CASE STUDIES ON THE EFFECT OF SAMPLE DIMENSIONS ON COMMINUTION TESTWORK RESULTS

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ABSTRACT

In several recent consulting assignments, DJB Consultants Inc. has found that comminution tests on a particular project have displayed completely different breakage characteristics relative to a database, depending upon which test procedure was performed. Some of these differences are attributed to the dimensions of the sample that is presented to a test, e.g., a Bond crushing test compared to a ball mill test, while other differences can be attributed to a hardness profile that is inherent in a particular size class compared to another coarser or finer size class, e.g., fracture density and mineral filling and/or grain size. Ore types can respond with a characteristic hardness profile by size which may not be identified if only one sampling and testwork regime is used. For thirty years, the Principal of DJB Consultants, Inc. has followed his philosophy of combining observations from geotechnical test results in ore (e.g., RQD, PLI, UCS, R-Value, and fracture characteristics) with comminution test results that have been obtained on different size classes for input to a power-based method for estimating specific power consumptions and sizing equipment for grinding circuits. For the last 15 years, however, it has become necessary to have an understanding of alternative test methods and the impact of interpretation of results from these methods in conducting due diligence reviews for clients. This paper will review the results and conclusions from some projects.

METHOD

Over 15 000 comminution testwork and geotechnical parameters from 36 projects in the DJB Consultants Inc. Millpower 2000 database are compared using two-dimensional plots of one parameter versus another where the two parameters are tested on identical samples (Barratt and Doll, 2008). Lithology, alteration, grain size and rock texture are noted either from the geological logs or from direct observation of drill core or mill feed. Parameters compared are grouped into four broad categories:

- Bond work index tests (used by Millpower 2000)
  - Ball mill (Wi_{BM})
  - Rod mill (Wi_{RM})
  - Low energy impact crushing (Wi_C)
- JK and SMC tests (used by JK SimMet & SMCC)
  - Appearance parameters A×b (SMC test or JK drop weight test)
  - Abrasion t_a (JK abrasion test)
- Minnovex SAG power index tests (used by CEET)
  - SAG power index (SPI)
  - Crushing index (CI)
- Geotechnical parameters (used for rock mechanics)
  - Rock Quality Designation (RQD)
  - R-value (also called UCS field-test, ISRM field test or IRS)
  - Fracture frequency
  - Unconfined Compressive Strength (UCS)
  - Point Load Index (PLI)

The three comminution tests (Bond, JK and SPI) mostly measure the effort required to reduce a sample from a feed size to a product size, exception Wi_c. The geotechnical parameters generally describe the state of a sample before testing, or the effort required to break a sample. Geotechnical tests are not interested in the final size of the broken rock, only the effort required to break the rock.

The comminution tests can be categorized into tests covering the same size ranges. Figure 1 shows the range of sizes from feed to product size, generally corresponding to the particle size range over which a test's results are valid (feed sizes on the right of a bar, product sizes on the left). Power-based modelling techniques such as Millpower 2000 and CEET combine the energy estimates of incremental size reductions (using the parameter appropriate for that size) to create an overall energy estimate for reducing a rock from a feed size to a product size. Certain JK SimMet practitioners use the A & b values for SAG population balance modelling and the Bond ball mill work index for ball mill power-based modelling.

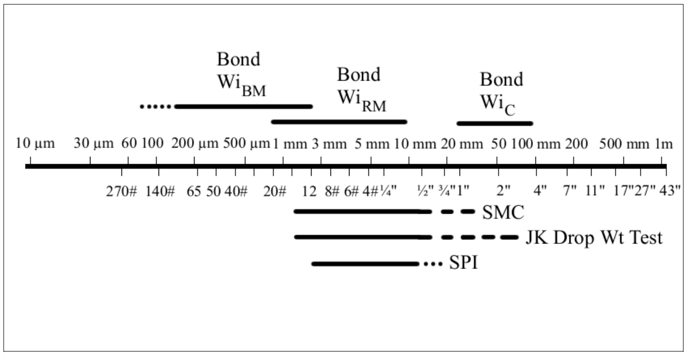

Figure 1: Size Ranges of Comminution Tests

The Bond ball mill work index test can be controlled to a product size range of interest by using a different closing screen opening in the test. This allows the work index result to be calibrated to the energy required to break particles to a desired size in heterogeneous ores.

RESULTS AND DISCUSSION

Parameter comparisons are performed on a two-dimensional plot where the two parameters are plotted against each other both for the project (or ore type) under investigation (the large points) and for the entire Millpower 2000 database of all projects (the small points). The combination of a project's results plotted above the database of results gives a very intuitive picture of how the hardness profile of a project relates versus other projects. Figures 2 and 3 plot the Bond rod mill work index versus the Bond ball mill work index for two different projects. The first project displays a much harder tendency at medium sizes (higher Wi_{RM} than Wi_{BM}) than the database, whereas the second displays consistently hard characteristic at both the medium and fine sizes. This different breakage characteristic leads to different circuit designs where more grinding energy is required in the primary (SAG) mill in the first project, and more energy in the secondary (ball) mill for the second.

Comparison of Test Results For Similar Sample Dimensions

Grinding tests that occur at similar sizes should report similar findings, and should lead to similar grinding circuit designs. Figure 1 indicates that the Bond Wi_{RM}, the SPI and the SMC/JK Drop Weight tests (A×b) all cover a range of sample sizes from 15 mm down to 2 mm. The Millpower 2000 database indicates that the tests do generally corroborate, as seen in Figures 4, 5 and 6. Lower A×b are harder, the inverse of Wi_{RM} and SPI where higher values are harder. Though there is scatter in the data, the expected relationship between Wi_{RM} and SPI is clearly visible in Figure 5. Figures 4 and 6 show that Wi_{RM} and SPI plot the same general shape against A×b.

