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ON THE DESIGN OF BALL MILLS FOR GRINDING ITABIRITE ORES[1]

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Abstract

In spite of its good track record and its wide acceptance in the minerals industry, the Bond method faces an important challenge when applied in the design of ball mills grinding some soft Brazilian iron ores, such as Itabirites. This is associated to the fact that these ores often contain significant proportions of fines, resulting in particle size distributions of the feed stream which do not plot as straight lines in log-log or Rosin-Rammler axes, as is highly recommended for the application of the Bond method. The paper demonstrates the implications of conducting the Bond grindability test using different procedures with friable Itabirites, and then compares the predictions of specific grinding energy to those obtained using the population balance model from well-controlled batch grinding tests and to data from an industrial mill in operation.
Key words: Grinding; Bond work index; Population balance model.

SOBRE O PROJETO DE MOINHOS DE BOLAS PARA A MOAGEM DE ITABIRITOS

Resumo

Apesar do seu histórico de sucesso e da sua ampla aceitação na indústria mineral, o método de Bond encontra um desafio importante quando é aplicado no projeto de moinhos de bolas de alguns minérios de ferro brasileiros, em particular, Itabiritos. Isso se deve ao fato que esses minérios contêm proporções significativas de finos, resultando em distribuições granulométricas da alimentação que não se apresentam na forma de linhas retas em escalas logarítmicas ou de Rosin-Rammler, como é altamente recomendado para a aplicação do método de Bond. O trabalho demonstra as implicações associadas à condução do ensaio de moabilidade de Itabiritos friáveis segundo diferentes procedimentos, e então compara as previsões de energia específica àquelas obtidas com o modelo do balanço populacional da moagem a partir de resultados de ensaios de moagem em batelada, bem como a resultados de moagem em um circuito industrial.
Key words: Grinding; Bond work index; Population balance model.

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1 INTRODUCTION

The Bond grindability test, through which the Bond ball mill work index (*Wib*) is measured,(1) is a very useful tool in the analysis of grindability of ores from different areas of a mineral deposit, being very successfully used in studies of ore variability by Vale S.A. The estimation of *Wib* values of samples from drill cores allows, in the preliminary circuit design stage, predicting the variation of circuit capacity in response to the different grindabilities of ores that will be found along the life of the mine.
In spite of its long history of application in the minerals industry, it is widely recognized design methodology as well as the method used to conduct the standard Bond ball mill grindability test have important limitations. Austin and Brame(2) list some of them, which include:

- The method does not take into account the following variables that influence operation in a closed-circuit operation:
  a. Circulating load ratio;
  b. Classifier efficiency;
  c. Size distribution of the ball charge;
  d. Variation of residence time distribution of particles within the mill as a function of mill length-diameter ratio and slurry density;
  e. Liner profile;
  f. Slurry rheology.
- It considers that the specific energy does not vary with mill filling.
- It considers exclusively the 80% passing sizes, although it is widely recognized that the shape of the feed size distribution influences the product size distribution.
- It does not take into consideration if the mill is operating under or overloaded.

Some of these problems associated to the Bond method result in the deviations in the order of 20% that are attributed to the method,(3,4) which can be even greater for mills with larger diameters.
An alternative and widely used tool in assessing the grinding response of ores is the direct measurement of the breakage distribution and breakage rate functions from batch grinding tests. From these functions, whose measurements normally require a greater experimental effort than the Bond test, it is possible to simulate the grinding and classification circuit in such a way that a significant number of the limitations of the Bond methods, as listed by Austin and Brame(2) can be overcome.
The present work compares different methods of determining the Bond ball mill work index, comparing the values obtained from a composite Itabirite sample to those obtained from simulation of a grinding circuit containing a ball mill operating in pilot scale. Predictions using the different approaches are then compared to results from an industrial grinding circuit processing another Itabirite ore.

2 MATERIALS AND METHODS

Samples used in the present work were iron ores from different deposits located in the Minas Gerais Iron Quadrangle, being classified as “friable” Itabirites.
Measurements of the Bond work index in ball mills have been conducted using the standard Bond mill (Table 1) operating in the standard conditions recommended by Bond.(1) The feed to the test was prepared by stage crushing so that 100% of the material passed the 3.35 mm (6#) opening sieve. The closing sieve (Am) used in all the tests was 150 µm.

