AN OVERVIEW OF THE SMALL-SCALE TESTS AVAILABLE TO CHARACTERIZE ORE GRINDABILITY FOR DESIGN PURPOSES

ANDRE MCKEN - GROUP LEADER COMMINUTION, STEVE WILLIAMS - VP METALLURGY AND BUSINESS DEVELOPMENT

ABSTRACT

The hardness of ore samples is measured through grindability testing. Several grindability tests, at various scales, have been developed over the years for different applications, from conventional circuit to autogenous grinding, and they all have strengths and weaknesses. The traditional approach to AG or SAG mill design, based on the testing of a large bulk sample in a pilot mill has been gradually supplanted by increasingly smaller tests. As a result, the sample requirement for a single AG/SAG test has gone down from 10,000 kg for a pilot plant to a few kilos in the case of geometallurgical mapping. This reduction in ‘sampling effort’ was necessary, but it occurred at the expense of gross simplifications in the test procedures and reduction in test deliverables. This paper summarises the current status of grindability testing and is intended as a tool for mill operators or managers of new projects, who wish to maximise their understanding of a deposit. A methodology for the small-scale testing of high-pressure grinding rolls is also presented as an acknowledgement of the emergence of this new technology.

INTRODUCTION

The resistance of ore samples to breakage (or hardness) is measured through grindability testing. Several grindability tests have been developed over the years for different applications and each test has its own strengths and weaknesses. Grindability testing is a compromise between test cost and its deliverable(s). Because a large fraction of the cost component is driven by the sampling requirement, the tests that can be performed on small drill cores offer a significant cost advantage over those that require large diameter drill cores and substantial weight. On the other hand, the test deliverables are generally superior for tests requiring more weight.

The highest degree of deliverables and certainty is achieved in a pilot plant, which is undoubtedly the most reliable test procedure to determine the resistance of ore samples to AG/SAG grinding, or ‘SAG hardness’. The pilot plant can test coarse feeds (6”), as well as essentially any test conditions, so it presents the lowest degree of scale-up within all the methodologies available. On the negative side, pilot testing is the most expensive test, as it requires the greatest sampling effort, in the form of bulk samples or large diameter cores (>6”). Therefore, it is not cost-effective to test a large number of samples at pilot-scale, so small-scale tests were developed for this purpose.

The compromise between testwork effort and deliverables has been reviewed by Mosher and Bigg. [1], [2]. In their papers, the various AG/SAG mill testing procedures were classified in a table based on various features such as their type, top size, sample requirement and peak energy achieved. This concept is re-utilized in Table 1.

It is obvious that the ability of testing coarse rocks is an advantage in AG/SAG mill testing, because they are generally responsible for impeding AG/SAG throughput and supply grinding media for low steel charge applications. The hardness of the coarse rocks cannot be inferred from fine rocks, because the gradient of hardness by size often differs from one sample to another. Unfortunately, tests that are performed at a coarse size will unquestionably result in larger samples, and thus a greater sampling effort.

Table 1 shows that the sample requirement of the tests generally increases with top size, with the media competency (6” rocks) being at the top of the scale. The work index series (ball mill, rod mill, and MacPherson autogenous) and pilot plant tests require relatively more samples (for a given top size) because they are run until a steady-state is achieved, which involves the mill charge to be replaced several times. The Bond tests are typically run for a minimum of seven cycles, while the MacPherson and pilot plant test are operated for ~6-10 hours. The achievement of a steady-state is desirable in a grinding test, because harder components may build up over time. For AG/SAG mills, this may result in a critical size build-up and associated throughput losses. The importance of steady-state testing increases with the ore heterogeneity.

Table 1: Summary of Grindability Testing

SMALL-SCALE TEST	TOP SIZE (mm)	CLOSING SIZE (mm)	SAMPLE REQUIREMENT[1] (kg)	TYPE	STEADY-STATE (y/n)	MILL DIAMETER (m)
Bond Ball Mill	3.3	0.149	5	Locked Cycle	Y	0.305
SAG Power Index (SPI)	19	N/A	5	Batch	N	0.305
SMC Test	22	N/A	5	Single Particle	N	N/A
Bond Rod Mill	13	1.2	10	Locked Cycle	Y	0.305
Bond Impact	75	N/A	10	Single Particle	N	N/A
Drop Weight	64	N/A	75	Single Particle	N	N/A
MacPherson Autogenous	32	1.2	100	Continuous	Y	0.45
Media Competency	165	N/A	300	Batch	N	1.83
LABWAL HPGR	12.5	N/A	25	Continuous	Y	0.25[3]

[1] Indicates the approximate minimum weight of sample required to run a typical test.
[2] Per unit mass, based on particles in the largest size fraction
[3] Roll diameter of the HPGR LABWAL

The following is a review of the principal grindability tests that are currently available to the Market for ore characterization and circuit design. It is presented as general information, and the reader is encouraged to perfect his knowledge by reading references that are more specific to each individual test.

