Magnetic concentration route for recovering pellet feed fines stored in a mining dam

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Abstract

The greatest and noblest challenge of mining engineering for the present and the future of iron ore treatment could be considered as the pursuit of optimizing the use of mineral resources. The use of mining tailings, in the mineral sector itself, or in another industrial branch, meets the needs of circular economy as it increases the useful service life of this material. In order to investigate this scenario, a technological characterization of a sample from a tailings dam was carried out along with magnetic concentration tests in a Wet High-Intensity Magnetic Separator (WHIMS) to propose a possible concentration route. In relation to the characterization itself, the results demonstrated a relative density of 3.04×10^3 Kg/m^{3}and an average superficial specific area of 3.75 cm^3/g. The granulometric analysis classified the material as fine, with d_{90} of 0.110 mm and $d_{50} \cong 0.049$ mm. Quartz, hematite, goethite, kaolinite and manganese oxide were identified in the sample. The test which presented the best results (66.83% Fe and 1.74% SiO_2) consisted of the Rougher, Cleaner and Recleaner phases, using a 1.5 mm grooved GAP matrix, a 7,000 Gauss magnetic field, 30% solids, and water pressure at 0.5 kgf/cm^2 (49.0×10^3 Pa). Finally, the conclusive results indicate that the studied material can be concentrated through magnetic concentration, keeping in mind the specifications concerning the pellet feed fines commercial product. Besides the financial gain, the activity prolongs the durability of the tailings dam and reduces the environmental impacts associated with these structures.

keywords: sustainable mining, WHIMS, tailings characterization, circular economy.

1. Introduction

One of the great challenges of modern society, which has a wide variety of technological goods, food, access to culture, leisure etc., is the high consumption of raw materials. In order to meet future needs, it is necessary to make better use of our natural resources in different sectors, since society works in an interconnected way; no industrial branch is completely isolated from another (Jones & Boger, 2012; Edraki *et al.*, 2014; Kinnunen & Kaksonen, 2019; Tayebi-Krorami *et al.*,2019).

Regarding this interrelationship, mining is an expressive area in the Brazilian gross domestic product - GDP. The Brazilian National Mining Agency reported that in 2020, the production of metallic substances generated a profit of approximately 129 billion reais. Of this amount, iron ore is the most traded metallic ore in the country (ANM, 2020). However, although it is extremely important for the economy, this activity generates high amounts of tailings. A study by Jones and Boger (2012) claims that the mineral industry is the world's largest producer of waste, producing around 65 billion tons/year, of which 14 billion are tailings made up mostly of fine particles (under 0.150 mm). A survey conducted by Gomes (2017) has shown that, in the year 2014 alone, over 110 million tons of iron ore tailings were stored in tailings dams in the state of Minas Gerais.

These tailings are deposited in piles or tailings dams, whose associated risks were emphasized by the rupture of Vale's Brumadinho dam, in 2019. When it comes to the use of mineral resources, the best way to preserve a non-renewable resource is rational consumption. However, population size and current living standards render the reduction of mineral consumption nearly utopian. That is why the concept of circular mineral economy has been gaining strength as it seeks to maximize the use of mineral resources. While the traditional linear economy is based on the extraction, production, use and disposal of waste; the circular economy proposes to rescue them and keep them in the production chain for as long as possible, even if in another industrial sector (Jones & Boger, 2012; Edraki *et al.*, 2014; Kinnunen & Kaksonen, 2019; Tayebi-Krorami *et al.*, 2019).

The reprocessing of fine ores through reuse is a way of evaluating these materials that are classified as tailings. This reuse is possible through technological characterization, which in turn is an essential step for optimum use of mineral resources. It is a specialized branch applied to mineral processing that studies specific aspects of the mineralogy of samples, and the information obtained is used for the development and optimization of the processes (Gomes *et al.*, 2011; Jones & Boger, 2012; Castro & Peres, 2013; Edraki *et al.*, 2014; Kinnunen & Kaksonen, 2019; Matos *et al.*, 2019; Pinto & Delboni Júnior, 2019; Tayebi-Krorami *et al.*, 2019; Chácara & Oliveira Filho, 2021).

