Laboratory Evaluation of Electrokinetic Dewatering of Bauxite Tailings

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Abstract. The mining tailings disposal system is often associated to the construction of large retaining systems, either for the great volume of materials generated by industrial plants or for the impossibility or difficulty of grants for new disposal areas. Due to increasing demand, these impoundments have become much more significant, triggering considerable increase of risk associated to them. In this context, new techniques must be developed aiming to decrease the volume of tailings produced and the optimization of disposal systems for these materials, particularly in terms of systems including tailings dewatering techniques. An alternative solution consists in dewater and consolidate mine tailings under current intermittence, technique called electroosmosis. This paper presents the development of an electroosmotic cell to measure the electrokinetic flow and the consolidation process of fine tailings under specified boundary conditions. The tailings are generated by the process of treatment of bauxite from BPM (Bauxita Paragominas Mining/Brazil), which consist of fine-grained materials, with initial solid content of 31%. The results of this experimental study are analyzed and discussed based on the principles of electrokinetic theory and has shown that the proposed technique would significantly accelerate the consolidation process of fine tailings (an average solid content of 58% was reached, within a 12-hour period), besides providing adequate design parameters for field applications.

Keywords: tailings, consolidation, electro-osmosis, electrokinetic phenomena.

1. Introduction

Activities of mineral exploitation are divided basically in the processes of mining extraction, corresponding to the direct exploration of the mineral deposit (often surface mining methods in Brazil), and in beneficiation processes, characterized by the physical and/or chemical operations necessary to change the mineral assembly in form and/or composition, in order to make them suitable to the desired industrial applications. The final product resulted from all this industrial process accounts for only a small part of all material extracted from the deposit, therefore it is necessary the proper disposal of residues generated by all the activities related to mining. Overburden, the soil and rock material that overlies the mine area, removed to expose the ore deposit, are stored in piles. Tailings as water containing suspended solids and dissolved materials are commonly stored in retaining dams.

One of the main processes which results in great environmental impacts from mining activities is related to the large volume of residues generated, in the extraction as well as in the ore beneficiation processes. So, there is need of large areas to dispose these materials, fact which, just by itself, would imply great concern with this sector of the production process. In addition to this fact, there are socio-economic and environmental risks associated to the large retaining structures usually built to store tailings (Vick, 1990). On the other hand, tailings are relatively low-density materials with a high degree of saturation and such conditions can generate problems of liquefaction (Gomes *et al.*, 2002; Pirete & Gomes, 2013).

The disposal of mining tailings can be made on the surface of the ground in the form of piles or in disposal basins formed by retaining dams or dikes, or it is even possible to be made in underground cavities or in exhausted mines. The tailings disposal techniques have developed significantly in past years, for instance the use of consolidation methods, aiming to dewatering the water content in the mine pulp and the acceleration of the global process. It is an interesting way to reduce the total volume to be disposed, with positive consequences in terms of increasing the capacity of preservation of available areas. However, one problem linked to tailings thickening is the transportation of these materials until the disposal site. Because it is a more viscous material, in the form of paste or thickened tailings, the transportation by pumping becomes much more expensive in energy consumption as well as in the logistics for the implantation of the pumping system itself.

It is an unquestionable fact that the commodities production has great importance in the Brazilian economic and social development, especially considering the high volume of exports currently presented by these products of mineral extraction. However, it has become increasingly surprising the proportions that the so called tailings-retaining structures (especially tailings dams) have gained. Some recent failures of tailings dams in Minas Gerais State

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(Mineração Rio Verde, 2001; Indústria Cataguases de Papel, 2003; Mineração Rio Pomba Cataguases, 2007), involving serious economic and environmental impacts, demonstrate the need for developing more thorough systems for tailings disposal in order to identify, reduce and manage the possible risks of accidents in a more effective way, besides the constant quest for optimization of operational costs and monitoring these structures during their useful lives and after their closure.

New approaches for mining tailings disposal systems have been developed all over the world seeking to suit these procedures to the currently existing demands. One of these alternative approaches for fine tailings disposal, which has a long consolidation process, is the technique to accelerate the consolidation process of this material in the form of pulp through the application of an external electric field (electro-osmosis). The fine tailings is a byproduct of the ore beneficiation process, which usually presents granulometry below 400# and low percentage of solids, being, therefore, material associated to large volumes of water. Electrokinetic consolidation is based on the application of an electric potential difference inside a soil mass, through electrodes inserted in this mass, inducing the movement of the liquid phase in the direction of one electrode and enabling the removal of this corresponding flow of water.

The present study aims to improve the knowledge of the electro-osmotic consolidation technique applied to the fine tailings, theme of incipient research in Brazil (Mello *et al.*, 2011). In order to do so, laboratory experiments were carried out, using one special equipment called electrokinetic cell, and using some bauxite tailings samples from BPM (Bauxita Paragominas Mining/Brazil).

2. Electro-Osmosis Phenomena

The combination between hydraulic and electric flows, with their respective gradients, may result in four well-known electrokinetic phenomena in materials which present fine granulometry and electrostatically charged solid particles, as in the case of clay soils and colloidal systems. These four electrokinetic phenomena are: electrophoresis (movement of particle in a stationary fluid by an applied electric field), electro-osmosis (movement of liquid past a surface by an applied electric field), streaming potential (creation of an electric field as a liquid moves along a stationary charged surface and sedimentation potential (creation of an electric field when a charged particle moves relative to stationary fluid). All the electrokinetic phenomena involve, essentially, a difference of electric potential, particles with surfaces electrostatically charged and a liquid phase.

Electro-osmosis refers to the movement of bulk liquid relative to a stationary charged surface due to an applied electric field that is primarily generated in the electrical double layer (EDL). The mobile portion of the EDL tends to migrate towards the cathode or anode depending on its polarity. This electromigration of ions constituting the EDL causes viscous shearing of the adjacent bulk-liquid molecules, ultimately resulting in bulk-liquid motion. For thin EDL's, the bulk-liquid motion or electro-osmotic flow is characterized by a plug-like velocity profile (Fig. 1).

Among many theories which describe electroosmotic flow, the Helmholtz-Smoluchowski theory is the most accepted and widely adopted by geotechnical engineers. This theory is based on a model proposed by Helmholtz (1879) and later refined by Smoluchowski (1914). In this conception, the pore radii are relatively large in comparison to the thickness of the diffuse double layer and the mobile ions are concentrated near the soil-water interface.

The zeta potential (ζ) and the charge distribution in the fluid adjacent to soil surface play important roles in determining the electro-osmotic flow. The ζ is the electric potential developed at solid-liquid interface in response to movement of colloidal particles; *i.e.*, it is the electrical potential at junction between the fixed and the mobile parts of the electrical double layer. The ζ is less than the surface potential of a particle and shows the value at the slip plane, which is located at a small unknown distance from the colloidal surface (Hunter, 1981; Jones *et al.*, 2008).

