Journal of Minerals and Materials Characterization and Engineering, 2025, 13(5), 267-291
https://www.scirp.org/journal/jmmce
ISSN Online: 2327-4085
ISSN Print: 2327-4077

The Effect of Particle Size Distribution on the BWI and Energy Consumption of Harder Ores

Wladmir José Gomes Florêncio[1*], Rafael Teixeira Rodrigues[2], Vládia Cristina Gonçalves de Souza[2]

[1]Federal Institute of Piauí, Paulistana, Brazil
[2]Department of Mining Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil
Email: *wladmir@ifpi.edu.br, rafael.teixeira@ufrgs.br, vladia.souza@ufrgs.br

How to cite this paper: Florêncio, W.J.G. and Rodrigues, R.T. and de Souza, V.C.G. (2025) The Effect of Particle Size Distribution on the BWI and Energy Consumption of Harder Ores. *Journal of Minerals and Materials Characterization and Engineering*, **13**, 267-291.
https://doi.org/10.4236/jmmce.2025.135015

Received: August 8, 2025
Accepted: September 23, 2025
Published: September 26, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

When it comes to fragmentation, the grinding process is the most significant in terms of energy consumption and can directly affect the viability of mining activities, especially in this new context of energy transition and hard minerals. Over the years, several researchers have presented various procedures for determining grindability. However, in practice, the Bond test remains one of the most widely used methods. The aim is to determine the Bond Work Index (BWI), which would describe the energy consumption to reduce a particle of infinite size to the so-called P_{80} (80% passing through 100 µm). However, the Bond test is time-consuming and does not take into account the particle size distribution of the ore during the test; it is only used when passing through the test mesh. Therefore, this study proposed a test similar to Bond, but carried out with a maximum of three grinding cycles, in addition to determining the SWI (Simplified Work Index) by means of a granulometric factor. The Reduction Ratios (RR) or A_{80}/P_{80} were correlated with the SWI and the SWIop (Simplified Operational Work Index)/SWI ratios or (RWI—Relationship between Work Index: SWIop/SWI). The effect of the particle size distribution of the feed in restricted size ranges was also verified. The results showed that the SWI estimated by the new methodology showed relative differences of less than 12% when compared to the BWI values. And that the particle size distribution of the feed influenced the results. The correlations (RR, SWI) and (RR, RWI) are strong, with R^2 very close to 1.

Keywords

Grinding, Bond Standard Assay, Breakage Characteristics, Harder Ores

1. Introduction

Comminution processes are the most significant regarding energy consumption, which directly impacts the viability of mining activities [1] [2]. Crushing and grindability became very important parameters to characterize the resistance of raw materials to fragmentation [3]. Especially, in this new context of energy transition and harder ores, with lower grades or smaller release sizes [4], we should review whether the main assays and grinding parameters could be better applied to the industrial scale.

There are several procedures to determine crushability and grindability; in practice among the most used methods is the Bond assay [5]. This study aims to determine the Work Index (WI), which would describe the energy consumption to reduce a particle of infinite size to the so-called P_{80} (80% passing through 100 μm). On the other hand, Bond law can be applied only to a restricted range of the Hukki function, which shows an increase in energy consumption when the particle size is smaller (P_{80} between 10.000 μm and 100 μm). Although we can make some corrections, changing the exponents of the equation provided by Bond, especially below 100 μm, energy consumption increases very rapidly according to the Hukki function, making this parameter easier to underestimate. Furthermore, not all materials adhere to the Bond law in the aforementioned size range.

The Rittinger law [6] is applied on a range between 100 μm and 10 μm, where the specific energy consumption can also be underestimated. Below 10 μm, the uncertainties increase dramatically as shown by [7] and [8]. In addition, the power of the mill should be estimated taking into account not only the WI, but also as function of the size and density distribution of the charge, as well as, the geometry of the equipment, the abrasiveness of the ore, the resistance to breakage of the ores for each particle size distribution, the breakage velocity and resultant size distribution of the particles (appearance function and selection function), according to [9]-[11]. All these parameters can impact the specific energy consumption. The mathematical functions that describe these processes can be determined with laboratory assays [12]. However, these assays are performed with a few samples and generally come from pieces of drill cores, which may not be representative on the industrial scale [13]. This also occurs because the ores are usually subjected to blasting, which can modify these breakage characteristics. The blending, the circuit design, the number and type of crushing and grinding equipment, work together with a specific configuration. All these factors can modify the breakage characteristics, as well as the specific energy consumption [14] and [15]. Then, industrial-scale testing based on the optimized sampling protocols and appropriately designed and automated sample collection equipment is essential and should perhaps be prioritized instead of laboratory assays. This is not always possible, unfortunately.

Although we know that tests with reduced amounts of mass may result in low representativeness [16], many researchers have discussed more about the time to carry out a Bond assay [17]-[20]. They are proposing alternative methods that would be simpler and faster to determine the WI (also called BWI, Bond Work Index). **Table 1** shows some of these alternative procedures.

Table 1. Procedures and equations proposed to determine the WI by contemporary researchers.

Authors	
Smith and Lee (1968)	$\text{WI,SL} = 1.1 \times \frac{16}{G^{0.82}} \times \sqrt{\frac{P_{100}}{100}}$ Bond WI estimation in the first grinding cycles
Kapur (1970)	$\text{WI,K} = 1.1 \times 2.648 \times P_{100}^{0.406} \times K_2^{-0.81} X\left(X \times M\right)^{-0.853} \times \left(1 - X\right)^{-0.099}$ Bond WI estimation in the first two grinding cycles
Karra (1981)	$\text{WI,Kr} = 1.1 \times 9.934 \times P_c^{0.308} \times G^{-0.696} \times F_{80}^{-0.125}$ Bond WI estimation in the first two grinding cycles
Mular and Jergensen (1982)	$\text{WI,An} = \frac{A}{\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right)}$ Does not require standard Bond mill (ANACONDA Methodology)
Menéndez-Aguado *et al.* (2005)	$\text{WI,MA} = \frac{44.5}{P_{100}^{0.23} \times \left(2.15G\right)^{0.82} \times \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right)}$ Smallest sample mass required for the test
Saeidi *et al.* (2013)	$\text{WI,SA} = \frac{5.6}{\left(-1E - 0.6t^2 + 0.0004t + 0.3397\right)^{0.75}} \times \frac{1}{\frac{10}{\sqrt{-0.1085t + 122.56}} - \frac{10}{\sqrt{F_{80}}}}$ Grinding cycles with time intervals of 20, 60, 120 and 180s
Duque *et al.* (2014)	$\text{BWI} = \frac{1.1 \times 44.5}{MT^{0.23} \times \left(0.0641 \times MT^{0.0641}\right)^{0.82} \times 10 \times \left(\frac{1}{\sqrt{0.7124 \times MT^{1.0271}}} - \frac{1}{\sqrt{A_{80}}}\right)}$ Determination of WI for titanium ore and any test mesh

[21] reduced the assay time by using only two grinding cycles to determine the BWI. Later, [22] proposed using three grinding cycles to obtain more reliable results. [23] used first-order grinding kinetics based on the results of two grinding cycle tests to develop a faster method and to determine the BWI (Bond Work Index). [24] provided an abbreviated method for determining BWI that consisted of two grinding tests. The first test was performed with only one grinding cycle and the second test with three grinding cycles. [25] also presented an abbreviated method that can be performed with two, three or four grinding cycles. Each grinding cycle was performed in the same way as in the standard Bond procedure.

[26] developed a methodology called Anaconda, which was implemented at the mining company Vale (Brazil). [27] proposed alternatives to the Bond test, but

the suggested equations require calibration (adjustment). Each material has a different correlation with Bond's WI, so their analyses are limited to a specific type of.

[28]-[32] proposed smaller mills to determine the BWI. They investigated variations in mass and size distribution of the grinding media in the standard Bond assay (mill 30.5 cm × 30.5 cm). [33]-[39] performed the Bond assay varying test meshes and verifying if there was an adherence to the Bond law. They interpreted their results according to the theory of Griffiths A.A. [40]: smaller particles are more resistant to breakage and show higher specific energy consumption.

[41] determined in the laboratory, a parameter called W_{Fm} (BWI for fine materials). These were tests with samples smaller than 3.35 mm, such as the standard Bond test. They generate an equation to estimate the BWI for meshes smaller than test mesh (reference mesh). For example, they perform the Bond assays for 150 μm (test mesh), and estimate the WI for 100 μm and 75 μm. Their experiments used a significant sample number as well as a large range of ores (dolomite, copper ore and quartzite). The authors considered this method to be very accurate (absolute errors did not exceed 2.5%).

