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Construction of the Puma 4 Dike Using Iron-Nickel Slag: Characterization and Geotechnical Performance

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ABSTRACT: The processing of lateritic nickel ores generates large volumes of iron nickel slag, creating environmental and operational challenges related to waste management. The reuse of this by product as construction aggregate represents a sustainable alternative, reducing waste stockpiles and the need for new borrow areas. This study presents the characterization and field application of iron nickel slag from the Onça Puma Unit as rockfill material in a free draining dike. Laboratory tests demonstrated that the slag presents physical, mechanical, chemical and environmental properties comparable to natural aggregates traditionally used in geotechnical works. In 2021, the first free draining dike using iron nickel slag was constructed to retain sediments from the Puma pit area. The reuse of slag reduced construction time, eliminated borrow areas and aggregate procurement, and reduced overall construction costs and stockpiled slag volume. The results confirm the technical feasibility and environmental suitability of ferronickel slag as a sustainable alternative for sediment retention structures, with continuous monitoring recommended to ensure long term performance

KEYWORDS: Slag, dikes, reuse, geotechnics, characterization, sediments.

1 INTRODUCTION

The increasing generation of industrial waste from mining and metallurgical activities poses environmental and economic challenges, particularly regarding the management of ferronickel slag. The reuse of such by products in geotechnical works represents a sustainable alternative capable of reducing environmental impacts and operational costs (SILVA FILHO et al., 2002; ZANIN et al., 2004). In mining regions of northern Brazil, large slag stockpiles reinforce the need for technically sound and environmentally safe reuse strategies.

In this context, the use of ferronickel slag as rockfill material in free draining overtopping dikes emerges as a feasible alternative for sediment retention structures of low to medium height. In 2021, the first dike using iron nickel slag as aggregate was constructed at the Puma Mine to retain sediments from the pit area. The Puma 4 Dike represents a pioneering large scale application of this industrial residue, integrating technical performance, environmental compliance and cost efficiency.

This article presents the characterization of the ferronickel slag used in the Puma 4 Dike, discusses laboratory and field results, and evaluates the geotechnical and environmental performance of the structure, contributing to the advancement of sustainable practices in geotechnical engineering.

2 MATERIALS AND METHODS

The suitability of iron nickel slag for use as rockfill material was evaluated through a comprehensive laboratory testing program combined with design criteria and operational monitoring. Physical, mechanical,

chemical, mineralogical and environmental tests were conducted in accordance with Brazilian and international standards. Table 1 summarizes the laboratory tests performed

Table 1 - Summary of tests performed in the laboratory.

Characterization	Experiments	Standard References
Physical	Particle Size	NBR 7181
	Los Angeles Abrasion	NBR-NM-51
	Specific Gravity, Unconfined Compressive Strength (UCS), Maximum Size Particle Size, Apparent Porosity, Water Absorption	NBR 5564
Environmental	Leaching	NBR 10005
	Solubilization	NBR 10006
Mechanical	Cycling	NBR 12697
Chemical and mineralogical	X-Ray Diffraction, Scanning Electron Microscopy, X-Ray Fluorescence	

Figure 1 presents an overview of the study area, showing the location of the stored material, sampling points and the general appearance of the slag

