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IMPACTS ON ENERGY CONSUMPTION AND WEAR IN GRINDING CIRCUITS WITH A PRE-CONCENTRATION STAGE

M.G. Bergerman [1,*], D. Jose Neto [2], E. S. Mano and [3] and A. P. Chaves [4]

[1] *Mining and Petroleum Engineering Department, University of Sao Paulo, e-mail: mbergerman@usp.br*

[2] *Mining and Petroleum Engineering Department, University of Sao Paulo, Brazil*

3 Mining and Petroleum Engineering Department, University of Sao Paulo, Brazil

[4] *Mining and Petroleum Engineering Department, University of Sao Paulo, Brazil*

ABSTRACT

More complex ore comminution and concentration operations have found increasing application in the mining industry due to lower grades and higher complexity of the available ores. An alternative to coping with the higher capital and operating costs of ore processing plants is the use of pre-concentration stages. They allow removing a significant mass of material with little or no content of the relevant mineral before the ore is fed into the processing plant, with the consequent reduction in the mass to be processed in downstream operations. Significant benefits arise out of the use of pre-concentration, such as higher contained metal output without the need to increase the grinding or flotation capacity, and longer mine life. The grade of marginal ores could be enhanced to a level that would make their exploration economically feasible, which would result in increasing exploitable reserves. Nevertheless, few studies to date have assessed the resulting impacts on ore grinding energy consumption and wear after the gangue is removed through pre-concentration operations. This study evaluated the energy consumption and wear of grinding circuits in Brazilian mining operations in which the feed has gone through a pre-concentration stage. Such assessment was based on different samples of sulfide and oxide ores. Laboratory tests were carried out to investigate the power consumption and wear of grinding circuits with and without a pre-concentration stage. Laboratory test results were used to simulate industrial grinding circuits based on both alternatives and illustrate the environmental and economic benefits of each one.

KEYWORDS

Concentration, Pre-concentration, Comminution, Bond Work index, Wear, Operational costs.

INTRODUCTION

Increasingly complex ore concentration operations in several stages have found broadening application in recent years in view of lower grades and higher complexity of the available ores. An alternative to coping with the higher capital and operating costs of ore processing plants is the use of pre-concentration stages. Different ore processing technologies can be used for that purpose, such as magnetic separation, density segregation, and separation methods based on high-tech sensors (ore sorting). Currently, the most common methods are gravimetric processes, in view of their low cost, particularly jigging and dense medium separation methods, such as the drum and cone separators manufactured by Western Machinery Company, Teska, Drewboy, Norwalt, Dynawhirlpool and Tri-flo, and dense medium cyclones (CAMPOS; LUZ; BRAGA, 2010). The use of dry ore sorters has also grown significantly in recent years (Jose Neto et al. 2017). The selection of the separator type depends essentially on the ore particle size, required flows, and operating density ranges. All these methods may even be used after preferential blasting in mining (Grigg & Delemontex, 2015).

The use of these technologies allows discarding an ore fraction with little or no amount of minerals of interest prior to feeding into the processing plant, which reduces the mass to be processed in downstream operations. The outcomes are lower capital and operating costs and mitigation of the project's environmental impact. Significant benefits arise out of the use of pre-concentration, such as higher contained metal output without the need to increase the grinding or flotation capacity, and longer mine life due to the reduction in the ore cut-off content and the possibility of disposing the coarse tailings from the pre-concentration into piles, which eliminates the need for tailings dams. Klein et al. (2010) estimate the savings in overall energy consumption at 20% in the case of projects using pre-concentration stages. Table 1 illustrates the main gains arising from this kind of approach.

Table 1 – Benefits of pre-concentration. Not all of these benefits occur simultaneously and they depend on each specific application (source: adapted from Bergerman *et al*., 2014; Cresswell, 2001; Grigg & Delemontex, 2015)

Benefits	**Cause**
Reducing energy consumption per ton of metal produced	The removal of gangue reduces the mass fed into the mill, so energy is not spent grinding material that is not of interest, thus reducing the required power. Furthermore, usually gangue material has a higher work index (WI) than that of ore and, therefore, once it is discarded, the grinding circuit's specific energy consumption decreases.
Increasing tailings dam life	A smaller volume of gangue is processed; consequently, a smaller amount of waste has to be disposed of in tailings dams.
Reusing waste	As the waste from the pre-concentration is coarse and can be easily dewatered, it may be used for paving roads or filling galleries (backfill), among other applications; depending on its characteristics, it can be sold as a byproduct, thereby generating profit.
Reducing water consumption	There is less ore mass to be treated.
Longer mine life	By rejecting part of the gangue, the mine cut-off grade decreases, which allows the exploitation of marginal ores; as a consequence, reserves increase.
Positive impact on	Pre-concentration eliminates fluctuations in the grade of the flotation feed. In such a

flotation	case, reagent consumption can be optimized and the circuit can be simplified through a possible reduction in the usage of rougher, cleaner, and/or scavenger cells.
Positive impact on thickening	Reduction in demand for thickening capacity and flocculent consumption, particularly in the tailings, whose volume is reduced.
Increased production	The plant's feed throughput is lower, but of a better grade. Thus, it is possible to produce the same amount of metal at lower feed rates, obtaining a margin for an increase in production without requiring plant capacity expansion.