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Within the standard proposed by Fred Bond there are two variations that may be used in measuring the grindability in a ball mill:

- with partial removal of fines from the feed prior to the test: in this option, material that is finer than the closing size of the test (Am) is partially removed by dry screening.
- with no removal of fines from the feed: in this option, which was recommended by Chalmers[5] the material prepared for the test, previously stage-crushed below 3.35 mm, is directly used in the test. When the amount of fine material, that is, the amount of material passing in Am contained in the feed is larger than 28%, then the standard Bond cycle is conducted with no grinding, that is, by discarding the fines in the feed of that cycle and incorporating the corresponding proportion from fresh feed. This is repeated until the proportion of fines in the material composed for each cycle is smaller than 28%.

For ores that present an “ideal” grindability behavior, the value of *Wib* should not vary with the option adopted. However, the validity of this premise is analyzed in the present work for Itabirite iron ores.

An alternative method to assess the grindability of ores is based on the measurement of breakage rate and breakage distribution functions in a batch mill. In this case, these functions, properly scaled for the mill whose performance one seeks to predict, allow simulating of industrial grinding circuits using the size-mass balance model.[6,7] Austin, Klimpel and Luckie[6] proposed a method that is based on the conduct of batch grinding tests with carefully-prepared narrow size feeds. In the present work, batch grinding tests were conducted in dry mode with the material previously classified in the ranges 4.75x3.35 mm; 1.70x1.18 mm; 0.600x0.425 mm and 0.212x0.150 mm.

Table 1. Summary of conditions used in the grinding experiments and simulations

		Bond mill		Batch mill		Pilot mill [9]		Industrial mill [11]	
Geometry	Diameter, D_m (m)	0.305		0.305		1.20		5.10	
	Length, *L* (m)	0.305		0.305		2.42		7.60	
Frequency	Rotation frequency (rpm)	70		54		45		13.8	
	Fraction of critical speed, φ_c	0.86		0.67		0.75		0.71	
Grinding media	Type	Alloy steel		Alloy steel		Alloy steel		Alloy steel	
	Specific gravity (g/cm^3)	7.8		7.8		7.8		7.8	
	Ball sizes, d_b (mm)	Frac.	d_b	Frac.	d_b	Frac.	d_b	Frac.	d_b
		0.386	37	1.0	25	0.160	76	1.0	63.5
		0.376	30			0.190	65		
		0.043	25			0.280	55		
		0.094	19			0.185	39		
		0.101	16			0.165	30		
						0.020	25		
	Filling, *J* (%)	20		32		35		31	
	Grinding media weight (kg)	20		30		3800		231055	
Ore	Voids filling, *U*(%)	50		100		100		100	

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3 RESULTS AND DISCUSSION

3.1 Bond Ball Mill Work Index (*Wib*)

A summary of results from Bond ball mill grindability tests conducted with a number of samples of friable Itabirite ore following the different modes of conduct the Bond test (described in item 2) is presented in Figure 1. Although the tests have been conducted using procedures which are both regarded as acceptable, it is evident that the tests resulted in very different values of *Wib*, with deviations as large as 52% between the measurements. Detailed results are presented elsewhere.(8) For all samples the values of *Wib* found whenever the material finer than 150 µm (Am) was not removed prior to conducting the test are higher than when it was partially removed. Indeed, the tests with the samples of friable Itabirite iron ore resulted in values which are, on average, 35% higher when the test is removed without prior removal of fines (Itabirite #1 in Table 2). Considering that the differences cannot be attributed to experimental errors, a more detailed analysis of the data becomes worthwhile.

