Evaluation of the crushing method impact on the mineral liberation in pre-concentration circuits

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Abstract

Mineral deposits have shown decreasing ore grade and increasing complexity, which has led mining projects to experience increased capital and operating costs. Pre-concentration is an alternative to minimize such costs. Notwithstanding the resulting rise in ore grade and reduction in feed mass, the generated tailings may contain significant amounts of the material of interest. In order to improve the mineral liberation at this stage, selective comminution proposes to explore different comminution mechanisms. This investigation compared three different crushing methods (jaw crusher, impact crusher, and high-pressure roller mill) for three different types of ores and the response of their products to pre-concentration, using a gravity method that was evaluated through heavy-liquid separation of the -6.35+3.35 mm crushed fraction. This fraction represents approximately 15% of the total sample, and is used as an indication of the gangue rejection potential for the -12+1.18 mm fraction. Copper and polymetallic ores showed good pre-concentration results for this size range at laboratory scale, with metallurgical recoveries greater than 90% and a rejection of over 20% of mass. Iron ore showed a 97% metallurgical recovery and 10% mass rejection. The impact crusher proved to be the best option for selective comminution for the polymetallic ore, with the highest metallurgical recovery. Finally, no significant differences were observed when using any of the three crushing mechanisms for the copper and iron ore.

keywords: pre-concentration, selective comminution, comminution, mineral liberation.

1. Introduction

Comminution is an extremely important step in mining operations, since the ore particle size is reduced in a controlled manner to achieve mineral liberation, a necessary condition for mineral concentration to occur. Around 2% of all electricity generated on the planet is estimated to be used in comminution (Napier-Munn, 2015) and no decrease is expected in this figure because of growing mineral concentration operations in the wake of decreasing ore grade and greater complexity (Norgate; Haque, 2010, 2013) In the case of copper ores, comminution is estimated to answer for 40% of a mine's energy cost (Ballantyne *et al*., 2012).

Pre-concentration is one of the alternatives to decrease energy consumption at this stage. It can take place after the crushing stage and before grinding, using techniques such as magnetic separation (cobbing), screening, gravity separation, and high technology sensors (ore sorting) to reject the liberated gangue (Dimas; Bergerman; Young; Petter ,2019; Krishna *et al*., 2013; Robben & Wotruba, 2019).

Should tailings be discarded prior to grinding, their particle size will be coarser, which enables disposal along with the mine waste in piles in a dump area or their use in road and other construction works, depending on the mineralogy.

Pre-concentration is being used by several mines around the world (Robben & Wotruba, 2019). Botswana's Tati Nickel Phoenix Mine reported significant gains, such as an increase from 470 t/h to 650 t/h in the grinding circuit output with the introduction of pre-concentration during the crushing stage (Morgan,2009).

Pre-concentration still finds limited application in Brazil. Several recent studies have shown the potential of applying this technology to deposits in the country. An ore sorting study for lithium ore in the municipality of Araçuaí showed a 25% mass recovery and greater than 80% metallurgical recovery of spodumene (Soraes *et al*., 2019). Ore sorting was also used for gold ore near the city of Belo Horizonte and the result was equally promising, with 65% and 89.9% of mass and metallurgical recovery, respectively (Assis et.al., 2021). Costa *et al*. (2014) also reported the feasibility of pre-concentrating marginal vanadium ore using a magnetic concentration with an enrichment of almost 1.5 times. Pilot pre-concentration studies of sulfide copper ore have also been carried out with positive results, particularly in terms of copper enrichment (almost twice as much copper content), 87% metallurgical recovery, and 47% mass recovery (Franco, Pedrosa and Bergerman, 2019). A study from Ero Copper (Ero Copper, 2020) at the Vermelho mine, in the city of Juazeiro, Bahia, reported a copper ore enrichment of 4.5 and a 20% mass recovery. The metallurgical recovery in this copper sample was 90.2%.