In another approach, [42] proposed a methodology to estimate the WI for product particle sizes (P_{80}) outside the range in which Bond law can be applied. They studied particle size distribution for restricted ranges and since it impacts the energy consumption, regarding the desired P_{80}. They tested the following ranges (F80): +2 mm, −2 mm + 0.9 mm and −0.9 mm. Furthermore, the experiments were carried out with a significant variety of ores (dacite, basalt and six types of copper ores) and for the following test meshes: 300, 212, 150, 106 and 75 μm. The authors proposed equations to correct the WI values, based on results of tests performed on an industrial scale. They found errors varying from 0% to 12%.

[43] used the Hardgrove mill traditionally used in laboratories to determine the energy required to grind coal in a roller mill. This test required 50 g of sample, and the result was based on the amount of fines at the end of grinding at a fixed time. Their research involved a modified Hardgrove to predict the BWI. Their test involved measuring torque, a fixed sample volume with different particle feed sizes from the Hardgrove standard, and determining the specific energy related to the percentage of product passing through the Bond test closing screen opening, defined as the size-specific energy. His results indicated that for a set of 13 samples with the 150 μm closing screen, the average error associated with the predicted BWI is within ±2.3%. Other results indicate an error of ±3.1% for 20 samples with the 106 μm closing screen.

From the research, it can be concluded that the Bond assay and WI parameter are still being widely applied. In addition, the general trend is to reduce the masses and make the grinding assays easier to perform. Researchers sometimes use mills smaller than the standard Bond mill. On the other hand, we believe that it would be better to use larger equipment (larger masses) to reduce the uncertainties of energy consumption estimates regarding the industrial scale.

The works cited above show that the determination of WI is largely dependent on the Mobility index (Mob), A_{80}, and P_{80}. In other words, they depend on the Bond method, which provides the result of only one point on the curve. This makes these methods very limited. Therefore, the motivation for our research is to present a new methodology that is capable of showing the complete particle size distribution of the feed and product, which does not require the calculation of P_{80} and Mob to determine the WI, which is a methodology that is totally independent of the Bond test for estimating WI, simulates the actual residence time of particles other than zero in the mill, and estimates WI based on its power.

Then, this study proposed an assay similar to the Bond, but carried out with a maximum of three grinding cycles, larger amounts of mass and in a mill with twice the length of the standard Bond mill. We would like to verify whether the results of the Bond assays (BWI) were similar to those obtained by the proposed new assay called Simplified assay (SWI—Simplified Work Index). We also wished to verify the effect of the particle size distribution of the feed (restricted size ranges) on the BWI and SWI (−3.35 + 0.85 mm and −0.85 + 0.15 mm).

The following parameters were measured in this study: particle size distribution of the product at different grinding time intervals, mass balance to define the work index (BWI and SWI), and the specific energy consumption. Furthermore, chemical and mineralogical characterization was carried out to verify possible differences in the composition of each tested size class.

In the end, we were able to present an equation to determine the SWI, based on the new assay, according to the particle size distribution of the feed samples and the P_{80} required. We measured the following parameters: laboratory mill power, mass and grinding time basically. After each grinding cycle of Bond standard assay, we had to remove the mass passing through the test mesh and replace it with a new material (new batch of feed). We also do not know, in fact, which size distribution is actually feeding the mill. The Bond assay only requires that the material be crushed below 3.35 mm, without considering the effect of the feed's size distribution. In the simplified test, all material is classified after a short time interval and all material is then mixed and returned to the mill for a new grinding cycle. This would simulate a residence time of the fine particles different from zero.

Therefore, despite the limitations of the Bond assay and the WI parameter itself, as the industry continues to use it frequently, we, firstly, wished to verify the effect of the particle size distribution of the feed on the energy consumption for a large range of P_{80}. This is especially important in cases where mining progresses and we come across harder rocks (resistant to breakage). At this stage, we almost always need to improve the blasting and one question often arises: can we reduce energy consumption by making the size of particles smaller (reducing the reduction rate in the mills, despite Griffiths A.A., 1921)?

2. Methodology

The simplified assay was carried out in a ball mill measuring 30.5 cm × 61.0 cm, with the same grinding media size distribution as the standard Bond assay, but with twice the grinding load and mass, due to the length of the mill. A significant number of tests were carried out with two types of Brazilian ores with high resistance to breakage: pegmatite from Paraíba (Brazil) and copper sulfide ore. Furthermore, Bond assays were carried out using the same materials from the same lots. About 75 kg of rock was prepared, consisting essentially of feldspar (pegmatite). This material was crushed to a granulometry minor than 3.35 mm, minimizing the generation of fines, as determined in the technical standard for the Bond WI [44]. Afterwards, granulometric analyses of the material were carried out with a sequence of Tyler series from -3.35 mm to +0.150 mm. The granulometric distribution showed a median of 0.85 mm, following the Gaussian pattern [45]. Based on this result, the material was separated into two portions according to the median: +0.85 mm (coarse) −0.85 mm (fine). Thus, two lots with very different granulometric distributions were produced to verify the effect on the BWI, among other measured parameters. Assays were also carried out with pegmatites with a particle size distribution of −3.35 mm, which was called "mixed lot". **Figure 1** shows the average of three lots for coarse, fine and mixed lots of feed.

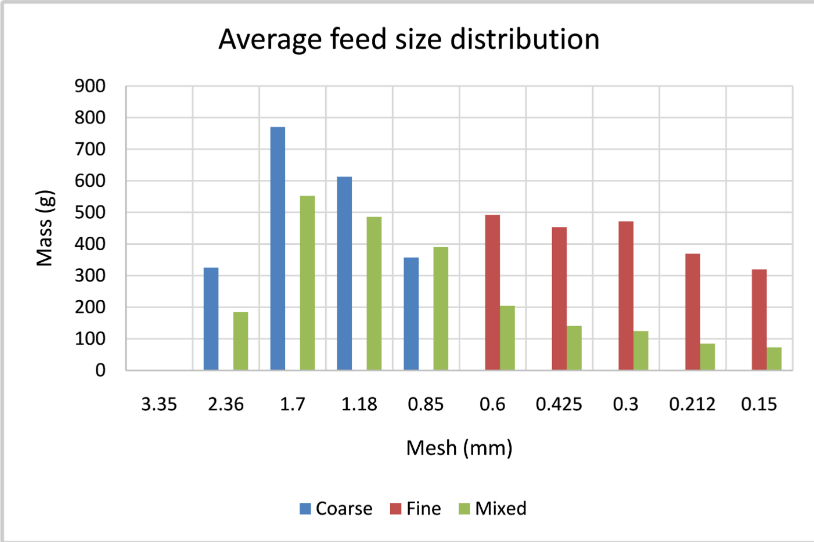


Figure 1. Particle size distribution for pegmatite ore.

Feldspar was used as the reference ore in this study due to its abundance, well-defined chemical composition, and physical properties, which make it a versatile material for various industrial applications.

In order to obtain the aliquots for carrying out the grinding assays, the mass was determined according to the procedures described by Bond [46]. In this case, a mass that occupies a volume of 700 ml is required in a beaker of 1 liter. This procedure is repeated three times, and the average value of the masses is used. For simplified assays, twice these mass amounts were used. For standard Bond and simplified assays, the test mesh was 0.150 mm for pegmatite and 0.106 mm for copper ore.

Assays with sulfide ore were carried out using only samples with a single feed particle size distribution (−3.35 mm) according to the standard Bond assay. Thus, these lots were not separated into coarse and fine (mixed lot), as shown in **Figure 2**.

Remembering, that the simplified assay is different because for each short grinding interval, the material passing through the test mesh is neither discarded nor replaced by new feed. After each grinding cycle, the complete particle size distribution is determined, and then, all the material is placed back into the mill for a new grinding cycle. This procedure continues until the desired mass passing through the test mesh is obtained. This mass corresponds to 28.5% of the feed material for both kinds of assay, simulating a closed circuit in a stationary state. Therefore, there is a fundamental difference: a simplified assay simulates a non-zero residence time of the finer particles. On an industrial scale, we know that a major part of the fine material still remains inside the mill, until it undergoes total classification and is removed from the grinding circuit.

