Advancing Sustainable Tailing Management: A Comprehensive Approach to the Geochemical Characterization of Iron Ore Tailing in Dry Stacks

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Abstract

Tailings dam failures in Brazil in 2015 and 2019 highlighted the critical need for safer and more sustainable tailings management practices in iron ore mining. In response, the Global Industry Standard on Tailings Management (GISTM) was established to promote best practices for ensuring the safety and integrity of tailings disposal structures. Among the innovative approaches, dry stacking has emerged as a viable alternative to conventional tailings dams, minimizing water retention within tailings and significantly reducing hydraulic risks.

This paper presents a detailed protocol for the chemical, mineralogical, and hydrogeochemical modeling—both conceptual and numerical—of iron ore beneficiation waste. Developed for one of Brazil's pioneering dry stacking facilities, implemented following the 2015 dam failure, the protocol facilitates continuous assessment of waste chemical stability. It integrates hydrochemical analyses and monitors reagents used during beneficiation processes. The systematic hydrogeochemical model consolidates data on fluid percolation and movement, encompassing geotechnical, hydrogeological, and hydrochemical factors alongside the physicochemical and mineralogical properties of the materials involved.

Three key conditions influencing the structure were identified: (1) seasonal water-level fluctuations impacting geochemical conditions, (2) the degradation of ether-amines—reagents used in the beneficiation process—altering redox environments within the structure, and (3) potential for chemical clogging in the dry stack's bottom drains. Successfully conceived and implemented, the protocol has proven effective in assessing the chemical stability of tailings, offering a comprehensive methodology for hydrochemical analysis of effluents and industrial waters while monitoring of organic reagents used in mineral processing. Results demonstrate compliance with international standards and best industry practices, reinforcing the commitment to sustainable and safe mining operations.

Keywords: Tailings, Management, Iron Ore Processing, Dam Failure, Geochemistry Characterization, Hydrogeochemical Modeling

Introduction

The Global Industry Standard on Tailings Management (GISTM, 2020) promotes best practices for tailings facility safety and environmental protection. Principle 2 emphasizes building an integrated knowledge base to support safe management throughout a facility's lifecycle, including closure. In Brazil, regulatory requirements from the National Mining Agency (ANM) have driven the adoption of innovative disposal methods, such as co-disposal in dry-stacked facilities.

While traditional research on metal leaching has focused on sulfide-rich tailings (AMIRA 2002; INAP 2009; MEND/CANMET 2009), advancements like dry stacking require new methodologies, particularly for iron ore tailings with low sulfide content. This study examines the Alegria Sul dry stack at the Germano Complex, developed after the 2015 dam failure. It establishes an approach for assessing contaminant leaching through data collection, statistical analysis, and hydrogeochemical modeling. Hydraulic and geotechnical properties, along with piezometric monitoring, were used to identify oxidizing and reducing zones affecting iron and manganese mobility. Without experimental simulations, geochemical modeling played a key role in predicting system interactions, supporting sustainable tailings management.

Geological and Climatic Setting of the Germano Complex

The Quadrilátero Ferrífero (QF) in southeastern Brazil, part of the São Francisco Craton, is a major metallogenic province composed of Archean to Paleoproterozoic rocks (Chemale and Rosière 1993; Alkmin and Marshak, 1998; Cutts *et al.* 2019). The Minas Supergroup, particularly the Itabira Group and its Cauê Formation, hosts Lake Superior-type banded iron formations (BIFs) rich in oxides (Biondi 2003). These formations originated from mid-ocean ridge exhalations and were later enriched through tectono-metamorphic events and supergene processes during the Cenozoic (Costa *et al.* 1998). The resulting itabirites underwent quartz dissolution and leaching, concentrating iron and increasing material friability. Due to natural leaching, reactive minerals like carbonates and sulfides were largely removed, leaving resistant minerals such as quartz and hematite in the Cauê Formation. For this reason, these minerals do not have relevant concentrations in the rock's composition from Caue Formation (and consequently, in the waste).

The region of the Germano Complex in Samarco experiences two well-defined seasons: a rainy season from October to March, and a dry season from April to September. The wettest period occurs from November to January, which together account for nearly 55% of the total annual precipitation. December is the month with the highest rainfall, with an average monthly precipitation of approximately 400 mm. The average annual precipitation in the Germano Mine area is approximately 1950 mm. Regarding temperature, the area experiences a tropical climate with an average annual temperature of approximately 23°C. During the rainy season (October to March), the average temperature is around 24°C, while in the dry season (April to September), the average temperature drops slightly to around 22°C.

