Hydrometallurgy 163 (2016) 148–155

Contents lists available at ScienceDirect

Hydrometallurgy

journal homepage: www.elsevier.com/locate/hydromet

Electroosmotic drainage, a pilot application for extracting trapped capillary liquid in copper leaching

J. Valenzuela [a], L. Romero [a,b,*], C. Acuña [c], M. Cánovas [d]

[a] *Centro de Investigación Tecnológica del Agua en el Desierto-CEITSAZA, Universidad Católica del Norte, Antofagasta, Chile*
[b] *Chemical Engineering Department, Universidad Católica del Norte, Antofagasta, Chile*
[c] *Chemical and Environmental Engineering Department, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[d] *Metallurgical and Mining Department, Universidad Católica del Norte, Antofagasta, Chile*

ARTICLE INFO

Article history:
Received 12 August 2015
Received in revised form 18 March 2016
Accepted 12 April 2016
Available online 13 April 2016

Keywords:
Electroosmotic drainage
Copper leaching
Electrode configuration
Moisture reduction

ABSTRACT

Electroosmotic drainage tests were carried out using one-cubic-meter tanks filled with solid residues from leaching copper. The main objective was to evaluate the efficiency of this technique for the removal of capillary-entrapped solution as a function of the following parameters or operational variables: electrode configuration, voltage applied, distance between electrodes, polarity reversal and intermittency of the applied voltage. The efficiency of this technique was compared to that of drainage by gravity, based on three indicators: moisture reduction, energy consumption per cubic meter of drained solution and drainage time factor, which allows a visualization of the reduction of drainage time in relation to natural drainage time by applying electroosmotic drainage. Of the three tested electrode configurations, hexagonal, linear and alternate linear, the last configuration with intermittency in applied voltage (12 V) and a distance of 0.6 m between electrodes gave the best results, with a moisture reduction of 2.02, an energy consumption of 6.7 kWh/m^3 and a drainage time factor of 6.45. Considering these results, it is demonstrated that the technology increases the spatial capacity of copper leaching and reduces the weight of the material to be transported.

1. Introduction

The Atacama Desert in northern Chile is one of the most important copper mining regions in the world. Copper ore, previously agglomerated by adding concentrated sulfuric acid, is heaped on an impermeable plastic and/or clay lined leach pad where it can be irrigated with a sulfuric acid solution to leach the ore. The solution then percolates through the heap and leaches out the copper contained in the solid phase into the aqueous phase, thereby generating an acid solution rich in copper as copper sulfate. The copper-rich solution is then collected and pumped to next step of solvent extraction and electrowinning to produce copper cathodes.

Ore heaps are typically 3 to 8 m high, with a base area of several thousand square meters, and are made up of 100,000 to 500,000 tons of ore (Domic, 2001). Depending on the ore, leaching can take several months to dissolve and extract 75–80% of the leachable copper compounds. Leaching generates large amounts of solid waste that contains mainly gangue (inert material) that is discarded and then accumulated. These wastes are stored above ground where they may constitute a potential risk of groundwater contamination (Dold and Fontboté, 2001).

After having removed much of the soluble copper, the heap is left standing to drain the solution trapped in the pores of the remaining solid. Two drying processes occur during the natural drainage of the heap: (i) gravitational drainage at the base; and (ii) evaporation through solar radiation and convective drying at the surface. After 25–35 days of natural drainage, the final moisture content reached by the solid is approximately 13–16% on a wet basis. The remaining lixiviant is trapped in the capillary interstices of the solid matrix and its extraction by conventional drainage techniques may be difficult. Drainage is particularly difficult in low permeability materials such as clay soils and where fine-grained material has accumulated due to the breakup of agglomerated particles that have interacted with the lixiviant.

Therefore, to reduce the remaining moisture content of the solid material after extracting most of the soluble copper and accelerate the drainage process, electroosmotic drainage technique is proposed. Electroosmotic drainage consists of applying a low electric potential to dewater a porous medium. Casagrande (1947, 1949, 1952) first employed this technique to consolidated clay soils as a simple and efficient way to accelerate dewatering in soils with low hydraulic conductivity. Since then, electroosmotic drainage has been successfully applied to wastewater treatment, remediation of contaminated soils, and industrial and drying processes, among other uses (Runnells and

---

* Corresponding author at: Centro de Investigación Tecnológica del Agua en el Desierto-CEITSAZA, Universidad Católica del Norte, Antofagasta, Chile.
E-mail address: leon@ucn.cl (L. Romero).

http://dx.doi.org/10.1016/j.hydromet.2016.04.005
0304-386X/

Wahli, 1993; Shapiro and Probstein, 1993; Reddy et al., 2006; Fourie et al., 2007; Bertolini et al., 2009; Pham et al., 2010; Athmer et al., 2012; Xue et al., 2015). Furthermore, Burns and Wright (1997a, 1997b) applied this technique for extracting gold from gold-containing or gold-bearing ores. Electroosmotic drainage is more efficient than conventional drainage techniques such as vacuum filtering, belt filter pressing and centrifuging in terms of operation time, energy consumption and treatment costs (Yoshida, 1993). According to Vesilind (1994), water in a porous material can be divided into four types: free water, interstitial or capillary water, surface or vicinal water and intracellular water. While conventional drainage techniques, which are based on mechanical pressure, are effective at removing free water, electroosmotic drainage can be applied to remove free, interstitial and vicinal water (Zhou et al., 2001).