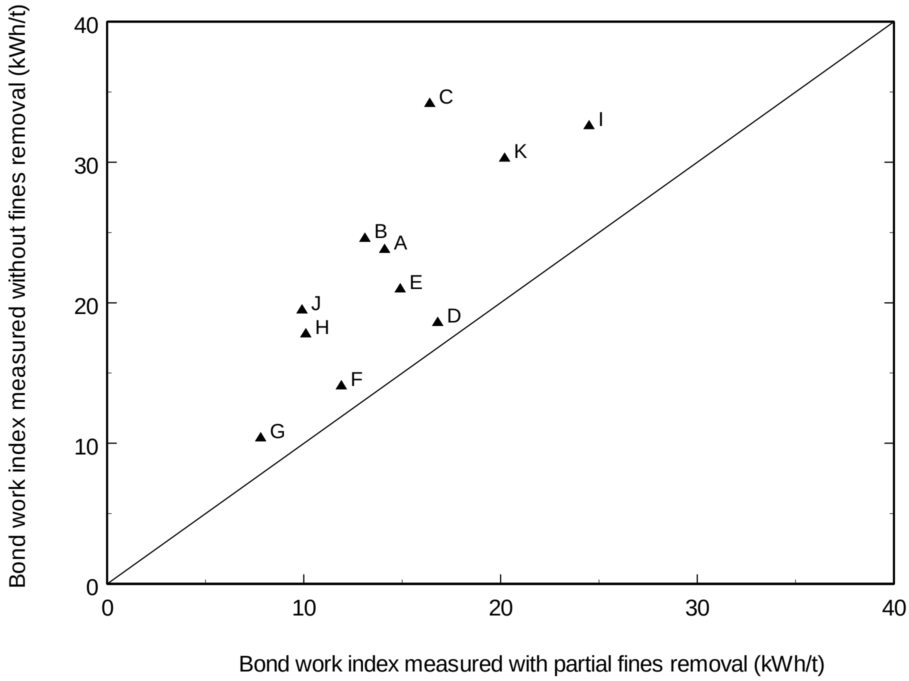

Figure 1. Comparison of Bond ball mill work index values obtained by different methods used to conduct the test with Itabirite ore samples.

Table 2. Bond ball mill work indices for iron ore samples

Sample	Bond ball mill work índex – *Wib* (kWh/t)	
	No removal of fines	With removal of fines
Itabirite #1 (composite)*	22.4 (7.6)	14.5 (4.9)
Itabirite #2	12.4	11.3

** Average values, with standard deviation in parentheses* (8)

At first, it is relevant to analyze critically the basic premise that was established by Fred Bond to ensure the validity of the grindability test to determine the Bond work index (*Wib*). It is related to how well single parameters from the feed and the product size distributions from the test can describe the change in size during grinding.

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Bond[1] suggested that it is highly desirable that feed and product cumulative size distribution curves plot approximately parallel in Rosin-Rammler axes. This is illustrated in Figures 2 and 3 for selected tests, which shows that curves are not parallel at all in neither of them. However, when fines are partially removed from the feed, curves become more parallel (Figure 3). It is evident that, in neither one of the cases, the feed size distributions may be appropriately described by the *F*80 size, given the point of inflection in the curves present at, approximately, 250 μm. Indeed, this is particularly critical in the case of some samples (B and D) when tested with no prior removal of the fines. In the case of these samples the reduced values of *F*80 (in the order or 250 μm), applied to Bond's third law of comminution would suggest that grinding would be an easier task. However, this ease is not observed in practice, since the material presents low values of grindability (G_{bp}).
It is now possible to analyze in greater detail the results from the tests in order to assess if there is any correlation between the values of *Wib* and *F*80. Figure 4 shows that there is a strong correlation between them when fines are removed or not, demonstrating a weakness in the Bond method.
In reality, this difficulty in the method and of the Bond method in characterizing the grindability of materials that present highly bimodal size distributions actually results in a significant underestimation of the grindability of the material. Therefore, it is possible to conclude that the exceptionally high values of *Wib* found, some higher than 30 kWh/t, for instance, for samples when no removal of fines is conducted, may not be associated to its difficult grindability, but to a limitation of the method proposed by Bond to characterize their true response in a grinding mill. One method that is more capable of appropriately characterizing the performance of these ores is based on measurements of breakage rate and breakage distribution functions from testing narrow-size samples. The results are presented as follows.