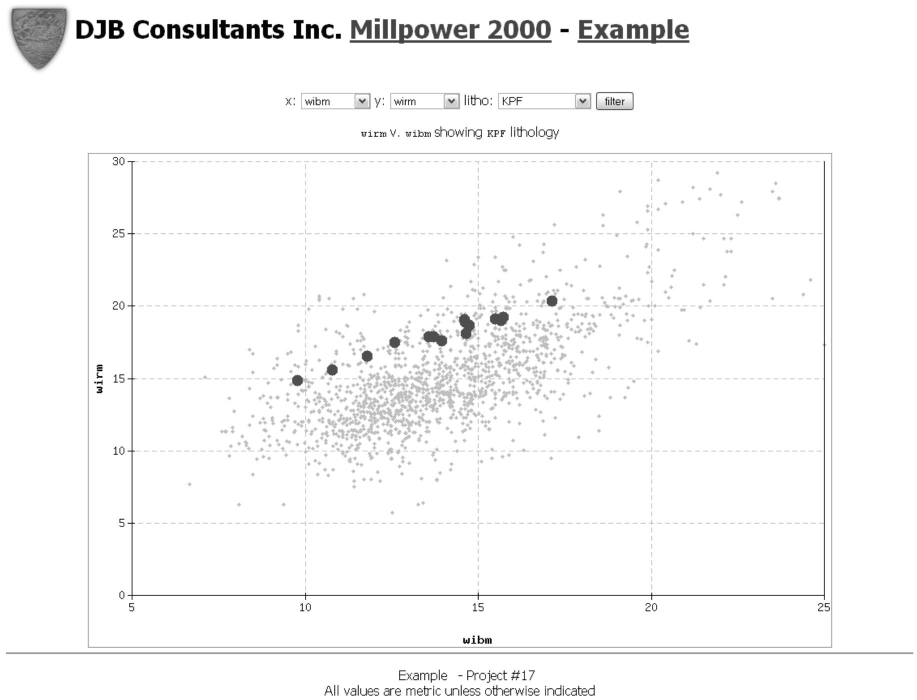

Figure 2: Wi_{RM} v. Wi_{BM} for a Canadian gold ore

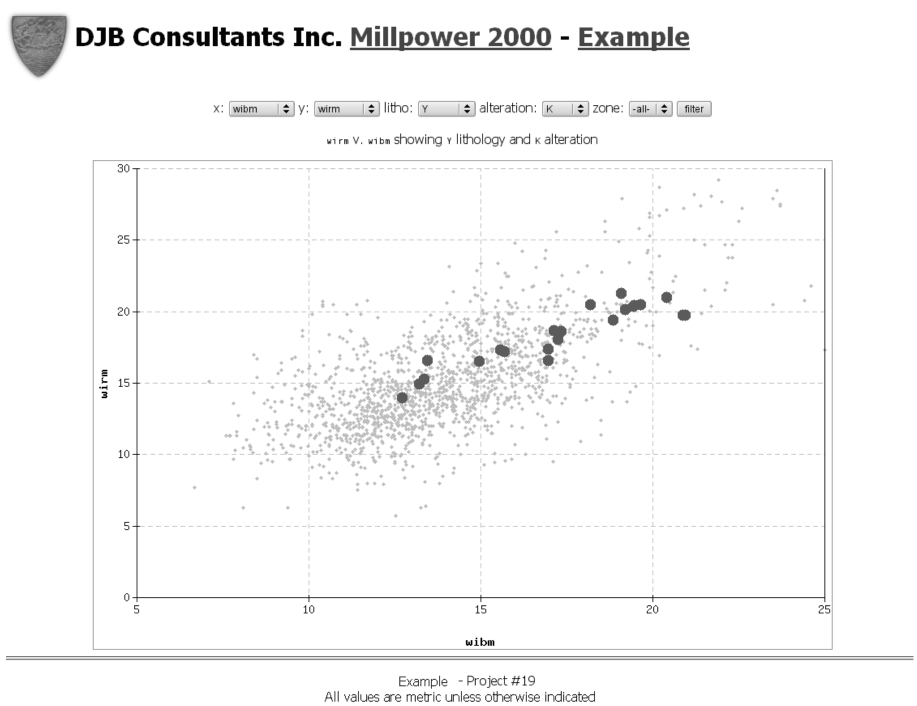

Figure 3: Wi_{RM} v. Wi_{BM} for a Copper Porphyry

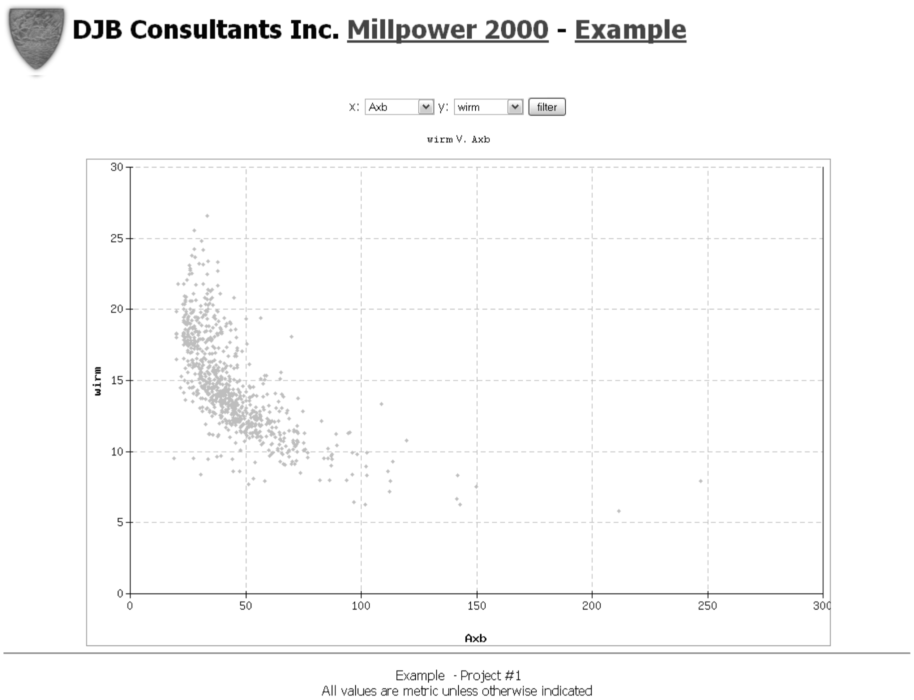

Figure 4: Database of Wi_{RM} v. A×b

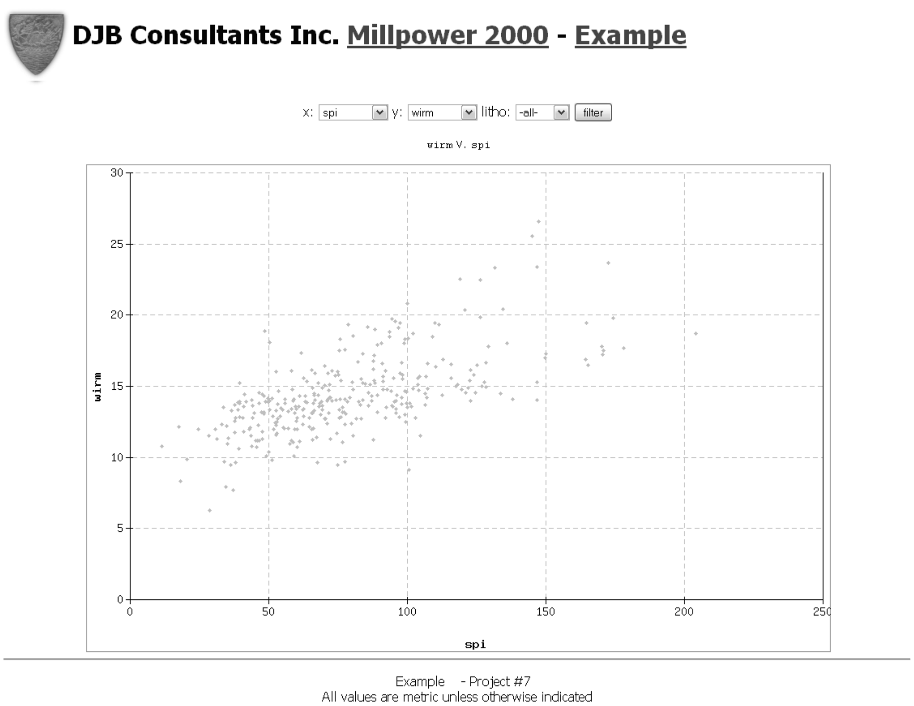

Figure 5: Database of Wi_{RM} v. SPI

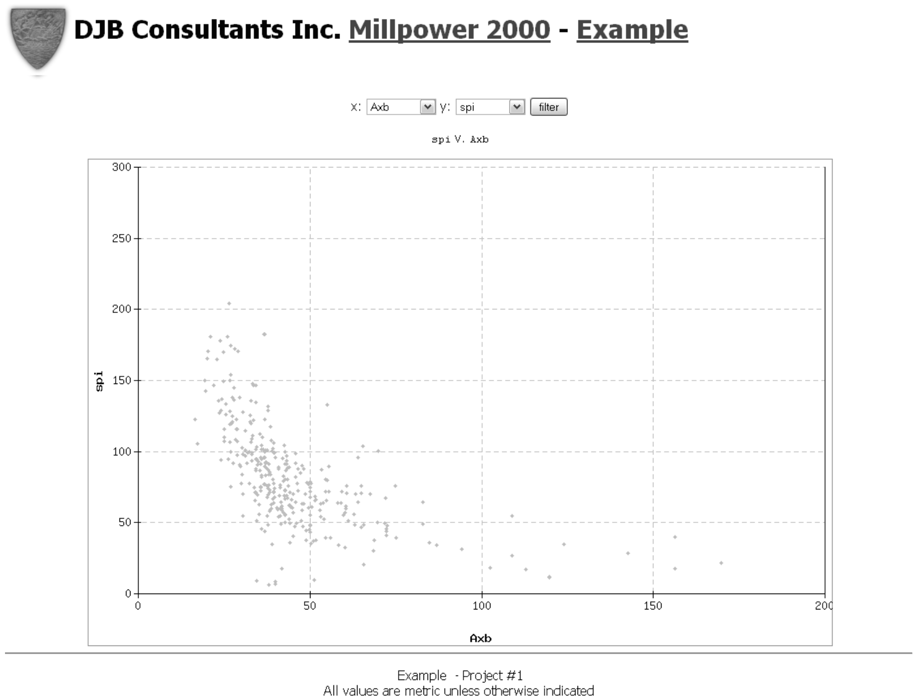

Figure 6: Database of SPI v. A×b

Though parameters in the same size class are usually comparable, there are ores that defy the expected relationships. Figure 7 shows a plot of an ore that responded with similar results to both the Bond Rod Mill Work Index and the SMC test. When Millpower 2000 (using Wi_{RM}) and JK SimMet (using A×b) were run head-to-head on this project, the circuit throughput projections were within 5%. The same head-to-head comparison of the project shown in Figure 8 showed a 20% to 30% difference in throughput estimates, with Millpower 2000 having higher throughput. The difference on this project was ultimately attributed to the fracture spacing where the samples for SMC fit inside the texture of the fractures, therefore appearing harder than the rod mill test result where the entire spectrum of particle sizes, as stage crushed, was fed to the test.

