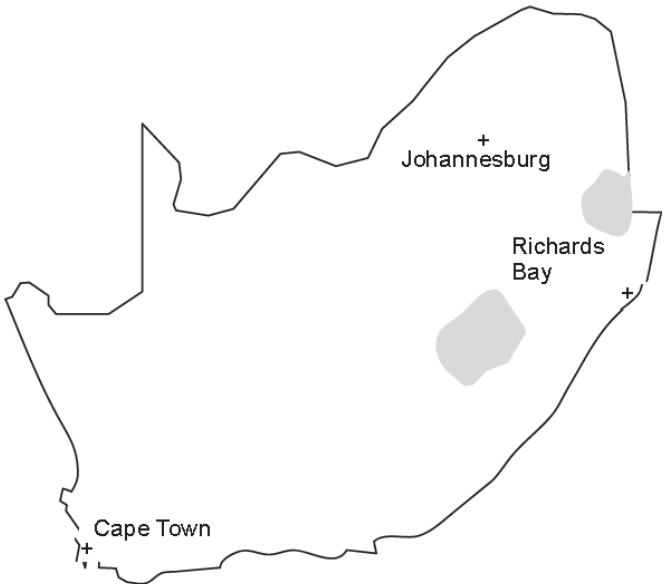
Early studies were characterized by the application of a fixed constant voltage between two electrodes. A definite benefit of intermittently switching the power supply off for short periods is reported by Sprute and Kelsh (1976), Mohamedelhassan and Shang (2001), and Micic et al. (2001). However, Lockhart and Hart (1988) suggested that it will produce no real benefit if the free water (produced at the cathode) is not efficiently removed.

Intermittent polarity reversal is even more beneficial. Without it, very little dewatering takes place at the cathode (Yoshida 1993; Bjerrum et al. 1967; Casagrande 1952). Bjerrum et al. (1967) even reported the occurrence of swelling at the cathode. Wan and Mitchell (1976) showed that with polarity reversal, dewatering would be much more uniform between electrodes and this was confirmed experimentally by Lo et al. (1991). Additional reported benefits include reduced soil desiccation and cracking at the anode (Abiera et al. 1999) and reduced anode corrosion (Shang et al. 1995).

Description of tailings tested

Tailings from a mining operation in the area between Richards Bay and Empangeni in the province of KwaZulu-Natal in South Africa (see Fig. 1) were studied. The mining of ancient dunes for the recovery of ilmenite, zircon, rutile, and leucoxene produces a proportion of very fine tailings (75% <2 μm), which may comprise as much as 23% of the mined material (the remainder being relatively coarse quartz sand (d_{50} = 0.2 mm)). Relevant properties are summarized in Table 2 and Fig. 2. Considering the criteria outlined by Gray and Mitchell (1967), the material was considered likely to respond favourably to electrokinetic dewatering. The fine residue is deposited into a preconstructed impoundment with a 5 m high compacted earth perimeter wall. The design philosophy called for subaerial deposition in very thin (150 mm) layers with a cycle time of between 6 and 10 days to allow solar drying to assist in achieving the required in

Fig. 1. Map of South Africa showing the location of the mineral sands mining site near Richards Bay on the east coast.



situ dry density (Williamson 1997). Once the tailings reached the height of the initial perimeter wall, the intention was to continue raising the height of the impoundment by upstream construction using the fine residue itself (as is done in many other mining operations in South Africa).

To obtain an initial slurry density that was satisfactory, it was decided to utilize ultra high rate thickeners. Three E-cat thickeners, equipped with scraper rakes and a venturi flocculant feed arrangement were installed and have been operational since mid-2001. The design feed rate is approximately 280 t/h at a solids concentration of 8%–10%. Relatively high flocculant dosages are required (150–200 g/t). The reported underflow density is between 28% and 32% solids content, which corresponds to gravimetric water contents of 257% to 212%. The thickened tailings are pumped up to 5 km from the wet plant using two Wïrth HP2200 positive displacement pumps.

For whatever reason, the estimates of likely initial, as-placed density were too low. As a result, the development of shear strength has not been as rapid as envisaged and at depths of 4 m below the surface, water contents as high as 100% are regularly measured (corresponding to an in situ dry density of only about 740 kg/m^3). The resulting low undrained shear strengths are thus not adequate for the proposed upstream method of construction.

Various options are currently being considered to address the problem of insufficient in situ undrained shear strength, and one option that was considered was the use of electrokinetic dewatering. Given the background to the particular project, the following section describes the test work carried out to investigate this possibility.