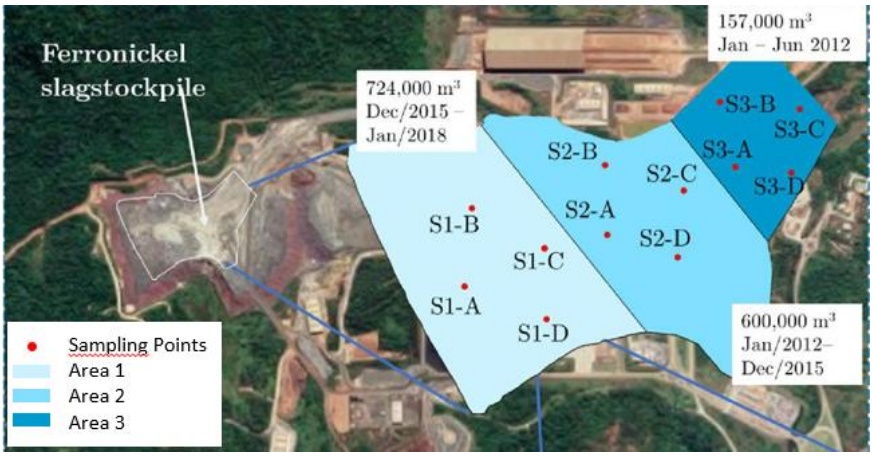


Figure 1: Overview of the study area, sampling points and appearance of the investigated iron-nickel slag.

2.1 Slag Characterization Methods

Granulometric analyses were performed according to ABNT NBR 7181, using sieving for coarse fractions and sedimentation analysis for particles finer than 0.075 mm. From the particle size distribution curves, the parameters Dmax, fineness modulus (Fm), coefficient of uniformity (Cu) and coefficient of curvature (Cc) were determined. Resistance to degradation was evaluated by Los Angeles Abrasion tests following ABNT NBR NM 51.

Environmental characterization included leaching and solubilization tests conducted in accordance with ABNT NBR 10005 and ABNT NBR 10006. Chemical elements were determined by ICP OES, and residue classification followed ABNT NBR 10004. Mechanical durability was assessed through accelerated weathering cycling tests with ethylene glycol, in accordance with ABNT NBR 12697, allowing identification of expansive or degradable minerals.

Chemical composition was determined by wavelength dispersive X ray fluorescence (XRF), while mineralogical characterization was performed by X ray diffraction (XRD). Particle morphology and surface texture were analyzed using scanning electron microscopy (SEM) coupled with EDS.

2.2 Free Draining Dike Design and Monitoring

The free draining dike was designed to retain sediments while allowing controlled water flow, reducing turbidity downstream. Filter and transition layers were designed based on classical retention and permeability criteria, expressed by Equations (1) and (2):

$$\frac{D_{F(15)}}{D_{S(85)}} \leq 4 \; to \; 5 \quad \text{(Equation 1)}$$

$$\frac{D_{F(15)}}{D_{S(15)}} \geq 4 \; to \; 5 \quad \text{(Equation 2)}$$

Where $D_{F(15)}$ is the diameter through which 15% of the filter material will pass, $D_{S(85)}$ represents the diameter through which 85% of the sediment will pass and $D_{S(15)}$ is the diameter through which 15% of the sediment material will pass.

Operational performance was evaluated through environmental monitoring at upstream (ASP 06) and downstream (ASP 80) points, shown in Figure 2. The monitored parameters include True Color, Settleable Solids, Total Dissolved Solids and Turbidity, summarized in Table 2.



Figure 2 – Location of the Puma 4 dike monitoring points.

Table 2 – Analysis parameters of surface water quality.

Bicarbonate Alkalinity	Hexavalent Chromium	DO
Soluble Aluminum	Total Chromium	Oils and Greases
Total Aluminum	BOD	pH (laboratory)
Ammonia	COD	Total Potassium
Total Arsenic	Total Hardness	Total Silver
Total Barium	Soluble Iron	Total Selenium
Total Cadmium	Total Iron	Total Sodium
Total Calcium	Total Magnesium	Total Dissolved Solids
Total Lead	Soluble Manganese	Total Suspended Solids
Chlorides	Total Manganese	Sulfate
Soluble Cobalt	Mercury	Sulfite
Total Cobalt	Soluble Nickel	Turbidity
Total Copper	Total Nickel	Total Zinc
Soluble Copper	Nitrate	-
Electrical Conductivity	Nitrite	-

3 RESULTS AND DISCUSSIONS

This section presents the results related to the characterization of the iron-nickel slag, the design and construction aspects of the free-draining dike, and its operational performance based on environmental monitoring data

3.1 Slag Characterization Results

The particle size distribution curves obtained for the twelve sampling locations are shown in Figure 3, which illustrates both the individual curves and the average granulometric behavior of the iron-nickel slag.

