Mine Water and the Environment
https://doi.org/10.1007/s10230-022-00883-6

TECHNICAL ARTICLE

Check for updates

Dry Covers Applied to Coal Tailings

Anderson Borghetti Soares[1] · Mario Valente Possa[2] · Vicente Paulo de Souza[2] · Paulo Sergio Moreira Soares[2] · Marcos Fábio Porto de Aguiar[3]

Received: 13 July 2021 / Accepted: 24 May 2022

Abstract
Covering coal mining tailings with layers of soil reduces the generation of acid mine drainage. These layers are designed to minimize water seepage and the flow of oxygen into tailing deposits. In Brazil, tailings from mineral coal processing are rich in pyrite, are often stored in piles, and are covered with layers of soil on the surface. This study provides results on the performance of four experimental soil cover models on tailings resulting from coal mining in southern Brazil. Pilot-scale physical models were constructed on-site, and the water balance of the covers, suction, volumetric moisture content, temperature in the tailings/cover layers, and quality of released effluent were measured. The covers designed with soil and bottom ash significantly reduced the volume of water seepage through the tailings and improved the quality of the generated effluents. Moreover, the results demonstrated that the performance of the cover depends on climate variations, and its behavior varies seasonally.

Keywords Acid mine drainage (AMD) · Dry covers · Unsaturated water flow

Introduction

The coal mines in southern Brazil produce tailings as part of their ore-processing operations. When the disposal of tailings (also known as coal refuse) is unsuitable, they can cause air, soil, and water pollution. One of the main environmental problems associated with improper disposal of such tailings is acid mine drainage (AMD), which is characterized by the formation of a metal-rich acid effluent with higher concentrations of metals than that provided by environmental legislation, originating from the contact of the tailing with water and oxygen from air. AMD, the result of the oxidation of pyrite (FeS_2), produces an acid effluent with a high concentration of sulfate, iron, and other sulfide minerals (aluminum, zinc, and manganese).

One possible strategy for overcoming this problem is to use dry covers, which are layers of materials applied over the tailings to inhibit chemical reactions that would occur inside the deposits of this material, thereby preventing the formation of AMD. Dry cover can use several layers of soil, non-reactive, or geosynthetic materials. In the case of coal mining facilities, the covers are designed to minimize oxygen or water ingress in tailing deposits using cover layers that maintain a high degree of saturation (Bussière et al. 2007; MEND Manual 2000; Nicholson et al. 1989; Yanful 1993). When correctly designed, dry covers act as barriers to help reduce the volume and/or pollution load of the water seeping through tailings (Adu-Wusu and Yanful 2006; Tallon et al. 2011), resulting in lower effluent treatment costs. Barriers reduce pollution in different ways, such as by excluding oxygen, consuming oxygen, or excluding water (Albright et al. 2010; Daniel and Koerner 1993; MEND Manual 2000). The layers comprising the dry cover may have different functions, such as waterproofing, drainage, and surface protection. In

✉ Marcos Fábio Porto de Aguiar
marcosporto@ifce.edu.br

Anderson Borghetti Soares
borghetti@ufc.br

Mario Valente Possa
mpossa@cetem.gov.br

Vicente Paulo de Souza
vpsouza@cetem.gov.br

Paulo Sergio Moreira Soares
psoares@cetem.gov.br

1 Federal University of Ceará, Fortaleza, CE, Brazil

2 Center of Mineral Technology/Ministry of Science, Technology, Innovation and Communication (MCTIC), Rio de Janeiro, RJ, Brazil

3 Federal Institute of Ceará, Fortaleza, CE, Brazil

regions exposed to wet and dry climate cycles, it is appropriate to use several layers to cover the tailings, so that the saturation degree of the materials remains unchanged, and to prevent dryness, which leads to the formation of cracks and preferential routes for oxygen and water ingress into the tailings, thus reducing the cover's performance (Song and Yanful 2011). Capillary barrier covers maintain the saturation of the cover's clay layer and have been used to cover coal mine tailings (Hotton et al. 2020; Weeks and Wilson 2005). This type of cover can reduce oxygen diffusion coefficients and acidity generation rates (Nicholson et al. 1989; Yanful 1993), resulting in lower treatment costs for effluents from waste disposal sites.

In Brazil, studies have been conducted not only on dry covers to cover solid waste but also on the use of alternative materials (non-reactive waste) to replace the soil layers (Almeida 2016; Almeida et al. 2015; Borghetti Soares et al. 2009, 2010; Borma et al. 2002, 2003; CETEM 2001; Mendonça 2007; Mendonça et al. 2006; Souza 2018; Souza et al. 2003; Ubaldo 2005). The Mineral Technology Center (CETEM), a research unit of the Ministry of Science, Technology and Innovation, has developed a three-stage procedure to evaluate the potential use of dry covers over coal processing tailings: (a) characterization (physical, chemical, and mineralogical) of the potential cover layer materials; (b) preliminary numerical modeling to determine the best layer configurations using the physical characterization data of the materials and the climate data of the region; and (c) pilot-scale field tests to check the performance of the designed covers.

This article discusses the results obtained from 5 years of field monitoring of covers designed to cover coal mine tailings. Borghetti Soares et al. (2009, 2010) discussed the stages of characterization, numerical modeling, and design and implementation of a pilot unit. It is particularly important to study the performance of dry covers as they undergo moisture variations during dry and wet seasonal cycles, which may result in long-term degradation with increased hydraulic conductivity and, consequently, seepage (Albright et al. 2010; Lu et al. 2015; Mellies and Schweizer 2011; Wang et al. 2014).

The performance of the covers were studied in a test pilot unit that contained four experimental cells: two containing only tailings, acting as benchmarks, and two with covers of soil and non-reactive materials (mineral coal ash from a thermal power plant) spread over the tailings. The cover and tailing layers of the cells were instrumented with sensors to measure the suction, moisture content, and temperature. The climate conditions were measured at a weather station installed at the site. The volumes and quality of the released effluents were measured over time to determine geochemical and physicochemical parameters. The results demonstrated the effectiveness of the designed soil covers, with significant reductions in the pollutant load of the effluent and the volume released in the tailings, and lower treatment costs.

Study Site

The pilot unit for cover performance was installed in a coal mine located south of Santa Catarina State, Brazil. The region has a temperate mesothermal climate, characterized by both intertropical air masses and cold polar masses, the latter being responsible for the mesothermal character. Cold front oscillations affecting the Santa Catarina territory throughout the year have two characteristics: unstable weather and heavy rainfall throughout the year (Borma et al. 2002). The average annual rainfall is 1479.9 mm/year, with the highest monthly averages occurring between September and March, and the lowest between April and August. The highest temperatures occurred from December to February and the coldest from June to August. The potential evapotranspiration was high from October to March and lows from April to September. However, in the region under study, precipitation was higher than evapotranspiration; hence, there is a water surplus of 670 mm/year (Borma et al. 2002).

Materials and Methods

Dry Cover Design

Our evaluation of covers had several stages, including: characterization of the materials to be used, numerical modeling of the water flow in different cover configurations, and on-site performance monitoring of the field pilot unit to check the performance (O´Kane et al. 2002) of the two better-performing covers based on the numerical modeling (Borghetti Soares et al. 2009, 2010).

At the characterization stage, different materials (regional soils and mineral coal ash) were selected that could be used to form dry cover layers. The characterization consisted of geotechnical grain size analyses (ABNT 2016a), consistency limits (ABNT 2016b, c), actual density (DNER 1994), permeability (ABNT 2000), compaction (ABNT 1986), mineralogical testing (x-ray diffraction, MeV, and x-ray fluorescence), and leaching and solubilization tests for waste (tailings and ash). A description of the test results can be found in Borghetti Soares et al. (2009), Mendonça (2007), and Ubaldo et al. (2006).