Previous experiments with electroosmotic drainage were conducted to test this technique, employing two formats: 9.5-l columns (0.20 m diameter) and 40-l cells (0.52 m length × 0.35 m width × 0.24 m height); these experiments were not published. The promising results obtained in these experiments led to the present study, which uses 1-cubic-meter tanks. In this study, the electroosmotic drainage technique was applied to the solid waste from heap leaching to reduce moisture levels beyond that of simple gravity assisted drainage.

The aim of this paper is to show the results of applying electroosmotic drainage to solid waste from copper leaching. A total of four sets of experiments were carried out to investigate the efficiency of drainage by measuring three indicators: (i) moisture reduction compared to natural drainage, (ii) drainage time factor and (iii) energy consumption. Finally, the influence of several operational parameters is reported and discussed.

2. Theory

Electroosmotic flow is generated by the electrical interaction between the surface of solid particles and the fluid, which leads to charge separation at a "double layer" interface. Fluid flow usually occurs in the same direction as the applied electric potential, i.e., from the anode to the cathode (Eykholt and Daniel, 1994). When the electrical field is applied, the excess counter ions on the other side of the double layer region adjacent to the medium particles are attracted to and move towards the electrode with the opposite charge (Acar et al., 1995). Electroosmosis can be considered a hydraulic flow induced by an electric field (Shapiro et al., 1989; Yeung, 1999; Alshawabkeh and Acar, 1996). In this way, electroosmosis depends on the properties of the double layer, the chemical composition of the porous material, the pore fluid, the geometry of the pores and the applied electric potential (Hunter, 1981).

For a saturated porous media, the Helmholtz-Smoluchowski (H-S) model is widely accepted to estimate electroosmotic flow (q_e), which is expressed by:

$$q_e = \frac{n\varepsilon\zeta}{\eta}\frac{\Delta V}{\Delta L} \tag{1}$$

where n is the soil porosity, ε is the electrical permittivity of the soil, ζ is the zeta-potential, η is the dynamic viscosity of the fluid, ΔV is the applied electric voltage and ΔL is the space between electrodes.

The electroosmotic flow can also be expressed in terms of the electroosmotic permeability coefficient of the porous media (k_e), which is a measure of the fluid flux per unit area of the porous media and per unit of electric gradient. The value of k_e is assumed to be a function of the zeta-potential of the soil-pore fluid interface, the viscosity of the pore fluid, soil porosity and soil electrical permittivity and is independent of pore size:

$$k_e = \frac{\varepsilon\zeta}{\eta}n \tag{2}$$

Casagrande (1949) stated that the electroosmotic permeability of the soil can be assumed to be constant around the value of 5×10^{-5} cm^2 V^{-1} s^{-1}.

Global fluid flux is the consequence of three gradients: hydraulic gradient $\nabla(-h)$ (Darcy's law), electrical gradient $\nabla(-\phi)$ (electroosmosis) and a chemical gradient, the latter being significant only in the presence of large molecular chains and in very active clay deposits (soil plasticity). Assuming that the chemical gradient is not significant, the fluid flux is thus estimated by:

$$J_w = k_h\nabla(-h) + k_e\nabla(-\phi) \tag{3}$$

where k_h is the hydraulic conductivity (Mitchell, 1992; Yeung, 1994; Page and Page, 2002). The contribution of the hydraulic and electrical gradients depends on the ratio of the coefficient of electroosmotic permeability to hydraulic conductivity (k_e/k_h). The factors affecting this ratio are soil type, microstructure and pore fluid conditions. In course-grained soil, the ratio is very low due to the almost non-existent electroosmotic flow and relatively high hydraulic conductivity (>10^{-3} cm/s) of such soils. In soft, fine-grained soils, the ratio is significant as k_e is usually on the order of 10^{-5} cm^2 V^{-1} s^{-1}, while k_h is <10^{-5} cm/s (or 10^{-7} cm/s for clayey soils) (Mitchell, 1992; Yeung, 1994; Acar and Alshawabkeh, 1993; Acar et al., 1993). Therefore, an electrical gradient is more effective than a hydraulic gradient for moving liquid through fine-grained soils.

For unsaturated porous media, Yuan and Hicks (2014, 2015) proposed another model for unsaturated clayey soils taking into account

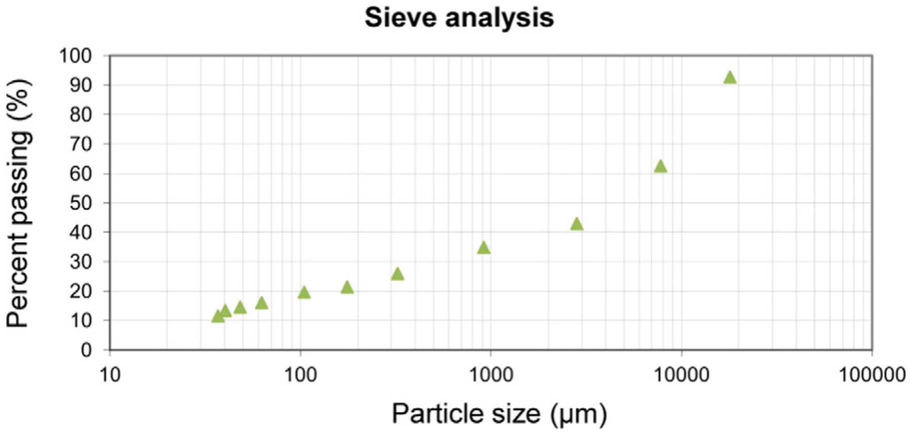

Fig. 1. Distribution of particle size in copper mineral sample used in the electroosmotic drainage test.

