A QUICK METHOD FOR BOND WORK INDEX APPROXIMATE VALUE DETERMINATION

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Abstract: The Bond work index is a measure of ore resistance to crushing and grinding and is determined using the Bond grindability test. Its value constitutes ore characteristic and is used for industrial comminution plants designing. Determining the Bond work index value is quite complicated, time-consuming and requires trained operating personnel and therefore is subjected to errors. A quick method for the Bond work index approximate value determination, which is based on the first order grinding kinetics, is presented in this paper. Comparative experiments for the Bond work index value determination using the standard and quick procedures were carried out on samples of limestone and andesite, and on composite samples containing both ores in different mass proportions. This quick procedure can be performed with an arbitrary number of milling cycles, depending on the desired accuracy.

Introduction

Fred C. Bond noted that experiments in an open grinding cycle are unsuitable for determining the energy consumption during grinding, and can cause inaccurate energy consumption prediction required for grinding, especially in a closed cycle, or for complex ore composed of different minerals. Based on these observations, Bond and others in Allis-Chalmers have developed a grinding test in a ball mill in a closed cycle until the establishment of stable recirculating load (Maxson et al., 1933).

The Bond work index is a parameter which represents a measure of an ore resistance to grinding. Numerically, the work index represents the energy (kWh/sht) required to reduce the material of one short ton from a theoretically infinite feed size to size at which 80 percent of material passes through sieve with square aperture100

micrometers in size. According to the Bond standard procedure, the work index is determined by simulating a dry grinding in a closed circuit in the Bond ball mill to achieve 250% circulating load (Bond, 1949, 1952, 1961). The test is performed on a raw material approximately weighing 10 kg, which coarseness is 100% -3.327 mm. The first grinding test is performed on a 700 cm^3 volume sample with an arbitrary number of the mill revolutions. After each grinding cycle ground material from the mill is screened on the control sieve. Then, the undersize material is removed and fresh material is added to the sieve oversize to obtain a starting mass sample, as in the first grinding circle. Mill revolutions number for all subsequent grinding is calculated using the data from the previous cycles to obtain 250% circulating load. The procedure is repeated until control sieve undersize produced per mill revolution becomes a constant in the last three milling cycles. This is also an indication that the desired circulating load has been achieved. The Bond standard method requires 7–10 grinding cycles. The Bond Work Index is calculated using the formula:

$$W_i = 1{,}1 \frac{44{,}5}{P_c^{0,23} G^{0,82} \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \tag{1}$$

where W_i – Bond work index (kWh/t)
      P_c – test sieve mesh size (µm)
      G – weight of the test sieve fresh undersize per mill revolution (g/rev)
      F_{80} – sieve mesh size passing 80% of the feed before grinding(µm)
      P_{80} – opening of the sieve size passing 80% of the last cycle test sieve
      undersize product (µm).

Determination of the energy consumption for ore grinding in a Bond ball mill requires samples of standard size, because changes in the size of the samples cause the change of the Bond work index (Magdalinovic et al., 2012). Due to the Bond test complexity and length, as well as the possibility to make mistakes during performance, many scientists have tried to simplify and shorten this procedure (Weiss, 1985).

Berry and Bruce (1966) invented an approximate procedure where the data of an unknown ore grindability are compared to reference ore of known grindability. This procedure can be carried out in any laboratory ball mill. Horst and Bassarear (1976) gave a similar procedure, but lasting a bit longer, where reference ore data and data of the ore for which the value of the Bond Index is determined, are also compared.

Smith and Lee (1968) have compared the data obtained through the standard Bond test and those from an open-cycle milling.

Kapur (1970) analyzed the data obtained during the execution of the Bond standard test, developed a mathematical algorithm that simulates this process and, on the basis of it, assessed the Bond work index.

Karra (1981) modified the method of Kapur considering that the Bond standard test circular load is harder than the fresh sample and therefore is grounded more slowly.

This method, by using mathematical algorithms, simulates the Bond test on the basis of the results from the first two milling cycles.

Magdalinovic (1989) proposed a shortened method for determining the Bond work index, which includes two milling. Magdalinovic (2003) gave the abbreviated method similar to the previous one, except that it includes three milling. His second method gives better results with smaller error than the previous ones.

Lewis et al. (1990) gave a mathematical algorithm that simulates the standard Bond test, which is based on the data obtained from the standard procedure first milling.