GRINDABILITY TESTS

BOND BALL MILL GRINDABILITY

The Bond ball mill grindability test is performed according to the original Bond procedure [3]. It requires 10 kg of minus 6-mesh material that is preferably prepared at the testing facility, by stage-crushing the sample to 100% passing 6-mesh. The test is closed with a fine screen (typically 65 mesh to 270 mesh), and the size of the screen is normally selected to achieve a required final product P_{80}. The test is performed as a locked-cycle with a circulating load of 250%, until it reaches a steady-state. The number of new grams per revolution (Gpr) created during each cycle is measured, and the Bond work index (BWi) is calculated as follows:

$$BW_i = \frac{44.5}{P_1^{0.23} \times Gpr^{0.82} x \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \qquad (1)$$

Where P_1 is the aperture of the closing screen in microns, and F_{80} and P_{80} are the 80% passing sizes of the test feed and product.

The world widely relies on the ball mill work index for the design and analysis of ball mill circuits, even those that treat AG/SAG mill or HPGR circuit products, which have a non-standard particle size distribution. One of the keys of the Bond work index success over time has been its reliability and reproducibility. Provided the original Bond procedure is followed, the Bond work index is relatively consistent anywhere in the world, and should be very repeatable [4]. Figure 1 shows a histogram of Bond ball mill work index frequency from A.R. MacPherson Consultants (ARMC). This database covers a fraction of all the tests performed by ARMC over the years and around the world. It shows that the ball mill work index is normally distributed with an average of 14.6 and a median of 14.8 kWh/t.

BOND ROD MILL GRINDABILITY

The Bond Rod Mill Grindability Test is performed similarly to the ball mill test. The feed sample is stage-crushed to ½" and the test is run under a 100% circulating load. As in the ball mill test, the test can also be closed with various sieve sizes, but for AG/SAG mill analyses the standard 14-mesh (1.18 mm) sieve is typically used.

The rod mill work index is computed with an equation very similar to that of the ball mill test, as follows:

$$RW_i = \frac{62}{P_1^{0.23} \times Gpr^{0.625} x \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \qquad (2)$$

The rod mill work index is also normally distributed. The database average and median are both 14.8 kWh/t, which is essentially the same as the ball mill average, showing that 'on average' the two indices are identical. However, it is common to observe a difference between the rod mill and ball mill values for a given ore type. These differences may be caused by a variation in ore hardness by size (13 mm for RWI and 3.35 mm for BWI), and/or grain size properties.

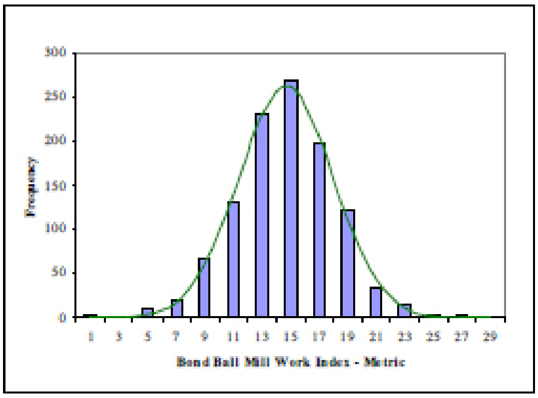

Figure 1: Frequency of Bond Ball Mill Work Index (ARMC)

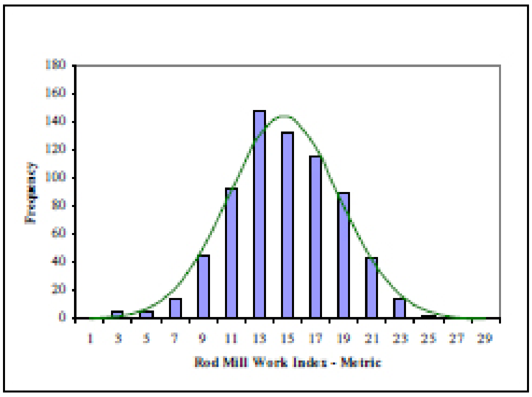

Figure 2: Frequency of Bond Rod Mill Work Index (ARMC)

The Bond rod mill work index is used to calculate the power requirement to grind from ~½" to about 14 mesh. The test has been mainly used for the design of rod mills or primary ball mills, but it can also be used along with the other Bond tests (BWI and CWI) for SAG mill design using semi-empirical relationship [5].