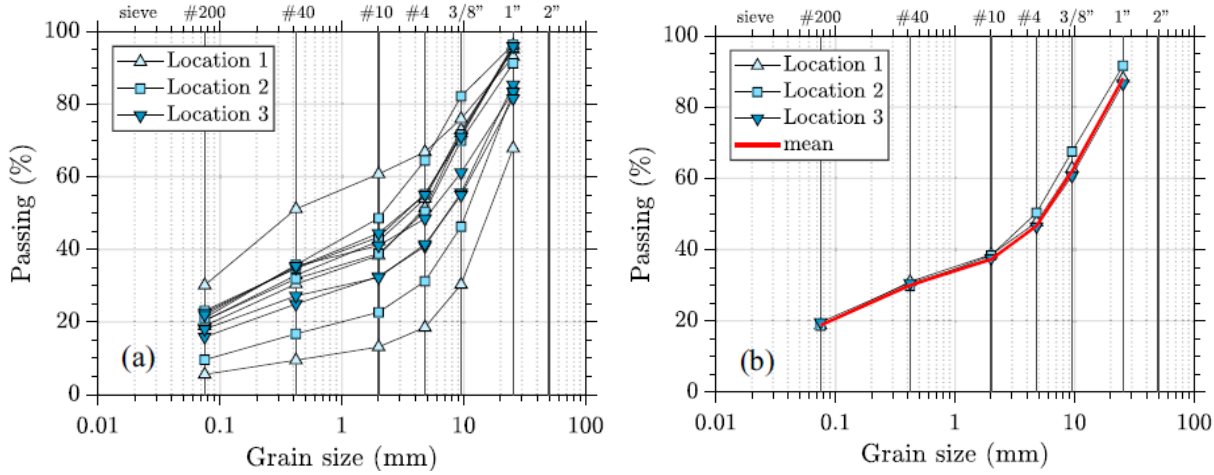


Figure 3 – Particle size distribution curves of iron-nickel slag samples.

The particle sizes range from 0.01 to 37.5 mm, with predominance of gravel and sand fractions. This granulometric composition is favorable for free-draining structures, as it promotes high permeability, mechanical interlocking and reduces the risk of clogging associated with excessive fine content.

Quantitative particle size indexes derived from the granulometric curves are summarized in Table 3.

Table 3 - Summary of particle size indexes of iron-nickel slag samples

Index	S1-A	S1-B	S1-C	S1-D	S2-A	S2-B	S2-C	S2-D	S3-A	S3-B	S3-C	S3-D
D_{max}	25	25	37.5	25	25	25	37.5	25	25	25	25	37.5
C_u	175	192.9	17.2	133.3	257.1	92.5	257.7	148.1	305.6	175	193.8	179.5
C_c	0.9	0.6	5.8	0.2	0.4	34.2	0.5	0.4	0.4	5.1	0.1	3.3
F_m	4.02	3.86	5.33	2.94	3.76	5.25	4.08	3.52	3.78	4.69	4.13	4.77

The Dmax values varied between 25 and 37.5 mm, with average values compatible with the requirements for rockfill and transition layers. The coefficients of uniformity (Cu) and curvature (Cc) indicate a non-uniform material, reflecting the absence of prior crushing or grading processes. Although this results in a wide distribution of particle sizes, it allows selective use of slag fractions for different structural zones of the dike.

Los Angeles Abrasion results remained consistently below 30%, indicating resistance to degradation comparable to natural igneous aggregates such as granite and basalt. Complementary physical properties obtained from the company database include an average specific gravity of 3.3, unconfined compressive strength of 139 MPa, apparent porosity of 3.7% and water absorption of 1.2%, further confirming the mechanical suitability of the iron-nickel slag for use as rockfill material.

