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Correction of Bond Ball Mill Work Index Test for Closing Mesh Sizes

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ABSTRACT

It is commonly known that one must run the Bond ball mill work index test such you pick a closing mesh to give a P_{80} close to desired grind size. This is because work index frequently changes as a function of the product size in comminution. If target grind size during a project is changed, or if the test is run at the wrong product size, then it is necessarily to provide a correction.

The goal of this work is to create an equation to adjust a Bond ball mill work index from one P_{80} basis to another. The proposed model consists of two components, the variable coefficient that is determined from a specific work index determination and a fixed exponent determined by a calibration procedure. The model has the benefit of retaining the variability in hardness that is built into a database of work indexes, while using Hukki's specific energy approach to adjust for P_{80}.

The laboratory test work program was carried out on SAG belt cut and geo-unit samples of two BC copper-porphyry orebodies yielding an exponent of -0.56 across the range of typical ball mill particle size targets. For validation, the equation was run against African data by Levin (1989) revealing that the exponent changes for different ore types, but generally remains constant within an ore type.

The results of this investigation confirm a sensible correlation between the existing theories that enable practitioners to calibrate and fit any work index data given the appropriate calibration exponent. Moreover, the experiments observed that Bond's work index is less sensitive to variation in P_{80} than Morrell's M_{ib} index on the ores tested.

INTRODUCTION

Creating a potential model of correcting the result of a bond ball mill work index test requires developing a database using reference-calibration samples. Extensive bond grindability test for determining the work index was conducted at five different closing mesh aperture sizes to observe the variations in outcome parameters such as: work index, product size P_{80}, and grams per revolution (g rev^{-1}). The purpose of this work is to develop a procedure to adjust a larger work index from one P_{80} basis to another and build modelling framework suitable for geometallurgical datasets that enables practitioners to calibrate and fit any work index at any changing closing size given the appropriate calibration.

In his Third Theory of grinding, Bond (1952) observes that the net energy required in comminution has the same units one obtains considering the geometry of linear cracks inside spheres. This resulting power-based model with an exponent of -0.5 has been widely accepted and applied in conventional milling practices. Hukki (1962) however, postulated that the constant exponent in energy-size relationship is only applicable in narrow size ranges and dependent on the characteristics of the ore, and therefore the exponents should be expressed as a continuous function of size. A crucial observation of Hukki is that Bond's equation is generally only valid in the range of primary and secondary grinding which product sizes between 1 mm – 100 μm. (Doll, 2017). The results of this investigation reveal a sensible correlation between existing theories of Bond and Hukki that provide a helpful correction model.

METHODOLOGY

Ore samples from Copper Mountain and New Afton mines were used for the Bond ball mill work index tests conducted at the University of British Columbia's CMP laboratory. The first sample is a composite of four Copper Mountain's geo-unit samples with similar alteration (Albite-Potassic-Argilic) sampled at different pit locations and benches. Three SAG belt cut samples from Pit 3 were collected at different spots along the conveyer belt with total interval length of 15 meters. The samples are the same general rock type, but still show some grindability variation between four of the them. One other sample was obtained from New Afton, a SAG belt cut, which later became the test subject for calibration and model fitting.

The test work program was carried out on those five ore samples obtained from the copper-porphyry orebodies. Total of 38 Bond work index tests, including duplicates, were done. Standard Bond ball mill test procedure were carried out on crushed (-3.35 mm / 6 mesh) material at different screen closing sizes (300 μm, 212 μm, 150 μm, 106 μm, and 75 μm). The screening process was conducted in four sets of 12-inch diameter screens for sufficient amount of time to avoid too much materials fed into the screen at one time. The test product from last grinding cycle was then wet-screened at 38 μm to remove fines entrainment before the final particle size distribution.