Experimental methodology

Laboratory test using an electroosmotic cell

Two different sets of laboratory tests were carried out, as well as a large outdoor on-site experiment. The initial set of laboratory tests were designed to test the viability of dewatering the tailings electrokinetically and to compare the rates of consolidation with and without an applied voltage gradient. An electroosmotic testing cell based on that described by Hamir et al. (2001) was manufactured and used to test the effect of electroosmosis on the rate of consolidation of the tailings under an imposed total vertical stress of 30 kPa. These tests are not described in detail here because the apparatus utilized copper discs as electrodes, and the results were thus not directly relevant to a discussion of the use of EKGs in dewatering mine tailings. The tests indicated an increase in the coefficient of consolidation from 1.5 m^2/year for a specimen tested under zero voltage to 5.4 m^2/year for one tested with an applied potential of 10 V. The resulting voltage gradient was 1.1 V/cm, which resulted in an energy consumption rate of 30 kWh per dry tonne dewatered. Although electroosmotic dewatering was successful, this relatively high energy consumption rate pointed to the need to run further tests at lower voltage gradients, as discussed in the following.

Laboratory tank tests

Details of electrokinetic geosynthetics used as electrodes

A major impediment to the use of electrokinetic dewatering for anything but emergency dewatering has been the high corrosion rate of metal electrodes. There have been attempts to use graphite electrodes or metal electrodes with a carbon coating, but with little success (Bergado et al. 2003). Hamir et al. (2001) describe the development of EKGs and in comparative tests they performed as well as copper electrodes. Filter tests showed no clogging of the EKGs or loss of material through the EKG. Jones et al. (2002) conducted tests using EKGs to dewater kaolin clay and observed no deterioration of the electrodes with time. They also reported an energy consumption rate of 4.66 kWh/dry tonne, which compares very favourably with the results summarized in Table 1. Therefore, there was excellent potential for further investigation of the use of EKGs for dewatering mine tailings.

The EKGs used in this study were described in detail in Pugh (2002) and only essential information is provided here. The EKGs consisted of an electrically conductive geonet core manufactured using the counter-rotating dies method utilizing a stationary outer die. The geonet was extruded from a specially formulated conductive compound based on conductive carbon black dispersed in a modified high-density polyethylene resin. The polymer was designed for extrusion applications and was originally developed for the minimization of electrostatic discharge hazards in electrostatic sensitive environments. An example of an EKG used in this study is shown in Fig. 3. Monofilament wires were located at the centre of alternate transverse ribs to act as current distribution stringers. The stringers were used because the electrical conductivity of wire is significantly higher than that of the conductive polymer and as such gives more efficient distribution of current through the length of the EKG. As described by Pugh (2002), the durability of the EKG electrodes is vastly superior to that of metallic electrodes and in tests in our laboratories we have been able to use them in six consecutive tests (in excess of 600 h) without an observable decrease in effectiveness.

Table 2. Properties of mineral sands tailings.

Specific gravity	Mineralogy	Liquid limit (%)	Plasticity index (%)	pH	Zeta potential (mV)
2.76	Kaolinite, quartz, chlorite, haematite	62	26	6.4	–19

Fig. 2. Particle-size distribution of the tailings tested.

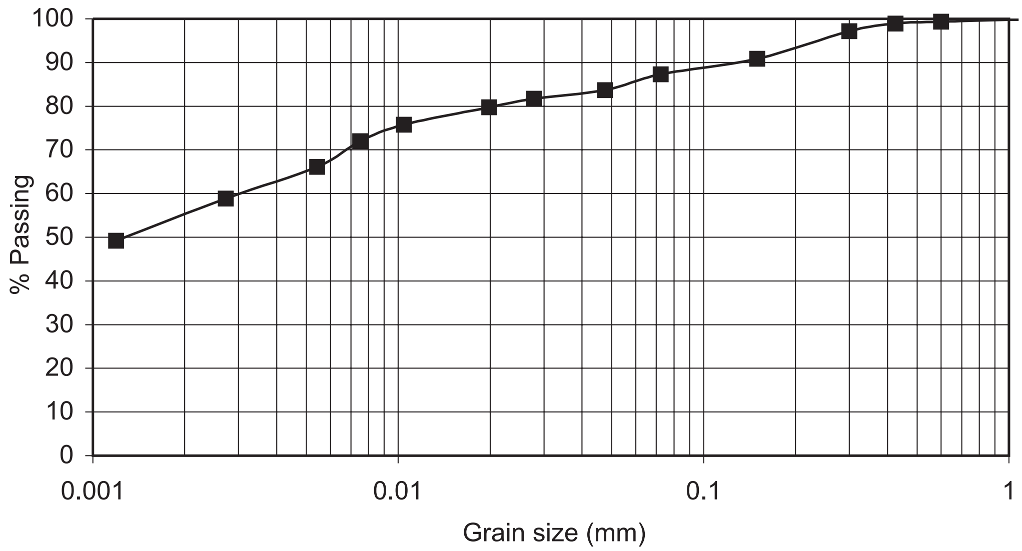


Fig. 3. View of electrokinetic geosynthetic (EKG) used in the tests.