Environmental characterization through leaching and solubilization tests generally complied with the limits established by ABNT NBR 10005 and ABNT NBR 10006, classifying most samples as Class II B (non-hazardous and inert). One sample from Area 2 presented elevated iron and surfactant concentrations and was classified as Class II A. Similar behavior has been reported in studies involving crushed slag and is associated with the generation of fine particles during laboratory preparation. Considering that field applications involve coarse material, the reuse of iron-nickel slag in free-draining dikes does not represent a significant environmental concern.

Accelerated cycling tests with ethylene glycol resulted in an average mass variation of only 0.05%, with no evidence of cracking, disintegration or particle degradation. Visual inspection confirmed preservation of particle shape after cycling, indicating the absence of expansive minerals. These results are consistent with the

chemical and mineralogical analyses, which identified low CaO content and predominance of stable silicate phases.

Mineralogical characterization indicated that silicates such as akermanite, albite, olivine and quartz comprise most of the mineral fraction, while oxides and sulfur phases occur as secondary components. Clay minerals were identified in limited samples and in low proportions. X-ray fluorescence analyses showed homogeneous chemical composition across all sampling locations, dominated by SiO_2 (49.1%), MgO (29.1%) and Fe_2O_3 (15.6%).

A comparison between the engineering properties of iron-nickel slag and natural rockfill materials commonly used in free-draining dikes is presented in Table 4

Table 4 - Engineering properties of different rocks used as rockfill materials and iron-nickel slag.

Property	Basalt (a)	Gneiss (b)	Granite (b)	Wethered basal (c)	Basaltc	This Work
Cu	5.1	n.a. (d)	n.a	1.12	1.12	177.3
Cc	n.a	n.a	n.a	2.7	2.7	4.3
Dmax(mm)	76	25-150	25-200	152	152	28
Los Angeles (%)	n.a	57-63	22	n.a	n.a	27
Specif gravity	2.8	2.5	2.6	1.8	1.8	3.3
Water abs. (%)	0.5	0.4-11	0.4	n.a	n.a	1.2
UCS (Mpa)	292	47-57	160-180	238	180	139
Change in mass (%)	n.a	0.03	n.a	n.a	n.a	0.05

Notes: (a) Maia (2001); (b) Basso (2007); (c) Kambole et. Al. (2017); (d) not available

3.2 Free-Draining Dike Design and Construction

Based on the favorable results of the laboratory characterization, iron-nickel slag was selected for use as rockfill and transition material in the Puma 4 Dike. Figure 4 presents the grain size envelopes of the different dike components and a conceptual cross-section of the structure.

The Puma 4 Dike was constructed in 2021, with a total length of 191 m and a height of 12 m. The crest width is 7 m and the toe width approximately 70 m. The structure was designed to retain about 71,000 m³ of sediments from a 413 ha watershed while allowing controlled overtopping during extreme hydrological events.

The main construction stages included foundation cleaning, construction of access embankments, placement of the rockfill and inclined filter layers, and installation of the quarry rock protection layer, as illustrated in Figure 5.

3.3 Operational Performance

Operational performance was evaluated through environmental monitoring conducted between 2023 and 2025 at upstream (ASP 06) and downstream (ASP 80) points, previously presented in Figure 2. The monitored parameters include True Color, Settleable Solids, Total Dissolved Solids and Turbidity, as summarized in Table 5.

The monitoring results indicate effective sediment retention by the Puma 4 Dike. True Color values remained low throughout the monitoring period, with no increase observed downstream (Figure 6).

