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Secrets of the Bond Ball Mill Grindability Test

Alex Doll
Alex G Doll Consulting Ltd, Ireland

Vladimir Nikolić
University of Belgrade,
Department for Mineral and Recycling Technologies,
Bor, Serbia

ABSTRACT

The Bond ball mill grindability test is one of the most common metrics used in the mining industry for ore hardness measurements. The test is an important part of the Bond work index methodology for designing and measuring the efficiency of mineral grinding circuits.

In spite of being called "Bond's Law," the work index equations are not a law of nature; but rather an empirically measured regression of a large data set collected by the Allis- Chalmers corporation in the period between 1930 and 1952. As a regression, it is valid within a specific "calibration space," and great care is required when deviating the test procedures or observing results that are outside of that calibration space.

This paper is a collected summary of other works by the Authors that describe feed sizes, product sizes, quality control checks, and other information about interpreting the test and using its results. Examples of adjustments that are sometimes required when using the test are: changing the test product (P80), and coping with a feed that is too fine to apply the "proper" feed preparation steps (such as is sometimes observed from HPGR or SAGDesign product testing). Related metrics, like the Morrell Mib value and Levin B value will be discussed, along with recommendations for their use on design projects.

The intended audience is any user of laboratory work index test data.

INTRODUCTION

The ball mill grindability test sometimes referred to as "the Bond test" was developed in the 1930s by the Allis Chalmers company to help them perform ore hardness characterisation testing to assist in industrial mill sizing Maxson et al, (1933). It was extended by Bond (1952) to provide a 'work index' result that was empirically calibrated to make a laboratory work index match the corresponding work index measured in an industrial grinding mill. The fitted equation, in metric form, is given as Equation (1).

$$Wi = \frac{1.1203 \times 44.5}{{P_{100}}^{0.23} \cdot G^{0.82}\left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)} \tag{1}$$

where:
Wi = work index (treat as unitless, metric basis)
P_{100} = closing screen size (µm)
G = net mass (grams) of undersize product per unit revolution of the mill, (g/rev)
P_{80} = the 80% passing product particle size (µm)
F_{80} = the 80% passing feed particle size (µm)

According to GMG (2021), the feed preparation for the ball mill grindability test should be as follows: *Stage crush the ball mill test feed sample and screen through a 3.36 mm (6 Tyler mesh) screen. Avoid over-crushing by screening, then crushing the oversize successively until it all passes the 3.36 mm screen.* The choice of the 3.36 mm top size is described by Man (2002).

Some samples arrive at the laboratory too fine to perform the stage crushing, and these samples are unsuitable for determining a work index using Equation (1).

Bond (1962) notes: *Laboratory grindability tests and commercial grinding results have shown that with many materials the work index does not remain constant for different product sizes as P becomes smaller, the Wi values may decrease, remain constant, or increase.* For this reason, *the work index has customarily been determined at a product size close to that desired.*

The "Bond" ball mill grinding apparatus is widely available at laboratories around the world and practitioners have come up with other metrics that can be generated using the same apparatus. Two of the more common examples are the 'Levin test' (Levin, 1989) used to investigate fine grinding of ores, and the 'Mib' value used in the context of Mi specific energy consumption calculations (GMG, (2021b).

METHODOLOGY

In the event that a ball mill grindability test can not be performed using the standard feed preparation method or in the event that the product size from the test is significantly different to the desired product size in the industrial plant, then correction methods should be used to try to salvage a work index that is adjusted for the expected difference due to improper feed or product size.

Correction for Incorrect Feed Size (Work Index)

Nikolić, Doll & Trumić (2022) published an algorithm for correcting for an incorrect feed size feeding a ball mill grindability test. The method involves a simplified "principal component" analysis, Figure 1, where the test reduction ratio forms the X axis (empirically calibrated to be F800.2/P$^{0.6}$) and the ore grindability terms form the Y axis (empirically calibrated to be $G^{-0.82}$/Wi). A database of over three hundred ball mill work index tests are plotted against these principal components with "valid" test feeds (arbitrarily set to where F80 > 2 mm) forming a regression equation. Laboratory tests that intentionally used finer feeds (as fine as 600 µm) are shown as data series that roughly match the "valid" regression curve.