Despite the aforementioned benefits, the use of pre-concentration always leads to the loss of the metal of interest to the waste. Several authors (Hesse, Popov and Lieberwirth, 2017 and Ozcan & Benzer, 2013) have cited selective comminution using different equipment and breaking mechanisms as a tool to enhance coarse liberation and thus improve pre-concentration results. Studies show the results for different breaking mechanisms varying with the different ores tested, so that an evaluation must be made on a case-by-case basis.

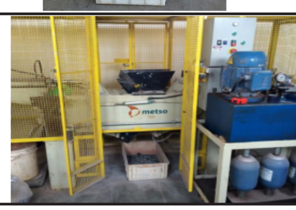
Notwithstanding positive pre-concentration results obtained for Brazilian ores, there are no studies illustrating the potential for gains in mineral liberation from selective comminution. This investigation evaluated the impact of different crushing methods (jaw crusher, impact crusher, and high-pressure roller grinder) on mineral liberation, specifically for circuits that include a gravity-based pre-concentration stage. Samples of sulfide copper ore, a polymetallic copper, lead and zinc ore, and an iron ore were used to compare the different breaking mechanisms.

2. Material and method

Samples from three different Brazilian mines were tested: a sulfide copper ore, a polymetallic copper, lead, and zinc ore, and an iron ore. The main minerals contained in the sulfide copper ore sample were: chalcopyrite, bornite, chalcocite, quartz, pyrite and pyrrhotite (Ero Copper, 2021). The polymetallic copper, lead, and zinc ore came from a mining site located in the state of Mato Grosso (Esteves *et al*., 2023). Its main minerals were pyrite, sphalerite, galena, quartz, calcite, chalcopyrite, and pyrrhotite. The iron ore was a typical compact itabirite from the Minas Gerais Iron Quadrangle. Hematite was the main mineral and the gangue was constituted mainly of quartz (Costa, 2009).

All materials went through the same processing route. Initially, a 20 kg sample with a 76.2 mm top size was fed to the crusher (jaw crusher, impact crusher and high-pressure grinding roll – HPGR) to comminute them down to a 12.7 mm top size. The crushers used are illustrated in Table 1.

Table 1 – Crushing equipment used.

Equipment	Type	
Jaw crusher	20.32 cm x 15.24 cm maximum feed	
Vertical impact crusher	37 cm diameter rotor	
HPGR	D1000™	

In the case of the jaw crusher, the jaw opening was reduced at each pass from the initial 38.1 mm down to 12.7 mm. The impact crusher was operated at a speed of 17.4 m/s. In the case of HPGR, the ore top size had to be previously reduced using a jaw crusher to maximum 38.1 mm. The test was done with a pressure of 4.5 N/mm². The tests using jaw and impact crushers were carried out in a direct closed circuit, whereas an open circuit with only one pass through the equipment was adopted for the HPGR. It should be kept in mind that, on an industrial scale, a cone crusher would be used instead of a jaw crusher. However, as there was no laboratory-scale cone crusher available, a jaw crusher was used. This could be investigated in more detail in future studies since, although both crushers' operational mechanism is mainly compression, in the cone, the material's residence time is longer, the number of breakage events is higher, and abrasion mechanisms play a more intensive part in vis-à-vis a jaw crusher. Figure 1 shows a flowchart of the entire process.

