A public Database of tumbling mill grindability measurements and their relationships

Alex Doll[1]*

1. *Consultant, Alex G. Doll Consulting Ltd. Canada*

ABSTRACT

This work presents a public database of over 800 grindability measurements and a set of equations for converting between different grindability tests based on this database. Several laboratory grindability measurements commonly used in the mining industry; each is generally applicable to a particular grindability model and is incompatible with other models. Conversion between different test types is possible using a series of empirical relationships between those tests conducted at similar size classes.

The commonly used grindability tests included in the database are the Bond work indices for ball milling, rod milling and crushing; the drop weight test results A, b, A×b, DWi, Mia, Mic, Mih and ta; SAG grindability index, SGI or SPI™; and other values such as Mib and point load index.

Some examples of power-based model specific energy predictions will be compared to published mill surveys to observe how well the different models predict the specific energy of an industrial mill.

Key words: Database, laboratory test, comminution, specific energy, models predict.

INTRODUCTION

Grindability measurements are a key input to the design and optimization of mineral process plants. As such, grindability parameters are often reported in published documents such as technical papers (here at Procemin) and in project evaluation reports such as the NI43-101 reports issued by companies listed on Canadian stock exchanges. Collecting and comparing these published grindability measurements provides a basis for basic research, such as calibration of specific energy models, and for benchmarking new projects.

Several specific energy consumption models have been published that require empirical laboratory measurements; often models use grindability measurements that are distinct from other models and incompatible with certain laboratory tests. Another benefit of collecting a database of grindability measurements is to provide relationships for comparing and, possibly, converting between the different measurement types.

METHOD

Grindability results have been collected from a large number of published documents. These have been entered into a database containing discrete tables for each class of test and where the test results are indexed using a `sample name` to link multiple tests performed on the same sample. If the report offers geological or other differentiating characteristics of a sample, these are captured in a `lithology` table. The database includes a summary `view` that consolidates the sample name, a unique ID number for the sample, the originating project or mine, and some of the most common grindability measurements. All tests on the same sample are identified with the same ID number, so the relationship between tests on the same sample can be tracked across the different database tables.

The database includes fields for optional details of the various tests. These optional data are entered in the database if they are published, and are left blank otherwise. Few authors provide a complete tabulation of the test details, so many of the detail fields are blank.

Example data from the Lithology table is given in Table 1 where the sample's name, ID number, the sample lithology (where it is known), and reference information is provided. The summary view for these samples is given in Table 2. Note that the ID numbers in this table match the ID numbers in Table 1 (and all the other database tables).

Table 1 Example Lithology database table

Id	Name	Litho	Litho comment
1529	Lik composite 7		Zazu metals NI43-101 March 3, 2014
1600	Gamsberg Pyrite		van Drunick Gerold & Palm, IMPC2010
1601	Gamsberg Pyrrhotite		van Drunick Gerold & Palm, IMPC2010
1602	Gamsberg Magnetite		van Drunick Gerold & Palm, IMPC2010
1603	New Gold Hypogene		New Gold NI43-101, Dec 2009
1604	New Gold Mesogene		New Gold NI43-101, Dec 2009
1605	Huckleberry SAG feed 2012		Wang et al, CMP 2013
1606	Huckleberry HPGR product		Wang et al, CMP 2013
1607	Cadia Hill		Englehardt et al, SAG 2011 speaker notes
1608	Ridgeway		Englehardt et al, SAG 2011 speaker notes
1609	Cadia East		Englehardt et al, SAG 2011 speaker notes
1643	53392-2	Metasediments	Alacer Gold NI43-101 July 29, 2014

Table 2 Summary view of major grindability results for example samples

Id	Name	Program	WiBM	WiRM	WiC	Density	Axb	SGI	Ai
1529	Lik composite 7	Lik	13.9	13.6	6.8		67.3		0.17
1600	Gamsberg Pyrite	Other	13.25			3.52	79.65		
1601	Gamsberg Pyrrhotite	Other	12.9			3.42	58.6		
1602	Gamsberg Magnetite	Other	13.9			3.61	67.9		
1603	New Gold Hypogene	Other	21.8	18.5	8	2.7			0.16
1604	New Gold Mesogene	Other	19.8	18.3	8	2.77			0.07
1605	Huckleberry SAG feed 2012	Huckleberry	18			2.76	31.1		
1606	Huckleberry HPGR product	Huckleberry	15.4						
1607	Cadia Hill	Cadia	17.5	20	30		35		0.33
1608	Ridgeway	Cadia	18.7	21	30		42		0.43
1609	Cadia East	Cadia	20.3	29	30		29.7		0.2
1643	53392-2	Çöpler	13			2.58	84.6	76.7	0.26