One-dimensional numerical models were produced using SoilCover software (GeoAnalisys 2000), Evapotranspiration flow was applied to the surface, with free drainage on the underside, to simulate the different tailing-cover systems. The modeling results revealed two promising models with the best performance in terms of reducing the volume of effluent release and maintaining high degrees of saturation in the waterproof layer (Borghetti Soares et al. 2009). The models used climatic data for 5 years (2000–2004) obtained from a nearby climatic station (evaporation and precipitation), with material parameters obtained through laboratory and field tests, such as saturated permeability (tailings in situ and compacted materials in the laboratory), compaction parameters by Proctor normal energy (ashes and clays), retention curve (filter paper method), and unsaturated permeability curve with the Van Genuchten method (1980). Twelve models were constructed with different cover configurations, and two models achieved the best results, maintaining high degrees of saturation in the clay layer and the lowest infiltrated volume into the tailings. These models were represented by cells 3 and 4, which were reproduced in the field.

The third stage of the project was to construct a pilot unit consisting of laboratory and experimental models (cells) to reproduce the best-performing dry covers in the numerical modeling stage. In addition to the two previously selected experimental models, another two cells were constructed containing only mining tailings (one without cover and the other with a compacted tailing layer on the surface) to be adopted as benchmarks, totaling four cells. Details of the implementation of the experimental model can be found in Borghetti Soares et al. (2010). The geometry of the experimental models consists of excavations in the shape of an inverted pyramid, made inside a 3-m-high embankment, to contain the experimental cells, as shown in Figs. 1 and 2. The bottom and sides of the excavations were covered with a high density polyethylene (HDPE) geomembrane of 0.6 mm thickness, and the excavations were later filled with uncompacted granular tailings (maximum particle diameter 37 mm) from mineral coal processing. The excavations covered areas of approximately 16 m^2 at the base and 64–80 m^2 at the top. A lysimeter, 2 m in height and 2 m in diameter, was placed inside the excavation to collect part of the effluent release volume, which was directed to a collection well through drainage pipes within the embankment, for geochemical and physicochemical quality analyses. Covers were implemented in the experimental models, which were compacted in 30 cm thick layers, at standard Proctor energy, using a manual compacter ("frog" and vibratory plate). A 30 cm thick layer of uncompacted topsoil was placed over the cover layers to protect the lower layers. Figure 1 shows the details of the experimental models and the cross-section of the embankment with four experimental models.

Materials Used in Experimental Models

Four experimental models were implemented on-site, the mixed tailings consisted of a 3:1 mixture of coarse tailings and fine coal tailings (particle size less than 1 mm): **(a) Cell 1**: coarse tailings; **(b) Cell 2**: coarse tailings + compacted mixed tailings (30 cm thick); **(c) Cell 3:** coarse tailings + compacted mixed tailings (30 cm thick) + compacted clay (30 cm thick) + uncompacted topsoil (30 cm thick); **(d) Cell 4**: coarse tailings + compacted mixed tailings (30 cm thick) + compacted coal ash (30 cm thick) + compacted clay (30 cm thick) + compacted coal ash (30 cm thick) + uncompacted topsoil (30 cm thick). Table 1 lists the geotechnical parameters of each layer of tailings and cover; Table 2 lists the consistency limits of clay materials (the other materials did not exhibit plasticity).

Data Collection Methodology

The monitoring consisted of: **(a) weather data collection**, by automatic data logging, using a weather station installed on site (model WeatherLink, Davis Instrument Corp) to obtain hourly data for rainfall, wind speed and direction, air humidity, environmental temperature, atmospheric pressure, daily rainfall data (Ville de Paris rain gauge), and potential evaporation (evaporation tank class A, in 2011 only); **(b) volume measurement of water balance in experimental cells,** by measuring daily released volumes in tailing-cover models and surface runoff volumes, whenever it rained; **(c) effluent sample collection**, to determine the quality of the samples using physicochemical and geochemical analyses of the effluent released in the tailing cells; and **(d) automatic data logging** of moisture, matrix suctions, and temperature measured by sensors installed in the cover and tailing layers.

A set of sensors consisting of temperature, moisture, and matrix suction sensors was installed at the center of each cover layer, except in the clay layers (of cells 3 and 4), in which two sensors were installed. In the coarse tailing, a set of sensors was installed one meter below the top elevation of the embankment. A total of 45 instruments were installed and connected to a data logger (model CR10X, Campbell Scientific) with hourly automatic data logging. The sensors used to measure moisture were the Campbell Scientific time-domain reflectometer model CS616, and moisture was measured from 0 to 60% with 3% accuracy. To measure matrix suctions, granular matrix sensors, Watermark 2000, and model 253 were used from 0 to 200 kPa. The temperatures in the layers were measured using Campbell Scientific temperature sensors, model 108, which enabled the measurement of temperatures between -5 °C and + 95 °C, with up to 0.1 °C accuracy.

Results

Weather data

Weather data were measured on-site using a weather station, model WeatherLink-Davis Instrument, with hourly

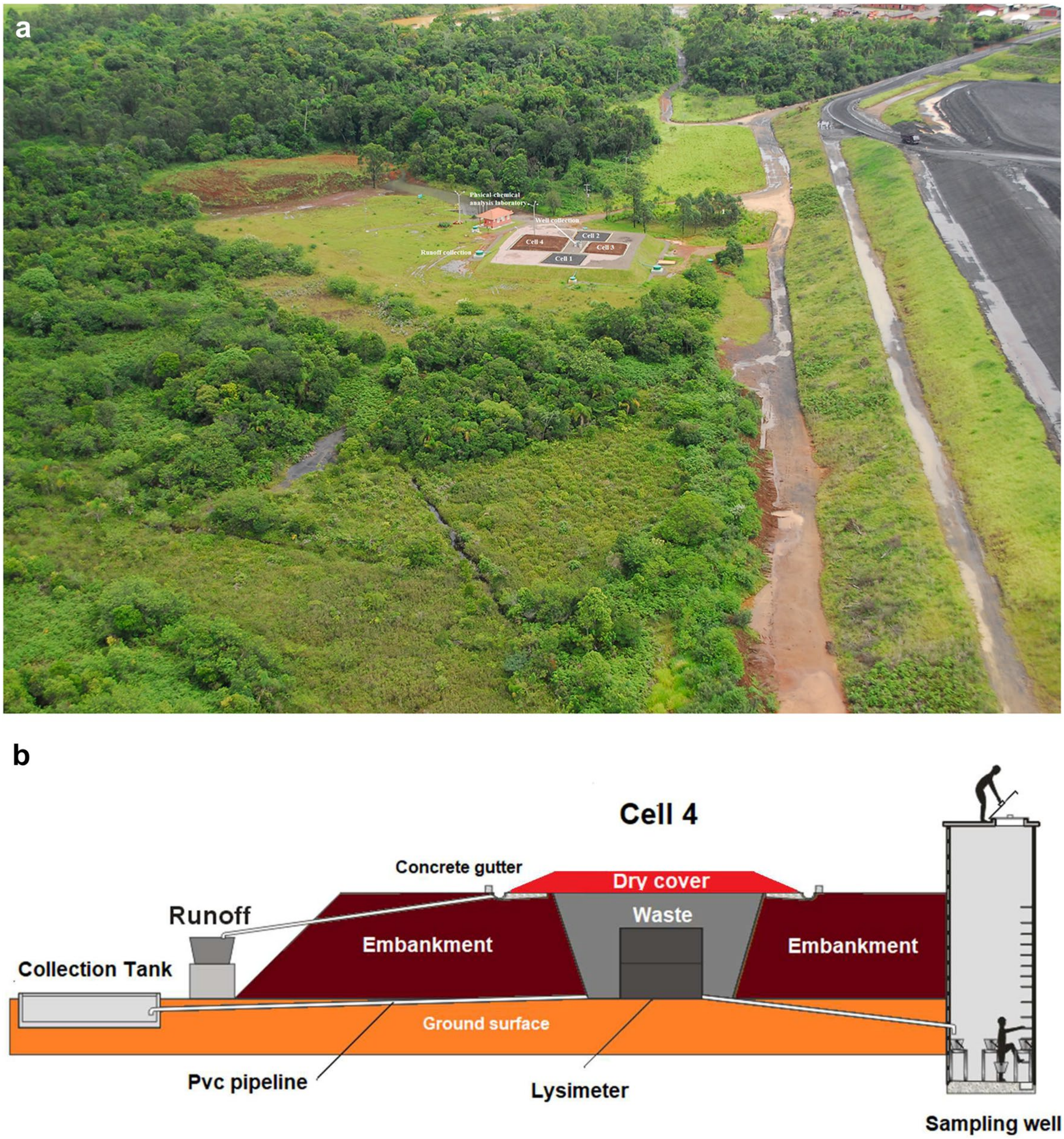

Fig. 1 Aerial view of pilot unit and experimental cells and cross-section of the embankment with an experimental model (cell 4)