In the event that a ball mill work index test can not use a properly prepared feed (for example, the test feed came from a laboratory HPGR or SAG mill instead of stage crushing), then the regression equation can be used to predict a corrected work index using Equation (2).

$$Wi_{corr} = \frac{G^{-0.82}}{0.033 \cdot \ln\left(\frac{2440^{0.2}}{P_{80}^{0.6}}\right) + 0.0904} \tag{2}$$

The test feed size is replaced with 2440 µm, a typical feed size observed for samples prepared by stage-crushing. Note that simply substituting 2440 µm into Equation (1) is not valid as the *G* term changes with the reduction ratio.

Correction for Incorrect Feed Size (Morrell Mib)

The Morrell (2008) Mib models are similar to the Bond model, but calibrated to a different size exponent. The same procedure described for work index can be applied. The same database of testwork is interrogated and principal component equations are iterated until the data set resolves to a single model, as per Figure 2.

The equations for the principal components are different to those for work index, resulting in a different correction Equation (3).

$$Mib_{corr}^{0.6} = \frac{G^{-0.6}}{0.03 \ln\left(\frac{2440^{0.8}}{P_{80}^{0.5}}\right) + 0.02} \tag{3}$$

Correction for Incorrect Product Size (Work Index)

Josefin & Doll (2018) published an algorithm to correct ball mill work index results to a different P80 size basis to what was observed in the laboratory test. The method requires a reference sample that has at least three ball mill work index determinations at three different closing sizes. The reference sample provides a "Hukki exponent," -α, after Hukki (1962) for the ore that is going to be somewhat different to the Bond exponent of -½. The reference sample work index is measured at three different closing sizes, which is turned into a "signature plot" by converting each test work index in the equivalent industrial mill specific energy consumption using the Bond third theory Equation (4).

$$E_{test} = 10 \times Wi_{test} \times \left(P_{test}^{-0.5} - F_{test}^{-0.5}\right) \tag{4}$$

The three *E* are plotted against their P80, and a power-model regression is fit that generates a signature plot. The exponent from this signature plot is the “Hukki exponent” (–α).

The ‘Ktest’ value of a test that requires correction is first computed using Equation (5), then the corrected work index is computed using Equation (6). The ‘K’ values should be reasonably constant for a sample in the size range being examined, so is independent of a test’s product size.

$$K_{test} = \frac{10 \times Wi_{test} \times \left(P_{test}^{-0.5} - F_{test}^{-0.5}\right)}{P_{test}^{-\alpha}} \tag{5}$$

$$Wi_{corrected} = \frac{K_{test} \times P_{test}^{-\alpha}}{10 \times \left(P_{desired}^{-0.5} - F_{test}^{-0.5}\right)} \tag{6}$$

Correction for Incorrect Product Size (Morrell Mib)

The algorithm is the same, except that the reference sample must use the Morrell (2008) Mi Equation (7) to generate the signature plot. The resulting correction Equations (8) & (9) are obtained using the same methodology as for Bond.

$$E_{test} = 4Mib_{test} \times \left([P_{test}]^{-0.293\frac{P_{test}}{10^6}} - [F_{test}]^{-0.293\frac{F_{test}}{10^6}}\right) \tag{7}$$

$$K = 4P_{test}^{\alpha} \times Mib_{test}\begin{pmatrix} P_{test}^{(-0.293 - 10^{-6}P_{test})} \\ -P_{test}^{(-0.293 - 10^{-6}F)} \end{pmatrix} \tag{8}$$

$$Mib_{corrected} = \frac{K \times P_{desired}^{-\alpha}}{4\begin{pmatrix} P_{desired}^{(-.0293 - P_{desired}\cdot 10^{-6})} \\ -F_{desired}^{(-.0293 - F_{desired}\cdot 10^{-6})} \end{pmatrix}} \tag{9}$$