Table 3 Bond ball mill work index database table for example samples

Id	Name	WiBM µclosing	WiBM f80	WiBM p80	WiBM gpr	WiBM	Synthetic	Laboratory	Comment
1529	Lik composite 7					13.9		ALS Kamloops	Zazu metals NI43-101 March 3, 2014
1600	Gamsberg Pyrite	106				14.1			van Drunick Gerold & Palm, IMPC2010
1600	Gamsberg Pyrite	150				12.4			van Drunick Gerold & Palm, IMPC2010
1601	Gamsberg Pyrrhotite	106				13.5			van Drunick Gerold & Palm, IMPC2010
1601	Gamsberg Pyrrhotite	150				12.3			van Drunick Gerold & Palm, IMPC2010
1602	Gamsberg Magnetite	106				14.6			van Drunick Gerold & Palm, IMPC2010
1602	Gamsberg Magnetite	150				13.2			van Drunick Gerold & Palm, IMPC2010
1603	New Gold Hypogene					21.8		SGS Lakefield	New Gold NI43-101, Dec 2009
1604	New Gold Mesogene					19.8		SGS Lakefield	New Gold NI43-101, Dec 2009
1605	Huckleberry SAG feed 2012	106	2578	77	0.99	18		SGS Lakefield	Wang, Nadolski, Mejia, Drozdiak & Klein, CMP 2013
1606	Huckleberry HPGR product	106	2302	76	1.2	15.4		SGS Lakefield	Wang, Nadolski, Mejia, Drozdiak & Klein, CMP 2013
1607	Cadia Hill					17.5			Englehardt et al, SAG 2011 speaker notes
1608	Ridgeway					18.7			Englehardt et al, SAG 2011 speaker notes
1609	Cadia East					20.3			Englehardt et al, SAG 2011 speaker notes
1643	53392-2					13		SGS Lakefield	Alacer Gold NI43-101 July 29, 2014

Database field definitions

Common fields in several of the database tables include:

- **Id –** The unique index number of this sample.
- **Name –** The human-readable sample name.
- **Synthetic –** Is this a `fake` sample, such as a mathematical average of actual test results?
- **Laboratory –** The laboratory where a particular test determination was performed.
- **Comment –** The document reference where the data originated or other comments.

The `summary` database table includes the following fields:

- **Program –** The project or mine this sample belongs to. Some samples belong to a `other` group as they do not have many related samples.
- **WiBM –** The Bond ball mill work index, in metric units.
- **WiRM –** The Bond rod mill work index, in metric units.
- **WiC –** The Bond impact crushing work index, in metric units.
- **Density –** The coarse particle density measured in either the Bond impact crushing work index test or the drop weight test, t/m^3.
- **Axb –** The product of the `A` and `b` parameters from a drop weight test, unitless.
- **Mia –** The coarse tumbling particle coefficient for a Morrell power equation, kWh/t.
- **Mib –** The fine tumbling particle coefficient for a Morrell power equation, kWh/t.
- **CI –** The Minnovex crushing index determined as part of a SPI™ determination, unitless.
- **SGI –** The SAG Grindability Index or SAG Power Index™, minutes.
- **Ai –** The Bond abrasion index, unitless.

The `litho` database table includes the following fields:

- **Drillhole –** Identifier of the drill hole a sample originated from.
- **Dist from –** Downhole position where a sample originated from, m.
- **Dist to –** Downhole position where a sample originated from, m.
- **Litho –** Lithology identifier for a sample.
- **Alteration –** Alternation regime identifier for a sample.
- **Zone –** Zone identifier for a sample.
- **Length –** Downhole contiguous length of a sample, m

The `ai` database table includes the following field:

- Ai – Bond abrasion index, unitless.