Concerning relevant studies dealing with the reprocessing of iron ore disposed in dams in Brazil in the last decade, Gomes *et al.* (2011) characterizated fines stocked in a pond and proposed a concentration route consisting of magnetic separation, desliming and flotation, and a secound route consisting of magnetic separation, which reached the best performance, aiming for a concentrate adequate for use in the metallurgical industry. According to Ribeiro & Ribeiro (2013) and Ribeiro & Ribeiro (2015), since the introduction, in 1963, of the Wet High Intensity Magnetic separator (WHIMS), the technology has proven to be efficient for separating several types of iron ore from their contaminants. WHIMS process variables, such as solid feed percentage, distance between grooved plate tips (GAP), magnetic field intensity and wash water pressure can be easily adapted to various ore types. Castro & Peres (2013) produced pellet feed fines material through a reprocessing route (magnetic concentration and flotation) of tailings disposed in dams. Ribeiro *et al.* (2017) discussed ways of scavenging iron from tailings produced by flotation using WHIMS. For the authors, mining companies should investigate the use of high magnetic fields intensity and matrixes with GAP smaller than 1.5 mm. Pinto & Delboni Júnior (2019) confirm the potential for pellet feed production from four tailings dams in the state of Minas Gerais through magnetic concentration. Rocha *et al.* (2019) recovered around 15% of the material disposed in a pond trough the magnetic concentration of the tailings. Their study showed that, in Brazil, on average, 33% of the iron ore is rejected as tailings during beneficiation. Chácara & Oliveira Filho (2021) affirm that today's tailings disposal is being reviewed worldwide. Techniques called alternative methods, which promote water and tailings reduction, have been receiving considerably more attention.

Thus, this article presents the technological characterization of iron ore tailings disposed of in a dam and proposes a magnetic concentration route, varying process variables of the wet high-intensity magnetic separator (WHIMS), aiming to obtain an iron ore product, having in mind its highly positive environmental impact and business opportunity.

2. Material and methods

The studied tailings come from a tailings dam of an iron ore mining company located at the Quadrilátero Ferrífero, located in Minas Gerais, Brazil; whose processing encompasses the stages of fragmentation, classification, gravimetric and magnetic concentration and solid-liquid separation. The mining company was responsible for sampling the dam through drilling holes. The dam has a volume of 2.8 x 10^6 m^3 and no longer receives any material from processing. All the collected material (300 kg) was dried, homogenized, and quartered by successive divisions in a Jones quartering machine, and representative aliquots of the total sample were obtained.

The iron-ore tailings were submitted to physical, chemical and mineralogical characterization, as well as laboratory tests of magnetic concentration in a Wet High-Intensity Magnetic Separator (WHIMS) separator (the same used in the mining company). The concentrates were sent for chemical analysis to evaluate the separation.

The physical characterization investigated the sample density (ρ), size distribution analysis, specific surface area (SSA) and pore size distribution. The sample density was obtained through gas pycnometry (helium), using a Quanta Chrome MVP-1 equipment, which works with 120V at a 50/60Hz frequency. For the particle size analysis, the fines (below 0.038 mm) were removed by wet sieving for 30 minutes with a water flow of 1 L/s. The oversize from this step was oven dried (100 ± 5^{0}C for 24 h) and subjected to dry sieving for 30 minutes (using Tyler series). Sieves with a mesh size between 1.18 - 0.038 mm were used. The undersize particles fed the tests on the Cyclosizer Warman M4, whose operating conditions were temperature (23°C), flow rate (200 mm/s), sample density of the tailings and elutriation time (20 min). The data obtained were plotted on a particle size curve. The specific surface area (SSA) analysis by the Brunauer, Emmett and Teller (BET) method and pore size distribution by the Barret, Joyner and Hallenda (BJH) model were performed in a Quantachrome, Nova 1000 model, with degassing temperature of 200°C using gaseous nitrogen as adsorbate.