Derivation of Equation

According to *Hukki* (1962), the specific energy required, E can be expressed in a general form of differential equation (1) for the case of a limited size range where C_2 is reasonably constant.

$$\frac{dE}{dx} = C_1 x^{c_2} \quad (1)$$

An integrated form of Hukki's general equation leads to a power function described in equation (2) for the situation where $F_{80} >> P_{80}$.

$$E = K(x)^{-a} \quad (2)$$

The total energy required to break the feed ore to a product size P_{80} stated by Bond in his third theory of comminution is shown in equation (3).

$$E = (10\,Wi) \times \left((P_{80})^{-½} - (F_{80})^{-½} \right) \quad (3)$$

The correction model (4) is obtained by manipulating the specific energy formula in (2) and (3), permitting a corrected work index to be computed at a P_{80} different to that obtained in a laboratory test. Two parameters are required from testwork, the Hukki coefficient K and exponent a.

$$Wi_{corrected} = \frac{K_{test} \times (P_{80})^{-a}}{10 \times \left((P_{80})^{-0.5} - (F_{80})^{-0.5} \right)} \quad (4)$$

In this model, the exponent '$-a$' comes from a reference sample (in our example, the Copper Mountain's exponent is –0.56), whereas the 'K' is a sample-specific coefficient that varies with different unknown samples. This has the benefit of retaining the variability in hardness that is built into the database of work index values, but also uses a Hukki's approach to adjust the P_{80}.

$$K_{test} = \frac{10 \times Wi_{test} \times \left((P_{80})^{-0.5} - (F_{80})^{-0.5} \right)}{(P_{80})^{-a}} \quad (5)$$

The power function shown in equation (2) is fitted by plotting the ore's specific energy versus P_{80} using equation (3) and fitting a power model using software regression tools. In order to accommodate the model fitting process, it is necessary to have two different samples, one as a reference sample, in this case the sample from the Copper Mountain mine, for calibrating the exponent ($-a$) and another one as the sample that is to be adjusted, in this case the sample from New Afton for which we will determine the Hukki coefficient (K).

The equation (4) above can be applied by using these following steps:

1. Compute the specific energy equation for each test of the calibration sample to establish energy – particle size relationship in equation (2).
2. Plot the energy versus size and fit the power equation. Read both the exponent $-a$ and coefficient K for the calibration sample.
3. Use a Bond work index test of a sample that requires adjustment (this is now a different sample than the calibration). Calculate the 'K' coefficient using equation (5) with the exponent obtained from the reference sample.
4. Finally, calculate the adjusted work index for an arbitrary P_{80} using equation (4) where the exponent ($-a$) is from the calibration sample and the coefficient (K) is from the adjusted sample.

RESULTS

Two sets of grindability tests were performed at the Coal and Mineral Processing laboratory at the University of British Columbia. The "calibration" sample is represented by a series of samples collected at the Copper Mountain mine in British Columbia. The "adjusted" sample is represented by a sample collected from the SAG mill feed belt at the New Afton mine, also in British Columbia and about 400 km north of Copper Mountain.

Copper Mountain Sample

The Copper Mountain's samples that consists of three SAG belt cuts at three feed belt locations and one geometallurgy-composite sample were tested, providing the results in Table 1. The average work index of these Copper Mountain samples is 24.3 metric units. The specific energy, E as a function of P_{80} is fitted to a power function from regression tools yielded an exponent of -0.56. If the graph was plotted in log-log scale as it had been previously published in Hukki's Conjecture, a declining straight line with a constant slope -0.56 will be established.

Table 1: Bond Ball Mill Grindability Test Summary

Closing size, µm	Copper Mountain	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index (metric)	Specific Energy, kWh/t
300	GeoMet Composite	2669.8	215.1	1.04	26.2	12.8
	SAG Belt End	2812.4	210.4	1.03	25.8	12.9
	SAG Belt Start	2626.5	216.0	1.03	26.6	12.9
	SAG Belt Mid	2627.2	212.1	1.05	25.8	12.7
212	GeoMet Composite	2627.2	154.9	0.92	25.1	15.3
	SAG Belt End	2812.4	152.2	0.93	24.4	15.2
	SAG Belt Start	2626.5	150.9	0.91	24.9	15.4
	SAG Belt Mid	2627.2	148.5	0.93	24.3	15.2
150	GeoMet Composite	2669.8	107.1	0.76	25.1	19.4
	SAG Belt End	2743.7	107.6	0.80	24.0	18.5
	SAG Belt Start	2626.5	108.5	0.80	24.2	18.5