In this model, the electro-osmotic flow (q) becomes a function of the electro-osmotic permeability of the soil (k_e), of the applied electrical gradient (i_e), which is the ratio between the potential difference (E) by the distance between the electrodes (L), and of the area of the section transversal to the flow direction (A) as established in the following equation (Haussmann, 1990):

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

The coefficient of electro-osmotic permeability is given by:
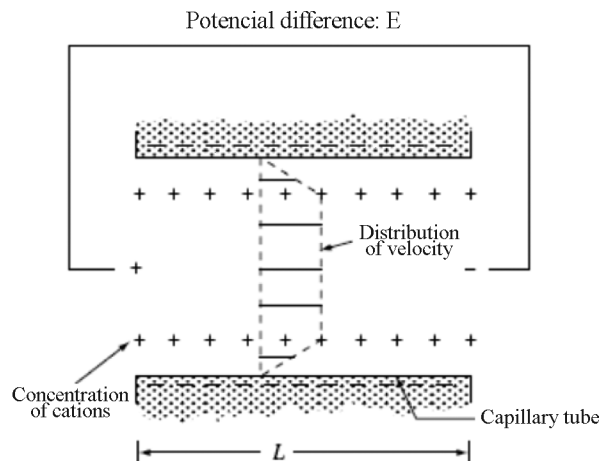
$$k_e = -\frac{\zeta \varepsilon n}{\mu} \tag{2}$$

Potencial difference: E

Distribution of velocity

Concentration of cations

Capillary tube

L

Figure 1 - Helmholtz-Smoluchowski model for electro-osmosis.

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in which ζ is the zeta potential in V (usually negative for clay soils), ε is the soil electric permittivity (F/m in SI units), μ is the fluid viscosity (N.s /m^2 in SI units) and n is the soil porosity.

The factors of the mineralogy which have a positive effect for good electro-osmotic phenomena potential (Fig. 2) include: high water content (w), clay minerals with low cation exchange capacity (CEC), low valence exchange cations, high surface charge density, a high surface area and nature of water. In terms of water composition, the main aspects are low conductivity (σ), low salinity, high pH and low surface charge density per unit pore volume (A_0).

Electrochemical reactions associated with the electrical field application in tailings are very complex, including electrolysis of water (generation of oxygen and hydrogen gases), reduction at the cathode and oxidation process at the anode. As a result, the pore water pH of tailings decreases at the anode and increases at the cathode; the anode corrodes and/or deteriorates quickly if it is made of a material highly susceptible to corrosion effects.

Besides the parameters associated to the mineralogy of the soil or tailings, and the physico-chemical conditions of the interstitial fluid, there are still factors related to the arrangement (set up) of the external electric field applied (especially concerning the intensity of electric current and potential difference), and to the nature, geometry and distance between electrodes (Shang, 1997). This makes the technique of electrokinetic consolidation a complex process based on several variables and demanding, therefore, previous studies in reduced models or laboratory tests, evaluating as many of these variables as possible, in order to establish parameters to provide applications in field scale.

3. Electrokinetic Cell

In laboratory, the mechanisms of the electrokinetic process can be analyzed under well controlled and varied conditions in test columns or in the electrokinetic cells (called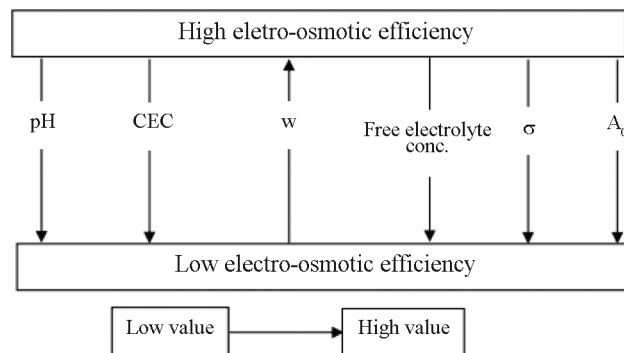 EK-cells), equipment which simulates, in reduced scale, the field setup. The EK-cell tests provide information on the electro-osmotic permeability as a function of material density (porosity), applied dc current (current density), voltage (voltage gradient), time and water chemistry. In addition, the EK-cell tests provide information on voltage losses at interfaces of electrodes and materials (for example, soils or tailings).

The electrokinetic cell shown in Fig. 3 has been developed to measure the electro-osmotic permeability in tailings (or soils) under well-controlled boundary conditions (according to Hamir *et al.*, 2001), consisting basically of the following devices (Ferreira, 2011):

- acrylic cell;
- electrodes;
- load application system;
- input system and electricity control device;
- water circulation system;
- monitoring system;
- data gathering system.

A pair of electrodes and a specimen compartment compose the electrokinetic cell (Fig. 3). The cell is made of 10-mm thick acrylic and bases of polyacetal (polyoxymethylene) material with the inside dimensions of 15 cm of diameter and 35 cm high. The tailings are placed in the specimen compartment and o-rings are placed on the top and bottom of the cell in order to guarantee the complete sealing of the whole system. The water flow through the tailings sample in the cell is essentially one-dimensional (vertical).

The electrodes are placed at both ends of the specimen compartment. In this study, two types of electrodes in the form of circular plates were used in the tests for comparison: copper and stainless steel (SS316). SS316 is the highest grade of corrosion resistant stainless steel commercially
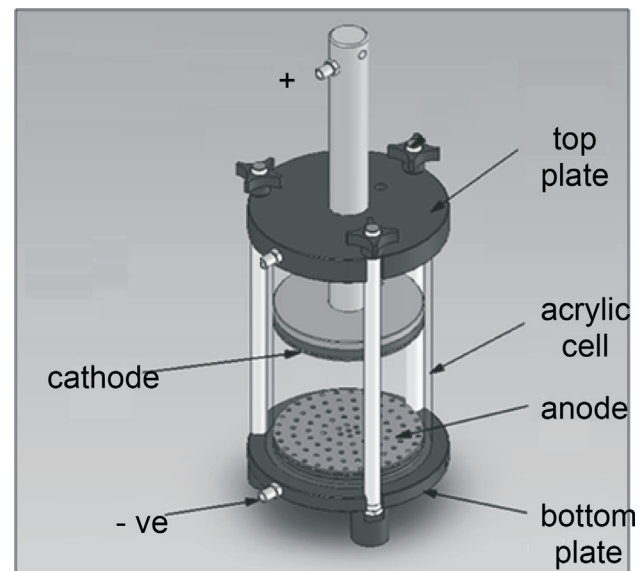

Figure 2 - Influence of soil variables on E-O efficiency (Jones *et al.*, 2008).