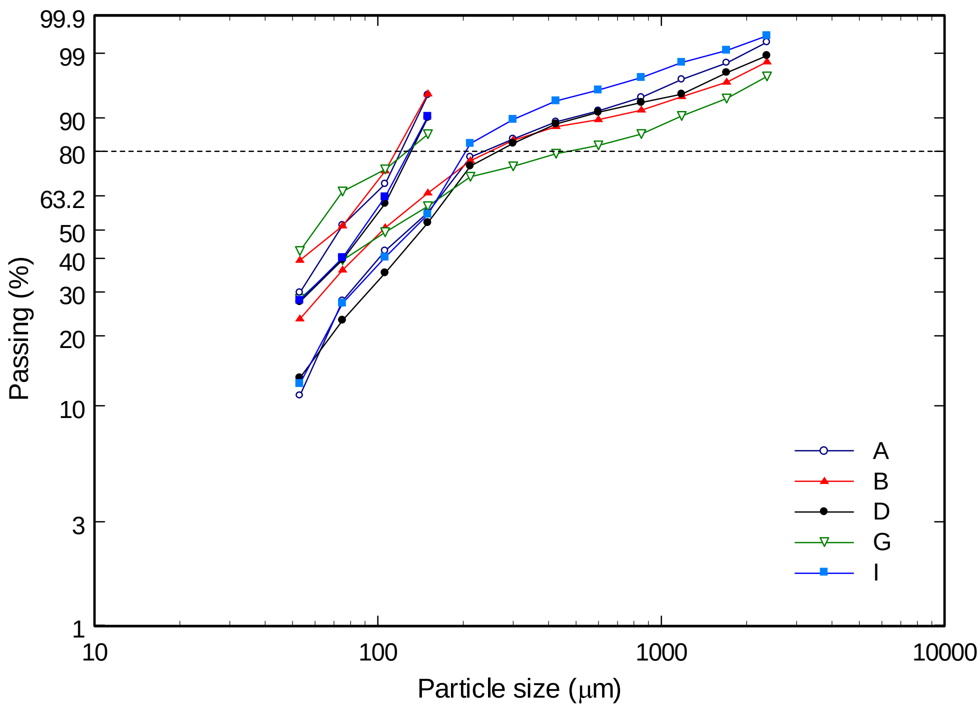

Figure 2. Comparison between feed and product size analyzes from Bond ball mill grindability tests when fines from the feed (< 150 μm) were not removed [8].

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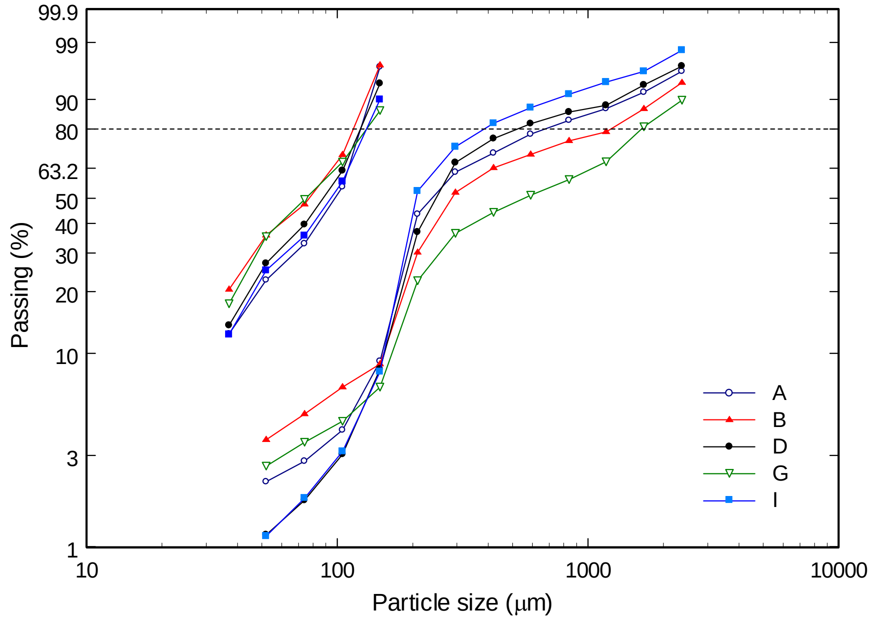

Figure 3. Comparison between feed and product size analyzes from Bond ball mill grindability tests when fines from the feed (< 150 µm) were partially removed.[8]

