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Assessment of the environmental behavior of Sabodala mine tailings using geochemical leaching tests in a Mini-Cell of Alteration (MCA)

Tidiane DIOP[1], El Hadji Mamadou SONKO[2], Adrienne NDIOLLENNE[1], Mariama BAKHOUM[1]

[1]*Inorganic and Analytical Chemistry Laboratory, Department of Chemistry, Faculty of Science and Technology, Cheikh Anta Diop University of Dakar*

[2]*Environmental Sciences Institute (ISE) - Cheikh Anta Diop university of Dakar*

Corresponding author, Email address: tidiane3.diop@ucad.edu.sn

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Abstract: Mining activity generates large quantities of metal and metalloid-rich waste. Mining discharges can be the source of major pollution affecting groundwater and surface water. Rainwater or wastewater can percolate through mine tailings, carrying with it soluble or particulate elements. These percolating solutions, known as leachates, are the vectors of pollutants to groundwater. The aim of this study is to evaluate the behavior of Sabodala mine tailings in Mini-Cell Alteration (MCA) in order to determine their potential impact on the environment. A mineralogical and physico-chemical characterization of the initial tailings was first undertaken. The tailings were then subjected to kinetic testing in Mini-Cells of Alteration (MCA). Mineralogical analysis by X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) show that the tailings consist of calcite ($CaCO_3$), ferrodolomite ($CaMg_{0.6}Fe_{0.4}(CO_3)_2$), quartz ($SiO_2$), albite ($NaAlSi_3O_8$), muscovite ($KAl_3Si_3O_{10}(OH)_2$) and chlorite ($(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8$). Tailings contain high levels of arsenic, antimony, cadmium and nickel. Results of Mini-Cell Alteration (MCA) tests have shown that the tailings are not acid-generating. Electrical conductivity (E.C.), sulfate and calcium levels decrease rapidly over time to very low levels. Toxic trace metals such as arsenic, antimony, nickel and cadmium can be considered as low leachables.

1. Introduction

Managing mine waste is one of the challenges facing the mining industry. Proper management is required to minimize the environmental impact of these discharges. One of the challenges for a mine is integrated waste management to avoid environmental consequences such as the production of acid mine drainage (AMD), contaminated neutral drainage (CND) and metal leaching (Mend 2004; Stantec Consulting 2004; Bussière *et al.*, 2005; Bussière *et al.*, 2007). When exposed to atmospheric conditions (air and water), the sulfides contained in the tailings can oxidize and produce acid mine drainage (AMD) or contaminated neutral drainage (CND). Several leaching tests have been proposed to predict the generation of AMD, CND or the release of metals into the environment. Batch or Mini-Cell

Alteration (MCA) leaching tests are used to predict the hydrogeochemical behavior of mine tailings (Benzaazoua *et al.*, 2004; Coussy *et al.*, 2012; Othmani *et al.*, 2013; Plante *et al.*, 2015) and enable tailings disposal planning. Kinetic tests are used to assess the behavior of a material under environmental conditions. The MCA are used to simulate accelerated or natural oxidation of mine tailings under controlled conditions (Bassolé, 2016; Pérez-López et al., 2007). MCA tests have been used to predict Contaminated Neutral Drainage (CND) or Acid Mine Drainage (AMD). The work of Plante *et al.* (2011) on waste rock from a Fe-Ti mine (Rio Tinto, Canada) has enabled the CND of waste rock to be predicted using CAM. Those of Chopard *et al.* (2015) enable the prediction of the AMD of various sulfide minerals and sulfosalts often encountered in mine waste. Hakkou *et al.*, (2008) also used the method to show the DMA potential and estimate the mineral reaction rates of fine and coarse tailings from the abandoned pyrrhotite mine (Kettara site, Morocco). In the case of predicting the geochemical behavior of waste rock and assessing the factors controlling the mobility of trace metal elements, Edahbi *et al.* (2018) (Kipawa project, Canada) used CAM. These MCA tests of mining discharges enable us to study the release of trace metal elements (TMEs) into groundwater, the variation in physico-chemical parameters (pH, redox potential, electrical conductivity, sulfates and salinity). Removal of metals from waters was largely studied and numerous methods were proposed (Fathy *et al*., 2025; Oladimeji *et al*., 2024; Errich *et al*., 2021). The objective of this study is to evaluate the release of contaminants from mine tailings by performing ACM leach tests. Tailings from the Sabodala mine, the subject of this study, are transported in pulp form to a so-called tailings impoundment, where they are confined by topography and watertight dikes. These discharges are likely to contain trace metals (TMEs) such as arsenic, antimony, nickel and cadmium. These contaminants are toxic, sometimes at very low levels (Lutandula *et al.*, 2013). Environmental characterization as envisaged in this work will focus on the application of kinetic tests in MCA to analyze the physico-chemical parameters of leachates (pH, ROP, C.E, sulfates) and the levels of mobilized TMEs.