The chemical composition of the tailings was verified with a Rigaku X-ray fluorescence (XRF) spectrometer, 2400 model. The mineral phases were investigated by X-ray diffraction (XRD) with a PANalytical X´Pert APD diffractometer using copper radiation (CuKa). The XRD diffractograms were interpreted using the Crystallography Open Database (COD). Sample images were acquired with a scanning electron microscopy SEM JSM-5410 from Jeol (accelerating voltage of 15 kV/ equipped with a backscattered electron detector) coupled with energy dispersive X-ray spectrometer (EDS). The chemical and mineralogical characterization was performed with the iron-ore tailings and with particle size fractions between 1.18 - 0.038 mm.

The iron-ore tailings (characterized) were subjected to magnetic concentration tests in a Wet High-Intensity Magnetic Separator (WHIMS) separator by varying the operational parameters matrix opening (GAP of 1.0 or 1.5 mm), solid feed percentage (30 or 50%) and magnetic field intensity (7,000, 9,000 or 11,000 Gauss). These values were suggested for concentration of fine-grained iron ore tailings by Gomes *et al.* (2011), Castro & Peres (2013), Silva *et al.* (2017), Pinto & Delbion Júnior (2019) and Rocha *et al.* (2019). Table 1 contains the conditions of the 12 magnetic concentration tests performed. They were carried out at pH 8.0 (pH of the tailings as collected), and average wash water pressure of 0.5 kgf/cm^2 (49.0 x 10^3 Pa). The Fe and SiO_2 grades of the concentrates were evaluated by XRF. The test that showed the best results was also evaluated using an average wash water pressure of 1.0 and 1.3 kgf/cm^2 (98.0 and 127.5 x 10^3 Pa). Figure 1 illustrates the flowchart of the concentration with the Rougher, Cleaner and Recleaner steps.

Table 1 - Magnetic concentration tests.

Test	GAP (mm)	Feed solids (%)	Magnetic field (Gauss)
1	1.5	50	11,000
2	1.5	50	9,000
3	1.5	50	7,000
4	1.5	30	11,000
5	1.5	30	9,000
6	1.5	30	7,000
7	1.0	50	11,000
8	1.0	50	9,000
9	1.0	50	7,000
10	1.0	30	11,000
11	1.0	30	9,000
12	1.0	30	7,000

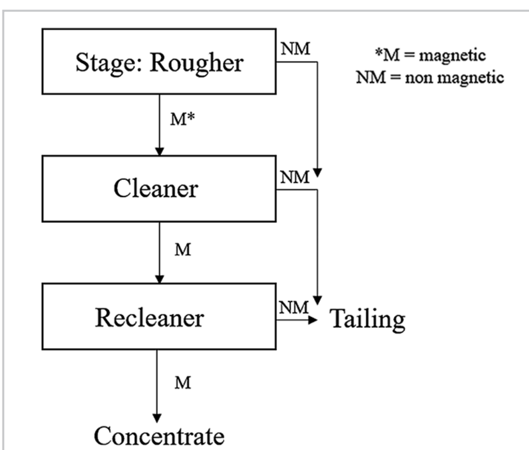


Figure 1 - Magnetic concentration flowchart.

3. Results and discussions

The sample density (ρ) of the iron-ore tailings analyzed by helium gas pycnometry showed a value of 3.04 x 10^3 Kg/m^3, which is within the expected value range, since the main minerals in iron ore in the Quadrilátero Ferrífero are magnetite (ρ ≅ 5.1 x 10^3 Kg/m^3), hematite (ρ ≅ 4.9 x 10^3 Kg/m^3), goethite (ρ ≅ 3.5 x 10^3 Kg/m^3), quartz (2.6 x 10^3 Kg/m^3), and feldspars (ρ ≅ 2.5 x 10^3 Kg/m^3- (Klein & Dutrow, 2012).

The size distribution analysis is represented in Figure 2. It can be seen that 100% of the particles are smaller than 0.300 mm, around 95% is below 0.150 mm, d_{90} is around 0.110 mm and d_{50} ≅ 0.049 mm. Luz, França, and Braga (2018), when discussing iron ore products commercialized in Brazil, stipulate the granulometry of the sinter feed between 6.30 and 0.150 mm, and less than 0.150 mm for pellet feed fines. Thus, almost 100% of the tailings have the appropriate grain size for the iron ore pellet feed fines product.