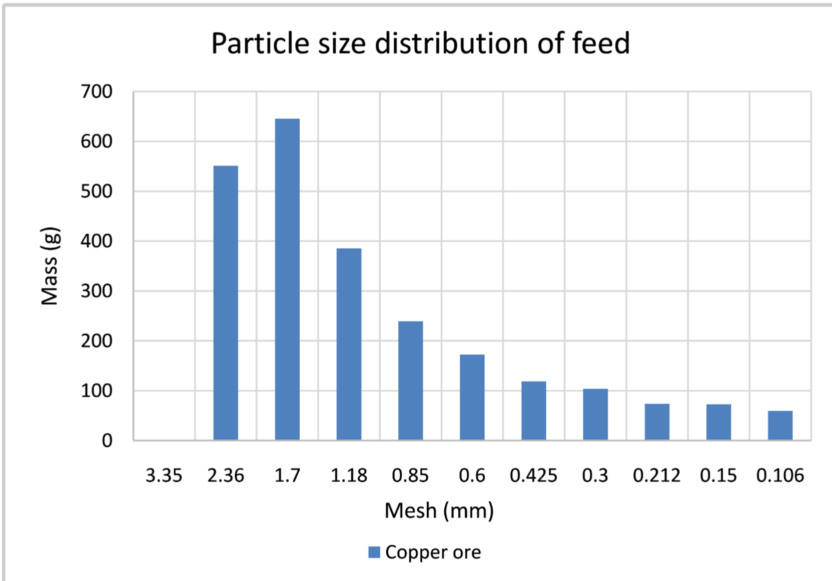


Figure 2. Feed particle size distribution for copper ore.

During the simplified assay, the material returns to the mill finer and possibly more resistant to breakage. When we simulate a non-zero residence time, regarding fine particles, we could, in theory, avoid an underestimation of the energy consumption. Therefore, it is very important to compare the parameters measured and obtained by the two types of assays. Generally, we expected higher energy consumption for results coming from the simplified assays. Anyway, by classifying the materials into two different and restricted size classes, we are trying to simulate the effect of the variation of the feed particle size distribution on the measured parameters. This objective arises from the fact that in the industry, blasted ore, even after crushing/classification, results in different particle size distributions [47].

The masses for each type of ore were respectively: 2.1 Kg for coarse and fine pegmatite and 2.25 kg for copper ore and mixed pegmatite. Dividing the masses obtained from the coarse and fine samples by 3.5, the mass to be achieved in the test mesh was approximately 600 g and 640 g for the mixed samples. In the case of copper ore, the mass to be obtained was 743 g.

Figure 3 shows a flowchart of the procedures to prepare the samples for the simplified assay (coarse and fine pegmatite, feldspar ore). Briefly, the samples were separated into narrow bands of particle size distribution. The test was then carried out as described, and based on the results, all parameters for the following test meshes: 0.300 mm, 0.212 mm, 0.15 mm, 0.106 mm and 0.075 mm were calculated.

Samples of mixed pegmatites and copper ore were prepared using the same procedures shown by the flowchart, Figure 3. The only difference is that there was no separation by class size, as already mentioned.

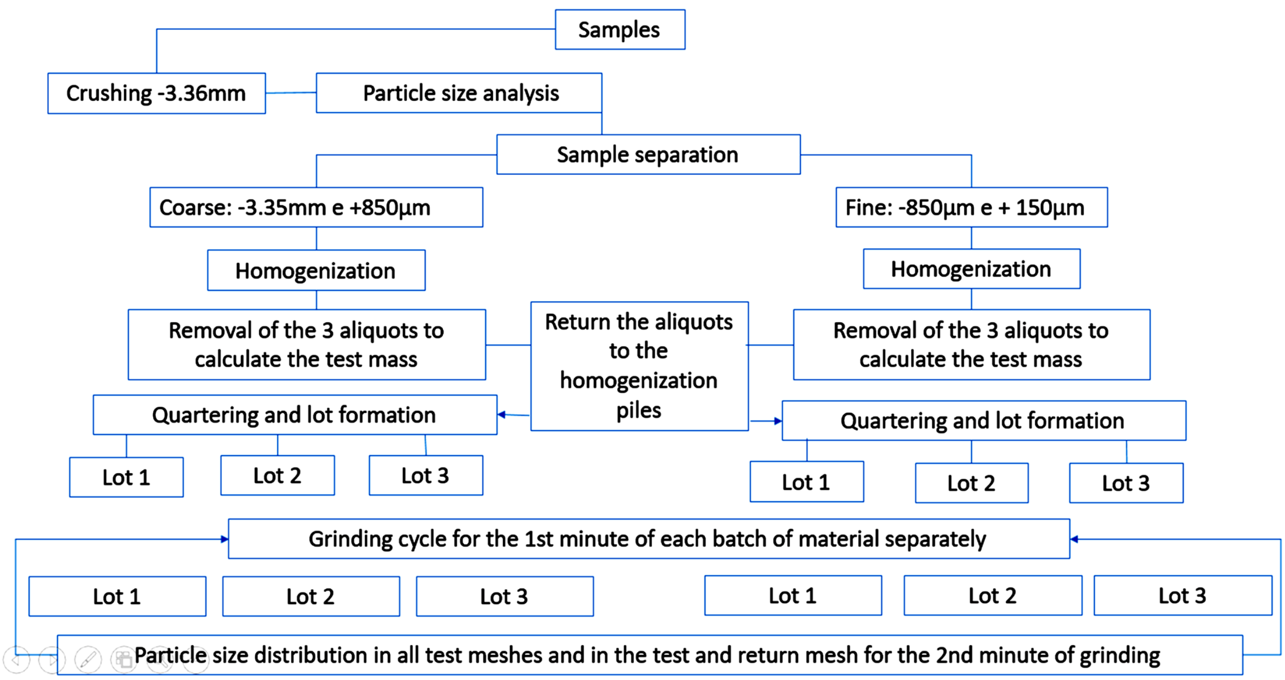


Figure 3. Flowchart of the procedures to prepare the samples for the simplified assay (coarse and fine pegmatite, feldspar ore).

During the simplified assay, the samples are comminuted initially for one minute and then the mill is unloaded and the complete particle size distribution is determined. The material is mixed and placed back into the mill, milled for another minute and procedures are repeated. After the second minute of grinding, an estimation of the time required to complete the test is made according to the desired mass (about 600g). The Bond assays were performed in a standard mill (30.5 cm × 30.5 cm), with a smooth coating, in order to compare the results obtained from both assays. The BWI was calculated by applying the Bond Equation (1).

$$\text{WI} = \frac{44.5}{Am^{0.23} \times Mob^{0.82} \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \times 1.102 \tag{1}$$

where, WI *is the* Work Index (kWh/t); *Am* is the test mesh (μm); *Mob is the* Grindability Index (g/rot); P_{80} is the mesh opening by where 80% of the product passes through and F_{80} is the mesh opening by where 80% of the feed passes through. The power of the mill was calculated applying Equations (2) and (3), according to [48]:

$$T = M_c g d_c + T_f \tag{2}$$

where, M_c is the total mass of the mill [kg]; d_c is the distance from the central point of the mill until the central point of gravity [m] and T_f is the required torque to overcome friction [N.cm].Finally, applying Equation 3, we have:

$$P = 2\pi N T_f \tag{3}$$

where, N is the rotation number of the mill (rpm); T_f is the required torque to overcome friction, which is calculated based on the mill information: power, reduction and rpm (**Table 2**). The mill rotation speed was only achieved due to the installation of a frequency inverter capable of increasing the mill rotation to 2.200 rpm when the reduction is applied.

Table 2. Technical information of the laboratory mill (simplified assay).

Power (HP)	Reduction	Rpm for 3 HP	Rpm applied
4.5	31	1.740	2.200

For a value of 70 rpm and a ratio 2.200/31, it was possible to find the required torque to overcome friction, by applying an empirical method, widely used in mechanical engineering as shown in Equation (4):

$$T_f = \frac{7.024 \times \text{Power}(\text{HP})}{\text{Rpm}(\text{reducted})} \tag{4}$$

Replacing the values in equation (4), we obtained 445.39 N.m. This is the torque required to mill rotate, according to the information shown by **Table 3** (replacing values in equation 2).

Table 3. Parameters for the laboratory mill (simplified assay).

Total load (Kg)	RPM	Dc (m)	g (m/s^2)
43.23 (Coarse Feldspar) 43.27 (Fine Feldspar) 43.41 (Mixed Feldspar) 43.76 (Copper ore)	70	0.13	9.81

The torque value applying equation 2 was 501.20 N.m and Applying equation

(3), we obtained a power of the mill equal to 2.70kWh. The energy consumption was calculated using Equation (5):

$$CE = P \times t \tag{5}$$

where EC is the energy consumption (kWh); P is the power of the mill and T is the grinding time (h).