Laboratory tank test

Small wooden tanks (30 cm × 20 cm × 20 cm) were built for the laboratory test. The inside surfaces were coated with marine varnish to make them impermeable. The effectiveness of this treatment was checked by leaving the covered tanks filled with water for 7 days. During this time no drop in water level occurred.

The mineral sands tailings was prepared for the test by mixing it at a water content of 147% (solids content of 40%) in a paddle mixer for 15 min before filling the tank. Prior to filling the tank, the geotextile-enclosed cathode was placed in the tank at one end. After filling the tank, the anode was pushed into the tailings at the opposite end of the tank. A schematic of the testing arrangement at the commencement of a test is shown in Fig. 4. The cathode EKG was wrapped in a nonwoven heat-bonded geotextile, whereas the anode was inserted with no covering. A constant voltage of 5 V was applied, with an intermittence ratio of 0.66. This translated into a voltage gradient of 0.24 V/cm, with the distance being measured between the two closest faces of the electrodes. The current was monitored throughout the test duration, as was the mass of the tank. Water was extracted from the cathode using a syringe whenever it was full and the volume measured (termed collected water in Fig. 5). The change in mass of another similar tank filled with the same tailings was also monitored to provide a measure of the volume of water lost by evaporation.

The results of this test are presented in Fig. 5, which shows the water lost versus time. The difference between the total volume of water lost and that lost by evaporation plus extracted water is water that is lost during the test owing to electrolysis and came to 26% of the total water lost. The results in Fig. 5 were converted to a variation in water content with time, as shown in Fig. 6. As can be seen, the final water content when the test was terminated was 109%, which is a 26% decrease from the starting value. The pH of the water extracted from the cathode at the end of the test had risen to a value of 11.3, from an initial value of 8.5, and the conduc-

Fig. 4. Layout of the laboratory test.

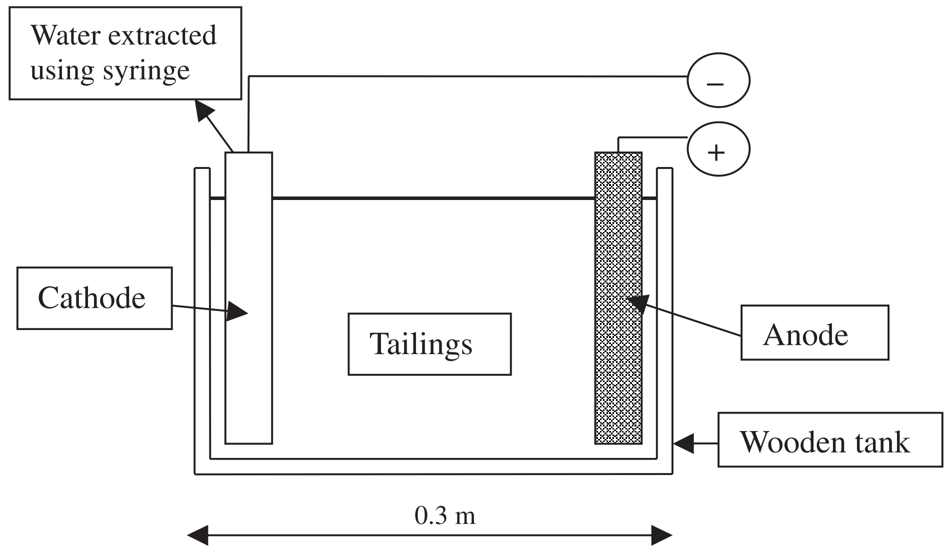


Fig. 5. Rate of water loss in the laboratory tank test.

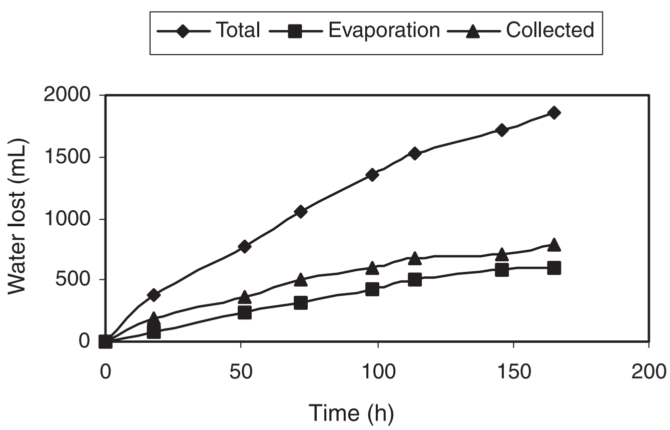
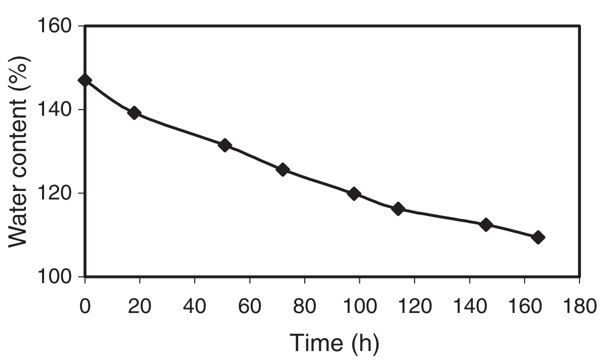