BOND LOW-ENERGY IMPACT TEST

The Bond low-energy impact test apparatus consists of two pendulum hammers mounted on two bicycle wheels, so as to strike equal blows simultaneously on opposite sides of each rock specimen. The height of the pendulum is raised until the energy is sufficient to break the specimen [6]. The crusher work index (CWI) or impact work index is calculated as follows:

$$CWI = \frac{53.49 \times (J / mm)}{S.G.} \qquad (3)$$

Where J is the energy at which the specimens broke, mm is the thickeness of the rock specimen, and S.G. is the specific gravity of the ore. The J/mm are transformed in kWh/t as follows:

$$\text{kWh/t} = \frac{45.5 \text{ X Joules/mm}}{\text{Specific Gravity}} \qquad (4)$$

The test is generally performed on 20 rocks, which is low. One of the strengths of the test is its ability to measure the natural dispersion in the sample. Another advantage of the test is the coarse size at which the rocks are tested (2" to 3"), which makes it unique in the Bond series.

SAG POWER INDEX (SPI) TEST

The SAG power index (SPI), was developed by John Starkey [7] and is offered by MinnovEX Technologies Inc. The SPI, expressed in minutes, is defined as the time (T) necessary to reduce an ore sample from a K_{80} of ½" to a K_{80} of 1.7 mm.

The batch test is carried out in a laboratory mill of 12" diameter x 4" length, loaded with 15% steel balls of 1" diameter. It requires 2 kg of ore with a top size of ¾" (19-mm). The sample is prepared by MinnovEX to have F_{80} of 13 mm, and the test is run at increasing times until the time requirement to reach a P_{80} of 1.7 mm can be interpolated.

Higher grinding time indicates higher resistance to grinding, thus a harder ore. A particle size distribution is performed on the products, and a P_{64} is used as an indication of the product size that the AG/SAG mill can deliver. The SPI is transformed into kWh/t and is used by MinnovEX for production forecast and circuit design using the CEET software [8]. The SPI has the advantage of requiring a low weight (5-kg), and is therefore well suited for geometallurgical mapping of ore deposits. The SPI test has been widely used in recent years so that the deposits that are submitted to the study can be compared to a database, in terms of hardness and variability, such as that presented in Figure 3.

JKTECH DROP-WEIGHT TEST

The JKTech drop-weight test, as shown by Napier-Munn et al [9], developed in the Julius Kruttschnitt Mineral Research Center, is divided into three components. First, the test measures the resistance to impact breakage of coarse particles in the range 63 to 13.2 mm (five fractions). Then, it evaluates the resistance to abrasion breakage of particles in the range 53 by 37.5 mm. Finally, the rock density of 20 particles is measured to assess the average ore density, as well as its dispersion.

The test generates the appearance function (e.g. breakage pattern) of the ore under a range of impact and abrasion breakage conditions, which is subsequently reduced to three parameters: A, b (impact) and t_a (abrasion). The appearance function can be used in the JKSimMet modeling and simulation package to predict the ore response comminution processes, including AG/SAG, crusher, ball mill and HPGR. The test procedure requires 75 kg of material, which is prepared by the testing facility, to generate 30-90 particles in five size fractions, in the range 13.2 to 63 mm.