The `dwt` (drop weight test) table includes the following fields:

- **A** – The fitted coefficient of a "t_{10} versus Ecs" curve in a drop weight test.
- **b** – The fitted exponent of a "t_{10} versus Ecs" curve in a drop weight test.
- **Axb** – The product of the fitted **A** and **b** parameters in a drop weight test.
- **ta** – The abrasion resistance measurement of a JK DWT™.
- **DWT density** – The coarse particle density determined in a drop weight test, t/m³.
- **SMC** – Boolean field indicating of this is a SMC Test™ result (value = 1 for SMC).
- **DWI** – The Drop Weight Index determination for a sample, kWh/m³
- **Mia** – The coarse tumbling particle coefficient for a Morrell power equation, kWh/t.
- **Mih** – The high pressure grinding roll coefficient for a Morrell power equation, kWh/t.
- **Mic** – The crushing coefficient for a Morrell power equation, kWh/t.

The `pli` (point load index) table includes the following fields:

- # **Specimens** – The quantity of specimens tested for a particular sample.
- **PLI** – The mean IS_{50} value of a set of specimens, MPa.
- **PLI Min** – The minimum IS_{50} value of a set of specimens, MPa.
- **PLI Max** – The maximum IS_{50} value of a set of specimens, MPa.
- **Std Dev** – The standard deviation of IS_{50} values in a set of specimens, MPa.

The `sgi` (SAG grindability index) table includes the following fields:

- **CI** – The Minnovex crushing index determined as part of a SPI™ determination, unitless.
- **SGI** – The SAG Grindability Index or SAG Power Index™, minutes.

The `ucs` (unconfined or uniaxial compressive strength) table includes the following fields:

- # **Specimens** – The quantity of specimens tested for a particular sample.
- **UCS** – The mean unconfined pressure of sample failure of a set of specimens, MPa.
- **UCS Min** – The minimum pressure of sample failure of a set of specimens, MPa.
- **UCS Max** – The maximum pressure of sample failure of a set of specimens, MPa.
- **Std Dev** – The standard deviation of pressure of sample failure in a set of specimens, MPa.

The `wibm` (ball mill work index) table includes the following fields:

- **WiBM µclosing** – The closing screen size used in the test, µm.
- **WiBM f80** – The test feed 80% passing particle size, µm.
- **WiBM p80** – The test product 80% passing particle size, µm.
- **WiBM gpr** – The test average grams per revolution of the final cycles, g/rev.
- **WiBM** – The Bond ball mill work index determination, metric units.

- **Mod BWI –** Boolean field indicating if this is a non-standard test, such as an open-cycle "modified BWI" test or a SAGDesign test with non-standard size distribution of the feed.

The \`wic\` (crushing work index or low energy impact work index) table includes the following fields:

- # **Specimens –** The quantity of specimens tested for a particular sample.
- **WiC –** The mean crushing work index of a set of specimens, metric units.
- **WiC Min –** The minimum crushing work index of a set of specimens, metric units.
- **WiC Max –** The maximum crushing work index of a set of specimens, metric units.
- **Std Dev –** The standard deviation of crushing work index of a set of specimens, metric units.
- **WiC density –** The coarse particle density measured in a crushing work index test, t/m³.

The \`wirm\` (rod mill work index) table includes the following fields:

- **WiRM μclosing –** The closing screen size used in the test, μm.
- **WiRM f80 –** The test feed 80% passing particle size, μm.
- **WiRM p80 –** The test product 80% passing particle size, μm.
- **WiRM gpr –** The test average grams per revolution of the final cycles, g/rev.
- **WiRM –** The Bond rod mill work index determination, metric units.

The rod mill work index table includes results from laboratories whose apparatus does not conform to Bond's original specification. The most significant deviation is several laboratories in Australia use a mill without a wave liner – the liner specified by Bond.

RESULTS AND DISCUSSION

The entire database is too large to tabulate in this document (it would be over 200 pages), so instead it is freely available for download as an OpenDocument spreadsheet on the author's website at this link: https://www.sagmilling.com/articles/28/view/?s=1 . The database will be updated periodically and the latest revision will always be available at the web link.

Comparisons and regression equations between different grindability metrics appear in Figures 1 through 9. The comparisons only consider tests done in the same size classes as defined by Doll & Barratt, 2009. Linear, logarithmic, exponential and power regression relationships are attempted on all plotted pairs and the relationship with the highest R^2 value is displayed.