Gharehgheshlagh (2015) provided a method which relies on monitoring the grinding kinetics in the Bond ball mill and established a series of relationships between grinding parameters and the Bond equation parameters. He stated that the error between the results obtained by his method and those obtained by the standard Bond test does not exceed 2.6%.

The aim of this study was to develop a new method for assessing the Bond work index in a ball mill (BBWI), which is based on a first order kinetics present in the Bond ball mill for grinding mineral raw materials (Austin et al., 1981; Ahmadi and Shahsavari, 2009).

Theoretical basis of quick procedure

Grinding of various mineral raw materials in the Bond ball mill occurs according to the first order kinestics (Magdalinovic, 2003; Deniz, 2004):

$$R = R_0 e^{-kt} \qquad (2)$$

where: R – test sieve oversize at time (t),

R_0 – test sieve oversize at the beginning of grinding ($t = 0$),

k – grinding rate constant,

t – grinding time.

The grinding rate constant (k) can be determined for each cycle of the standard Bond grinding procedure:

$$k = \frac{\ln R_0 - \ln R}{t} = \frac{n(\ln R_0 - \ln R)}{N} \qquad (3)$$

where: N – total number of mill revolutions,

n – mill revolutions per minute RPM (min^{-1}).

Grinding rate constant slowly rises from the second to the last cycle during the execution of the standard Bond grinding procedure. The main reason is that circulating load is finer with each subsequent grinding and therefore it is easier to obtain the desired product of milling, i.e. comparative sieve undersize. For the second, third and fourth cycle of grinding, constants would be k_2, k_3 and k_4 and their relationship $k_2 < k_3 < k_4$.

By using the obtained constant k, it is possible to calculate how long it takes for grinding, i.e. required mill revolutions to grind material when a steady state is achieved (circulating load 250%).

In cases where equilibrium state is achieved with 250% circulating load:

$$R_0 = \frac{2{,}5}{3{,}5}M + \frac{M}{3{,}5}X \quad \text{and} \quad R = \frac{2{,}5}{3{,}5}M \tag{4}$$

where: M – weight of the starting sample (700 cm^3) (g),

        X – mass content of size fraction coarser than the opening of the comparative sieve Pk in the starting sample (fractions of unit).

$$t = \frac{1}{k}\left[\ln\left(\frac{2{,}5}{3{,}5}\cdot 100 + \frac{X}{3{,}5}\cdot 100\right) - \ln\left(\frac{2{,}5}{3{,}5}\cdot 100\right)\right] \tag{5}$$

$$N = \frac{n}{k}\left[\ln\left(\frac{2{,}5}{3{,}5}\cdot 100 + \frac{X}{3{,}5}\cdot 100\right) - \ln\left(\frac{2{,}5}{3{,}5}\cdot 100\right)\right] \tag{6}$$

For the second grinding the values are t_{2e} and N_{2e}, for the third t_{3e} and N_{3e} and for fourth t_{4e} and N_{4e}. When the calm state is achieved, the newly formed comparative sieve undersize is

$$Z = \frac{M}{3{,}5} - \frac{M}{3{,}5}(1 - X) = \frac{M}{3{,}5}X.$$

Using calculated value N it is possible to calculate parameter G (g/rev.):

$$G = \frac{Z}{N} = \frac{\frac{M}{3{,}5}\cdot X}{N}. \tag{7}$$

In this way, obtained values for second, third and fourth grinding are G_{2e}, G_{3e} and G_{4e}.

During the execution of the standard Bond procedure on over thirty samples of different materials with various physical-chemical properties and grindability, it was noted that the G values obtained in this way are in the same constant relation to the value of G_e from the last grinding cycle. For two grinding cycles $\frac{G_e}{G_{2e}}$ ranges from 1.077 to 1.239. For three grindings cycles $\frac{G_e}{G_{3e}}$ ranges from 1.047 to 1.145. For four grinding cycles $\frac{G_e}{G_{4e}}$ ranges from 0.998 to 1.075. Mean values of these ratios are:

$$\frac{G_e}{G_{2e}} \approx \text{const} = 1.158 \quad \frac{G_e}{G_{3e}} \approx \text{const} = 1.096 \quad \frac{G_e}{G_{4e}} \approx \text{const} = 1.037 \tag{8}$$

So, it is possible to perform two grinding cycles according to the standard Bond procedure, calculate G_{2e} , multiply by a constant and get an approximate G_e value of the last grinding. The same rule applies to the third and fourth grinding.