Figure 3 - Electrokinetic cell and electrodes.

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available. The lower electrode has a diameter of 148 mm, while the diameter of the upper electrode is 134 mm (due to the characteristics of this sealing of the cell). The plates used in the tests have a thickness of 2.0 mm and specific opening areas between 8.0 and 8.7%. In the tests, the electrodes are wrapped with geotextile or a filter paper for filtering and drainage.

A special designed loading plate (50 cm long x 10 cm wide) equipped with dia1 gauge was placed on the top of the specimen compartment to apply a surcharge through the dead weights. The water in both reservoirs in the cell is controlled at the same level via recharge and discharge tubes to ensure different hydraulic gradients or water flow due solely to the applied dc current. The electrodes were connected to a dc power supply (Instrutherm FA 3005 model, with 0-32 V and 0-3 A ranges); the dc current and voltage were measured using a high precision multimeter. The measuring apparatus consists in three main parts: the transducers (of displacement, pressure, load and volume measurement), data acquisition board and the management software.

Polarity inversion, *i.e.* the change between the anode and cathode has been applied in the performed tests. Under the normal polarity (NP) mode, the lower electrode of the EK-cell is the anode and upper electrode is the cathode. Under the reversed polarity (RP) mode, the applied dc voltage is reversed, *i.e.*, the electrodes are inverted, whereas all other conditions remain the same. The water flow in the tailings reverses direction after the polarity change but the water discharge was measured through a drainage valve at the upper part of the cell in both setups (NP or RP modes).

In the experiments performed in this research, other following design criteria for EK-cell system were considered (Micic, 1998):

- EK-cell had to be water-tight and electricity insulated;
- EK-cell had to be big enough to allow a measurable flow of fluid and electricity through the tailings sample under combined influences of imposed hydraulic and electrical gradients;
- to achieve consolidation by electro-osmosis, the drainage should have been available at the cathode, while the anode could be impermeable;
- an accurately controlled DC electrical potential could be applied across the sample; voltage distribution in the soil sample and the electrical current passing through the sample could be measured as a function of time;
- volume of flow rate of water through the soil sample could be measured accurately as a function of time;
- measurements to be made during electrokinetic treatment could not interfere with the process.

The EK-cell apparatus (Ferreira, 2011), as shown in Fig. 4, was designed and manufactured for the electrokinetic bench-scale experiments performed in this study.

4. Tailings Characterization and Properties

The electrokinetic tests were performed with tailings samples from a bauxite mine (MBP) at Paragominas in the north of Brazil. Morphologically, the bauxite is thin layer, which covers tens of square kilometers. It lies beneath 5 to 20 m of overburden along vast plateaus, which characterize the ore bodies and were created by differential erosion of the plain where the laterites developed. On average, the ore is about 1.5 meters thick and the overburden is 12 m thick. The overburden consists of a thick oxisol and the top 1.5 to 2 m of the laterites, of which the bauxite layer is a part. The main constituents of the overburden are silt and clay.

Paragominas bauxite is washed to remove the free clay that it contains, before shipping to refineries. Washing leaves about 30% of the run-of-mine ore at the mine, in the form of clay rich tailings, which would otherwise reduce the alumina content of the product, increase the refinery cost and increase the volume of red mud for disposal at the refinery site.

In the MBP concept, run-of-mine bauxite is reduced below 8 inches through two stages of double roll crushers. The crushed ore is fed to a SAG mill, usually part of the primary stage in the grinding process in mining operations, which continues reduction and slurries the ore with water. From the SAG mill, most of the slurry goes to a ball mill, which adjusts the particle size distribution of the solids to meet the specification for pipeline transport. Between the two mills, larger pebbles exiting the SAG mill are crushed to control the ball mill feed top size and the greater mass of the slurry is diluted and then classified by hydro-cyclones into three streams. The first stream, with particles greater
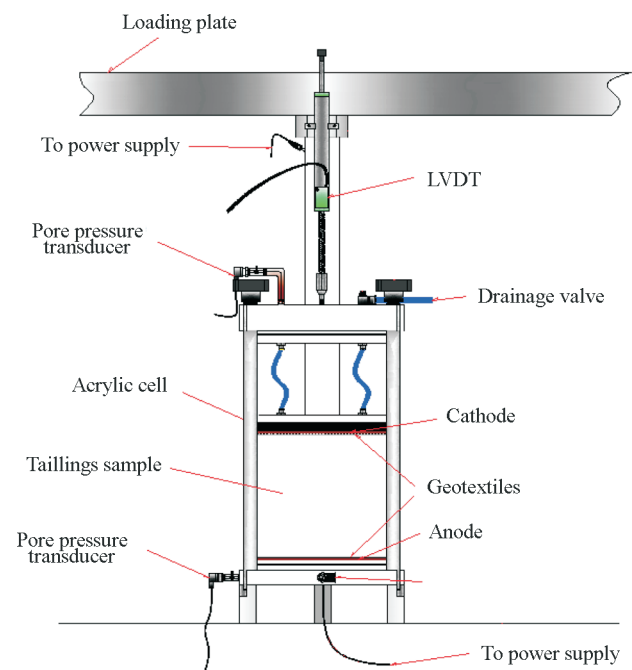

Figure 4 - Schematic of electrokinetic testing cell.

than 150# is directed to the ball mill and the second stream, with particles between 150# and 400#, bypasses the ball mill directly to the product tank. The third stream, with particles below 400#, is waste and proceeds to the tailings thickener. Tailings are approximately 30% of the dry mass of ore, or about 0.38 million tons for each million ton of product, or 220 million tons over the project lifetime.

The deposition area is located in a valley not far from the plant. Tailings are confined laterally by the valley sides and longitudinally by dykes, which divide the total area into four storage basins. Dumping is cyclic; each basin is used for 10 days then allowed to rest for 30 days before repeating the cycle. During the resting time, the tailings consolidate and dry to reach solids content of 70 to 80%, at which point they should be stable and occupy their minimum volume. However, further expansion and production for 40 years at the maximum rate require extensions to the current technique, and so, electrokinetic consolidation can be an interesting alternative solution.

The tailings and original supernatant were directly collected from the spigot and sent to the laboratory in sealed plastic containers, and used in all tests. Table 1 and Table 2 present the main geotechnical and chemical properties of the tailings (obtained by the ICP technique), respectively.