Geochemical Assessment of Germano Complex Tailings in Accordance with GISTM

The Germano Complex, with an annual production capacity of 33 million tons of iron ore, employs a beneficiation process that includes comminution, desliming, flotation, and thickening. Desliming removes particles smaller than 10 µm, which are deposited in a mined-out pit, while larger particles undergo flotation for silica removal. Filtered tailings are thickened and deposited as a dry-stacked cake, enhancing geotechnical safety and environmental compliance in line with the GISTM. Key reagents used in beneficiation include starch, caustic soda, amines, coagulants, and flocculants, which influence flotation, dispersion, and thickening. The residual water in tailings provides critical data for assessing hydrochemical quality in bottom drains.

The protocol for characterizing shared waste rock, drained tailings, and cake samples at the Germano Complex involved extensive data collection and analysis to support conceptual and numerical modeling. Key data included beneficiation inputs, geological models, and climate records, along with solid material and hydrochemical monitoring plans. Sampling methods used representative grids, trenching for drained tailings, and drill core analysis for waste rock. Hydrochemical monitoring tracked effluents and inputs to ensure compliance with Brazilian Environmental Standards.

Chemical and mineralogical characterization was performed by an ISO/IEC 17025 certified laboratory using techniques like XRF, ICP-OES, XRD, and MLA. These methods provided detailed insights into mineral composition and geochemical processes. Statistical data treatment ensured accuracy, and MLA offered microscopic analysis of processed materials.

Geochemical characterization and numerical modeling integrated piezometric, hydraulic, and geotechnical data to predict iron and manganese mobilization. PHREEQC Interactive was used to model the chemical and mineralogical analysis of dry stack materials, filtration residues, and monitoring data, providing insights into water percolation and geochemical interactions. The potential for chemical clogging in the internal drainage system was assessed by evaluating drain geometry, porosity, and flow dynamics.

Hydrogeochemical Model

The hydrogeochemical conceptual model for the Alegria Sul dry stack integrates geotechnical, hydrogeological, hydrological, and geochemical data to understand fluid dynamics and redox processes within the structure. Drained tailings (sandy tailings) and waste rock materials (waste rock belt) deposited in the structure are moistened using sprinklers operated by water trucks to achieve optimal compaction according to geotechnical requirements.

Water outflows from the dry stack consist of drainage through drains located at the bottom of the structure (Fig. 1). The drainage system includes nine drains, classified into shallow (4) and deep (5). After percolating through the sandy tailings, water exits the structure via shallow drains. Piezometric data did not indicate a significant hydraulic connection between the deep and shallow drains. Based on this, it is inferred that the effluent percolating through the waste rock is predominantly captured by the shallow drains. A possible explanation for this behavior is the presence of a leveling platform between the drainage layers, whose low hydraulic conductivity limits the infiltration of percolated effluents towards the deep drains. Thus, the deep drains appear to primarily function in draining water from buried springs formed during the construction of the waste pile, rather than capturing significant volumes of percolated effluent.

The dry stack's predominantly unsaturated structure creates non-reducing conditions in its upper and intermediate layers, while the basal sections occasionally transition to saturation, fostering reducing conditions. Redox variations along the structure influence the transport of gases like O_2 and CO_2, driving mineral dissolution and precipitation processes. These dynamics are closely tied to factors such as groundwater level fluctuations, organic matter oxidation, and the degradation of nitrogenous compounds, which shape the system's geochemical behavior.

Specific conditions, such as organic matter burial and deep drainage points, contribute to localized reducing zones within the dry stack. The oxidation of buried organic material and amines, along with oxygen depletion, supports the mobilization of metals like iron and manganese. Hydrochemical analyses of drainage flows reveal redox-related transformations, especially between shallow and deep drainage systems. The results highlight the progressive depletion of oxygen with depth, along with changes in dissolved species concentrations. For instance, Fe^{2+}-rich solutions from deeper layers may precipitate iron oxides upon exposure to atmospheric conditions at surface drains. It is important to note that the chemistry of rainfall was not considered in the geochemical model. Instead, a more conservative scenario was adopted, using water from water trucks, which presents more saturated concentrations compared to rainfall.

The methodology adopted in this study involved geochemical modeling using the PHREEQC software (version 3; Parkhurst and Appelo, 2013) to evaluate the saturation of different mineral phases in relation to the hydrochemical conditions. The main minerals in the solid matrix and the geochemical processes influencing their dissolution and precipitation were considered.