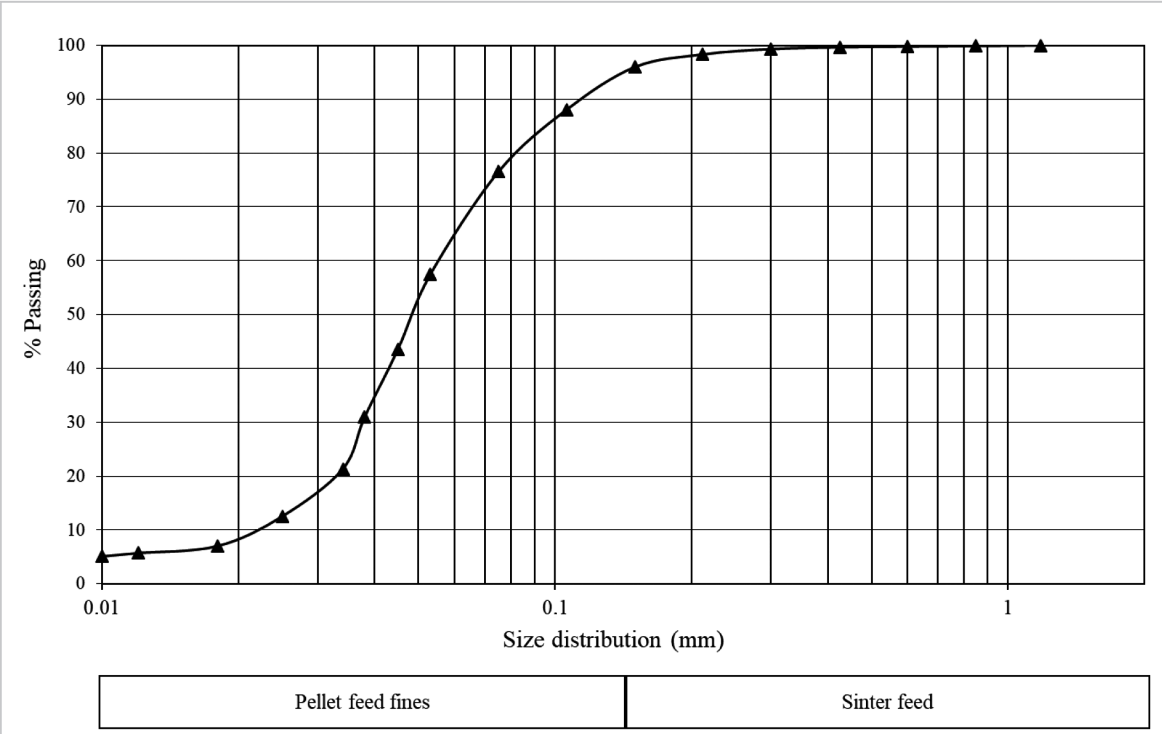


Figure 2 - Iron ore tailings: size distribution.

Concommitantly with the results of the size distribution analysis, the tailings showed a specific surface area of 3.71 m^2/g, which is a compatible value for iron ore with this grain size (d_{90} = 0.110 mm and d_{50} ≅ 0.049 mm). As an example, Silva (2014) observed an SSA of 1.5 m^2/g for goethitic iron ore with d_{50} = 0.150 mm; Mangabeira (2009) found values between 3.0 and 2.0 m^2/g for a different iron ore, mined by Samarco, with d_{90} < 0.100 mm. The pore size distribution and total pore area data was 3.82 nm and 0.023 cm^3/g, respectively.

Regarding the chemical characterization performed, Table 2 contains the results of the XRF analysis. It is observed that the iron-ore tailings and the granulometric ranges cannot be classified as a commercial iron ore product, since the specifications of pellet feed fines, appropriate for the tailings granulometry, require Fe grades of approximately 65% and contaminants (SiO_2 + Al_2O_3) with grades around 3% (Luz, França e Braga, 2018).

Table 2 - Tailings Chemical analysis by XRF.