Undersize parameter P_{80}, from the first to the last cycle of the standard Bond grinding procedure, is also changed according to a precise rule that is similar for

different raw materials. For two grinding cycles $\frac{P_{80}}{P_{2\,80}}$ ranges from 1.012 to 1.058. For three grinding cycles $\frac{P_{80}}{P_{3\,80}}$ ranges from 0,989 to 1.072. For four grinding cycles $\frac{P_{80}}{P_{4\,80}}$ ranges from 1.000 to 1.035. Mean values of these ratios are:

$$\frac{P_{80}}{P_{2\,80}} \approx \text{const} = 1.035 \qquad \frac{P_{80}}{P_{3\,80}} \approx \text{const} = 1.030 \qquad \frac{P_{80}}{P_{4\,80}} \approx \text{const} = 1.017 \qquad (9)$$

So, it is possible to perform two grinding cycles according to the standard Bond procedure, do undersize particle size distribution, determine graphically parameter P_{80}, multiply by a constant and get an approximate value of P_{80} of the last grinding. The same rule applies to the third and fourth grinding.

Method and material

The experimental execution conditions of the standard Bond test, together with the specification of the Bond mill are given in Table 1.

Table 1. Bond's mill specification and grinding conditions

Mill diameter, D_m, cm	30.48
Mill Length, L_m, cm	30.48
Number of mill rotations in minutes, n, min^{-1}	70
Mill balls weight, M_b, kg	21.125
Geometry of mill liner	smooth
Grinding type	dry
V_{ore}, cm^3	700

Andesite and limestone samples were prepared by crushing in a laboratory jaw crusher and roll crusher in a closed cycle with screening to size 100% -3.327 mm. Composite samples of andesite and limestone were prepared in ratios:

limestone : andesite = 25 : 75,

limestone : andesite = 50 : 50,

limestone : andesite = 75 : 25.

The Bond work index determination according to the standard Bond test was done on all samples with a comparative sieve size of 74 micrometers. After each grinding cycle, particle size distribution and parameter P_{80} determination were performed on comparative sieve undersize.

Procedure for quick method execution

A quick procedure with two grinding cycles for the determination of the Bond work index approximate value is exactly the same as in the first two grinding cycles of the standard Bond test and consists of the program.

- Prepare a sample, the same as for the standard Bond test (grind to 100% -3.327 mm).
- Determine the starting sample particle size distribution and value F_{80} (µm) as well as the participation of a larger size, then comparative sieve openings X (fractions of unit).
- Take a sample of volume 700 cm^3, determine its mass M (g), charge it into the Bond ball mill and grind for an arbitrary number of mill revolutions ($N_1 = 50$, 100 or 150 revolutions).
- After grinding, screen the sample on the comparative sieve and determine undersize mass D, (g) and oversize R, (g). Undersize D consists of a undersize mass D_u, which is entered with fresh feed and newly formed undersize in mill D_n.

$$D = D_u + D_n, \text{ g.} \tag{10}$$

- Calculate the newly formed undersize mass D_n:

$$D_n = D - D_u. \tag{11}$$

In first grinding cycle it is:

$$D_u = M \cdot (1 - X), \text{ g.} \tag{12}$$

In subsequent cycles it is:

$$D_u = D_{(n-1)} \cdot (1 - X), \text{ g} \tag{13}$$

where: $D_{(n-1)}$ is the undersize mass from the previous cycle, g.

- Calculate the newly formed undersize mass per mill revolution:

$$G = \frac{D_n}{N}, \text{ g/rev.} \tag{14}$$

where: N – mill revolutions in a given grinding cycle.

- Calculate the mill revolutions for following grinding cycle:

$$N_n = \frac{\frac{M}{3,5} - D_{(n-1)} \cdot (1 - X)}{G}, \text{ rev.} \tag{15}$$

- Add to comparative sieve oversize fresh sample a mass equal to the undersize mass from the previous cycle $D_{(n-1)}$. Thus, the formed feed sample is charged into the mill and ground for N_n revolutions.