This technology has found extensive application in sulfide ore mines, like copper, nickel, lead, and zinc, in Africa, North America, and Australia. Located in Botswana, the Tati Nickel Phoenix Mine (MORGAN, 2009) reports the installation of a crushing and pre-concentration stage with dense medium cyclone (DMS) with 1,600 t/h capacity to process ores from 25 mm to 1 mm. This plant enabled to discard 60% of the ROM ore. Due to the change in the grinding circuit feed characteristics as a result of the pre-concentration, an additional gain was achieved, i.e., the grinding circuit capacity was increased by 40%, to 650 t/h. Fourie et al. (2007) present the assessment results of using the DMS arrangement at Rosh Pinah Zinc Corporation's mine in Namibia. Ore from an underground mine, with an approximately 3% zinc content, went through pre-concentration, crushing, and classification between 32 and 16 mm. The zinc content in the concentrated reached 9%. For a 2.85 t/m^3 density ore, metallurgical recoveries of around 90% were achieved, with a 30% mass recovery. The use of a pre-concentration technology based on ore sorters and X-ray sensors is also under evaluation. The company is planning to build an underground pre-concentration plant with an aim to avoid transporting tailings to the surface. Cresswell (2001) cites the great application potential of this technology and describes a number of positive results in mines in Africa, Mexico, and China. The author reports metallurgical recoveries ranging from 90% to 95% of the metals of interest upon disposal of 15% to 30% of the mass that would otherwise be fed into the mill. Other examples of industrial applications for pre-concentration are shown in Table 2.

Table 2 – Industrial applications of pre-concentration and process performance

Pre-concentration method	Ore type	Mine location	Feed size (mm)	Mass rejected (%)	Metal recovery (%)	Reference
DMS cyclone	Ni sulfide	Phoenix, Botswana	25–1	60	85	Morgan, 2009
Coarse screening after preferential blasting	Au and Cu sulfide	Telfer, Australia	<20	60	> 80 (both Au & Cu)	CRC ore, 2016
Pressure jig	Polymetallic (Ag, Zn, Pb)	Pirquitas, Argentina	12–2	50	80–90	Grigg and Delemontex, 2015
Ore sorting	Wolframite pipes in quartz	Wolfram Camp, Australia	100–15	90–95	80–85	Lessard et al., 2014
Magnetic separator	Ni associated with pyrhotite	Whistle, Canada	5–2.5	38	80	Vatcha et al., 2000

This technology has already been used in Brazil's Nitroquímica's fluorite mine, which was shut down in 2009, at Morro da Fumaça, state of Santa Catarina (SAMPAIO et al., 2001). The Largo Resources' vanadium mine in Maracás, state of Bahia, makes use of a pre-concentration stage with magnetic separators. Anglo American's niobium mine in Catalão, state of Goiás, is implementing a similar circuit, also using magnetic separation. Laboratory studies on Brazilian deposits of different ores of nickel, zinc, lead, and copper sulfides indicate significant gains in terms of enhanced metallurgical recovery, with disposal of approximately 50% of the ore mass as tailings containing less than 10% of overall metal in the case of laboratory tested ore feeds (Bergerman et al. 2012; Bergerman et al. 2014; Uehara et al. 2017; Peres et al. 2017, Moreira et al. 2017; Jose Neto et al. 2017)).

In addition to the aforementioned gains arising from pre-concentration, benefits such as lower energy consumption and reduced grinding circuit wear are also expected, as the elimination of the gangue prior to the grinding stage may reduce the material Work Index (WI) and abrasiveness (AI), once the gangue minerals are more competent and abrasive. This study evaluated the energy consumption and wear in Brazilian grinding circuits in which the feed went through a pre-concentration stage. Such assessment was based on different samples of sulfide and oxide ores. Laboratory tests were carried out to investigate the power consumption and wear of grinding circuits with and without a pre-concentration stage. Laboratory test results were used to simulate industrial grinding circuits based on both alternatives and illustrate the environmental and economic benefits of each one.