Size fraction (mm)	%Fe	%Mn	%SiO_2	%Al_2O_3
Head sample	36.53	0.225	53.64	1.56
0.150	30.01	0.149	65.61	1.58
0.106	35.95	0.411	52.08	1.73
0.075	36.10	0.262	54.54	1.36
0.053	33.05	0.176	59.64	1.19
0.045	28.99	0.155	65.60	1.29
0.038	27.40	0.160	68.22	1.53
<0.038	41.82	0.331	43.88	2.09

In all samples submitted to X-ray diffraction (head sample and size fraction 0.150 – 0.038 mm), the same majority phases were identified (quartz, hematite, goethite and kaolinite). Figure 3 represents the diffractogram found for the iron-ore tailings.

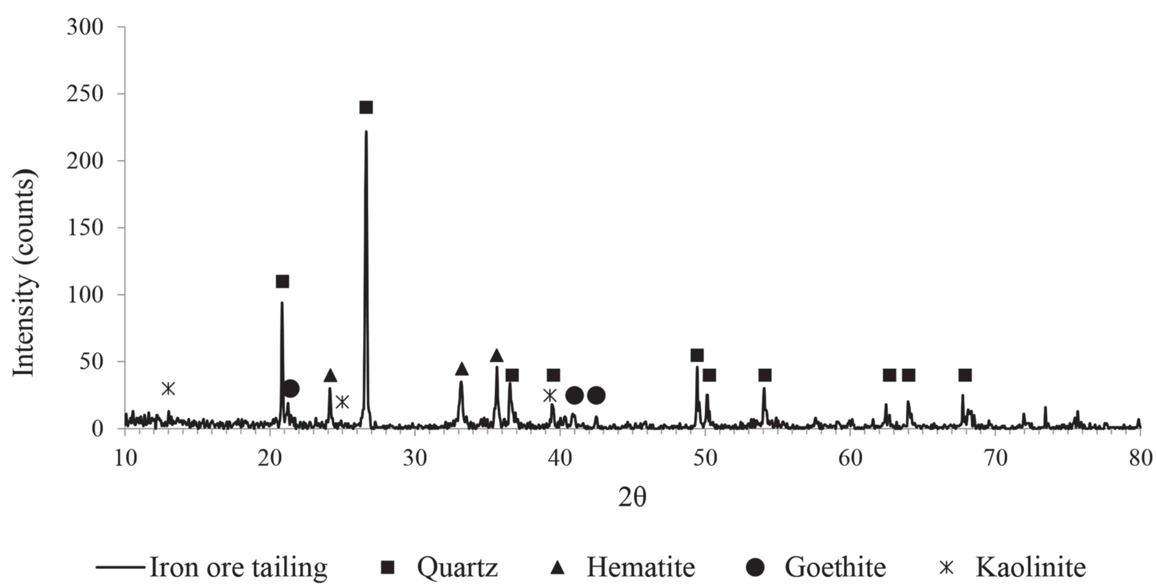
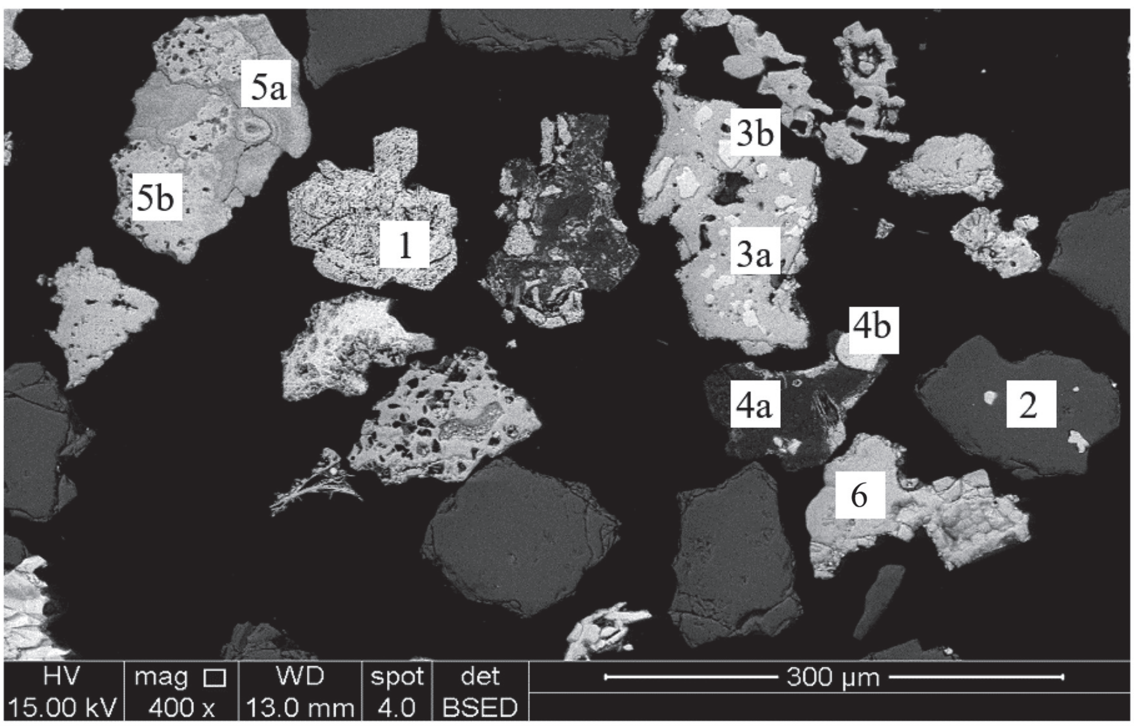