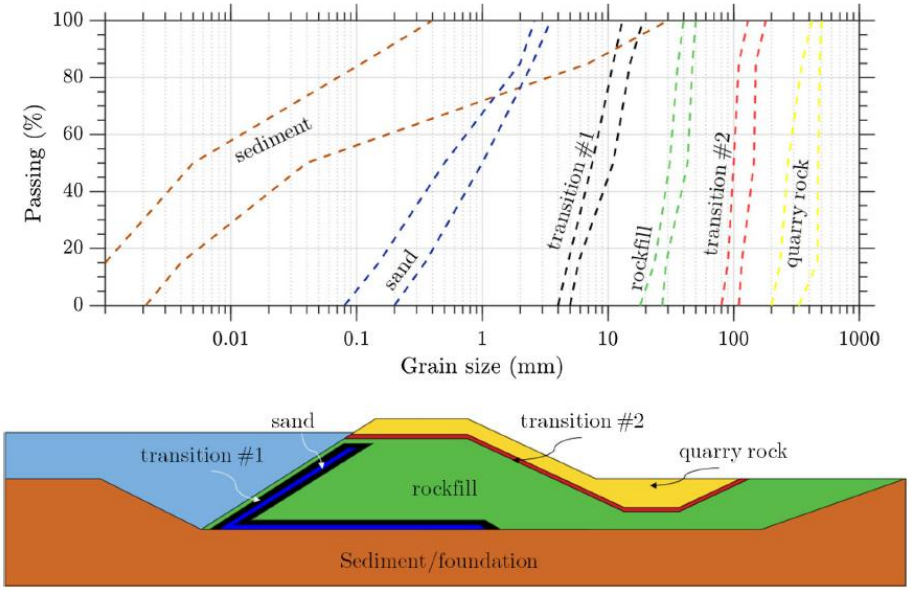


Figure 4 - Grain size curves of different dike materials and a typical cross section of the free draining dike built using iron-nickel slag.



Figure 5 - Construction phases of the free draining dike: foundation cleaning (a); embankment for equipment access (b); rockfill and inclined filter (c); quarry rock protection layer (d); mobile screen plant (e); and aerial view of the finalized free draining dike (f)

Settleable Solids were absent in all monitoring campaigns, indicating no transport of coarse material downstream of the structure.

Total Dissolved Solids (Figure 6) remained low and were generally higher upstream, confirming that the structure does not contribute to chemical enrichment of downstream waters.

Significant reductions in turbidity were observed downstream, with reductions ranging from approximately 37% to 93%, demonstrating the effectiveness of the dike in retaining suspended sediments and maintaining downstream water quality (see Figure 8).

Table 5 – Analysis Parameters for the Effectiveness of the Puma 4 Dike

ASP 06	Limites Resolução CONAMA nº 357/2005 - Classe II	Background		Resultados Analíticos					
PARÂMETROS	**Unidade**	**VMP**	**Chuva**	**Seca**	**26/04/23**	**26/07/24**	**21/01/25**	**25/04/25**	**16/07/25**	**23/10/25**
Cor Verdadeira	mg/L	75	-	-	12	< 4	< 4	5	8	12
Resíduos Sólidos Objetáveis	---	Ausentes	-	-	Ausente	Ausente	Ausente	Ausente	Ausente	Ausente
Sólidos Dissolvidos Totais	mg/L	500	412	286	207	247	211	226	224	260
Turbidez	NTU	100	50	45.26	14.5	1.86	42.4	21.5	1.91	1.55

ASP 80	Limites Resolução CONAMA nº 357/2005 - Classe II	Background		Resultados Analíticos					
PARÂMETROS	**Unidade**	**VMP**	**Chuva**	**Seca**	**27/06/23**	**26/07/24**	**21/01/25**	**25/04/25**	**16/07/25**	**06/10/25**
Cor Verdadeira	mg/L	75	-	-	< 10	< 4	< 4	< 4	6	12
Resíduos Sólidos Objetáveis	---	Ausentes	-	-	Ausentes	Ausente	ausente	Ausente	Ausente	Ausente
Sólidos Dissolvidos Totais	mg/L	500	412	286	190	226	122	172	244	232
Turbidez	NTU	100	50	45.26	37.2	1.17	2.89	1.51	0.86	0.55