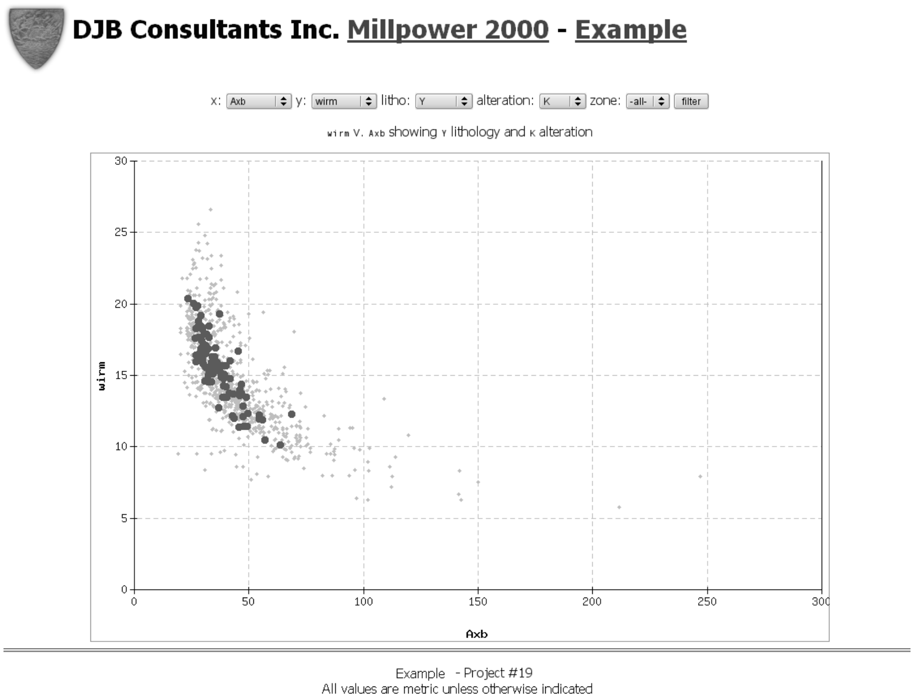

Figure 7: Wi_{RM} v. A×b for Project With Expected Results

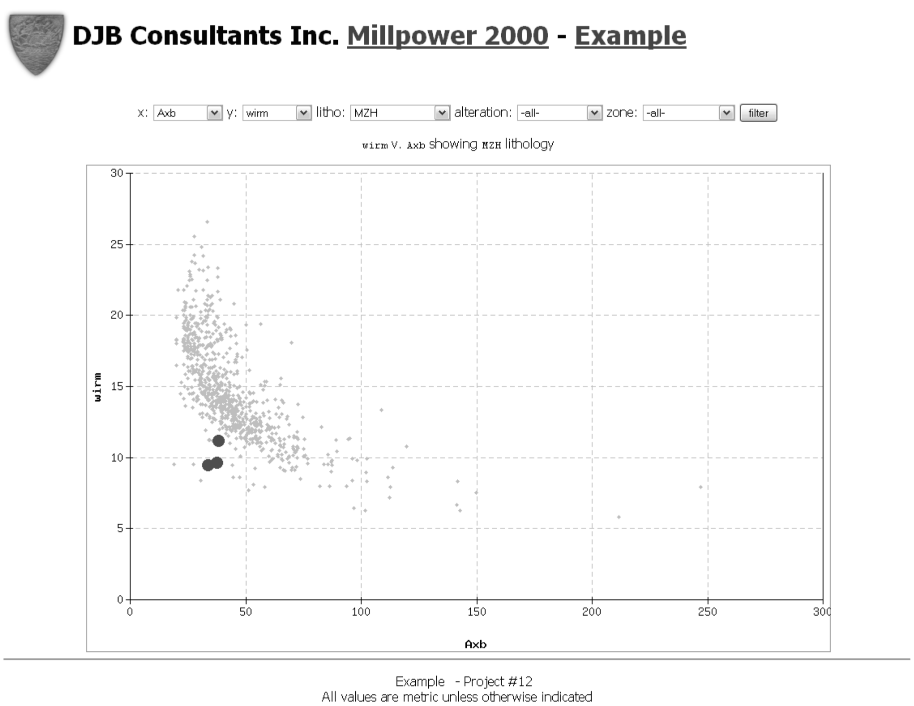

Figure 8: Wi_{RM} v. A×b for Project With Unexpected Results

Comparison of Test Results For Different Sample Dimensions

Another copper porphyry ore type demonstrates a difference in results for tests performed on medium-sized samples versus coarse-sized samples.

The tests using medium-sized samples are:

- SMC tests (returning A×b values) conducted on discrete, hand-picked pieces approximately 12 mm in effective diameter; and
- Bond Rod Mill Work Index (Wi_{RM}) conducted on stage-crushed material to an F_{80} of approximately 10 mm.

The tests using coarse-sized samples are:

- Unconfined Compressive Strength (UCS), a rock-mechanics test performed on flat-ended rock cylinders of not less than 33 mm in diameter by 2.5 to 3.0 times diameter in length; and
- Bond Low Energy Crushing Work Index (Wi_C), a pendulum test performed on discrete, hand-picked pieces of roughly 50 mm diameter by 75 mm long.

