PAPER #01

Grinding: Why So Many Tests?

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ABSTRACT

There are a number of comminution tests commonly used in the mining industry. Many of the tests are used for a particular grinding model or mill sizing program and are incompatible with other tests of different models. This paper provides an overview of the commonly used grinding & crushing tests, which models (or practitioners) use a particular combination of tests, and draws some relationships between the incompatible tests based on the DJB Consultants Inc. database of projects.

Case studies will demonstrate similarities and differences between major mining districts with some comments about homogeneous and heterogeneous behaviour within the grindability results.

INTRODUCTION

There are a number of bench-scale grindability tests in use for sizing and predicting throughput for grinding circuits. Part of the reason for this variety is there are a number of different grinding models in use in the Industry, and those models operate using incompatible test results as input (Doll & Barratt, 2008).

By using the database of testwork in the DJB Consultants, Inc. (DJB) Millpower 2000 database (ref Table 1), some of the more commonly used tests are compared and relationships will be drawn.

Table 1: Quantity of Projects & Samples in the Millpower 2000 database

Test	Model Type	Qty of projects	Qty of results
Abrasion Index	Bond	37	2348
CI	CEET2	18	1753
Drop Weight	JK SimMet/SMC	34	278
SAGDesign	SAGDesign	0	0
SMC	JK SimMet/SMC	22	2014
SPI	CEET2	29	2043
Wi for ball milling	Bond + JK + CEET2	55	4326
Wi for crushing	Bond	52	1847
Wi for rod milling	Bond	54	2635

SUMMARY OF TESTS & MODELS

Bond Series, Work Index

One of the first suites of comminution testwork protocols was assembled by Fred Bond at the Milwaukee Allis-Chalmers laboratories in the 1950's (Bond, 1952). The tests of interest in this paper are the Bond ball mill work index (Wi_{BM}), Bond rod mill work index (Wi_{RM}), and Bond low-energy impact crushing work index (Wi_C). The rod mill and ball mill tests are locked-cycle and are run until an equilibrium is established between product size generated in subsequent cycles. The crushing work index is a single-particle test performed on 20 specimens subjected to repeated impacts of increasing energy until first fracture (i.e., no chipping).

Each of the work index tests targets a different size class and when combined, can be used as a pseudo-breakage function in models such as the Millpower 2000 model used by DJB Consultants, Inc. (Barratt, 1989)

All three Bond tests can be performed on samples consisting of 30-50 kg of whole large-diameter core (+63 mm). More commonly, 10 kg of whole core is sampled for the crushing work index and a separate 30-40 kg sample of crushed or half-core material is taken for the rod mill, ball mill and Bond Abrasion Index (Ai) (Doll & Barratt, 2008).

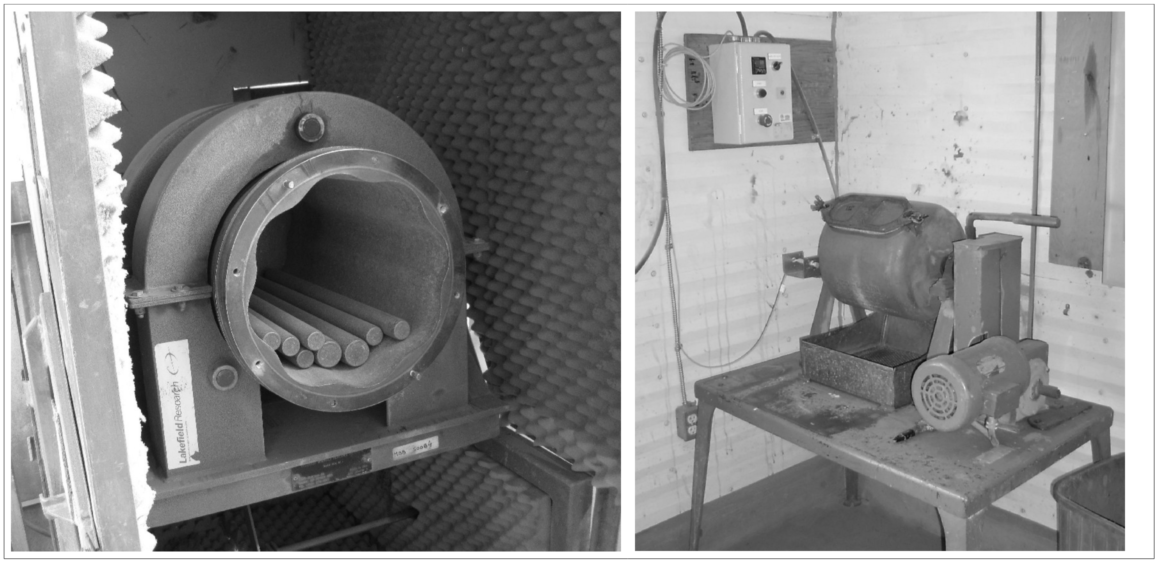

Figure 1: Bond Rod Mill and Ball Mill

JK Drop Weight & SMC

The JK Drop Weight Test (JKDWT) and SAG Mill Comminution (SMC) tests originate from Australia and both use the same apparatus. They also provide a common output in the form of a "A×b" value, though each provides a somewhat incompatible set of derivative values and inputs. In both cases, the test is a single-particle test conducted on a number of specimens.

The principal difference between the JKDWT and the SMC is the size classes of material tested. The JKDWT is conducted on a series of samples in size classes ranging from 63 mm down to 13 mm, whereas the SMC test is typically conducted on a single size class of -22 mm/+19 mm (Doll & Barratt, 2009). Much larger quantities of sample are needed to conduct a JKDWT than an SMC test, 60-100 kg versus about 8 kg.

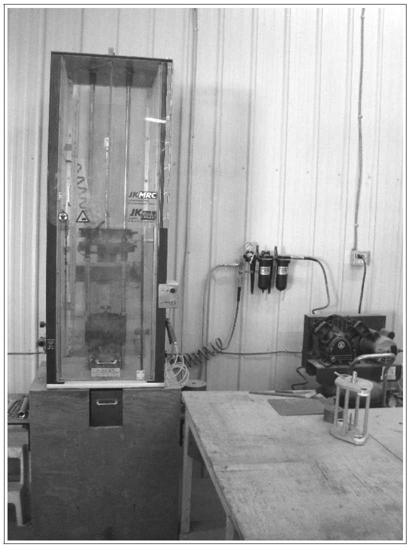

Figure 2: JK Drop Weight Testing Machine

Minnovex SPI & CI

The SAG Power Index (SPI) test was developed in Canada by Minnovex (now SGS) in the early 1990's. It is a batch, open-cycle SAG mill test where a 2 kg charge of -12.5 mm ore is placed in the mill and ground until 80% of the charge passes 1.7 mm. The crushing index (CI) parameter was added in the late 1990's and is determined in the sample preparation phase of the SPI test by comparing the amount of 19 mm screen oversize in sequential crushing steps (Starkey & Dobby, 1996).

