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KINETIC GRINDING TEST APPROACH TO ESTIMATE THE BALL MILL WORK INDEX

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Abstract: The standard Bond method is the most acceptable method for designing and selecting ball/rod mills described by their basic parameter called work index (W_i). The standard Bond method is a tedious time consuming procedure requiring at least 7 – 10 grinding cycles, so that many researchers have tried to simplify this method to be able to perform a rapid calculation of a work index. This study aims to develop a new approach toward estimating the Bond ball mill work index (BBWI) by applying a series of kinetic grinding tests with Bond standard mill. Establishing a series of relationships between grinding parameters and Bond equation parameters, this approach is fast and practical due to eliminating laboratory control steps while reducing the number of milling steps. In this scope, thirteen ore samples were used to compare W_i values obtained by standard Bond method with those of the proposed kinetic approach. The kinetic periods were determined as 0.33, 1, 2, 4 and 8 minutes. The results of kinetic tests were found to be logical and acceptable as they were so close to the values obtained by Bond standard method, for all samples error was ≤ 2.60%. It was therefore concluded that the proposed approach could be considered as a simple yet practical alternative for the standard Bond method.

***Keywords**: work index, Bond method, kinetic grinding test, grindability, ball mill*

Introduction

The standard Bond (1952; 1961) method is widely used in the course of design, selection, scale up, energy calculation and performance evaluation of grinding circuits in mineral processing industry. This is mainly owed to the wide and valid database this method uses to derive its empirical equation (Bond, 1952; 1960; 1961). The most important parameter in this empirical equation is the Bond work index (W_i) which expresses the resistance of a material to comminution. In mineral industry, this is generally used for comparing the resistance of different materials in milling, estimating the required energy for milling (Levin, 1989) and mill scaling-up (Man, 2002).

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The W_i parameter is obtained from Bond's ball mill grindability test (Bond, 1961). This test is performed according to the standard Bond procedure which proposed model is presented in Eq. 1. This standard grindability test simulates a closed-cycle dry grinding and screening process, which continues to carry out until the steady state condition of 250% circulating load is obtained. This grindability test is conducted in a Bond ball mill of $\Phi D/L$= 0.3048/0.3048 m dimensions at the speed of 70 rpm. The mill is loaded with 21.125 kg standard sized balls and 700 cm^3 of grinded materials to under 3.35 mm. The test procedure takes from 7 to 10 grinding cycles with the required amount of material for whole procedure being approximately 10 kg. Once steady state condition is achieved, the work index, W_i, can be calculated according to the following Eq. 1.

$$W_i = \frac{48.95}{D^{0.23}\, G_{bp}^{0.82} \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)}\ , \frac{kWh}{Mg}\ . \tag{1}$$

Determining W_i via the standard Bond method needs careful grinding cycles and screen procedures. However, these are tedious time-consuming procedures with potential errors in sieving steps. Considering the difficulties of the standard Bond method in the course of determining W^i, a number of simpler and faster alternative methods have been developed by various researchers (Berry and Bruce, 1966; Smith and Lee, 1968; Horst and Bassarear, 1977; Karra, 1981; Yap et al., 1982; Armstrong, 1986; Magdalinovic, 1989; Nematollahi, 1994; Aksani and Sonmez, 2000; Deniz and Ozdag, 2003; Yalcin et al., 2004; Ipek et al., 2005; Ahmadi and Shahsavari, 2009; Ahmadi et al., 2013).

The aim of this study is to develop a new approach to estimate the Bond ball mill work index (BBWI) using a combination of Bond standard mill and initial test conditions by conducting kinetic grinding tests. The proposed approach differs from the previous methods in that it determines the required grinding parameters for calculating work index by the resultant distributions from the sieve analysis of the kinetic grinding tests, with no need to the control step using the 106 μm sieve. Although the same methodology was used for all materials, different relationships were established depending on the material. The kinetic method is implemented in two steps: 1) conducting laboratory grinding tests, and 2) calculation process in which the relationships between laboratory and Bond equation parameters are established.

Method and material

The experimental conditions of kinetic grinding tests together with mill specifications are given in Table 1. Except for grinding time, revolution numbers, sample amount and sieving procedures, all other operational conditions were set according to the standard Bond procedure.