Fig. 6. Variation of mean water content with time in the laboratory tank test.



tivity had risen from 0.51 to 1.15 mS/cm. The energy consumption during the test was 1.9 kWh/dry tonne, which is about 10 times lower than the best value achieved in the electroosmotic cell tests. A value of around 2 kWh/dry tonne certainly improves the viability of electroosmotic dewatering of mineral sands tailings, and when an opportunity arose to carry out a larger scale field test, the opportunity was pursued, as describedin the following.

Outdoor tank test on electroosmotic dewatering of mineral sands tailings

A 3 m diameter container made from high-density polyethylene (HDPE) was filled with tailings directly from the thickener underflow. The tailings was left to stand for 3 weeks, after which it was found to be at a water content of 158% and 750 mm deep. This meant that the initial volume of material was 5.3 m^3. Before describing the experiment in more detail, it is important to describe the strength characteristics of the tailings.

Variation of undrained shear strength with water content

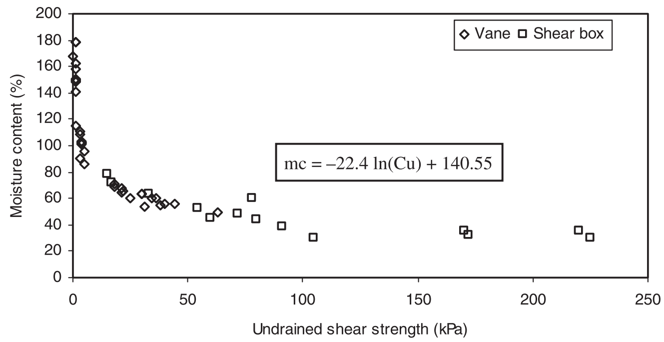
The chosen residue management system relies to some extent on the undrained shear strength of the tailings and its variation with water content (and thus degree of consolidation) is extremely important. du Plessis (2001) carried out 67 consolidated undrained direct shear tests as well as vane shear tests on large drums of the mineral sands tailings. The results of these tests are summarized in Fig. 7 and although there is a high degree of variability, the trend of decreasing undrained shear strength with increasing water content is clear. The regression curve fitted to these data gave a coefficient of correlation of 0.906, with the equation of the curve given in Fig. 7.

The implication of these results is that at the start of the field test, the undrained shear strength of the tailings was much less than 1 kPa. To reach an undrained shear strength of 10 kPa would require the water content be reduced to approximately 89%. Tests by mine personnel over a period of 3 years of operation showed in situ water contents of between 55% and 140%, with only a weak positive correlation between depth and undrained shear strength, indicating that accelerated dewatering could be very beneficial in ensuring the undrained strength of the in situ material is adequate to support upstream raising of the embankment.

Test configuration

A view of the test tank is shown in Fig. 8 and a schematic cross section in Fig. 9. An access footbridge was constructed over the tank to facilitate installation of electrodes and periodic emptying of the cathode. A single EKG cathode,

Fig. 7. Variation of undrained shear strength with moisture content for the mineral sands tailings.



wrapped in a nonwoven, needle-punched geotextile was inserted by hand into the centre of the tank. Enclosing the cathode in a PVC tube, which had a detachable base, facilitated insertion. The tube was inserted, the free end of the cathode firmly gripped, and the tube extracted, leaving the cathode in place. The process took less than 1 min. Six anodes were inserted by hand in a hexagonal pattern around the cathode, at distances of 900 mm from the cathode (see Fig. 9). Immediately after insertion of the anodes, they were connected to the power supply and the voltage increased to 30 V over a 10 min period. This provided an initial voltage gradient of 0.33 V/cm. Water was regularly pumped out of the cathode using a small submersible pump. The volume, pH, and conductivity were measured regularly. The polarity was reversed whenever mine personnel visited the site, which was usually once a day, after the first week of more intense monitoring. Although the tank was within a fenced site, the endemic theft in the area meant the power supply could not be left on-site overnight or unattended for long periods of time. The power supply was thus switched to a 12 V rechargeable battery and housed in a small shed adjacent to the tank. Although the voltage was still occasionally switched to 30 V, this was only for short periods, and thus the voltage gradient for most of the test was 0.11 V/cm.