The SPI value is principally used to estimate the power draw of a SAG mill using the CEET2 model (though it is used elsewhere in the model), and the CI value is used to predict the feed size distribution to a SAG mill.

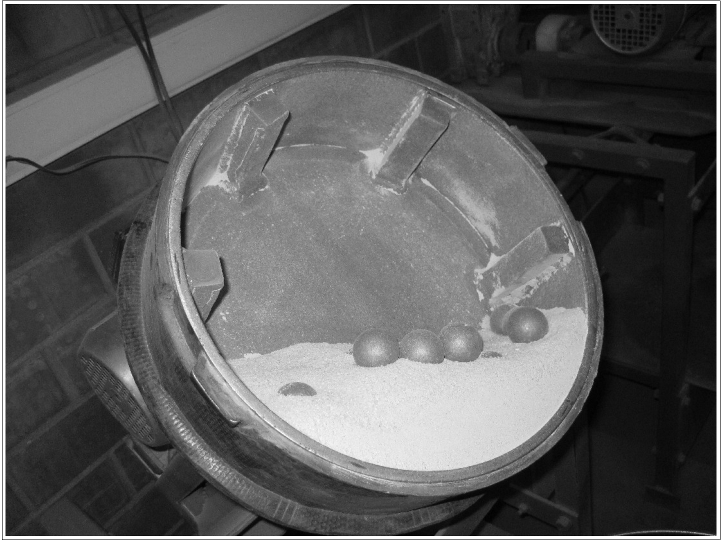

Figure 3: SPI Mill with Silica Sand Charge

Starkey SAGDesign

John Starkey left Minnovex in the early 2000's and created a new test that bears similarity to the SPI test except that the test is conducted with a much larger sample size (8 kg sample charge versus 2 kg) and the ore charge declines during the test as finished product is removed from the mill. The results of a SAGDesign test are usually expressed in kWh/t of specific energy for milling, although mill revolutions to achieve test completion is an alternative output. The ground product from a SAGDesign test is then used as feed to a modified Bond ball mill work index test to assess the effect of the quantity of fines in the SAG product (Starkey et al, 2006).

Though the SAGDesign test has been around for over five years, DJB Consultants, Inc. has not had an occasion to work with the test and model on a project. The comparisons presented in this paper are made from published literature on the SAGDesign test rather than head-to-head comparisons from actual projects.

Geotechnical Tests and Measurements

The rock breakage properties of orebodies are of interest to both geotechnical and comminution engineers. Geotechnical tests are used to characterize properties of rock at coarse and very-coarse sizes relative to what is typically considered in comminution circuit design (Siddall et al, 1996). In that sense, geotechnical tests are most relevant to the sizing of crushers and SAG mills – the equipment that operates at the coarse end of the spectrum of particle size.

Geotechnical tests generally characterize either the in-situ properties of a rock, or measure the energy to first failure of a rock specimen. The first failure principle is similar to the method employed in the Bond low energy impact crushing work index test, and it is this work index test that DJB tends to compare against geotechnical tests.

EFFECT OF PARTICLE SIZE

Each grindability test is fed particles of a particular size and reduces that feed to a typical product size. In some tests (SPI, SAGDesign) the product size is specified by the test procedure as a P_{80} value; other tests (Wi_{RM}, Wi_{BM}) specify the closing screen mesh and produce a P_{80} finer than this screen. The impact tests (JKDWT, SMC, Wi_C) do not specify a product size, but simply break rocks by applying known amounts of energy. However, this impact energy does tend to create product material of a particular size range even though the range is not specified in the test procedure (the JKDWT and SMC measure the product sizes, Wi_C does not).

Plotting the principal grindability test feed and product sizes against a scale results in Figure 4.

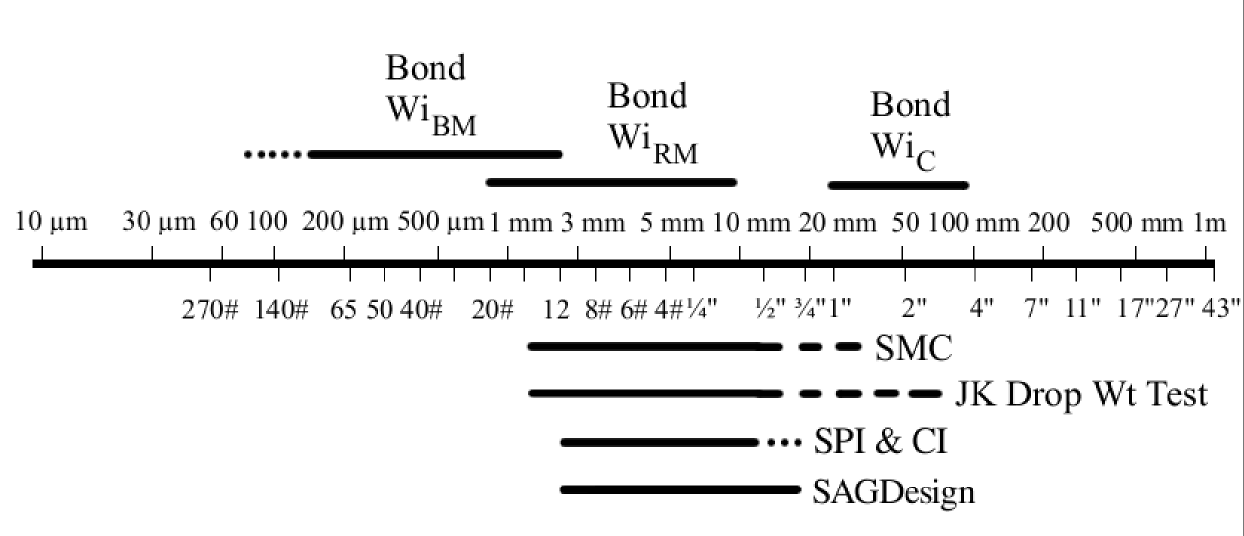

Figure 4: Comminution Tests Showing Typical Range of Feed & Product Sizes

By observation, there appear to be three classes of tests when grouped by size. There is a single "fine" test, the Bond ball mill work index. The "coarse" size range is dominated by the Bond crushing work index, though the upper end of the JKDWT overlaps much of the size range (geotechnical tests, not shown, would also be in this coarse range). The "medium" size range, from about 2 mm to 20 mm is where most of the common "SAG Milling" tests occur, including the Bond rod mill work index, SMC test, SAGDesign, SPI and the lower end of the JKDWT. The CI measurement sits at the top of the medium size range, but as will be demonstrated later, DJB tends to group it with the "coarse" tests.