Table 1. Conditions of kinetic grinding test and mill specifications (more in Appendix A)

D_m,cm	30.48
L_m, cm	30.48
V, rpm	70
C_v	0.91
J_B, %	19.27
M_B, kg	21.125
d_B, mm	36.38
Geometry of mill liner	smooth
Grinding type	dry
V_{ore}, cm^3	700
T, min	0.33, 1, 2, 4, 8

Thirteen samples of different ores and materials such as copper, iron and clinkers were collected for testing. According to the Bond method, these samples were prepared via repeated crushing in a laboratory jaw crusher following by sieving into appropriate sizes (100% < 3.35mm). Then, a representative feed sample of 700 cm^3 was taken followed by measuring its weight (W). Particle size distribution of feed sample was measured, so that F_{80}, $F_{(-106)}$ and G_{feed} were determined.

The proposed method

The test procedure shown in Fig. 1 performs in the followings steps.

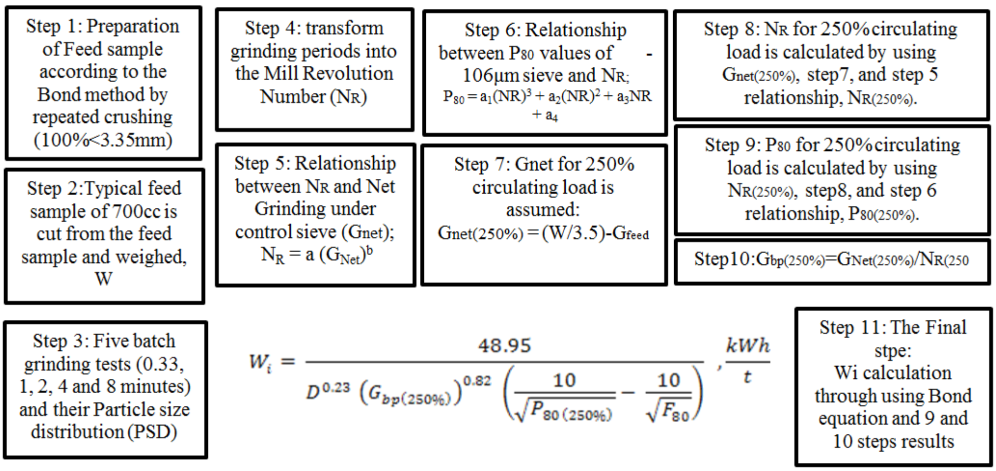

Fig. 1. Kinetic grinding approach procedure for BBWI calculation

Kinetic grinding

Exactly 700 cm^3 of 100% passing 3.35 mm material from each sample was progressively grounded in periods of 0.33, 1, 2, 4, and 8 minutes. Our experience has shown that the required number of revolutions to achieve the circulating load of 250% is most likely to be between 200 to 300 rotations. However, it will be suitable to select a grinding time of 8 minutes (560 cycles) to ensure achieving the desired condition while creating an additional point to reduce the associated errors to the fitted model. After each grinding step, the mill contents were removed and dry sized. Particle size distributions were recorded for fresh feed as well as the product obtained at the end of each grinding step. As an example, particle size distributions of hematite sample are presented in Fig. 2. The $G_{tot(i)}$, $G_{Net(i)}$ and $P_{80(i)}$ were determined graphically and numerically for each grinding step.

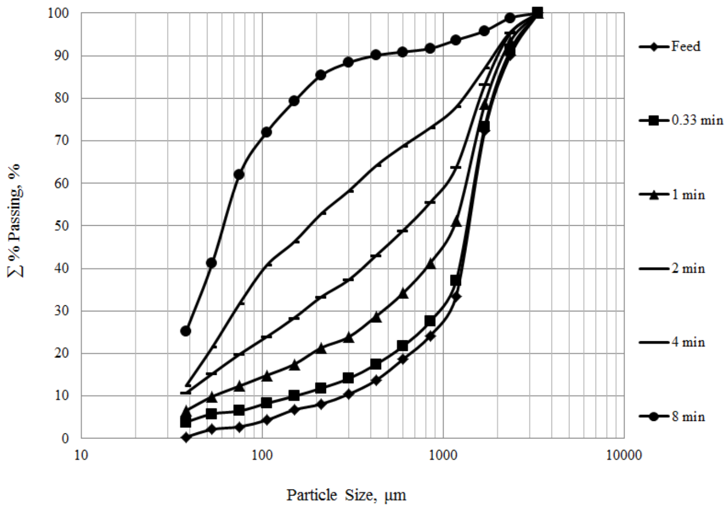

Fig. 2. Kinetic grinding results, hematite sample

t – N_R conversion

Referring to the mill speed, 70 rpm, the grinding period (t) was converted into the mill revolution number (N_R).