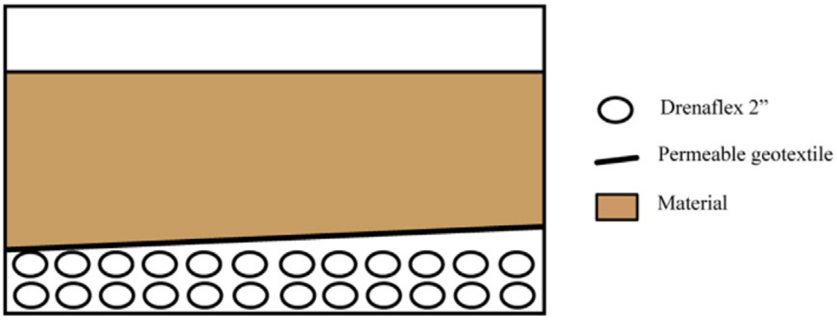

Fig. 2. Scheme of the one-cubic-meter tanks used as electroosmotic drainage chambers. Dimensions of tanks: 1.04 × 0.90 × 1.06 m (length × width × height).

the Esrig's assumptions (1968) and the Darcy's law to obtain the total flow:

$$J_w = -\frac{k_{rw}k_w}{\gamma_w}\nabla(p_w + \gamma_w z) - k_{reo}k_{eo}\nabla(V) \tag{4}$$

where k_{rw} is the coefficient of relative hydraulic conductivity, γ_w is the unit weight of water, z is the elevation, p_w is the pore water pressure, k_{reo} is the coefficient of relative electroosmosis conductivity, V is the electrical potential and k_w and k_{eo} are the intrinsic hydraulic conductivity and electroosmosis permeability matrices, respectively. Some authors (Revil et al., 2007) state that the porous material is saturated with two immiscible phases, a wetting phase (water) and a nonwetting phase (air), considering Darcy's law, while others authors (Linde et al., 2007; Allegre et al., 2012) considers Richards´ equation (Richards, 1931) to describe flow in unsaturated porous media.

3. Experimental procedure

Four sets of experiments were conducted to test the drainage capacity of two electrode configurations, including hexagonal and linear, with the application of a constant voltage and a fixed distance between electrodes. The solid sample used in all tests was solid residue from copper leaching with a particle size distribution defined in Fig. 1.

Since the solution holding capacity is associated with the amount of fine-grained material in the solid matrix, it is important to determine the particle size distribution of the solid sample using a 200 mesh. Fig. 1 shows that >20% of the solid matrix is composed of finely-grained material (<200 μm), which favors water retention.

The tests employed one-cubic-meter tanks filled with copper leaching residues. As Fig. 2 shows, the tanks were open at the top, with the bottom conditioned to obtain a 3.3% slope to facilitate drainage. The drainage of the solution was obtained using a permeable geotextile membrane over two layers of drainage tubes. The tanks were irrigated with acid solution at a rate of 4 L/h/m^2 for 15 days to reach the moisture level of the residues when the irrigation process of the heap leaching was stopped. The tanks were covered with plastic to prevent evaporation. After the irrigation phase, a constant voltage was applied to the tanks for 7 days, which in the case of the 0.9-m-deep tanks used, was enough to gravitationally drain the solution in the largest pores as free form drainage.

The number of electrodes required for electroosmotic applications depends on spacing between electrodes of the same polarity (anode-anode or cathode-cathode spacing). Decreasing the spacing between same-polarity electrodes minimizes the area of inactive electric field, but increases the cost of the process. The electrodes can be placed in a hexagonal or square configuration to generate the electrical fields. Areas of inactive electrical fields may develop depending on the configuration selected. Since this affects the cost of electrodes, it is necessary to select the configuration with the optimum number of electrodes per unit area while minimizing the area of ineffective electrical fields (Yoshida, 1993).

Fig. 3 shows the two types of configurations used: a) hexagonal and b) linear. The goal of the hexagonal arrangement is to achieve radial flow of current towards the center cathodes. The linear arrangement creates a uniform and parallel distribution of flow from anode to cathode.

The objective of these experiments was to determine the most suitable configuration under the application of constant voltage between electrodes. The tests involved applying either 12 or 24 V, with distances between electrodes ranging between 0.3, 0.4, 0.5 and 0.8 m. The anodes were 0.8 m long with the lower 0.6 m extending vertically into the material. To stimulate a flow with vertical and horizontal components, the cathodes (0.8 m long) were buried 0.1 m deeper than the anodes.

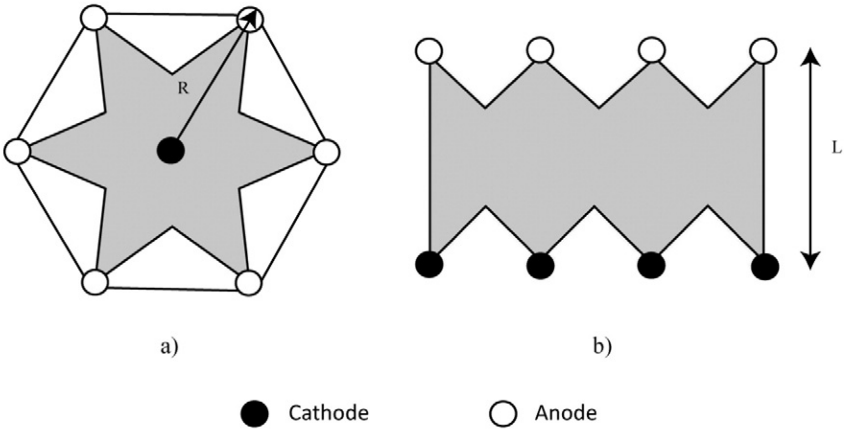

Fig. 3. Scheme of configurations employed in this work: a) hexagonal and b) linear; with R as the distance from the central electrode to the peripheral electrode and L as the distance between positive and negative electrodes.