The results show the predominant presence of the elements: iron (Fe), aluminum (Al), titanium (T_i), zirconium (Z_r) and sulfur (S) with all the other elements presenting much lower concentrations. There is no silicon (S_i) in the chemical analysis of the tailings due to the technique of preparation of the sample for test performance. In this case, the sample, air dried, was solubilized in fluoridic acid (HF), which causes the elimination of the silicon by evaporation.

The grain size distributions, with and without use of deflocculant during the test, are shown in Table 3. The results enable us to verify the effective action of the additive incorporated to the tailings in relation of clay particle flocculation (in situ situation), indicating that the tailings solids consist essentially of fines particles. The tailings have high plasticity with a plasticity index of 33.1%.

The results of X-ray of tailings using a powder diffractometer are indicated in Fig. 5, plotted as 2θ angle on the x axis vs. X-ray intensity as measured by the detector on the y axis, usually expressed as counts per second. Peaks are labeled by d-spacings (Å) indicating the predominant presence of kaolinite, goethite, gibbsite and hematite.

5. Electrokinetic Dewatering Tests

The tailings slurry was agitated by a mixer to a uniform consistency, and then it was poured into the cell with preinstalled electrodes. After the cell was filled, the slurry was allowed to settle by gravity until the water flow through the bottom drains stopped and a soft sediment was formed. During the sedimentation stage, the drain valves at the top of the cell were open and drainage water was collected. Electrokinetic tests were performed immediately after sedimentation stage. In the electrokinetic tests, the applied voltage in all tests was 15 V in order to ensure an uniform voltage gradient along the tailings samples of 95 V/m.

Tests were conducted to study the combined effect of surcharge and electro-osmosis, using the following termi-

Table 1 - Tailings geotechnical properties.

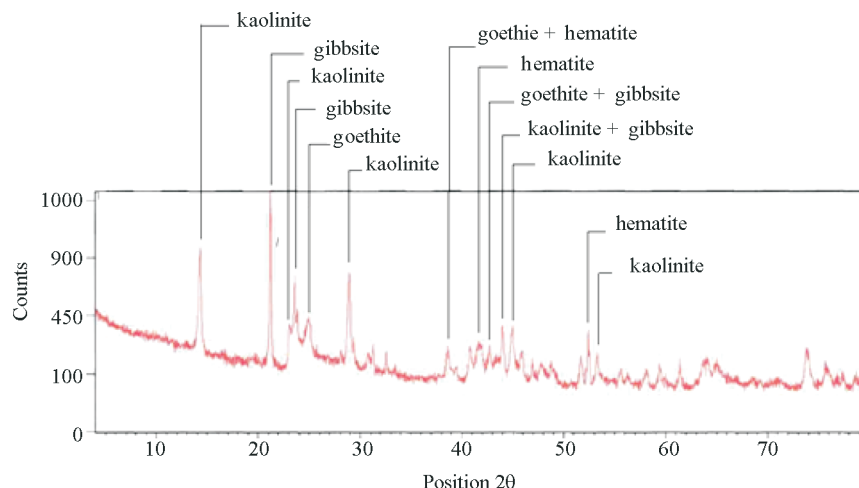|	
Specific gravity	2.67
Liquid limit	64%
Plasticity Limit	31%
Plasticity Index	33%
pH	5.33
CEC (cation exchange capacity)	4.88 cmol/kg
Hydraulic conductivity (for initial solids content= 30%)	5.7×10^{-7} m/s

Figure 5 - X-ray diffraction pattern for bauxite tailings.

nology: EKC tests for the electrokinetic consolidation tests with copper electrodes (standard tests); EKS test for the electrokinetic consolidation test with steel electrodes (for comparison) and CCT for the conventional static consoli-

Table 2 - Tailings chemical properties by ICP (Inductively Coupled Plasma).

Elements	Concentration (μg/kg)
Al	240134
Ba	26.8
Ca	101
Co	17.1
Cr	110
Fe	103904
K	127
Mg	49.6
Mn	153
Na	92
P	178
S	356
Sc	4.6
Sr	27.4
Th	51.6
Ti	8997
V	265
Y	18.1
Zn	16.7
Zr	559

Table 3 - Particle size distribution of bauxite tailings.

Grain size	With deflocculant (%)	Without deflocculant (%)
Clay	49.1	2.5
Silt	48.8	89.8
Sand	2.0	7.7

dation test (control test, without electrokinetic effects, using only surcharge for consolidation). Prefixes to represent the filter element used in the test setup were insered to those tests (F for tests performed only with paper filter and G when the filtering element adopted was a layer of a nonwoven polyester geotextile with apparent opening size of 0.17 mm according to ASTM D4751). Six tests were performed on the bauxite tailings as summarized in Table 4 (prefixes T and B are explained hereafter). The initial parameters of each test, such as water content (w_i), solids content (ψ_i) and initial height (H_i) are presented. Solids contents were calculated by subtracting the mass of collected filtrate from the original mass of sample and the results were checked against changes in the volume of the sample, which were determined using an LVDT measurement of the cylinder piston displacement.

During the test, the application of the static load, due to the drainage imposed next to the upper base of the sample, produces an upward axial flow in the slurry sample. On contact with the bases of the sample, the two electrodes (cathode with the upper base and anode with the lower one) generate an electro-osmotic flow parallel to that generated by the static load.

So the original prescriptions for the boundary condition for drainage were that the anode would remain closed and the cathode open. In this condition, the continuous supply of water was not made and the drainage valves in the anode remained closed during the entire test, with the drainage being made through a drainage valve in the cathode. However, during the tests, it was observed that the electro-osmotic flow happened in bigger proportions in the direction of the anode and not the cathode, unlike the commonly reported results in several scientific works.

This fact, which will be discussed ahead, led to the inversion of electrodes placement in the boundary condition previously described in some tests. These variations generated some changes in the nomenclature of the tests, with new inclusion of prefixes T and B to the codes (see Table 4), according to the position of the cathode at the top or bottom of the electrokinetic cell, respectively.

As initial prescription, it was defined for the interruption of the test whenever two consecutive readings of the volume of drained water, done by a calibrated burette, re-

Table 4 - Summary of the bauxite tailings tests.

Test	Cathode position	Filtering element	$w_{initial}$ (%)	$\psi_{initial}$ (%)	$H_{initial}$ (cm)	Voltage (V)
EKC-TF1	top	paper filter	208.73	32.39	16.0	15.0
EKC-BF2	bottom	paper filter	222.04	31.06	15.7	15.0
EKC-TG1	top	geotextile	223.33	30.94	15.7	15.0
EKC-BG2	bottom	geotextile	230.54	30.26	14.6	14.0
EKS-BF2	bottom	paper filter	218.85	31.36	16.0	15.0
CCT-F1	-	paper filter	218.25	31.42	16.0	-

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mained constant within an interval of 2 h. Such procedure resulted in a standard time for test of 24 h, which was then adopted as reference for all the series of tests. As exposed previously, the voltage applied to the electrodes was kept constant (over a voltage gradient of 95 V/m) and without polarity inversion during the execution of all tests.