2. Methodology

2.1. Material

The Sabodala mine is located in south-eastern Senegal, about 700 km from Dakar. In particular, it is located about 110 km north of the town of Kedougou, in the Saraya department. The tailings sampling mission took place on 2024-02-18. The tailings in the tailings pond consist mainly of fine, unconsolidated materials that are easily erodible and have a variety of colorations. We took a 0.5 to 1 kg sample using a shovel. The sample was placed in a clean plastic bag to avoid contamination. The sample was ground with an agate mortar and sieved with a < 63µm mesh sieve. The fine fraction recovered is used for MCA testing.

2.2. Environmental characterization tests

Mini-Cell Alteration tests are based on a methodology developed by Cruz *et al.* (2001), modified by Villeneuve (2004). The interest of the MCA leaching test lies in assessing the reactivity of a sample by accelerating weathering processes (Hakkou *et al.*, 2008) through wetting-drying cycles. The first test, known as the control test, involves placing 100 g of mining residue on 1.2 µm filter paper in a Büchner with an internal diameter of 9 cm. The Büchner surmounts a 250 ml vacuum Erlenmeyer flask to recover the leaching water, as shown in **Figure 1**. Samples were subjected to leaching cycles of two rinses per week with 100 ml deionized water. Contact of the rinse water with each sample lasted approximately 3-4 hours before recovery. After each rinse, the samples were left in the open air for two to three days. The physico-chemical parameters of the leachates were measured using a multi-parameter instrument from Eutech instruments / Thermo Scientific. Sulfates were analyzed using a Hach DR3600 spectrophotometer. Trace metals were analyzed by ICP-OES at SGS Mali.

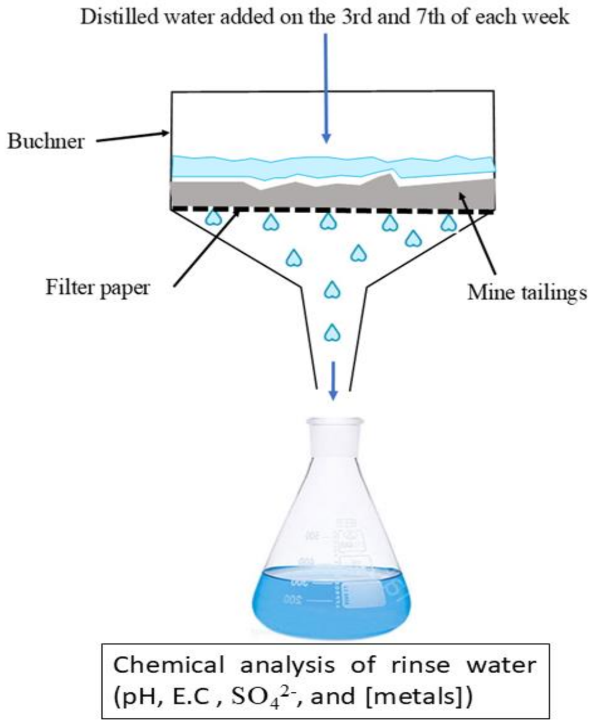

Figure 1: Schematic diagram summarizing Mini-Cell Alteration tests (Bussière *et al*., 2005, adapted from Cruz *et al*., 2001)

3. Results and Discussion

3.1. Physicochemical and mineralogical characterization

The mine tailings diffractometer is shown in Figure 2. The results of the X-ray diffraction semi-quantification showed that the tailings are mainly composed of carbonate minerals and silicates (Table 1). Carbonates include calcite, $CaCO_3$, and ferrodolomite, $CaMg_{0.6}Fe_{0.4}(CO_3)_2$. Quartz ($SiO_2$), albite ($NaAlSi_3O_8$), muscovite ($KAl_3Si_3O_{10}(OH)_2$) and chlorite $(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8$) form the silicates.