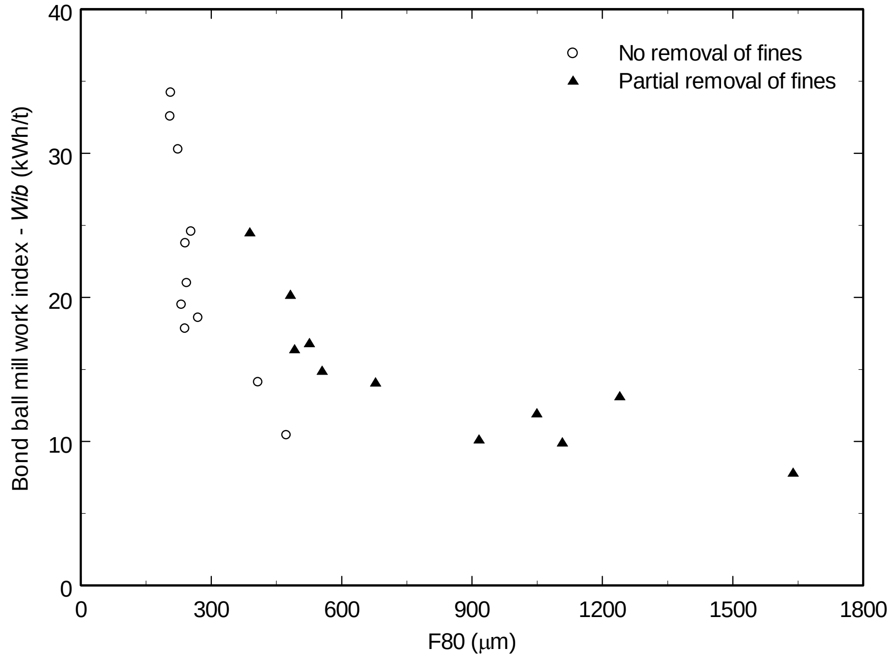

Figure 4. Comparison between values of *Wib* and *F*80 in the Bond ball mill grindability tests.

3.2 Batch Grinding Tests

As an alternative to Bond ball mill grindability tests, batch grinding tests following the procedure recommended by Austin, Klimpel and Luckie,[6] have been conducted with the two samples listed in Table 2, one of which (Itabirite #1) being a composite of samples that were previously subjected to Bond grindability tests (Figure 1). A summary of results from these tests is presented in Figure 5. It demonstrates that, for the ore and conditions studied, the assumption of validity of the first order breakage rates is generally valid for sizes below about 3.35 mm.

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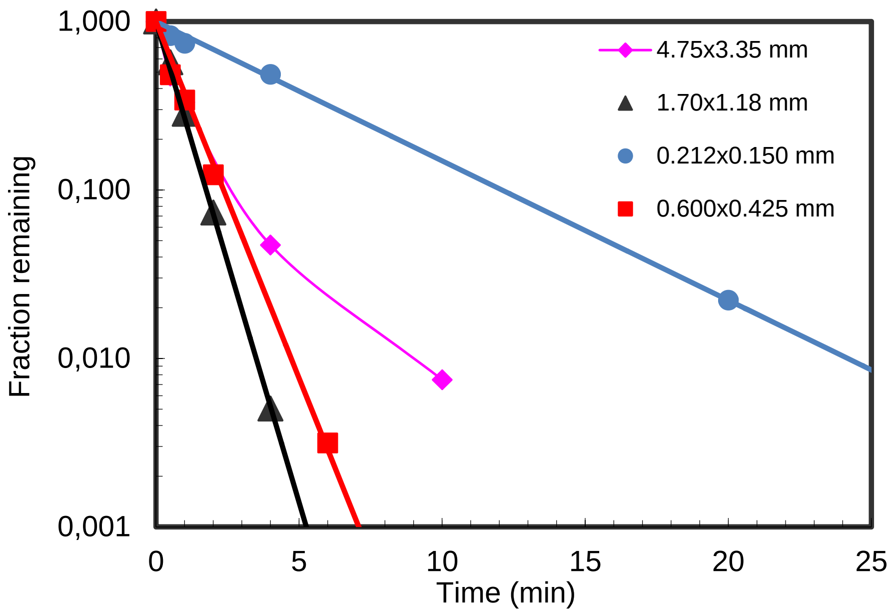

Figure 5. First-order plots from testing selected sizes of Itabirite #1 sample.