Relationship between N_R and G_{Net}

In this step, a relationship was established between N_R and G_{Net} using non-linear least squares fitting techniques. The value of G_{Net} was estimated for each N_R using particle size distribution graphs obtained from the kinetic grinding tests in section 3.1, ($N_{R(i)}$, $G_{Net(i)}$). An exponential relationship was found between N_R and G_{Net} with the corresponding equations presented in Table 3 for all samples. Figure 3 shows N_R - G_{Net} relation of hematite sample, as an example.

Table 3. Obtained N_R - G_{Net} equations for all samples

Sample No.	Ore type	N_R - G_{Net}	R^2
1	Bauxite	$N_R = 0.3883\ G_{Net}^{1.0624}$	0.9995
2	Hematite	$N_R = 0.3749\ G_{Net}^{1.1178}$	1.0000
3	Chromite1	$N_R = 0.4171\ G_{Net}^{1.0984}$	0.9945
4	Chromite2	$N_R = 0.4396\ G_{Net}^{1.0899}$	0.9998
5	Chalcopyrite1	$N_R = 0.5518\ G_{Net}^{1.0371}$	0.9985
6	Chalcopyrite2	$N_R = 0.4673\ G_{Net}^{1.0489}$	0.9983
7	Clinker1	$N_R = 0.6346\ G_{Net}^{1.033}$	0.9982
8	Clinker2	$N_R = 0.5097\ G_{Net}^{1.0574}$	0.9991
9	Dolomite	$N_R = 0.5004\ G_{Net}^{1.0486}$	0.9986
10	Magnetite	$N_R = 0.3955\ G_{Net}^{1.0784}$	0.9995
11	Limestone1	$N_R = 0.5937\ G_{Net}^{1.032}$	0.9982
12	Limestone2	$N_R = 0.7076\ G_{Net}^{0.9845}$	0.9989
13	Quartzite	$N_R = 0.3523\ G_{Net}^{1.1083}$	0.9954

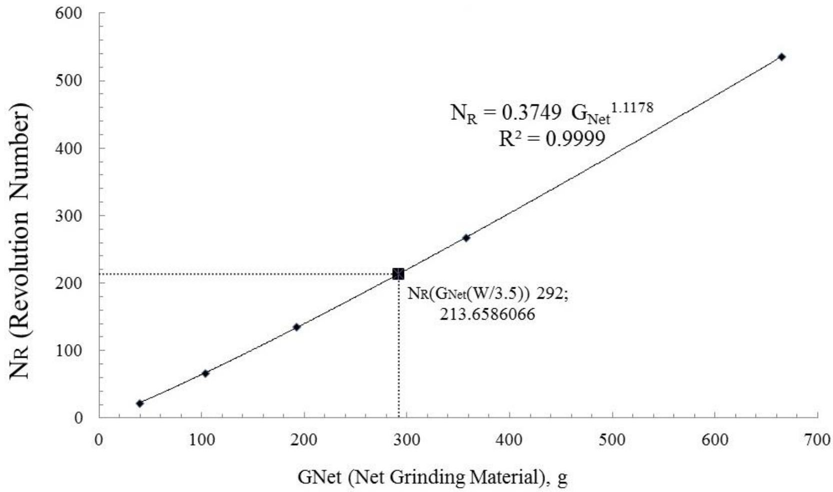

Fig. 3. N_R - G_{Net} relationships, hematite sample

Relationship between N_R and P_{80}

Based on non-linear least squares fitting techniques, relationships among P_{80} values, $P_{80(i)}$, and N_R values were established. These are polynomial relationships presented in Table 4 for all samples. Figure 4 shows the relationship between P_{80} and N_R for the Hematite sample, as an example. In order to avoid extraneous oscillations in the cubic relationship established between N_R and P_{80}, a linear interpolation might be preferred. In Fig. 4, P_{80} increases with $N_{R(280)}$ possibly because of the agglomeration of fine particles.