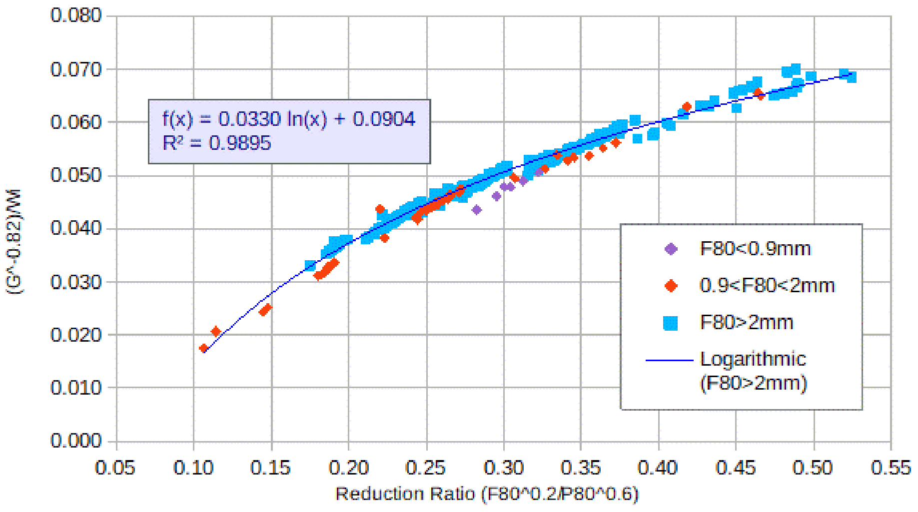

Figure 1. Database of Bond ball mill work index tests plotted against simplified principal components

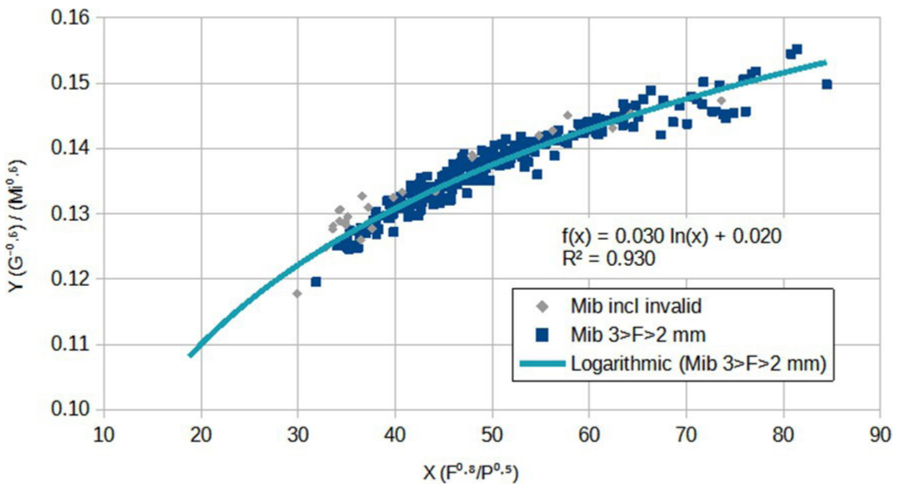

Figure 2. Database of Morrell Mib tests plotted against simplified principal components

Levin B Value

Levin (1989), proposed a method to generate a signature plot suitable for fine grinding using the apparatus of the Bond ball mill. The Levin B value is generally used in three contexts,

- specific energy prediction for fine grinding,
- performing quality-control benchmarking of laboratory results, and
- a modified Functional Performance assessment of a ball milling circuit Doll et al, (2020).

The Levin B value is computed using the parameters of a Bond ball mill work index test, per Equation (10):

$$B = \frac{4900 \times G^{0.18}}{P_{100}^{0.23}\,(100 - Fp\%passing)} \tag{10}$$

where, *Fd%passing* is the percentage of the feed to the test that already passes the closing screen size (P100).

RESULTS AND DISCUSSION

Feed Size Correction Example

The correction for feed size should be applicable to the case of a "Sd-bwi" result from a SAGDesign test program. The Sd_bwi is determined by placing the SAGDesign mill contents into a Bond ball mill grindability apparatus, and then running the ball mill test using the standard Bond procedure. Only the feed size distribution is different to a standard Bond ball mill work index test.

A series of 10 samples for an Andean copper project were treated to both the SAGDesign test (including Sd_bwi) and the standard Bond ball mill work index test with 180 µm closing screens. The SAGDesign results (with the non- standard ball mill feed) are given in Table 1.