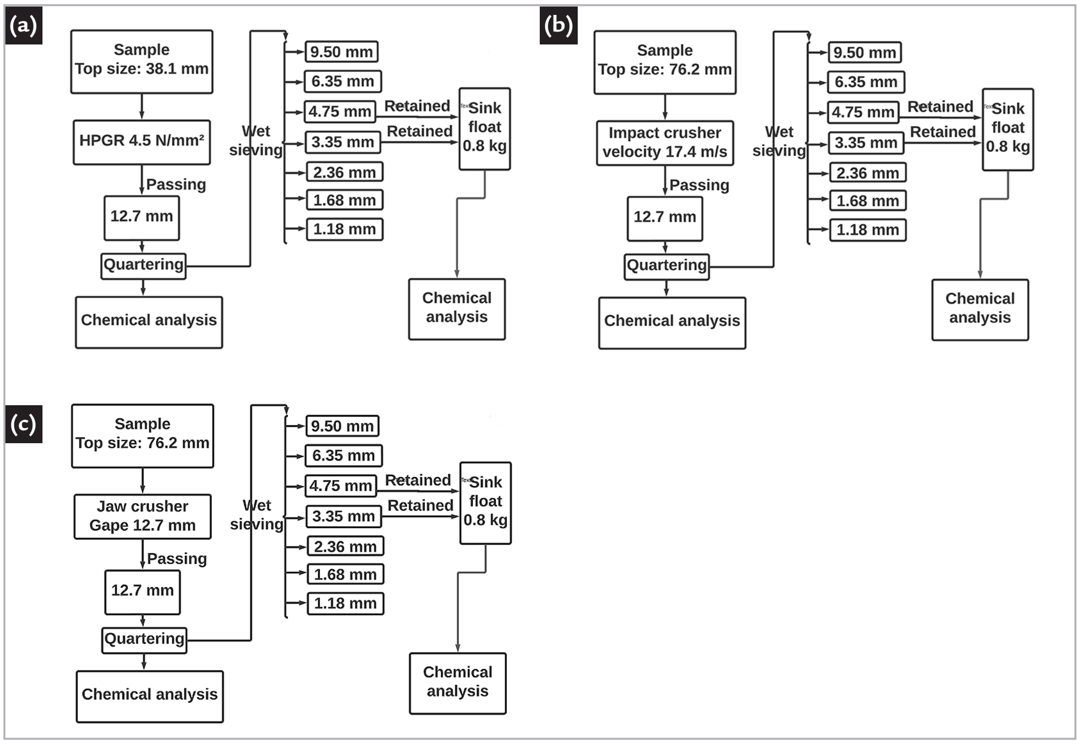


Figure 1 – Test flowchart. HPGR (a), Impact crusher (b), Jaw crusher (c).

Particle size was determined by wet sieving using square sieves with the following sizes: 12.7 mm, 9.50 mm, 6.35 mm, 4.75 mm, 3.35 mm, 2.36 mm, 1.68 mm, and 1.18 mm, which provided a particle size distribution curve and prepared samples for the sink-float test.

All tests were carried out at the USP Escola Politécnica's Ore Treatment Laboratory, except for the HPGR test, which was conducted at Metso Outotec, located in Sorocaba in the state of São Paulo.

The heavy liquid tests were done only with the -6.35+3.35 mm size fraction. The industrial pre-concentration stage would be applied to the -12+1.18 mm size fraction. For the laboratory tests, however, the evaluation of the -12+6.35 mm sample would require 2 kg for each size fraction. For the -6.35+3.35 mm the sample requirement is only 800 g. In view of the high cost and risk involved in dense liquid tests, which use expensive, toxic reagents, only the -6.35+3.35 mm size fraction was evaluated as a proxy for the complete size fraction. Additional studies should be done to evaluate the complete response of the ores to pre-concentration and selective comminution. Each sample in the -6.35+3.35 mm size fraction was submitted to the dense liquid test with the following liquid densities: 2.95 g/cm³ of tetrabromoethane, 2.85 g/cm³ of bromoethane, and 2.75 g/cm³ of bromoethane diluted with ethyl alcohol. Four products were collected from each test using the separation method: 2.95 g/cm³ sunk, 2.85 g/cm³ sunk, 2.75 g/cm³ sunk, and 2.75 g/cm³ floated. The flowchart of the sink-float test is shown in Figure 2. Chemical analyses were carried out at the Technological Characterization Laboratory (LCT), São Paulo, using the multi-acid digestion method and dosed in an optical emission spectrometer (ICP OES).