- After grinding, screen the sample on the comparative sieve and measure the oversize mass R (g).
- Calculate constant k with formula (3) using equation:

$$k = \frac{n \cdot (lnR_0 - lnR)}{N} = \frac{n \cdot \left[ln\left(\frac{R_{(n-1)}}{M} \cdot 100 + \frac{D_{(n-1)}}{M} \cdot X \cdot 100\right) - ln\left(\frac{R}{M} \cdot 100\right) \right]}{N}. \tag{16}$$

- Calculate the required mill revolutions number N. In the case the grinding material quantity is the same as when the equilibrium was reached (circulating load 250%), with grinding rate constant as in the second grinding, using formula (6).
- Calculate parameter G (g/rev) with formula (7). Obtained value G is multiplied by the constant of 1.158, giving value G_e, which should be approximately equal to the value of G at the last grinding cycle during the execution of the standard Bond test.
- Determine the grain size distribution and parameter $P_{2\,80}$ for the second grinding undersize. The obtained value is multiplied by constant 1.035. Calculated result should be approximately equal to the P_{80} value of undersize from the last grinding cycle during the execution of the standard Bond test.
- Using the achieved values of G_e , P_{80} and formula (1) an approximate value of W_i (kWh/t) is obtained.

In case of a quick method with three or four grinding, three or four grinding cycles should be carried out, in the same way as the standard Bond procedure. Parameters G_e and P_{80} are calculated as in the procedure with two grinding, except for being multiplied by the appropriate parameters for three or four cycles grinding. The Bond work index is also calculated using formula (1).

Results and discussion

Comparative results, obtained by the standard Bond procedure and by the quick procedure with two, three and four grinding cycles, parameters G, P_{80} and the Bond work index are shown in Tables 2, 3 and 4.

During the performance of the quick procedure with two, three and four grinding cycles and the standard Bond grinding test, it can be seen that when observing parameter G, that the maximum difference decreases from 5.1% to 3.7%, and the mean difference decreases from 2.45% to 2.26%. This clearly indicates that with the increase of grinding cycles number, the estimated parameter G accuracy increases as well.

During the performance of the quick procedure with two, three and four grinding cycles and the standard Bond grinding test, it can be seen, when observing parameter P_{80} , that the maximum difference ranges from 8.26% to 14.63%, and the mean difference from 2.39% do 4.48%.

Table 2. A comparison of parameter G obtained by the standard Bond procedure
and quick procedure with two, three and four grinding cycles

Sample	Sieve, μm	G_e, g/rev	2 Grinding		3 Grinding		4 Grinding	
			G_{r2}, g/rev	Differ., %	G_{r3}, g/rev	Differ., %	G_{r4}, g/rev	Differ., %
Limestone: andesite 0 : 100	74	0.920	0.943	+2.17	0.963	+4.35	0.944	+2.57
Limestone: andesite 25 : 75	74	0.980	0.935	-5.10	0.997	+2.04	0.996	+1.58
Limestone: andesite 50 : 50	74	1.070	1.061	-0.93	1.102	+2.80	1.110	+3.70
Limestone: andesite 75 : 25	74	1.230	1.209	-1.63	1.262	+2.44	1.265	+2.86
Limestone: andesite 100 : 0	74	1.340	1.369	+2.44	1.339	0.00	1.348	+0.60
Maximum difference		/	5.10		4.35		3.70	
Mean difference		/	2.45		2.33		2.26	

Table 3. A comparison of parameter P_{80} obtained by the standard Bond procedures
and quick procedure with two, three and four grinding cycles

Sample	Sieve, μm	P_{80}, μm	2 Grinding		3 Grinding		4 Grinding	
			$P_{80\,r2}$, μm	Differ., %	$P_{80\,r3}$, μm	Differ., %	$P_{80\,r4}$, μm	Differ., %
Limestone: andesite 0 : 100	74	58.00	56.93	-1.84	57.68	-0.55	58.99	+1.71
Limestone: andesite 25 : 75	74	57.00	56.93	-0.12	56.65	-0.61	56.95	-0.09
Limestone: andesite 50 : 50	74	55.00	54.86	-0.25	53.56	-2.62	54.92	-0.15
Limestone: andesite 75 : 25	74	59.00	56.93	-3.51	56.65	-3.98	57.97	-1.75
Limestone: andesite 100 : 0	74	62.00	68.31	+10.18	71.07	+14.63	67.12	+8.26
Maximum difference			10.18		14.63		8.26	
Mean difference			3.18		4.48		2.39	
First four samples maximum difference			3.51		3.98		1.75	
First four samples mean difference			1.43		1.94		0.92	

In the case of the pure limestone sample during determining particle size
distribution of comparative sieve undersize by manual screening on sieves, there was
fine particles agglomeration. For this reason unrealistic results were obtained for
parameter P_{80}, so that the resulting difference of this sample is significantly bigger.