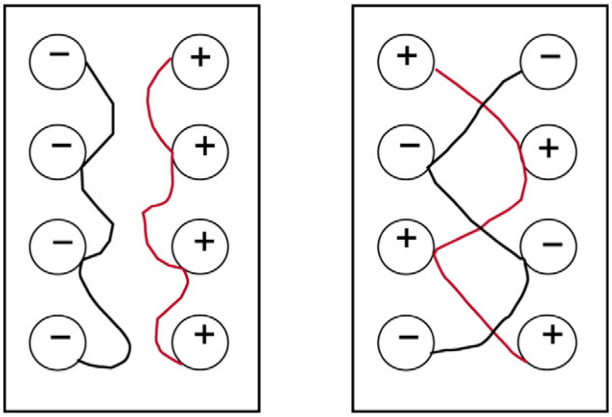

Fig. 4. Variant of the linear configuration including alternate polarity of electrodes, as shown in the scheme on the right.

Vertical electrode configuration was chosen instead of horizontal electrode configuration as the practical implementation of this technique would not be feasible due to the dimensions of the leach heaps. The electrodes were made of 316 L grade steel, and the power source was an Extech 382276 (1-30VDC, 20A).

Due to electroosmotic flow from anode to cathode, the layer is dried in the vicinity of the anode and wetted in the vicinity of the cathode (Barton et al., 1999), resulting in increased electrical contact resistance at the anode. It may be possible to avoid contact resistance issues by changing polarities during electroosmotic drainage. The change is simulated by alternating the polarity of the electrodes, as shown in Fig. 4. It is hypothesized that reversing polarity results in a better interaction between anodes and cathodes and increases the effective area of the electrical field in the tank. In addition to the changes in voltage and distance between electrodes, the influence of the intermittent current and polarity reversal was studied.

To compare the results to those of the electroosmotic drainage test (EOD), in each of the four sets of tests, one tank was used as experimental control to simulate natural drainage. Fig. 5 shows the cell, i.e., the tank used in the experimental pilot test.

4. Measurement of the indicators

The efficiency of electroosmotic drainage depends on the measured values of three indicators: moisture reduction, drainage time factor and energy consumption.

(i) Moisture reduction (MR) is defined as the difference in moisture as a percentage point reduction between tests carried out with and without application of an electrical potential. Furthermore, variations in the moisture level reached by the drainage test (either through natural or electroosmotic drainage) are determined by the difference between the mass of the tank measured at the beginning and the end of each test.

Table 1
Results of experiments to evaluate the effect of the type of configuration associated with an increase in voltage on the indicators of moisture, drainage time, and energy consumption (Natural drainage moisture 11.19%, natural drainage time: 168 h).

Tank	Configuration	Voltage	Distance	Moisture reduction	Drainage-time Factor	Energy consumption
		Volts	Meters	Δ %	–	kWh/m^3
1	Hexagonal	12	0.3	1.27	3.04	13.97
2	Hexagonal	12	0.3	1.31	2.64	14.90
3	Hexagonal	24	0.3	1.10	2.22	80.07
4	Hexagonal	24	0.3	1.04	2.03	85.77
5	Linear	12	0.4	0.75	1.87	36.47
6	Linear	12	0.4	0.82	1.73	31.89
7	Linear	24	0.4	0.74	2.00	126.61
8	Linear	24	0.4	0.89	1.82	123.88

$$MR = \Delta H_{EOD} - \Delta H_{ND} \tag{5}$$

with ΔH_{EOD} as the percentage of moisture reduction reached through electroosmotic drainage and ΔH_{ND} as the percentage of moisture reduction due to natural drainage.

In addition, due to the heterogeneity of the material and to compare the different tests of each set (which were carried out using material with different mineralogy due to the production rate of the mine), the concept of standard moisture is used. For each test or tank, the standard moisture is defined as the instantaneous moisture divided by the initial moisture, as a result the standard moisture covers the range [0,1]. This data is presented in figures in the next section for each set of tests.

(ii) Drainage-time factor (DTF) is calculated by:

$$DTF = \frac{t_{ND}}{t_{EOD}} \tag{6}$$

Where t_{ND} is the time at which the cumulative volume of the solution drained gravitationally (natural drainage) reaches 95% of the final liquid content. The figure of 95% was chosen because the drainage typically asymptotes towards a final liquid content, i.e., the last part of the liquid to drain out can take much longer than all the rest of the drainage. When an electroosmotic drainage test is run for a sample of mineral similar to that used in natural drainage, t_{EOD} is defined as the time taken to reach the 95% moisture reduction reached in a natural drainage test. This factor allows the reduction in drainage time in relation to the natural drainage time due to the application of electroosmotic drainage to be visualized.

Fig. 5. Photograph showing the tanks used in the pilot tests of electroosmotic drainage in operation, the linear distribution of the electrodes and verticality of their positioning.

Table 2
Results of the set of experiments to evaluate the effect of the distance between electrodes, taking in consideration the type of configuration and the increase in voltage on the indicators of moisture, drainage time, and energy consumption (Natural drainage moisture 11.45%, natural drainage time: 152.5 h).