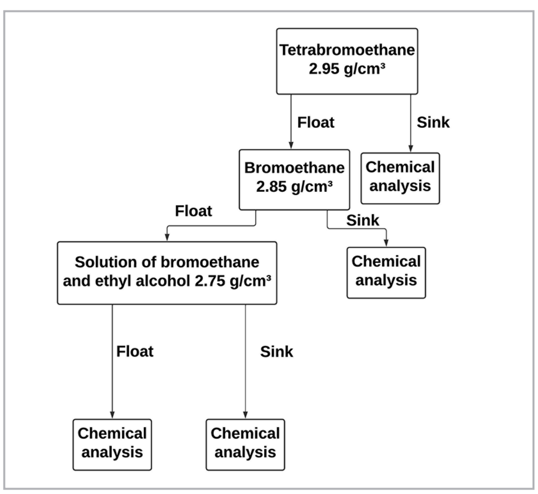


Figure 2 – Sink-float test flowchart.

3. Results and discussion

3.1 Particle size distributions

Figure 3 presents the particle size distributions for copper, polymetallic, and iron ore products from the jaw crusher, impact crusher, and HPGR.

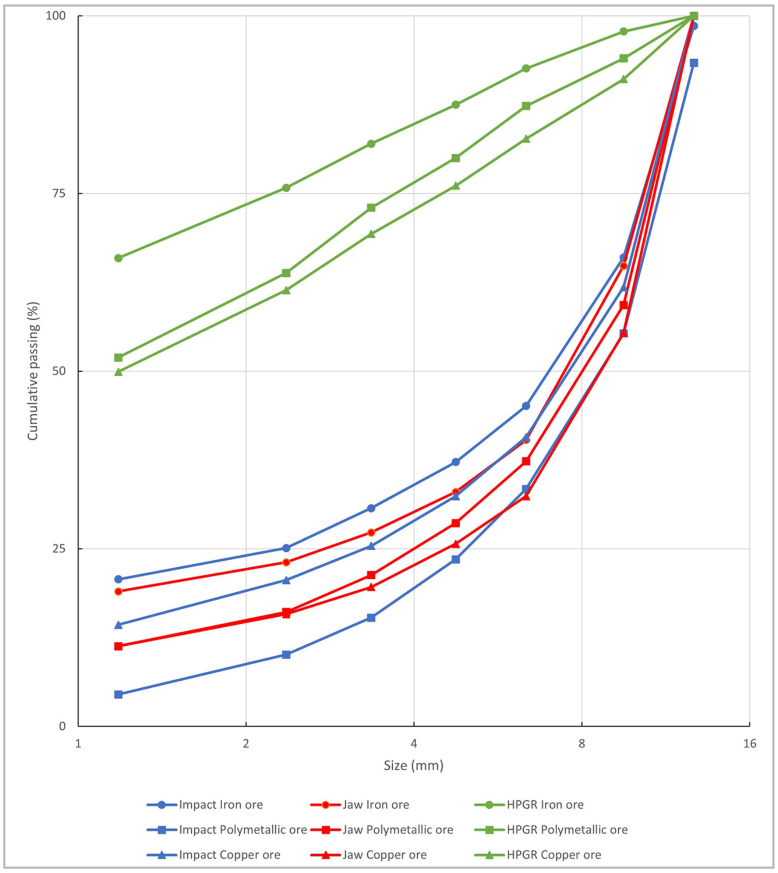


Figure 3 – Particle size distribution curves.

When compared with the jaw and impact crushers, HPGR generated a larger amount of fines and higher comminution ratio. The difference between the impact and jaw crusher products is lower than 5% for all the 3 ores tested.

3.2 Chemical analysis and sink-float test

The sink-float test results for sulfide copper ore, polymetallic ore, and iron ore using different crushing methods are given in Tables 1, 2, 3 and Figure 4, respectively.

Table 2 – Sink-float test for sulfide copper ore.