Figure 3 - Tailings mineralogic analysis by XRD – head sample (the background was subtracted).

The scanning electron microscopy (SEM) and the energy dispersive spectroscopy (EDS) analysis, represented in Figure 4, show that the minerals identified in the XRD (quartz, hematite, goethite and kaolinite) were confirmed, and one minor phase, a manganese oxide, was also identified. Two variations of hematite were detected, the granular and the martite with the octahedral habit characteristic of magnetite. Several mixed particles were identified, such as particle 2 in Figure 4, where there is the inclusion of hematite in a quartz matrix. It was observed that the iron minerals are practically liberated in the 0.106 mm range. As verified in the SEM analysis, the iron-ore tailings are not porous. It presents a variety of hematite, martite, which gives a greater porosity to the hematite, responsible for increasing the specific surface area, but not in an exorbitant way.



EDS/ Particle	1	2	3a	3b	4a	4b	5a	5b	6
High	Fe	Si	Fe	Fe	-	Fe	Mn	Mn	Fe
Medium	-	-	-	-	Al	-	-	-	-
Low	Si	-	Si	-	Fe	-	Fe, Al, K	Al, K, Ba, Fe	Si
Trace	-	Fe	Al, P	Si, P, Al	Si	Si, Al	Si	Si	Al
Mineral	Hematite (martite)	Quartz -	Goethite -	Hematite (granular)	Kaolinite -	Hematite (granular)	Manganese oxide	Manganese oxide	Goethite -

Figure 4 - SEM images for the iron-ore tailings.

An EDS analysis was performed and, even though it indicated the presence of manganese oxide or hydroxide (Figure 4), it could not specify which minerals are present. This occurs mainly due to the varied mineralogy of these compounds. In addition, Carvalho Filho *et al*. (2011) point out the inaccurate knowledge of Mn mineral structures.

Regarding the magnetic concentration tests in a Wet High Intensity separator (WHIMS), the results obtained for Fe and SiO_2 content in the concentrates and metallurgical recovery are shown in Figure 5. It can be observed that the higher the feed solids percentage, the higher the proportion of quartz in the concentrate. Pairs 1 and 4, 2 and 5, 3 and 6, 7 and 10, 8 and 11, and 9 and 12 were performed under the same conditions (GAP, magnetic field, and wash water pressure) except for the solid feed percentage; the odd ones were performed with 50% solids in the feed, and the even ones, with 30%. The even ones presented a concentrate with a lower content of contaminant because the higher the mineral dilution, the lower the probability of non-magnetic particle entrainment into the concentrate (Rocha *et al*., 2019).