	SAG Belt Mid	2627.2	106.8	0.83	23.3	18.0
106	GeoMet Composite	2669.8	71.5	0.67	23.5	23.2
	SAG Belt End	2743.7	73.7	0.69	23.3	22.7
	SAG Belt Start	2626.5	75.3	0.69	23.7	22.7
	SAG Belt Mid	2627.2	73.0	0.71	22.7	22.1
75	GeoMet Composite	2669.8	45.8	0.52	24.4	31.3
	SAG Belt End	2675.0	46.7	0.52	24.5	31.1
	SAG Belt Start	2626.5	50.9	0.58	23.4	28.2
	SAG Belt Mid	2627.2	49.7	0.60	22.5	27.6
Average					**24.3**	**19.8**

New Afton Sample

To test the accuracy of the correction model, New Afton *SAG belt* sample was used for adjustment. The BBWI test was done at closing size of 150 µm and yielded a corresponding work index value of 19.50 metric that was used to compute the coefficient 'K' of the corrected model. Work indexes at other sizes then can be predicted by using the generated model. To confirm the validity and accuracy of the model, BBWI tests at other sizes were also conducted and compared with the model's.

Table 2: Bond Ball Mill Grindability Test Summary

New Afton	Closing Size, µm	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index	Specific Energy, kWh/t
Hypogene	212	2590.6	141.5	1.03	21.6	13.9
Mesogene	212	2649.6	149.2	1.05	22.0	13.7
Supergene	212	2729.5	151.7	1.44	17.1	10.6
SAG Belt	300	2422.3	212.8	1.34	20.9	10.1
SAG Belt	212	2422.3	145.4	1.18	19.9	12.5
SAG Belt	150	2422.3	104.6	1.03	19.5	15.1
SAG Belt	106	2422.3	75.0	0.89	19.4	18.5
SAG Belt	75	2422.3	50.5	0.74	19.4	23.3

Correction of New Afton Sample Using Copper Mountain Calibration

A sample calculation below shows the procedure to perform the work index adjustment from a P_{100} of 150 µm to an arbitrary P_{80} target for New Afton sample. This correction model allows a work index calibration from one closing size to another in case the result was run at wrong P_{80} and no more sample available for a second test. The estimated work index from the equation will be compared with the actual test result to evaluate the accuracy and consistency of the model. An exponent of -0.56 from Copper Mountain reference sample is used for the calculation.

1. Perform a bond ball mill work index determination of the desired sample at any closing size, in this case is New Afton ore at 150 μm.
2. Compute the new 'K' coefficient using equation (5) above. The P_{80} and F_{80} values are obtained from the screening result. An exponent of -0.56 will be used for the calculation.
3. Calculate the new calibrated work index at the desired P_{80} with the established 'K' value obtained from the previous step.
4. Compare the accuracy of calibrated work index with the actual number from test result.

$$K_{test} = \frac{10 \times Wi_{test} \times \left(\left(P_{80}\right)^{-0.5} - \left(F_{80}\right)^{-0.5} \right)}{\left(P_{80}\right)^{-0.56}}$$

$$K_{test} = \frac{10 \times 19.50 \times \left(\left(104.6\right)^{-0.5} - \left(2422.3\right)^{-0.5} \right)}{\left(104.6\right)^{-0.56}} = 200.4$$

$$Wi_{corrected} = \frac{K_{test} \times \left(P_{80}\right)^{-a}}{10 \times \left(\left(P_{80}\right)^{-0.5} - \left(F_{80}\right)^{-0.5} \right)}$$