The results obtained are graphically presented according to the variation of the following magnitudes with the time and during the EK-treatment period:

- Volume of drained water;
- Electric current variation;
- Axial deformation;
- Porepressures generated at the base of the electrokinetic cell;
- pH of drained water.

The results of the tests are presented in next sections, for EKC tests, respectively (using for comparison the results from EKS test and CCT control test). They are reported in terms of changes of sample volume (settlement and expelled water), porepressures, current magnitudes and chemical properties of collected water at the completion of the tests. During the tests, the variations of water contents and of solids contents were also registered at three distinct regions of the sample: near the top electrode, in the middle of the sample, and near the bottom electrode.

6. EKC Test Results

Figure 6 presents the scheme for a one-dimensional electrokinetic consolidation test type T on a saturated specimen (Tamagnini*et al*., 2010), *i.e.*, assuming free drainage at the cathode and no hydraulic flow at the anode (impervious boundary).

By imposing a constant potential difference through the specimen, a uniform water flow is induced due to electro-osmosis. In this case, a uniform water flow tends to be recovered from the cathode if the material is assumed to be saturated. But, in reality, water hydrolysis at the electrodes develops oxygen gas at the anode, and hydrogen gas at the cathode. The oxygen produced at the anode remains entrapped by the inward water flow and slowly penetrates into the sample, affecting substantially the flow conditions. Thus the initial flow rate tends to decrease as the duration of the test increases associated to the progressive unsaturation

at the anode due to gas production. By increasing the amount of gas produced at the anode, an unstable outflow rate is generated at the cathode.

As water drainage at the anode is prevented, a pore pressure gradient must develop to counteract locally with the electro-osmotic induced flow. Water can flow out from the sample at the draining boundary (cathodic interface) only if an equal amount of pore volume reduction is induced by soil skeleton deformation. As the drainage process is controlled by the volumetric deformation rate of the soil skeleton, which in turns depends on the changes in vertical effective stress, the specimen undergoes a time-dependent deformation process whose time evolution is ruled by soil hydraulic conductivity, soil stiffness and specimen thickness (Tamagnini *et al.*, 2010). Similar considerations can be applied to the B tests based on the effects due to hydrogen gas produced at the cathode.

Figure 7 shows the accumulated water flow induced by the dc current for all EKC tests (in comparison with results from CCT control test).

The tests were performed with normal polarity (without periodical inversion of the electrodes during the experiments). The water flow was collected at the drainage system coupled at the upper part of the cell and measured in real time by a graduated cylinder. The water flow tended to stabilize after about 24 h in all tests.

The general configuration of the curves shows that there is no relevant effect of preloading when comparing results from the electrokinetic tests. The effects of electrokinetic process in the dewatering become more evident around one hour after the start of the tests and were essentially similar in all tests, regardless the filtering interface used (paper filter or nonwoven geotextile). The best response was obtained in the tests where the bottom electrode was the cathode (EKC-BF2 and EKC-BG2). The limit behavior was obtained for EKC-TF1 test; in this case, the sample presented lower initial water content and higher solids content, thus showing the great influence of these parameters on the electro-osmotic dewatering process.

The electrokinetic effects are better observed by the results of collected water during the period of electro-osmotic application (Table 6). In relation to the total volume of expelled water during the tests, more than 90% had
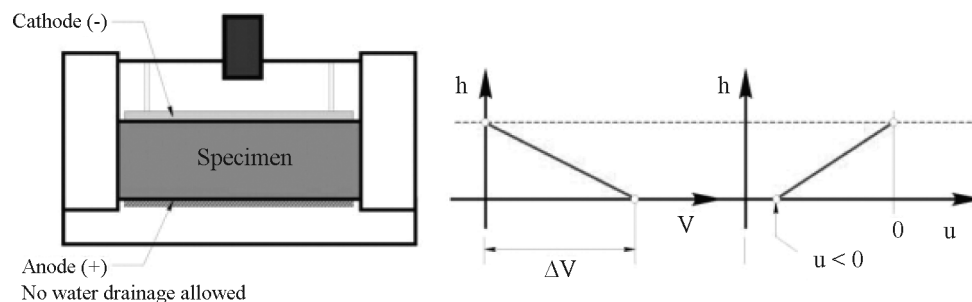

Figure 6 - Scheme of one-dimensional electrokinetic consolidation (EKC-T Tests).
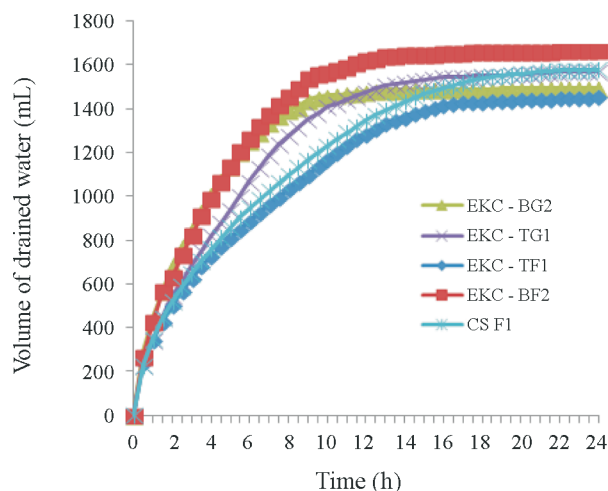
Figure 7 - EKC Tests: Volume of drained water *vs.* time of electrokinetic treatment.

already been extracted in all electrokinetic arrangements after the first 12 h of the test. For the sake of comparison, this table also shows the percentage of drained water during the first 8 hours of test.

The consolidation process under static load (15 kPa) and electric potential(0.95 V/cm) is associated with a deformation in the medium which only occurs in the vertical direction (settlements). The settlements of the tailings specimens during the EKC tests (compared with results from CS control test under static load only) are shown in Fig. 8. In all tests, the settlements of the tailings specimens were measured by a LVDT attached on the top of the loading plate.

Except for test TF1, which presented a discrepant performance (as already evidenced by the results of the test concerning the volume of drained water), all other tests provided final deformations equivalent and of the same order of magnitude as the value obtained in the conventional consolidation test (deformations in the range 57% to 59% after 24 h). On the other hand, the results indicate that the consolidation process is considerably accelerated when an electric field is applied to the tailings sample (Fig. 9). The research showed that the application of the electric gradient of 0.95 V/cm reduces the consolidation time by up to 60%.