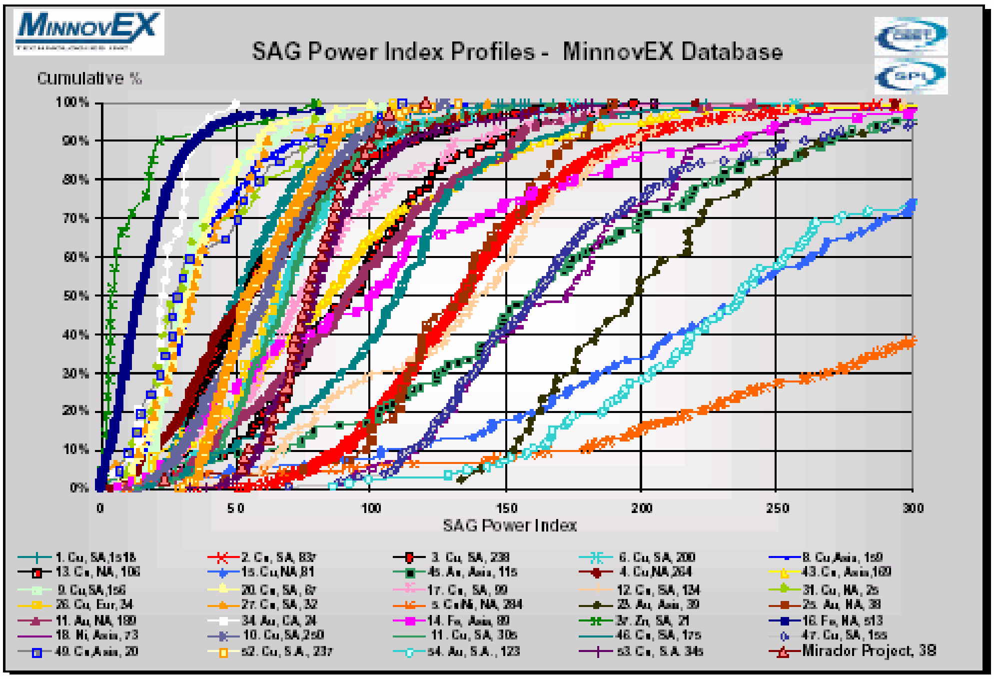

Figure 3: SPI Profile Database (MinnovEX)

In the impact test, the five size fractions are submitted to three series of impact testing at different energy levels, for a total of 15 test series. Each series of tests is composed of 10-30 rock specimens. All the particles of each series are submitted to an impact of a known energy level, given by the height and weight of the drop weight head. The fragments from all the test series are collected and submitted to particle size analyses, which are reduced to a family of normalized 't' values, representing size reduction. The t values are defined as the percent weight of fragments that passes 1/t of its original size.

$$t_{10} = A\left(1 - e^{-bE_{cs}}\right) \qquad (5)$$

For the AG/SAG mill model, the t_{10} values are reduced to two parameters, the A and the b, using the equation below. A and b are the parameters of the model and E_{CS} is the specific energy of comminution in kWh/t. An example is presented in Figure 4.

For the abrasion test, a 3-kg sample of 53 x 37.5-mm rocks is used. The sample is rotated in a 30 cm x 30 cm tumbling mill for 10 minutes after which the product is submitted to a size analysis. By convention, the abrasion parameter is equal to 1/10 of the t_{10} achieved in the abrasion test.

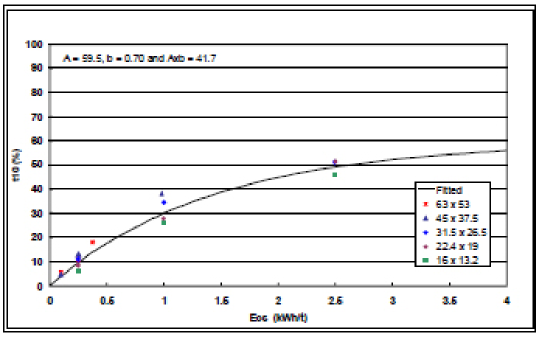

Figure 4: Drop-weight Test Interpretation

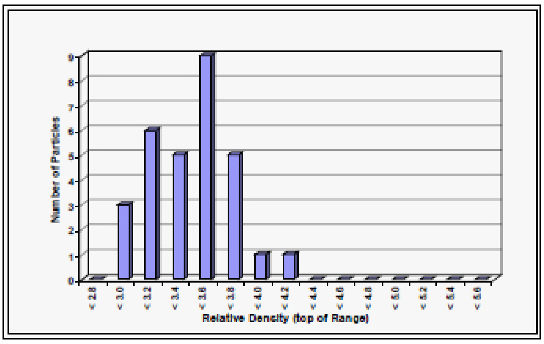

Figure 5: Relative Density of Particles in the Drop-weight Test Procedure

Also, part of the drop-weight test procedure is the density determination of 20 rock samples, using water displacement techniques. An example is presented in Figure 5, for an ore showing a relatively wide range of densities. The density distribution of the ore is important in AG/SAG milling because it affects the bulk density of the charge and associated power draw. This is more significant for AG/SAG mill designed for a low steel charge, or for pebble mills.

A great number of drop-weight tests have been performed over the years, which allows for comparison between ore types in a database. The frequency distribution of 'A x b' from JKTech is presented in Figure 6.

One other interesting feature of the drop-weight test procedure is that it provides a measurement of the variation in rock hardness by size, from 13.2 mm to 63 mm. An example is presented in Figure 7 for three different energy levels, i.e. 0.25, 1.0 and 2.5 kWh/t. Typically, the t_{10} values will increase with rock size, which means that the hardness of the ore actually decreases. For very competent ore, the curve will be nearly horizontal, while non-competent fractured ore will show a high gradient of t10 with increasing size.

These curves can be used to infer the competency of the ore at coarser size for those tests which are carried out on finer material, as the low end of the size spectrum.