Figures 9 and 10 show a considerable range in UCS values (112 MPa to 221 MPa) but a minimal range of A×b values (23.5 to 26.8) and Wi_{RM} (13.7 to 15.0, metric). Figure 11 shows another plot of a medium sized sample (Wi_{RM} shown, but A×b shows same pattern) against a different coarse parameter, the Bond low energy impact crushing work index (Wi_C). The sample feed size to the Wi_C test is similar to the sample size for the UCS test and, similarly, there is no discernible relationship between the Wi_C and the two medium-sized parameters.

Contrast these results with Figure 12 where the Wi_C (12.3 to 24.8, metric) does show a relationship with UCS. The rock shows similar variability in hardness at the coarser sizes (UCS, Wi_C) and both of the coarse tests agree on which samples are hard or soft; whereas it does not at the medium-sizes (A×b, Wi_{RM}).

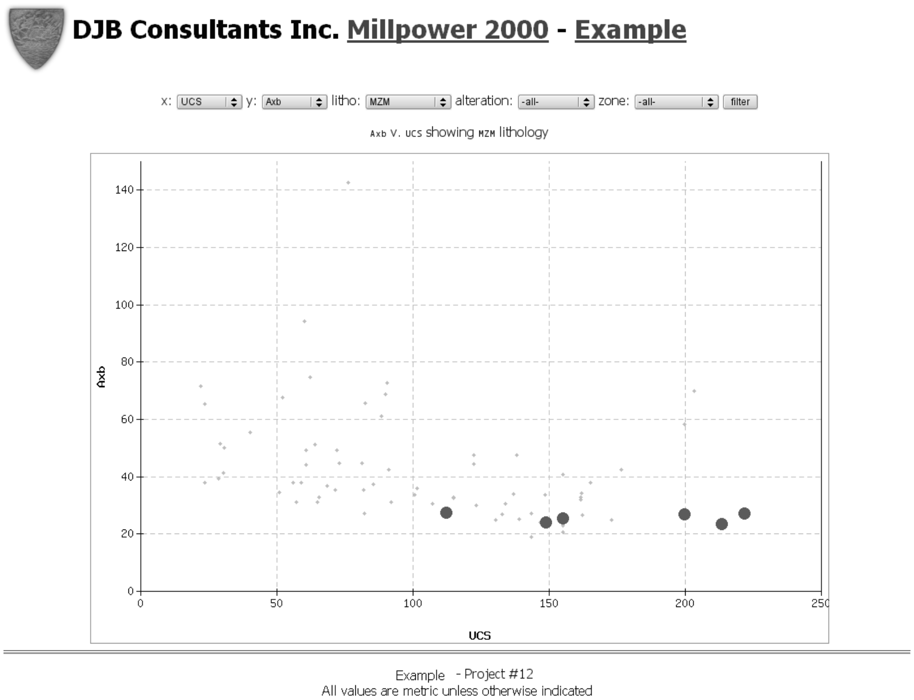

Figure 9: Medium (A×b) v. Coarse (UCS) for a Copper Porpyry Ore

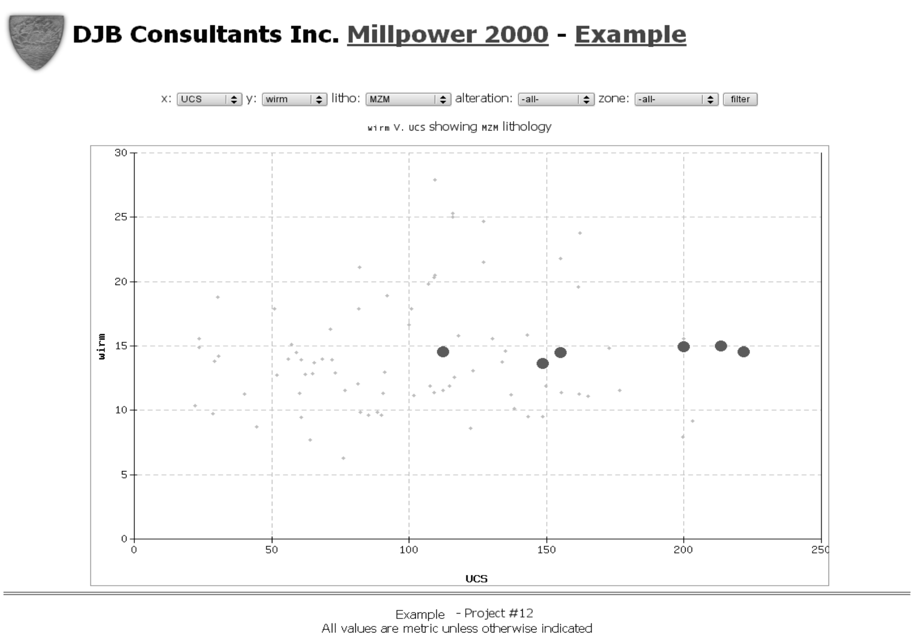

Figure 10: Medium (Wi_{RM}) v. Coarse (UCS) for a Copper Porphyry Ore

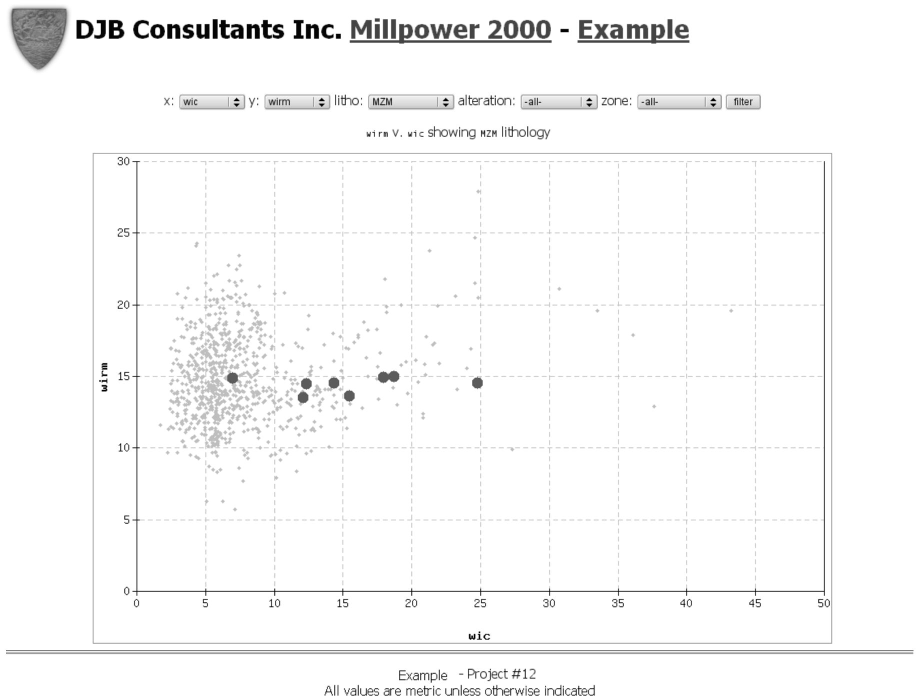

Figure 11: Medium (Wi_{RM}) v. Coarse (Wi_C) for a Copper Porphyry Ore

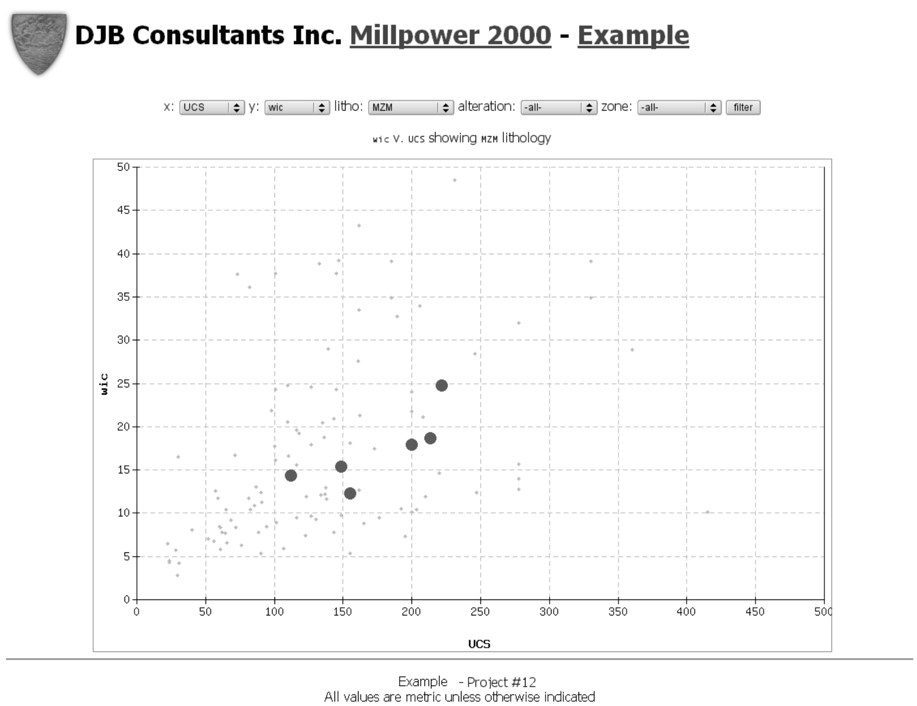

Figure 12: Coarse (Wi_C) v. Coarse (UCS) for a Copper Porphyry Ore

The Importance of Texture and Size