Homogeneous Versus Heterogeneous Ore

DJB defines homogeneous ore as having similar breakage characteristics across the three size classes. More broadly, a homogeneous ore that measures hard with a Bond ball mill work index will also measure hard with any other test, such as the Bond crushing work index.

Heterogeneous ore is defined has having step-changes in breakage energy at particular size ranges where breakage characteristics cannot be predicted from one side of the step-change to another. An example of a common heterogeneous ore is a heavily fractured porphyry where the fracture spacing, on the order of 10-20 mm, means the material is soft at the coarse end (where breakage occurs along fractures) and material could be any of soft, moderate or hard in the medium to fine range (where breakage happens within the rock matrix between any fractures).

Figures 5 and 6 demonstrate a coarse-size test (crushing work index) plotted against a medium-size test (rod mill work index) for both homogeneous and heterogeneous ore subsets of the Millpower 2000 database. The correlation coefficient (R^2) for the homogeneous value is reasonable (0.55) suggesting that a relationship exists. No such relationship can be assigned to the heterogeneous sample due to the R^2 of 0.09.

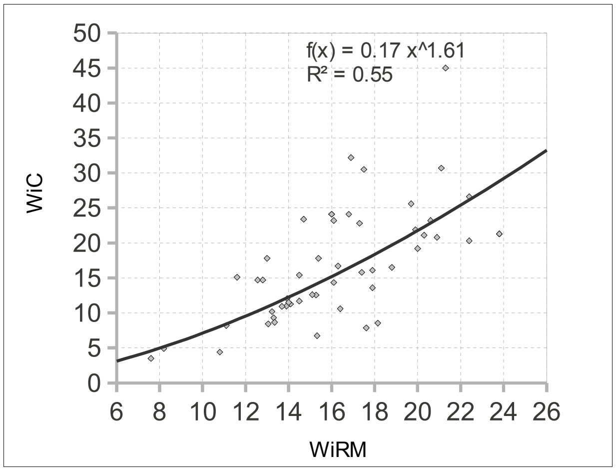

Figure 5: Database of Homogeneous Ores, Crushing versus Rod Mill Wi

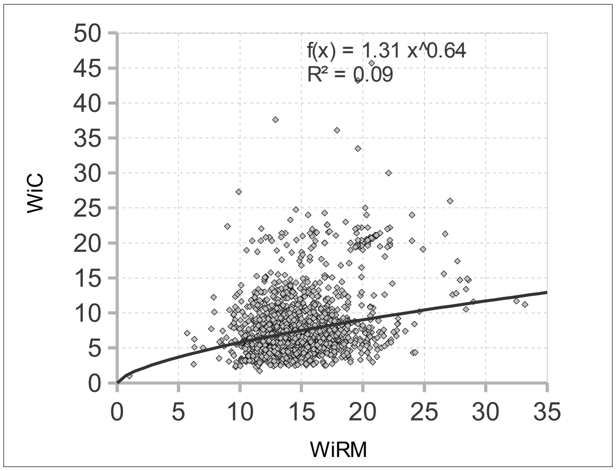

Figure 6: Database of Heterogeneous Ores, Crushing versus Rod Mill Wi

Case study: Figure 7 shows a specimen of heterogeneous porphyry ore where the highlighted fractures are a locus for failure by crushing.

Figure 7: Example Heterogeneous Sample with Fractures Highlighted

This sample originated from a project that conducted SMC tests (top size of 12 mm) and Bond crushing work index tests (on whole core, 65-83 mm) and compared the results to see if there was a relationship (see dark points on Figure 8).

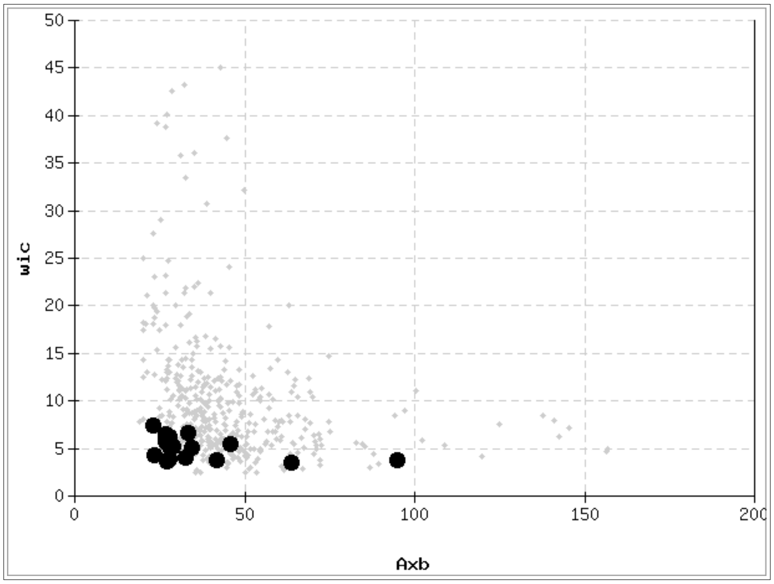

Figure 8: Heterogeneous Rock Type, No Relationship between Wi_C and SMC

DJB feels that the crushing work index test result is determined by the competence of fractures whereas the SMC result is determined by the competence of the matrix of the rock. Because the two tests are measuring different properties of the rock (fractures versus matrix), the lack of a relationship is reasonable.

Case study: A homogeneous ore from an Australian project (Figure 9) shows the crushing work index has a reasonable relationship with two medium-size tests (JKDWT and Wi_{RM}). Though not shown, there is also a relationship with the fine-size Wi_{BM} test, meaning that variability in this ore can be measured at any size class and the results extrapolated to all other size classes.

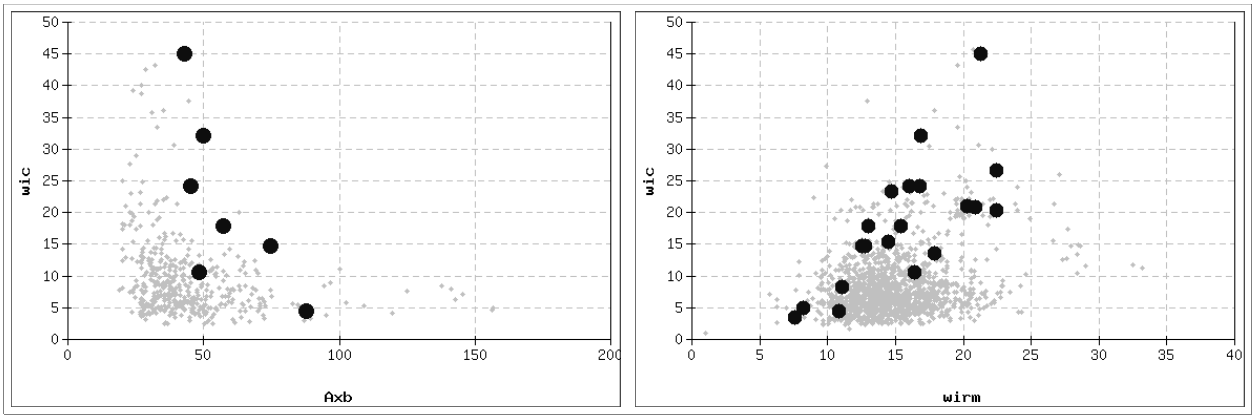

Figure 9: Homogeneous Rock Type, Relationship between Wi_C and SMC & Wi_{RM}

Based on over 25 years of experience, the principal of DJB Consultants, Inc. offers Figure 10 as a first approximation of where homogeneous and heterogeneous ore types can be found.

