Original Article

Characterization and processing of an haematitic stockpile for pellet feed production

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Abstract

A current concern related to low-grade stockpiles is to develop processing routes for the production of high-grade pellet feed. The stockpiles possess complex mineralogical composition of hematite and undesirable minerals bearers of aluminium and sulphur that require the development of a processing route aiming the production of high iron grade material with acceptable grades of contaminants. With an average iron grade of 48.6%, the material of the haematitic stockpiles was produced at the end of a beneficiation process consisting of crushing and screening. After grinding to achieve P80 106 µm, satisfactory concentration was achieved by magnetic separation (WHIMS) in three or four stages, depending on the desired product quality. Such flexibility led to the proposal of two possible processing routes. When the scavenger stage product is incorporated into the pellet feed, although the iron grade diminishes, the mass recovery increases by approximately 5%. The investigation proved that it is possible to produce pellet feed from the haematitic stockpiles with the processing routes tested. However, further grinding is required in order to adequate the material granulometry for its application as pellet feed.

Keywords: Iron ore stockpiles; Characterization; Magnetic separation; Pellet feed.

Caracterização e processamento de uma pilha de estoque de minério hematítico para a produção de *pellet feed*

Resumo

Uma preocupação ligada a pilhas de estoque de baixo teor é desenvolver rotas de processamento para produção de pellet feed de alto teor. As pilhas possuem uma complexa composição mineralógica de hematita e minerais de alumínio e enxofre, que requerem uma rota de processamento para produzir um material com alto teor de ferro e teores aceitáveis de contaminantes. Com teor médio de ferro de 48,6% o material das pilhas de estoque foi produzido em um processo que consiste em britagem e peneiramento. Após a moagem para atingir P80 de 106 µm, uma concentração satisfatória foi alcançada por separação magnética (WHIMS) em três ou quatro estágios a depender da qualidade do produto que se deseja. Tal flexibilidade levou à proposta de duas possíveis rotas de processamento. Quando o produto da etapa scavenger é incorporado ao pellet feed, embora o teor de ferro diminua, a recuperação mássica aumenta em cerca de 5%. O trabalho realizado demonstrou ser possível produzir um pellet feed a partir das pilhas de estoque com as rotas de processamento testadas. Entretanto, uma moagem adicional é necessária para adequar a granulometria do material para sua utilização como *pellet feed*.

Palavras-chave: Pilhas de estoque; Caracterização; Separação magnética; *Pellet feed*.

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1 Introduction

Some of the reasons that lead mining companies to stockpile low-grade ores are the non-economic feasibility of its processing at current market prices, the absence of appropriate technology or simply the priority of beneficiating high-grade ores. The processing of these stockpiles means not only the decrease in costs related to its management but also the implementation of mining production regulations. Those reasons explain the growing inclination of mining companies in developing technologies towards the processing of low-grade stockpiles [1]. Given this, the goal of the present work was to develop a beneficiation route that would enable the transformation of the material that composes the haematitic stockpiles into a usable high-grade pellet feed, to meet an additional demand required to completely feed a steel making plant.

The haematitic piles investigated are originated from the beneficiation circuit of Las Truchas, a mining complex located in the city of Lazaro Cardenas, state of Michoacán, Mexico. According to Gustavson Associates [2], the processing plant is fed with different types of ores. One of them is the massive magnetite ore from Santa Clara and El Mango mines, which is directed to a three-stage crushing process, with magnetic separation after each stage, followed by ball milling with magnetic separation of sands and fines. The second ore is a lump hematite, from the Santa Clara mine, which is processed in a hematite plant consisting of crushing and screening. This comminution and classification circuit produces two materials: a coarser fraction (38 to 12.7 mm) denominated lumpy hematite, and a finer fraction (below 12.7 mm) called hematite fines, which is stockpiled forming the haematitic piles, object of this study.

The ore forming the stockpiles is composed mainly by hematite and magnetite, which are paramagnetic and ferromagnetic minerals, respectively. Although all substances are affected in some level when submitted to a magnetic field, even if the effect is too weak to be detected [3], their significant magnetic susceptibility compared to other substances allows the successfully use of magnetic separation as concentration method.