Samples of the tailings were taken regularly for determination of water content using a modified thin-walled piston sampler and the thickness of tailings in the tank measured with a graduated rod. Water that accumulated in the cathode overnight was only decanted the following morning. This sometimes resulted in water from the cathode discharging onto the tailings surface overnight, which could have decreased the effectiveness of this system because this free water was then able to flow into the cracks that formed around the electrodes. There were a few periods of light rain during the experiment and these are discussed later in the paper.

Results

The total volume of water lost over the 2 month test period is shown in Fig. 10. These data were obtained by converting the average (of four) measured water contents into volume of water remaining in the tank and subtracting from the initial volume. This was considered to be more accurate than using the measured tailings thickness, because cracks began developing soon after the test started (see Fig. 8, which shows the tank after 1 week of testing), and the volume of these cracks would not be accounted for in the measurements of thickness only. As a check, the estimated settlement based on the change in water content (and thus change in volume of the material in the tank) was compared with the measured settlement after 9 weeks and there was only a 3% difference, indicating the effect of the cracks on the calculated volume change would in fact have been minor. In excess of 2 m^3 of water was lost in total. A noticeable feature of the results in Fig. 10 is the gradual but consistent decline in the rate of water lost. This is due to the gradual decrease of the water content and thus water availability, plus the slight loss of contact between the upper part of the electrodes and the tailings over the period of the test. The water recovered from the cathode, corrected for rainfall, is shown in Fig. 11. During the 9 weeks of testing reported in Fig. 10, the total rainfall was 179 mm. The size of the test (7.5 m^3) precluded the use of a control test and it would therefore be necessary to estimate the potential evaporation rate based on evaporation pan readings. Pan evaporation measurements were not made on site, but data from a local area weather station gave potential evaporation (based on A-pan measurements) for this period of 189mm (a mean of 3 mm/day).

On the tailings storage facility itself, drying of the tailings is characterized by the development of a thin (typically 15–20 cm thick) desiccated surface crust, with the material below this level having a much higher water content. Once this surface crust develops, further solar drying of the underlying tailings is inhibited and has on numerous occasions resulted in the low contact-pressure mini-excavator that is used on site becoming bogged down as it punched through the surface crust into the underlying soft tailings.

The variation of water content with depth is shown in Fig. 12. All data points are an average of four measurements. Measurements were taken approximately 10 and 35 cm above the base of the tank, with a further set of measurements taken 5 cm below the surface of the tailings. There is initially more rapid drying at the surface than at depth, but after 2 weeks the changes in water content with depth are relatively uniform. Drying was clearly not confined to the surface, unlike the natural condition described previously.

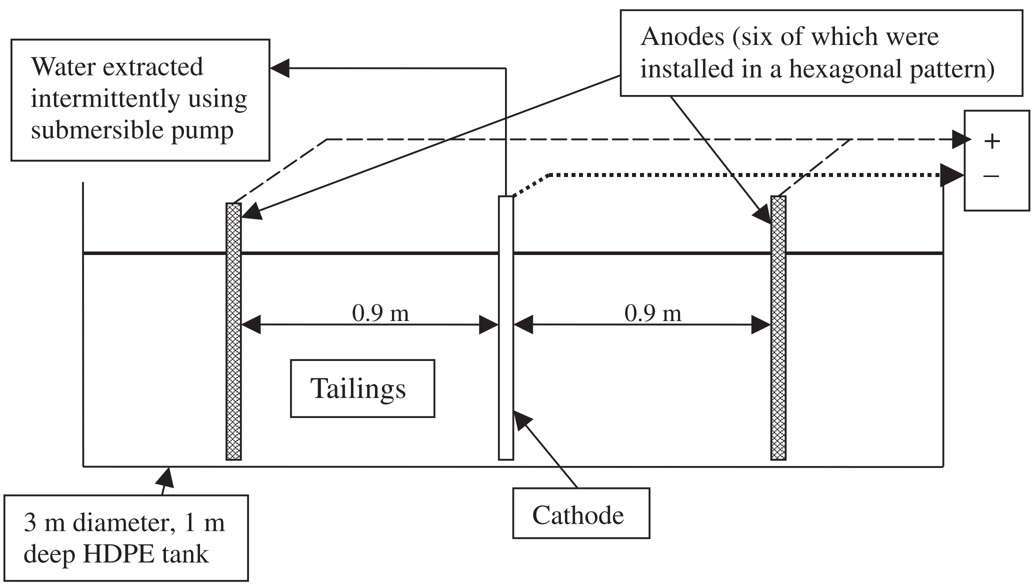
The relative volumes of water lost are not as significant as the consequences of the water removal. At the end of the 2 month period, the mean water content of the tailings was 75%, varying from 54% near the top surface of the tailings (between cracks) to 92% at the bottom of the tank. The mean value of 75% corresponds to an undrained shear strength (see Fig. 7) of 18 kPa, which is a very significant improvement over what was achieved merely by in situ drying.