SAG MILL COMMINUTION (SMC) TEST

The SAG mill comminution (SMC) test was developed by Steve Morrell [10]. It is an abbreviated drop-weight test, which can be performed at low cost on small rocks (+19/-22 mm) or drill cores. Bulk samples, or essentially any size of small core is adequate for the test, and 5 kg is normally sufficient. Cores are normally cut into ¼ cylinders using a diamond saw and the test is subsequently performed similarly to the standard drop-weight test procedure, except that a single size fraction is tested.

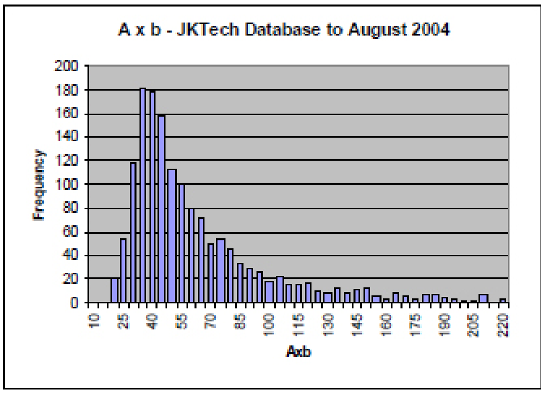

Figure 6: A x b Frequency Distribution (JKTech)

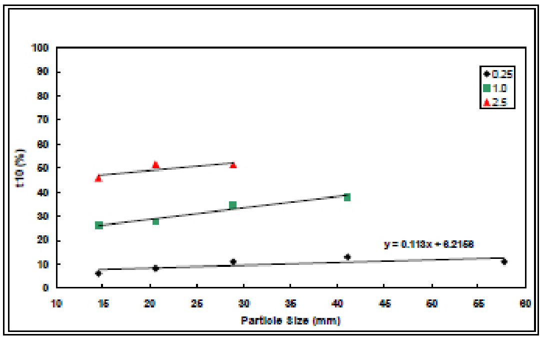

Figure 7: Variation of Hardness by Size from a Drop-weight Test

The test generates the drop-weight index (DWI) expressed in kWh/t, as well as the A and the b parameters, but it does not generate the t_a and crusher parameters, which must be obtained through a full drop-weight test. Normally, the main ore zone(s) in the deposit is tested using the full procedure and the SMC tests are used to measure the variability within the main ore zone(s). If the gradient of hardness has been measured through the full procedure, the results from the SMC test can be calibrated to better reflect the hardness of the ore on the size range of interest.

The A and b values can be used directly in JKSimMet for plant design, expansion and operational forecasting. For existing plants, this would be better achieved along with the calibration of a JKSimMet model from a plant survey. The drop-weight index can also be used outside of JKSimMet, using power-based relationships, as those proposed by Morrell [12].

The advantage of the SMC test is that it generates the energy versus breakage relationship with a small quantity of sample of a single size fraction. Because the test can be performed on small rocks, it is well suited for geometallurgical mapping.

MACPHERSON AUTOGENOUS GRINDABILITY TEST

The MacPherson autogenous grindability test, as shown by Arthur MacPherson et al [11], is a continuous test performed in an 18” (46-cm) semi-autogenous mill, with an 8% ball charge. A draft fan supplies the airflow required to remove the ground material from the mill, and a collection system recovers the ground material from the air stream. This includes a vertical classifier, a cyclone and a dust collector (baghouse). The cyclone underflow is classified on a 14-mesh screen with the oversize returning to the mill. The mill is fed from a feed hopper by a Syntron feeder actuated automatically by a Milltronics control system. This control system continuously regulates the feed rate by maintaining a pre-set sound level with a microphone located below the mill shell, controlling the mill level to 25% charge by volume. The circulating load is controlled to 5% by adjusting the airflow through the mill.

The test requires material with a top size greater than 1-1/4”, and sufficient weight to operate until all the steady-state conditions are met, and for a minimum of six hours. This can normally be achieved with less than 100 kg, but typically, a 175-kg sample is requested to allow for soft and/or dense ores.

The test is run continuously, similar to a small pilot plant, for a minimum of six hours and until steady state is achieved. Every 15 minutes the test outputs, including the screen undersize, screen oversize, and cyclone underflow are collected and weighed separately. The screen oversize is returned to the feed tray as a circulating load, and the products weights and control settings are recorded. The sampling is performed over a one-hour period, every 15-minutes. The throughput rate and circulating load are maintained constant over the sampling period.

At test completion, all the products are submitted for particle size analysis, and the mill charge is dumped and observed. The charge is submitted to a particle size analysis, and size-by-size S.G. determinations. This allows the evaluation of any coarse material build-up, of if any heavier component is present in the mill.

