Thermo-hydraulic behaviour of the vadose zone in sulphide tailings at Iberian Pyrite Belt: Waste characterization, monitoring and modelling

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ABSTRACT

Unsaturated conditions favour the oxidation of sulphide minerals from mine wastes, which results in the release of contaminant products into groundwater. An abandoned high-sulphide impoundment in the Iberia Pyritic Belt, wherein tailings have undergone oxidation for more than 28 years, was investigated for hydrological purposes. The objective was to understand the interactions between those mining tailings and the atmosphere under natural semiarid conditions (wet and dry seasons, short intensive rain events and strong daily temperature differences during the dry season). After the deposition, the sequence of waste textures that results from the sedimentation process is strongly dependent on the distance to discharge point. The spatial continuity of the sedimentation layers was studied by means of small scale dynamic penetration tests. The thermo-hydraulic characterization of the waste includes the determination of the water retention curve, saturated and unsaturated permeability, pore size distribution and thermal properties for the different textures. Atmospheric and waste physical measures, from 2002 to 2006, were performed using different techniques. The important changes in the salinity of the waste avoided the use of a single calibration for the electromagnetic sensors; a valid alternative was the evaluation of the water content from thermal conductivity estimations. Finally, a numerical model using the HYDRUS-1D software is presented. Model results reasonably fit the in-situ measures of soil moisture, soil temperature, soil water potential and soil heat flux in the vadose zone of tailings impoundment. Moreover, they provide information for energy and water balance determinations.

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1. Introduction

The acid mine drainage (ACM) caused by pyrite oxidation in old and abandoned mine tailings is one of the most harmful sources of environmental contamination (Banks et al., 1997). Pyrite oxidation chemical mechanisms in moist air have been largely studied and there is certain consensus that the main reaction is (Singer and Stumm, 1970; Jerz and Rimstidt, 2004; Demers et al., 2009):

FeS₂ + 7/2 O₂ + H₂O → Fe²⁺ + 2SO₄²⁻ + 2H⁺ (1)

The increase on acidity caused by oxidation, favours the dissolution of the contaminant metals that are transported by the movement of the liquid phase. In abandoned mine tailings, in which the superficial water has been removed, a water and vapour flow is established conditioned by thermo-hydraulic boundary conditions and by the waste characteristics (porosity, particle size and cementation degree). The saturation degree of the material is an important factor to be considered in the oxidation process, as it affects the gas permeability and the amount of available oxygen and water.

The oxidation mechanisms, water and heat flows, and minerals dissolution and precipitation processes were studied in the laboratory using waste columns, which simulate the liquid and heat flow conditions. Hydraulic, thermal and geochemical variables are simultaneously measured (Simms et al., 2000, 2007; Rodriguez et al., 2006; Acreo et al., 2007; Bryan et al., 2010; Fisseha et al., 2010). In this kind of test, a crust formation in the column surface was observed, caused by the precipitation of dissolved minerals transported when the evaporation and the ascending liquid flow prevailed.

Continuous monitoring of hydro-thermal processes in abandoned mine tailings is not very common and generally the available techniques used to characterise the hydraulic variables in most natural soils (Cui and Zornberg, 2008; Tarantino et al., 2008) or artificial covers (O’Kane et al., 1998; Swanson et al., 2003; Bussière et al., 2007) have barely been employed in reactive mine tailings in contact with the atmosphere. Evaporation and other environmental variables were also studied and measured by Elberling (2001) and Newson and Fahey (2003). Additionally geochemical characterization of “in situ”
sulphide mine tailings was performed by Blowes and Jambor (1990), Yanful (1993), and Heikkinen et al. (2009).

The “in situ” direct observation demonstrates that the oxidation rates are very variable and could be significantly lower than the ones observed in laboratory conditions (Dubrovsky et al., 1985). A part from the variable climatic conditions, these discrepancies could be caused by the physical and chemical waste property variations along depth caused by the sedimentation process. In addition, hardpans originated by mineral precipitation in waste pores may largely reduce the permeability. The existence of changes in the structure of the material and the size of the particles has great effect on the flow and transport conditions of reactive products (Singer and Stumm, 1970; Blowes et al., 1991; Moncur et al., 2005).

Numerous numerical modelations were carried out using several degrees of complexity in the thermo-hydro-geochemical coupling. The results obtained in columns in the laboratory environment as well as “in situ” were modelled in 1D (Eriksson and Destouni, 1997; Mayer et al., 2002; Simms et al., 2007; Acero et al., 2009). Additionally the hydraulic behaviour of the covers normally being used as superficial barriers for the water and oxygen was modelled (Woyshner and Yanful, 1995; Choo and Yanful, 2000; Swanson et al., 2003). The 2D hydro-geochemical behaviour was covered by Gerke et al., 1998; Lefebvre et al., 2001; Molson et al., 2005. To a great extent of the problems covered, a domain was considered composed by a homogeneous material or a few layers of different homogenous material with simple boundary conditions.