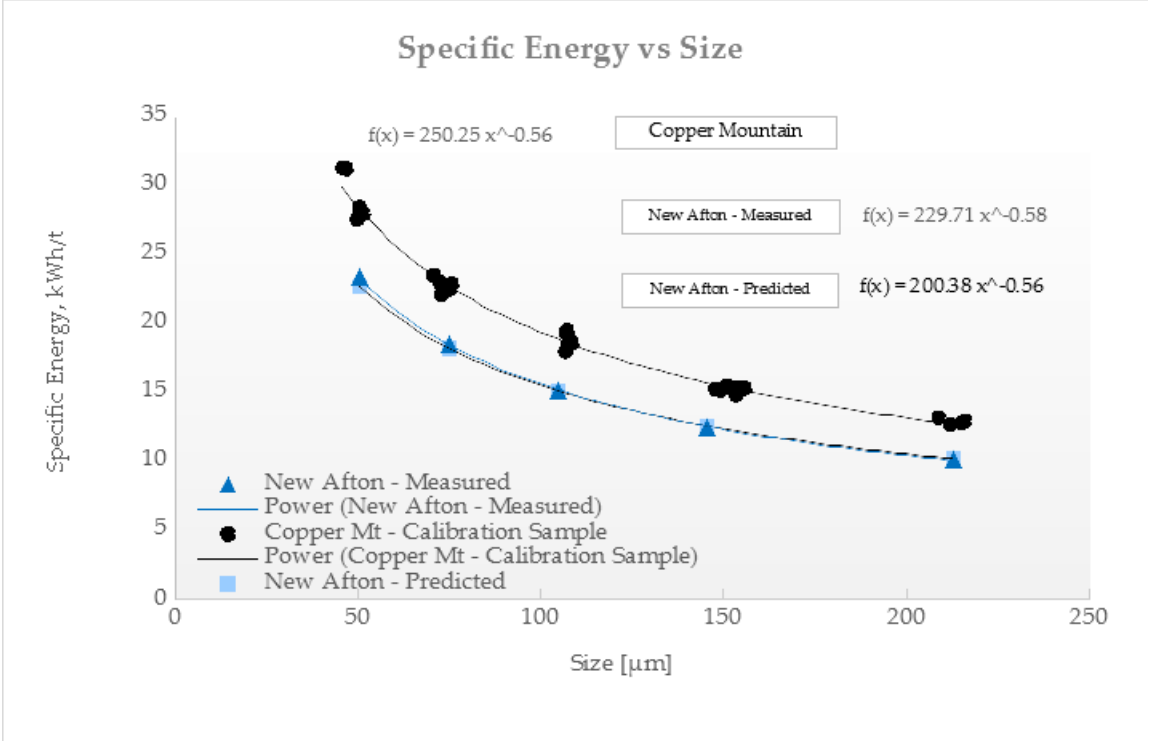
$$Wi_{corrected} = \frac{200.4 \times \left(50.5\right)^{-0.56}}{10 \times \left(\left(50.5\right)^{-0.5} - \left(2422.3\right)^{-0.5} \right)} = 18.8\, metric$$

The calibrated work index is equal to 18.8 metric or about 3% difference to the actual test result of 19.4 metric. Complete comparison is shown in table 3. The average %difference from each test is less than 5%. Figure 1 shows how the calibration ore align with the adjusted ore.

Table 3: Calibrated – Measured Comparison

New Afton	Closing Size, μm	Measured Work Index	Calibrated Work Index	Measured Energy, kWh/t	Calibrated Energy, kWh/t	% Difference
SAG Belt	300	20.92	21.09	10.09	10.17	0.8%
SAG Belt	212	19.89	20.08	12.45	12.57	1.0%
SAG Belt	150	19.50	19.50	15.10	15.10	0.0%
SAG Belt	106	19.39	19.09	18.45	18.17	1.5%
SAG Belt	75	19.37	18.80	23.32	22.64	2.9%

Figure 1: Specific Energy vs Particle Size



DISCUSSION

The proper way of choosing closing mesh size for work index determination is to pick the mesh that gives the closest ball mill product P_{80} to the industrial setting. This calibration procedure is only applicable to the situation where the product of a series of tests is very different from the industrial setting, for example, when the design criteria of flotation feed changes in the middle of a process plant design project. This calibration is a way to salvage a large database of Bond tests by conducting a calibration set of three or four tests on a calibration sample, and then using the calculated (–*a*) exponent to "correct" the whole database. Each "invalid" Bond test is converted into a Hukki coefficient (*K*) using Equation (4)

Bond's work index formula exponent (-0.5) is relatively close to the calibration sample (-0.56), suggesting Bond models are a good fit for this ore. However, users are cautioned that this exponent

is ore-specific and could vary significantly with different ore types. Using -0.56 as fixed exponent for different type of ores whose actual exponent are far off from the dataset's reference would produce a high percent error to be measured values. This exponent is only applicable for copper porphyry ore and other type of ores whose exponent is within the range. In order to create a calibration dataset, it is necessary for a user to run a calibration set of tests at different aperture closing sizes such that the variation in parameters (e.g product size, ground per revolution, and specific energy) as a function of changing sizes can be captured.