data logged on a laptop. The annual rainfall data for the monitoring period are listed in Table 3. Figure 3 shows the rainfall distribution during the monitoring period. The data in Table 3 show that there was a variation in the annual total rainfall in relation to the average annual rainfall index of the region, which is 1479.9 mm/year, evidencing the importance of checking the performance of the covers, considering not only the average rainfall data but also the drier and wetter periods. The rainfall data measured by the weather station were consistent with those obtained from a rain gauge (Ville de Paris) installed on the site.

The air temperatures measured at the weather station were typical of the region, with the highest in December to February and the lowest in June to August, as shown in Fig. 4 for 2009. In the other years, the temperature variation trend was the same.

In addition to the rainfall data and maximum and minimum air temperatures, the other data recorded at the weather station (wind speed and direction, relative air humidity, and atmospheric pressure) were used to determine the actual evaporation in the experimental models using the Vadose program (GeosStudio 2008), which adopts the

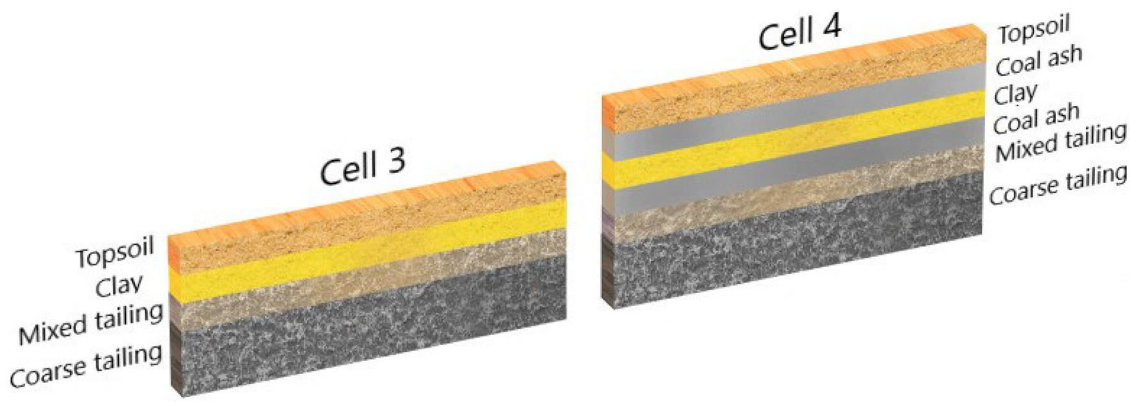

Fig. 2 Experimental models

Table 1 Geotechnical parameter of materials

Materials	Site density	Laboratory compaction*		Site compaction		Degree of compaction	K_{sat}	G_s	n	Class
	γ_n (g/cm^3)	γ_d (g/cm^3)	$\omega_{ót}$ (%)	γ_d (g/cm^3)	ω (%)	GC (%)				USCS
Topsoil	1.35	–	–	–	–	–	5.22×10^{-6}	2.65	0.52	CL
Coarse tailing	1.35	–	–	–	–	–	1.6×10^{-2}	2.41	0.44	GW-GC
Mixed tailing	–	–	–	2.0	–	–	9×10^{-3}	2.34	0.20	GW-GC
Clay (cell 3)	–	1.68[a]	16.3[a]	1.69	15.4	100	3.25×10^{-6}	2.67	0.35	CL
Clay (cell 4)	–			1.75	14.7	104	3.25×10^{-6}	2.67	0.35	CL
Bottom ash	–	0.99[a]	42.0[a]	0.90	34	90	2.45×10^{-4}	2.04	0.52	SM

[a]Compacted in Standard Proctor Energy

Table 2 Consistency limits of clay materials

Material	LL	LP	IP	ω_{sat}	S_{LP}
Clay	30	12	18	20	59.5
Topsoil	57	28	29	41	68.5

ω_{sat} = saturated gravimetric volumetric moisture (S = 100%); S_{LP} = degree of saturation in plasticity limit

Penman–Wilson equation to estimate actual evaporation (Fredlund et al. 2016; Wilson 1990).

Water Balance in Experimental Cells and Water Flow Data in Cover Layers

The portions of water balance were periodically measured on-site during the years of monitoring. Figures 5 and 6 show the accumulated volumes of the water balance portions measured in cells 3 and 4, respectively, which were covered with soil cover on the tailing. Rainfall was measured hourly using a pluviograph and confirmed daily using rain gauge data, as described in the previous section. Whenever it rained, the surface runoff volume of the water in the cells was carried to the individual water tank of each cell, where the surface runoff volumes were measured. The seeped volumes in the experimental cells were measured daily for each cell considering the seepage volumes in the lysimeters (carried to the collection well) and in the tank outside the embankment.

By scrutinizing the data in Figs. 5 and 6, it was found that cell 3, consisting of a compacted clay layer and a protective layer, performed better than cell 4. The cover of cell 4 significantly reduced the seepage volumes in the tailings (volume accumulated on 01/01/2012 was equal to 448 mm), but the reduction was more efficient in cell 3 (volume accumulated on 01/01/2012 was equal to 17 mm). With regard

Table 3 Annual rainfall in the monitored period

Year	2008	2009	2010	2011	2012	Average
Rainfall (mm)	1416	1915	1635	1939	1037	1588

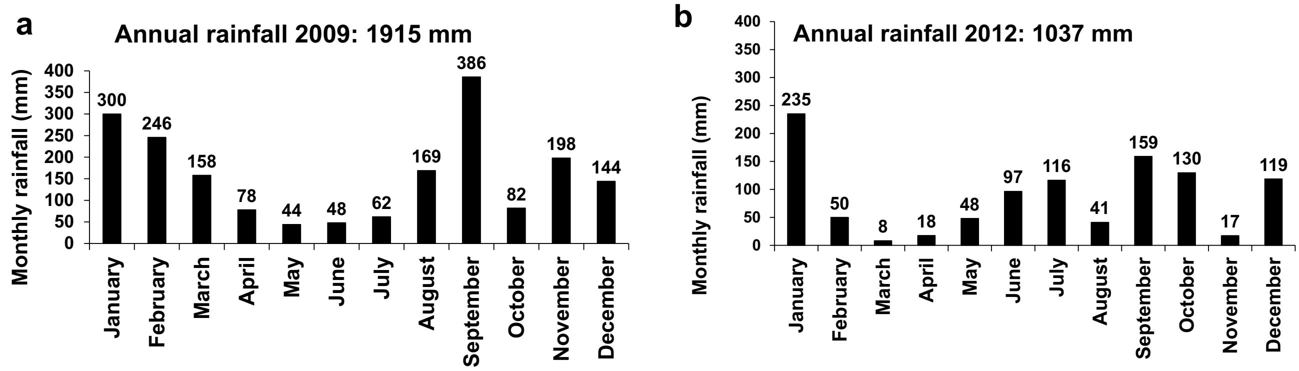

Fig. 3 Rainfall distribution years: **a** 2009 (wet) and **b** 2012 (dry)