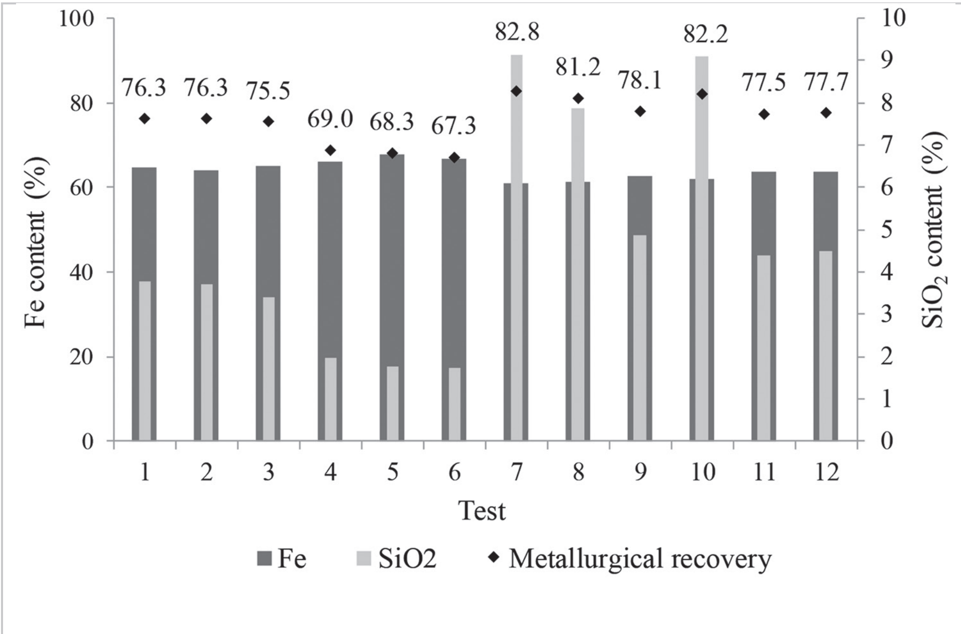


Figure 5 - Magnetic concentration tests.

The smaller the GAP, the greater the gradient caused by the matrix. Consequently, the increased gradient causes a larger proportion of non-magnetic particles to be entrained into the concentrate (Ribeiro & Ribeiro, 2013; Ribeiro & Ribeiro, 2017; Pinto & Delboni Júnior, 2019; Rocha *et al*., 2019). Tests 1 and 7, 2 and 8, 3 and 9, 4 and 10, 5 and 11, and 6 and 12 were performed under the same conditions (feed solids percentage, magnetic field, and washing water pressure), except for the matrix opening, with the former being performed with a GAP of 1.5 mm, showing higher selectivity, and the latter with a GAP of 1.0 mm.

Regarding the intensity of the magnetic field, in general, the higher the field, the greater the recovery of iron in the concentrate. However, the proportion of contaminants also increases. A possible explanation is the reduction of the matrix area due to the large amount of material deposited in it, which, in addition to attracting non-magnetic material to the concentrate, increases the pulp runoff (Gomes *et al*., 2011; Ribeiro & Ribeiro, 2013; Pinto & Delboni Júnior, 2019; Rocha *et al*., 2019). Tests 1 and 3, 4 and 6, 7 and 9, and 10 and 12 were performed under the same conditions (feed solids %, GAP, and washing water pressure), except for the magnetic field intensity; the first ones were performed with a magnetic field of 11,000 Gauss and showed a higher SiO_2 content in the concentrate, and the second ones, with a field of 7,000 Gauss.

It can also be seen from Figure 5 that tests 4, 5 and 6 achieved the chemical specifications for the iron ore pellet feed fines product (~ 65% Fe and ~3% SiO_2), and that they achieved similar metallurgical recoveries of 69.0, 68.3 and 67.3, respectively. Test 6 (GAP =1.5 mm, feed solids % = 30 and magnetic field = 7,000 Gauss), because it had the lowest contaminant content in the concentrate (1.74%), was also performed using average wash water pressures of 1.0 kgf/cm^2 (68.14% Fe and 1.70% SiO_2) and 1.3 kgf/cm^2 (68.51% Fe and 1.68% SiO_2). The results obtained for iron content in the concentrate and metallurgical recovery are shown in Figure 6, where it is observed that increasing the wash water pressure, while slightly increasing the Fe content in the concentrate, promoted a decrease of the metallurgical recovery, from ~75% at 0.5 to ~68% at 1.3 kgf/cm^2. From a commercial point of view, as for all the tests, the grades were within specifications or exceeding them, a recovery loss is not interesting. Tests to verify if lower water pressures could increase recovery while still adhering to the specifications would be justified, since the circular economy proposes to rescue the maximum amount of mineral tailings as possible.