The measured bond ball mill work index for Copper Mountain ore from table 1 shows no significant difference in hardness between the Geomet and SAG belt ore samples. However, the work index experiences some fluctuations with a tendency to decrease at finer P_{80} size. Similar trend was also observed in New Afton ore where the measured work index exhibits a decreasing trend at finer product size. From the test results it was also evident that New Afton ore is relatively softer than Copper Mountain's. Mesogene ore type was observed to be the hardest among the hypogene, supergene, and SAG belt cut.

According to Hukki's conjecture, for a sufficiently narrow range of sizes, the exponent can be assumed to be constant. The resulted exponent of the power model (-0.56) is close to Bond's which is only applicable in primary – secondary grind region (1 mm – 100 μm). Upon investigation, it was found that the model works well with P_{80} below the specified range, in this case when the product size is around 50 μm. Any sizes beyond this size range will cause the exponent to change, and further investigation is required.

Review of Works by Other Authors

The view that varied materials have their own specific properties has shown itself to be true throughout the fact that both of the exponent and coefficient in the equation change with different ore samples. Figure 2 shows the specific energy versus product size computed on five different Levin's datasets. The exponent varies from -0.48 to -1.5, while the coefficient 'K' seem to have no correlation between samples. Figure 2 on the other hand, displays the same chart with different ore samples. Both measured Copper Mountain and New Afton models have similar trend and slopes that can be reflected from the closeness of their exponents. These two cases have proven that different ores can have their own exponent, though similar ores have similar exponents; for our example: copper porphyry ores seem to have an exponent in the range of -0.56. This is similar to the work of Doll (2017) where porphyry ores are reported with an exponent of -0.50.

Upon investigation, it can be concluded that the calibration model would have produced close results to the measured values with 5% difference, had the calibrated sample had an exponent between -0.4 to -0.6 regardless the ore type. Two samples from Levin's datasets (uranium and dolomite ore) whose exponents fall into this range were calibrated using equation (4) to confirm the

assumption. Both uranium and dolomite samples yielded a coefficient 'K' of 163.5 and 136.2 respectively. Table 4 shows how the calibrated work index differs with the measured values.