Fine size class:

Morrell Mib versus Bond ball mill work index. Variation expected due to different exponents in the two equations.

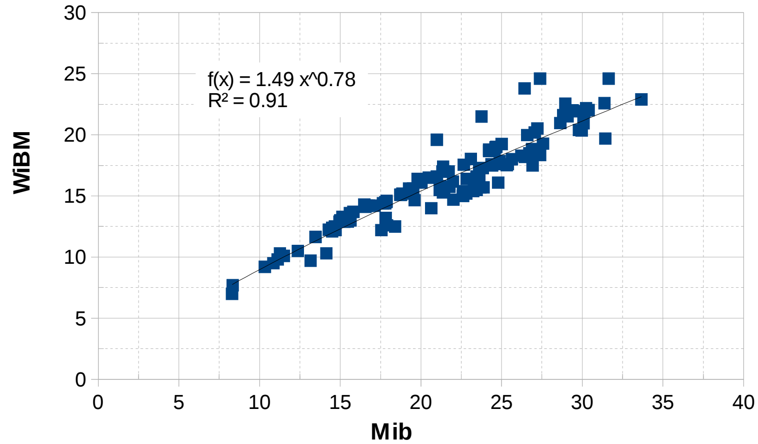

Figure 1 Bond ball mill work index v. Morrell Mib

No relationship between Bond abrasion index and ball mill work index.

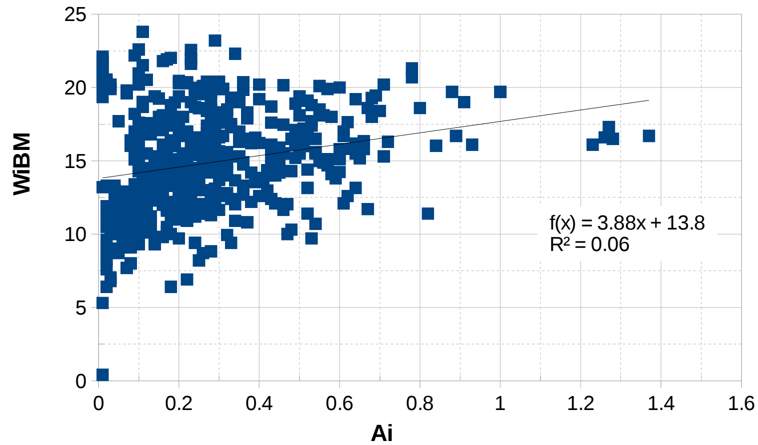

Figure 2 Bond ball mill work index v. Bond abrasion index

Medium size class:

Best relationship requires separating the Bond-type mills with wave liners from the non-standard mills.

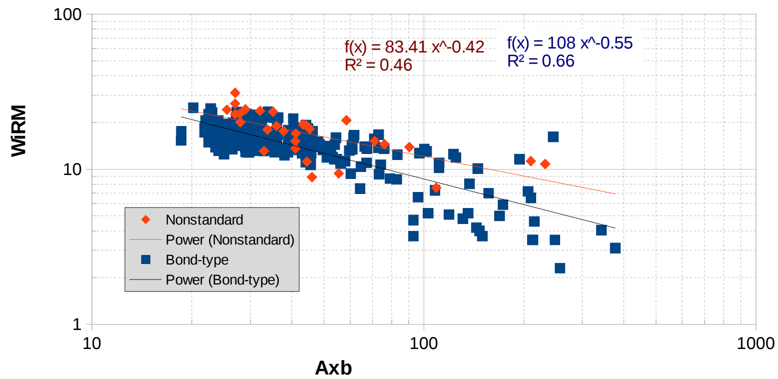

Figure 3 Bond rod mill work index v. Drop weight A×b

Generally a good relationship between the two parameters.