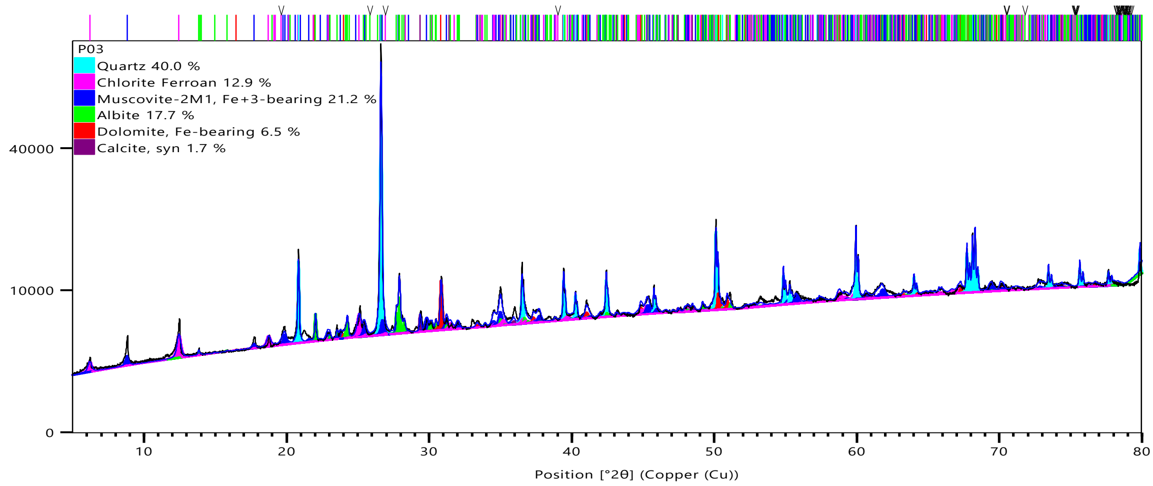

Figure 2: XRD spectrum of mine tailings

Table 1: Mineralogical data of mine tailings by x-ray diffraction with semi-quantification using the Rietveld method

Mineral names		Content (%)	Chemical formula
Silicates	Muscovite	21,2	$KAl_3Si_3O_{10}(OH)_2$
	Albite	17,7	$Na_{0.98}Ca_{0.02}Al_{1.02}Si_{2.98}O_8$
	Chlorite	12,9	$(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8$
	Quartz	40,0	SiO_2
Carbonates	Ferrodolomite	6,5	$CaMg_{0.6}Fe_{0.4}(CO_3)_2$
	Calcite	1,7	$CaCO_3$

Scanning electron microscopy (figure 3) of the fresh mine tailings confirmed the presence of carbonates such as calcite, $CaCO_3$, and ferrodolomite, $CaMg_{0.6}Fe_{0.4}(CO_3)_2$. Elemental analysis by EDS also revealed silicates such as quartz (SiO_2), albite ($NaAlSi_3O_8$), muscovite ($KAl_3Si_3O_{10}(OH)_2$) and chlorite $(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8$.