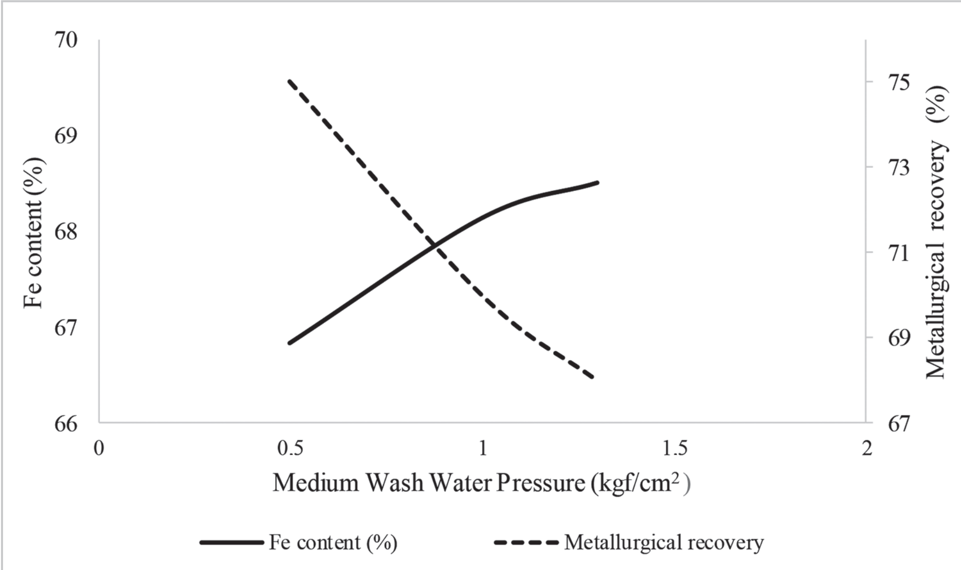


Figure 6 - Magnetic concentration test 6 varying the average water pressure.

4. Conclusions

The tests proved that the studied material (tailings from an iron ore dam), with initial contents of 36.53% Fe and 53.64% SiO_2, reached the specifications of the commercial iron ore pellet feed fines product (material < 0.150 mm / ~ 65% Fe and 3% contaminants) through magnetic concentration using the Wet High-Intensity Magnetic Separator (WHIMS) equipment. The best concentration result (66.83% Fe and 1.74% SiO_2) was achieved with a 1.5 mm GAP, 30% solids under a 7,000 Gauss magnetic field. Therefore, it was concluded that the studied tailings dam can be reprocessed, and the generated product can be used by the company in a blast furnace, for direct reduction, or as a blend material.

The results showed that the magnetic separation of these tailings would be responsible for the recovery of approximately 50% of all stored material (1.4 x 106 m^3 of tailings) and ~ 67% of Fe, which, in addition to providing revenue, would reduce the associated environmental damage, meeting the recommendations of circular economy in mining. The chemical composition of the remaining material is approximately 13% Fe and 70% SiO_2. The recovering of the pellet feed fines stored in a mining dam meets the objectives of mining circular economy, since this pratice has the potential to turn lower-grade materials into a raw material source. The processing route considered a magnetic separator equipament that is already used by the studied mining company. It was observed that the content of iron in the concentrate can be raised by modifying WHIMS parameters such as GAP, % solid feed, magnetic field and average wash water pressure.

Finally, due to the particularities of each ore, it is recommended that each mining company invest in their own methods to reuse tailings, as those who invest in their management contribute to the sustainable development of the community where they operate, due to the reduction in the volume of tailings dams.

Acknowledgments

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