Magnetic separation methods uses as differentiating property the behaviour of mineral particles when they are submitted to a magnetic field. The minerals can be separated in at least five groups. The first one, named diamagnetic, is constituted by atoms with no magnetic moment; its magnetic susceptibility is small and negative, like inert gases, for example. The second one is the paramagnetic, which presents atoms with randomly oriented magnetic moments, being its susceptibility small and positive, such as some metals and diatomic gases. The atoms that constitute the third group, called ferromagnetic, present parallel-aligned magnetic moments. Therefore, its magnetic susceptibility is large, for example, transition metals, like iron. The fourth group, antiferromagnetic, has atoms with anti-parallel aligned magnetic moments. The susceptibility is small, like transition metals. Finally, the ferrimagnetic group is constituted by particles where there are parallel alignment of atoms in some of the crystal sites and anti-parallel alignment in others [4].

Among the magnetic separators, WHIMS (Wet High Intensity Magnetic Separator) has become a powerful equipment, mainly used in the recovery of weakly ferromagnetic minerals. During WHIMS operation, there are some forces acting upon the particles: magnetic forces, which will attract paramagnetic particles, and hydrodynamic drag and gravity, which will act against the magnetic force. To pick a magnetic particle from the slurry, the magnetic force must be stronger than the hydrodynamic forces [3,5]. The magnetic force (Fm) on a particle under an increasing magnetic field is described by Equation 1:

$$Fm = \frac{k}{\mu o} \mathrm{VB\Delta B} \tag{1}$$

Where is the particle's volumetric magnetic susceptibility, μo is the magnetic permeability of vacuum, V is the volume of the particle, B is the external magnetic induction and $\Delta \mathrm{B}$ is the gradient of magnetic induction [6].

The equipment is composed of a magnetic funnel that has grooved plates with openings (gap) that can vary from 1.1 to 10 mm. The funnel is inserted between two coils that generate a magnetic field which can be changed according to the applied current, which is set according to the intensity of the magnetic field (MF) desired. The material is poured within the funnel in the form of pulp, with a predetermined solid percentage, and passes through the matrix. The magnetic particles will get attached to the matrix's slots under the MF effect, while non-magnetic particles will pass straight to the tailings' receptacle. Still under the MF effect, wash water is used to boost the concentrate grade by carrying away non-magnetic particles that eventually get stuck in the matrix whilst they should go to tailings. After this procedure, the MF is turned off and the magnetic material is collected from the matrix.

2 Methodology

The methodology aimed at the definition of a beneficiation route to produce pellet feed. A sample of ore from the haematitic stockpiles was collected in Las Truchas Mining Complex, with which a study about the particular characteristics and properties of the ore has been carried out in order to determine which processing routes could be implemented.

The sample characterization consisted of granulochemical analysis, X-ray diffraction, liberation study, and grinding kinetics.

The size-by-size analysis was performed using sieves of Tyler series, 8" (20.32 cm) diameter, for the size range from 6300 μm to 53 μm, and to determine chemical elements percentage in the samples, chemical analysis tests were performed adopting the method of X-ray fluorescence.

Among the substances analysed there are total iron content (FeT), FeO, SiO$_2$, Al$_2$O$_3$, S, loss-on-ignition (LOI) and magnetite content, which was measured apart by using the equipment Satmagan 135. The X-ray diffraction of each oversize obtained by the sieving was performed by using a Bruker D2 Phaser. The results from the qualitative XRD analysis were treated adopting DIFFRAC.EVA, Bruker software.

To establish a presumable liberation size, the size ranges (- 106 + 75 μm) and (-75 + 53 μm) were observed in the stereoscopy loupe using the fiber optic light source LEICA KL 200 LED before and after grinding. The quantification of the liberation of the valuable minerals was done by applying the optical method developed by Gaudin, by counting liberated and mixed particles on the images, according to Equation 2 [7]:

$$ldi = \frac{li}{li + mi} * 100 \tag{2}$$

Where ldi is the liberation degree of the specie i, li is the quantity of the specie i that occurs as liberated particles, and mi is the quantity of the specie i that occurs as mixed particles.