Textures in rocks govern differences in the breakage response by size. At the finest size, a rock's dominant grain size poses a step-change in power draw for breakage. The work index above that grain size is usually lower than that which is required to break the grains. At coarser sizes, discontinuities, natural fractures (and orientation), and the competence of infill mineralization govern the size for which a step change in the ore's work index is manifested.

Figure 13: PQ-sized Drill Core Highlighting Natural Fractures

The drill core depicted in Figure 13 shows a recrystalized volcanic sedimentary rock where the matrix exhibits no evident natural grain size, but does demonstrate natural fractures spaced roughly 20 to 50 mm apart. The grinding characteristic is consistent below 20 mm, as demonstrated in Figures 3 and 7: samples of this ore type that have a high rod mill work index also have a high ball mill work index (and vice-versa). The relationship between Wi_{RM} and A×b also appears consistent.

The grinding characteristic totally changes above 20 mm, as shown in Figures 14 and 15. There is no apparent relationship between the Wi_C and A×b (R^2=0.0), and a weak relationship with Wi_{RM} (R^2=0.3). The interpretation is that texture (the fractures and the competence of their infill mineralization) cause a completely different response to comminution above and below the nominal fracture spacing size. The grinding characteristic of this rock at a feed size above 20 mm cannot be estimated by tests conducted on medium-size ore.