Tank	Configuration	Voltage	Distance	Moisture reduction	Drainage time factor	Energy consumption
		Volts	Meters	Δ %	–	kWh/m^3
1	Hexagonal	12	0.4	1.34	5.19	19.55
2	Hexagonal	12	0.5	1.28	4.50	12.85
3	Hexagonal	24	0.4	1.08	5.63	34.75
4	Hexagonal	24	0.5	1.22	4.79	39.15
5	Linear	12	0.5	1.41	4.95	32.49
6	Linear	12	0.8	1.36	5.82	52.45
7	Linear	24	0.5	1.40	5.34	55.99
8	Linear	24	0.8	1.06	4.71	96.46

Table 3
Results of the set of experiments to evaluate the effect of alternate polarity of the electrodes in a linear configuration on moisture, drainage time, and energy consumption (Natural drainage moisture 10.77%, natural drainage time: 153.8 h).

Tank	Configuration	Voltage	Distance	Moisture reduction	Drainage time factor	Energy consumption
		Volts	Meters	Δ %	–	kWh/m^3
1	Linear	12	0.4	1.58	4.16	11.46
2	Linear	12	0.6	1.27	3.75	15.21
3	Linear	12	0.8	0.94	3.91	15.87
4	Alternate	12	0.4	2.03	6.33	13.54
5	Alternate	12	0.6	1.58	5.78	6.38
6	Alternate	12	0.8	1.34	4.93	6.76

(iii) Energy consumption is calculated as Wh per amount of drained water (Gazbar et al., 1994; Banerjee and Law, 1998; Larue et al., 2001; Zhou et al., 2001) by the following equation:

$$\text{Energy consumption} = \Delta V \int_{t0}^{tn} \left(\frac{I(t)}{Vol}\, dt\right) \approx \left(\frac{\Delta V\, I \Delta t}{Vol}\right) \tag{7}$$

where energy consumption is the energy consumed per unit volume of drainage water (Wh/m^3), ΔV is voltage (V), I is current (A), t is the processing time (h) and Vol is the volume of water drained from the solid residues (m^3). The voltage and current were measured with a Fluke Multimeter 3000 series model FC and corroborated with readings of the power supply. The volume of the collected draining solution was measured periodically.

5. Results

The tests performed in the laboratories of CEITSAZA-UCN (Technological Center for Research on Water in the Desert - Universidad Católica del Norte) are presented in Tables 1 to 4 in order to validate the electro-osmotic drainage technique. Table 1 lists the results of comparing hexagonal versus linear arrangement for 12 and 24 V. The experiments were carried out in duplicate to check the validity of the technique, so tests 2, 4, 6 and 8 are replicates of tests 1, 3, 5 and 7.

The results in Table 1 indicate that the hexagonal electrode configuration is the best choice based on the indicators of its power usage, with higher moisture reduction and increased time factor compared to the indicators for the linear configuration. The linear configuration provides acceptable time factor values as the hexagonal configuration, but at a greater expense in power consumption. Oddly, the application of higher voltage increases energy consumption, but does not increase moisture

Table 4
Results of the set of experiments to evaluate the effect of alternating electrode polarity (*) and intermittent voltage (**) on the indicators of moisture, drainage time, and energy consumption (Natural drainage moisture 11.50%, natural drainage time: 126.8 h).

Tank	Configuration	Voltage	Distance	Moisture reduction	Drainage-Time Factor	Energy consumption
		Volts	Meters	Δ %	–	kWh/m^3
1	Linear*	12	0.6	1.55	4.14	27.17
2	Alternate*	12	0.6	1.84	6.21	33.70
3	Linear**	12	0.6	1.34	5.53	16.14
4	Alternate**	12	0.6	2.02	6.45	6.70

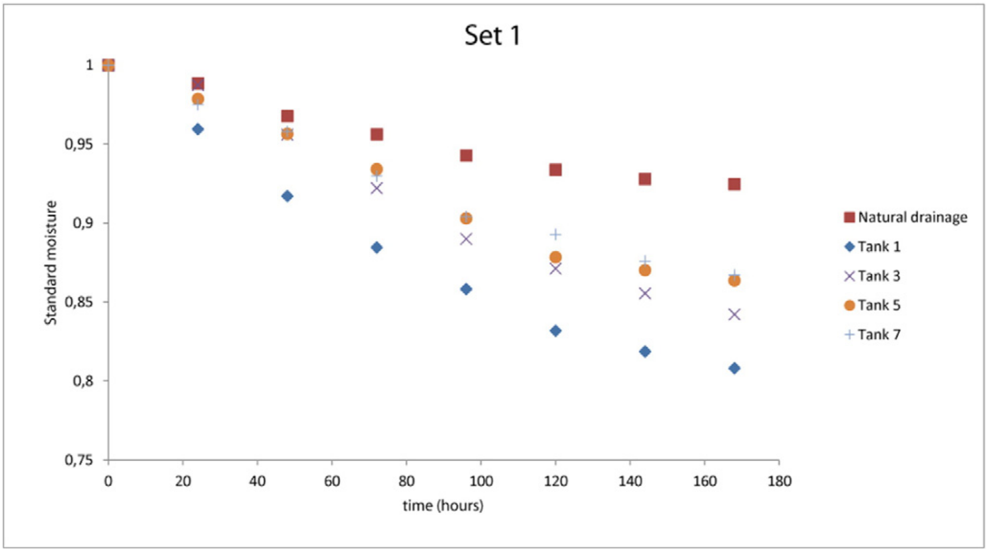

Fig. 6. Graphical representation of the standard moisture for the first set of tests.