To establish the necessary time to achieve 80% passing in 106 μm, a grinding kinetics analysis was performed adopting the ball mill Sepor, which has a length of 20 cm, diameter of 18 cm and a total internal volume of 5.080 L. The ball charge was composed by 8 balls of 40 mm, 17 balls of 34 mm, 27 balls of 21 mm and 28 balls of 15 mm (the dimensions refer to the diameters). The pulp solids percentage was 70% in weight; 1273.83 g of ore, 570.0 g of water and the mill speed was 70% of the critical speed, which was determined by Equation 3 [8].

$$Vc = 42.3 / \sqrt{(D - d)} \tag{3}$$

Where D is the ball mill internal diameter and d the maximum diameter of balls (both in meters). Since the mill critical speed was 112.8 rpm, 70% corresponds to 79 rpm. Three grinding kinetics test were performed using those parameters to construct the grinding kinetics curve.

The magnetic separation was performed in a WHIMS GS-50 from Gaustec, in which five tests (test 1, tests 2.1 and 2.2, tests 3.1 and 3.2) were carried out in three different configurations, as shown in Table 1. To prepare the pulp, 20 g of sample were poured in a beaker, which was completed with 46.7 millilitres of water, yielding 30% solids. This pulp fed the matrix composed by a set of grooved plates separated by a gap of 1.5 mm. The products obtained were dried in an oven at 120 °C. After this process, the materials were weighed, homogenized and quartered to obtain aliquots to be sent to chemical analyses.

Once the concentrate has been obtained, Blaine number was calculated to estimate its specific surface area, since it is a relevant parameter that must be considered when producing a pellet feed. Blaine number is a parameter obtained by using the Air Permeability Apparatus to determine the specific surface of a powder sample. The equipment measures the time spent by a certain volume of air to cross a sample. By this time, the specific surface area of the particles is calculated. Therefore, the finer the particles, the larger the area. The amount of material used to perform the test depends on its density, being different for each material [9].

At the end of this process, the characterization of the ore and final products was complemented by using the system SEM/EDS (Scanning Electron Microscope coupled to an Energy Dispersive System).

3 Results and discussion

3.1 Size-by-size and chemical analyses

Fe and SiO$_2$ grades of each fraction size are displayed in the particle size distribution curve of Figure 1. While most fine iron ores have P$_{100}$ of 12 mm and P$_{50}$ of 1 mm [10], the results reveal a material with P$_{80}$ and P$_{50}$ equal to 5 and 1.18 mm, respectively, showing an average coarseness finer than the average fine ore. As for the chemical composition, the highest Fe grade and the lowest SiO$_2$ grade in the sample are in the same size fraction, above 6.3 mm.

The size-by-size chemical analysis is shown in Table 2. The iron grade decreases towards the finer fractions. In contrast, the highest grades of silica and aluminium oxide are in the fraction below 0.053 mm.