Figure 10 shows the distribution of the excess pore pressures at the bottom of the cell in the tests when both

static load and electric field are applied. The results show significant variations of pore water pressures at the bottom of the cell in the electrokinetic tests, in comparison with the conventional consolidation test (rising flow inside the cell as exclusive effect from loading). The initial value of the pore pressure at the bottom of the cell (about 20 kPa) corresponds to the sum of the excess of pressure generated by applying the vertical load (15 kPa) and due to the weight of tailings sample and water column pressure from the upper drainage tube of the cell.

It can be seen that pore pressure progressively decreases near the lower electrode region. The null values of pore water pressures (indicated over the t-axis) should be considered only like the final of positive pore water pressures; in reality, from this point on, negative pore water pressures tend to be developed. The consolidation process is directly related to the development of negative excess pore pressure in later stages of electrokinetic process.The reduction of excess pore pressures induces the increase in density via the increase of effective stresses.

Electro-osmotic consolidation (and not properly the electrokinetic dewatering) reduced substantially the water content of the testing samples. At the end of each test, the final water contents and solids contents of the tailings sam-
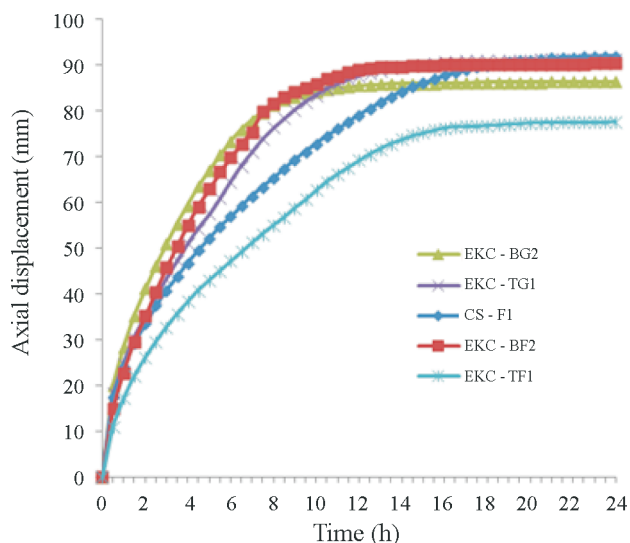

Figure 8 - EKC Tests: Settlements of the tailings specimens *vs.* time of electrokinetic treatment.

Table 6 - Volume of drained water in the tests.

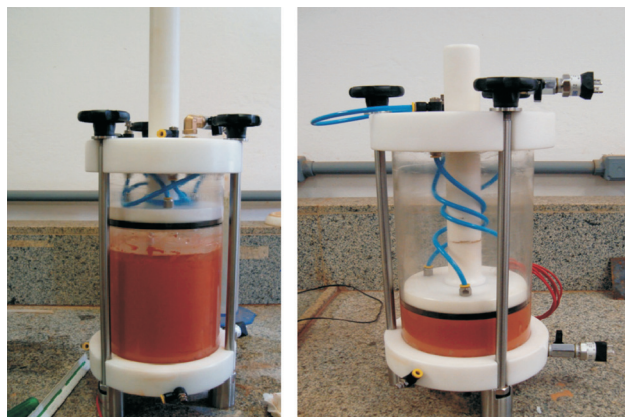| Test	% of volume drained in 8 h	% of volume drained in 12 h	Total volume of drained water (mL)
EKS-TF1	70.96	88.53	1453.0
EKS-BF2	87.38	97.42	1664.0
EKS-TG1	81.53	94.00	1570.0
EKS-BG2	93.44	99.00	1494.0
CCT-F1	69.65	85.24	1579.0

Figure 9 - EKC Test: Example of static and electrokinetic consolidation of bauxite tailings.
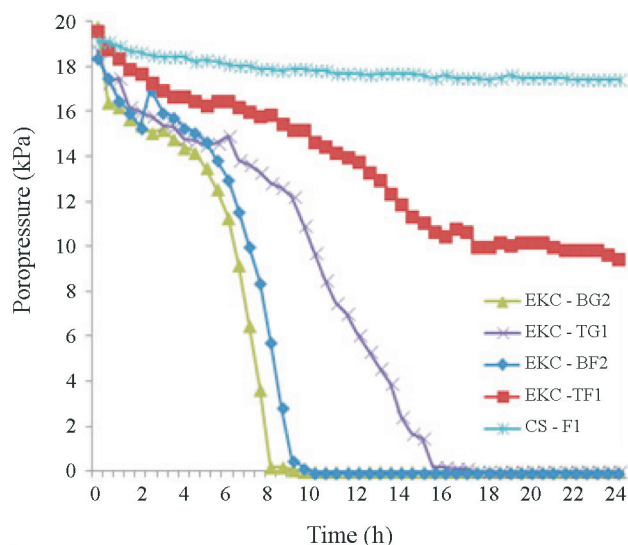

Figure 10 - EKC Tests: Excess pore pressures at the bottom of the cell *vs.* time.

ples were measured in three distinct sections of the specimen (near the upper electrode, in the middle of the sample and near the bottom electrode along the sample axis). The results are presented in Table 7.

In T tests, the water content presented higher values at the anode (sample bottom) and lower values at the cathode

(sample top). The results were opposite in the case of G tests, with lower range variation in relation to the previous tests. This behavior happened regardless the initial value of water content of the samples. These experimental results suggest that the general flow is influenced in different ways by the development of pore water and gas pressure gradients generated within the sample in both test configurations. But the main explanation for this fact is due to the inversion of the electro-osmotic flow into the cell. The bauxite tailings presents a specific kaolinite-goethite-gibbsite composition which presents more positive than negative charges in the clayey mineral surfaces that favors anionic absorption (and not a conventional cationic exchange) inducing, as a result, the occurrence of an electro-osmotic reversal flow (cathode-anode direction).

These aspects were observed directly during the electrokinetic tests. Indeed different patterns of cracks were observed along the samples under consolidation, as a result of different conditions of interstitial water flow, induced in combination by the hydraulic flow ϕ_h (surcharge of 15 kPa) and by the electrokinetic flow ϕ_{ek} (indicated in Fig. 11).

These cracks tended to be predominantly parallel to the direction of the interstitial water flow for the tests with the cathode as top electrode and predominantly normal to the flow for the tests with the cathode as bottom electrode (Fig. 12).

The cracks in the test with the cathode at the top of the cell tended to appear in the region near the center of the sample, disappearing as the consolidation advanced. The cracks in the tests with the cathode at the bottom of the cell tended to appear in regions diametrically opposite of the sample, and occasionally remained until the end of the tests. In the region of the cracks, the water content assumed locally maximum values measured in the tests (maximum value of 99.61% for a final solids content of 50.1%). Figure 13 shows the consistency states of the tailings tested, before and after the electrokinetic consolidation process.