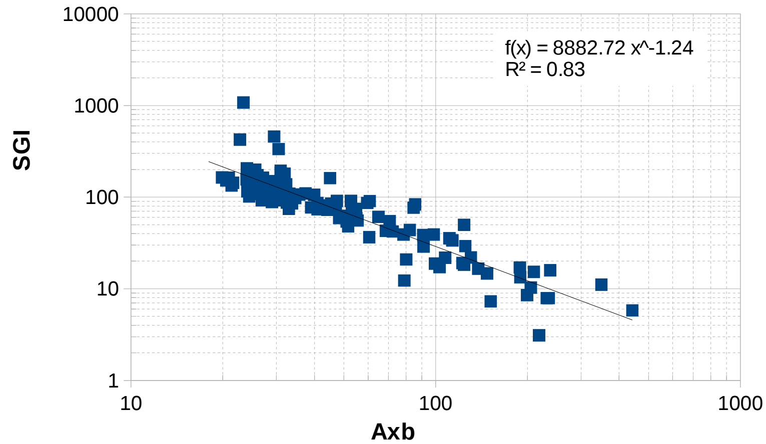

Figure 4 SAG Grindability Index v. Drop weight A×b

Compares the Mia parameter determined from the SMC test™ used in Morrell power equations to the A×b parameter reported from any drop weight test (both SMC test™ and the JK DWT are drop weight tests).

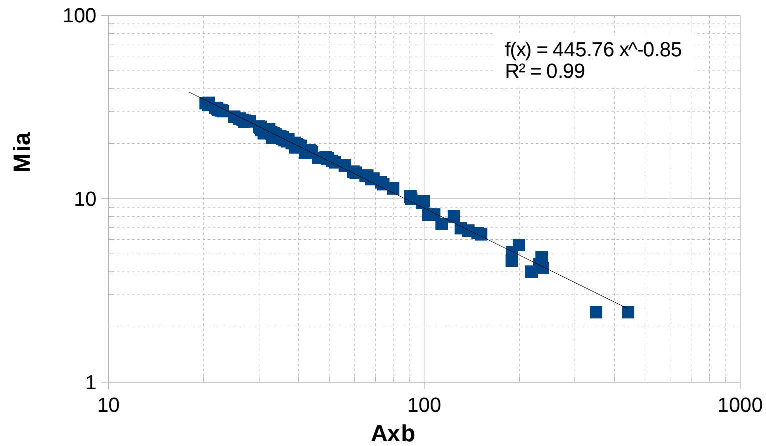

Figure 5 Morrell Mia v. Drop weight A×b

DWI is a volumetric parameter (kWh/m³) determined from the SMC test™. Dividing DWI by the sample density gives a mass parameter (kWh/t) suitable for comparing to A×b.

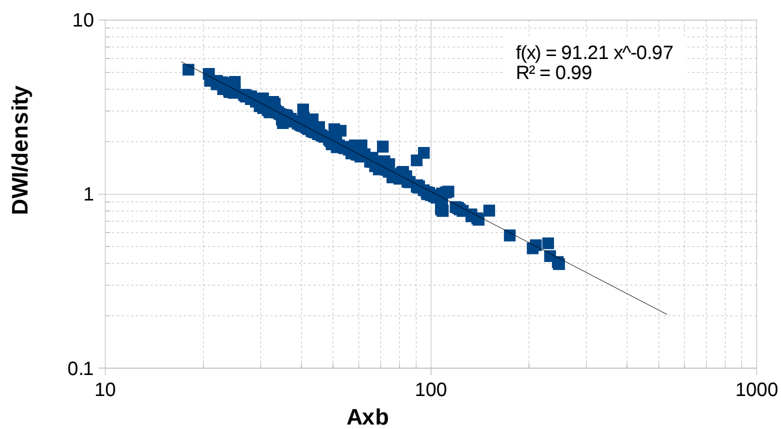

Figure 6 (Morrell DWI ÷ density) v. Drop weight A×b

Only regression for Bond-type apparatus shown. Too few examples of samples tested on both the non-standard rod mill apparatus and the SAG Grindability Index.

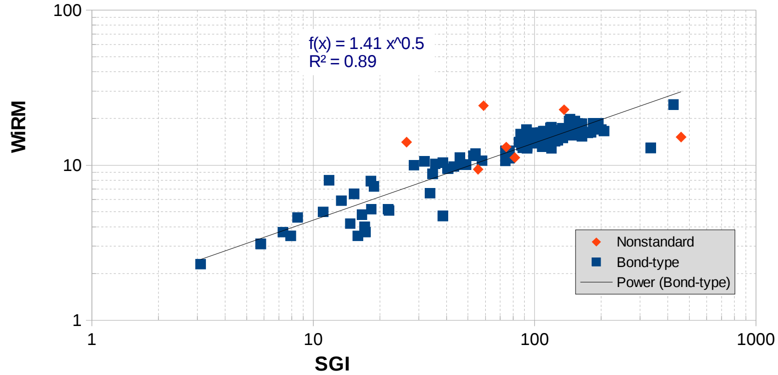

Figure 7 Rod mill work index v. SAG Grindability Index

Morrell's crushing parameter Mic is (perfectly?) related to the drop weight test A×b determination.