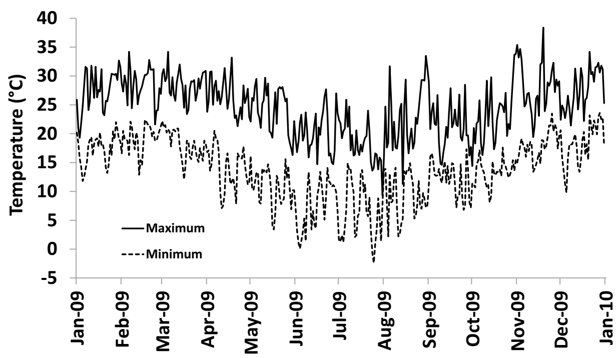

Fig. 4 Typical maximum and minimum air temperatures in the experimental station (2009)

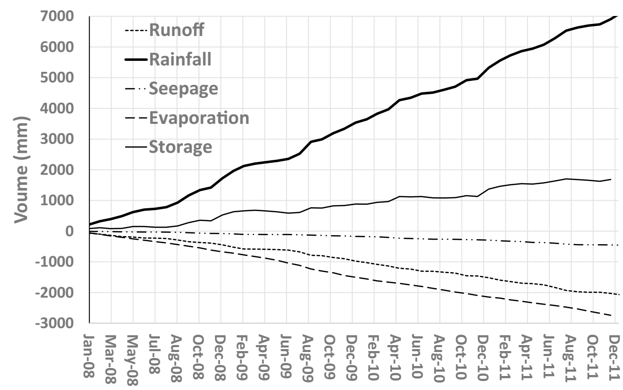

Fig. 6 Cell 4 water balance

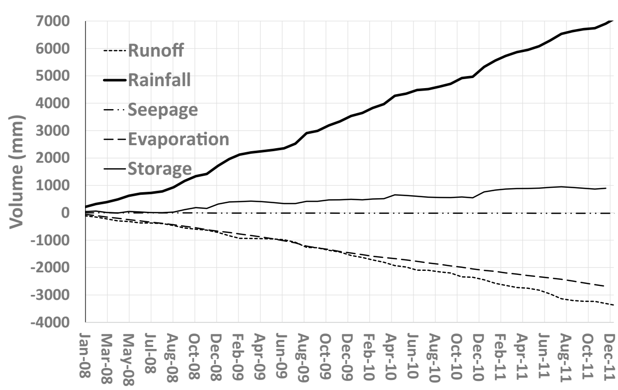

Fig. 5 Cell 3 water balance

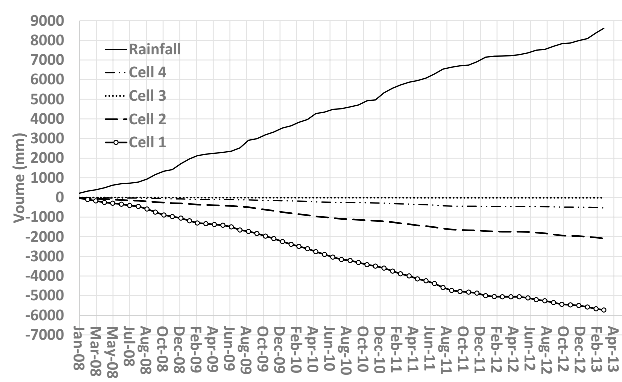

Fig. 7 Seepage volumes in experimental cells

to the accumulated volumes of surface runoff, cell 3 had larger volumes than cell 4, suggesting that there was more rainwater seepage in cell 4, with greater saturation of the cell 4 cover layers.

Figure 7 shows the total accumulated seepage volumes of the four cells. The measured water seepage corresponded to 67% of the rainfall volume when the tailings were not covered. The application of cover layers resulted in a significant drop in the seepage volume, reaching approximately 91% drop in cell 4 and 99.7% drop in cell 3, compared to the seepage volume in cell 1. In this aspect, cell 3 performed the best, as it not only reduced the seepage volume but also required fewer cover layers, which would imply a decrease in construction costs.

The suction and saturation data of the layers of cells 3 and 4 were obtained by reading the instruments installed in half of them. The readings were obtained hourly and stored in a data logger. The period monitored using electronic instrumentation was from the start of 2008 to October 2012. Figure 8 shows the variations in the saturation of the cell 3 layers. A seasonal variation trend was observed in the saturation in the layers, which was modified in 2012, the driest of the monitored period, when the rainfall was less than in the previous years, particularly in the first months of the year. As expected, the topsoil exhibited lower saturation degrees than the clay layer because it was more exposed to the weather. Notably, the clay layer in cell 3 had saturation degrees of less than 85% throughout the monitoring period, which is not sufficient to minimize the oxygen ingress of air into the lower layers (MEND Manual 2000; Yanful 1993). Both moisture sensors installed in the clay layer of cell 3 practically matched the moisture content.

Figures 9 and 10 show the variations in the saturation degree with time in cell 4 layers. Similar to cell 3, the saturation data of cell 4 layers exhibited a seasonal variation trend, dropping in 2012, which was the driest in the monitored period. However, it is noticeable that during a large part of the monitored period, the clay layer had saturation degrees of over 85%, thereby effectively barring oxygen flow from the air to the lower layers in wetter periods. However, in November and May of each year, the saturation degree in the clay layer had values below 85%. The topsoil of cell 4 had higher saturation degrees than that of cell 3, indicating greater water retention in the topsoil layer of cell 4. For the granular layers (ash), this seasonal variation was also noted, such that the topmost ash layer had slightly higher saturation degrees than the deeper ash layer situated below the clay.

During the monitoring period, it was found that, for every cell, in wetter seasons, the seepage volume increased, whereas in drier seasons, the seepage volume dropped, as shown in Fig. 10. This behavior can be ascertained in cell 4, indicating that the lower ash layer did not act as a capillary barrier to water flow. At specific monitoring times, the saturation degrees were also high in the lower ash layer. In the case of cell 3, the seepage volumes were low, except for the period between the end of 2008 and start of 2009, when its released effluent was not a good quality, as will be shown by the geochemical and physicochemical analyses.