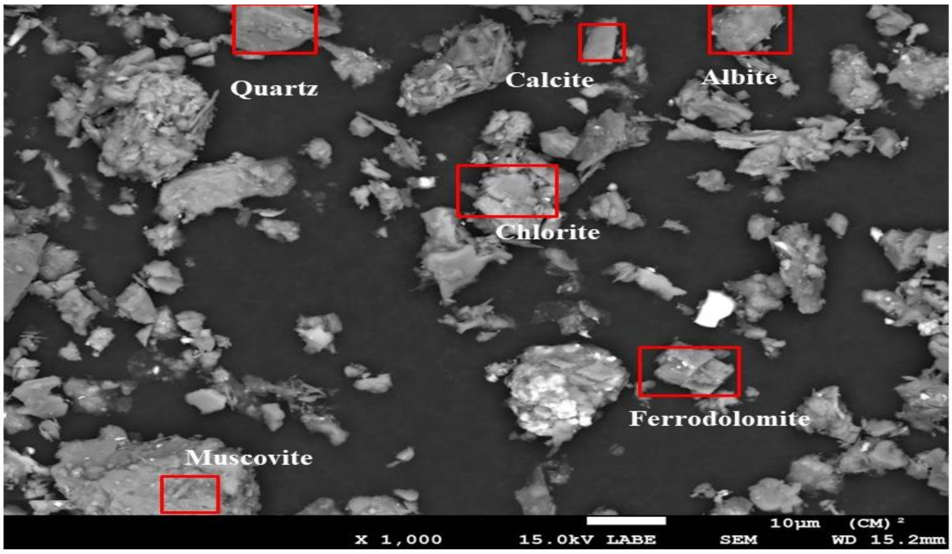

Figure 3: Electronic image Various carbonates (calcite, dolomite) and silicates (quartz, muscovite, albite and chlorite) found in Sabodala mine tailings.

The masses of arsenic, cadmium, nickel and antimony analyzed by ICP-OES in the tailings are 420.16, 5.41 55.33 and 70.72ppm respectively.

3.2. Leaching tests

The results of analyses of tailings leachates during one-month ACM leaching tests are presented in Table 2. The following parameters were analyzed: pH, Eh, conductivity, sulfates, hardness and trace metals (As, Sb, Ni, Cd).

Table 2: Results for physico-chemical parameters (pH, C.E and sulfates) for leachates

Number days	pH	E.C (µs/cm)	Sulfates (mg/l)
0	7.16	8750	4600
3	6.93	2230	1054
7	7.09	1080	471
13	7.25	810	843
17	7.21	1670	439
20	7.63	1150	318
24	7.19	600	106
27	7.31	330	38
30	6.73	120	19
34	6.88	190	10

3.2.1. Variation of leachate pH with time

Figure 4 shows the evolution of pH as a function of time in ACM leachates from mine tailings. Leachate pH varies little overall, hovering around neutrality, i.e. 6.88 to 7.6. This alkalinity is caused by the dissolution of neutralizing minerals such as carbonates and silicates. Mineral neutralization reactions are described below (Hedin *et al*., 1994).

- ✓ $2\ CaCO_3 + H_2SO_4 \rightarrow 2\ Ca^{2+} + 2\ HCO_3^- + SO_4^{2-}$
- ✓ $CaMg(CO_3)_2 + H_2SO_4 \rightarrow Ca^{2+} + Mg^{2+} + 2HCO_3^- + SO_4^{2-}$

These include iron, aluminum and silicate oxides, oxyhydroxides and hydroxides (Lawrence *et al*., 1997; Dutrizac *et al*., 2007). The latter family includes muscovite and chlorite, minerals found in significant proportions in the residues studied.

- ✓ $(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8 + 8H_2SO_4 \rightarrow 5\ Mg^{2+} + Fe^{3+} + Al^{3+} + 3\ SiO_2 + 8\ SO_4^{2-} + 12H_2O$

Analysis of the data set shows that the discharges studied from the Sabodala mine are classified as non-acid mine drainage generators like those from the Sidi Bou Othmane mine (Morocco) (Goumih *et al*., 2012).

3.2.2. Variation in leachate electrical conductivity as a function of time

Figure 5 shows that the ions contained in the residues become mobile after the first watering, but by the second watering there is little ion mobility. The electrical conductivity of the first leachate is 8750 µS/cm. This value decreases very rapidly, reaching a pseudo-stationary state after 6 leaching cycles.