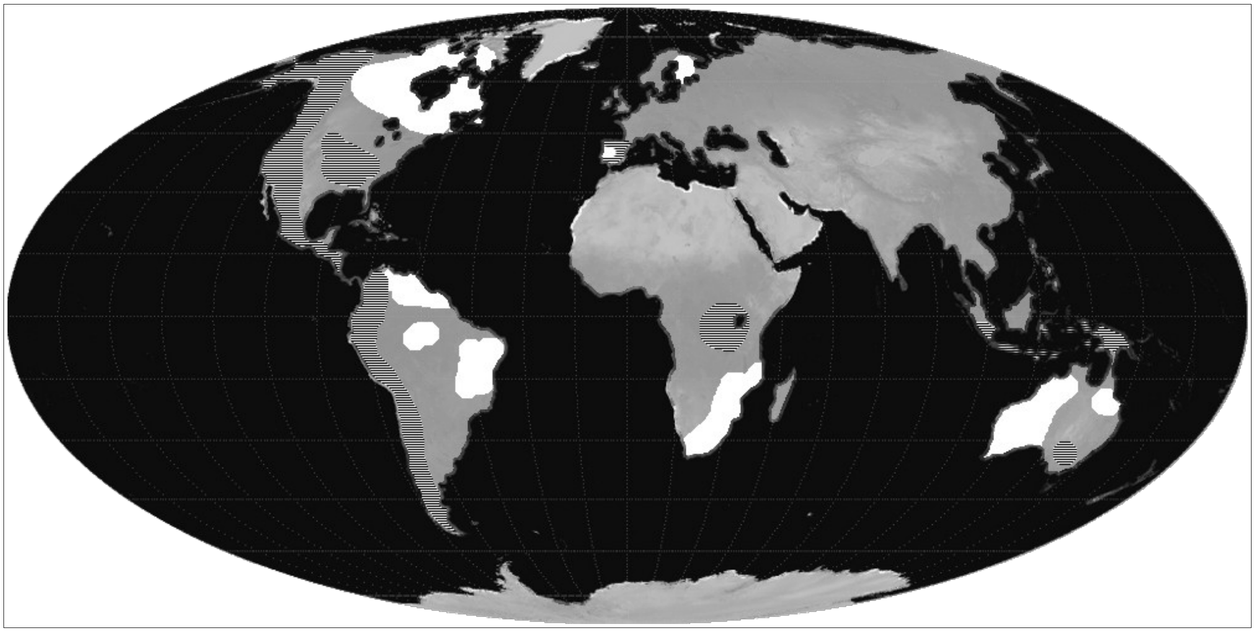

Figure 10: Typical Locations of Homogeneous (white) and Heterogeneous (dashed) Ores

Two-Parameter Versus Three-Parameter Models

The commonly used SAG design tests can be classified into two types: those that depend on parameters from three size classes, and those that depend on only two size classes.

Table 2: SAG Models, Classified by Size Parameters

Model	Type	Fine size	Medium size	Coarse size
Millpower 2000	3 parameter	Wi_{BM}	Wi_{RM}	Wi_{C}
CEET2	3 parameter	Wi_{BM}	SPI	CI
JK SimMet	2 parameter	Wi_{BM}	A, b	-
SMC	2 parameter	Mi_{b}	DWI, A×b	-
SAGDesign	2 parameter	Wi_{BM} (modified)	SAGDesign	-

The JK SimMet model appears to use three parameters, however the A & b parameters actually measure different properties of roughly the same size class, thus they are merged for the purposes of Table 2. Further, the JKDWT appears to cover a coarse size range (per Figure 4), but the results of all size classes in a JKDWT are averaged making a composite result that effectively behaves like a 12-20 mm size class. Figure 11 displays a JKDWT result for a heterogeneous ore and shows how the test result (solid line) is determined by averaging the very different properties of the coarse (upper dashed line) and medium (lower dashed line) size classes.

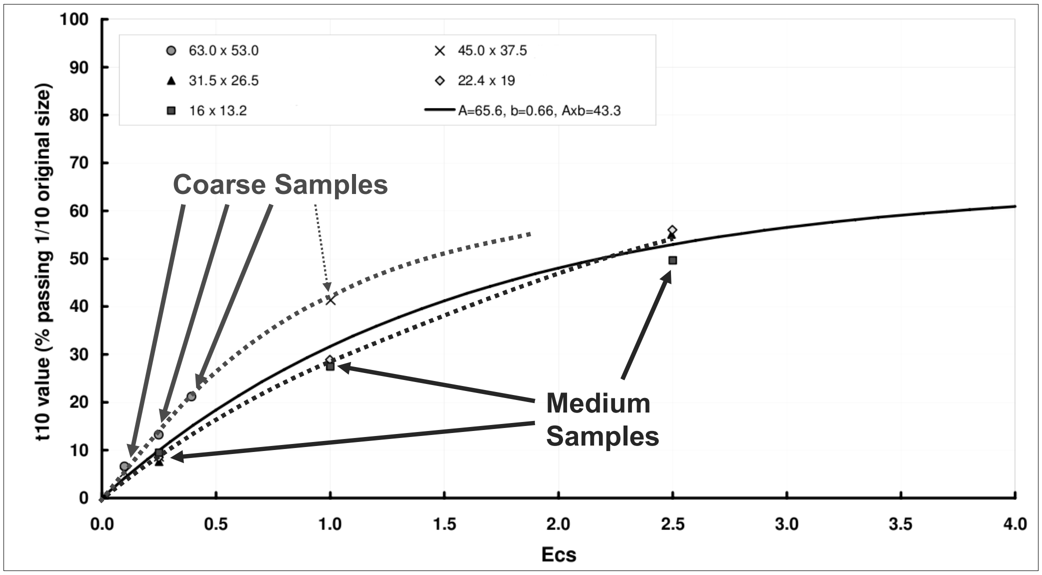

Figure 11: JKDWT Test Result, Highlighting Difference in Coarse/Medium Sizes

The SAGDesign test feed is approximately the same dimension as the feed to a CI determination, but the specific energy required for coarse particles is blended with medium-size particles and any difference between the size classes is lost.