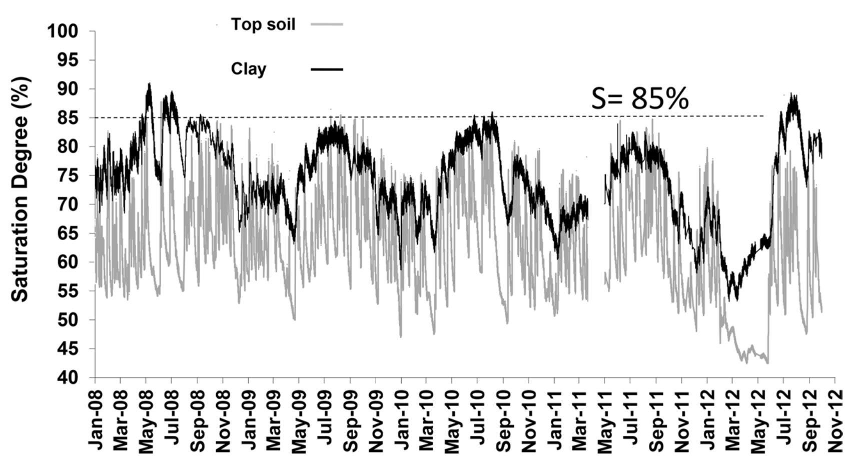

Fig. 8 Saturation of cell 3 layer: clay and protection

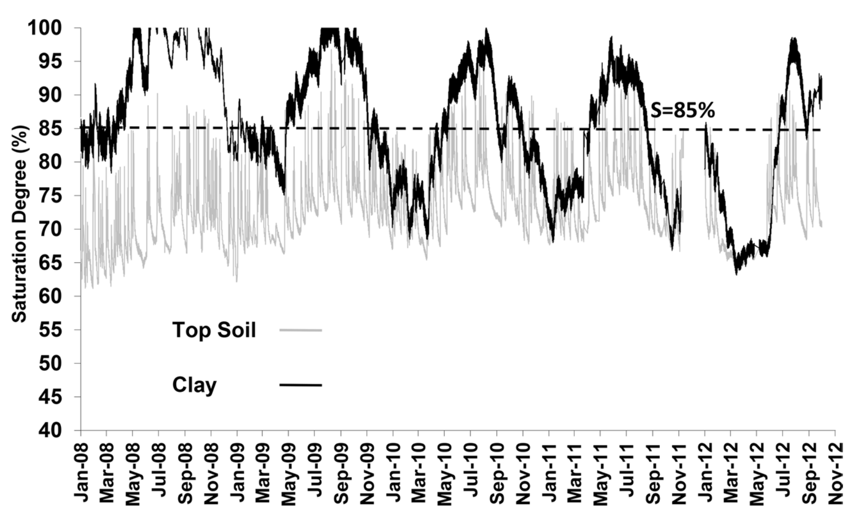

Fig. 9 Saturation of cell 4 layers: clay and protection

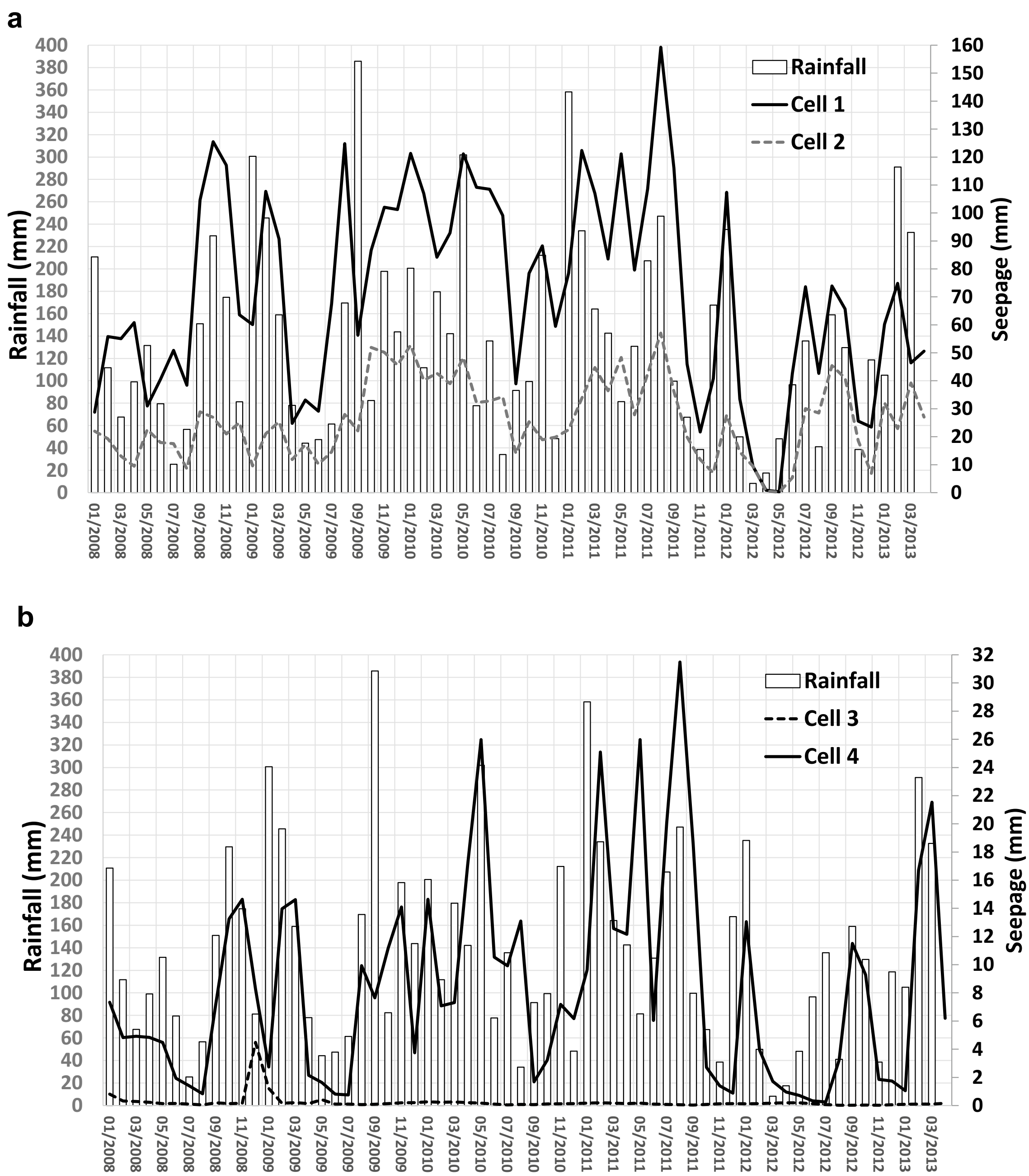

Fig. 10 Monthly seepage volumes in cells

The clay layer of cell 3 had a saturation degree of less than 85%, regardless of the period analyzed (wet or dry). In addition, in the same cell, the degree of saturation of the clay layer ranged between 60 and 85%, with 59% in 2012 between March and April. This is below the plastic limit of clay, which can lead to the formation of cracks (Tollenaar et al. 2017). However, as noted in the monthly seepage data in Fig. 11, no increase in the seepage volume, but rather a drop in effluent quality (pH < 3.0), was noted after this drought period in 2012. In 2009, the saturation degrees in the clay layer of cell 4 were greater than in the clay layer of cell 3, reaching values higher than or close to 85% for most of the year. During the driest period in 2012, the lowest saturation degree found in this cell was approximately 65%, which is still above the plastic limit of clay, suggesting that there was no formation of cracks at the measuring depth. Neither model with a designed compacted clay cover (cells 3 and 4) had saturation degrees greater than 85% in the clay layer throughout the monitoring period and that cell 4 cover was more efficient in minimizing oxygen ingress for the

Fig. 11 Details of typical coloring of effluents collected per cell (08/05/2011)

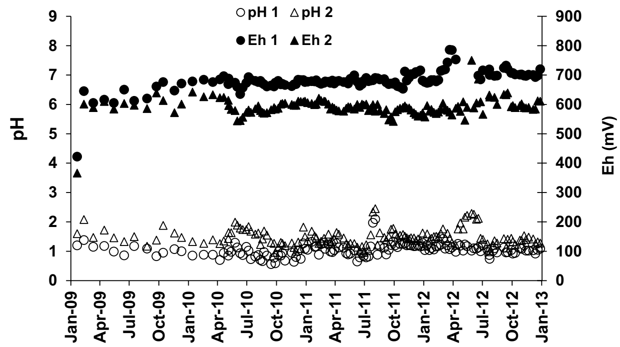

Fig. 12 Eh × pH of effluents released into cells 1 and 2

tailing by presenting saturation degrees greater than 85%. Moreover, during drier periods, cell 4 was found to have a significantly reduced seepage volume in the tailings, with the clay layer acting as a hydraulic barrier. The sensors used to measure the suction had several problems (e.g. malfunction after installation, defect after time of use, and wear in contact with acid effluent), with mainly installed at deeper layers; therefore, it was only possible to obtain the variations in suction in layers closer to the surface and installed in the topsoil.