The variation of pH and conductivity of the cathode water with time are shown in Fig. 13 for the first 23 days of the test (after this time no further pH or conductivity measurements were taken). The pH rose immediately to a value in excess of 11 and the conductivity peaked on the third day, after which it gradually decreased, along with the pH. The effect of dilution because of rainfall on these results could not be accurately quantified but was certainly beneficial as the distinct drops in both pH and conductivity evident in Fig. 13 corresponded to rainy periods.

The applied voltage and the resulting current drawn are shown in Fig. 14. Not shown is the polarity reversal that oc-

Fig. 8. View of outdoor experiment after 1 week of testing.

Fig. 9. Cross section of the outdoor experimental layout.



curred for about 30 min daily (at 30 V). Converting these data to energy consumption, the total energy used during the 2 month test was approximately 2.5 kWh. The initial dry density of the tailings at the start of the test was 510 kg/m^3, so this translates into 0.9 kWh/dry tonne to dewater from a water content of 158% to 75%.

The voltage gradient used in the field test (0.11 V/cm for most of the time) was about one-tenth of that used in the electroosmotic cell and about half that used in the laboratory tank test. It resulted in an energy consumption rate of 0.9 kWh/dry tonne, compared with rates of 1.9 and 30 kWh/dry tonne for the tank test and the electroosmotic cell test, respectively. Increasing the voltage gradient could have accelerated the rate of dewatering, but this would have been at the expense of decreased energy efficiency. The designer of an electroosmotic dewatering system thus has a great deal of flexibility in operational parameters that may be adjusted to suit a range of criteria, from maximizing rate of dewatering to minimizing energy consumption.

Evaluation of potential for large-scale dewatering of mine tailings in situ using electrokinetic geosynthetics

The vast majority of work on electrokinetic dewatering of surface deposits of mine tailings to date has been at a rela-

Fig. 10. Decrease in volume of water with time, calculated from measured water contents for the outdoor test on mineral sands tailings. Measured daily rainfall data are also shown.

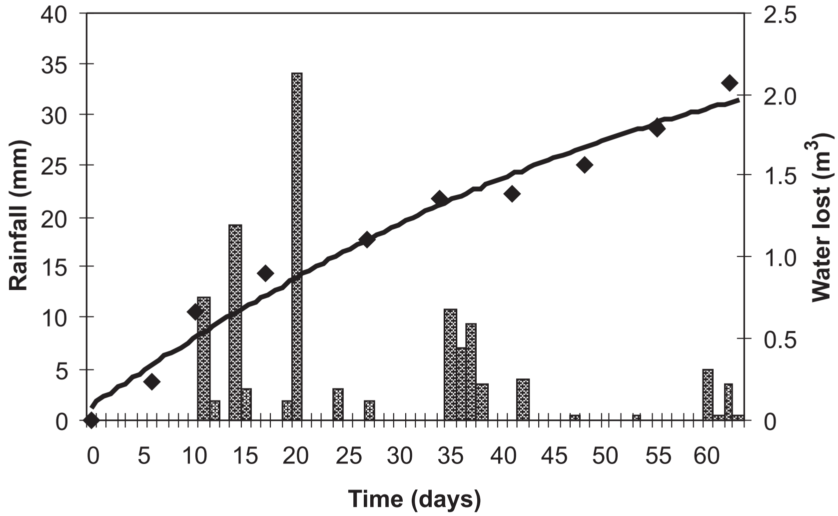
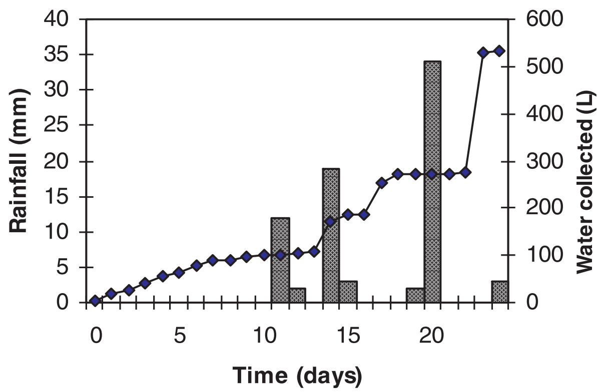


Fig. 11. Volume of water pumped from the cathode, corrected for rainfall, for the first 2 weeks of the outdoor test (MS1 tailings).



tively small scale. With the exception of some of the work at the USBM and the tests on coal waste by Lockhart and Stickland (1984), the work has primarily been carried out at laboratory scale. The obvious question is, if the technique is viable (as claimed in this paper) why is there such a lack of field applications? It is suggested that there are two prime barriers, namely the perceived benefits do not justify the likely costs and the expected logistical problems in actually implementing the technique on a large scale are significant.