Table 1. Parameters adopted in the series of tests on WHIMS

Tests	Stages	Electric current (A)	Magnetic field (Gauss)
Test 1	Rougher	0.4	1500
	Scavenger	2.8	9000
Tests 2.1 and 2.2	Rougher	0.4	1500
	Cleaner		
	Scavenger	2.8	9000
Tests 3.1 and 3.2	Rougher		
	Cleaner	0.4	1500
	Recleaner		
	Scavenger	1.6	6000
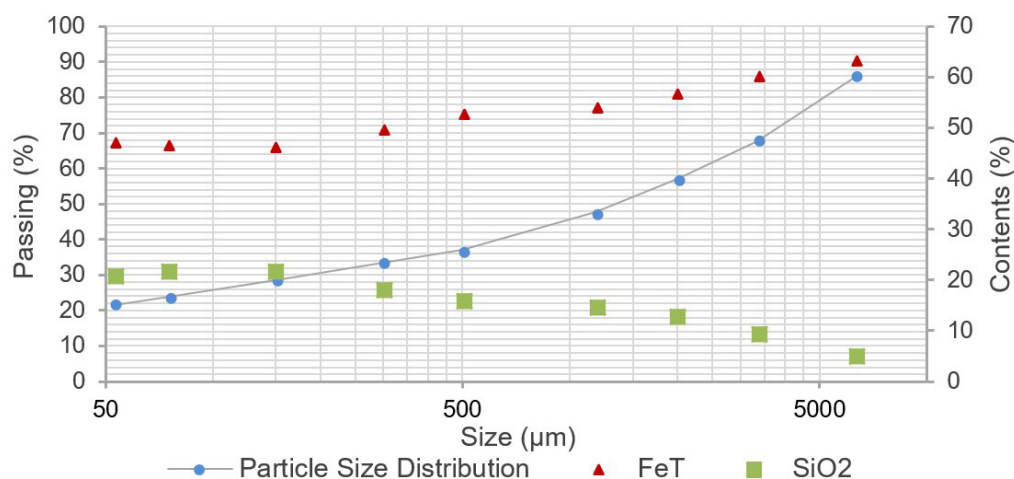
Figure 1. Particle size distribution of the haematitic ore with Fe and SiO$_2$ grades.

Table 2. Size-by-size chemical analysis

Opening (μm)	Mass retained (%)	Cumulative passing (%)	Magnetite content (%)	FeTotal (%)	SiO$_2$ (%)	Al$_2$O$_3$ (%)	S (%)	LOI (%)
6300	14.08	85.92	30.73	63.11	4.85	0.65	1.36	1.87
3350	18.13	67.80	31.20	59.98	9.27	1.78	0.89	1.50
2000	10.87	56.93	34.72	56.63	12.75	2.53	0.60	1.67
1180	9.26	47.67	31.40	53.88	14.75	3.11	1.41	2.57
500	10.62	37.05	29.19	52.67	15.70	3.24	2.12	3.01
300	3.61	33.44	26.48	49.67	18.15	3.58	3.20	4.04
150	4.89	28.55	26.33	45.92	21.80	4.55	2.50	3.71
75	4.65	23.90	26.18	46.35	21.70	4.57	1.74	3.05
53	2.28	21.62	27.82	46.99	20.90	4.37	1.11	2.34
-53	21.62	0.00	25.60	34.31	**28.30**	**11.80**	0.35	5.67
Head sample			27.41	50.51	16.35	4.42	1.510	3.35

3.2 X-ray diffraction

A qualitative study performed with the fractions obtained in the previous sieving revealed a wide mineralogical assembly. The minerals that are present in all fractions are hematite (Fe$_2$O$_3$), magnetite (Fe$_3$O$_4$) and goethite (FeO(OH), which are the three most common iron ore minerals [10]. In addition, other abundant minerals are quartz (SiO$_2$), albite (NaAlSi$_3$O$_8$), clinochlore (MgAl)$_6$(OH)$_8$[(SiAl)$_4$O$_{10}$] and pyrite (FeS$_2$). Normally, pyrite is not considered an economically viable iron ore mineral, since it results in unacceptable SO$_x$ emissions during subsequent agglomeration and high temperature processing [10]. Minerals that were present in fewer fractions were chalcopyrite (CuFeS$_2$), sphalerite (ZnS), rutile (TiO$_2$), ilmenite (FeTiO$_3$), chromite (FeCr$_2$O$_4$), muscovite (KAl$_2$(OH,F)$_2$(AlSi$_3$O$_{10}$), biotite (K(MgFeMn)$_3$(OH,F)$_2$[AlSiO$_{10}$]), dolomite (CaMg(CO$_3$)$_2$), cordierite (Mg,Fe)$_2$Al$_3$(AlSi$_5$O$_{18}$) and maghemite (Fe$_{2,67}$O$_4$). Although the mineralogical composition will always be the most relevant aspect to be considered when selecting a processing route [11], Clout and Simonson [12] states that ore textures related to ore deposit genesis also plays an important

role to be considered, since it controls metallurgical process performance, in the case of agglomeration in pelletizing for example. A diffractogram with the main minerals identified is shown in Figure 2.