Table 4. Obtained $P_{80} – N_R$ equations for all samples

Sample No.	Ore type	$P_{80} – N_R$	R^2
1	Bauxite	P_{80} = (–2*E*–06) N_R^3 + 0.0014 N_R^2 – 0.3094 N_R + 87.923	0.968
2	Hematite	P_{80} = (–1*E*–06) N_R^3 + 0.0011 N_R^2 – 0.2803 N_R + 83.408	0.9971
3	Chromite1	P_{80} = (–2*E*–06) N_R^3 + 0.0017 N_R^2 – 0.3394 N_R + 93.704	0.9647
4	Chromite2	P_{80} = (–9*E*–07) N_R^3 + 0.0008 N_R^2 – 0.1858 N_R + 95.371	0.9876
5	Chalcopyrite1	P_{80} = (–2*E*–06) N_R^3 + 0.0015 N_R^2 – 0.3097 N_R + 91.002	0.982
6	Chalcopyrite2	P_{80} = (–2*E*–06) N_R^3 + 0.0015 N_R^2 – 0.3464 N_R + 102.7	0.9956
7	Clinker1	P_{80} = (–1*E*–06) N_R^3 + 0.0012 N_R^2 – 0.2643 N_R + 95.144	0.9834
8	Clinker2	P_{80} = (–1*E*–06) N_R^3 + 0.0012 N_R^2 – 0.2426 N_R + 92.183	0.9967
9	Dolomite	P_{80} = (–1*E*–06) N_R^3 + 0.0011 N_R^2 – 0.2607 N_R + 97.003	0.9831
10	Magnetite	P_{80} = (–2*E*–06) N_R^3 + 0.0016 N_R^2 – 0.3955 N_R + 102.23	0.9808
11	Limestone1	P_{80} = (–1*E*–06) N_R^3 + 0.0011 N_R^2 – 0.2605 N_R + 94.201	0.9788
12	Limestone2	P_{80} = (–1*E*–06) N_R^3 + 0.0011 N_R^2 – 0.2836 N_R + 104.38	0.9868
13	Quartzite	P_{80} = (–1*E*–06) N_R^3 + 0.0009 N_R^2 – 0.1658 N_R + 67.834	0.9566

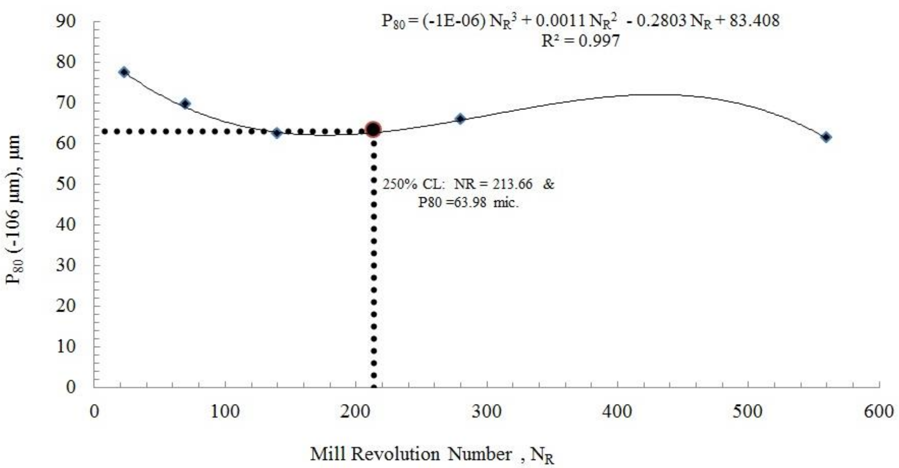

Fig. 4. P_{80} - N_R relationships, hematite sample

Estimation of P_{80} and N_R for 250% circulating load

In the standard Bond grindability method, the *CL* of the grinding cycle is considered to be 250%. It means that the total charge in the mill is 350% or 3.5 times the fresh feed. Considering the weight *W* for all samples in the standard Bond grindability test, the purpose of the test will be to keep the passed amount of grinded material through the controlled sieve constant at *W*/3.5. Therefore, in order to reach the equilibrium grinding condition when *CL* is 250%, the G_{Net} must be equal to $G_{Net(250\%)} = \left(\frac{W}{3.5}\right) \times$

$\left(\frac{100-F_{(-106)}}{100}\right)$. This is taken as the base-assumption-factor. The value of N_R for 250% CL, $N_{R(250\%)}$, is determined by using $G_{Net} - N_R$ plot or relationship, while the value of P_{80} for 250% CL, $P_{80(250\%)}$, is determined by using $N_R - P_{80}$ plot or relationship.