Physical–Chemical and Geochemical Data of Effluent Release

Effluents released into the experimental cells were periodically collected from individual drainage outlets installed inside the collection well (Fig. 2). The physicochemical parameters were measured on-site, and more continuously read data from these parameters were first obtained from 2009, after completing the physical structure and operating standards of the analysis laboratory situated next to the experiment site. Figure 11 shows typical aspects of the effluent release samples in the cells. Figure 12 shows the pH × Eh diagrams of the cells containing only tailings: cell 1 (uncovered) and cell 2 (with a compacted mixed tailings cover in the upper part). These cells had pH values of less than 2.0, with the formation of an acid effluent. The effluent released into cell 1 was dark in color (orangey–brown), indicating the presence of Fe^{3+}, unlike the effluent released into cell 2, the color of which suggested little or no Fe^{3+} formation. However, in the case of the effluents released from cells 3 and 4 (with covers), the pH values were between 6.0 and 7.0, in wetter seasons, with a drop in pH (and increase in Eh) in drier seasons, mainly in the effluent release in cell 4, as shown in Fig. 13.

The equations of AMD formation for pyrite oxidation are widely known in the literature (Boscov 2014; MEND Manual 2000; Moodley et al. 2018; Rose and Cravota III 1998; Souza 2001). In the case of the effluent released in cell 2, the mixed tailings layer seemed to minimize Fe^{2+} oxidation. The effluent released in cell 3 was acidic in two periods (Fig. 13a): (a) January 2009, associated with exceptional rainfall during this period, resulting in higher volumes of effluent release than those normally found in cell 3, and (b) 2012, the driest period of monitoring. For cell 4 (Fig. 13b), the effluent releases varied seasonally, with lower pH values in the drier periods (less saturation of the clay layer) associated with low rainfall. The pH values are consistent with the measured Eh. The electrical conductivity (EC) values were higher in the cells without soil cover, as expected (Fig. 14).

The redox potentials were high in cells 1 and 2 and in line with the pH values obtained in these cells, typical of AMD. As shown in Fig. 15, the temperatures read by the sensors installed in the tailings (1 m deep) indicated that temperatures were higher in the cells containing tailings with no soil cover (cells 1 and 2), because the reactions associated with the AMD are exothermic.

Effluent samples released from the tailings were collected and analyzed for Fe, Fe^{2+}, Al, Mn, Cu, Zn, acidity, and SO_4. Applying a compacted tailings cover on the surface of cell 2 resulted in a total iron concentration very close to the Fe^{2+} concentration (Fig. 16), indicating that that the mixed tailing layer seems to have had limited oxygen access to generate Fe^{3+}. In contrast, cells 3 and 4 generally reached iron concentrations between 10 and 25 mg/L.

Conama 430 (2011) establishes the following effluent release conditions in water bodies: pH between 5.0 and 9.0; minimum concentrations: Cu < 1.0 mg/L; Zn < 5.0 mg/L; Mn < 1.0 mg/L; and Fe < 15 mg/L. There is no mention of Al and SO_4 limits, which are defined by state agencies. For instance, the Ceará State Environment Council (Coema 2017) has established concentrations of Al < 10 mg/L and SO_4 < 500 mg/L.

The Al, Mn, Zn, Cu, and SO_4 concentrations were high for the uncovered cells (1 and 2), far above the acceptable limits, and much lower in cells 3 and 4 with a soil cover. For cells 3 and 4, Al, Zn, and Cu concentrations reached acceptable limits, though the Mn and SO_4 concentrations

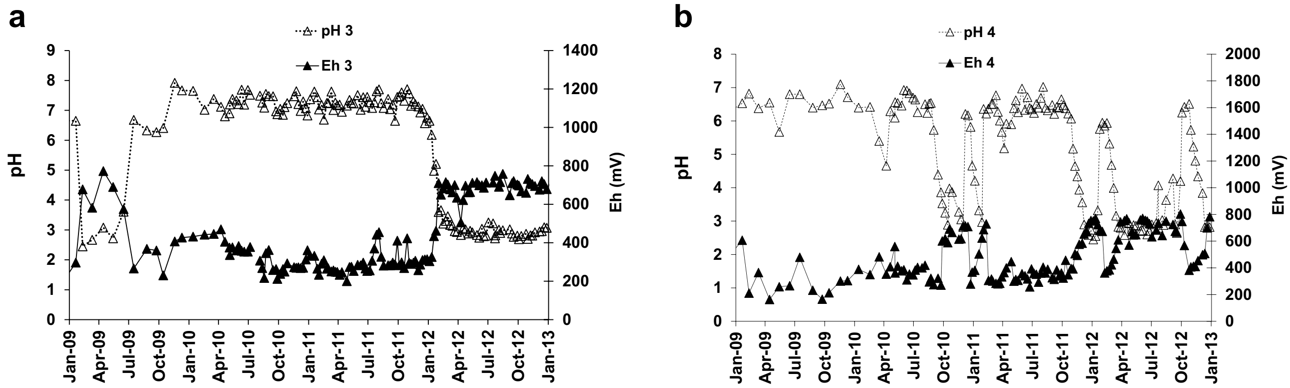

Fig. 13 Eh × pH of effluent release into (a) cell 3 and (b) cell 4

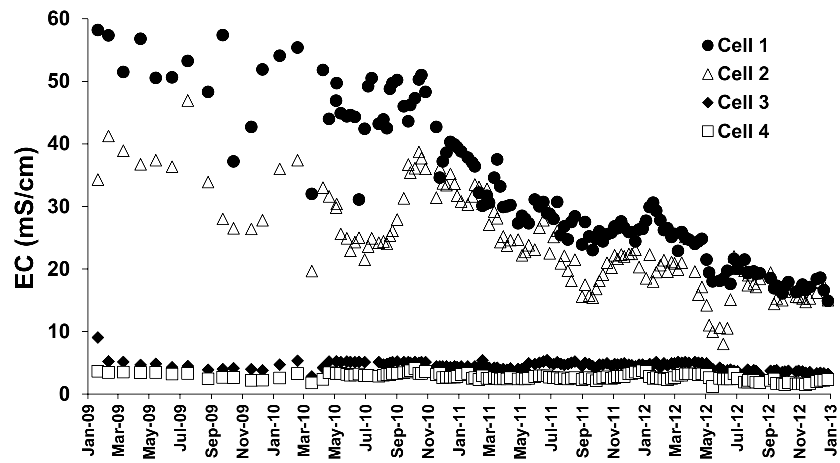

Fig. 14 EC of effluent released into cells

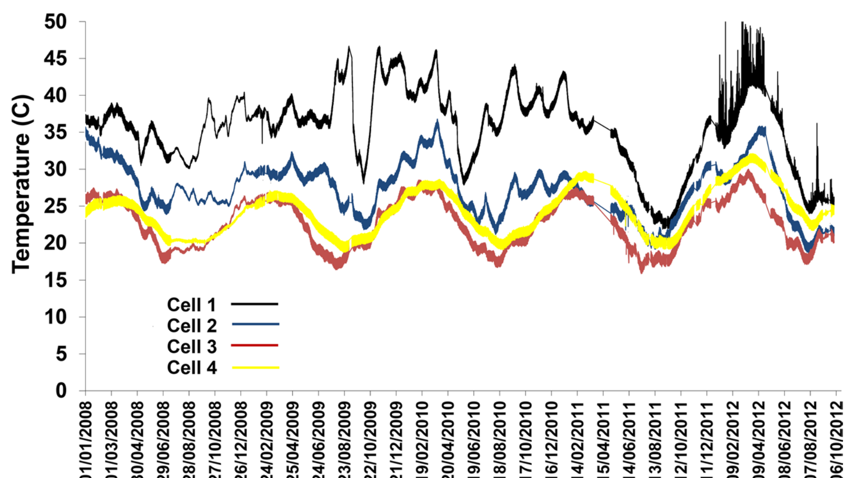

Fig. 15 Temperatures measured hourly in the coarse tailing (1 m depth from top of embankment)

still indicated a need for water treatment. In general, the soil cover reduced the polluting potential of the tailings, thereby reducing the need for water treatment.