Figure 2: Levin's Datasets

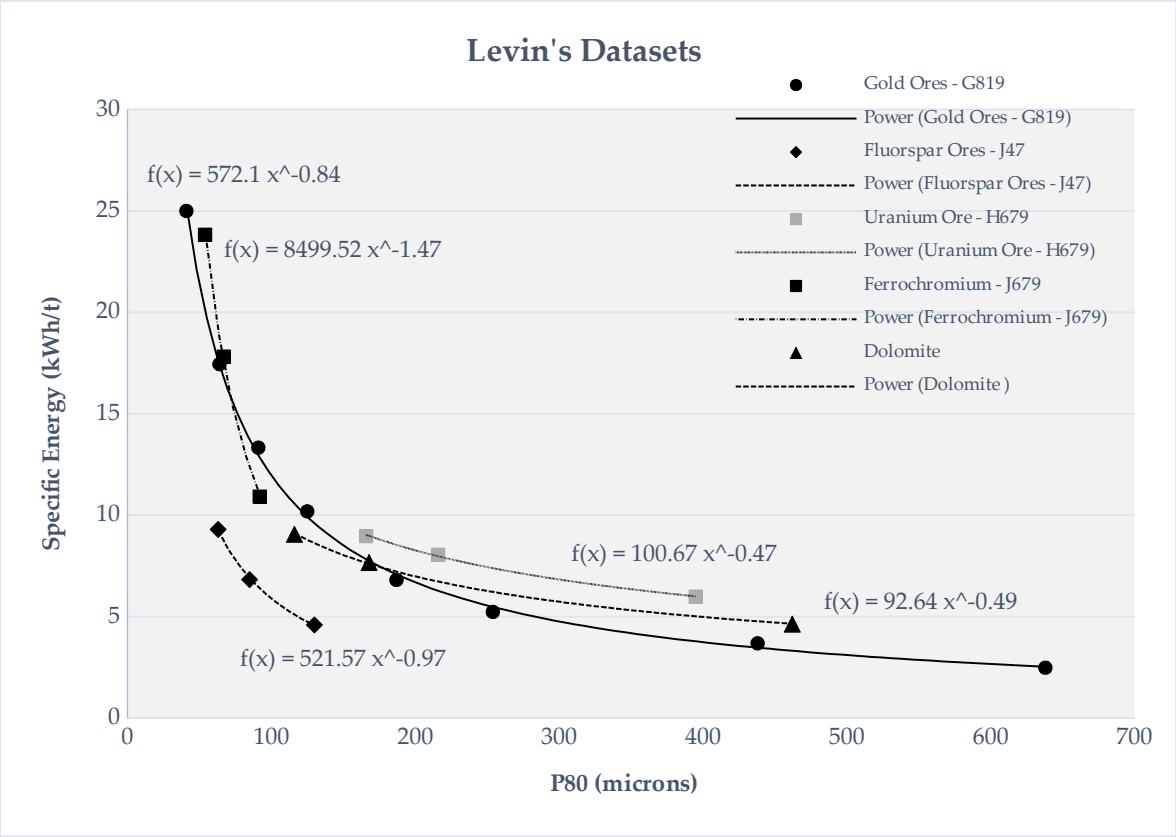


Table 4: Levin Datasets Comparisons

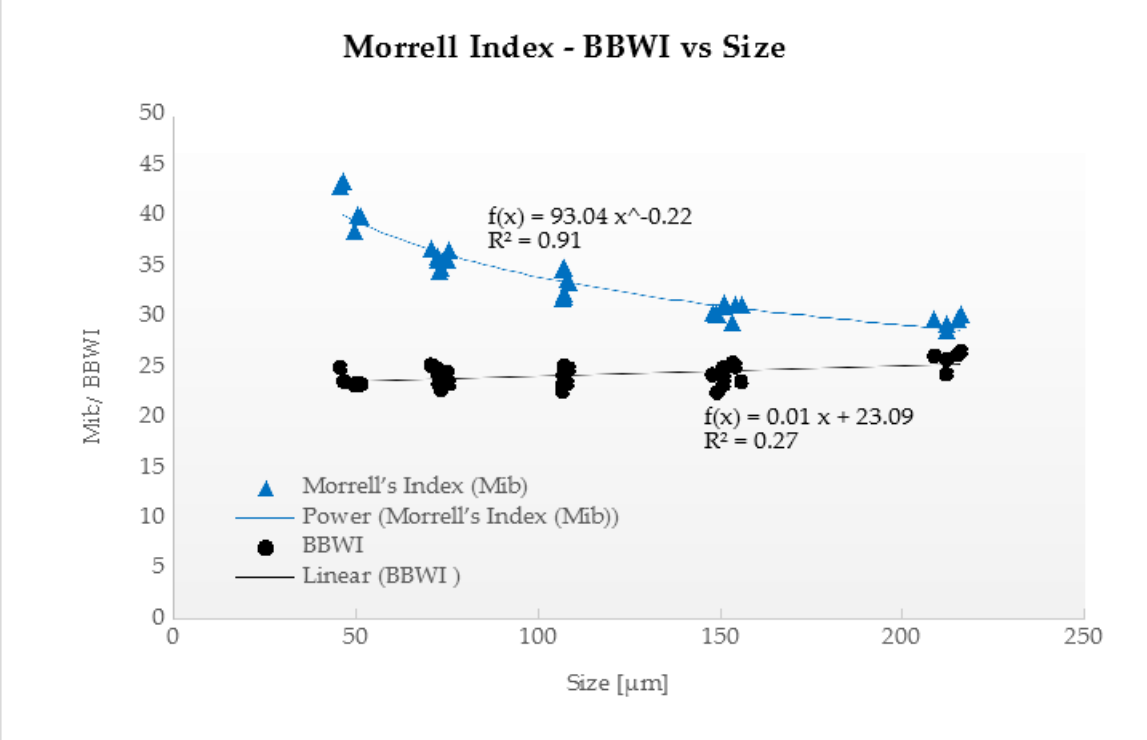
Ore	K	Mesh opening (µm)	P80 (µm)	Measured Work Index	Calibrated Work Index	%difference
Uranium	163.5	540	395	21.5	20.7	3.9
		297	216	18.4	18.4	0.1
		212	166	17.1	17.8	4.1
Dolomite	136.2	550	462	19.7	18.7	5.3
		212	168	15	15.1	0.8
		150	116	13.7	14.4	5.0