In Table 3 additionally are shown maximum and mean differences for parameter P_{80} excluding a sample of pure limestone. The maximum difference of parameters P_{80} for the first four samples ranges from 3.98% to 1.75%.

Table 4. A comparison of the Bond work index *Wi* obtained by the standard Bond procedure and quick procedure with two, three and four grinding cycles

Sample	Sieve, μm	W_i, kWh/t	2 Grinding		3 Grinding		4 Grinding	
			W_{ir2}, kWh/t	Differ., %	W_{ir3}, kWh/t	Differ., %	W_{ir4}, kWh/t	Differ., %
Limestone: andesite 0 : 100	74	18.09	17.53	-3.09	17.37	-3.98	17.90	-1.05
Limestone: andesite 25 : 75	74	17.03	17.69	+3.87	16.73	-1.75	16.80	-1.33
Limestone: andesite 50 : 50	74	15.50	15.58	+0.51	14.89	-3.93	15.03	-3.02
Limestone: andesite 75 : 25	74	14.51	14.39	-0.82	13.86	-4.48	14.03	-3.34
Limestone: andesite 100 : 0	74	13.90	14.50	+4.32	15.14	+8.93	14.53	+4.52
Maximum difference			4.32		8.93		4.52	
Mean difference			2.52		4.61		2.65	
First four samples maximum difference			3.87		4.48		3.34	
First four samples mean difference			2.07		3.53		2.18	

During the performance of the quick procedure with two, three and four grinding cycles and the standard Bond grinding test, it can be seen that when observing Bond work index W_i the maximum difference ranges from 8.93% to 4.32%, and the mean difference from 4.61% to 2.65%.

Higher parameter P_{80} differences for pure limestone sample resulted also in a higher value of the Bond work index Wi difference.

In Table 4, additionally, the maximum and mean differences for the Bond work index (W_i) excluding the sample of pure limestone are shown. The maximum difference of the Bond work index for first four samples ranges from 4.48% to 3.34%. The mean difference for the first four samples ranges from 3.53% to 2.07%.

The most realistic picture of the reliability of the quick procedure is given by a comparative overview of parameter *G* in Table 2.

The results achieved in investigations with their abbreviated procedures in relation to the standard Bond procedure results are: Berry and Bruce (1966) mean square relative difference 8%, Kapur (1970) mean square relative difference 9.7%, Karra (1981) mean square relative difference 4.8%, Magdalinovic(1989) mean square relative difference 4.9%, Lewis et al. (1990) the maximum difference does not exceed 6.2%, Magdalinovic (2003) the maximum difference does not exceed 3.5%.

Comparing the results that the researchers have achieved in the past and the results obtained by this method, it can be concluded that the results are satisfactory.

Conclusion

Grinding in a laboratory Bond ball mill occurs according to the first order kinetics. Parameter P_{80} of comparative sieve undersize, for all raw materials, changes according to a precise rule. These facts allow, by using data from each cycle of the standard Bond grinding test, to calculate approximate values of parameters G and P_{80} and, consequently, to calculate the value of W_i.

In case of two, three and four grinding cycles the Bond work index W_i maximum differences, excluding the sample of pure limestone, all amounted to 3.87%, 4.48% and 3.34%. The procedure reliability increases with the number of grinding cycles carried out.

Reliability verification of this procedure on limestone and andesite composite samples with their different mass portions, with comparative sieve openings 74µm, gave very good results. Further research with these samples should be carried out on other comparative sieves.

The accuracy of this method, for the parameter G value, can easily be checked using the data of already performed experiments by the standard Bond procedures on different raw materials.

Appendix A. Determination of Bond work index approximate value by the quick method on limestone : andesite = 25 : 75 sample with two grinding cycles

Sample was prepared according to the Bond standard method. The quick method uses the Bond mill operating under the same conditions as those in the Bond standard procedure.

Specification of limestone : andesite = 25 : 75 sample
$V = 700$ cm^3 (volume of sample mill charge),
$M = 1106.5$ g (weight of 700 cm^3 sample volume),
Circulating load 250%,
$M/3.5 = 316.1$ g (weight of milling product when circulating load is 250%),
$F_{80} = 1760$ µm (sieve mesh size passing 80% of the feed before grinding),
$X_{74} = 0.9314$ (content of the class +74 µm in the starting sample).