Table 1. SAGDesign Sd_bwi results (with non-standard feed)

Sample	F_{80}, µm	P_{80}, µm	g/rev	Sd_bwi
A	1373	145	2.625	12.8
B	1381	138	2.665	11.9
C	1370	138	2.748	11.7
D	1369	139	3.083	10.5
E	1829	139	2.309	13.0
F	1734	137	2.579	12.1
G	1798	138	2.265	13.2
H	1618	137	2.519	12.1
I	1639	136	2.445	12.8
J	1602	137	2.442	12.3

The regular Bond ball mill work index test, with feed prepared by stage-crushing, was also determined for all samples. This "proper" Bond test (Wi_Bond) is compared with the corrected Wi values from the Sd_bwi samples (Wi_corr), as shown in Table 2. Assuming a normal variation of ±8% on the repeatability of the Bond ball mill work index test, then all samples have less deviation between the corrected Wi and the actual Bond Wi versus what we would expect from a simple repeated test.

The conclusion is the difference observed between a regular Bond ball mill work index and a Sd_bwi is not due to the feed to Sd_bwi being ground in a SAG mill, it is due to the finer size of feed material introduced into the ball mill grindability apparatus.

Product Size Correction Example

Calibration sample chosen for this example had three ball mill grindability tests performed at different closing screen sizes. Three Bond ball mill work index tests performed for a Canadian gold mine are presented in Table 3.

The signature plot in Figure 3 is obtained by fitting a power-model to the E versus P80 data from Table 3. The Hukki exponent ($-\alpha$) for Bond equations is –0.56, and the Hukki exponent ($-\alpha$) for Morrell equations is –0.69.

These exponents can now be used to correct a larger data set of samples "similar to" the calibration samples by computing each sample's *K* values using

Table 2. Bond ball mill work index results (with standard feed) and corrected Wi from Sd_bwi

	F80, µm	P80, µm	g/rev	Wi_Bond (Wi units)	Wi_corr (Wi units)	Diff (Wi units)	Diff (%)
A	2288	145	2.58	11.0	**10.5**	–0.5	–4.9%
B	1927	144	2.82	10.4	**10.1**	–0.4	–3.7%
C	1926	143	2.96	10.0	**9.9**	–0.2	–1.8%
D	1601	145	3.44	9.3	**9.0**	–0.3	–3.2%
E	1845	144	2.54	11.5	**11.4**	–0.1	–1.1%
F	1887	143	2.83	10.5	**10.3**	–0.1	–1.0%
G	1840	143	2.45	11.8	**11.5**	–0.3	–2.3%
H	1877	143	2.96	10.1	**10.5**	0.5	4.6%
I	1928	144	2.66	10.9	**10.8**	–0.2	–2.1%
J	1948	143	2.73	10.7	**10.8**	0.1	1.1%

Table 3. Calibration sample laboratory data

Test P100, µm	**150**	**212**	**300**
Metric BM work index	**15.5**	**16.1**	**17**
Measured P_{80}, µm	**114**	**170**	**243**
Measured F_{80}, µm	**2342**	**2342**	**2342**
Measured grams/rev	**1.47**	**1.75**	**2.02**
Feed %passing CSS	**10.2%**	**13.0%**	**15.9%**
Bond E, kWh/t	11.31	9.02	7.39
Morrell exponent P_{80}	*–0.295*	*–0.295*	*–0.295*
Morrell exponent F_{80}	*–0.297*	*–0.297*	*–0.297*
Measured Morrell Mib	*19.1*	*17.8*	*17.1*
Levin B, mWh/rev	18.5	18.2	17.8
Morrell E, kWh/t	*11.3*	*8.6*	*6.7*

Equation (5), then computing the corrected work index using Equation (6).

Levin B Value as a Laboratory QA Check

Levin B values should normally be in the range of 15 mWh/rev to 25 mWh/rev, and are known to vary with test P_{80} and with ore hardness. Plotting the Levin B versus ball mill work index of a particular test against a database of such values is a quick quality control check on the results of a laboratory program. Figure 4 shows an example data set (bold points) plotted against a background of a larger database where the QA check is "satisfied" – the bold points generally fit the trend observed in the larger database.