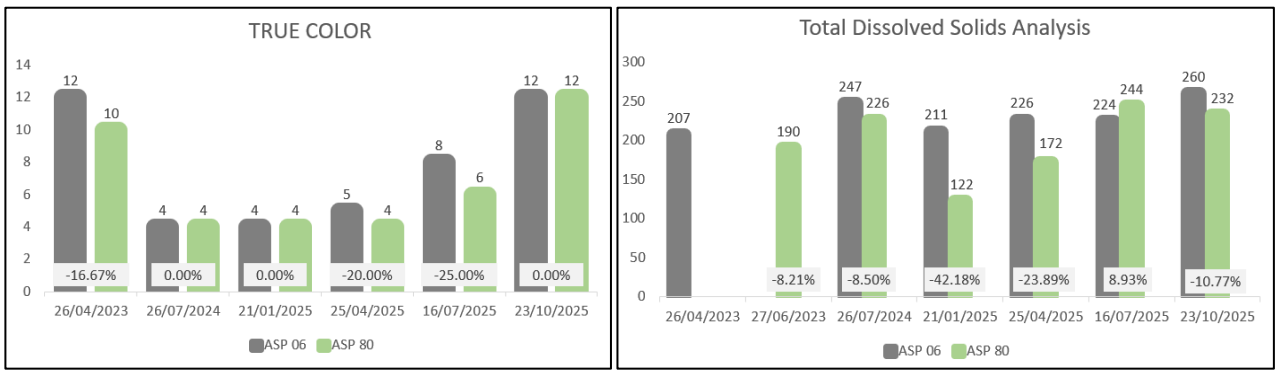


Figure 6 – True color analysis and Total Dissolved Solids Analysis

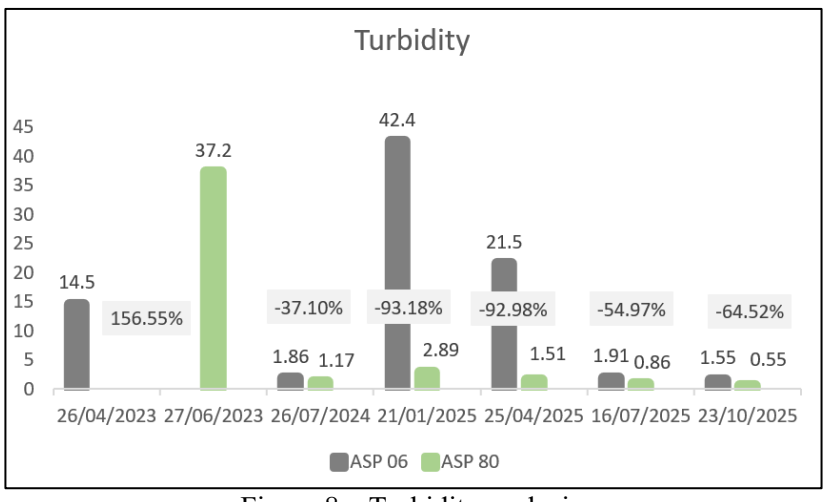


Figure 8 – Turbidity analysis.

4 CONCLUSIONS

Iron-nickel slag proved to be technically feasible and environmentally safe for use as rockfill in free-draining overtopping dikes. The material presents adequate granulometric distribution, abrasion resistance and durability, with environmental behavior compatible with regulatory requirements. The construction and operation of the Puma 4 Dike demonstrated effective sediment retention without adverse effects on downstream water quality. The reuse of ferronickel slag resulted in economic and environmental benefits by reducing construction time, eliminating borrow areas and decreasing stockpiled waste, confirming its suitability as a sustainable alternative material for sediment retention structures in mining environments.

5 ACKNOWLEDGEMENTS

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