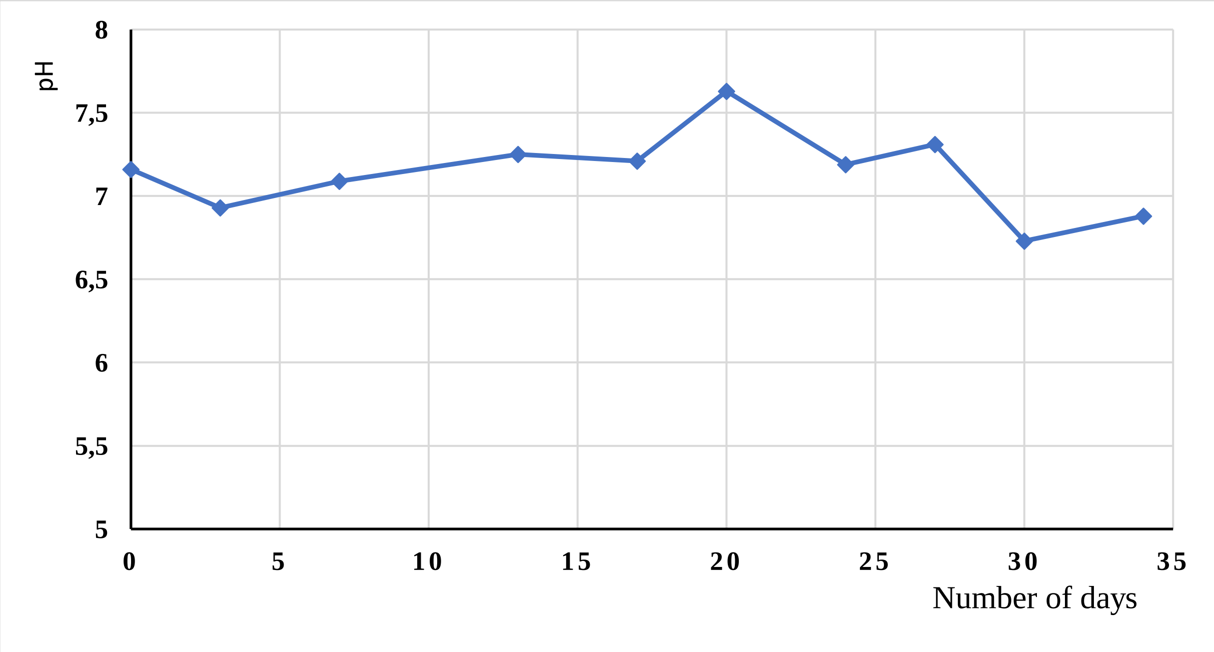

Figure 4: Evolution of pH values of leachates recovered from the MCA as a function of time