The mill power draw, throughput and product size distribution are used to compute a specific energy input and the MacPherson autogenous work index (AWI).

Because the test is run continuously, an actual steady-state throughput rate (kg/h) and a specific energy input (kWh/t) are both measured, which is unique to this test and much desirable for a AG/SAG mill test, where the ability of controlling the product size is very limited. For a given power draw (kW), the specific energy input in kWh/t input is purely driven by the AG/SAG mill throughput, which in turn is driven by the dynamic of the ore. The traditional approach to measure the specific energy requirement has been to run a pilot plant, in which the mill feed rate is controlled to maintain a constant mill charge set-point. The MacPherson mill is operated exactly the same way, so it offers a cost-effective alternative to obtain a kWh/t measurements on numerous samples. Over the years, about 750 tests were performed on about 275 deposits, so there is a large database available for comparison. In Figure 8 and Figure 9 are presented the frequency of throughput rates and specific energy inputs to the MacPherson mill. Ninety percent of the values in the database are between 3 and 17 kWh/t.

Although the importance to achieve a steady-state in a grinding test is widely accepted (Bond tests), the MacPherson test remains the only small-scale AG/SAG mill test that offers this option. Steady-state is especially important in AG/SAG mills where a harder component can build up over time and affect the production negatively.

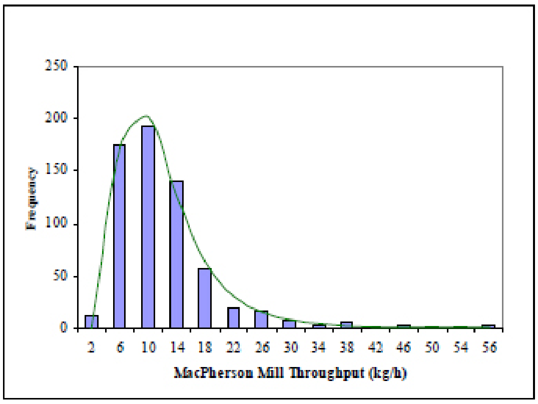

Figure 8: Frequency of MacPherson Mill Throughput (ARMC)

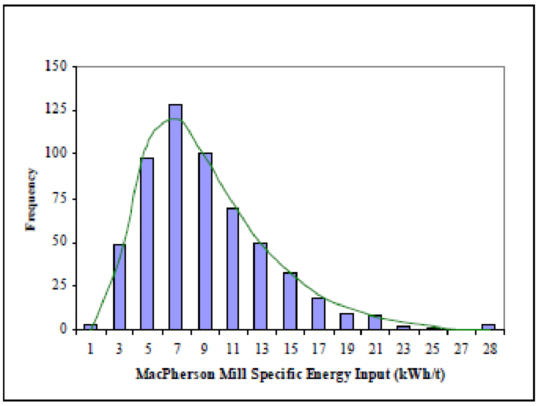

Figure 9: Frequency of MacPherson Mill Specific Energy Input (ARMC)

MEDIA COMPETENCY TEST

There has been some variations of media competency tests developed over the years with the assessment of media survival in autogenous milling being the main objective. The advanced media competency test developed by Orway Mineral Consultants and Amdel [12], [13] features a ‘tumble test’ in a 6’ x 1’ mill using ten large rocks in five size fractions in the range 104 to 165 mm. The mill is rotated for 500 revolutions and the charge is dumped and size analyzed. The surviving rocks are submitted to the fracture energy test procedure, which consists in a series of Bond low-energy impact tests in five size fractions. The fracture energy test provides the relationship between the first fracture energy requirement and rock size. The relationship is used for data interpretation, along with the other Bond indices (Rod and ball), and a database support.

With a top particle size of 165 mm, the media competency test is the most suitable to address media competency issues.

HIGH PRESSURE GRINDING ROLL (HPGR)

High-pressure grinding rolls have been used for many years and are emerging as an energy-efficient alternative to conventional and AG/SAG comminution circuits. As for autogenous mills, the traditional methodology for the testing and scale-up of HPGR’s has consisted of processing a large sample in a pilot mill (by the supplier).

This has the disadvantage of requiring a large quantity of material. Bench-scale units, requiring a minimum of about 25 kg per test, are available and may eventually be used as an alternative to pilot, providing suitable scale-up methodologies are developed. Other testing procedures, based on unrelated tests may also emerge in the near future, which would make HPGR testing more accessible and eventually lead this technology to a wider level of consideration for the design of new circuits.