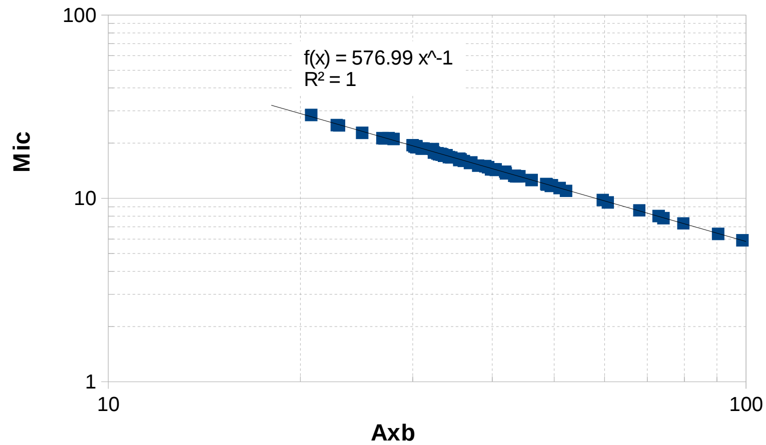

Figure 8 Morrell Mic index v. Drop weight test A×b

Coarse size class:

Noisy data with poor overall relationship.

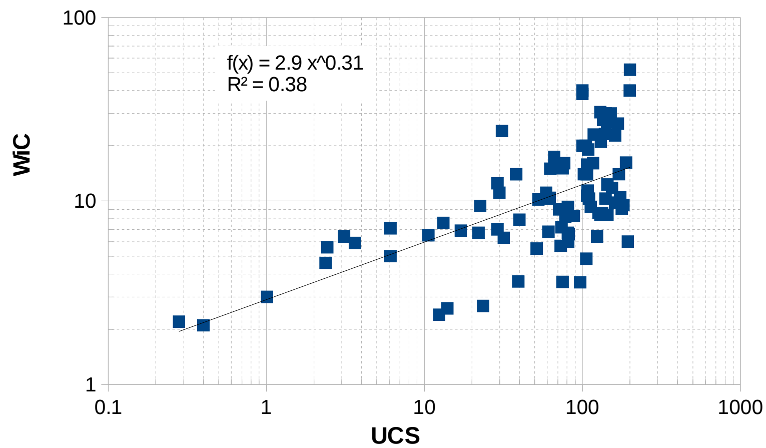

Figure 9 Crushing work index v. Unconfined compressive strength

Specific energy predictions

Some of the samples that include all the parameters for Bond work indices, SMC tests and SGI values were run against different power-based specific energy models using SAGMILLING.COM software. The samples were run in a circuit consisting of mills based on Los Bronces Confluencia operating in an SABC-B configuration grinding from feed F_{80} of 150 mm to a cyclone overflow product P_{80} of 180 µm. No attempt to optimize any of the simulations was done.