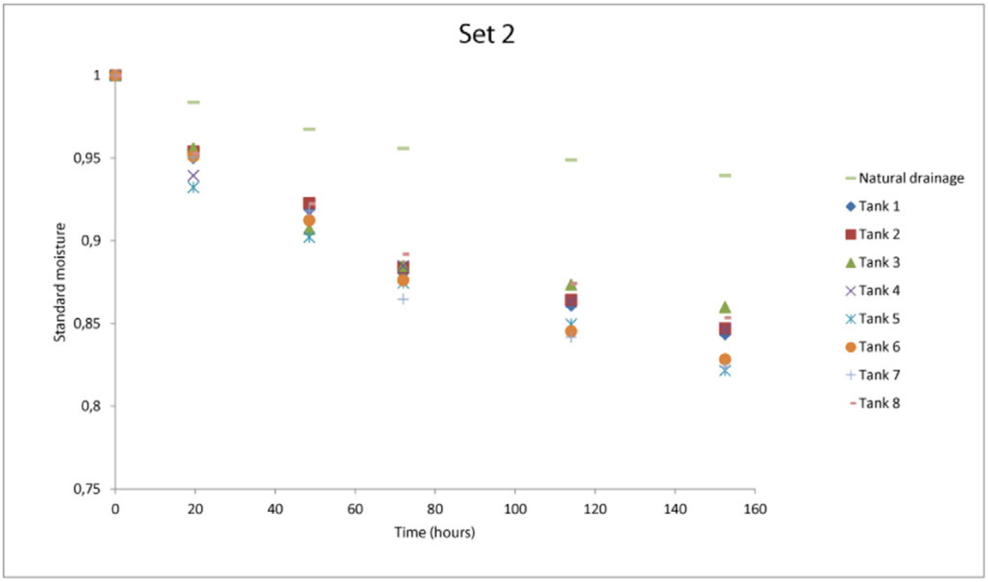

Fig. 7. Graphical representation of the standard moisture for the second set of tests.

reduction or drainage time. The results for the replicates show the experiments can produce similar values within an acceptable range of errors. The standard moisture values for the tests (without the replicates), as a function of time, are shown in Fig. 6.

Table 2 explores the differences that electrode distances have on drainage. In general, a decrease in electrode distance decreases the moisture of the material for the same configuration and applied voltage. In general terms, a shorter distance between electrodes implies an increase in the time factor and a decrease in energy consumption. On the other hand, a shorter distance between electrodes means a higher cost because more electrodes are needed to cover the same distance. Fig. 7 shows the standard moisture results for this set of experiments.

For the alternate linear configuration, with cathodes positioned between two anodes and anodes between two cathodes (see Fig. 4-b), moisture reduction and time factor increased and energy consumption decreased, indicating that this configuration is much more effective than the others. The positive results, shown in Table 3, may be due to improved cathode-anode-cathode interaction and the larger effective area of the electric field in the tank. The standard moisture results are shown in Fig. 8.

In this last set of experiments, the main issues were to evaluate the effects of polarity reversal and intermittent applied voltage on the indicators defined. Reverse polarity implies changing the direction of electroosmotic flow, which offers the advantage that residues are remoistened and the mobility of the solution is enhanced when the system returns to normal polarity. Table 4 shows that the reverse polarity configuration is more efficient than the linear configuration (in Fig. 4a) in terms of moisture reduction and drainage time. The larger area of the electrical field generated partly supports this behavior. In the intermittence experiments, the alternate configuration presents the best results for the three indicators, especially energy consumption. Fig. 9 shows the standard moisture results for this table.

Based on the results shown in Tables 1–4 and Figs. 6–9, it is possible to state that the electroosmotic drainage technique allows a reduction in moisture content and an acceleration in drainage time.

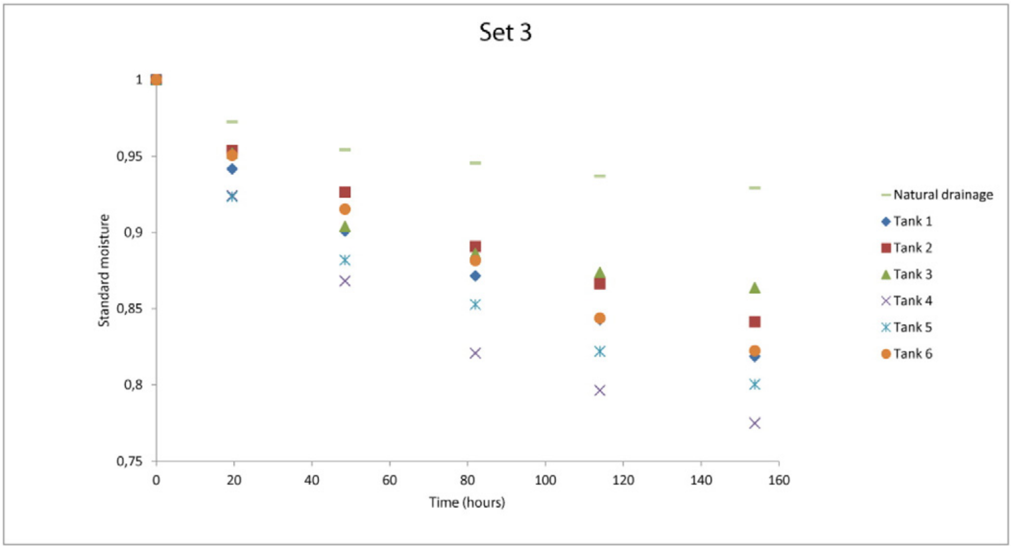

Fig. 8. Graphical representation of the standard moisture for the third set of tests.