The current induced across the sectional area of tailings specimen during the EK-cell tests is shown in Fig. 14 (typical range between 1.5 e 5.0 mA). The pattern indicates a decreasing profile along time as a result of the continuous increase in material resistivity, generation of internal cracks and development of discontinuous gaps near the tail-

Table 7 - EKC Tests: Final water contents and solids contents values.

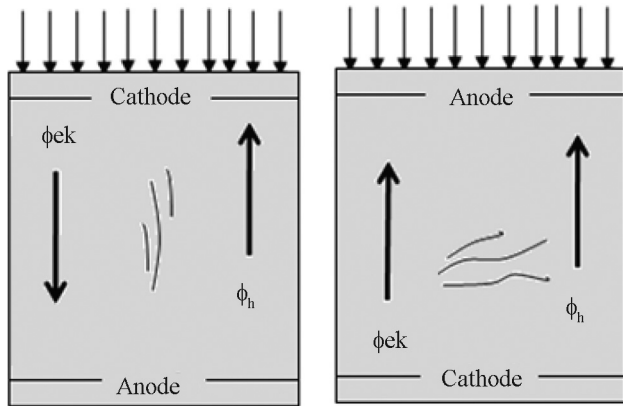| Test	Final water contents (%)				Final solids contents (%)		
	Top	Middle	Bottom	Top	Middle	Bottom
TF1	76.45	84.23	92.64	56.68	54.26	51.92
BF2	70.00	69.30	65.70	58.82	58.94	60.35
TG1	74.00	75.70	83.88	57.48	56.92	54.38
BG2	73.19	69.63	67.51	57.74	58.95	59.70

Figure 11 - Cracks pattern and flow conditions in the tested samples.

ings-electrode interfaces due to corrosion effects on the electrode material.

The initial values of electric current were higher in the tests having the cathode as the top electrode. The biggest drop of current was measured in the TG1 test, using geotextile as filtering element at the top of the cell (a reduction of around 77.5% in the current magnitude), whereas the smallest variation occurred in the BG2 test, using geotextile as filtering element and the cathode as bottom electrode (reduction of 50.0% in the electric current during the test).

The changes in the tailings pore water pH are presented in Fig. 15. The values were measured directly from the expelled water during the electrokinetic tests and collected at the drainage system coupled at the upper part of the cell. The tailings pore water pH increases at the cathode and decreases at the anode due to the effects of the electro-osmotic reversal flow and hydrolysis reactions.

Thus, in the surroundings zones of the cathode, the environment tends to become basic (condition observed in the tests TF1 and TG1, with the cathode being the drainage interface). TF1 test presented, in this region, pH values near 10.0, while in TG1 test, water pH reached 9.7. On the other
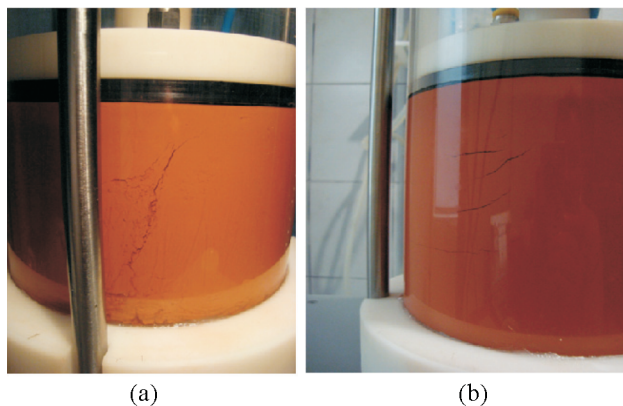
hand, the concentration of hydrogen ions tends to produce acid media in the surrounding zones of the anode (condition

Figure 13 - Consistency states of the tailings tested (before and after the EKC test).
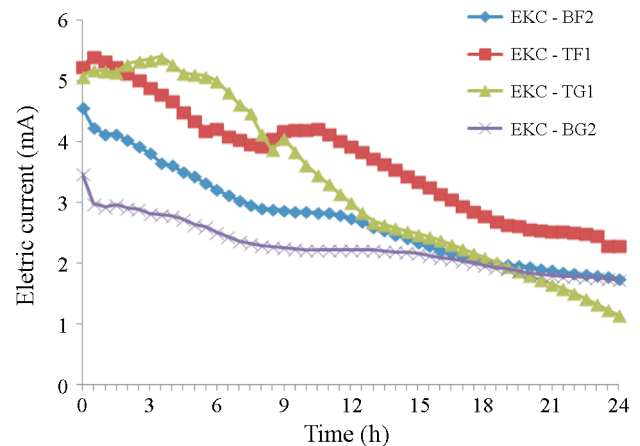

Figure 12 - Cracks pattern: (a) EKC-TF1 test; (b) EKC-BF2 test.

Figure 14 - EKC Tests: Electrical current *vs.* time of electrokinetic treatment.

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observed in BF2 and BG2 tests, with the anode being the drainage interface). The values of water pH in this region were practically invariable during the tests, reaching minimum values of 5.17 for BG2 test. The pH control for tailings pore water constitutes a relevant procedure in order to sustain a continuous water flow under dc current.

The coefficients of electro-osmotic permeability (k_e) relate the velocity of the water flow and applied voltage gradient and are calculated from Eq. 1. Because tailings are highly variable in mineralogy, particle size and water chemistry, k_e results also show a great range along the time (Fig. 16). The initial k_e values measured from EKC tests varied between 7.6 x 10^{-8} m^2/Vs and 9.5 x 10^{-8} m^2/Vs, which decreased with time and tended to a mean value of 1.0 x 10^{-10} m^2/Vs after 24 h of voltage application. The mean hydraulic conductivity after the tests was estimated in over 2.1 x 10^{-8} m/s (ψ_{final} = 60%) compared to the initial value of 5.7 x 10^{-7} m/s ($\psi_{initial}$ = 30%). This variation may be attributed to blockage of pores in the tailings sample associated with electrokinetic phenomena.

Chemical analyses results of drained water during the CS-F1 and EKC-BG2 tests are presented in Table 8 for comparison with those obtained in tailings. In both tests, the water samples were collected in the first 30 min of the tests.

Comparing the original tailings solution composition (Table 2) and the consolidation tests drained water samples (Table 8), it can be observed a significant reduction of the chemical element concentrations with time in EK tests. The variations on the concentrations of these chemical elements in the drained water happen due to the ionic migration resulting from the potential difference applied, and due to the cationic changes occurring during the electro-osmotic consolidation process.