To obtain SWI values equivalent to BWI values, based on the mill power, equation (6) was applied, where K is a granulometric factor, as shown in Equation (7).

$$\text{SWI} = \left(\frac{P \times t}{M}\right)^{K} \tag{6}$$

where, SWI is the Simplified Work Index (KWh/t); P is the power of the mill (kWh); t is grinding time (h); k is the granulometric factor and M is the mass (metric tons) passing through the opening of the test mesh.

The granulometric factor (K), shown in Equation (6), is the result of the relationship between specific energy consumption (CE) and the reduction ratio (RR), which are the relationships between the averages of A_{80} and P_{80}, as the reference opening of each sieve. The granulometric factor (K) also depends on the diameter of the mill. Based on these correlations, it was possible to establish an empirical formula for determining K. Thus, a ($K = 0.48$) was obtained for coarse pegmatites, a ($k = 0.55$) for fine pegmatites, ($k = 0.49$) for mixed pegmatites, and ($k = 0.49$) for sulfide ore.

$$K = \left(\sqrt{\frac{CE}{RR}}\right)^{D} \tag{7}$$

where, K: Granulometric factor; RR: Reduction ratio A_{80}/P_{80}; CE: Specific energy consumption in kWh and D: Mill diameter in m.

The operational energy consumption (SWI_{op}) was calculated by Equation (8).

$$\text{SWI}_{\text{op}} = \frac{CE}{Mt} \tag{8}$$

where (Mt) is the total mass of the assay. In addition, we performed a mineralogical characterization of the samples in order to show the possible differences between the fine and coarse samples.

We carried out X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD), in the Technologic Characterization Laboratory of the University of São Paulo (USP, Brazil). X-Ray Fluorescence (XRF) analyses were determined on the molten sample with lithium tetraborate, in the QZF-1 calibration (Quartz and Feldspar), relative to the quantitative analysis by comparison with certified reference materials, in an X-ray fluorescence spectrometer, Malvern Panalytical, Zetium model. Loss on Ignition (LF) was performed at 1020˚C for 2 h. X-Ray Diffraction (XRD) analyses were performed using the powder method for global feldspar (coarse + fine), using an Empyrean X-ray diffractometer with a position-sensitive detector. The crystalline phases were identified by comparing the sample diffractogram with the PDF2 databases of the ICDD—International Centre for Diffraction Data and ICSD—Inorganic Crystal Structure Database.

3. Results and Discussions

3.1. XRF and XRD Analysis

Table 4 shows the results of the X-ray fluorescence analyses for the coarse and fine feldspar samples. X-Ray Diffractogram. XRF analyses showed that coarse and fine feldspars are homogeneous, even after separating the sample into two fractions (coarse and fine), since they presented practically the same (%) SiO_2 and Al_2O_3 in their main constituents for both kinds of samples.

Table 4. X-ray fluorescence chemical analysis of the feldspar samples.

PEGMATITE (feldspar ore)		
Sample	COARSE	FINE
SiO_2 (%)	66.0	65.4
Al_2O_3 (%)	18.0	18.1
Fe_2O_3 (%)	0.06	0.20
MnO (%)	<0.01	<0.01
MgO (%)	<0.05	<0.05
CaO (%)	0.05	0.13
Na_2O (%)	3.19	3.15
K_2O (%)	10.9	11.0
TiO_2 (%)	<0.01	<0.01
P_2O_5 (%)	0.43	0.40
Cr_2O_3 (%)	<0.01	<0.01
ZrO_2 (%)	<0.01	<0.01
PF (%)	0.53	0.73

Table 5 shows the results for the global feldspar sample (coarse and fine), as does **Figure 4**, which presents the X-ray diffractogram. **Figure 4** shows the mineralogical composition. No difference was found between the samples. Samples are composed of minerals, such as microcline, anorthite, quartz and muscovite in minor quantities (possible presence).

Table 5. Mineralogical analysis by global XRD for feldspars (coarse and fine).

Legend	Mineral	
(blue)	Microcline	$K(AlSi_3O_8)$
(green)	Anorthite	$(Na_{0.45}Ca_{0.55})(Al_{1.55}Si_{2.45}O_8)$
(light green)	Quartz	SiO_2
(dark red)	Muscovite	$K(Al_3Si_3O_{10})(OH)_2$

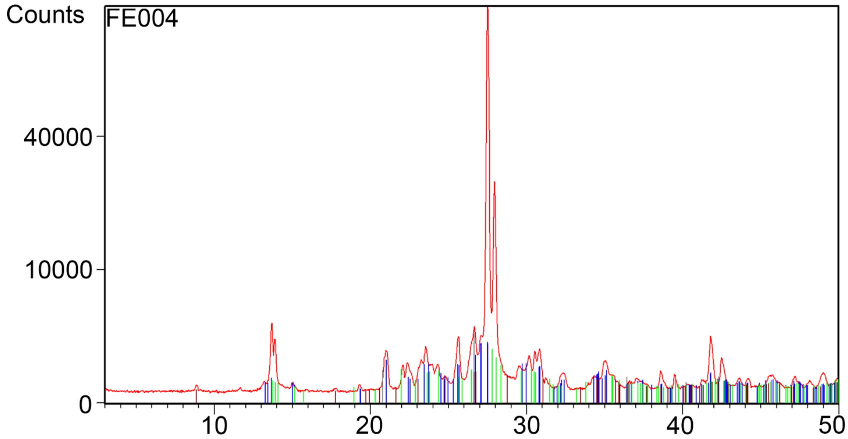


Figure 4. X-Ray diffractogram.

3.2. Grinding Assays

Parameters as EC, SWI and SWIop were calculated by equations (5), (6) and (8) for the test meshes of 0.300 mm, 0.212 mm, 0.150 mm, 0.106 mm and 0.075 mm as shown in **Tables 6-8**. We chose, as a reference for validation purposes, the 0.150 mm test mesh for coarse, fine and mixed feldspar samples. For the cooper ore, the tested mesh size was 0.106 mm.

Table 6. Results for coarse feldspar pegmatite samples.

Mesh (mm)	Parameter	LOT 1	LOT 2	LOT 3
0.300	Time (min)	1.92	1.99	2.00
	Mass (g)	592.56	592.88	591.53
	EC (kWh)	0.09	0.09	0.09
	SWIop (kWh/t)	0.70	0.72	0.73
	SWI (kWh/t)	10.93	11.12	11.16
0.212	Time (min)	2.25	2.27	2.26
	Mass (g)	591.23	591.38	591.31
	EC (kWh)	0.10	0.10	0.10
	SWIop (kWh/t)	0.82	0.82	0.83
	SWI (kWh/t)	11.81	11.86	11.83
0.150	Time (min)	3.38	3.58	3.59
	Mass (g)	593.00	631.00	593.00
	EC (kWh)	0.15	0.16	0.16
	SWIop (kWh/t)	1.22	1.30	1.32
	SWI (kWh/t)	14.33	14.30	14.75

Continued

	Time (min)	4.31	4.18	4.52
	Mass (g)	591.00	591.00	591.00
0.106	EC (kWh)	0.19	0.19	0.21
	SWIop (kWh/t)	1.50	1.59	1.60
	SWI (kWh/t)	16.13	15.90	16.51
	Time (min)	5.71	5.43	6.02
	Mass (g)	591.00	591.00	591.00
0.075	EC (kWh)	0.26	0.24	0.27
	SWIop (kWh/t)	1.87	1.98	2.00
	SWI (kWh/t)	18.47	18.03	18.96

Table 7. Results for fine feldspar pegmatite samples.

Mesh (mm)	Parameter	LOT 1	LOT 2	LOT 3
	Time (min)	1.56	1.59	1.59
	Mass (g)	601.21	602.26	601.67
0.300	EC (kWh)	0.07	0.07	0.07
	SWIop (kWh/t)	0.56	0.57	0.57
	SWI (kWh/t)	13.72	13.84	13.85
	Time (min)	1.97	2.00	1.78
	Mass (g)	601.88	601.30	601.35
0.212	EC (kWh)	0.09	0.09	0.08
	SWIop (kWh/t)	0.70	0.71	0.63
	SWI (kWh/t)	15.61	15.72	14.74
	Time (min)	2.56	2.90	2.56
	Mass (g)	581.00	606.00	575.00
0.150	EC (kWh)	0.12	0.13	0.12
	SWIop (kWh/t)	0.91	1.03	0.91
	SWI (kWh/t)	18.33	19.20	18.45
	Time (min)	3.63	3.91	3.41
	Mass (g)	601.00	601.00	601.00
0.106	EC (kWh)	0.16	0.18	0.15
	SWIop (kWh/t)	1.13	1.31	1.08
	SWI (kWh/t)	21.10	22.33	20.74

Continued

0.075	Time (min)	4.56	5.27	4.42
	Mass (g)	601.00	601.00	601.00
	EC (kWh)	0.21	0.24	0.20
	SWIop (kWh/t)	1.38	1.66	1.32
	SWI (kWh/t)	24.38	26.28	23.93

Table 8. Results for mixed feldspar pegmatite and copper ore samples.