The Iberian Pyrite Belt (SW of Spain) is a region where metallic sulphide ore mines have been in operation over the past centuries and where there is a great number of abandoned tailings that generate important environmental impacts (Hudson-Edwards et al., 1999; Sánchez España et al., 2005; Hinojosa et al., 2008). Due to its location, the climate in the area includes heavy showers and a wide yearly and daily temperature range. The temperatures may vary from −10°C to more than 40°C in a typical year, and the average annual rainfall is about 1000mm. The present paper presents the results of the study of the thermo-hydraulic behaviour of an abandoned tailing in the Monte Romero mining complex (Huelva, Spain; 37º46′29″N; 6º47′45″W; elev. 246 m; (Figure 1)), (Blanco, 2009). The “in situ” monitoring of several variables was performed along with the laboratory characterization of its properties. The use of numerical model helps to understand the observed behaviour and the knowledge of physical variables that are impossible to measure. In addition, it allows predicting the effect of different remediation actions.
2. Material description

Fig. 1 shows a view of the tailing impoundment where the existence of a shallow pool can be observed, as well as a slight slope of the waste from the frontal dam. The construction method of the tailings-dam system was probably based on a downstream scheme, as shown in Fig. 2. Additionally, the delivery of tailings into a water filled impoundment gave rise to overlapped sequences of lobular bodies, truncated toward the dam where the delivery pipe ran. The sequence of material textures that results from this sedimentary process is strongly dependent on the distance to the discharge point. The complexity of the depositional sequences would increase in zones of the impoundment where the tailings were supplied from more than a single discharge system. The texture of the tailings in the studied area (a distance of about 3 to 8 m from the frontal dam) ranged from fine-medium sand to silt.

Once the mining activity ceased (1978), the consolidation and desiccation of the tailings gave rise to porosities in the range 0.5–0.6. A pool over the distal zone (see Figure 1) is formed by the runoff during wet periods (October–April) and is frequently consumed by evaporation during the summer (May–September). In the studied area the phreatic surface oscillated approximately from 1 to 3 m in depth.

The original greyish waste consists of quartz (52 wt.%, (weight–weight percentage)), muscovite/illite (20 wt.%), clinochlore (4.7 wt.%), albite (4.5 wt.%) and pyrite (around 12 wt.%). The amount of other sulphides, namely sphalerite, chalcopyrite and galena is much smaller. However, carbonate minerals have not been detected in the waste material (Acero et al., 2007). The chemical weathering of the tailings formed a yellowish horizon in the surface of the waste as a consequence of the sulphide oxidation produced by sulphates. In addition, the width of the yellowish horizon varies from 10 to 30 cm and it diminishes toward the distal pool.

Pore water has a pH of around 2.5 and the main dissolved species are $\text{SO}_4^{2-}$, $\text{Al}^{3+}$, $\text{Mg}^{2+}$, $\text{Fe}^{2+}$, $\text{Zn}^{2+}$, $\text{Fe}^{3+}$ and $\text{Cu}^{2+}$ (Acero et al., 2009). The decrease in pH produced by pyrite oxidation may increase the dissolution rate of accompanying mineral phases. Dissolved species may precipitate as sulphates or hydroxy-sulphates when the water content diminishes by evaporation forming crusts over the surface of waste materials (Newson and Fahey, 2003; Acero et al., 2009) or hardpans in their pores (Moncur et al., 2005). $\text{Fe}^{3+}$ bearing yellow-orange to dark red–brown hardpans have been described by Moncur et al. (2005) in sulphurs mine tailings. These hardpans are composed of secondary goethite and lepidocrocite, ferrithidrite, jarosite and gypsum, and appear in the zone of active oxidation. Fig. 3 shows a detail of a superficial crust with a thickness of 5 mm and the desiccation cracks that appear on tailings surface during dry and hot summers. The hardpans detected close to the area of study were located at depths of 5 cm, 11 cm, 16 cm and 20 cm (see photograph in Figure 4) in the oxidized horizon.

The hardpans and texture changes due to waste sedimentation sequence lead to a relevant vertical heterogeneity in grain size, pore size, porosity, permeability, stiffness and strength. A small scale dynamic penetration test was used to detect this heterogeneity and control the lateral continuity of the hardpans. During the test a mass of 1.014 kg was released from a constant height of 8 cm to push a 45°...
angled conical tip of 15 mm in diameter. Moreover, in this test, the number of blows necessary to advance 2 cm vertically into the tailings was recorded. The total number of tested profiles was 17, with distances ranging from 70 to 300 cm. The maximum depth reached with this method was 125 cm. It has been observed that penetration resistance is especially sensitive to moisture content and cementation. The lateral continuity of the different layers can be controlled by means of a mercury intrusion porosimeter. In one sample of the tailing dam (see Figure 15), no significant differences can be observed between the oxidized material and the original waste. Additionally, the same group of samples was taken from the original material. However, it can be observed that in the samples extracted in profile Pr3, these are finer than the ones from other profiles. Independently of the oxidation level, the samples could be grouped into two different families (fine and coarse). The fine samples have a percentage of fines (diameter < 75 μm) between 78 and 96% with an average diameter, D50, of about 20 μm; while the coarse samples have a percentage of fines between 44 and 64% and a value of D50 of about 60 μm. The pore size distribution of some samples was determined by means of a mercury intrusion porosimeter. In one sample of the finer group, a unimodal pore size distribution was obtained with a predominant diameter of 1.2 μm. In two other samples from the coarse group a bimodal pore size distribution was obtained with predominant pore sizes of about 10−30 μm and 2−5 μm.