A summary of the breakage distribution and breakage rate functions that are back-calculated for both samples is presented in Table 3, whereas Figure 6 compares the measured and calculated breakage rates. The following expressions have been used to describe these functions[9,10]

$$S_i = S_1 \left(\frac{x_i}{x_o}\right)^{\alpha} \frac{1}{1+(x_i/\mu)^{\Lambda}} \quad (1)$$

$$B_{ij} = \Phi\left(\frac{x_{i-1}}{x_j}\right)^{\gamma} + (1-\Phi)\left(\frac{x_{i-1}}{x_j}\right)^{\beta} \quad (2)$$

and for $x_j < k$

$$B_{ij} = \Phi\left(\frac{x_{i-1}}{x_j}\right)^{\gamma}\left(\frac{x_{i-1}}{k}\right)^{\omega} + (1-\Phi)\left(\frac{x_{i-1}}{x_j}\right)^{\beta} \quad (3)$$

Where α, β, γ, ω and Λ are model parameters that are fitted to data.

Table 3. Breakage rate and breakage distribution parameters fitted from batch grinding of Itabirite ore samples

Sample	Breakage distribution function					Breakage rate function			
	β	γ	Φ	k (mm)	ω	S_1 (1/min)	α	μ (mm)	Λ
Itabirite #1	4.69	0.41	0.52	0.064	1,27	3.27	1.48	0.92	2.60
Itabirite #2	3.30	0.57	0.61	-	-	0.82	1.82	1.17	3.25

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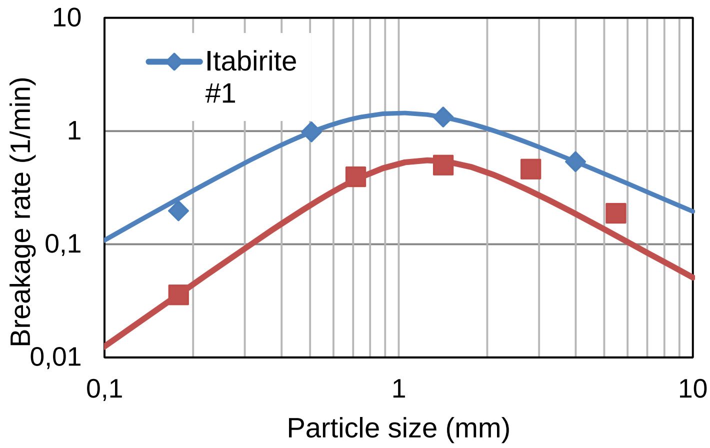

Figure 6. Comparison between measured and fitted breakage rates (Equation 1).

A comparison between measured and fitted results using the batch grinding model is presented in Figure 7, which demonstrates the good fit of the model to data. The figure, as well as breakage function parameters, demonstrates the strong non-normalizable character of the breakage function for Itabirite #1, which is associated to the very unusual breakage response of this material, which was already evident from the size analyzes of the feed samples shown in Figures 1 and 2.

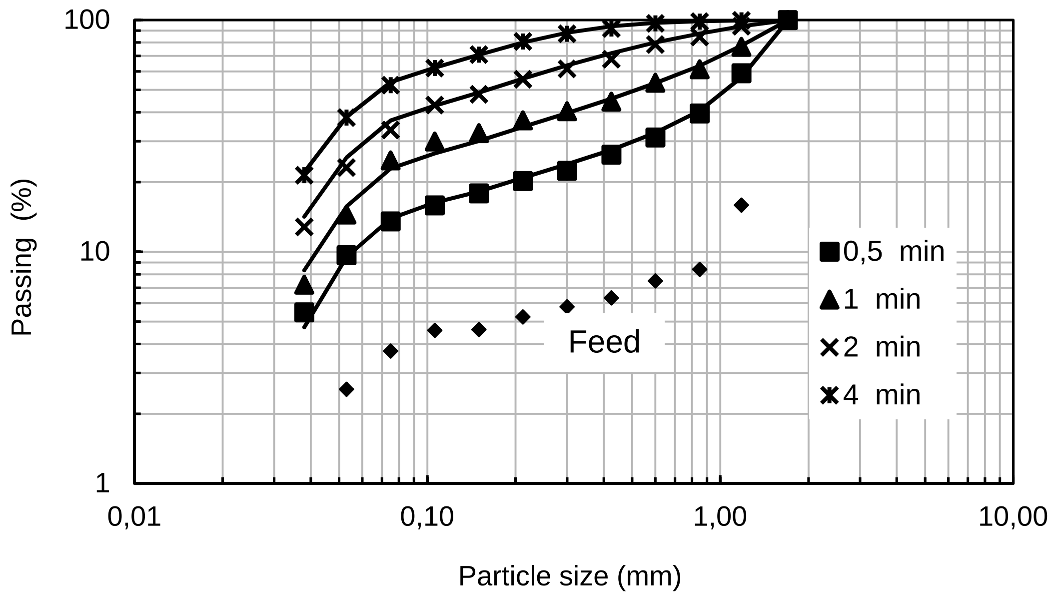

Figure 7. Comparison between measured and fitted size distributions for batch tests with Itabirite #1 (symbols represent experimental results and lines the model fit).