3.3 Liberation study

The liberation study was executed on two size fractions on both natural size distribution and ball milled material: (- 106 + 75 μm) and (- 75 + 53 μm). The results shown in Table 3 reveal that, although the size of the fractions are the same, after grinding, the liberation degree increased considerably. The particles bellow 106 μm are presenting a feasible liberation degree, between 81% and 86%.
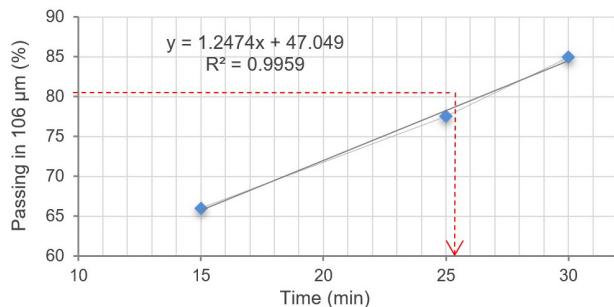
3.4 Grinding kinetics

The grinding kinetics (Figure 3), generated with bases on the results of three grindings, reveals that the third grinding provided 85% passing in the liberation size, with a corresponding time of 30 minutes. The equation indicates that for achieving 80% passing in the liberation size, 26.4 minutes of grinding are required.

Table 3. Liberation study results

Particle	BEFORE grinding		AFTER grinding	
	(-106 + 75 µm)	(- 75 + 53 µm)	(-106 + 75 µm)	(- 75 + 53 µm)
Free Fe-bearing	124 units	196 units	190 units	325 units
Free gangue	95 units	198 units	44 units	95 units
Mixed	46 units	70 units	43 units	54 units
Total	265 units	464 units	277 units	474 units
Liberation degree	73%	74%	81%	86%
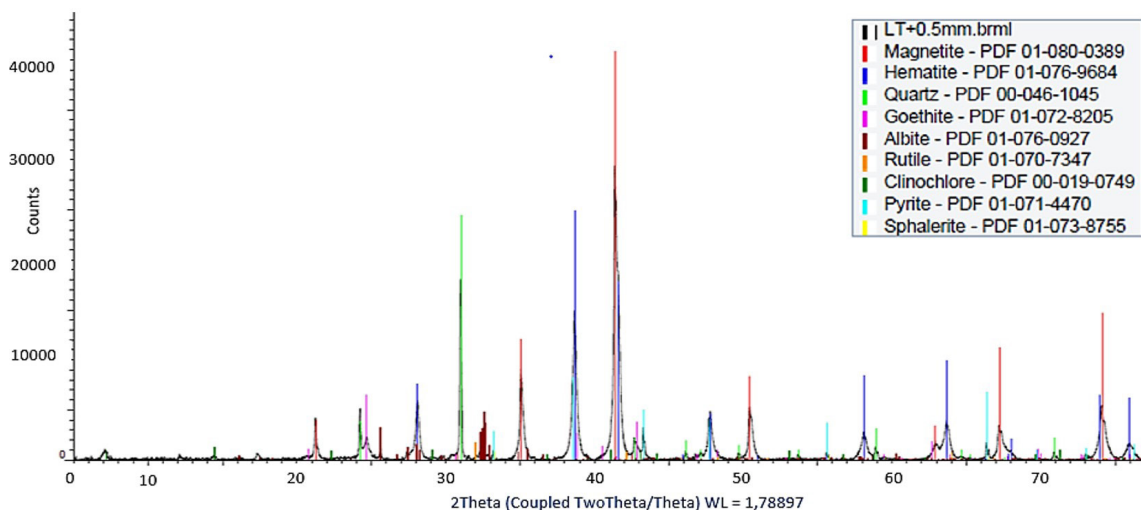
Figure 2. Diffractogram of the material.