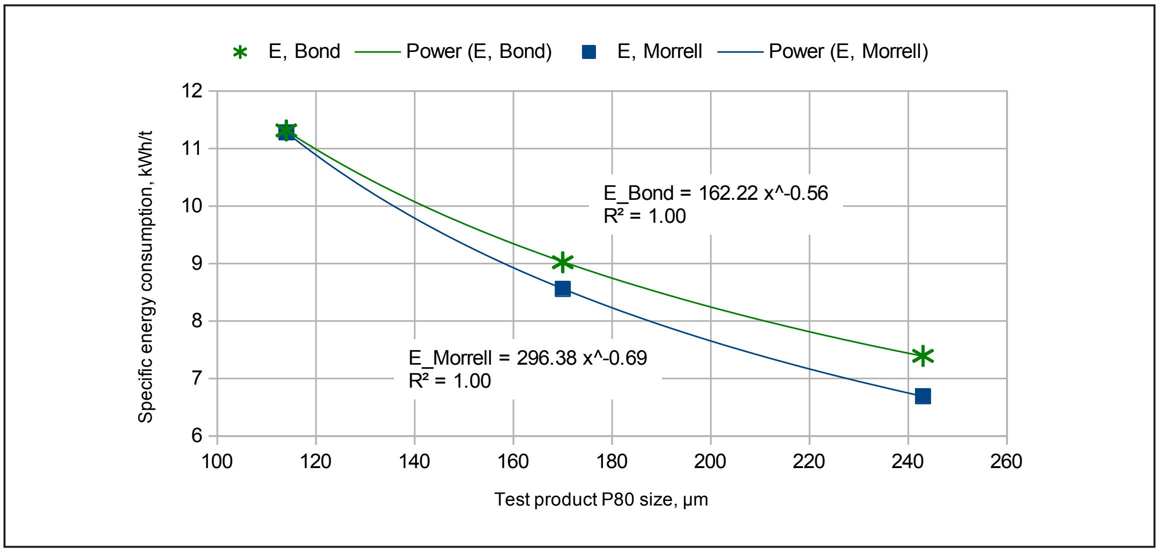

Figure 3. Signature plots for Bond & Morrell models

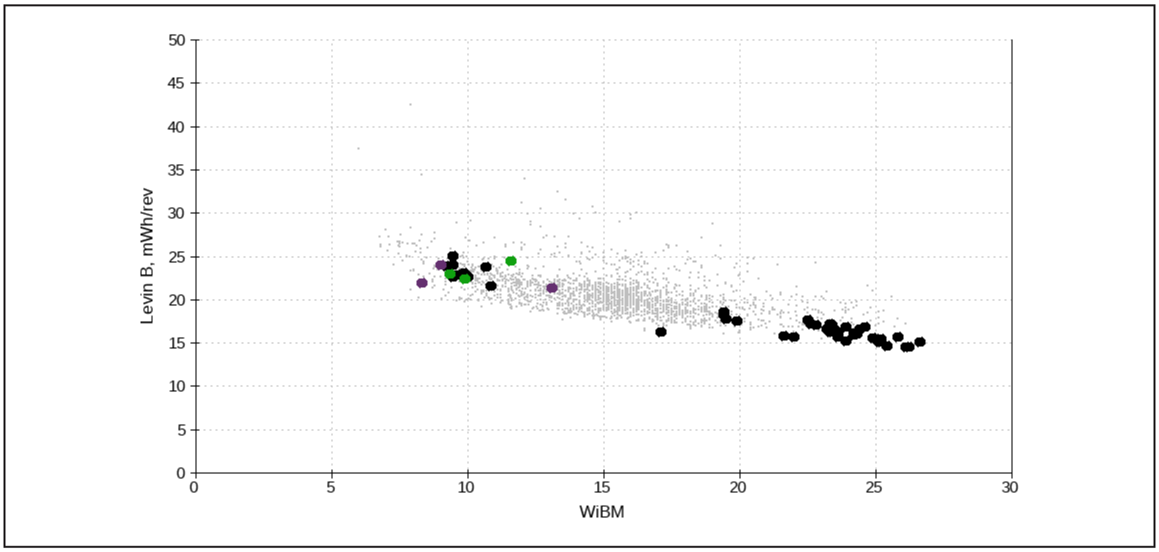

Figure 4. Levin B versus ball mill work index (bold points) as a quality-control check versus a larger database

CONCLUSION

The Bond ball mill work index test is empirically calibrated to a very specific feed preparation and is sensitive to changes in the product size. It is always desirable to conduct the test “properly,” but for circumstances where that isn’t possible (Eg. only a fine feed is available), correction algorithms are available to salvage value from the tests.