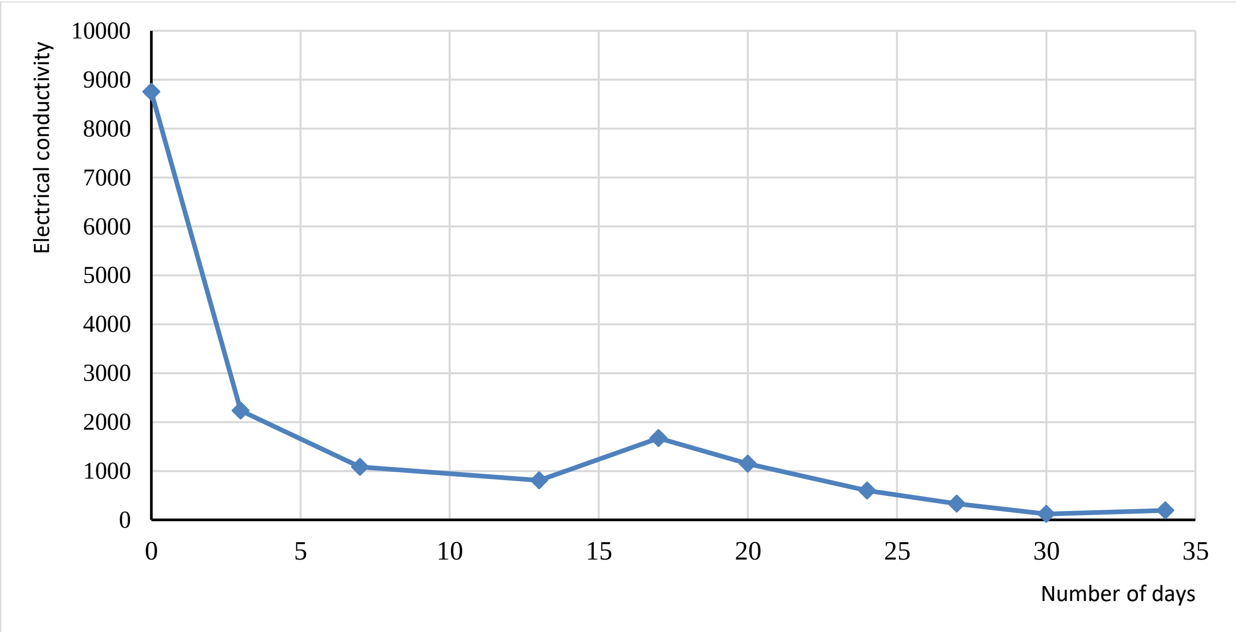

Figure 5: Evolution of leachate electrical conductivities as a function of time

3.2.3. Variation of sulfate content in leachate as a function of time

At the first watering, the sulfate content in the leachate is 4600 mg/L. It decreases to 1054 mg/l in the second leaching cycle, and continues on this trend until 10 mg/l in the tenth leaching cycle. Sulfate levels in the fresh residue are higher than in the old residue. This is due to pre-oxidation of sulfides in the tailings, as explained by Mayer *et al.* (2002). It's interesting to note that pre-oxidation of a grain can modifies the reactivity of sulfides, so the contact between our samples and water plus oxygen enabled the oxidized surface part of the particles to be removed, taking 20 days to arrive at the unoxidized core of the mineral (sulfide passivation).