One of the interesting features of HPGR's is its capability to produce a particle size distribution with a greater than typical amount of fines, which reduces the power requirement for the downstream ball mill. This makes the use of standard ball mill analyses based on the K_{80}'s inadequate, unless appropriate corrections are made [14]. (This problem is shared by AG/SAG mill circuits.) The most appropriate way to get around this problem is to run the entire circuit at pilot-scale and analyze the data based on the overall power applied in kWh/t. This requires a fair quantity of material, and the difficulties inherent to performing such a pilot plant make it difficult to come up with accurate conclusions.

The use of a small locked-cycle scale test, such as the Bond ball mill grindability is proposed as a cheap alternative to achieve the same objective in a better-controlled manner, and more importantly, with a smaller sample. ARMC has developed a simple methodology that is based on the 0.25 m LABWAL HPGR from Polysius, which has a top size of 12.5 mm. Several HPGR tests are performed to assess the effect of operating pressure and moisture content on the HPGR's performance and the power input to the unit is recorded. An example of the test output is presented in Figure 10.

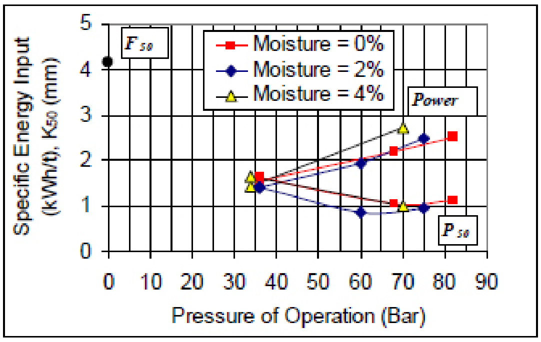

Figure 10: LABWAL HPGR Testing

The HPGR product corresponding to the best condition is submitted to the standard Bond ball mill grindability test. The Bond ball mill grindability test was designed to measure hardness as an index, regardless of the feed size, so it does not give credit for the additional fines. Therefore, the index itself is more or less ignored and the results are analyzed in terms of throughput rate or specific energy requirement. Assuming one Bond ball mill revolution draws constant power, the kWh/t are inversely proportional to the 'gross' gram per revolution in the Bond test, as shown below. The gross gram per revolution is based on the entire feed going to the Bond ball mill, as opposed to the 'net' gram per revolution, which only considers the fraction that is coarser than the mesh size, thus ignoring the benefit of the additional fines.

$$\frac{kWh}{t} \propto [Gpr_{Gross}]^{-1} \qquad (6)$$

This power can be added to that of the LABWAL to come up with a total requirement from 12.5 mm to final product size. The total power for the HPGR system can be compared to that required using a conventional circuit based on the rod and ball mill work indices and the Third Theory of comminution. The power comparison can also be done against autogenous milling. This methodology has only been used to scope the potential energy savings of HPGR's at small-scale, as it cannot, at the moment, be scaled up to industrial units.

CONCLUSION

For AG/SAG mills, grindability testing is always a compromise between testing/sampling effort, and test deliverables. The cost of testing generally increases with the deliverable and advantages related with the tests. In order to make AG/SAG mill testing available to small samples, test designers had to make compromises. This included either a reduction in the top size of the rocks tested and/or the elimination of the steady-state methodology of testing. Simple tests requiring low sample weights can now be used for AG/SAG variability testing and geometallurgical mapping of an ore deposit, but they have to compromise the deliverables. On the other hand, the more sophisticated tests provide a more accurate and complete picture of ore grindability, but they require more material, so they can only be performed on a minimum of samples. Grindability testing programs should be designed by the mill operator or the project manager in consultation with the test facility, based on their specific requirements. Every project is different, so there is no standard recipe for the design of a test program, but the following guidelines should be considered.

1. It is highly desirable to understand the variation of ore hardness by size should for all the major ore types. This can be measured in the range 13.2 to 63 mm using the JKTech drop-weight test. The trend obtained may be used to extrapolate potential problems at coarse size or even to calibrate the tests that can only be performed at finer size.

2. The main ore types should also be submitted to a steady-state test, especially if the ore is showing signs of heterogeneity, as a hard component can build up and modify the mill performance over time. In the absence of a pilot plant, the MacPherson autogenous grindability test offers a cost-effective alternative, because it can be performed on 100-175 kg of drill core. The test will show if a hard component of the ore will build up over time, and if it is causing throughput losses over time. If autogenous and/or pebble milling is contemplated, the test procedure provides an easy mean to produce pebbles for analysis.

3. Variability in the ore deposit should be addressed through a proper program. SPI and/or SMC tests may be used to test SAG mill variability, while the Bond ball mill grindability

test remains the most appropriate mean to test ball mill hardness. The number of samples to be tested will largely depend on the project size and economics.