COMPARISONS OF "SIMILAR" TESTS

The following comparisons will be made using parameter-versus-parameter plots for tests at similar sizes. Generalized relationships will be presented where warranted.

Coarse Sizes, > 20 mm

Figure 12 compares the Millpower 2000 database of results for three "coarse" tests: the Bond impact crushing work index (metric Wi_C), the CI parameter from the SPI protocol, and the geotechnical Unconfined Compressive Strength test (UCS, in MPa).

Breakage in coarse samples is dominated by fractures in those ores that have fractures. The geotechnical and crushing work index test products, when observed in the laboratory, tend to show a preference for breaking along fracture surfaces rather than breaking through the matrix of a rock. Tests in this size range are not so much testing the rock hardness, rather the competence of fractures. The CI determination (in the SPI feed preparation) is also heavily influenced by the presence or absence of fractures (it can be considered an "amenability to crushing" measurement), which is why DJB typically groups this result with the coarse size tests.

That said, the correlation coefficients on these comparisons is poor, partly due to the noisy nature of coarse tests. The Wi_C versus CI comparison is exacerbated by the difference in size classes where these two tests are performed (50-100 mm versus 19 mm, respectively). The Wi_C does show a higher R^2 versus CI (0.16) than it does versus a medium-size test such as the rod mill work index (R^2=0.10, per Figure 13), thereby giving some comfort to the classification of

CI as a "coarse" test. Note that one medium test, the SPI, appears to give a similar R^2 to the CI when compared to the Wi_C, but that a visual interpretation suggests the relationship breaks down at high values of either Wi_C or SPI. The two "tails" apparent in Figure 14 (high SPI/medium Wi_C, high Wi_C, medium SPI) are each composed of a number of projects. This is interpreted as meaning there is no single viable relationship between the parameters, in spite of the computer picking the high Wi_C, medium SPI "tail" for performing a regression.

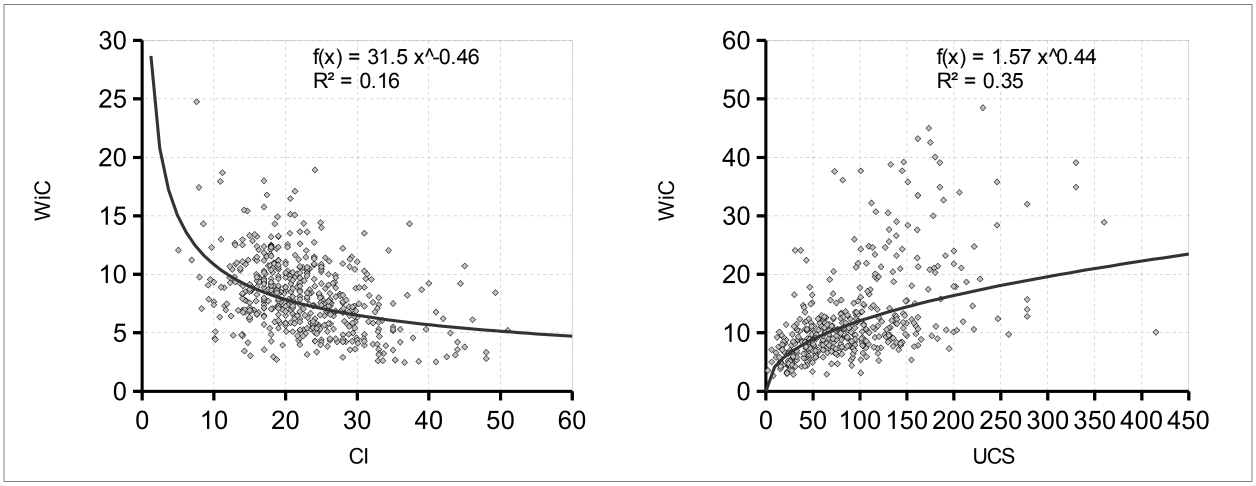

Figure 12: Millpower 2000 Database Comparison of Coarse Test Results

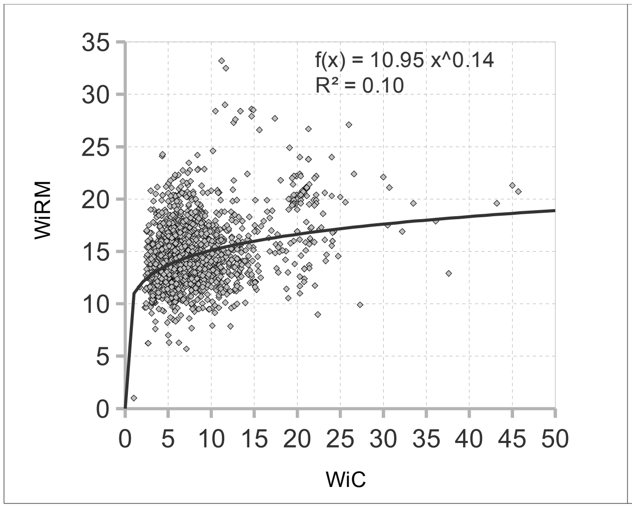

Figure 13: Millpower 2000 Database Comparison of Medium test (Wi_{RM}) versus Coarse test (Wi_C)

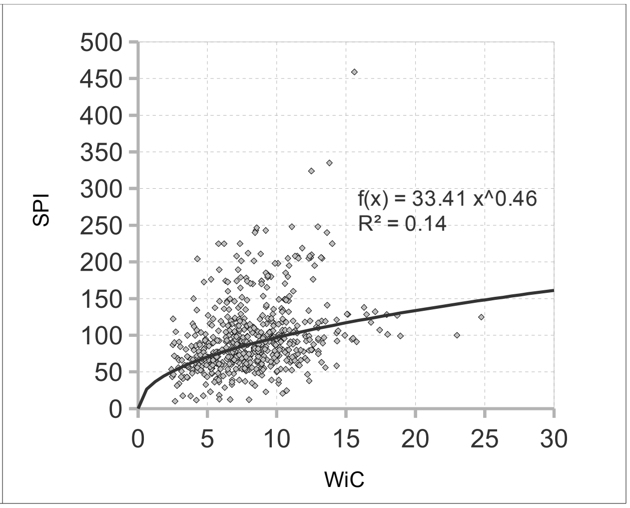

Figure 14: Millpower 2000 Database Comparison of Medium test (SPI) versus Coarse test (Wi_C)

Medium Sizes, 2 mm to 20 mm

The following graphs compare the Millpower 2000 database of results for three "medium" tests, the Bond rod mill work index (metric Wi_{RM}), SPI (in minutes), and the combined A×b value from the JKDWT and SMC.