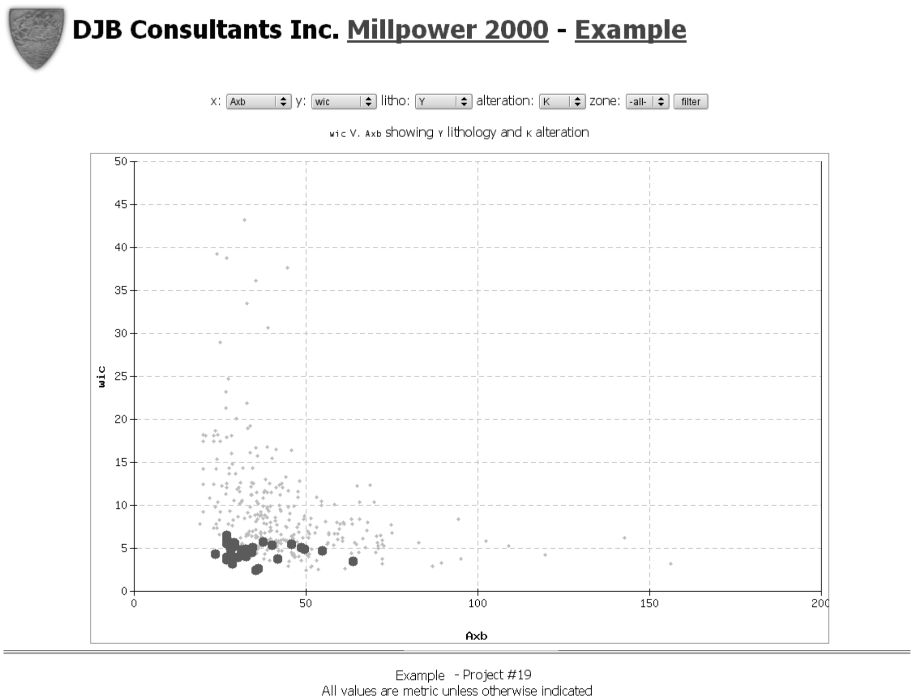

Figure 14: Wi_C v. A×b Showing No Correlation

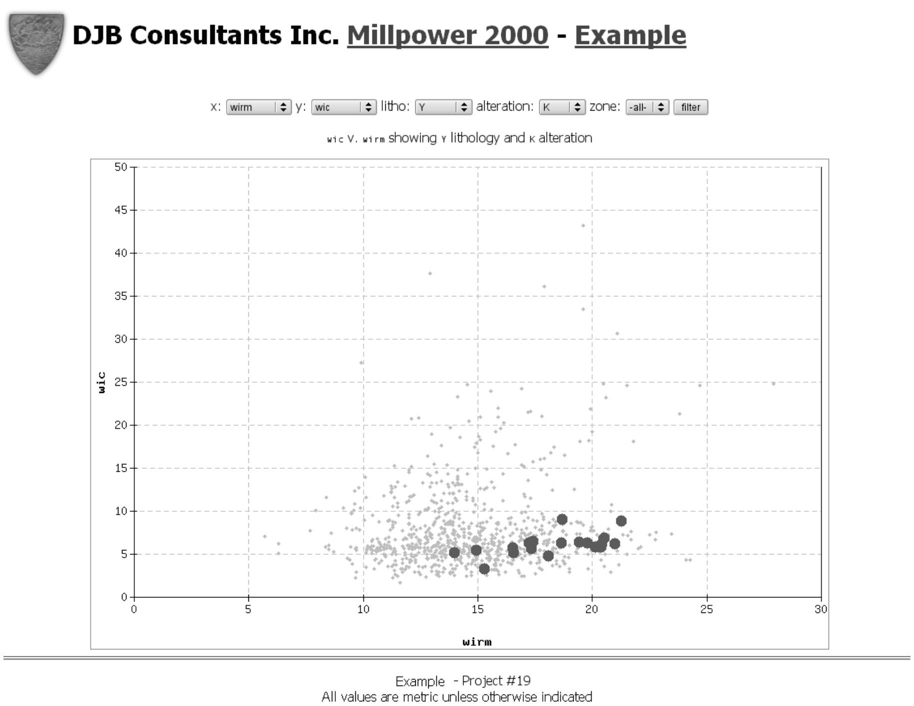

Figure 15: Wi_C v. Wi_{RM} Showing Minimal Correlation

The Effect of Grain Size on Ball Mill Work Index

The Bond ball mill work index is the most commonly used comminution testwork procedure in the Millpower 2000 database, with more than double the number of results of the second most common (the combined drop-weight test methods).

The ball mill work index is defined as "the kW-hr per ton to break from infinite size to 100 µm" (Bond, 1952). In his "Third Theory of Comminution", Bond also derived the -½ exponent on size based on the propagation of a crack through a homogeneous material (Bond, 1952). Further, Bond states: "If breakage characteristics of a material remain constant over all size ranges [...] then the values of the work index calculated under all different conditions should be constant. [...] The variations [in work index] reveal differences in the breakage characteristics at different sizes" (Bond, 1952).

Bond recognized that there is no inherent significance associated with the 100 µm size, and that the work index of a heterogeneous ore measured at a P_{80} of 100 µm may not be appropriate for estimating the grinding energy at, for example, a P_{80} of 225 µm. He states: "When [...] results show an appreciable and consistent difference in the work index at different product sizes, indicating a difference in the breakage characteristics, the work index at the proper size should be used."

The variation in ball mill work index for two ores is given in Figures 16 and 17. Figure 16 is a porphyritic granitoid with a groundmass grain size of approximately 100 µm. Figure 17 is a fine-grained andesite with a groundmass grain size less than 75 µm.