The numerical model was structured to represent, in a one-dimensional approach, the reactive transport of water and solutes within the waste matrix. The model was based on discretizing the waste pile into cells, allowing the simulation of compositional evolution along depth. Water flow was modeled using Darcy's equation for saturated media and the van Genuchten formulation for the unsaturated zone. Solute transport was described through advection and dispersion processes, while chemical reactions were incorporated through thermodynamic equilibria and kinetic processes.

The residence time of the solution in the pile was estimated using the cross-correlation function (Padilla and Pulido-Bosch, 1995; Warner, 1998, which analyzes the relationship between the precipitation and drain flow time series from August 2023 to May 2024. The cross-correlation identifies the time lag and the intensity of the relationship between the phenomena, with statistical analysis using a p-value ≤ 0.05 to determine significance.

Hydrochemical data defined the initial conditions of aqueous solutions and parameterized the model, considering the concentrations of major and trace elements. The modeling enabled the calculation of mineral saturation indices, identifying phases that tend to remain stable, dissolve, or precipitate under the evaluated conditions. The analyzed mineral phases included carbonates, sulfates, oxides, and silicates, considering their influence on chemical equilibrium. The evaluation of saturation indices was essential for understanding the mobility of elements and the geochemical evolution of the system. Additionally, the modeling incorporated the biodegradation of organic compounds using the R-Monod kinetics, describing substrate consumption as a function of nutrient availability and microbial activity. Monitoring at Alegria Sul confirmed ammoniacal nitrogen levels remained within regulatory limits. Research by Chaves (2001) observed a decline from 31.7 mg/L to 4.7 mg/L in Samarco flotation tailings over 12 days.

The model was iteratively adjusted to represent the interaction between water and minerals, predicting the chemical composition evolution of the solution over time and under different scenarios. The results provide support for interpreting the processes controlling water quality and trends in mineral precipitation and dissolution.

Results and Discussion

The chemical and mineralogical characterization of the Alegria Sul dry stack tailings and waste rock shows a predominantly inert composition with low environmental risk. The primary components include quartz and iron oxides (hematite, goethite, and magnetite), with minimal concentrations of

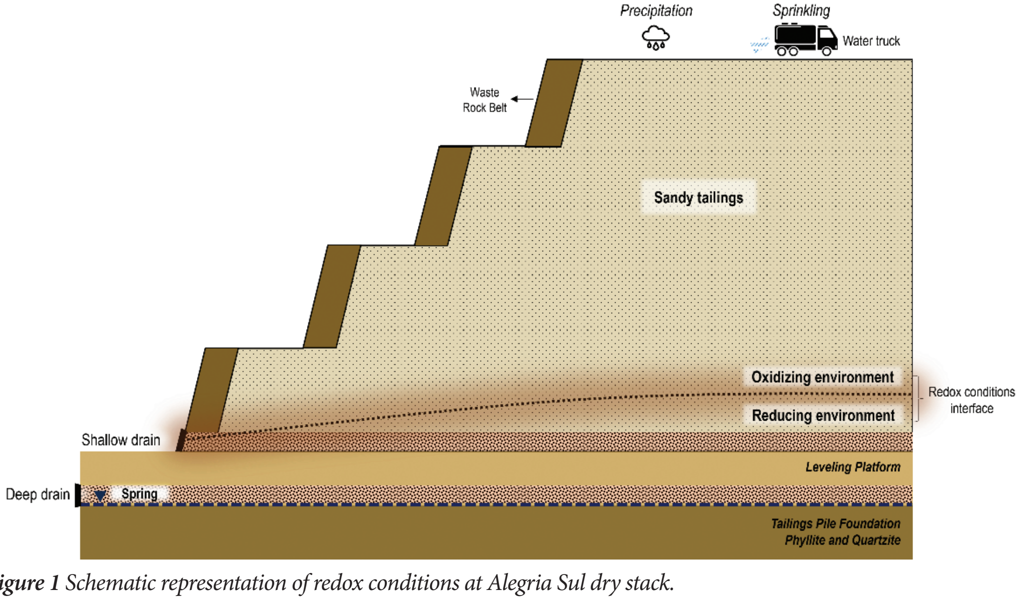

***Figure 1** Schematic representation of redox conditions at Alegria Sul dry stack.*

trace elements like arsenic, cadmium, and lead. The absence of sulfide minerals and low sulfur content indicate stability under oxidizing conditions, suggesting limited potential for acid mine drainage or pollutant release.