Note that the A×b value from the JKDWT and SMC tests is a volumetric measure. It must be multiplied by the rock density to compare it to work index and SPI values. To demonstrate, two charts of Bond rod mill work index against A×b are given in Figure 15 where correcting for density results in a higher correlation coefficient (0.51) than the same chart without a correction (0.45).

The SPI and Bond rod mill work index can also be modelled with a linear relationship ($Wi_{RM}=0.04\times SPI + 10.81$) that gives almost the same R^2 value (0.47 versus 0.49). The relationship between A×b and the other parameters is certainly not linear, and at very hard values (small values of A×b) becomes very difficult to model.

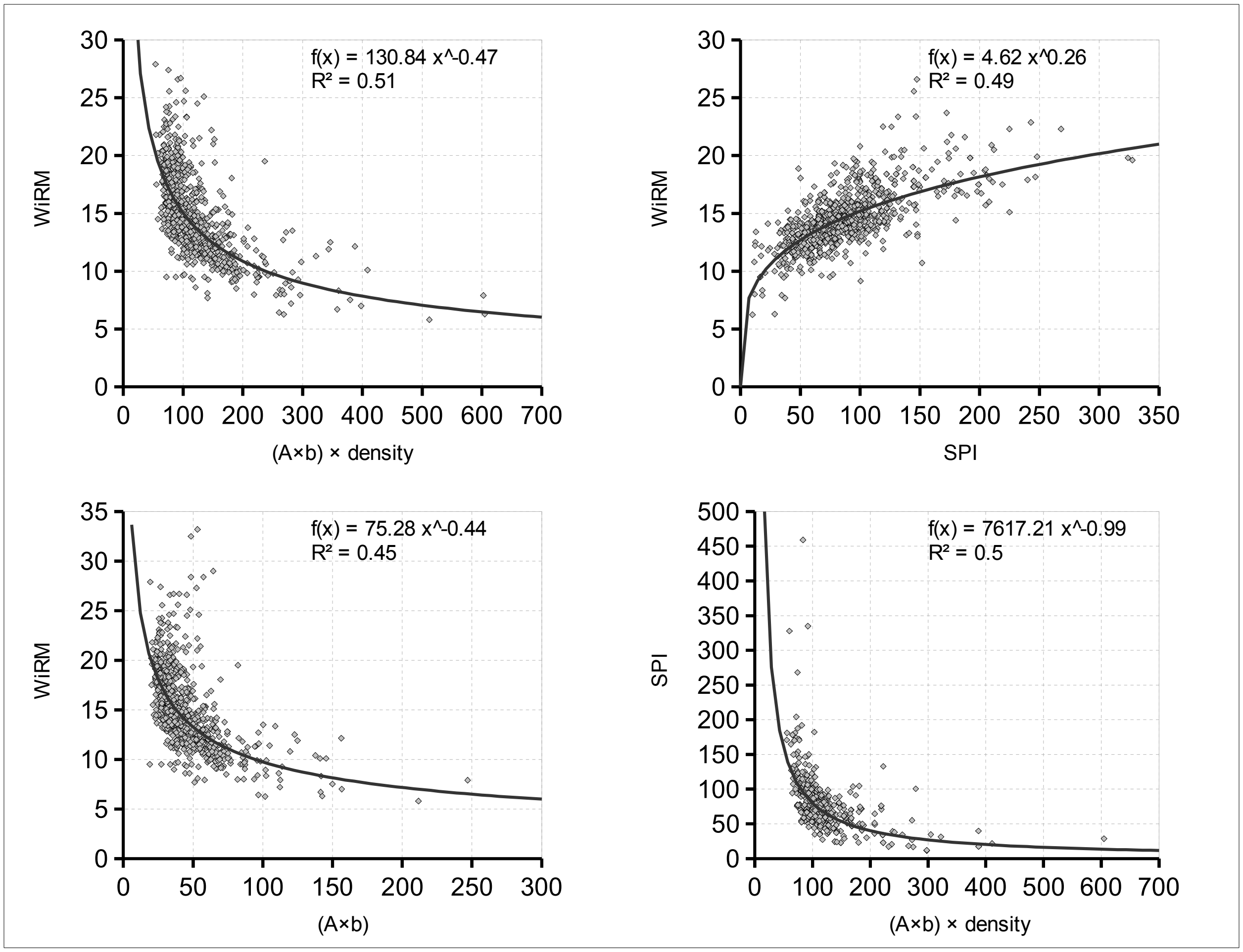

Figure 15: Millpower 2000 Database Comparison of Medium Test Results

Fine Sizes, 100 µm to 2 mm

Only one test fits this category, the Bond ball mill work index test. The Millpower 2000, JK SimMet and CEET2 models use the standard Bond test and result in calculations, while the other two models use variations on this test. The SMC test uses grindability results from a standard Wi_{BM} test and applies a proprietary formula to develop a Mi_b result which is used in the SMC model for ball milling. The SAGDesign test forgoes the standard stage-crushing sample preparation procedure and uses instead product from the SAG mill test as feed to the ball mill test.

Notwithstanding the two non-standard variations on the ball mill test, there is an important aspect to running the test that must be reiterated. The test procedure of a Bond ball mill work index test requires a choice of the "closing screen" mesh size which will determine the P_{80} of test product. In heterogeneous ores, the Wi_{BM} result is sensitive to this choice. Choose a closing screen size that will give a test P_{80} size that comes closest to the target grind P_{80} for the process.

Case study: The two heterogeneous ore types shown in Figure 16 display a strong variation in ball mill work index result with test closing size (each line is one specimen tested at multiple closing screen sizes). By observation, grain sizes were identified in these ores that are encountered as a rock is ground finer. The step-change in grinding energy required to break a set of grains causes a spike in work index as a test moves through that grain size, but if the test continues to grind finer, then that spike is blended out as the reduction ratio of the test increases. Performing visual and microscope evaluation of an ore prior to testing will assist in identifying grain sizes, and such observation governs the interpretation of the tests, i.e., a higher result versus a lower result.