Morrell Index and Bond Ball Mill Work Index Comparison

Morrell's M_{ib} model was computed using the equation below. This was done to compare the effect of changing aperture size to both Morrell and Bond work index. Figure 3 demonstrates that Bond work index is relatively more constant at different product size while M_{ib} varies more. The flatter line suggests that Bond's work index is less sensitive to small deviation in P_{80} over the size range investigated. Morrell's index, M_{ib} increases exponentially at finer product size, Bond's index on the other hand, fluctuates with a tendency to decrease under similar circumstance. This phenomenon indicates that "Morrell" exponent of -0.295 shown in equation below is significantly different from experimentally determined exponent of -0.56 in the previous discussion. However, by looking at the trend shown in figure 3, it is very possible that both work indexes will cross over at coarser particle size range (~230 μm)

$$M_{ib}=\frac{18.18}{P_{100}^{0.295}\,Gpr\left(P_{80}^{f(P_{80})}-F_{80}^{f(F_{80})}\right)} \quad \text{where} \quad f(x)=-\left(0.295+\frac{x}{10^6}\right)$$

Figure 3: Morrell vs Bond Index



ACKNOWLEDGMENTS

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CONCLUSION

A four-step correction procedure can be used to correct the work index measured on a sample from one P_{80} size to another P_{80} size by using a calibration sample and the equation (4). The model predictions by Equation (4) are expected to be within 5% given all testing is done at the same laboratory with the same operator. Exponents (determined by the calibration samples) are material-specific and can vary widely between ore types. The exponent for a copper porphyry can probably be used for a nearby copper porphyry but shouldn't be used for a gold ore.

NOMENCLATURE

a	exponent of a Hukki equation
C_1, c_2	arbitrary fitted constants
E	specific energy consumption, kWh/t
e	natural exponential (Euler's number)
F_{80}	80% passing size of feed to a comminution process, μm
K	coefficient of a Hukki equation
P_{80}	80% passing size of product from a comminution process, μm
Wi	work index, metric
x	particle 80% passing size, μm
α	scale parameter
β	shape parameter
M_{ib}	Morrell's Index

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APPENDIX

Table A-1: Geomet Sample Grindability Test Results

Sample Name	Mesh opening, µm	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index (metric)	Wi %diff to avg	Mib kWh/t	Levin B $\frac{10^{-7}\ kWh}{rev}$	% U/size in feed
GeoMet Composite	300	2670	215.1	1.04	26.2	5.97	29.73	146	8.92
GeoMet Composite	212	2670	154.1	0.92	25.1	1.42	31.17	151	6.67
GeoMet Composite	212	2670	155.8	0.92	25.2	1.63	31.24	151	6.67
GeoMet Composite	150	2670	107.2	0.76	25.2	1.97	34.93	155	5.05
GeoMet Composite	150	2670	106.9	0.76	25.0	0.90	34.70	155	5.05
GeoMet Composite	106	2670	70.6	0.66	23.6	4.71	36.78	162	3.80
GeoMet Composite	106	2670	72.4	0.68	23.4	5.60	35.94	163	3.80
GeoMet Composite	75	2670	45.8	0.52	24.4	1.58	42.89	166	2.74
Average					***24.7***		***34.67***	***156***	

Table A-2: Cu. Mt SAG belt End Grindability Test Results

Sample Name	Mesh opening, µm	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index (metric)	Wi %diff to avg	Mib kWh/t	Levin B 10-7 kWh rev	% U/size in feed
Cu. Mt SAG Belt	300	2812.4	208.8	1.01	26.1	7.08	29.83	145	9.04
Cu. Mt SAG Belt	300	2812.4	212.0	1.05	25.4	4.21	28.73	146	9.04
Cu. Mt SAG Belt	212	2812.4	153.4	0.96	23.9	1.96	29.47	153	6.97
Cu. Mt SAG Belt	212	2675.0	150.9	0.91	24.9	2.09	31.16	156	9.95
Cu. Mt SAG Belt	150	2812.4	107.2	0.81	23.6	3.12	32.34	158	5.35
Cu. Mt SAG Belt	150	2675.0	107.9	0.79	24.3	0.29	33.77	161	7.74
Cu. Mt SAG Belt	106	2812.4	72.3	0.68	23.3	4.57	35.72	163	3.98
Cu. Mt SAG Belt	106	2675.0	75.0	0.70	23.4	4.18	35.61	167	5.95
Cu. Mt SAG Belt	75	2675.0	46.7	0.52	24.6	0.74	43.48	169	4.52
Average					**24.4**		**33.35**		