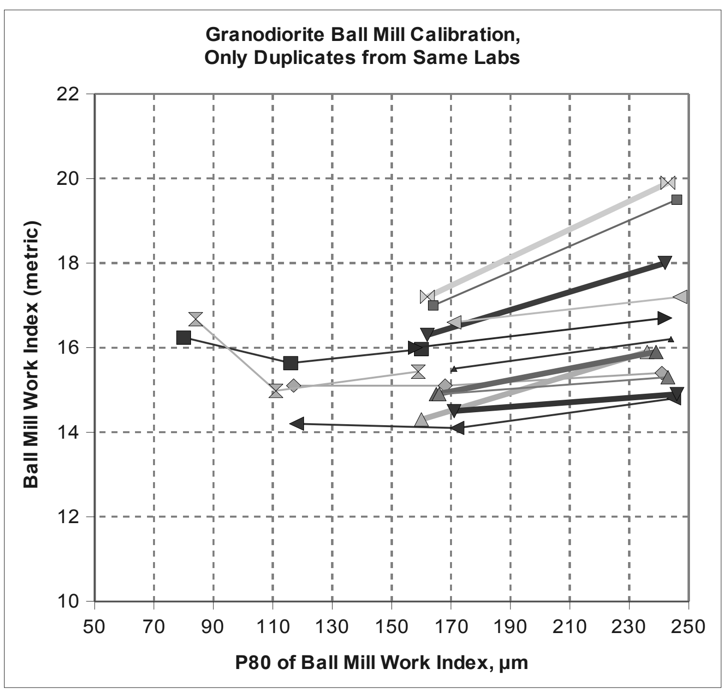

Figure 16: Variation in Ball Mill Work Index by Product Size for a Granodiorite Copper Ore

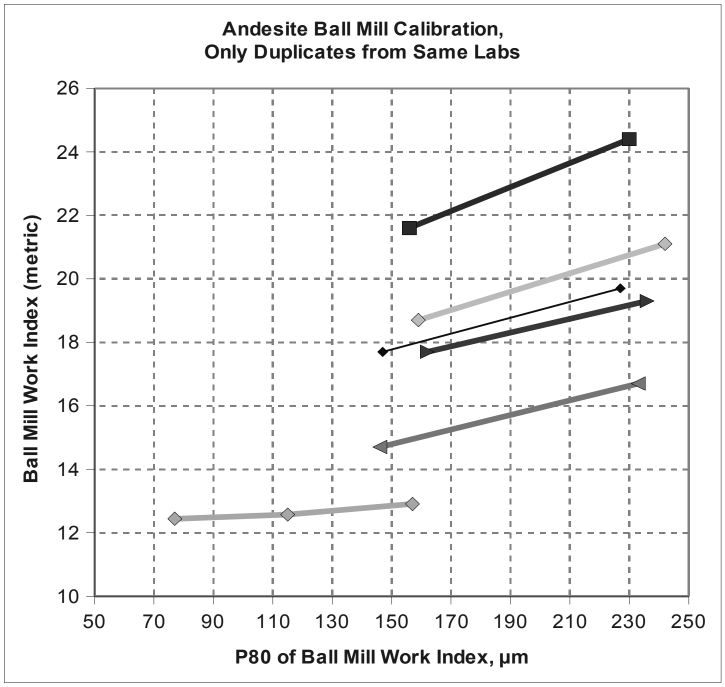

Figure 17: Variation in Ball Mill Work Index by Product Size for an Andesite Copper Ore

The coarsest size tested (a 48# Tyler closing screen) consistently reports higher work index values than the next finest. The work index decreases as size diminishes until the porphyritic samples encounter the groundmass grain size -- then extra energy is required to break the grains causing an increase in the work index measurement. The work index measured at a product size of 80 µm (150# Tyler closing screen) is not suitable for estimating the grinding energy at 120 µm in the porphyritic material due to the grain size.

The andesite sample is more homogeneous than the porphyritic sample at the finer sizes. As a result, the work index is relatively unchanged between 75 and 150 µm and it fits well with Bond's Third Theory. But the increase in work index observed in the coarsest samples on both ores does not fit the Third Theory (the work index is not reasonably constant with size). The following possibilities are offered to explain this observation:

- The samples are not homogeneous between the 100 µm and 250 µm size ranges. There is a hidden texture in the rock that is causing coarser sizes to report harder values.
- The mechanism of breakage is not entirely crack propagation, and the -½ exponent on size in the grindability formulae is not correct for these size ranges.

CONCLUSIONS

- Heterogeneous ores with discernible texture and grain size require different test methods to predict breakage energy requirements across a range of sizes;

- Grinding work indices should not be extrapolated over boundaries of texture or grain size;

- Grinding sample selection & testwork programs should be constructed to determine comminution parameters above and below the sizes of the principal textures;
- Ball mill work index tests should be operated with closing screen sizes chosen to give a P_{80} size that approximates the full-scale operation.

NOMENCLATURE

F_{80}	80% passing size of the feed to a test, μm
P_{80}	80% passing size of the product from a test, μm
Wi_{BM}	Bond ball mill work index (unitless, but based on metric tonnes)
Wi_{RM}	Bond rod mill work index (unitless, but based on metric tonnes)
Wi_{C}	Low energy impact crushing work index (unitless, but based on metric tonnes)
SMC	SAG Mill Comminution drop weight test (provides parameters used by JK SimMet & SMCC)
A×b	Appearance parameters for JK SimMet model
SPI	Minnovex SAG Power Index used by the CEET model
UCS	Unconfined Compressive Strength, a geotechnical parameter used for rock mechanics
PLI	Point Load Index, a geotechnical parameter used as a proxy for UCS

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