		Mixed Feldspar		Copper Sulphide Ore
Mesh (mm)	Parameter	LOT 1	LOT 2	Single Lot
0.300	Time (min)	2.02	1.97	2.16
	Mass (g)	640.53	640.28	758.41
	EC (kWh)	0.09	0.09	0.09
	SWIop (kWh/t)	0.68	0.66	0.61
	SWI (kWh/t)	11.34	11.20	10.78
0.212	Time (min)	2.24	2.23	2.22
	Mass (g)	640.19	640.7	765.18
	EC (kWh)	0.10	0.10	0.10
	SWIop (kWh/t)	0.75	0.75	0.62
	SWI (kWh/t)	11.93	11.90	10.88
0.150	Time (min)	3.93	3.62	2.31
	Mass (g)	642.8	611.5	759.14
	EC (kWh)	1.32	1.21	0.65
	SWIop (kWh/t)	5.17	4.39	1.50
	SWI (kWh/t)	15.68	15.44	11.14
0.106	Time (min)	4.86	4.44	6.20
	Mass (g)	640	640	753.40
	EC (kWh)	0.22	0.20	0.28
	SWIop (kWh/t)	1.63	1.49	1.74
	SWI (kWh/t)	17.78	17.54	18.15
0.075	Time (min)	6.25	5.63	6.53
	Mass (g)	640	640	762
	EC (kWh)	0.28	0.25	0.29
	SWIop (kWh/t)	2.09	1.88	2.22
	SWI (kWh/t)	20.91	20.58	21.32

The masses and times for the 0.300 mm openings in **Table 6** of batches 1 and 2, as well as for the 0.300 mm and 0.212 mm openings in **Table 7**, were obtained from interpolations. With the exception of batch 2 of the fines, for the 0.212 mm test mesh, the time was exactly two minutes. Therefore, it was not necessary to interpolate the data. It was only possible to estimate the mass and time of these tests for all test meshes, because the complete particle size distributions were performed for each grinding cycle.

As expected, the SWI values suggest that fine feldspars are more resistant to breakage than coarse feldspars. According to the previous results, SWI values are not different because of the mineralogical and chemical characterization.

The graphs in **Figure 5** and **Figure 6** show the average SWI for coarse and fine feldspars when performed by the new test until the system reaches equilibrium.

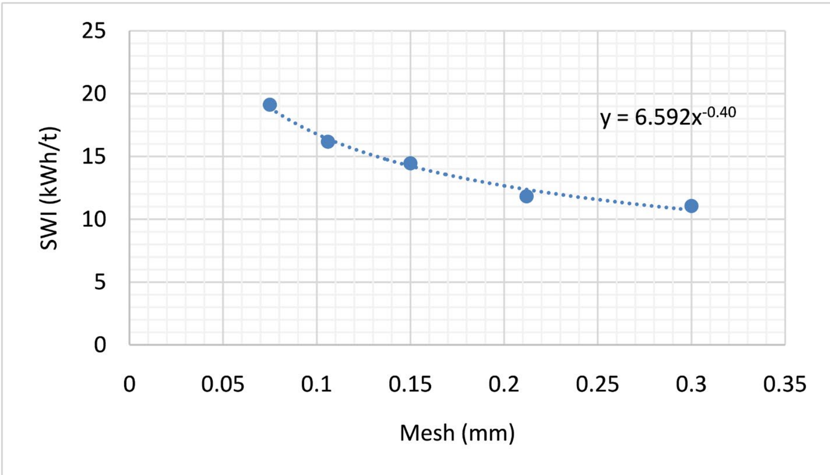


Figure 5. Coarse feldspar samples.

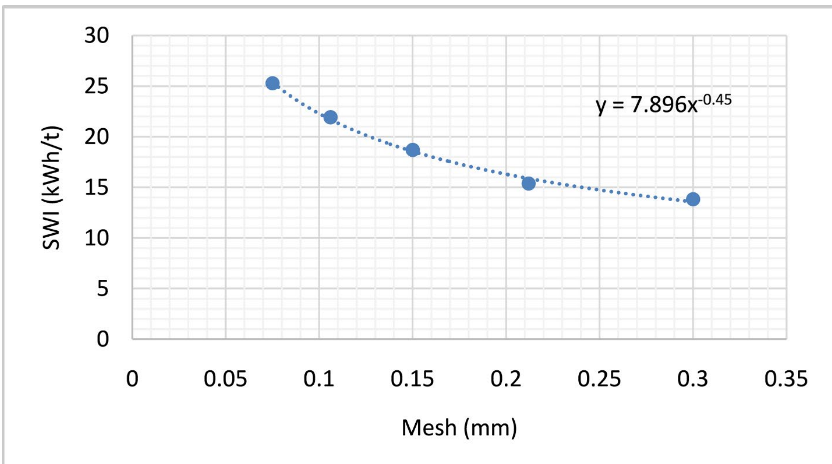


Figure 6. Fine feldspar samples.

The graphs in **Figure 5** and **Figure 6** show that the SWI increases as the test mesh decreases, which in turn is related to the grinding time, since the longer the grinding time, the SWI tends to increase.

It was observed that the slopes of the straight lines for the averages of pegmatite samples have very similar behaviors. However, the equations present a small difference in their exponents. Generally, these exponents are −0.5 when the WI is calculated by the Bond method, and are very close, showing that the new test presents results within the conventional grinding range.

Two Bond tests were also performed for the feldspars, one for coarse and one for fine feldspars on the 0.15 mm mesh, in order to compare their results with the SWI estimated by the new assay. The results can be seen in **Table 9**.

Table 9. Results for both essays: Bond x Simplified.

	Bond (BWI)		Simplified (SWI)					
			(Lot 1)		(Lot 2)		(Lot 3)	
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
WI (kWh/t)	14.7	18.6	14.33	18.46	14.30	19.20	14.75	18.45
Relative difference (%)			0.81	1.2	0.54	3.22	3.64	0.59

The average SWI values for coarse feldspar were 14.46 kWh/t and 18.70kWh/t for fine feldspar. This represents a difference of 1.63% and 0.53% for coarse and fine feldspar respectively, regarding the WI obtained by the standard Bond test.

Bond tests were also carried out on the 0.106 mm test mesh for a copper sulfide ore and for the mixed feldspar on the 0.150 mm mesh, which were fed with a −3.35 mm grain size in accordance with the standard for the Bond test. Their WI values were compared with the SWI values, both of which are shown in **Table 10**.

Table 10. Results for both essays: Bond x Simplified.

	Bond (BWI)		Simplified (SWI)		
	Mixed feldspar ore [49]	Copper ore	Mixed feldspar ore		Copper ore
			(Lot 1)	(Lot 2)	
WI (kWh/t)	14.01	18.2	15.68	15.55	18.01
Relative difference (%)			11.92	10.99	0.05

It was observed that the SWI values were very close to the BWI, with differences of less than 12% for mixed feldspar and less than 1% for copper sulfide ore. The particle size factor (k) can be calibrated according to the power of the mill and the grinding time. It is also suggested that pegmatite ore be used as a reference for testing other ores. It is easier to estimate a heterogeneity factor: the difference between the reference ore and the ore to be tested.

3.3. Correlations between Work Index and Size Reduction Ratios

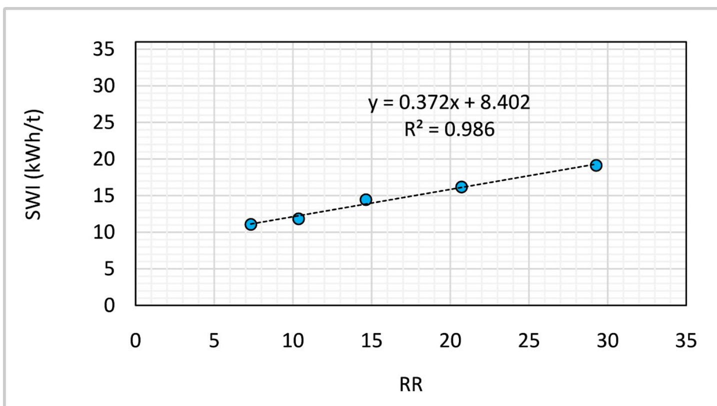
We found a strong correlation between the average values of the SWIop/SWI ratio (called RWI) and the A_{80}/P_{80} reduction ratio (called RR) for the coarse feldspar samples, which had an average A_{80} of 2.195 mm and 0.631 mm for the fines. Table 11 presents the P_{80} sieve meshes and the results.