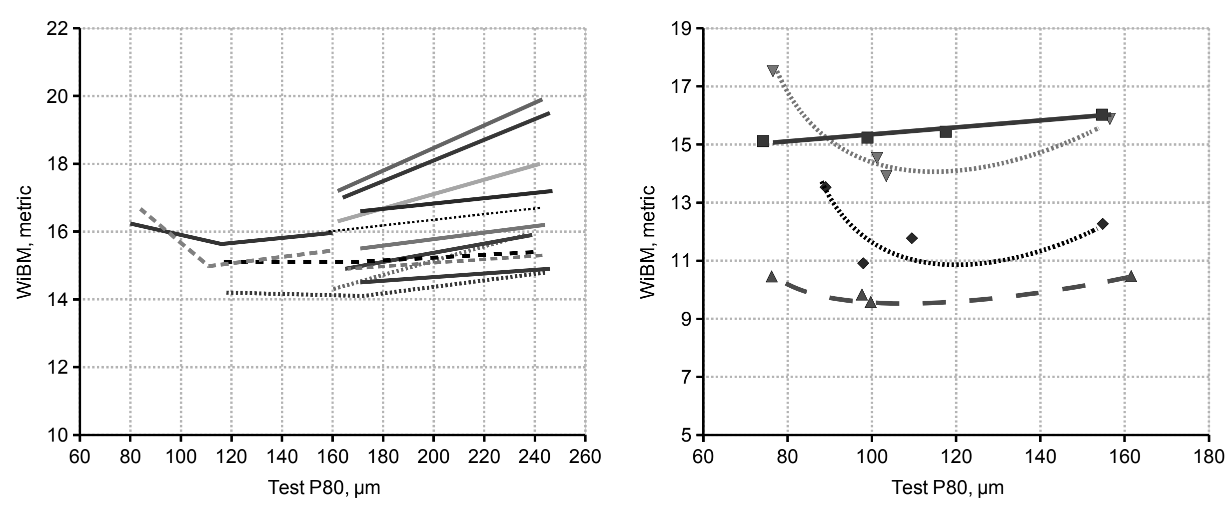

Figure 16: Variation of Ball Mill Work Index with Product Size for Two Projects

DJB recommends that test results of a ball mill work index test not be extrapolated to a substantially different P_{80} size than that which was observed in the test unless the relationship between Wi_{BM} and product size has been established for that ore. There is no "rule-of-thumb" allowing conversion between ball mill P_{80} values that works for all ores.

OBSERVED DIFFERENCES IN "SIMILAR" TESTS

The correlation coefficient between the different medium and coarse tests is generally mediocre, even for tests conducted at substantially the same size. This is attributed to a pair of factors: differences in test procedures and differences in ores.

Differences in Test Procedures

One simple difference is tests is the quantity of sample analyzed (see Table 3). Tests such as SPI use a small sample size (2 kg) which makes it more likely to suffer “nugget effect” from a small quantity of hard material when compared to the Bond rod mill work index (15 kg). SMC, JKDWT and Wi_C tests can also suffer from a “selection effect” where an operator has to physically pick specimens to test, leaving other potential specimens untested.

A difference that is more difficult to access is the effect of open-cycle tests versus closed-cycle tests. The Bond ball mill and rod mill tests are closed-cycle, meaning that after the mill has been run, finished product size material is removed from the mill charge and replaced by fresh feed. The cycles continue until an equilibrium is established between product generated in cycles.

In contrast, the SMC, JKDWT and Wi_C tests are conducted on samples that are tested completely independently of any other rock samples. Any autogenous effect (rocks affecting neighbouring rocks) is not measured in these tests, though the SMC and JK SimMet models do add autogenous effects based on survey databases and other calculations.

The SPI and SAGDesign fit between these two extremes. Both are open-cycle, batch tests where only the autogenous effect is due to material of the same “age” in the mill. Effectively, worn rock is rubbing against worn rock, whereas worn rock can rub against fresh rock in the closed-cycle tests.

Table 3: Cost and Sample Sizes for Different Tests

Test	Size Class	Circuit type	Typical Cost, USD	Sample Size, kg
Wi_{BM}	small	Closed	\$300 - \$800	10
Wi_{RM}	medium	Closed	\$500 - \$900	15
SPI	medium	Open	\$1000	2 (10 to include CI)
SMC	medium	Specimens	\$1000 - \$1500	8
SAGDesign	medium	Open	not in database	8
JK Drop Weight	medium	Specimens	\$5000 - \$10 000	100
CI	coarse	Closed	(included in SPI)	10
Wi_C	coarse	Specimens	\$300 - \$750	10

HOW MANY SAMPLES FOR YOUR PROJECT?

DJB Consultants, Inc. recognizes two phases of a project's early life that have a huge impact on the viability of a project. The pre-feasibility stage is characterized by a project that has just begun metallurgical testing and the characteristics of the orebody are not yet known. The second, much longer phase is the combination of the feasibility stage through to early mine production.

No single comminution model or testing regime can completely describe all the world's ore types in absolute detail. DJB recommends collecting testwork suitable for two of the aforementioned models when conducting a pre-feasibility study, and for three models when conducting a feasibility study or detailed design. Collecting multiple data sets both allows a due-diligence to be conducted on a design and facilitates decisions regarding power requirement and the throughput capability of selected grinding equipment.

Pre-feasibility Studies

Little is known about the grindability of an ore at the outset of a pre-feasibility study. To help guide the sample selection process, it is necessary to review the geology and alteration mapping that is done by the exploration geologists. A typical project will have two to four ore types, each characterized by a common lithology and alteration regime. Often there is some basic geotechnical mapping of core that can assist in assessing regions of the orebody that need sampling: RQD, ISRM "R-value", and fracture frequency.

DJB recommends the mill sizing for a pre-feasibility study be performed using cumulative plots (Figure 17) of grinding results from a variability program that targets 50 to 100 samples per orebody that is significant in the first five to ten years of the mine plan. DJB also recommends that samples appropriate for a second testwork/modelling protocol be collected in the pre-feasibility stage for quality-control and due-diligence purposes. A bare minimum would be to perform a second-protocol duplicate on one in five samples; DJB specifies performing the second protocol on all samples at the pre-feasibility stage.

Use of a cumulative plot of grinding energy or throughput requires some explanation. Assuming the samples in the pre-feasibility data set are indicative of the overall variability in the orebody, then choosing a mill design to provide a desired throughput (40,000 t/d in this example) on a target proportion of the samples (75%) will provide a robust design to carry into the next phases of engineering. The proportion of the samples where the mill design fails to meet the target throughput (25%) will be offset by the proportion where the design exceeds the target (75%). Setting the proportions so the target is mostly exceeded will account for other factors that impact throughput, such as hydraulic constraints and control allowances.