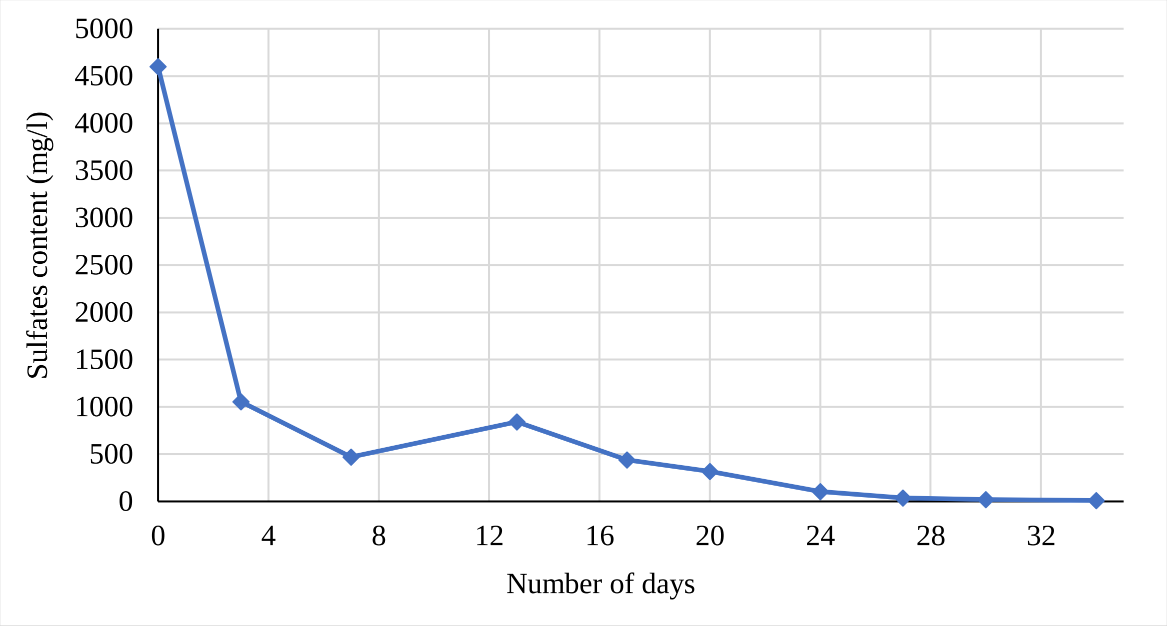

Figure 6: Changes in sulfate levels in ACM leachates as a function of time

3.2.4. Variation in TME content (As, Sb, Cd and Ni) in leachates as a function of time

Chemical analysis of trace metals (As, Cd, Ni and Sb) in leached tailings is presented in the following Table 3. Figure 7 shows the cumulative quantity of arsenic as a function of time. Arsenic release is low. Indeed, the cumulative mass of arsenic in the fresh residue leachate is 0.054.

Table 3: Results for metals (As, Sb, Cd and Ni) in tailings leachates

Number of days	Cumulative As mass leached (mg)	Cumulative Cd mass leached (mg)	Cumulative Ni mass leached (mg)	Cumulative Sb mass leached (mg)
0	0.018	0.0002	0.038	0.009
3	0.026	0.0002	0.038	0.014
7	0.034	0.0002	0.038	0.020
13	0.043	0.0002	0.038	0.029
17	0.048	0.0002	0.038	0.035
20	0.050	0.0002	0.038	0.041
24	0.053	0.0002	0.038	0.041
27	0.054	0.0002	0.038	0.041
30	0.054	0.0002	0.038	0.041
34	0.054	0.0002	0.038	0.041

For antimony, the cumulative mass during leaching is 0.041 mg, i.e. a total leached content of 0.0041 mg/l. For cadmium and nickel, the cumulative masses released are very low. Trace metal leaching percentages are 0.13, 0.037, 0.69 and 0.52 for arsenic, cadmium, nickel and antimony respectively. This low leaching of trace metals is linked to the buffering capacity of carbonates (dolomite and calcite), which precipitate metals. Trace metals known to be toxic, such as arsenic, antimony, nickel and cadmium, can be considered as non-leachable elements, so groundwater presents a low risk of heavy metal contamination. This result is a good indicator for groundwater protection.