To evaluate the hydraulic conductivity, the six samples taken on February 2005 (Profile Pr2) and the two samples of April 2004 (Profile Pr1) were saturated with an iron (Fe²⁺ and Fe³⁺) sulphate solution in order to reduce the fluid solid chemical interaction. The liquid dissolved 31,580 ppm of sulphate (4905 ppm came from FeSO₄ and 26,675 ppm from Fe₂(SO₄)₃). Nitric acid (0.00375 ml/L, 70%) was added in order to increase the iron sulphate (II) dissolution. The liquid was stabilized at pH 1.5. A constant head permeameter was used to measure the hydraulic conductivity, as described in Klute and Dirksen (1986). Fig. 9 shows the hydraulic conductivities derived from the tests, along with the fines content of each sample. As expected, a good correlation between the two variables was obtained in the greyish material; nevertheless this was not the case for the yellowish waste. Additionally, the same figure shows how the value of the hydraulic conductivity of the hardpan located at 70 cm in depth is one order of magnitude smaller than the lowest values of the hydraulic conductivity of the other samples.

The water retention curves of some samples taken from profile Pr2 were obtained using Tempe cells following a multipressure outflow technique. The cumulative outflow was recorded continuously using a data acquisition system (van Dam et al., 1994; Wildenschild et al., 2001). Measurements ranged from −0.1 m to −5 m from the

![Fig. 6. Direct measurements of volumetric water content in shallow tailings.](image1)

![Fig. 7. Profile of matrix suction measured with a minitensiometer in June 2005.](image2)
pressure head. A pressure plate apparatus was used for pressure heads between −5 m and −150 m. More information concerning retention characteristics may be obtained from pore size distribution (Romero et al., 1999). Water retention curves obtained following the different procedures are shown in Fig. 10. The effect of material texture on the air entry pressure of the different samples is limited. The water retention curves deduced from mercury intrusion porosimetry in a fragment of the superficial crust, as well as a sample of the hardpan located at a depth of 70 cm in profile Pr1 are shown in Fig. 11.

Tailings samples extracted in February (Profile Pr2) and June 2005 were compacted in 5 cm wide layers into PVC columns (40 cm in height and 30 cm in diameter) maintaining field porosity (0.57 for yellowish tailings, and 0.53 for greyish tailings) and water content (0.23 (February) and 0.15 (June) for yellowish samples, and 0.26 (February) and 0.17 (June) for greyish samples). February and June samples can be considered as a valid representation of the waste state during the wet and dry seasons respectively. February samples were dried by applying infrared light. After drying, the samples were wetted with deionized water until their initial moistures were attained. June samples were only wetted. Each moisture stage for both types of tailings was used to measure the thermal parameters, apparent electrical conductivity and apparent dielectric permittivity. Thermal conductivity measurements were performed with a dual-needle sensor manufactured by Thermal Logic. Fig. 12 shows that thermal conductivity depends linearly on volumetric water content and not on waste mineral composition and on the salt content of the pore water during the different seasons of the years.

A four-electrode soil conductivity probe (Rhoades and van Schilfgaarde, 1976) facilitated by the Salinity Lab (Riverside, California) were used to measure the apparent waste electrical conductivity. The results of electrical conductivity measurements are shown in Fig. 13. Due to the presence of metallic components, the apparent electrical conductivity of the waste is high. Greyish tailings are more conductive than the yellowish ones due to the different mineral composition. The electrical conductivity of each type of waste varies along the year according to the variations on its liquid salinity.

3. Field monitoring

In order to monitor the main physical variables involved in thermo-hydraulic flows, approximately 0.1 m³ of waste was intensively instrumented. In addition, a number of instruments, including a meteorological station, were installed in a wider area of 25 m² (Figures 14 and 15). Details of measures and sensors are compiled in Table 1. Except for the micro-meteorological station (January 2004) and the two most superficial thermometers (June 2003), the rest of the sensors were installed in February 2002. All probes were connected to a datalogger.
system (Campbell, CR10X + AM16/32 multiplexer) equipped with GSM-modem technology to facilitate remote data transfer. The instrumentation system remained operative until the end of 2006 with small maintenance works.

The insertion of instruments into the main instrumented area (Figure 16) is not easy because the waste must be disturbed as little as possible and sensors must be set at a sufficient distance from the vertical front of the excavation. Furthermore, the final depth of the instruments must be controlled as the temperature and water potential gradients are abrupt near the surface. In order to facilitate the excavation of the waste and the installation and maintenance of the sensors, a Perspex plate (100 cm wide and 50 cm high) was vertically driven in the location of the sensors. Specific tools were developed to guide horizontally the sensors during their insertion.

Piezometers open at depths of 195 cm and 255 cm allow monitoring the deep water flow. Three tensiometers were installed close to the piezometers at depths of 60 cm, 110 cm and 155 cm (Figure 15). A temperature sensor (model 108) was tied to the ceramic cup of the 110 cm deep tensiometer. In addition, two cylindrical lysimeters (10 cm in diameter and 17 and 25 cm in depth) were designed to record the amount of infiltrated water, however their measures were not useful because it was suspected that the sand placed between the waste and the deposit formed a capillary barrier that hindered the flow of water.

The behaviour of the sensors listed in Table 1 was in general satisfactory. These sensors underwent extreme conditions (most of them from February 2001 to 2006). Figure 17 shows the profiles of temperature measurements during the year 2004. Maximum temperature gradients were observed near the surface during the summer.