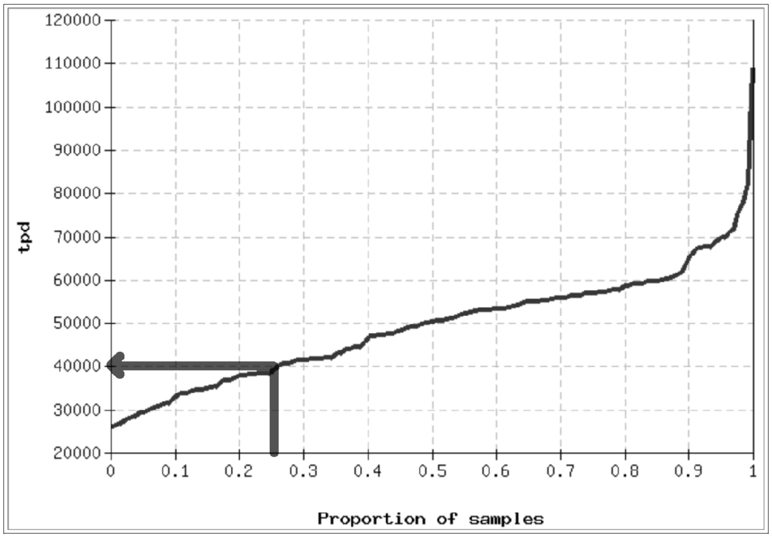

Figure 17: Example Cumulative Tonnes/Day Chart Targeting 40,000 t/d on 75% of Pre-feasibility Samples

Case study: a recent pre-feasibility program completed in Chile on a project with three orebodies consisted of 128 samples, each tested for the three Bond work index values plus SPI/CI as the quality-control check. The results showed a dramatic difference in grinding character between the Bond and SPI protocols (Figure 18) where the Wi_{RM} forms a tight band of results when plotted against Wi_{BM}, but the SPI show significant scatter. Further, the Wi_{RM} result for the project (black) overlaps the overall database of 54 projects (grey) whereas the SPI result for the project appears displaced from the database.

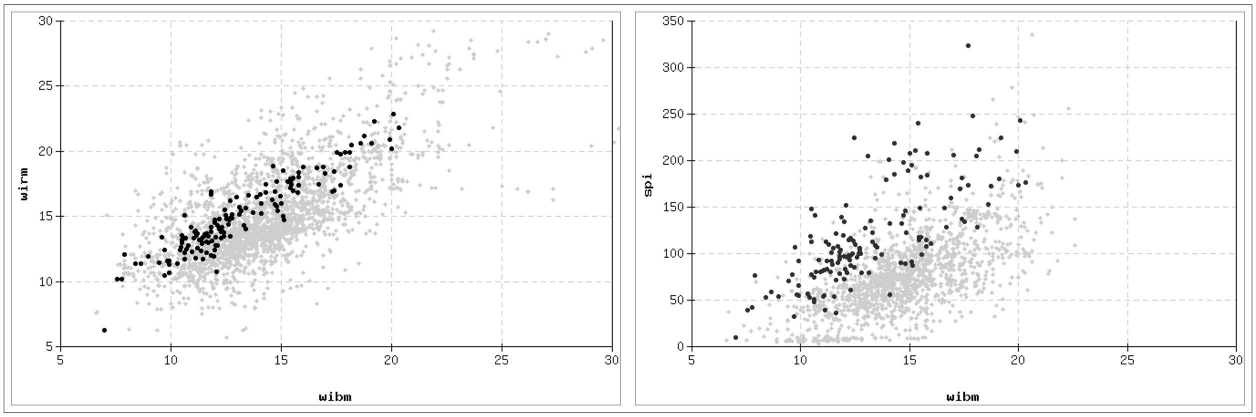

Figure 18: Plots of Rod Mill Work Index and SPI versus Ball Mill Work Index for a Pre-feasibility Study

DJB expects throughput estimates for the project in Figure 18 based on the SPI and Millpower 2000 (Bond-based) to be different by about 25%. Typically, these two methods give results within 10% (which is close to the accuracy of the test measurements), thus the differences on this project are considered significant. More test work is proposed for the feasibility stage of the project in Figure 18 to attempt to understand why these two methods are giving such different results.

Feasibility Studies and Early Mine Years

The desired outcome for a feasibility level grindability program is enough grinding samples that geostatisticians can load grindability into the mine production block model. The exact number of samples needed to achieve this varies depending on the project (one project has over 700), but a rule-of-thumb is 200-400. The geostatisticians will only be able to tell at the end of the program if the quantity of samples in insufficient (the area-of-influence of a sample from the variograms is shorter than expected), so it is better to err on the high side and collect more samples than needed, particularly within the five-year pit shell.

Collecting samples for three models is recommended when doing a detailed design and mine production plan. Some models, such as JK SimMet, are particularly useful at modelling the mass balance of a plant; whereas, the SPI and Bond models are better suited to mine production forecasting (though any of the three models can do some of both tasks). Operating several models requires acquiring multiple data sets, but lends the strengths of each model to the design.

At the feasibility stage, DJB uses:

- the Bond series of results for performing throughput estimates and providing mine planning throughput formulae;
- the SPI and CI series as a quality-control check on the Bond series, and as proxy values where Bond values are unavailable; and
- the JK DWT and/or SMC for JK SimMet modelling for material balance purposes.

Pilot Plant Testing

There are three situations where a pilot plant test is recommended in either the feasibility or detailed design stage of a project:

1. If a project is proposed to use fully-autogenous grinding;
2. If the different bench-scale tests that should be "similar" are giving contradictory results;
3. If the prediction of the quantity of pebbles generated is particularly important to the project.

The number of projects that need a grinding pilot plant test prior to detailed design is relatively small, in the order of 10-20%. Those projects that do need pilot testing are either trying to characterize the competency or pebble-generation character of ore, or are looking to characterize ores that do not behave predictably in the bench-scale tests.

RECOMMENDATIONS

DJB recommends grinding test programs be constructed to:

1. Include a comprehensive mineralogical investigation for determination of liberation sizes of both valuable and gangue minerals, grain structure, and middling characterization ("know your ore").
2. Do tests at three different sizes to establish if an ore is homogeneous or heterogeneous.

3. Do one alternate modelling method at the pre-feasibility stage; do two alternate methods at the feasibility stage.
4. Do enough variability tests at the pre-feasibility stage to develop a cumulative plot of throughput (or hardness).
5. Do enough variability tests at the feasibility stage to populate grinding data into a mining block model.

If a deposit is demonstrated to be homogeneous, then it is reasonable to proceed solely based on modelling by 2-parameter models (though 3-parameter models may still be used). Be very wary of circuit designs and throughput estimates for a heterogeneous orebody based on 2-parameter models; opt instead for 3-parameter models that have a higher likelihood of characterizing the competence of fractures.

If the different models give contradictory results, consider running a grinding pilot plant.

CONCLUSIONS

No single comminution model or testing regime can completely describe all the world's ore types in perfect detail.

Collecting multiple grinding data sets allows a due-diligence to be conducted on a design, enhances decisions related to circuit design and grinding power requirements, and facilitates estimation of the throughput capability of selected grinding equipment.

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