Figure 3. Grinding kinetics

3.5 WHIMS products

The results upon the products obtained in the WHIMS tests are shown in Table 4. The terms Rougher, Scavenger, Cleaner and Recleaner are denominating the concentrates that came from those respective stages. The results presented as Test 2 and Test 3 are averages of the tests 2.1/2.2 and 3.1/3.2 respectively, since they have demonstrated good repeatability. The Fe grade increases adding the cleaner stage, but not significantly when the recleaner stage is added. At the same time, SiO_2 grade decreases as the Fe grade becomes higher. It is interesting to highlight the values of the iron grade corresponding to the scavenger concentrate in Tests 1 and 2, since they are lower than the iron grade in

the feed, which is 48.6%. It is an indication that the high magnetic field (9000 Gauss) is excessively dragging mixed particles to the concentrate, decreasing the Fe grade, which was solved by decreasing the magnetic field in Test 3 (now 6000 Gauss). Although oxidized iron ores are much more difficult to upgrade by magnetic separators, since their magnetic susceptibility are only about 1% or less of that of magnetite [13], WHIMS has been providing satisfactory concentrate grades, around 66%, depending on the addition or not of a recleaner stage. However, for direct reduction purposes, Fe grade has to be higher than 67%, requiring further beneficiation, through reverse flotation or gravity concentration to reduce silica grade [10].

Hematite concentrates have a typical P_{80} range of 45 – 120 µm, but for pellet feed applications the most common range is 45 – 60 µm [10]. The actual values of P_{80} and P_{50} presented by the recleaner concentrate are 78 µm and 40 µm, respectively.

Thus, it can be concluded that the material needs to present a finer particle size distribution, as it can be also verified by the Blaine number in the next subsection.

3.6 Blaine number

The results of the specific surface area determination using the Blaine permeabilimeter (designated as Blaine) with the feed used in WHIMS and its recleaner concentrate
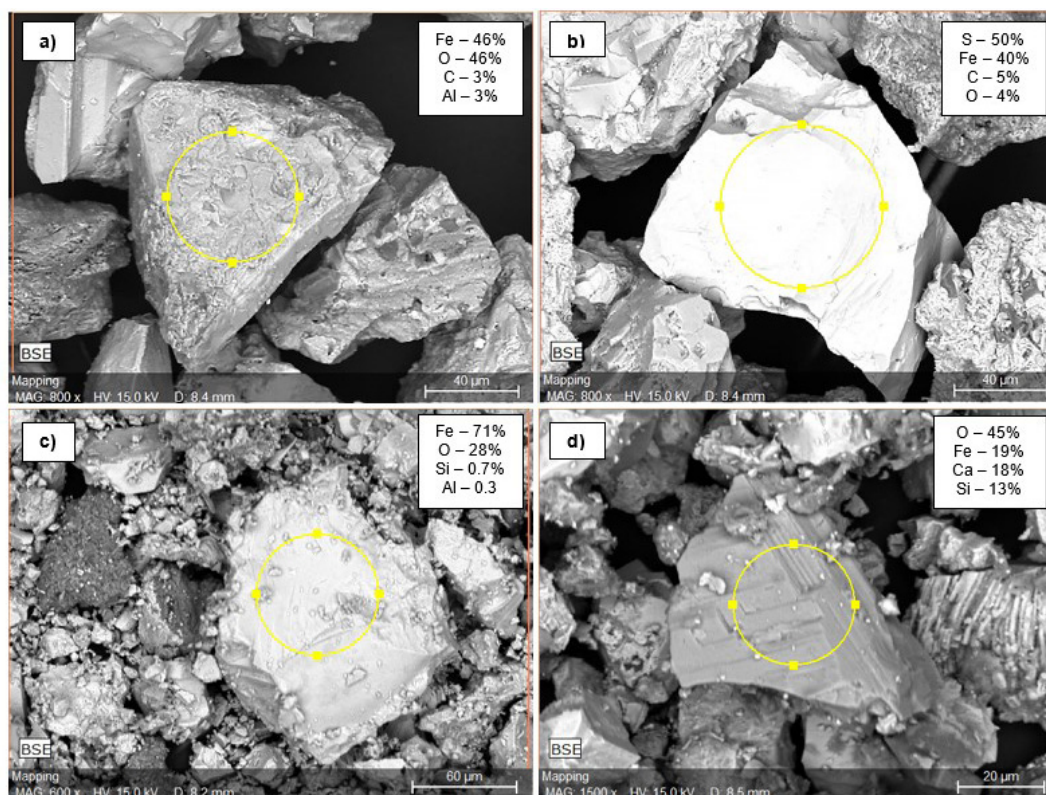
Figure 4. a) Free Fe-bearing particle of the feed; b) Liberated pyrite of the feed; c) Fe-bearing particle of a recleaner concentrate; d) Free gangue particle of a scavenger concentrate.