It is clear that electrokinetic dewatering can be successful at a large scale. The study of the dewatering of an excavation in soft clay reported by Bjerrum et al. (1967) was a success. Undrained shear strengths were found to increase from initial values of 10 kPa to about 40 kPa, although the increase was not uniform between electrodes (being much more significant adjacent to the anodes than the cathodes). It is worth noting that the electricity costs alone were 25% of the total costs of the project (excluding items listed as overheads, geotechnical investigations, design, control, and measurements). It is this level of energy cost that has in all likelihood detracted from the perceived attractiveness of electrokinetic dewatering at a large scale. However, as argued in this paper, these costs can be significantly reduced by using a low voltage gradient, by utilizing techniques such as intermittent power supply and polarity reversal, and the provision of electrodes that are not subject to rapid corrosion. Conventional metallic electrodes (particularly the anode) corrode rapidly, with a significant loss of efficiency and effectiveness. This can be overcome by the use of EKG materials. For the mineral sands tailings discussed in this paper, dewatering took place at an electrical energy consumption rate of less than 1 kWh/dry tonne. At this rate, the energy costs should become a relatively small percentage of total project cost.

It is important to point out that not all mine tailings will respond as well to electrokinetic dewatering as did the mineral sands tailings. Indeed, Johns (2004) found the energy consumption rate in laboratory tests on kimberlite tailings was between 130 and 615 kWh/dry tonne, which is markedly greater than for the mineral sands tailings and in the same range reported by Wilmans and van Deventer (1987) for their tests on kimberlite tailings. With this level of variability in performance (which is confirmed by the results summarized in Table 1), it is clearly necessary to develop a suite of characterization tests that will accurately predict the viability of electrokinetic dewatering of particular tailings. The work of Gray and Mitchell (1967) provides a very useful point of departure, and their recommendations are consistent with the response found in this paper.

Supposing a particular tailings proves to be amenable to electrokinetic dewatering, at an acceptably low energy consumption rate, what are the considerations influencing possible in situ dewatering using this technique? No matter how low the energy costs associated with dewatering, they remain a cost that cannot be offset against an income. Tailings are after all not an income generator. In evaluating the viability of electrokinetic dewatering of tailings, the costs should be compared with the costs of doing nothing (such as increased liability owing to potential instability, increased closure costs associated with capping very compressible material, and the loss of valuable storage volume by storing tailings at a high moisture content (and thus low density)).

Fig. 12. Variation of water content with depth during 9 weeks of testing in the outdoor experiment. Legend indicates weeks since start of test. Each data point is the mean of four samples.

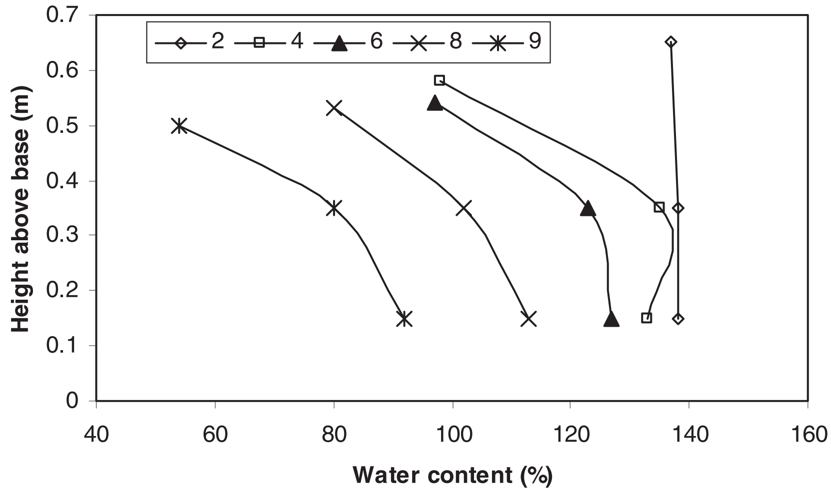


Fig. 13. Variation of pH and conductivity of water collected at the cathode for first 3 weeks of the outdoor tests.