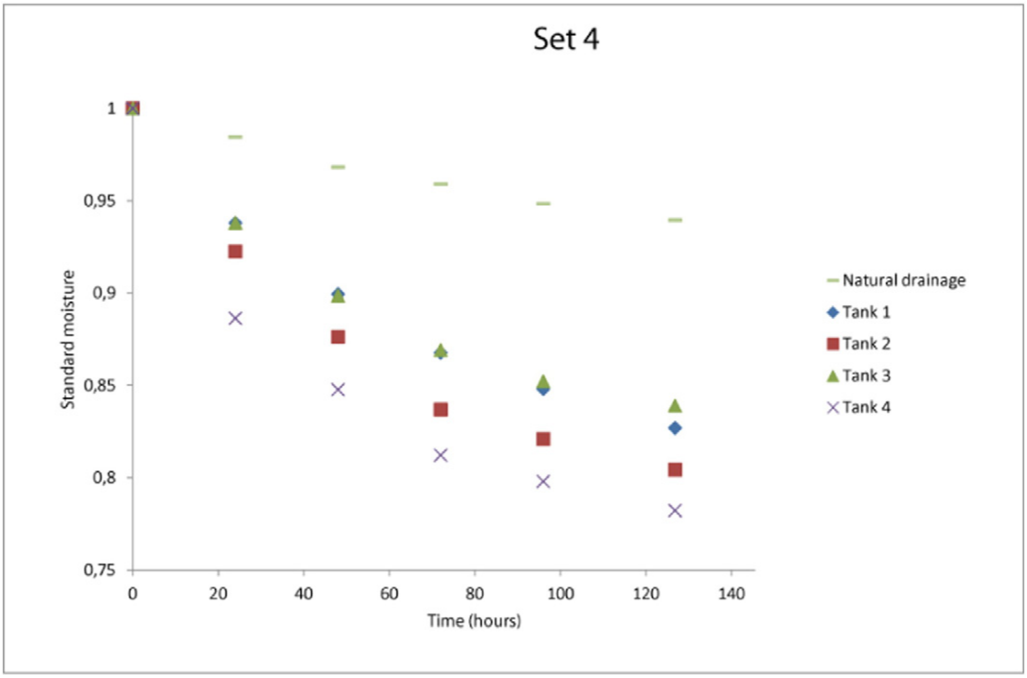

Fig. 9. Graphical representation of the standard moisture for the fourth set of tests.

6. Conclusions

Electroosmotic drainage tests were conducted with one-cubic-meter tanks filled with solid residues from copper leaching. Considering the established indicators of efficiency and the results of the experiments, we draw the following conclusions:

- All of the tests applying constant voltage resulted in lower moisture levels than that obtained by gravity drainage tests using the same running time. The drainage time factor was also reduced in relation to gravity drainage tests.
- The behavior of the electrode distance parameter was as expected (see Eq. (1)); a shorter distance reduced moisture and drainage time. However, the behavior of applied voltage was not as expected; an increase in voltage did not increase drainage, possibly because the increase from 12 to 24 V was not sufficient.
- Of the three electrode configurations, including hexagonal, linear and alternate linear, the alternate linear configuration obtained the best results, with the highest reduction in moisture, the highest time factor and the lowest energy consumption.
- Finally, the application of reversed polarity did not improve the indicators. However, drainage is more efficient with intermittent voltage.

To summarize, the best results were obtained with the alternate linear configuration with intermittent voltage (12 V) and a distance of 0.6 m between electrodes, resulting in a moisture reduction of 2.02, a drainage time factor of 6.45 and an energy consumption of 6.7 kWh/m^3. With respect to the drainage time factor, the value of 6.45 obtained means that the operation time for the stage when the heap is left standing to drain the solution trapped in the pores of the remaining solid after having removed much of the soluble copper, is made shorter by application of the electroosmotic drainage technique as compared to natural or gravitational drainage. With regards to the moisture reduction value of 2.02, this means that the weight of the material to be transported is reduced. Applying these results to a typical dynamic leach heap (480 × 80 × 3 m) and considering total moisture reduction by natural and electroosmotic drainage, power consumption is estimated at approximately 7100 kWh to remove 3179 m^3 of solution.