Table 4. WHIMS products

Tests	Magnet.Field (Gauss)	Products	Mass Rec. (%)	Fe_T	SiO_2	Al_2O_3	S	LOI	MetalRec. (%)
	1500	Rougher	50.25	64.08	6.12	1.40	0.22	0.28	72.05
Test 1	9000	Scavenger	13.89	**44.38**	20.30	6.13	0.89	5.37	13.79
		Tailings	35.86	17.64	40.80	12.05	2.64	9.48	14.15
	1500	Cleaner	51.28	66.00	3.95	0.68	0.08	-0.39	70.93
Test 2	9000	Scavenger	13.40	**44.90**	19.93	6.08	0.55	5.21	12.60
		Tailings	35.34	22.24	41.90	12.25	2.63	7.41	16.47
	1500	Recleaner	53.48	66.47	3.51	0.56	0.05	-0.35	71.83
Test 3	6000	Scavenger	4.90	51.61	14.75	3.72	0.64	4.62	5.11
		Tailings	41.62	27.42	36.50	10.75	2.77	7.49	23.06
Feed				48.59	18.65	5.22	1.13	3.13	-

Table 5. Blaine results

Sample	Blaine (cm²/g)
Ground material (Feed)	3495.54
Concentrate Recleaner	1197.02

are shown in Table 5. The Blaine number of the concentrate was considerably lower than the ideal value for hematite ore fines, which is around 2145 cm²/g, requiring further grinding to increase its specific surface area. With such low value, the material does not provide enough strength both to green and indurated pellets [14]. Thus, it is a control process parameter that must be optimized, since an excessively high Blaine number also causes problems in

pellets making and unnecessary grinding energy consumption. The considerable drop in the values is due to the desliming action in the feed during the magnetic separation. Thus, the magnetic field is attracting the magnetic/coarser particles to the concentrate, making its specific surface area much smaller when compared to the ground material, which has a higher number of fine particles and consequently, a larger specific surface.