The net radiation recorded with the meteorological station is compared in Figure 18 to the global solar radiation database of three meteorological stations near the abandoned mine (distances from 10 to 45 km). Waste heat flux measurements at a depth of 10 cm were also included in the same figure. The net radiation trend denoted a general reduction in its amplitude with a ratio net radiation/total radiation ranging from 0.3 to 0.4. The average fraction of net radiation that penetrated the waste at the depth of 10 cm was equal to 13.5%. The energy that flows at a depth of 10 cm is generally lower than the net radiation over the surface, except for the wet season, when heat flux and net radiation are close to zero. Daily minimum values of net radiation are negative and lower than heat flux values at a depth of 10 cm. A negative value means that flux runs upward, which always occurs at night. The net longwave radiation from 20 h to 7 h each day is approximately equal to −5.5 MJ m⁻² day⁻¹. The soil heat flux, at a depth of 10 cm, changes from 0 MJ m⁻² day⁻¹ (22 h) to −3 MJ m⁻² day⁻¹ (8 h), and reverses to a downwards (positive value) flux around 11 h each day, achieving a maximum at 16 h.

Pressure transducers in piezometers and tensiometers yielded stable outputs and reasonable values (Figure 19). The groundwater level at the piezometers was also checked by a portable water level probe. After recharging each tensiometer tube, readings maintained their previous measurements. In the wet season, a downwards gradient
prevailed between 0.6 m and 1.1 m, whereas in the dry season, the gradient maintained equilibrium (2004) or underwent an upwards trend (2005). The demand of deeper water by the waste surface increased during the drought period in 2005. The increase in rainfall in 2006 led to a reappearance of the phreatic levels at a depth of 2.55 m. The liquid pressures measured deeper in the tailings represented generally upwards gradients of liquid, regardless of some short episodes of rainfall deep infiltration. In addition, the profiles of water pressure could also reflect some horizontal fluxes during the infiltration episodes (Blanco, 2009).

Groundwater levels recorded during a short event of infiltration in spring 2002 are shown in Fig. 20. The total rainfall accumulated was 110.6 mm, leading to an increase of 67 cm of the groundwater. The runoff very probably represented an important fraction of the superficial water balance during this particular event.

The measurement of the water potential by using relative capacitive hygrometers, that have been successfully used to measure high suction in bentonite barriers (Villar et al., 2005), proved to be unhelpful because the measures always exceeded 98% of RH and the absolute error attained 2% of RH. Infiltrations or condensations over the hygrometer shell could affect these sensors, resulting in inoperative periods or irreversibly damaged hygrometers.

The working life of CS615 probes under acid conditions in the pyritic tailings lasted from February 2001 to May 2006. In general, the life of ECH2O probes was shorter. ECH2O sensors at depths of 0.15 m, 0.25 m, and 0.40 m were replaced after 1.3, 1.6 and 3.3 years, respectively. Due to salinity changes in the waste, the electromagnetic sensor output does not depend on a single calibration. The moisture profile obtained from undisturbed samples is compared in Fig. 21 to estimations from electromagnetic (EM) probes installed less than a meter into the waste. For the EM transducers, two calibrations were used: (i) standard calibration for electrical conductivity equal or inferior to 0.1 S m$^{-1}$ (Topp et al., 1980; Campbell-Scientific, 1996), and (ii) specific material calibrations using wastes extracted in summer 2001. From Fig. 21(a), it seemed that using generic calibration for soils with low liquid electrical conductivity was more appropriate than the specific calibration in summer 2001 for the samples extracted in February 2002. In addition, measures using calibration in summer 2001 showed a good fit with the sampled moistures of the profile in summer 2003 and 2004 (Figure 21 (b)). Fig. 22 shows variations of volumetric water content at different depths during a rainfall period in February 2003 and 2004 (Figure 21 (b)). The ECH2O electro-magnetic sensors installed in the first 0.2 m of tailings recorded a sharp increase in the values of water content between the end of April and May 2004. Moreover, there is an increase...
of less magnitude during the same period of the year 2005 (see Figure 23). The CS615 sensors produce a similar trend. The changes detected in the tailings match the seasonal change characterized by the decrease in rainfall, the increase in temperature and the fall in environmental relative humidity. These seasonal changes induce a decrement of water content and an increment of waste salinity that have