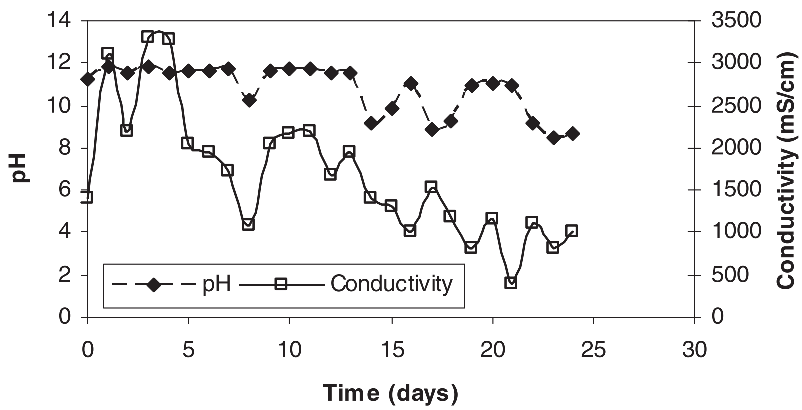
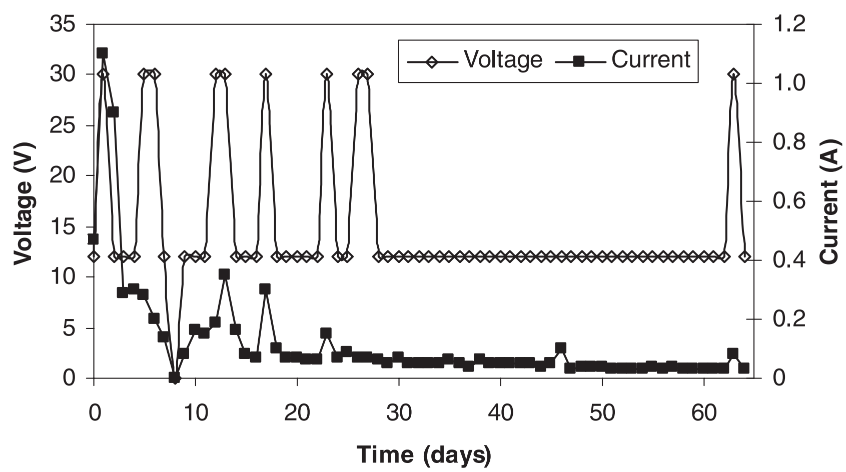


Fig. 14. Variation of applied voltage and current drawn during the outdoor test.



It is also possible to speculate on how the technique may be implemented on a large scale. Sprute and Kelsh (1982) presented a conceptual procedure for the in situ dewatering of a 1.6×10^6 m^3 tailings pond. For reasons that are not explained, this project did not proceed. The large outdoor tests reported in this paper utilized a similar layout to that proposed by Sprute and Kelsh (1982), having a single, central cathode surrounded by six equi-spaced anodes. This arrangement could be replicated many times over in a full-scale application of the technique, providing as much coverage as required. With the excellent durability of the EKG electrodes, they could also potentially be moved at specific times, thereby treating only a portion of the tailings volume at any time.

Issues that would still remain to be solved revolve around the logistics and safety of installation activities. For example, if the tailings were extremely soft and compressible, how would access to the tailings surface be gained to install the electrodes? This can be relatively easy to solve at minimal cost (e.g., using duckboards to decrease the surface contact pressure or a technique such as the primary stage construction method described by Fakher et al. 1999). Another question that may arise is the feasibility of installing electrodes to great depth. To date we have only installed electrodes to a 1 m depth. Greater depths could be achieved by the utilization of hollow mandrels such as are commonly used for the installation of conventional prefabricated vertical drains.

In short, it seems that the logistical constraints to utilizing electrokinetic dewatering of mine tailings in situ can be overcome. The major issue that still needs to be addressed is the financial benefits that will accrue versus the installation and running costs.

Concluding remarks

In situ dewatering of tailings deposits appears to be technically feasible. Results from experiments at three different scales using tailings derived from mineral sands mining operations were positive. Dewatering from a water content of 158% to 75% was achieved at an energy consumption rate of only 0.9 kWh/dry tonne. A key to achieving such a low value was the utilization of a low voltage gradient (0.11 V/cm).

A novel feature of the work reported in this study was the use of electrokinetic geosynthetics (EKGs) as electrodes. The EKGs showed no sign of deterioration, even after 2 months of continuous use in a large outdoor experiment. The form of EKG used as a cathode, being a conductive core enveloped by a geotextile sheath, also facilitated the collection and removal of water.

Whilst it is unlikely that the proposed technique will work in all tailings materials, the results of the study reported here are certainly encouraging enough to warrant further investigations. We are currently engaged in similar work to that described in this paper on the dewatering of kimberlite tailings and these results will be reported on subsequently.

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