Table 11. Simplified assay results.

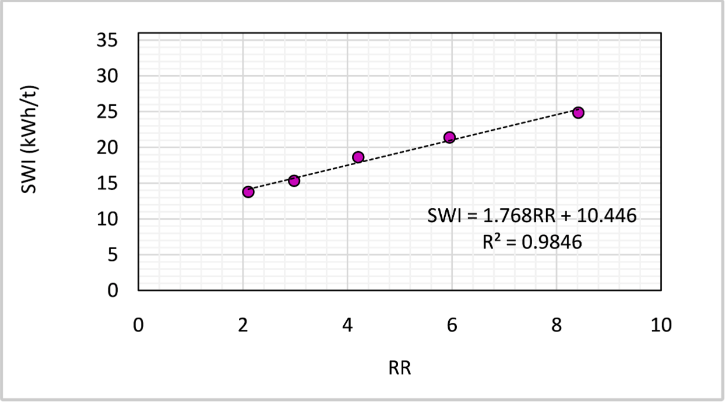
	Feldspar			
	Coarse		Fine	
Mesh (mm)	RWI	RR	RWI	RR
0.300	0.06	7.32	0.04	2.10
0.212	0.07	10.35	0.04	2.98
0.150	0.09	14.63	0.05	4.21
0.106	0.10	20.71	0.05	5.95
0.075	0.11	29.27	0.06	8.41

It is observed that the RWI values for both materials increase when the test mesh opening decreases. These ratios are lower for fine feldspars when compared to coarse feldspars. This occurs due to the grinding time being shorter for fine feldspars; thus, the particle size distribution directly impacts these ratios.

During a project to optimize the blasting process and reduce energy consumption, we have doubts on the effect of the ROM particle size distribution on the comminution. This project lasted about 10 years. The results showed a significant reduction of the A_{80} of the ROM: from 100 cm to 60 cm [47]. On this occasion, we obtained very low wear of the grinding media and energy consumption. Now, we can deduce why this happened, regarding Figure 7(a) and Figure 7(b): we can observe a strong correlation between RR and SWI for coarse and fine feldspar samples.



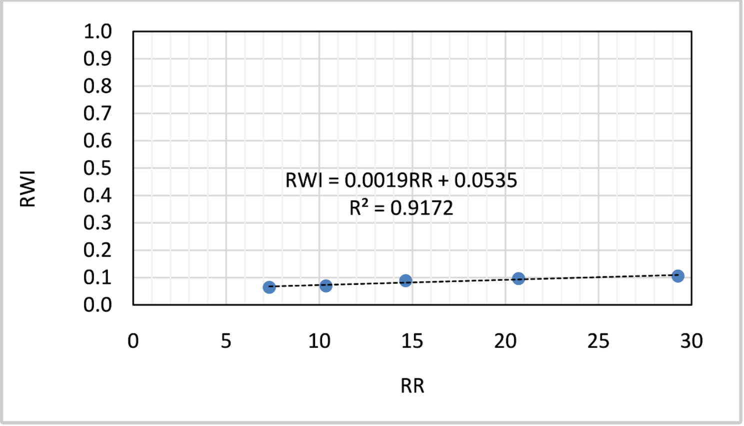
(a)



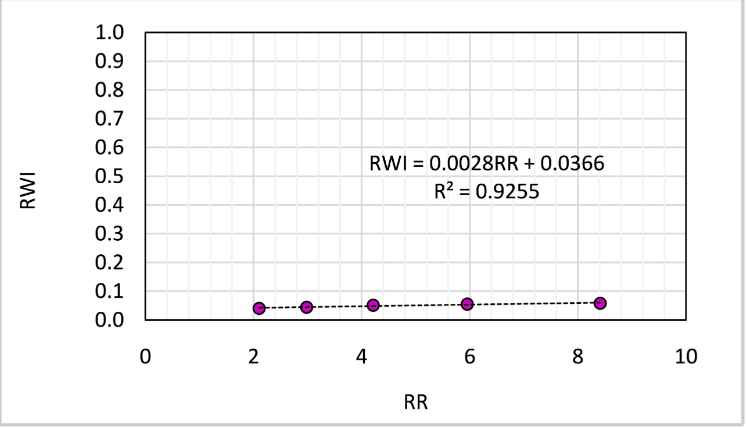
(b)

Figure 7. (a) RR and SWI for coarse feldspar; (b) RR and SWI for fine feldspar.

This suggests that for a determined Reduction Ratio (RR), it is possible to estimate the SWI for any size classes. The graphs in **Figure 8(a)** and **Figure 8(b)** show the behavior of the curve when the RR values are correlated to the RWI values for coarse and fine feldspar samples respectively.



(a)



(b)

Figure 8. (a) RR and RWI for coarse feldspar; (b) RR and RWI for fine feldspar.

Finally, we can obtain a very accurate prediction about RWI as a function of RR. In this case, for coarse samples, the RWI would be 6% for RR equal to 7.32 (P_{80} equal to 0.300 mm), according to Table 11). For the fine feldspar samples, this energy relationship would be 4% for a reduction ratio of 2.10 (P_{80} equal to 0.300 mm). The RWI of coarse samples is greater than of fine samples for P_{80} of 0.075 mm. Therefore, this methodology could be applied to better understand the effect of the particle size distribution on RWI, especially, after optimizing the blasting.

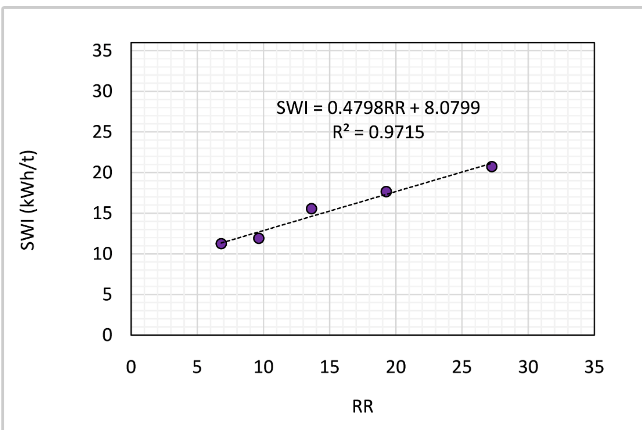
Correlations were also found between the average RWI and RR values for the mixed feldspar samples, which had an average A_{80} of 2.043 mm and 2.390 mm for the copper sulfide ore. The results are shown in Table 12.

Table 12. Simplified assay results.

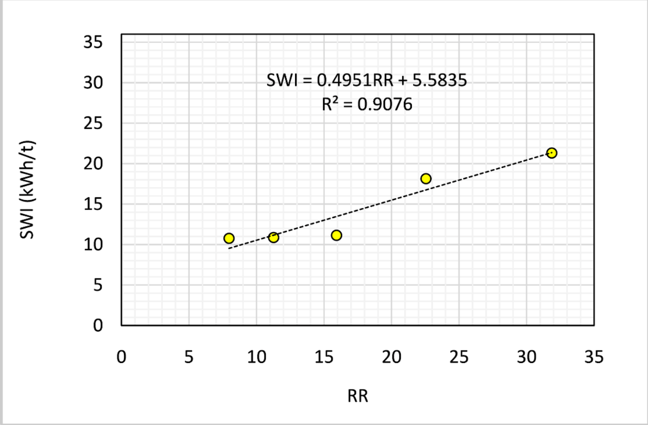
	Mixed Feldspar		Copper Sulfide Ore	
Mesh (mm)	RWI	RR	RWI	RR
0.300	0.06	6.81	0.06	7.97
0.212	0.06	9.64	0.06	11.27
0.150	0.08	13.62	0.06	15.93
0.106	0.09	19.28	0.10	22.55
0.075	0.10	27.25	0.10	31.87

As had already occurred with the coarse and fine feldspars, the RWI values for both materials increased as the test mesh opening decreased. The RWI values were very similar for both materials. This may have been due to the particle size distribution of the feed, which was unique at −3.36 mm even though the grinding time for the sulfide ore was longer than that for the mixed feldspar.

Figure 9(a) and Figure 9(b) show the correlation between RR and SWI for mixed feldspar samples and sulfide ore.