Table 1
Sensors installed to monitor the different variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Model</th>
<th>Units</th>
<th>Range</th>
<th>Accuracy</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric pressure</td>
<td>RPT410F-Druck</td>
<td>1</td>
<td>600–1100 hPa</td>
<td>±0.5 hPa</td>
<td>Resonant silicon pressure sensor</td>
</tr>
<tr>
<td>Air temperature and relative humidity</td>
<td>MP100A-Campbell</td>
<td>2</td>
<td>−40 ... + 60 °C</td>
<td>±0.5 °C</td>
<td>PRT (100)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5–95% RH</td>
<td>±1%</td>
<td>Capacitive sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;5% ... &gt;95% RH</td>
<td>±2%</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>A100R-V-Vector Instrument</td>
<td>1</td>
<td>0.2–75 m/s</td>
<td>±0.1 m/s</td>
<td>3-cup rotor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.3–10 m/s);</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±1% (10–55 m/s);</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>52203-R.M. Young</td>
<td>1</td>
<td>50 mm/h</td>
<td>2% up to 25 mm/h;</td>
<td>Tipping bucket mechanism (two cups of 0.1 mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3% up to 50 mm/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net radiation</td>
<td>NR-LITE – Kipp&amp;Zonen</td>
<td>1</td>
<td>±2000 W m⁻²</td>
<td></td>
<td>Blackened thermopile</td>
</tr>
<tr>
<td>Waste Temperature</td>
<td>108–Campbell</td>
<td>4</td>
<td>−5... + 95 °C</td>
<td>±0.5 °C</td>
<td>BetaTherm 100K6A Thermistor</td>
</tr>
<tr>
<td>Water pressure</td>
<td>PDCR1830-Druck</td>
<td>3</td>
<td>0–35 kPa</td>
<td>±0.1 °C</td>
<td>Pressure sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.3–10 m/s);</td>
<td></td>
<td>Transmission Line Oscillator (TDR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(10–400 MPa);</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±2% RH</td>
<td></td>
<td>Capacitive hygrometer</td>
</tr>
<tr>
<td>Matric suction</td>
<td>SMS2500S-DEC</td>
<td>3</td>
<td>0...− 999 hPa</td>
<td>±0.2% F.S</td>
<td>Pressure sensor</td>
</tr>
<tr>
<td>Volumetric water content (dielectric constant)</td>
<td>CS615-Campbell</td>
<td>2</td>
<td>0–40% VWC</td>
<td>±2% (when using calibration for specific material)</td>
<td>Transmission Line Oscillator (TDR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electrical conductivity &lt; 5dS m⁻¹</td>
<td>±2% (when using calibration for specific material)</td>
<td>Capacitive sensor</td>
</tr>
<tr>
<td>Volumetric water content (dielectric constant)</td>
<td>EC10-ECH2O – Decagon</td>
<td>4</td>
<td>0–40% VWC</td>
<td>±2% (when using calibration for specific material)</td>
<td>Capacitive sensor</td>
</tr>
<tr>
<td>Soil Heat Flux</td>
<td>HF601-Campbell</td>
<td>1</td>
<td>±2000 W m⁻²</td>
<td>−15% ... + 5%</td>
<td>Thermopile</td>
</tr>
</tbody>
</table>

Fig. 16. Main instrumented area in Fig. 15. (a) Perspex plate where guides for probe installation were tied. (b) Frontal view of the excavation during the installation of the probes. (c) Location of the different instruments (C is CS615, V is HMP230, E is ECH2O, T is Thermistor 108, and O are tubes for soil gas extraction).
opposite effects on dielectric constant changes. During the wet seasons the effect of water content prevails over the salinity change effects although during the dry seasons the changes in salinity prevent the use of this type of sensors for water content monitoring using standard calibrations. However, for the period 2001–2004, the estimation of the water content using the electromagnetic sensors in summer is satisfactory when the 2001 summer calibrations are applied.

The almost linear dependency of the thermal conductivity of the waste on its volumetric water content (see Figure 12) and its independence on the electrical properties of the waste is useful when obtaining the water content from the thermal conductivity estimations (Bernier and Neerdael, 1996; Alonso et al., 1998). If it is assumed that heat flow measured with the sensor is the same as the conductive flow in the waste, the thermal conductivity can be obtained from the measurement of heat flux at 10 cm deep and the thermal gradient derived from temperature measurements at depths of 7 cm and 15 cm. Fig. 24 shows how the water content that is obtained with CS615 sensor by applying a standard calibration fits the water contents estimated from thermal conductivity during the wet season. In addition, the water content estimated diminished in the period March–June. Heat flux was evaluated at 4 am because a stable temperature gradient was frequently observed between 4 am and 6 am. Days with rainfall were initially discarded in this analysis given that it affects the thermal conditions of the upper layer. Moreover, days when temperature gradients were close to zero were discarded as well.

4. Numerical modelling

In order to have a better understanding of the heat and water flows in the shallowest zone of the tailings, a numerical analysis was carried out. In general, at intermediate scale, water flow in mine tailings is two dimensional, due to the existence of lateral fluxes from the distal deposits (far from the zone of discharge) to the proximal deposits during summer seasons, and from the proximal tailings to the distal ones during wet seasons (Moncur et al., 2005). Geometry and hydraulic characteristics of the substrate and dam permeability also influence the water movement. Nevertheless, to study the local flux in the shallowest tailings a one-dimensional approach may be illustrative.

The software used to simulate water flow and heat transport in one-dimensional variably saturated media was HYDRUS-1D (Simunek and Suarez, 1998; Simunek et al., 2009). The program numerically solves Richards’ equation for saturated–unsaturated water flow and advection-dispersion type equations for heat and solute transport. The complete set of continuity equations and atmospheric boundary condition implemented in this numerical code was discussed by Saito et al. (2006).

In one-dimensional conditions, water mass balance equation (Saito et al., 2006) is obtained combining liquid and vapour fluxes:

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K_h \frac{\partial h}{\partial z} + 1 \right] + K_w \frac{\partial \theta}{\partial z} + K_{\text{hyd}} \frac{\partial \theta}{\partial z} - F \]  

(2)

where \( \theta \) is the volumetric total water content (including liquid and vapour phases, \( \text{m}^3 \text{m}^{-3} \)), \( z \) (m) and \( t \) (s) are the spatial and temporal variables, \( h \) is the pressure head (m), \( T \) is the temperature (K), and \( K_h \) (m s\(^{-1} \)) and \( K_w \) (m \(^2\) K\(^{-1}\) s\(^{-1} \)) are the (isothermal and thermal) hydraulic conductivities for liquid phase fluxes due to gradients in \( h \) and \( T \), respectively; and \( K_{\text{hyd}} \) (m s\(^{-1} \)) and \( K_T \) (m\(^2\) K\(^{-1}\) s\(^{-1} \)) are the isothermal and thermal vapour hydraulic conductivities, respectively. \( F \) (s\(^{-1} \)) is a sink term that usually accounts for root water uptake.

