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

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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

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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:

$$q_e = \frac{n\varepsilon\zeta}{\eta}\frac{\Delta V}{\Delta L} \qquad (1)$$

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:

$$k_e = \frac{\varepsilon\zeta}{\eta}n \qquad (2)$$

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

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:

$$J_w = k_h\nabla(-h) + k_e\nabla(-\phi) \qquad (3)$$

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 $10^{-5}\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$, 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

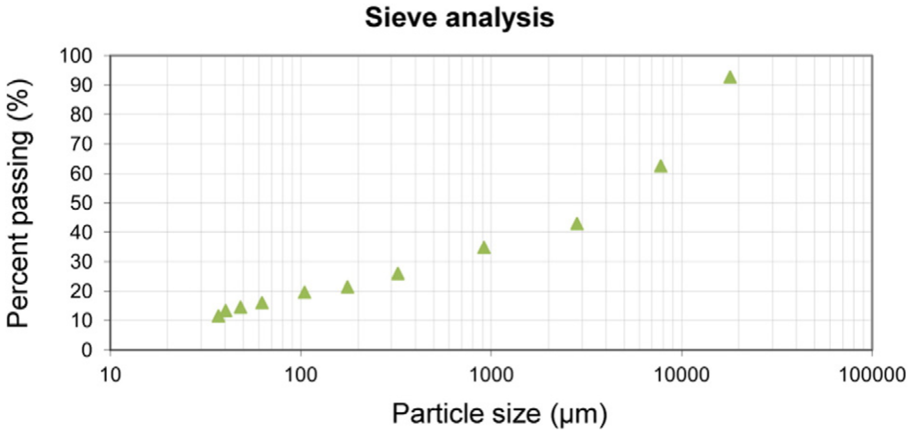

Fig. 1. Distribution of particle size in copper mineral sample used in the electroosmotic drainage test.