Estimation of $G_{bp(250\%)}$

The value of G_{bp} can be calculated by means of obtained N_R and G_{Net} values for 250% circulating load, $G_{bp(250\%)} = G_{Net(250\%)} / N_{R(250\%)}$.

Calculation of *BBWI* (W_i)

Finally, the *BBWI* or W_i can be calculated using the Bond equation (Eq. 1) and the estimated $G_{bp(250\%)}$ and $P_{80(250\%)}$ parameters for kinetic grinding tests.

Table 5. Comparison of standard Bond method and kinetic tests results

Sample No.	Ore type	Used Method	P_{80}	G_{bp}, g/rev	W_i, kWh/t	Error, %
1	Bauxite	kinetic test	66.42	1.771	10.321	-1.47066
		Bond Standard	65.21	1.779	10.172	
2	Hematite	kinetic test	63.48	1.374	12.525	0.04788
		Bond Standard	62.97	1.365	12.531	
3	Chromite1	kinetic test	81.30	1.358	14.330	-1.76406
		Bond Standard	81.09	1.384	14.082	
4	Chromite2	kinetic test	83.83	1.360	14.649	-1.04807
		Bond Standard	81.56	1.349	14.497	
5	Chalcopyrite1	kinetic test	74.44	1.460	13.054	0.733376
		Bond Standard	75.11	1.457	13.150	
6	Chalcopyrite2	kinetic test	78.03	1.601	12.298	0.951632
		Bond Standard	78.62	1.592	12.416	
7	Clinker1	kinetic test	87.78	1.304	15.471	0.985496
		Bond Standard	85.24	1.260	15.625	
8	Clinker2	kinetic test	86.74	1.410	14.865	0.898863
		Bond Standard	87.02	1.398	14.999	
9	Dolomite	kinetic test	82.45	1.505	13.479	-1.73527
		Bond Standard	80.56	1.510	13.249	
10	Magnetite	kinetic test	71.31	1.598	11.806	2.590589
		Bond Standard	73.25	1.579	12.120	
11	Limestone1	kinetic test	79.66	1.400	13.998	-0.01085
		Bond Standard	79.48	1.398	13.997	
12	Limestone2	kinetic test	86.16	1.548	13.646	0.584285
		Bond Standard	87.22	1.551	13.727	
13	Quartzite	kinetic test	62.40	1.527	11.238	0.387378
		Bond Standard	64.39	1.555	11.282	

Comparison of the results of standard method and the kinetic tests

Once the calculations were conducted, a comparison was performed between the results of the standard Bond method and those of kinetic tests and presented in Table 5. The complete W_i estimation procedure using the kinetic method is presented in Appendix A.

Results and discussion

In this study, a new approach was developed toward determination of the work index based on kinetic tests and Bond standard conditions. The G_{Net} value for 250% CL was assumed as $G_{Net(250\%)} = \left(\frac{W}{3.5}\right) \times \left(\frac{100- F_{(-106)}}{100}\right)$. This assumption was taken as the base-assumption-factor of the current study. The Bond method along with the kinetic approach was used to determine the work indices of different materials within thirteen samples. The results showed that the obtained values for work indices by means of kinetic tests were in good agreement with those of the standard Bond method, for all samples: error $\leq$ 2.60%, indicating usefulness of the Base-Assumption-Factor for estimation of W_i. The proposed procedure included five batch grinding tests, their sieve analyses in laboratory and the calculation process according to laboratory results and the Bond equation. This method is fast and practical as it eliminates laboratory control steps and reduces the number of milling steps. It also reduces the required weight of material from about 10 kg to approximately 1.5 kg. Due to these results and the simplicity of the method, the new developed approach can be used instead of the standard Bond method. It should be carefully noted that if an ore sample contains small amounts of very hard fractions, it will be necessary to apply a full Bond test to accumulate these fractions. This approach gives a raise to the possibility of using the collected data to change the test screen size and the assumed circulating load without collecting further data. This issue will be discussed in future studies.