Heat balance equation utilized in Hydrus 1-D code is:

\[ \frac{\partial C_T}{\partial t} + L_0 \frac{\partial \theta}{\partial z} - \frac{\partial}{\partial z} \left[ \lambda(\theta) \frac{\partial T}{\partial z} \right] - C_w \frac{\partial q_v T}{\partial z} - L_0 \frac{\partial q_v}{\partial z} - C_v \frac{\partial \theta}{\partial z} - C_w \frac{\partial T}{\partial z} - C_v \frac{\partial T}{\partial z} \]  

(3)

where \( C_w, C_v, \) and \( C_T \) are volumetric heat capacities (J m\(^{-3}\) K\(^{-1}\)) of the, liquid water, water vapour, and moist soil, respectively, \( L_0 \) is the volumetric latent heat of vapourization of liquid water (J m\(^{-3}\)), \( \lambda(\theta) \) is the apparent thermal conductivity of soil (J m\(^{-1}\) s\(^{-1}\) K\(^{-1}\)), \( q_v \) is the volumetric water vapour content (expressed as an equivalent water content, m\(^3\) m\(^{-3}\)) and \( q_v \) and \( q_w \) are the flux densities of liquid water and water vapour (m s\(^{-1}\)), respectively.

The length of the column of tailings to be modelled was adjusted to the depth of the deepest tensiometer (i.e. a depth of 1.10 m). At this same depth, another sensor recorded the temperature. The measures of these sensors were incorporated as lower boundary conditions in the model. The upper boundary condition is established by the numerical code using the external conditions measured by the meteorological station (precipitation, net radiation and wind velocity at a height of 2.40 m, hourly maximum and minimum temperature and hourly averaged relative humidity at a height of 2 m). The simulation period selected goes from January 27th to August 31st 2004. This period includes winter, spring and summer local weather conditions.

According to the data obtained in the sample profile of February 2005, six different types of material were considered in the waste. In addition two hardpans (5 cm thick) were included at depths of 11 and 16 cm. Finally, to take into account the superficial crust, a new layer (5.5 mm thick) is located at the waste surface from day 104 (May 10th 2004) till the end of the simulation period.

A dual-porosity model was used to define the hydraulic behaviour (Durner, 1994). This approach suggests a linear superposition of two
van Genuchten-type sub-curves for retention and conductivity functions (van Genuchten, 1980):

\[
S_e(\psi) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \begin{array}{ll}
\sum_{i=1}^{2} w_i S_{ei} = \sum_{i=1}^{2} w_i \left[ 1 + (\alpha_i |\psi|)^{n_i} \right]^{-m_i} & \text{for } \psi \geq 0 \\
\tau \cdot \left( \sum_{i=1}^{2} w_i \alpha_i \right)^{-2} & \text{for } \psi < 0 
\end{array} \right.
\]

(4)

\[
K_r(S_e) = \left( \sum_{i=1}^{2} w_i S_{ei} \right)^{-2} \left( \sum_{i=1}^{2} w_i \alpha_i \left[ 1 - (1 - S_{ei})^{1/m_i} \right] \right)^{2} / \left( \sum_{i=1}^{2} w_i \alpha_i \right)^{2}
\]

(5)

where \( S_e \) is the effective saturation; \( \psi \), the pressure head; \( \theta \), the volumetric water content; \( \theta_r \) and \( \theta_s \), the residual and saturated volumetric water content; \( w_i \) are the weighing factors for the sub-curves subject to the constraints \( 0 < w_i < 1 \) and \( w_1 + w_2 = 1 \); \( \alpha_i, m_i, \) and \( n_i \) are the shape parameters of the sub-curves and \( \tau \) is an empirical shape parameter that accounts for the tortuosity and correlation between pore sizes. The relative hydraulic conductivity function \( (K_r) \) is coupled with the retention curve through the semi-empirical model of Mualem (1976) and by applying the same constraint to all \( m_i \) parameters \( (m_i = 1 - 1/n_i) \). The parameters were obtained in laboratory tests using the inverse analysis techniques available in the HYDRUS-1D code.

Fig. 19. Measured tailings hydraulic head at -0.6 m, -1.1 m, -1.57 m, -2.505 m high, and total daily rainfall.

Fig. 20. Tailings hydraulic head evolution during an event of precipitation on April 4th to 13th 2002.
The set of hydraulic model parameters for all materials is included in Table 2. Note that the water conductivity of the hardpans and the superficial crust is higher than the conductivity values obtained in the constant head laboratory tests (see Figure 9). The preliminary analysis carried out (Blanco, 2009) using the directly measured conductivities of cemented materials was not able to accurately reproduce the flow pattern measured “in situ”, probably due to the discontinuity of the hardpans and the cracking of the superficial crust and by the 2D hypodermic drainages. The parameter values shown for hardpans and superficial crust in Table 2 were derived from their pore size distribution obtained in mercury intrusion tests that disregard the layered structure of the cemented materials. The effect of discontinuity of cemented layers may be taken into account in the model because their conductivities are notably higher than the ones belonging to the rest of the waste. The influence of hypodermic drainages at the instrumented area or discontinuity of cemented layers may be evaluated by switching conductivity values obtained by direct and indirect methods from the hardpans and the superficial crust. Exceptionally, in the case of the heat flux record, during the rainfall episode occurred from the 21st to the 26th of February, the simulations including low-permeability hardpans provided the best description for the thermal flux monitored at this depth (Blanco, 2009).