Sample Name	Mesh opening, µm	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index (metric)	Wi %diff to avg	Mib kWh/t	Levin B $\underline{10^{-7}\ kWh}$ rev	% U/size in feed
Cu. Mt SAG Belt [start]	300	2626.5	216.0	1.03	26.6	9.24	30.26	152	12.47
Cu. Mt SAG Belt [start]	212	2626.5	150.9	0.91	25.0	2.56	31.28	155	9.43
Cu. Mt SAG Belt [start]	212	2626.5	151.0	0.92	24.9	2.22	30.98	155	9.43
Cu. Mt SAG Belt [start]	150	2626.5	108.5	0.80	24.2	0.47	33.47	160	6.98
Cu. Mt SAG Belt [start]	106	2626.5	75.1	0.70	23.5	3.66	35.72	166	5.09
Cu. Mt SAG Belt [start]	106	2626.5	75.6	0.69	23.9	1.73	36.56	168	6.98
Cu. Mt SAG Belt [start]	75	2626.5	50.3	0.58	23.4	3.95	40.10	171	3.75
Cu. Mt SAG Belt [start]	75	2626.5	51.4	0.59	23.3	4.21	40.00	171	3.75
Average					***24.3***		***34.80***		

Table A-3: Cu. Mt SAG Belt Start Grindability test results

Sample Name	Mesh opening, µm	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index metric	Wi %diff to avg	Mib kWh/t	Levin B $\underline{10^{-7}\ kWh}$ rev	% U/size in feed
Cu. Mt SAG Belt [mid]	300	2627.2	212.1	1.05	25.8	9.16	29.27	157	15.25
Cu. Mt SAG Belt [mid]	212	2627.2	147.8	0.93	24.3	2.88	30.42	161	12.35
Cu. Mt SAG Belt [mid]	212	2627.2	149.1	0.94	24.2	2.71	30.26	161	12.35
Cu. Mt SAG Belt [mid]	150	2627.2	107.0	0.83	23.4	0.99	32.02	166	10.00
Cu. Mt SAG Belt [mid]	150	2627.2	106.7	0.84	23.2	1.55	31.82	166	10.00
Cu. Mt SAG Belt [mid]	106	2627.2	72.7	0.72	22.6	4.24	34.49	172	8.03
Cu. Mt SAG Belt [mid]	106	2627.2	73.2	0.71	22.8	3.39	34.79	171	8.03
Cu. Mt SAG Belt [mid]	75	2627.2	49.7	0.60	22.5	4.57	38.44	177	6.36
Average					***23.6***		***32.69***		

Table A-4: Cu. Mt SAG belt Start Grindability Test Results

Table A-5: New Afton Grindability Test Results

Sample Name [New Afton]	Mesh opening, µm	F80 (µm)	P80 (µm)	Gram per Revolution	Work Index metric	Wi %diff to avg	Mib	Levin B 10-7 kWh/rev	% U/size in feed
Hypogene	212	2590.6	141.5	1.03	21.6	-	26.76	158	9.25
Mesogene	212	2649.6	149.2	1.05	22.0	-	26.83	157	7.92
Supergene	212	2729.5	151.7	1.44	17.1	-	19.69	163	6.21
SAG Belt	300	2422.3	212.8	1.34	20.9	5.61	23.61	-	-
SAG Belt	212	2422.3	145.4	1.18	19.9	0.38	24.03	175	15.86
SAG Belt	150	2422.3	104.6	1.03	19.5	1.60	25.92	178	12.70
SAG Belt	106	2422.3	75.0	0.89	19.4	2.14	28.45	182	9.88
SAG Belt	75	2422.3	50.5	0.74	19.4	2.25	31.94	186	7.53
Average					***19.8***		***26.79***		