4. HPGR should also be considered as a power-efficient alternative to conventional or autogenous circuits early in a project. Universally-accepted HPGR test procedures, based on small-scale tests, have yet to be established, but current knowledge allows for pre-feasibility level evaluation.
5. It is highly recommended and common practice to combine different test procedures and design methodologies in order to maximize the information and reduce the risk.
6. Ultimately, the most reliable way to establish the grindability of an ore is to process it in a pilot mill, which minimizes the magnitude of the scale-up. Pilot testing sits at the far end of the sampling effort, but it will also offers the most detailed set of deliverables. It is always desirable to perform a pilot plant, before proceeding with the sizing of a commercial AG/SAG mill or HPGR's, especially if a tight design is required to meet the project economics. A pilot plant will eliminate most of the surprises, as well as minimize the risk.

The objective of this paper was to review the various grindability test methodologies that are currently available on the market. The proposed list was intended to cover the principal tests, but it is not believed to be an exhaustive one.

Each test has strengths and weaknesses and this paper was intended to provide the mill operators and project engineers with guidelines, as well as useful references, which they can use to achieve their objectives in a cost-effective manner.

REFERENCES

Mosher J.B. & Bigg A.C.T. (2001) "SAG Mill Test Methodology for Design and Optimization." Proceedings Autogenous and Semi-autogenous Grinding, UBC, Vancouver BC, Canada.

Mosher J.B. & Bigg A.C.T. (2001) "Bench-scale Testing and Pilot Plant Tests for Comminution Circuits Design." SME Mineral Processing Plant Design, Practice and Control, Proceedings Volume 1. eds. Mular L., Halbe N. and Barratt D.J.

Bond F.C., (1960) "Crushing and Grinding Calculations." British Chemical Engineering, Vol.6 (Rev 1961 by A/C Pub. 07R9235B).

Mosher J. B. and Tague C.B. "Precision and Repeatability of Bond Grindability Testing." Mineral Engineering, Volume 14, No. 10.

Barratt D.J., Matthews, B.D. and deMull, T. (1996) "Projection of AG/SAG Mill Sizes, Mill Speeds, Ball Charges and Throughput Variation from Bond Work Indices." Proceedings International Autogenous and Semi-autogenous Grinding Technology 1996, eds. A.L. Mular, D.J. Barratt, and D.N. Knight, II.

Bond F.C., (1947) "Crushing Tests by Pressure and Impact" Trans AIME, Vol. 169, pp 58-66.

Starkey and Dobby G. (1996) "Application of the SAG Power Index at Five Canadian SAG Plants." Proceedings Autogenous and Semiautogenous Grinding 1996, UBC, Vancouver, BC.

Dobby G., Bennett C., Kosick G., (2001) "Advances in SAG Circuit Design and Simulation Apllied – The Mine Block Model." International Autogenous and Semi-autogenous Grinding Technology 2001, Vol. 4. eds. A.L. Mular, D.J. Barratt, and D.N. Knight, II.

Napier-Munn T.J., Morrell S., Morrison R.D., Kojovic T. "Chapter 4 Rock Testing – Determining the Material-specific Breakage Function, Mineral Comminution Circuits – Their Operation and Optimization", University of Queensland, JKMRC, Qld, Aust.

Morrell, S., (2004) "Predicting the Specific Energy of Autogenous and Semi-autogenous Mills from Small Diameter Drill Core Samples." Minerals Engineering, Vol. 17/3 pp 447-451.

MacPherson A.R., and Turner R.R, (1978) "Autogenous Grinding from Test Work to Purchase of a Commercial Unit.", Mineral Processing plant design, A.L. Mular and R.B. Bhappu, Chapter 13, pp 279-305, eds., AIME, New York.

Siddall G B and White M, (1989) "The Growth of SAG Milling in Australia", in Advances in Autogenous
and Semiautogenous Grinding Technology, Mular and Agar.

Lunt D J, Thompson A and Ritchie I, (1996) "The Design and Operation of the Kanowna Belle Milling Circuit", in International Autogenous and Semiautogenous Grinding Technology, Mular, Barratt and Knight, 1996.

McKen A., Raabe H., Mosher J. (2001) "Application of Operating Work Indices to Evaluate Individual Sections in Autogenous-Semiautogenous/Ball Mill Circuits", in International Autogenous and Semiautogenous Grinding Technology 2001, Barratt, Allan and Mular.

CONTACT INFORMATION

Email us at minerals@sgs.com

WWW.SGS.COM/MINERALS

WHEN YOU NEED TO BE SURE