The simulation of the temperature and heat flux in the tailings was satisfactory (see Figures 25 and 26). During the wet season at a depth of 35 cm the fitting of the temperature was particularly remarkable. However, a relevant underestimation of the measurements was observed during the rainfalls taking place from the 21st to the 26th of February. At a depth of 2.4 cm, the simulations underestimated the daily maximum and minimum temperatures with deviations inferior to 6 °C for the maximum one and inferior to 2 °C for the minimum one.

In Fig. 27 the different components of the energy balance are plotted as a cumulative function of the time. The soil heat flux maintained its secondary role at the tailing surface during the whole simulation period. There was an outflow of heat in the surface until the end of May that turned into inflow from June to the end of the represented period.

Fig. 21. Comparison between measurements of water content obtained by sampling and by instrumentation using different calibrations.

Fig. 22. Event of water infiltration during rainfall in February 2004. Volumetric water content was deduced by applying standard low liquid electrical conductivity calibrations.
time. Sensible heat magnitude is comparable to soil flux, and latent heat flux is similar to incoming net radiation until the end of May. During this wet period most of the energy is used to evaporate the water in shallow layers of waste. However, during the dry season, drying of shallow layers leads to an increase of the sensible heat flux, which predominates over the latent flux. During the analyzed period, the calculated accumulative latent heat, sensible heat and soil fluxes represent approximately 63%, 33% and the 4% of the total incoming net radiation, respectively.

Fig. 28 presents the water head (referred to waste surface) calculated at a depth of 60 cm. Both the pressure peaks linked to rainfall events during the wet season and the decreasing tendency during the dry season were satisfactorily fitted with the model results. The computed profiles of volumetric water content are conditioned by

Fig. 23. Volumetric water content measured from ECH2O transducers, upon application of standard calibrations assuming low liquid electrical conductivity.

Fig. 24. Volumetric water content at a depth of 10 cm, obtained using the thermal approach and the output of CS615 probe using the standard calibrations for low liquid electrical conductivity. Rainfall is also included.
the water retention characteristics of the different materials used in hard-pan modelling. In particular, the small retention capacity of the hard-
Pans may be appreciated in the results shown in Fig. 29. The compar-
ison of the evolution of the computed and measured volumetric
water contents is shown in Fig. 30. During the wet season the results
are in good agreement with the volumetric water content measured
with a CS615 sensor when the standard calibration for low electrical
conductivity soils is used. During the dry season, the computed re-
sults slightly underestimate the measures obtained using the summer
2001 calibration.

The results of the numerical analysis enable the understanding of
the different components of the water balance on the boundaries of
the vertical column of waste. Table 3 and Fig. 31 show the comparison
of the results obtained considering the existence of a highly perme-
able superficial crust during the dry season with the results obtained
without the inclusion of the crust. In general, a low value of the runoff
and a high value of the surface evaporation were obtained. On the
other hand, in the lower boundary the ascending flux during the
dry season and the downwards infiltration during the wet season
donates. During the wet season, almost 60% of rainfall flows
down across a depth of 110 cm. The high water conductivity associat-
ed to the superficial crust leads to small effects of including the crust
on the superficial fluxes. However, the decrement of water storage
during the dry period is lower when the superficial crust exists,
which is mainly due to the increment of upwards water flow in the
lower boundary. When the superficial crust is set at the top of a tail-
ings column, lower-boundary water flow increases substantially,
whereas evaporation into the upper limit only increases slightly. Its
balance results in a rise of its water storage term. In terms of surface
energy balance, these changes in the vapour flow lead to an incre-
ment of the latent heat outflow and to a minor decrease of the soil
heat flow (Figure 27). Obviously, the consideration of a continuously
superficial crust with a low permeability changes the pattern of the
computed results (Blanco, 2009).

5. Conclusions

The paper describes the laboratory tests, the “in situ” monitoring
campaign and the numerical analysis performed to enhance the
knowledge of thermal and hydraulic behaviour of the shallowest