Comminution	Fraction (mm)	Density range	Sample (%)	-6.35+3.35 mm		
				Mass (%)	Cu (%)	Recovery (%)
Impact	-6.35+3.35	d > 2.95	9.4	61.7	0.56	87.0
		2.85 < d < 2.95	1.3	8.3	0.30	6.3
		2.75 < d < 2.85	2.0	12.8	0.15	4.9
		d < 2.75	2.6	17.1	0.04	1.8
Jaw	-6.35+3.35	d > 2.95	7.5	52.9	0.84	87.3
		2.85 < d < 2.95	1.6	11.6	0.27	6.1
		2.75 < d < 2.85	0.9	6.5	0.20	2.6
		d < 2.75	4.1	29.0	0.07	4.0
HPGR	-6.35+3.35	d > 2.95	7.2	54.1	0.78	87.7
		2.85 < d < 2.95	2.4	18.2	0.21	8.0
		2.75 < d < 2.85	1.8	13.7	0.13	3.6
		d < 2.75	1.9	14.0	0.03	0.7

Table 3 - Sink-float test for polymetallic ore.

Comminution	Fraction (mm)	Density range	Sample (%)	-6.35+3.35 mm		
				Mass (%)	Cu (%)	Recovery (%)
Impact	-6,35+3,35	d > 2.95	3.2	16.9	0.29	71.7
		2.85 < d < 2.95	2.4	12.6	0.02	3.7
		2.75 < d < 2.85	8.3	43.3	0.03	17.0
		d < 2.75	5.2	27.3	0.02	7.7
Jaw	-6.35+3.35	d > 2.95	2.0	12.5	0.32	66.4
		2.85 < d < 2.95	2.5	15.5	0.03	7.0
		2.75 < d < 2.85	6.8	42.2	0.02	16.3
		d < 2.75	4.8	29.8	0.02	10.3
HPGR	-6.35+3.35	d > 2.95	2.3	15.5	0.31	47.4
		2.85 < d < 2.95	2.3	15.5	0.09	13.7
		2.75 < d < 2.85	4.4	29.4	0.08	23.2
		d < 2.75	5.9	39.7	0.04	15.7

Table 4 - Sink-float test for iron ore.

Comminution	Fraction (mm)	Density range	Sample (%)	-6.35+3.35 mm		
				Mass (%)	Fe (%)	Recovery (%)
Impact	-6,35+3,35	d > 2.95	12.1	84.7	45.67	96.0
		2.85 < d < 2.95	0.5	3.4	16.54	1.4
		2.75 < d < 2.85	0.8	5.7	11.86	1.7
		d < 2.75	0.9	6.2	5.80	0.9
Jaw	-6,35+3,35	d > 2.95	11.3	86.9	45.35	96.6
		2.85 < d < 2.95	0.4	3.3	16.15	1.3
		2.75 < d < 2.85	0.8	6.1	10.70	1.6
		d < 2.75	0.5	3.7	5.33	0.5
HPGR	-6.35+3.35	d > 2.95	9.4	88.7	44.61	96.5
		2.85 < d < 2.95	0.3	2.4	16.78	1.0
		2.75 < d < 2.85	0.7	6.9	12.76	2.1
		d < 2.75	0.2	2.0	6.92	0.3