Table 4 Example specific energy predictions by three models

	Test results or predictions								Model E_{total}, kWh/t		
Name	**Wi_{BM}**	**Wi_{RM}**	**Wi_C**	**A×b**	**SGI**	**Mi_c**	**Mi_a**	**Mi_b**	**Optimized Bond/Barratt**	**Morrell Mi**	**SGI**
Los Bronces median	16.5	16.7	*10.0*	30.0	130.0	*19.2*	24.8	20.5	15.3	19.1	15.2
Antapaccay UGM 1	17.6	13.5	5.6	47.1	79.4	*12.3*	*16.9*	*12.3*	15.0	12.6	14.5
Antapaccay UGM 2	16.7	13.5	5.7	54.8	74.5	*10.5*	*14.8*	*10.5*	14.2	11.0	13.8
Antapaccay UGM 3	15.5	11.6	5.2	44.1	72.7	*13.1*	*17.8*	*13.1*	12.5	13.4	13.0
Antapaccay UGM 4	14.7	12.1	7.9	53.1	72.4	*10.9*	*15.2*	*10.9*	12.1	11.3	12.5
Antapaccay UGM 5	10.0	10.8	7.3	64.9	61.0	*8.9*	*12.8*	*8.9*	8.1	9.4	10.0
Antapaccay UGM 6	14.6	14.3	8.2	47.5	90.8	*12.2*	*16.8*	*12.2*	12.6	12.6	12.9
Boddington Apr 2010 survey	14.4	20.0	27.7	30.0	*130.9*	*19.2*	*24.7*	17.7	16.2	18.2	15.2
Volta Grande comp 2-3	16.5	16.0	*20.0*	30.6	133.2	*18.9*	*24.3*	*18.9*	15.9	18.5	15.3
Huckleberry SAG feed 2012	18.0	*16.3*	*7.0*	31.1	*125.2*	*18.6*	*24.0*	25.6	16.5	20.2	15.8
Malartic Sep 21 survey	16.3	16.3	18.5	24.1	115.3	*23.9*	*29.8*	*23.9*	13.4	23.0	14.5
Yanacocha	17.5	13.8	*10.0*	72.9	*43.5*	*7.9*	12.3	25.3	15.4	14.0	12.9
Meadowbank Vault	13.9	15.9	*10.0*	40.9	86.4	*14.1*	*19.0*	*14.1*	13.2	14.3	12.3
Corani avg	15.1	10.2	6.3	111.0	35.6	*5.2*	*8.1*	*5.2*	11.8	5.8	11.2

Italics indicate test parameters based on interpolations (Figures 1 through 9) or assumed.

This particular sub-set of the overall database shows the Optimized Bond/Barratt model and the Amelunxen SGI model are generally very close in their specific energy consumption predictions (average absolute difference is 6.4%), but the Morrell Mi model is substantially different from the other two models (average absolute difference of 20.4% versus Bond/Barratt and 20.6% versus SGI).

The Author's experience is that any ore sample can potentially confuse any grindability test, so the observation that the Morrell Mi model is substantially different from the other two is likely an artifact of the sub-set of results that were chosen for Table 4. One might observe a different pattern had a different set of samples been chosen for the specific energy consumption calculations.

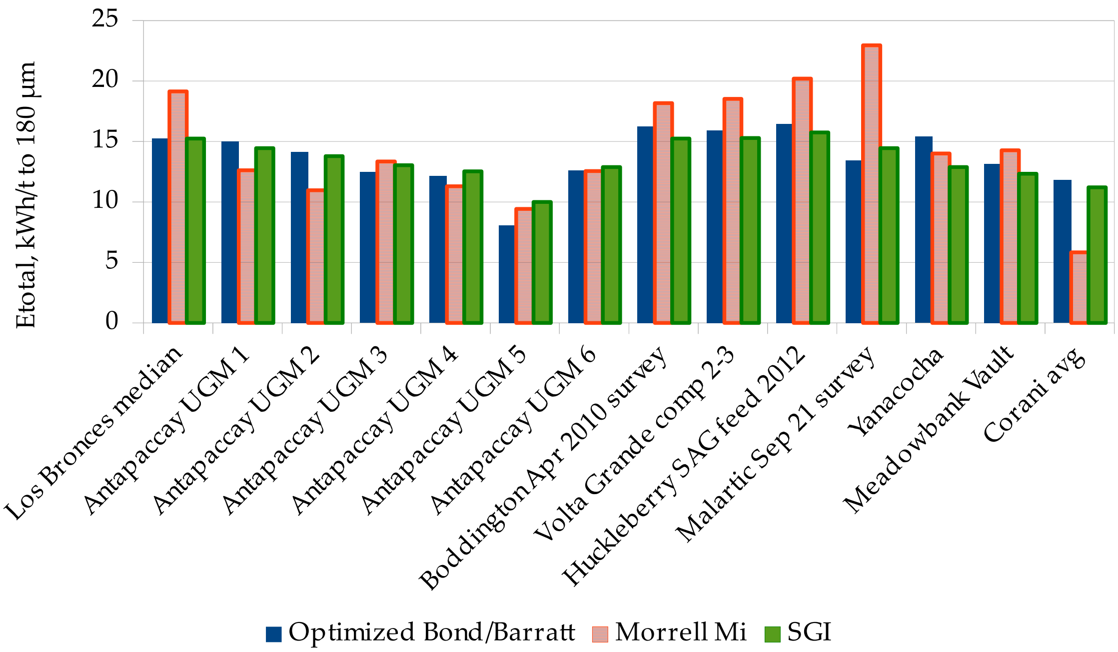

Figure 10 Specific energy consumption predictions for three models

CONCLUSIONS

A large quantity of grindability test results have been published in conference proceedings, NI43—101 reports and other works. The author has collected and collated over 800 examples of such published grindability results and generated a public database of test results suitable for benchmarking other projects or performing research such as extracting relationships between the different test parameters.