3.3 Simulation of a Closed Circuit Grinding in a Pilot-Scale Mill

A comparison between predictions using the Bond work index and those using the population balance model requires simulating the circuit composed of a mill and a classifier. A convenient way to conduct these comparisons is then to calculate the operating work index (Wi_o) of this simulated circuit, using the expression

$$Wio = \frac{W}{EF\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \quad (4)$$

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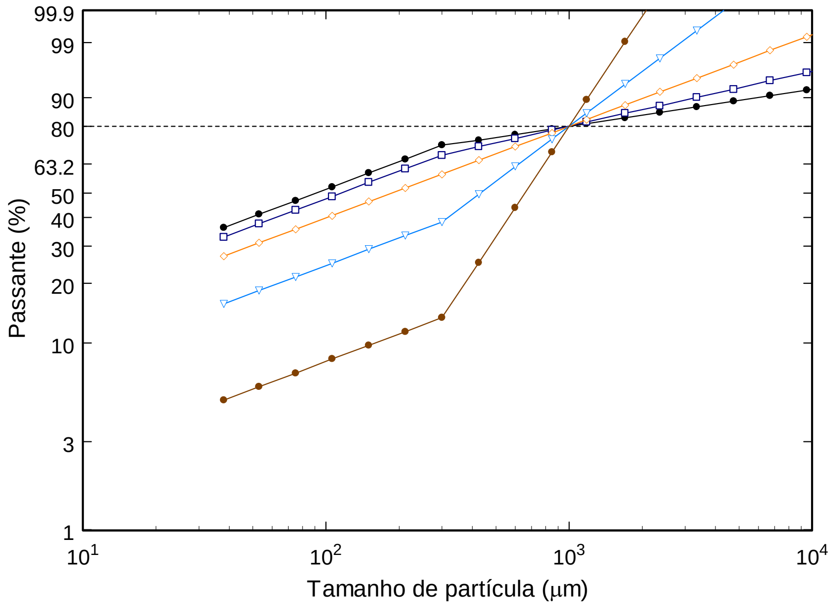
Where *EF* is the product of all Rowland correction factors. *W* is the specific energy consumption, obtained by simulation, and calculated by the ratio between the mill power, estimated using the Morrell(10) power equation, and the simulated fresh feed rate to the circuit.
In the simulations it was considered that the fresh feed to the circuit would be described by a sum of two Rosin-Rammler distributions, but with a fixed value of *F*80 and variable values of *F*90. As is illustrated in Figure 8, these distributions have some similarity to those corresponding to the feeds used in the Bond grindability tests presented in Figures 1 and 2.



Particle size (mm)

Figure 8. Feed size distributions tested in the simulations of grinding of Itabirite #1.

The grinding circuit that is simulated is the one described by Austin et al.(9) In summary, the mill operates in pilot-scale and has 1.2 m of diameter and 2.42 m length (Table 1), in closed-circuit with a hydraulic classifier. In the simulations, geometrical and operating conditions, besides model parameters for the classifier, were used from Austin et al.(9) who tested iron ore from Carajás. Simulations were conducted fixing the residence time in 9.1 minutes and using a software developed in the *Laboratório de Tecnologia Mineral* of COPPE, written in Matlab® environment. Simulation results are presented in Figure 9 for Itabirite #1, with the mean values of Bond work indices also shown and compared to the operating work index values calculated using Eq. (4). As it is evident, the operating work index calculated on the basis of the population balance model is lower than the measured Bond work index values measured with and without fines removal from the feed. The simulated value, however, more closely matches the value of *Wib* measured with partial removal of fines from the feed.