Hydrochemical monitoring reveals distinct chemical profiles in input (water truck) and output (drains) phases, with alkaline water truck solutions and mild acidity in deep drains. Shifts in redox conditions with depth affect dissolved iron and manganese concentrations. The degradation of organic compounds from beneficiation reagents influences these dynamics, including the destabilization of hematite under reducing conditions, releasing soluble iron.

The numerical hydrogeochemical model simulates solute transport and the degradation of ether-amines used in flotation, revealing ammonia release and stabilization. It incorporates various mineral phases, such as quartz and iron oxides, into simulations. The model also assesses transport dynamics and the residence time of solutions within the dry stack, identifying significant correlations between precipitation and drainage responses. The results indicate that at least 70% of the flow peaks in the drains are influenced by precipitation, with response times ranging from 3.5 to 5 months. Some drains show greater sensitivity, with flow increasing within 45 days after the onset of rain, peaking at 100–150 days. Other drains take 60 to 90 days to respond to precipitation. The correlation between precipitation and flow is approximately 72%, indicating a response that has not yet fully developed at these points. The analysis suggests that the correlation between the phenomena is robust, with at least 70% significant correlation.

The model further evaluates the potential for chemical clogging in the drains, predicting minimal clogging over 100 years due to $Fe(OH)_3$ precipitation. However, since most precipitation occurs outside the system, the effect on drainage efficiency is limited. Overall, the results demonstrate the environmental viability of the dry stack system and the stability of the geochemical processes within the site.

This table presents the chemical composition of different water sources in the Alegria Sul dry stack. The "Water Truck" column shows the median concentrations of water sprayed by trucks, monitored over 18 months. Q1 and Q3 represent the median concentrations within the interquartile range for shallow drains. The last two columns, "Drain Outflow" and "Equilibrium with Atmosphere", present the calibrated effluent concentrations at the drain outflow and after exposure to the atmosphere, respectively.

Conclusions

This study presents an interdisciplinary approach to address environmental

Table 1 Calibrated Water Chemistry Data for the Alegria Sul Dry Stack.

Parameters	Water Truck (median)	Q1 (Shallow Drains)	Q3 (Shallow Drains)	Drain Outflow	Equilibrium with Atmosphere
Temperature (°C)	21.90	23.20	25.20	21.90	21.90
pH	8.36	6.98	7.65	7.46	7.46
pe	6.60	2.30	6.30	-4.90	2.30
Al (mg/L)	0.10	0.01	0.04	0.10	0.10
Alkalinity (mg/L)	4.80	113.30	269.10	37.20	6.30
Ca (mg/L)	1.50	2.11	67.75	1.50	1.50
Cl (mg/L)	0.50	0.50	0.50	0.50	0.50
Fe (mg/L)	0.13	0.03	1.83	5.55	0.13
K (mg/L)	0.29	4.10	5.00	0.29	0.29
Mg (mg/L)	0.18	2.40	7.62	0.18	0.18
Mn (mg/L)	0.02	0.11	0.34	0.28	0.28
Na (mg/L)	1.40	36.00	110.50	1.40	1.40
NH_3/NH_4^+ (mg/L)	0.21	3.34	5.71	5.92	0.00

complexities in tailings management, integrating geochemistry, geotechnics, hydrogeology, geometallurgy, mine planning, and ore beneficiation. Hydrogeochemical modelling was employed to simulate interactions between sprinkler truck water and sandy tailings in the Alegria Sul dry stack, focusing on ether-amine degradation (used in Samarco's iron ore beneficiation) and mineral dissolution. Key findings included:

- Sandy tailings are predominantly quartz (≈89%), iron oxides (≈10%), silicates (≈0.7%), and trace minerals (≈0.7%), with short water residence times (100–150 days) limiting silicate dissolution.
- Ether-amine degradation is influenced by chemical structure, environmental conditions (e.g., pH, oxygen, nutrients), and microbial activity, producing organic carbon and ammoniacal nitrogen.
- Rapid degradation under reducing conditions destabilized hematite, releasing iron, while oxidizing conditions favored $Fe(OH)_3$ precipitation and nitrate formation.
- Simulations indicate ether-amines degrade within days and pose negligible environmental risks, with ammoniacal nitrogen concentrations remaining environmentally insignificant.

This methodology demonstrates a robust framework for managing uncertainties and systematically analysing data, aligned with ESG (Environmental, Social, and Governance) principles and Principle 2 of the GISTM to support safe tailings management throughout facility lifecycles.

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