The exponential increase of copper concentration in the second analysis is a straight result of the high corrosion effects of the copper electrodes used in the tests of electrokinetic consolidation. As a result, in the conventional con-
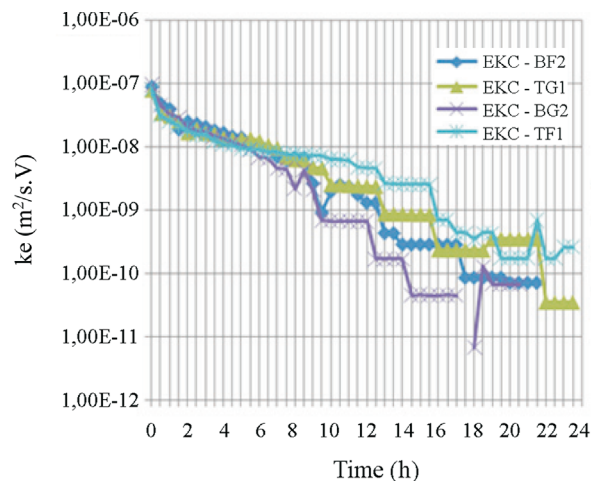

Figure 16 - EKC Tests: coefficients of electro-osmotic permeability (k_e) vs. time.

solidation test, by action of axial loading only, the copper concentration was 13.3 µg/L of water. In the electrokinetic consolidation test, however, this concentration was 3952 µg/L, approximately 298 times higher than the previous test.

Due to the substantial effects of corrosion on copper electrodes, the EKC-BF2 test was remade for purpose of comparison using stainless steel (SS316) cathodes which present a higher grade of corrosion resistance (the new test was named as EKS – BF2, whereas all other conditions remained the same). The results show similar behavior between the tests, in relation to the reversal flow and measured quantities, including voltage losses and electric fields generated along the time. Figure 17 presents the corresponding pore pressure profiles induced in both tests. The values of electroosmotic permeability were equivalent and independent of electrode materials but, unfortunately, the new drained water composition was not spared for comparison with previous tests.

7. Conclusions

The processes of electro-osmotic consolidation and dewatering of mining tailings vary according to specific conditions presented by each project, because of the particle mineralogy, the chemical composition of the interstitial fluid, electrodes arrangement, and boundary conditions of drainage. Therefore, the design of structures which use electrokinetic phenomena as accelerators for the process of consolidation of mining tailings requires previous laboratory analyses in order to establish general guidelines for its application to real problems.

It is important to consider the complexity of electrokinetic phenomena in tailings processed in an industrial plant, characterized by milling and addition of several chemical products at different stages of operation. In the specific case of bauxite tailings from MBP (Paragominas -
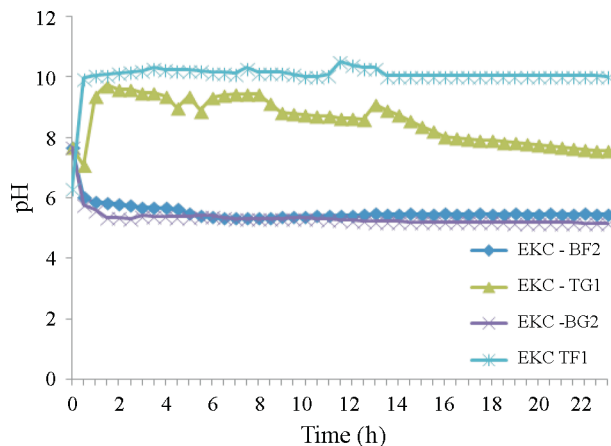

**Figure 15** - EKC Tests: Tailings pore water pH *vs.* time of electrokinetic treatment.

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Table 8 - Chemical analysis of drained water in the CCT-F1 and EKC-BG2 tests.

Element	Concentration (µg/L)	
	CCT-F1 Test	EKC-BG2 Test
Ba	1.13	3.1
Ca	0.978	2.36
Cu	-	3952
K	1.16	1.18
Mg	0.0397	0.0963
Mn	8.06	23.1
Na	4.57	1.9
Ni	-	18.8
P	< QL*	0.282
S	0.187	0.769
Si	0.529	0.917
Sr	4.53	11.2
Zn	10.7	88.8

*QL – Quantification Limit.

PA), very fine residues are generated (particles smaller than 400 #) which are treated with conventional thickeners and enhanced with synthetic flocculants for pH adjustments and optimization of the consolidation processes. This condition is very different of dewatering applications by the electro-osmotic technique for granular tailings (Shang & Mohamedelhassan, 2001).

The conjugation of a specific clay mineral composition, an surcharge of 15 kPa and the application of an external electric field of 0.95 V/cm, induced an electro-osmotic reversal flow in the direction cathode - anode, regardless the different placements and nature of the electrodes (with drainage always made by the superior electrode of the
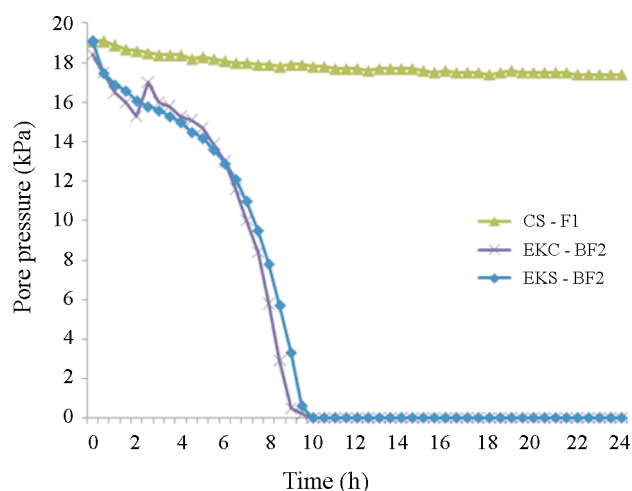
Figure 17 - EKC and EKS Tests: Excess pore pressures at the bottom of the cell *vs.* time.

setup). Such flow condition is opposite to the electro-osmotic flow commonly observed, resulting from the mineralogy presented by the tailings used as well as from its pH, fact already observed in other researches related to problems of soils decontamination (Souza, 2002).

The device designed and developed in this study enables a large versatility of tests, including the use of electrodes of distinct natures, application of external loadings and adoption of different boundary conditions of drainage of the samples (tailings or soils). The research showed that the application of the electric gradient of 0.95 V/cm reduces the consolidation time by about 60%. The adoption of stainless electrodes material solved the problems due to the high corrosion effects observed in the copper electrodes in the electrokinetic dewatering tests. The results obtained were pertinent, representative of the conditions inherent to the phenomena of electrokinetic nature, liable of repeatability and of direct confrontation among themselves.

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