MATERIALS AND METHODS

Copper sulfide ore and oxide niobium ore from Brazilian greenfield projects were used in this study. Copper ore samples were taken from the product of a jigging pre-concentration trial carried out on material with particle size ranging from 3 to 10 mm. Details of the jigging process are described in [3]. Niobium ore samples were taken from a magnetic pre-concentration trial carried out with particle size ranging from 32 to 12,7 mm. The samples were weighed and prepared to obtain the required mass for chemical and mineralogical characterization, based on X-ray fluorescence (FRX) and X-ray diffraction (DRX) techniques, at LCT/USP.

The method proposed by Bond (1960) was used to assess the energy consumption in grinding circuits using the sample under study. The adopted procedure was in line with the parameters described by the author, with a 150 m closing mesh.

Abrasiveness tests on niobium ore were carried out according to the Bond method described by Bergstrom (1985), which is also called Bond's Abrasiveness Index. The standard test is carried out in a small 12-in diameter 4.5-in height drum, which is fitted with a 4.5-in concentric rotor inside. A 3x1x0.25-in steel plate (500 Brinell) is fastened to the rotor and the drum is charged with 400 gr of sample with particle size ranging from - ¾" + ½". The objective is to wear out the plate, with the drum containing the sample running at 70 rpm for 15 minutes in one direction. This procedure was repeated four times for each sample. The resulting AI is the steel plate's loss of mass (in grams).

The Bond test could not be used to determine the abrasiveness of copper ore because the sample particle size was smaller than 10 mm. Instead, the LCPC test was used, which has a good correlation with the Bond's AI, as illustrated in the literature (Metso, XXXX, Peres, 2017). Figure 1 illustrates the results achieved by Peres et al. 2017, showing the correlation between AI results provided by the Bond and LCPC methods.

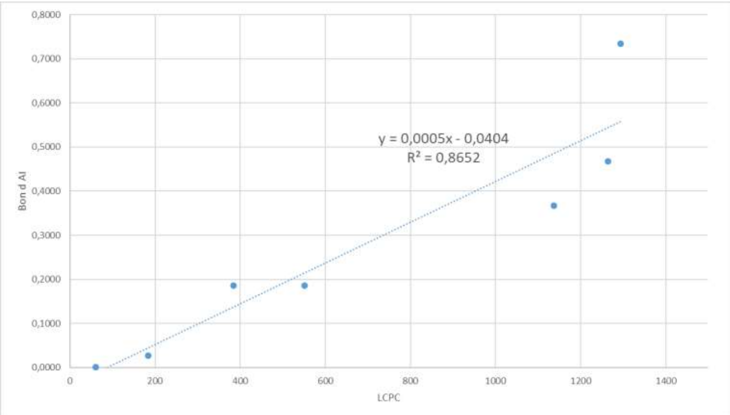

Figure 1: Correlation between Bond AI and LCPC [8]

The LCPC tests were carried out according to the test procedures set out by the French standard P18-579. The abrasion equipment consists of a motor that rotates a metal plate inside a cylindrical recipient containing 500 g of sample with a grain size between 4 and 6.3 mm. The standard metal plate is manufactured from low carbon steel (C1015), 50x25x5 mm in size, with Rockwell hardness from 60 to 75 HRB. The rotor to which the metal plate is coupled rotates for five minutes at 4,500 rpm inside the sample recipient. Abrasiveness is determined by weighing the metal plate before and after the test. The recorded loss of mass is used to calculate the characteristic material abrasiveness. The higher the loss of mass, the more abrasive the material. As set out in the French standard, the LCPC abrasiveness index is calculated according to Equation 1:

$$\mathrm{LCPC} = 1000 \times 1000\ (\mathrm{m_{ip}} - \mathrm{m_{fp}})\ /\mathrm{M} \qquad (1)$$

Where: mip is the plate mass prior to the LCPC test;
mfp is the plate mass after the LCPC test; and
M is the sample mass (500 ± 0.2 g).

Prior to commencing the tests, the test metal plates for LCPC and Bond Abrasion tests were submitted to Rockwell B hardness tests and measurements at IPT to ensure that their hardness met the applicable requirements. The results confirmed that the plates had the required hardness for each test. Care was taken to use plates from the same lot and manufacturer in all tests, with an aim to prevent possible manufacturing variations from affecting the test results. Moreover, all samples were submitted to duplicate or triplicate tests to minimize the influence of possible test errors. The average relative standard deviation was 5% for the WI test, 2% for LCPC, and 10% for Bond's AI, which were deemed adequate for the respective tests.

RESULTS AND DISCUSSION

Tables 3 and 4 illustrate the chemical and mineralogical characterization results for both samples.