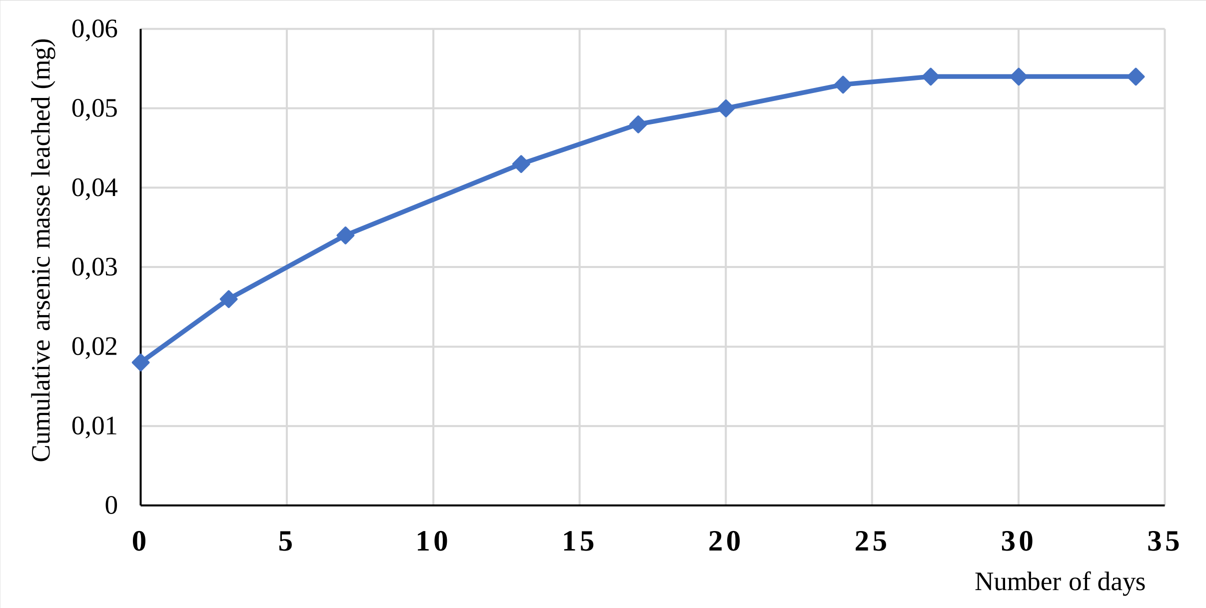

Figure 7: Cumulative leached mass of arsenic in leachates

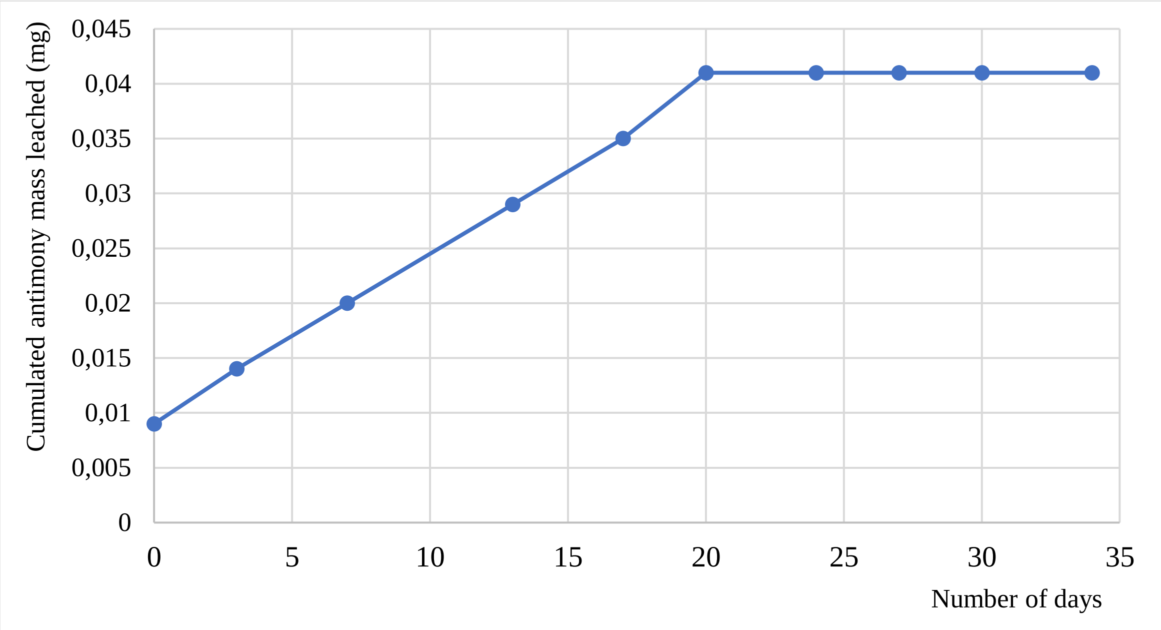

Figure 8: Cumulative mass of antimony in ACM residue leaching tests

Table 4: Leaching rates for trace metals

	As	Cd	Ni	Sb
Total mass (mg)	42.01	0.54	5.53	7.84
Cumulative leached mass (mg)	0.054	0.0002	0.038	0.041
Leaching percentage (%)	0.13	0.037	0.69	0.52

Conclusion

Detailed characterization of the Sabodala mine tailings was carried out in order to better explain their geochemical behavior during kinetic testing. Mineralogical characterization shows that the tailings are composed of silicates and carbonates and trace metals. Carbonates include calcite ($CaCO_3$) and ferrodolomite $CaMg_{0.6}Fe_{0.4}(CO_3)_2$. Quartz ($SiO_2$), albite ($NaAlSi_3O_8$), muscovite ($KAl_3Si_3O_{10}(OH)_2$) and chlorite $(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8$) form the silicates. The leachates obtained over the entire duration of the MCA test show neutral pH values, loaded with ions such as sulfates, and low levels of trace metals. The discharges studied from the Sabodala mine do not generate Acid Mine Drainage, and have a low potential for the release of trace metals (As, Ni, Sb and Cd), which are considered toxic. Groundwater presents a low risk of contamination.

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