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (cm)</th>
<th>Number of elements</th>
<th>θr</th>
<th>θs</th>
<th>w1</th>
<th>α1 (cm⁻¹)</th>
<th>n1</th>
<th>α2 (cm⁻¹)</th>
<th>n2</th>
<th>τ</th>
<th>Ksat (m/s)</th>
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<td>YC1</td>
<td>5</td>
<td>58</td>
<td>0.036</td>
<td>0.5</td>
<td>0.65</td>
<td>0.015</td>
<td>2.72</td>
<td>0.00079</td>
<td>2.31</td>
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<td>2.7 10⁻⁶</td>
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<td>YC2</td>
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<td>0.046</td>
<td>0.51</td>
<td>0.52</td>
<td>0.0076</td>
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<td>0.00343</td>
<td>2.50</td>
<td>0.00</td>
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<td>0.82</td>
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<td>0.07</td>
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<tr>
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<td>35</td>
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<td>2.98</td>
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<td>-0.01</td>
<td>7.0 10⁻⁶</td>
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<td>11</td>
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<td>0.011</td>
<td>2.45</td>
<td>0.00141</td>
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<td>0.27</td>
<td>4.0 10⁻⁸</td>
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<tr>
<td>GF2</td>
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<td>61</td>
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<td>0.41</td>
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<td>0.0064</td>
<td>1.72</td>
<td>0.50</td>
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<tr>
<td>HP</td>
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<td>0.3</td>
<td>0.84</td>
<td>0.012</td>
<td>5.00</td>
<td>0.0005</td>
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</tr>
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<td>0.012</td>
<td>5.00</td>
<td>0.003</td>
<td>1.8</td>
<td>-1.00</td>
<td>8.1 10⁻⁴</td>
</tr>
</tbody>
</table>

Table 2

Fig. 25. Calculated and measured evolution of temperatures at 2.4 and 35 cm deep: (a), (c) without superficial crust. (b), (d) with superficial crust after May 10th 2004.
zone of abandoned mine tailings. In particular, the old tailing of Monte Romero mining complex in the Iberian Pyrite Belt was studied. Samples extracted from different profiles of tailings were tested in the laboratory to obtain their hydraulic and thermal parameters by means of direct, indirect and inverse methods. The retention curves obtained in this study showed mostly the effect of a dual porosity structure on the curves that was also detected in the void distribution functions from MIP tests. The historic displacement of the discharge zones, along with the delivery pipe, leads to the imbrication of the deposits and to the heterogeneity in the texture of the waste. Small scale penetration tests were used successfully to identify some horizontal correlations between layers, especially hard (cemented) materials and extremely soft materials.

An autonomous station monitored the waste and the atmosphere physical variables needed to calculate surface energy balances and water mass balances in the tailings. The station was equipped in order to permit remote data downloads and control activities. The instrumented area was installed close to the frontal dam of this impoundment. The waste salinity proved to be the main handicap to the electromagnetic instrumentation used during this project. These transducers should not be used in porous media capable of reaching an elevated and fluctuant electrical conductivity. Measurements based on the thermal conductivity, or on the simultaneous permittivity, as well as electrical conductivity measurements may be a good alternative to monitor the water content changes in the tailings.

According to the local climatic conditions, the water pressures measured deeper in the tailings represented generally upwards gradients of liquid, regardless of some short episodes of rainfall deep infiltration.

The coupled nature of the phenomena taking place requires a proper numerical tool to perform the simulation analysis. Computer code HYDRUS-1D was used in the analyses reported here. The model sequence included the presence of cemented layers embedded in the shallow depths or at the waste surface. Furthermore, in numerical models it was necessary to systematically increase the values of water conductivity of the cemented layers measured in the laboratory to understand the control that they could be exerting over the heat and the water transport in this sector of the impoundment. The discontinuity of hardpans cracks in the superficial crust, and 2D hypodermic flow may explain the necessity of this permeability increase.

The computed low values of volumetric water content associated to a large evaporation favour the oxygen availability necessary for pyrite oxidation. However, the important upwards flows computed at the lower boundary difficult the transport of contaminants to the deeper zones.

Acknowledgements

This work was funded by the Spanish Ministry of Science and Technology (PAROXIS project: REN2000-1003-C03-01 and BIGRISK
Fig. 28. Calculated and measured evolution of water head at 60 cm deep: (a) without superficial crust, and (b) with superficial crust after May 10th.

Fig. 29. Measured by sampling and calculated volumetric water content profiles at different times: (a) without superficial crust, and (b) with superficial crust after May 10th.

Fig. 30. Evolution of sensor-measured and calculated volumetric water at different depths: (a) without superficial crust and using standard calibration for the sensor, and (b) with superficial crust after May 10th and using summer calibrations for the sensors.
Table 3

Components of water mass balance resulted from different simulations and time periods.

<table>
<thead>
<tr>
<th>Period</th>
<th>Superf. crust</th>
<th>Total rainfall (mm)</th>
<th>Runoff (mm)</th>
<th>Liquid flow in upper boundary (mm) (+,1)</th>
<th>Vapour flow in upper boundary (mm) (+,1)</th>
<th>Liquid flow in lower boundary (mm) (+,1)</th>
<th>Water Storage (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 28th</td>
<td>No</td>
<td>331</td>
<td>29</td>
<td>302</td>
<td>-300</td>
<td>-153</td>
<td>-151</td>
</tr>
<tr>
<td>August 31st</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January 28th</td>
<td>No</td>
<td>300</td>
<td>28</td>
<td>272</td>
<td>-202</td>
<td>-176</td>
<td>-106</td>
</tr>
<tr>
<td>May 11th</td>
<td>No</td>
<td>31</td>
<td>1</td>
<td>30</td>
<td>-98</td>
<td>23</td>
<td>45</td>
</tr>
<tr>
<td>August 31st</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 11th</td>
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<td>31</td>
<td>0</td>
<td>31</td>
<td>-105</td>
<td>68</td>
<td>6</td>
</tr>
<tr>
<td>August 31st</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 31. Calculated tailings water mass balance. (a) Modelled period: January 11th to August 31st 2004. (b) Modelled period: May 10th to August 31st 2004 including superficial crust (SC).

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References