Table 3 – Chemical and mineralogical characterization results for the copper ore sample

Sample	Mineralogical composition (prevailing phases)	Mass (%)	Metal (%)	Concentration of components (%)							
				Cu	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
Feed	Quartz, pyrite, magnetite and chalcopyrite	100	100	0.75	52.6	8.36	15.9	2.19	2.11	3.42	1.02
Concentrate	Chalcopyrite, quartz, pyrite and magnetite	44	85	1.45	40.5	6.02	25	1.62	1.52	1.85	0.673
Tailings	Quartz, albite, chlorite, microcline and mica	56	15	0.2	65	10.6	8.42	2.45	1.77	4.67	1.35

Table 4 – Chemical and mineralogical characterization results for the niobium ore sample

Sample	Mineralogical composition prevailing phases mass (%)	Mass (%)	Metal (%)	Concentration of components (%)					
				Nb2O5	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
Feed	Pyrochlore (1,1), K-Feldspar (24), Clay minerals (12), FeMg silicates (6,7), Calcite (23), FeMg carbonates (11) and magnetite (4,7)	100	100	0,96	33,55	7,28	14,94	14,53	6,03
Concentrate		38,4	89,0	2,22	20,02	3,54	27,29	17,22	6,37
Tailings		61,6	11,0	0,17	41,96	9,60	7,26	12,85	5,82

The results given in Table 3 show that the jigging pre-concentration operation allowed concentrating 85% of the copper in the sample in just 44% of the mass, which represents a significant gain in the ore beneficiation process. For the niobium ore, in Table 4, the magnetic pré-concentration operation allowed concentrating 89% of the niobium in the sample in just 38% of the mass.

Tables 5 and 6 illustrate the WI results for copper and niobium feeds and pre-concentration products.

Table 5 – Bond's WI results for copper ore pre-concentration products

	F80 (mm)	P80 (mm)	g/rev	WI (kWh/t)
Feed	2159	126	1.38	17.57
Concentrate	1732	116	1.56	15.64
Tailings	2452	134	1.15	20.76

Table 6 – Bond's WI results for niobium ore pre-concentration products

	F80 (mm)	P80 (mm)	g/rev	WI (kWh/t)
Feed	2568	117	1,96	12,19
Concentrate	2330	117	2,01	12,14
Tailings	2246	109	1,93	12,05

In the case of the copper ore sample, a significant reduction (approximately 10%) in the WI for the pre-concentration product (15.64 kWh/t) can be noticed when compared to the pre-concentration feed (17.57 kWh/t).

Such reduction was expected in view of the elimination of the gangue, which consists mainly of silicates, whose WI is higher, while the pre-concentration product has a larger proportion of sulfides, whose WI is lower.

In the case of the niobium ore sample, no variation was found in the WI result. This is explained by the sample's mineralogical characteristics, as the pre-concentration product features a high magnetite content, whose WI is high.

Tables 7 and 9 show the abrasiveness test results.

Table 7 – Abrasiveness test results for the copper ore sample

	LCPC	Bond's AI (g)*
Feed	1059	0.489
Concentrate	782	0.350
Tailings	1105	0.512

*Calculated from the LCPC result

Table 8 – Abrasiveness test results for the niobium ore sample

	Bond's AI (g)
Feed	0.131
Magnetic	0.097
Non-magnetic	0.187

The abrasion test results point to significant gains from the pre-concentration process in terms of lower abrasiveness of the ore to be fed into the mill. In the case of the copper ore, the pre-concentration product AI (0.350 g) was lowered by approximately 28% in relation to the sample fed during the pre-concentration stage (0.489 g). Such reduction was expected in view of the elimination of the gangue, which consists mainly of silicates, whose abrasiveness is higher, while the pre-concentration product has a larger proportion of sulfides, whose abrasiveness is lower. A similar result was obtained for niobium ore, with a 26% reduction in the pre-concentration product abrasiveness (AI of 0.097 g) when compared to the feed abrasiveness (AI of 0.131 g).

CONCLUSIONS

This study described the gains in the comminution process in projects using a pre-concentration stage. In addition to the gain in terms of reduction of the mass to be fed into the mill, the elimination of the gangue has led to a significant reduction in the grinding energy as measured by the Bond's AI. In the case of copper ore, the Bond's WI and AI were reduced by 10% and 28%, respectively, in the material to be fed into the mill. In the case of niobium ore, the Bond's AI was lowered by 26%, although no impact has been seen in the Bond's WI. Quantifying such gains is of utmost importance to justify the implementation of pre-concentration projects because they require additional capital and operational costs, notwithstanding the gains achievable through the reduction in the feed mass. Such costs can be better explained through proper quantification of the gains for the whole process arising from pre-concentration operations.

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