The Morrell Mib parameter is even more sensitive to these disturbances, and requires correction for product size any time that the test P80 deviates from the model P80.

The Levin B value is another parameter that practitioners can extract from a Bond ball mill work index determination. This metric is useful for performing Quality Assurance on the laboratory tests, and is used in certain Functional Performance efficiency bench-marks on ball mill circuits.

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NOMENCLATURE

$-\alpha$—the exponent measured in a signature plot, interpreted according to Hukki’s Conjecture (unitless)

B—the Levin B value that represents the amount of industrial machine power consumed per rotation of a laboratory mill (mWh/rev)

E—specific energy consumption (kWh/t)

F, F_{80}—the 80% passing feed particle size (μm)

Ftest—the 80% passing size observed in the laboratory test (μm)

Fd%passing—the percentage of the feed to the test that already passes the closing screen size

G—net mass of undersize product per unit revolution of the mill (g/rev)

K—coefficient measured in a signature plot, interpreted according to Hukki’s Conjecture (unitless)

Mib—the Morrell ore hardness index for ball milling (kWh/t)

P_{100}—closing screen size (μm)

P, P_{80}—the product 80% passing particle size (μm)

P_{test}—the 80% passing size observed in the laboratory test (μm)

$P_{desired}$—the 80% passing size desired to run the work index calculation at (μm)

Sd_bwi—the modified ball mill work index obtained from the product of a SAGDesign laboratory SAG mill (metric basis)

Wi—work index (treat as unitless, metric basis)

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24-081

Selection and Application of Cutoff Grades in Underground Mine Planning—Practical Application

John Barber
JC Barber LLC, Prescott, AZ

Paul Schmidt
Stantec Consulting Inc., Chandler, AZ

ABSTRACT

This paper discusses the determination of cutoff grade (COG), including all revenue and cost factors and how to apply the COG in the world of engineering studies and mine planning for underground mines. It provides the engineer with important considerations and practical methods to establish COG and methods of using the COG in the work of mine planning, including the application of Mineable Stope Optimizer (MSO) software which is available on several 3D mine planning packages.

INTRODUCTION

Why this Paper is Required

The authors, in the course of their work, have seen wide variations of how COGs are developed and applied while evaluating and planning underground mines. We recognize that one set of practices will not satisfy all situations but do believe that methodology can be more clearly defined than we have experienced. This paper is not intended to revise the strategic work of Lane, Rendu, and others, but to look at the issue at a more granular level, after the global and strategic issues are addressed. Some may consider this paper a refresher on basic mine cost engineering and economics.

Definition of Cutoff Grade

From *SME Mining Engineering Handbook*: “Cutoff grade is traditionally defined as the grade that is normally used to discriminate between ore and waste within a given ore body. This definition can be extended to differentiate various ore types for different metallurgical processing options.”

Ultimately, the COG is determined by economics (i.e., the economic value [revenue] of the contained material must exceed a certain threshold).

Another way of considering COG is that it defines the boundary between ore and waste, or is the minimum grade used to plan mining operations.

From the perspective of the mine planner, there may be more than one COG that must be considered in his/her work.

- **Break-Even COG (Incremental)** – the minimum grade that recovers all direct mining, process, and site costs. It includes in-stope (ore) development, but does not include level or access development, or any capital recovery. The break-even COG is used to refine stope shapes and mineable outlines but should not be used to determine mineable shape.
- **Planning or Design COG**—the minimum grade that recovers all operating costs (direct mining, required stope specific access development, processing, and site costs). Normally, a stope should not be included if it will not meet this grade. This should be the minimum COG used in reporting mineral reserves. The planning COG is the starting point for determining mineable shapes.