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Appendix A. Determination of the Bond work index using thekinetic method

In order to determine Bond work index of a material, firstly, it must be prepared according to the Bond standard method. The kinetic method uses the same mill operating under the same conditions as those in Bond standard procedure, except for the grinding time, revolution numbers, sample amount and sieving procedure. Specifications of hematite sample, as an example, are presented in Table A.1.

Table A.1. Specifications of hematite sample

V_{ore},cm^3	W, g	F_{80}, μm	$F_{(-106)}$, %	CL, %	W/3.5, g
700	1022	1983	4.89	250	292.00

Calculation of W_i through the proposed kinetic method was performed at five grinding cycles. The sieve analysis of the fresh feed and these grinding cycles were measured and plotted. The obtained graph for the hematite sample is presented in Fig. 2, as an example. Then, the calculation procedure was conducted as follows:

1. for a 250% circulating load, the net grinded material was $G_{Net(250\%)} = \left(\frac{W}{3.5}\right) \times \left(\frac{100 - F_{(-106)}}{100}\right)$ = 279.27 g
2. each grinding period, t, was converted into a Mill Revolution Number, N_R
3. for each N_R, the values of G_{Net} and P_{80} were estimated through using particle size distribution graphs shown in Fig. 2
4. for hematite samples, an exponential relationship was established between N_R and G_{Net} ($N_R = 0.3749\ G_{Net}^{1.1178}$, Fig. 3), so that
5. $N_{R(250\%)} = 0.3749 \times (279.27)^{1.1178} = 203.27\ rev$
6. for hematite sample, the following polynomial relationship was established between N_R and P_{80}: $P_{80} = (-1E-06)N_R^3 + 0.0011\ N_R^2 - 0.2803N_R + 83.408$, Fig. 4, so that the P_{80} value for $N_{R(250\%)}$ was calculated as $P_{80(250\%)} = 63.48\ \mu m$
7. the grindability factor, G_{bp}, could be calculated by means of obtained N_R and G_{Net} for 250% circulating load: $G_{bp(250\%)}=(G_{Net(250\%)})/N_{R(250\%)}$ = 279.27/203.27 = 1.374 g/rev
8. finally, the Bond equation was used to determine the work index, which was equal to 12.525 (kWh/Mg) in our example.

Nomenclature	
$BBWI$	Bond Ball Mill Work Index (kWh/Mg)
CL	Circulating Load (%)
C_v	Mill speed (fraction of critical)
D	Control sieve size = 106 μm
d_B	Ball top size (mm)
D_m	Inner diameter of mill (cm)
$F_{(-106)}$	Amount of -106 μm in the mil Feed, before grinding, (%)
F_{80}	80% passing size of the mill feed, before grinding, (μm)
G_{bp}	Grindibility factor (g/rev)
$G_{bp(250\%)}$	Grindibility factor for 250% circulating Bond ball mill work index load (g/rev)
G_{feed}	Weight of -106μm material in the mill feed, before grinding, (g)
G_{Net}	Net grinding material of -106 μm (g)
$G_{Net(250\%)}$	Net grinding material under control sieve for 250% circulating load (g)

$G_{Net(i)}$	Weight of net grinding material of -106 µm for any step that is equal to $G_{tot(i)}$ minus G_{feed} for i=1,2,..,5
$G_{tot(i)}$	Weight of -106 µm material in the mill product at any step (g)
J_B	Ball load (% by volume)
L_m	Inner length of mill (cm)
M_B	Total mass of balls (kg)
N_R	Mill revolution numbers
$N_{R(250\%)}$	NR for 250% circulating load
$N_{R(i)}$	amount of revolution number for each step, i = 1, 2, .., 5
P_{80}	80% passing size of the final product (µm)
$P_{80(250\%)}$	P80 for 250% circulating load
$P_{80(i)}$	80% passing size of the -106µm material for any step for i=1,2,..,5 (µm)
R^2	R-squared or coefficient of determination
t	Grinding period (min)
V	Mill speed (rpm)
V_{ore}	Ore volume, required material (cm3)
W	Mass of mill content (g)
$W/3.5$	Weight of material for 250% circulating load (g)
W_i	Work index (kWh/Mg)

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