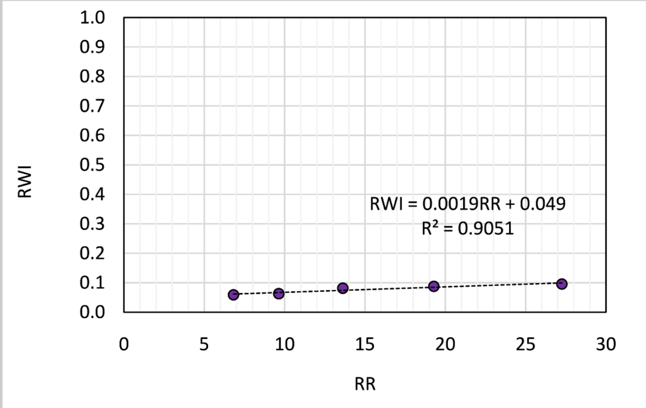
(a)



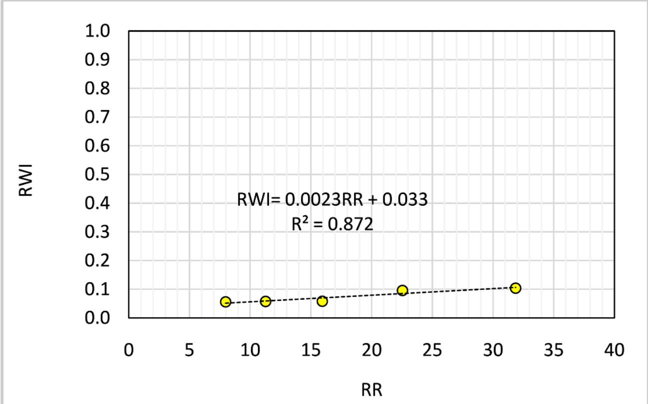
(b)

Figure 9. (a) RR and SWI for mixed feldspar; (b) RR and SWI for copper sulfide.

Figure 9(a) shows a very strong correlation for the mixed feldspars, as was the case with the coarse and fine feldspars. For sulfide ore, **Figure 9(b)** shows a very good correlation, above 0.9, but not as strong as for feldspars. Even so, for a given reduction ratio (RR), it is possible to estimate the SWI for any size class, obtaining a good correlation. The graphs in **Figure 10(a)** and **Figure 10(b)** show the behavior



(a)



(b)

Figure 10. (a) RR and RWI for mixed feldspar; (b) RR and RWI for copper sulfide.

of the curve when the RR values are correlated to the RWI values for mixed feldspar and sulphide ore samples, respectively.

Even so, we can get a very accurate prediction of the RWI as a function of RR. In this case, for mixed samples, the RWI would be 6% for RR equal to 6.8 (P_{80} equal to 0.300 mm), according to **Table 12**. For the sulfide sample, this energy ratio is also 6% for a reduction ratio of 7.9 (P_{80} equal to 0.300 mm), because the grinding times are very close for this mesh. However, on the 0.150 mm mesh, the RWI of the mixed samples is greater than that of the sulfide ore.

4. Conclusions

The results strongly suggest that the new assay could be an alternative to the Bond Standard assay. The simplified assay presented very reliable SWI results with relative differences not exceeding 2% for coarse and fine feldspars, less than 12% for mixed and 1% for Copper ore.

We concluded that the granulometric factor K depends on the Energy Consumed (EC), the RR, and the diameter of the mill. Based on this finding, it may vary for certain types of ores. This study found that the K values were the same for sulfide and mixed pegmatite. This may be related to the particle size distribution of the feed, which was unique, −3.35 mm.

The particle size distribution of the feed influenced the BWI and SWI results: different values were obtained for coarse and fine feldspar samples by both kinds of assays.

For the simplified test, only three grinding cycles were necessary. This kind of test is advantageous because we can estimate very important parameters for several P_{80}.

The results of both assays show similar behavior, as they presented logarithmic equations with exponents close to -0.5, within the range where we can apply Bond law, according to the Hukki function. In addition, everything indicates that the new test could be applied to release sizes below 100 µm. It is necessary, however, to have tests carried out on an industrial scale. In industry, there are many physical and operational factors that interfere with energy consumption, such as the lining profile, the distribution of the grinding load, and the viscosity of the pulp, among many others. It is worth remembering that the Bond test is performed with a smooth and dry lining.

The correlations between RR and SWI are strongly correlated for pegmatites, with an R^2 = 0.98, and show a good correlation for sulfide with R^2 = 0.90. This is interesting because it will be possible to estimate SWI using the reduction ratio that relates A_{80} to the test mesh. The correlations between RR and RWI are strong, but with R^2 = 0.91 for pegmatites on average and R^2 = 0.87 for sulfide. Thus, it is possible to know how much SWIop will be less than SWI. Finally, the results strongly suggest that WI is not a constant and that it depends on the blasting, crushing and grinding, particle size distribution and equipment power. The better the blasting, the lower the reduction ratios, the lower the WIop, whereby the required minimum equipment power can be lower, even with higher WI values.

There is a much larger variety of ores, in addition to blends, so we should perform more tests. It is also recommended to carry out tests with mills of different sizes, including tests on an industrial scale to verify the effect on the variables studied. Although we have not found significant differences between BWI and SWI, it is strongly suggested that larger masses be used, as they will be more representative.

Acknowledgements

The authors would like to thank the Graduate Program in Mining, Metallurgy, and Materials Engineering (PPGE3M), through CAPES/PROEX, for the financial support received. To Professor Luiz Pedro Guzzo of the Federal University of Pernambuco (UFPE) and his team at the mineral processing laboratory, thank you for sharing the results of the BWI test performed on the pegmatite used in this study.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Nadolski, S., Klein, B., Kumar, A. and Davaanyam, Z. (2014) An Energy Benchmarking Model for Mineral Comminution. *Minerals Engineering*, **65**, 178-186. https://doi.org/10.1016/j.mineng.2014.05.026

[2] Jose-Luis, P., Abadias, A., Valero, A., Valero, A. and Reuter, M. (2019) The Energy Needed to Concentrate Minerals from Common Rocks: The Case of Copper Ore. *Energy*, **181**, 494-503. https://doi.org/10.1016/j.energy.2019.05.145

[3] Nikolić, V., García, G.G., Coello-Velázquez, A.L., Menéndez-Aguado, J.M., Trumić, M. and Trumić, M.S. (2021) A Review of Alternative Procedures to the Bond Ball Mill Standard Grindability Test. *Metals*, **11**, Article 1114. https://doi.org/10.3390/met11071114

[4] Magdalena, R., Valero, A. and Calvo, G. (2023) Limit of Recovery: How Future Evolution of Ore Grades Could Influence Energy Consumption and Prices for Nickel, Cobalt, and PGMs. *Minerals Engineering*, **200**, Article 108150. https://doi.org/10.1016/j.mineng.2023.108150 https://www.sciencedirect.com/journal/minerals-engineering

[5] Bond, F.C. (1961) Crushing and Grinding Calculation Part I and II. *British Chemical Engineering*, No. 6, 378-548.

[6] Von Rittinger, P.R. (1867) Lehrbuch der aufbereitungs kunde. Ernst and Korn.

[7] Hukki, R.T. (1962) Proposal for a Solomonic Settlement between the Theories of Von Rittinger, Kick, and Bond. *Transactions of the American Institute of Mining and Metallurgical Engineers*, No. 223, 403-408.

[8] Napier-Munn, T.J., Morrell, S., Morrison, R.D. and Kojovic, T. (1996) Mineral Comminution Cicuits—Their Operation and Optimisation. JKRMC (Austrália).

[9] Austin, L.G., Klimpel, R.R., Luckie, P.T. and Rogers, R.S.C. (1982) Simulation of Grinding Circuits for Design. In: Mular, A.L. and Gerald II, V.J., Eds., *Design and Installation of Comminution Circuits*, American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., 301-324.

[10] Morrell, S., Napier-Nunn, T.J. and Andersen, J. (1992) The Prediction of Power Draw for Comminution Machines. In: Kawatra, Ed., *Comminution*: *Theory and Practice*, AIME, 405-426, 233-248.

[11] Morrison, R. and Freeman, N. (1990) Grinding Control Development at ZC Mines. *Proceedings AusIMM*, **295**, 45-49.

[12] Austin, L.G. and Luckie, P.T. (1972) Methods for Determination of Breakage Distribution Parameters. *Powder Technology*, **5**, 215-222. https://doi.org/10.1016/0032-5910(72)80022-6

[13] Ballantyne, G.R., Peukert, W. and Powell, M.S. (2015) Size Specific Energy (SSE)—energy Required to Generate Minus 75 Micron Material. *International Journal of Mineral Processing*, **136**, 2-6. https://doi.org/10.1016/j.minpro.2014.09.010

[14] Eloranta, J. (1997) The Efficiency of Blasting Versions Crushing and Grinding. *Proceeding* 23*rd Annual. Conference*, *International Society of Explosives Engineers*, New York, 12-15 January 1997, 2-10.