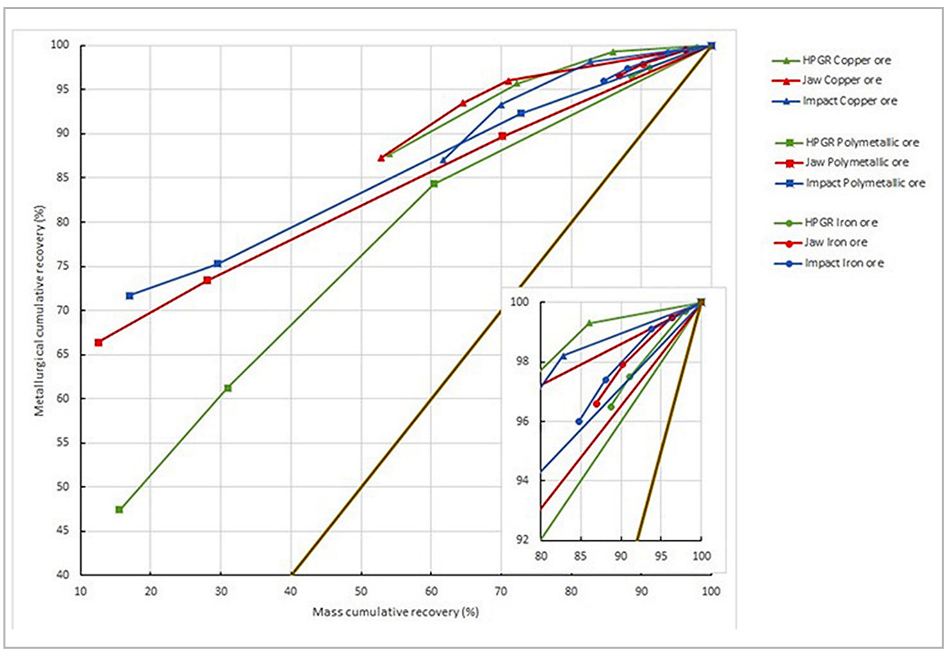


Figure 4 – Metallurgical recovery vs. Mass recovery – fraction – 6.35 + 3.35 mm.

Figure 4 and Tables 1, 2, and 3 show that pre-concentration, for the size fraction evaluated, is effective for sulfide copper and polymetallic ores, since they indicate high metallurgical recovery along with reduced mass recovery. Therefore, these two ores presented a good ore liberation from the gangue. In the case of iron ore, approximately 15% of the mass with less than 5% iron could be discarded. This gain is not as significant as in the case of other ores, but the method could still be an option to be further investigated in the future. It is noteworthy that the results illustrated here refer to the evaluation of the pre-concentration for the studied size fraction and with the use of the dense liquid test. Industrially, the results will be lower than those illustrated here. The use of dense media equipment, more expensive and complex, will result in results closer to those illustrated here. If jigs are chosen, which are simpler to operate and with lower operational costs, the results will be lower (Sampaio & Tavares, 2005).

Regarding selective comminution, for the size fraction evaluated, polymetallic ore showed a slightly higher metallurgical recovery for the floated at 2.75 g/cm3 using an impact crusher, with an approximately 3% difference compared to the jaw crusher and a remarkably low metallurgical recovery when using the HPGR. The copper ore and the iron ore, in turn, showed no differences when using different comminution methods. Thus, different ores have different physical characteristics, resulting in higher or lower mineral liberation depending on the comminution mechanism adopted (Hesse; Popov; Lieberwirth, 2017).

4. Conclusions

Using different samples of sulfide copper, polymetallic, and iron ores, tests were conducted based on different breakage/comminution mechanisms (compression, impact, and bed compression) to assess the pre-concentration and selective comminution responses.

Test results for the size fraction evaluated have shown that sulfide copper and polymetallic ores provided a good response to pre-concentration, with iron ore presenting inferior performance. For a 2.85 g/cm³ cut-off density, the sulfide copper ore's mass and metallurgical recoveries were 65% and 95.9%, respectively. The polymetallic ore delivered 70% mass recovery and around 90% metallurgical recovery for copper provided the separation density was 2.75 g/cm³. Mass recovery in the case of iron ore amounted to 84.7% and metallurgical recovery to 96% for a separation density of 2.95 g/cm³. Discarded masses (35% for sulfide copper ore, 30% for polymetallic ore, and 15% for iron ore) would represent savings for ore processing plants as they would not go through the subsequent comminution and concentration stages.

A comparison among the various comminution mechanisms showed that the impact crusher presented the best response for polymetallic ore in terms of copper mineral liberation. The copper ore and the iron ore, in turn, did not show significant differences among the tested methods.

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