I grinding

A 700 cm^3 sample was ground in a Bond ball mill at $N = 150$ rpm. After grinding, the sample was screened on a sieve with 74 µm aperture, and in this way we obtaine oversize $R_1 = 890.3$ g and undersize $D_1 = 216.2$ g.

The 74 µm undersize mass which is entered with fresh sample in the first grinding:

$$D_{u1} = M(1 - X) = 1106.5\,(1 - 0.9317) = 75.9 \text{ g.}$$

The newly formed undersize mass for the first grinding:

$$D_{n1} = D_1 - D_{u1} = 216.2 - 75.9 = 140.3 \text{ g}.$$

The newly formed undersize mass per mill revolution for first grinding:

$$G_1 = \frac{D_{n1}}{N_1} = \frac{140,3}{150} = 0.94 \text{ g/rev}.$$

II grinding

Fresh sample weighing $D_1 = 216.2$ g was added to the oversize of the first grinding and thus we got the mass of the sample for the second grinding equal to $M = 1106.5$ g.

Mill revolutions for the second grinding cycle:

$$N_n = \frac{\frac{M}{3,5} - D_1 \cdot (1-X)}{G_1} = \frac{\frac{1106.5}{3,5} - 216.2 \cdot (1-0.9317)}{0.94} = 322 \text{ rev}.$$

After grinding, sample was screened on a sieve with 74 µm aperture, and in this way we gained oversize ($R_2 = 823.3$ g) and undersize ($D_2 = 283.2$ g).

The calculated grinding rate for the second grinding cycle was:

$$k = \frac{n\left[ln\left(\frac{R_1}{M} \cdot 100 + \frac{D_1}{M} X \cdot 100\right) - ln\frac{R_2}{M} \cdot 100\right]}{N} = \frac{70 \cdot \left[ln\left(\frac{890.3}{1106.5} \cdot 100 + \frac{216.2}{1106.5} \cdot 0.9317 \cdot 100\right) - ln\frac{823.3}{1106.5} \cdot 100\right]}{322} =$$

$$0.0604.$$

Grain size analysis was performed on the milling product of the second grinding cycle and it was determined that $P_{2\,80} = 55$ µm.

Calculation

Required mill revolutions number N, in the case when the grinding material quantity is the same as when the equilibrium was reached (circulating load 250%), same as in the final grinding cycle of the standard Bond procedure, with grinding rate constant as in the second grinding:

$$N = \frac{n}{k}\left[\ln\left(\frac{2,5}{3,5} \cdot 100 + \frac{X}{3,5} \cdot 100\right) - \ln\left(\frac{2,5}{3,5} \cdot 100\right)\right]$$
$$= \frac{70}{0.0604}\left[ln\left(\frac{2,5}{3,5} \cdot 100 + \frac{0.9317}{3,5} \cdot 100\right) - ln\left(\frac{2,5}{3,5} \cdot 100\right)\right].$$

The calculated value G_{2e} was:

$$G_{2e} = \frac{Z}{N} = \frac{\frac{M}{3,5} \cdot X}{N} = \frac{\frac{1106.5}{3,5} \cdot 0.9317}{367} = 0.80 \frac{g}{rev}.$$

The calculated value of G_{r2} was $G_{r2} = 1.158 \cdot G_{2e} = 1.158 \cdot 0.80 = 0.935$ g/rev.
The calculated value of $P_{80\,r2}$ was $P_{80\,r2} = 1.158 \cdot P_{2\,80} = 1.035 \cdot 55.00 = 56.93$ µm.
The obtained approximate Bond work index value by quick method was:

$$W_i = 1.1 \cdot \frac{44.5}{P_c{}^{0.23} \cdot G_{r2}{}^{0.82} \cdot \left(\frac{10}{\sqrt{P_{80\ r2}}} - \frac{10}{\sqrt{F_{80}}}\right)} = 1.1 \cdot \frac{44.5}{74^{0.23} \cdot 0.935^{0.82} \cdot \left(\frac{10}{\sqrt{56.93}} - \frac{10}{\sqrt{1760}}\right)} = 17.69 \frac{\text{kWh}}{\text{t}} \ .$$

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