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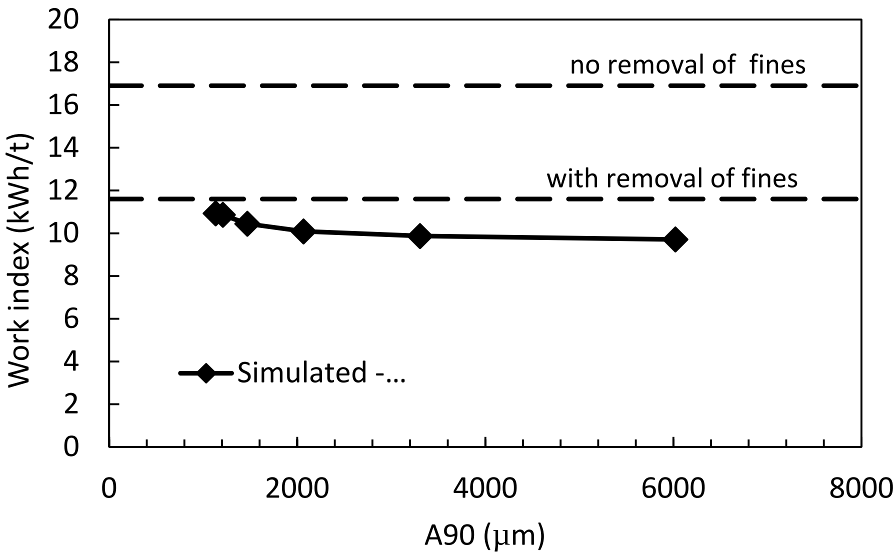

Figure 9. Comparison between the operating and the measured Bond work index values for the simulated pilot-scale grinding circuit described by Austin et al.[9] when grinding Itabirite #1.

3.4 Simulation of a Closed Circuit Grinding in an Industrial Mill

Continuous grinding tests in an industrial grinding circuit have been reported elsewhere[11] with Itabirite #2, and a comparison between the different methods is shown here. Some information on the conditions used in the test, ran at Timbopeba plant in Mariana, can be found in Table 1. In these tests, two different product fineness were considered, which resulted in different specific energy consumptions that are compared in Table 4 to predictions using the different scale-up methods.
From Table 4 it is evident that all methods overestimated the energy consumption in grinding the Itabirite ore. In the case of the Bond method, values were overestimated by as much as 115%, more so when the *Wib* used was the one determined with no prior removal of fines from the feed. Although it also overestimating the required energy consumption, the size-mass balance model predicted differences in the order of 16 to 24% in comparison to the measured values.

Table 4. Comparison of specific energy consumption (*W*) of an industrial grinding circuit mill under two different *P*80s grinding Itabirite #2

Condition	*P*80 = 87.6 µm		*P*80 = 106.7 µm	
	kWh/t	%	kWh/t	%
Measured [11]	6.48	-	4.08	-
Predicted (*Wib* without removal of fines)	9.90	53	8.77	115
Predicted (*Wib* with partial removal of fines)	9.06	40	8.02	97
Predicted using size-mass balance model	7.51	16	5.07	24

4 CONCLUSIONS

Initially, a comparison was conducted between different methods used to determine the Bond work index in a ball mill on samples of Itabirite iron ore from the Iron Quadrangle in Minas Gerais. It was observed that values of *Wib* obtained without prior removal of fines from the feed were, on average, 30% larger than those measured then fines were partially removed from the feed prior to conducting the Bond grindability test.

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Parameters in breakage distribution and rate functions determined according to procedures suggested by Austin, Klimpel and Luckie(6) were estimated from batch grinding tests. These functions were then used to simulate a pilot-scale grinding circuit(8) and it was concluded that estimates of *Wib* obtained using either method used in conducting the test lead to predictions of energy consumptions in grinding that were higher than those obtained using the population balance method.
A comparison between measured and calculated specific energy consumptions while grinding Itabirite #2 in a full scale ball mill demonstrated that predictions using the Bond ball mill work index overestimated severely the energy consumption required in the actual plant operation. Predictions using the population balance method, on the other hand, more closely matched the measured results.
As such, it is concluded that the removal of fines prior to conducting Bond ball mill grindability tests of Itabirite iron ores improved the usefulness of the result of the test (*Wib*) and is recommended for this type of ore. However, it did not rectify the bias towards overestimating the energy consumption in grinding. On the other hand, the population balance method should be regarded as the most appropriate method to simulate mills when grinding Itabirites.

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