References

Acar, Y.B., Alshawabkeh, A., 1993. Principles of electrokinetic remediation. Environ. Sci. Technol. 27 (13), 2638–2647.
Acar, Y.B., Alshawabkeh, A., Gale, R.J., 1993. Fundamentals of extracting species from soils by electrokinetics. Waste Manag. 13 (2), 141–151.
Acar, Y.B., Gale, R.J., Alshawabkeh, A.N., Marks, R.E., Puppala, S., Bricka, M., Parker, R., 1995. Electrokinetic remediation: basics and technology status. J. Hazard. Mater. 40 (2), 117–137.
Allegre, V., Lehmann, F., Ackerer, P., Jouniaux, L., Sailhac, P., 2012. A1-D modelling of streaming potential dependence on water content during drainage experiment in sand. Geophys. J. Int. 189 (1), 285–295.
Alshawabkeh, A.N., Acar, Y.B., 1996. Electrokinetic remediation. Theoretical model. J. Geotech. Eng. 122 (3), 186–196.
Athmer, C., Ruef, C., Jones, T.J., Wilkens, R.J., 2012. Desalinization of kaolin soil using radial electromigration and electroosmosis. J. Hazard. Toxic Radioact. Waste 17 (1), 16–20.
Banerjee, S., Law, S.E., 1998. Electroosmotically enhanced drying of biomass. IEEE Trans. Ind. Appl. 34 (5), 992–999.
Barton, W.A., Miller, S.A., Veal, C.J., 1999. The electrodewatering of sewage sludges. Dry. Technol. 17 (3), 498–522.
Bertolini, L., Coppola, L., Gastaldi, M., Redaelli, E., 2009. Electroosmotic transport in porous construction materials and dehumidification of masonry. Constr. Build. Mater. 23 (1), 254–263.
Burns, C. J., Wright, D., 1997a. U.S. Patent No 5,626,739. Washington, DC: U.S. Patent and Trademark Office.
Burns, C.J., Wright, D., 1997b. Electrokinetic leaching. Hydrometallurgy 46 (3), 394.
Casagrande, L., 1947. The Application of Electroosmosis to Practical Problems in Foundations and Earthworks. Building Technical Paper No. 30. H.M.S.O., London.
Casagrande, L., 1949. Electroosmosis in soils. Geotechnique 1, 159–177.
Casagrande, L., 1952. Electroosmotic stabilization of soils. J. Boston Soc. Civ. Eng. 39, 51–83.
Dold, B., Fontboté, L., 2001. Element cycling and secondary mineralogy in porphyry copper tailings as a function of climate, primary mineralogy, and mineral processing. J. Geochem. Explor. 74, 3–55.
Domic, E., 2001. Hidrometalurgia: Fundamentos, Procesos Y Aplicaciones. Andros Impresos, Chile.
Esrig, M.I., 1968. Pore pressures, consolidation and electrokinetics. J. Geotech. Eng. Div. ASCE 94 (4), 899–921.
Eykholt, G.R., Daniel, D.E., 1994. Impact of system chemistry on electroosmosis in contaminated soil. J. Geotech. Eng. 120 (5), 797–815.
Fourie, A.B., Johns, D.G., Jones, C.F., 2007. Dewatering of mine tailings using electrokinetic geosynthetics. Can. Geotech. J. 44 (2), 160–172.
Gazbar, S., Abadie, J., Colin, F., 1994. Combined action of electro-osmotic drainage and mechanical compression on sludge dewatering. Water Sci. Technol. 30 (8), 169–175.
Hunter, R.J., 1981. Zeta Potential in Colloid Science: Principles and Applications. Academic, London.
Larue, O., Mouroko-Mitoulou, T., Vorobiev, E., 2001. Pressurized electroosmotic dewatering in a filter cycle. Dry. Technol. 19 (1), 185–198.
Linde, N., Jougnot, D., Revil, A., Matthäi, S.K., Arora, T., Renard, D., Doussan, C., 2007. Streaming current generation in two-phase flow conditions. Geophys. Res. Lett. 34 (3).

Mitchell, J.K., 1992. Fundamentals of Soil Behavior. second ed. Wiley, New York.

Page, M., Page, C., 2002. Electroremediation of contaminated soils. J. Environ. Eng. 128 (3), 208–219.

Pham, A.T., Sillanpää, M., Virkutyte, J., 2010. Sludge dewatering by sand-drying bed coupled with electro-dewatering at various potentials. Int. J. Min. Reclam. Environ. 24 (2), 151–162.

Reddy, K.R., Urbanek, A., Khodadoust, A.P., 2006. Electroosmotic dewatering of dredged sediments: bench-scale investigation. J. Environ. Manag. 78 (2), 200–208.

Revil, A., Linde, N., Cerepi, A., Jougnot, D., Matthäi, S., Finsterle, S., 2007. Electrokinetic coupling in unsaturated porous media. J. Colloid Interface Sci. 313 (1), 315–327.

Richards, L.A., 1931. Capillary conduction of liquids through porous medium. Physics 1, 318–333.

Runnells, D.D., Wahli, C., 1993. In situ electromigration as a method for removing sulfate, metals and other contaminants from groundwater. Ground Water Monit. Rem. 13 (1), 121–129.

Shapiro, A.P., Probstein, R.F., 1993. Removal of contaminants from saturated clay by electroosmosis. Environ. Sci. Technol. 27 (2), 283–291.

Shapiro, A.P., Renaud, P.C., Probstein, R.F., 1989. Preliminary studies on the removal of chemical species from saturated porous media by electroosmosis. Physico-Chem. Hydrodyn. 11, 785–802.

Vesilind, P.A., 1994. The role of water in sludge dewatering. Water Environ. Res. 36, 4–11.

Xue, Z., Tang, X., Yang, Q., Wan, Y., Yang, G., 2015. Comparison of electro-osmosis experiments on marine sludge with different electrode materials. Dry. Technol. 33 (8), 986–995.

Yeung, A.T., 1994. Electrokinetic Flow Processes in Porous Media and Their Applications. In: Corapcioglu, M.Y. (Ed.), Advances in porous media 2. Elsevier Science, Amsterdam, The Netherlands, pp. 309–395.

Yeung, A.T., 1999. Coupled flow equations for water, electricity and ionic contaminants through clayey soils under hydraulic, electrical and chemical gradients. J. Non-Equilib. Thermodyn. 15 (3), 247–267.

Yoshida, H., 1993. Practical aspects of dewatering enhanced by electro-osmosis. Dry. Technol. 11 (4), 784–814.

Yuan, J., Hicks, M.A., 2014. Numerical modelling of electro-osmosis consolidation of unsaturated clay at large strain. Proc. of the 8th European Conf. on Numerical Methods in Geotechnical Engineering, pp. 1061–1066.

Yuan, J., Hicks, M.A., 2015. Numerical analysis of electro-osmosis consolidation: a case study. Geotech. Lett. 5 (3), 147–152.

Zhou, J., Liu, Z., She, P., Ding, F., 2001. Water removal from sludge in a horizontal electric field. Dry. Technol. 19 (3–4), 627–663.