The database is freely available for download as an OpenDocument spreadsheet on the author's website at this link: https://www.sagmilling.com/articles/28/view/?s=1

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SMC Test™ is a trademark of SMC Testing Pty Ltd.

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Project reports

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NI43-101 report on the **Asmara** project, prepared for Sunridge Gold Corp 2014-03-27 by SENET (Pty) Ltd., Modderfontein, South Africa.

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NI43-101 report on the **Masbate** Gold Project, prepared for CGA Mining Limited 2011-10-31 by M.B. Turner, A.J. Vigar and S.T. Jones.

NI43-101 report on the **Mercedes** gold-silver project, prepared for Yamana Gold Inc. 2014-02-25 by RPA Inc., Toronto, Canada.

NI43-101 report on the **Metates** Gold-Silver Project, prepared for Chesapeake Gold Corp. 2013-03-13 by M3 Engineering & Technology Corporation, Tucson, USA.

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NI43-101 report on the **Moose River** Consolidated Project, prepared for Atlantic Gold Corporation 2015-08-13 by Ausenco Engineering Canada Inc., Vancouver, Canada.

NI43-101 report on the **Mount Milligan** project, prepared for Terrane Metals Corp 2009-10-23 by Wardrop Engineering Inc., Vancouver, Canada.

NI43-101 report on the **Namoya** Gold project, prepared for Banro Corporation 2013-12-31 by Venmyn Deloitte (Pty) Ltd., Woodmead, South Africa.

NI43-101 report on the **New Afton** project, prepared for New Gold Inc. 2009-12-31 by Scott Wilson Roscoe Postle Associates Inc., Toronto, Canada.

NI43-101 report on the **New Liberty** Gold Project, prepared for Aureus Mining Inc. 2012-10-22 by AMC Consultants (UK) Limited, Maidenhead, UK.

NI43-101 report on the **Nico** gold-cobalt-bismuth-copper deposit, prepared for Fortune Minerals Limited 2012-07-02 by P&E Mining Consultants Inc., Brampton, Canada.

NI43-101 report on **Niobec** Expansion, prepared for Iamgold Corporation 2013-12-10 by Iamgold Corp., Longueuil, Canada and Niobec Inc., St-Honoré, Canada.

NI43-101 report on the **Nkout** Iron Project, prepared for Afferro Mining 2013-05-28 by SRK Consulting (UK) Limited, Cardiff, UK.

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NI43-101 report on the **Pebble** project, prepared for Northern Dynasty Minerals Ltd. 2014-12-31 by Hunter Dickinson Inc., Vancouver, Canada.

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NI43-101 report on the **Platreef** project, prepared for Ivanhoe Mines Ltd. 2014-03 by OreWin Pty Ltd., Adelaide, Australia.

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NI43-101 report on the **Sabodala** gold project, prepared for Teranga Gold Corporation 2014-03-13 by AMC Consultants (Canada) Ltd., Toronto, Canada.

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NI43-101 report on the **Snelgrove Lake** property, prepared for Mamba Minerals Limited 2013-12-20 by King and Bay West Management Corp. and BBA Inc., Montréal, Canada.

NI43-101 report on the **Spanish Mountain** project, prepared for Spanish Mountain Gold Ltd. 2010-12-20 by AGP Mining Consultants Inc., Barrie, Canada.

NI43-101 report on the **Tepal** project, prepared for Geologix Explorations Inc. 2013-04-30 by JDS Energy & Mining Inc., Vancouver, Canada.

NI43-101 report on the **Tulsequah Chief** deposit, prepared for Chieftain Metals Inc. 2010-11-08 by SRK Consulting (Canada) Inc., Vancouver, Canada.

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