[15] Eloranta, J. (2014) Non-Ideal Blasting for Ideal Grinding—Part Two. *Journal of Explosives Engineering*, 31, 1-7.

[16] Gy, P. (1982) Sampling of Particulate Materials Theory and Practice. Elsevier.

[17] Jankovic, A., Suthers, S., Wills, T. and Valery, W. (2015) Evaluation of Dry Grinding Using HPGR in Closed Circuit with an Air Classifier. *Minerals Engineering*, **71**, 133-138. https://doi.org/10.1016/j.mineng.2014.10.023

[18] Kelly, E.G. and Dawe, G.A. (1989) Modified Bond Method for the Evaluation of Crusher Efficiency. *Mining*, *Metallurgy & Exploration*, **6**, 14-17. https://doi.org/10.1007/bf03402519

[19] Menéndez-Aguado, J.M., Coello-Velazquez, A.L., Tijonov, O.N. and Rodríguez Díaz, M.A. (2006) Implementation of Energy Sustainability Concepts during the Comminution Process of the Punta Gorda Nickel Ore Plant (Cuba). *Powder Technology*, **170**, 153-157. https://doi.org/10.1016/j.powtec.2006.09.004

[20] Saeidi, N., Noaparast, M., Azizi, D., Aslani, S. and Ramadi, A. (2013) A Developed Approach Based on Grinding Time to Determine Ore Comminution Properties. *Journal of Mining and Environment*, **4**, 105-112.

[21] Magdalinović, N. (1989) A Procedure for Rapid Determination of the Bond Work Index. *International Journal of Mineral Processing*, **27**, 125-132. https://doi.org/10.1016/0301-7516(89)90010-0

[22] Magdalinovi'c, N. (2003) Abbreviated Test for Quick Determination of Bond's Work Index. *Journal of Mining and Metallurgy*, **39**, 1-10. https://scindeks.ceon.rs/article.aspx?artid=1450-59590304001M

[23] Ahmadi, R. and Shahsavari, S. (2009) Procedure for Determination of Ball Bond Work Index in the Commercial Operations. *Minerals Engineering*, **22**, 104-106. https://doi.org/10.1016/j.mineng.2008.04.008

[24] Ford, E. and Sithole, V. (2015) A Comparison of Test Procedures for Estimating the Bond Ball Work Index on Zambian/DRC Copper-Cobalt Ores and Evaluation of Suitability for Use in Geometallurgical Studies. *Copper Cobalt Africa*, *Incorporating the 8th Southern African Base Metals Conference*, Livingstone, 6-8 July 2015, 65-68.

[25] Todorovic, D., Trumi'c, M., andric, L.J. and Milosevic, V. (2017) A Quick Method for Bond Work Index Approximate Value Determination. *Physicochemical Problems of Mineral Processing*, **53**, 321-332.

[26] Alves, V.K., Mazzinghy, D.B., Rosa, M.A.N., Mendonça, A.M., Machado, L.C., Oliveira, G.O.D., Souza, M.G., *et al.* (2013) Aplicação de método simplificado de

determinação de wi na previsão de desempenho dos moinhos de bolas da usina do sossego. *Tecnologia em Metalurgia Materiais e Mineração*, **10**, 318-323. https://doi.org/10.4322/tmm.2013.051

[27] Duque, T.F.M.B., Schneider, C.L., Mazzinghy, D.B. and Alves, V.K. (2014) BWI em função da malha de teste. *Holos*, **3**, 112-121.

[28] Jauregui, R.O. (1983) Simplified Bond Work Index determination. In: *Encontro Nacional de Tratamento de Minérios e Hidrometalurgia*. 9, Gráfica e Editora NSB, 358-367.

[29] Menéndez-Aguado, J.M., Dzioba, B.R. and Coello-Valazquez, A.L. (2005) Determination of Work Index in a Common Laboratory Mill. *Mining, Metallurgy & Exploration*, **22**, 173-176. https://doi.org/10.1007/bf03403133

[30] Mwanga, A., Rosenkranz, J. and Lamberg, P. (2017) Development and Experimental Validation of the Geometallurgical Comminution Test (GCT). *Minerals Engineering*, **108**, 109-114. https://doi.org/10.1016/j.mineng.2017.04.001

[31] Nematollahi, H. (1994) New Size Laboratory Ball Mill for Bond Work Index Determination. *Minerals Engineering*, No. 46, 352-353.

[32] Yap, R.F., Sepulveda, J.L. and JaureguI, R. (1982) Determination of the Bond Work Index Using an Ordinary Batch Ball Mill. In: Mular, A.L. and Jergensen, G.V., Eds., *Design and Installation of Comminution Circuits*, Aime, 176-203.

[33] Deniz, V., Sütçü, N. and Umucu, Y. (2003) The Effect of Circulating Load and Test Sieve Size on the Bond Work Index Based on Natural Amorphous Silica. 18*th International Mining Congress and Exhibition of Turkey-IMCET*, Antalya, 10-13 June 2003, 517-522.

[34] Kaya, E., Fletcher, P.C. and Thompson, P. (2003) Reproducibility of Bond Grindability Work Index. *Mining, Metallurgy & Exploration*, **20**, 140-142. https://doi.org/10.1007/bf03403146

[35] Menéndez, M., Gent, M., Torno, S. and Crespo, N. (2017) A Bond Work Index Mill Ball Charge and Closing Screen Product Size Distributions for Grinding Crystalline Grains. *International Journal of Mineral Processing*, **165**, 8-14. https://doi.org/10.1016/j.minpro.2017.05.011

[36] Menéndez, M., Muñiz Sierra, H., Gent, M. and de Cos Juez, F.J. (2018) The Comminution Energy-Size Reduction of the Bond Mill and Its Relation to Vickers Hardness. *Minerals Engineering*, **119**, 228-235. https://doi.org/10.1016/j.mineng.2018.01.017

[37] Mosher, J.B. and Tague, C.B. (2001) Conduct and Precision of Bond Grindability Testing. *Minerals Engineering*, **14**, 1187-1197. https://doi.org/10.1016/s0892-6875(01)00136-4

[38] Smith, R.W. and Lee, K.H. (1968) A Comparison of Data from Bond Type Simulated Closed Circuit and Batch Type Grindability Tests. *Transactions of the Metallurgical Society of AIME*, No. 241, 91-99.

[39] Tüzün, M.A. (2001) Wet Bond Mill Test. *Minerals Engineering*, **14**, 369-373. https://doi.org/10.1016/s0892-6875(01)00009-7

[40] Griffith, A.A. (1921) The Phenomena of Rupture and Flow in Solids. *Philosophical Transactions, Series A*, **221**, 163-198.

[41] Nikolić, V. and Trumić, M. (2021) A New Approach to the Calculation of Bond Work Index for Finer Samples. *Minerals Engineering*, **165**, Article 106858. https://doi.org/10.1016/j.mineng.2021.106858

[42] Nikolić, V., Doll, A. and Trumić, M. (2022) A New Methodology to Obtain a Corrected Bond Ball Mill Work Index Valid with Non-Standard Feed Size. *Minerals Engineering*, **188**, Article 107822. https://doi.org/10.1016/j.mineng.2022.107822

[43] Bergerman, M.G., Pamparana, G., Junior. H.D. and Klein, B. (2023) Development of a Simplified Test for Determination of the Bond Ball Mill Work Index Using a Modified Hardgrove Test. *Minerals Engineering*, **203**, Article 108359.

[44] Associação Brasileira de Normas Técnicas (1990) Moinho de bolas, determinação do índice de trabalho: NBR 11376.

[45] Montgomery, D.C. (2013) Design and Analysis of Experiments. 8th Edition, John Wiley & Sons.

[46] Bond, F.C. (1960) Confirmation of the Third Theory. *AIME Transactions*, **217**, 139-153.

[47] Moura, L.P., Costa, L.V., Koppe, J.C. and Souza, V.C.G. (2025) Otimização operacional—Impactos do fragcom na eficiência da lavra e beneficiamento de uma mina em cajati. *Revista foco*, **18**, e7876. https://doi.org/10.54751/revistafoco.v18n2-154

[48] King, R.P. (2001) Simulation of Ore Dressing Plants. Butterworth Heinemann.

[49] Santos, B.C.D., Pimentel, B.J.E., Guzzo, P.L. and Machado, A.O.D. (2006) Determinação da energia específica de moagem de feldspatos da província pegmatítica do seridó-borborema pelo método de bond. *IV Congresso de Engenharia Mecânica*, Recife-PE, 22-25 August 2006, 2-10.