The net acidity (in terms of $CaCO_3$ equivalence) was significantly reduced by the soil covers, representing a substantial drop in treatment costs. In the uncovered cells, the net acidity was between 40 and 140 g/L $CaCO_3$, whereas in the covered cells, it was orders off magnitudes less, between 50 and 300 mg/L $CaCO_3$.

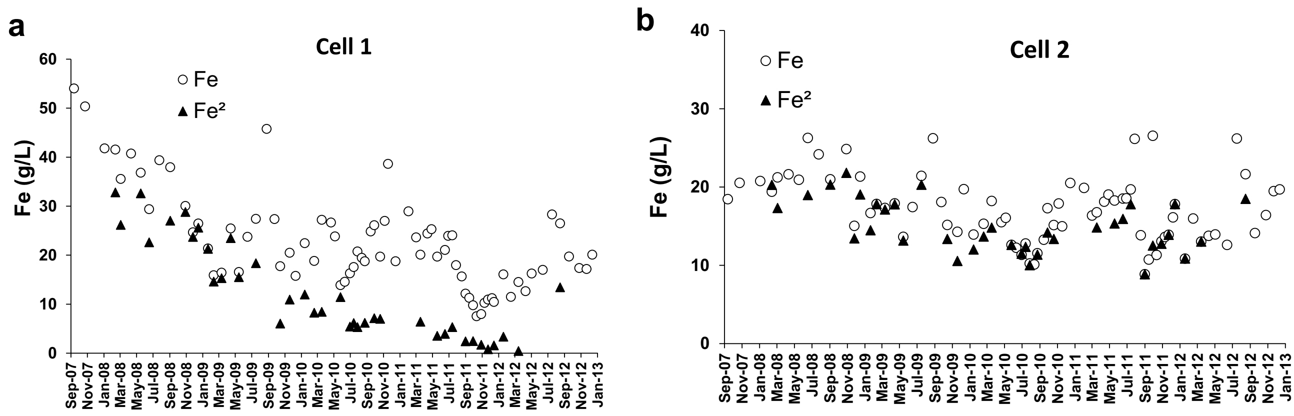

Fig. 16 Concentrations of total Fe and Fe^{2+} in cells 1 and 2

Conclusions

This article addressed the results of soil-cover experimental trials constructed on site in the state of Santa Catarina in southern Brazil. The data demonstrated the importance of measuring on-site climate conditions. Since there was a variation in the annual total rainfall relative to the average annual rainfall index, it was important to check the cover performance in both drier and wetter seasons, and not just the average rainfall data. The results demonstrated that the cells designed with clay covers or non-reactive waste considerably reduced the volume of effluent released by the tailings by 91% to 99% compared to the uncovered cells.

There was also a significant improvement in the quality of the effluent released when soil covers were applied, though sulfate and manganese concentrations still exceeded regulatory limits. The clay layers designed as waterproofing agents failed to maintain saturation degrees greater than 85% throughout the monitored period, with the clay layer surrounded by coal ash exhibiting higher saturations than the clay layer just covered by top soil, which was always less than 85%. In the case of cell 4, in which the cover was designed with coal ash layers between the clay layers, saturation degrees always exceeded the plastic limit of clay, though it consistently exceeded 85% during the wetter periods.

These results suggest that the formation of cracks would have been minimized in the clay layer, but oxygen still reached inside the tailings, as evidenced by a decrease in pH and a slight increase in acidity and some metal concentrations. In wetter seasons, the effluent released into cell 4 had a better quality than in the drier periods; however, in drier periods, there was a very sharp drop in the seepage volume. In general, the covers were effective in reducing effluent volume and improving the quality of the effluent, implying lower leachate treatment costs. Cell 3 had a constructive advantage over cell 4, as it was still efficient though designed with fewer layers.

Dry covers can mitigate of the effects of the AMD in regions with seasonal variations in precipitation if high degrees of saturation in the clay layer are maintained throughout the year. For these regions, covers with thicker layers, such as impervious and drainage layers, can reduce losses by evaporation and could be an alternative way to improve the global performance of dry covers.

Acknowledgements The authors thank the Brazilian Ministry of Science and Technology (Finep) for financial support, and Carbonifera Criciúma S/A and Tractebel Energia S/A for providing the ash from coal combustion.

Data availability The water balance, physical–chemical and geochemical, waterflow, and weather data that support the findings of this study are available from the corresponding author.

References

ABNT (1986) Soil—compaction test [Ensaio de compactação]. Brazilian Technical Standards Assoc, NBR 7182, Rio de Janeiro, Brasil (**in Portuguese**)

ABNT (2000) Soil—determining the permeability coefficient of clay soils and variable load [Determinação do coeficiente de permeabilidade de solos argilosos e de carga variável]. Brazilian Technical Standards Assoc, NBR 14545, Rio de Janeiro, Brasil (**in Portuguese**)

ABNT (2016a) Soil—grain size analysis[Análise granulométrica]. Brazilian Technical Standards Assoc, NBR 7181, Rio de Janeiro, Brasil (**in Portuguese**)

ABNT (2016b) Soil—determining the liquid limit [Determinação do limite de liquidade]. Brazilian Technical Standards Assoc, NBR 6459, Rio de Janeiro, Brasil (**in Portuguese**)

ABNT (2016c) Soil—determining the plastic limit [Determinação do limite de plasticidade]. Brazilian Technical Standards Assoc, NBR 7180, Rio de Janeiro, Brasil (**in Portuguese**)

Adu-Wusu C, Yanful EK (2006) Performance of engineered test covers on acid-generating waste rock at Whistle mine, Ontario. Can Geotech J 43:1–18. https://doi.org/10.1139/t05-088

Albright WH, Benson CH, Waugh WJ (2010) Water Balance cover for waste containment: principles and practices. American Soc of Civil Engineering

Almeida RP (2016) Assessment of dry covers to reduce acid rock drainage. [Avaliação de coberturas secas para redução de drenagem ácida de rocha]. PhD Diss, Federal Univ of Ouro Preto (UFOP) Brazil [in Portuguese]

Almeida RP, Leite ADL, Borghetti Soares A (2015) Reduction of acid rock drainage using steel slag in cover systems over sulfide rock waste piles. Waste Manag Res 33(4):353–362. https://doi.org/10.1177/0734242X15572178

Borghetti Soares A, Ubaldo MO, Souza VP, Soares PSM, Barbosa MC, Mendonça RMG (2009) Design of a dry cover pilot test for acid mine drainage abatement in southern Brazil. Part 1: material characterization and numeric modeling. Mine Water Environ 28(3):219–231. https://doi.org/10.1007/s10230-009-0077-5

Borghetti Soares A, Possa MV, Souza VP, Soares PSM, Barbosa MC, Ubaldo MO, Bertolino AVFA, Borma LS (2010) Design of a dry cover pilot test for acid mine drainage abatement in southern Brazil. Part 2: pilot unit construction and initial monitoring. Mine Water Environ 29(4):277–284. https://doi.org/10.1007/s10230-010-0126-0

Borma LS, Mendonça RMG, Souza VP (2002) Mitigation process of acid drainage formation using dry covers. Basic design of Instrumentation and Pilot Unit - Preliminary assessment of installation costs and pilot operation." [Processo de mitigação da formação de drenagens Ácidas utilizando Coberturas Secas. Projeto Básico da Unidade Piloto e da Instrumentação - Avaliação Preliminar dos Custos de Instalação e Operação de Piloto]. RT 2002–038–00: Technical Report for Siecesc (Syndicate of Coal Mining Companies of the State of Santa Catarina) CETEM/RJ Brazil (**in Portuguese**)