3.7 SEM/EDS (Spectroscopy Dispersive System)

The images obtained by SEM/EDS system are shown in Figure 4. Images (a) and (b) correspond to the feed for magnetic separation tests. Image (a) shows a free
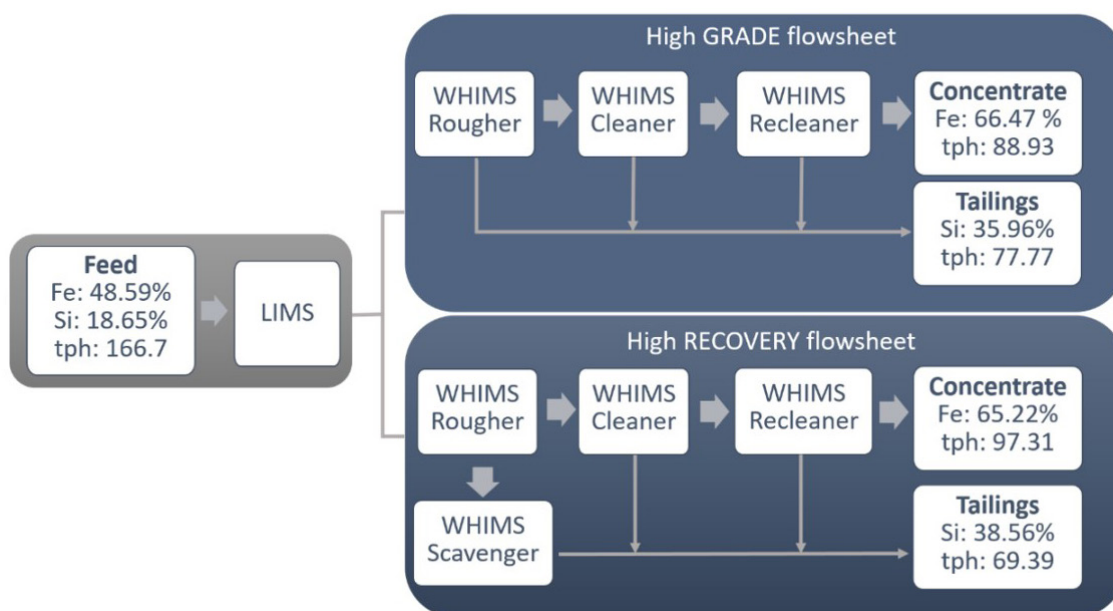
Figure 5. Beneficiation flowcharts.

Fe-bearing particle (likely magnetite) and image (b) presents a well-liberated pyrite particle. Images (c) and (d) refer to the products from WHIMS. Image (c) depicts a Fe-bearing particle of a cleaner concentrate, probably hematite. Since magnetite and hematite share similar chemistries and similar average atomic numbers, they might be problematic minerals to be distinguished in this kind of analysis [15]. However, their differentiation is possible by looking at the Fe grades of each composition. Image (d) shows free gangue particle in a scavenger concentrate. The high Si and Al grades suggest that it might be a clinochlore, an Al-bearing silicate.

3.8 Proposed processing flowsheets

Laboratory test results have led to propose two different flowsheets shown in Figure 5, according to what is the priority: high recovery or high grade. Both consist of the same process, however, the difference is the scavenger stage, which can be added or not. The decision of keeping the recleaner stage even without observing significant improvement in the Fe grade is justified by the possibility of achieving 70% Fe by doing adjustments in the operational parameters and as a consequence, the economic gains that such achievement can bring, allowing its implementation in the circuit.

In the first flowsheet, prioritizing the Fe grade, there is no scavenger stage. Therefore, the process consists of rougher, cleaner, and recleaner stages only. This process leads to enriching 48.59% of iron content in the feed to a marketable 66.47% of Fe in the concentrate generating a metal recovery around 73%. At the same time, this first flowsheet provides a low grade of silica and contaminants. The production of a high iron grade concentrate must be analysed, since it represents a lower mass recovery. As for the flowsheet prioritizing the mass recovery, the presence of a scavenger stage leads to obtaining

a second poorer concentrate, which is incorporated into the first richer concentrate obtained by the recleaner stage. Such configuration, when compared to the first flowsheet, causes a slight decrease of the Fe grade in the concentrate, 65.22%, as well as an increase of SiO_2 grade and other contaminants, such as sulfur and alumina, which must be considered. However, it provides an increase in the mass recovery (58.38%) and on metal recovery, from 73% to 78.35%.

4 Conclusion

As these stockpiles present significant iron content, a complex flowsheet to concentrate the haematitic ore is not necessary. By comminuting this ore to a mesh of grinding (MOG) of 106 μm it is possible to achieve a high-grade concentrate with 73% of Fe recovery by a processing flowsheet which prioritizes the grade (66.5% of iron grade) or iron recovery around 78% by a processing flowsheet prioritizing the mass recovery (65.2% of iron grade). Both concentrates obtained with the proposed processing flowsheets have significant lower sulphur than the original sample, with a sulphur reduction above 95%. However, if these concentrates are to be used in pelletizing, further grinding will be required to increase its specific surface area.

Ackowledgments

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