Borma LS, Mendonça RMG, Souza VP, Soares PSM (2003) Ash use for rehabilitating coal mining áreas. [Utilização de cinza no contexto da reabilitação de áreas de mineração de carvão]. In: Proc, 5th Brazilian Congress on Environmental Geotechnics (V REGEO), Porto Alegre/RS, Brazil (**in Portuguese**)

Boscov MEG (2014) Environmental geotechnics [Geotecnia ambiental]. Oficina de textos, São Paulo, Brazil (**in Portuguese**)

Bussière B, Aubertin M, Mbonimpa M, Molson JW, Chapuis RP (2007) Field experimental cells to evaluate the hydrogeological behavior of oxygen barriers made of silty materials. Can Geotech J 44:245–265. https://doi.org/10.1139/t06-120

CETEM (2001) Conceptual design for environmental recovery of a carboniferous basin in southern Santa Catarina [Projeto Conceitual para Recuperação Ambiental da Bacia Carbonífera Sul Catarinense], RT/33/2000 - Technical Report for Siecesc (Syndicate of Coal Mining Companies of the State of Santa Catarina), Vols. I, II e III, CETEM/RJ, Brazil [in Portuguese]

COEMA N°2 (2017) Provides standards and conditions for liquid effluent release generated by pollutant sources [Dispõe Padrões e condições para lançamento de efluentes líquidos gerados por fontes poluidoras]. State Environment Council, Ceará (**in Portuguese**)

CONAMA Resolution 430 (2011) Conditions and standards for releasing effluents [Condições e padrões de lançamento de efluentes]. National Environment Council (**in Portuguese**)

Daniel D, Koerner RM (1993) Cover Systems. In: Daniel DE (ed) Geotechnical practice for waste disposal, 2nd edn. Chapman & Hall, London, pp 455–496

DNER (1994) Soils—determining actual density. Highway Regulations, ME09, Test method. [Solos Determinação da densidade real. Método de ensaio], Brazil (**in Portuguese**)

Fredlund MD, Tran D, Fredlund DG (2016) Methodologies for the calculation of actual evapo-transpiration in geotechnical engineering. Int J Geomechs 16(6):D4016014. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000730

GeoAnalisys (2000) SoilCover Software. Univ of Saskatchewan, Saskatoon

GeosStudio (2008) VADOSE/W. Vadose zone and soil cover analysis. User's guide, 3rd edn. GEO-SLOPE International Ltd.

Hotton G, Bussière B, Pabst T, Bresson E, Roy P (2020) Influence of climate change on the ability of a cover with capillary barrier effects to control acid generation. Hydrogeol J 28:763–779. https://doi.org/10.1007/s10040-019-02084-y

Lu H, Li J, Wang W, Wang C (2015) Cracking and water seepage of Xiashu loess used as landfill cover under wetting-drying cycles. Environ Earth Sci 74:7441–7450. https://doi.org/10.1007/s12665-015-4729-4

Mellies WH, Schweizer A (2011) Long term performance of landfill cover - Results of Lysimeter test fields in Bavaria (Germany). Waste Manag Res 29(1):59–68. https://doi.org/10.1177/0734242X10385748

MEND MANUAL (2000) Prevention and control, vol 4. Natural Resources Canada

Mendonça RMG (2007) Study of oxygen diffusion in cover materials [Estudo da Difusão do Oxigênio em Materiais de Cobertura]. PhD Diss, Program of Civil Engineering, Coppe/UFRJ, RJ, Brazil [in Portuguese]

Mendonça RMG, Barbosa MC, Borma LS (2006) Discussion on theoretical and practical aspects of gas fluxes in mining waste deposits. In: Proc, 5th International Congress on Environmental Geotechnics (5ICEG), Balkema, Cardiff, UK, Vol 1: 942–949

Moodley I, Sheridan CM, Kappelmeyer U, Akcil A (2018) Environmentally sustainable acid mine drainage remediation: research developments with a focus on waste/by-products. Miner Eng 126:207–220

Nicholson RV, Gillham RW, Cherry JA, Reardon EJ (1989) Reduction of acid generation in mine waste through the use of moisture-retaining cover layers as oxygen barriers. Can Geotech J 26(2):1–8. https://doi.org/10.1139/t89-001

O´Kane MA, Ayres B, Christensen D, Meiers G (2002) CANMET-CETEM Manual on cover system design for reactive mine waste. Report N° 689–01, Canmet-CETEM

Rose AW, Cravota III CA (1998) Geochemistry of coal mine drainage. Brady KBC, Smith MW, Schueck JH eds. In: Chapter I:coal mine drainage prediction and pollution in Pennsylvania, Harrisburg, Pennsylvania Departament of EnvironmentalProctection p 1.1-1.22

Song K, Yanful EK (2011) Laboratory and numerical modeling of water balance in a layer sloped soil cover with channel flow pathway over mine waste rock. Environ Earth Sci 62:1–17. https://doi.org/10.1007/s12665-010-0488-4

Souza VP (2001) Formation of geochemical barrier for reduction of acid drainage in piles of pyrite rich waste rocks [Formação de barreira geoquímica para abatimento de drenagens ácidas de pilhas de estéril piritoso]. PhD Diss, São Paulo State Univ (USP), São Paulo/SP, Brazil (**in Portuguese**)

Souza HP (2018) Use of mineral coal ash from Pécem thermal power plant as dry cover material from waste deposits [Uso de cinzas de carvão mineral da termelétrica do Pécem como material de cobertura seca de depósitos de resíduos]. M.Sc Thesis, Civil Engineering Post-Graduation Program: Geotechnics, Federal Univ of Ceará, Brazil

Souza VP, Borma LS, Mendonça RMG (2003) Dry cover design for control of acid drainage in acidity generating deposits [Projeto de coberturas secas para controle da drenagem ácida em depósitos geradores de acidez]. Brazil-Canada Seminar on Environmental Mine Rehabilitation, Florianopolis, pp 210–228

Tallon LK, O'Kane LA, Chapman DE, Phillip MA, Shurniak RE, Strunk RL (2011) Unsaturated loping layered soil cover system: field investigation. Can J Soil Sci 91:161–168. https://doi.org/10.1139/CJSS10090

Tollenaar RN, Paassen LA, Jommi C (2017) Observations on the desiccation and cracking of clay layers. Eng Geol 230:23–31. https://doi.org/10.1016/j.enggeo.2017.08.022

Ubaldo MO (2005) Coal ash use in the composition of mine tailings [Uso de Cinza de Carvão na Composição de uma Cobertura de Rejeitos de Mineração]. MSc Thesis, Civil Engineering Program, Coppe/UFRJ/RJ, Brazil [in Portuguese]

Ubaldo MO, Barbosa, MC, Borma LS (2006) Technical and environmental viability study of the use of coal ash as covering material for mining rejects. In: Proc, 5th International Congress on Environmental Geotechnics (5ICEG), Cardiff, Wales, UK, Vol. 2: pp 1593 -1600

Van Genuchten MT (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Am J 44(5):892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wang Y, Xue Q, Liu L (2014) Study on the permeability evolution law and the micro-mechanism of CCL in a landfill final cover under the dry-wet cycle. Bull Eng Geoenviron 73:1089–1103. https://doi.org/10.1007/s10064-014-0604-x

Weeks B, Wilson GW (2005) Variations in moisture content for a soil cover over a 10-year period. Can Geotech J 42:1615–1630. https://doi.org/10.1139/t05-070

Wilson GW (1990) Soil evaporative fluxes for geotechnical engineering problems. PhD Diss, University of Saskatchewan, Saskatoon

Yanful EK (1993) Oxygen diffusion through soil cover on sulphidic mine tailings. ASCE J Geotech Eng 199(8):1207–1228. https://doi.org/10.1061/(ASCE)0733-9410(1993)119:8(1207)