AN OVERVIEW OF THE SMALL-SCALE TESTS AVAILABLE TO CHARACTERISE ORE GRINDABILITY

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ABSTRACT
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, down to a few kilos in some cases. This reduction in ‘sampling effort’ was necessary, but it occurred at the expense of simplifications in the test procedures and reduction in test deliverables. This paper summarises the current status of grindability testing for AG/SAG mill analysis and design.

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. A pilot plant can test coarse feeds (>6”), as well as 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 was 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 and sample requirement. This concept is re-utilized in Table 1.

It is obvious that the ability to test coarse rocks, which are generally responsible for impeding AG/SAG throughput, but also for the supply of grinding media for low steel charge applications, is an advantage in AG/SAG mill testing. The hardness of coarse rocks cannot be inferred from fine rocks, because the gradient of hardness by size varies from one sample to another. Unfortunately, tests that are performed at a coarse size will statistically require 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 weight (for a given top size) because they are run until a steady-state is achieved, which involves replacing the mill charge several times throughout the test. The Bond tests are typically run for a minimum of seven cycles, while the MacPherson and pilot plant tests are operated for about 6-10 hours. The achievement of 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.

Testing large rocks in AG/SAG mill evaluations is also desirable, and will result in larger weights. The top size, or minimum core size, is also presented in Table 1 for reference. The weight requirements are based on typical ore with an S.G. around 2.8g/cm³. Heavier ores will typically require more weight (proportional to the S.G.), as most of the tests are designed for a given volume (SPI being the exception).

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 a reference guide and the reader is encouraged to consult the references that are more specific to each individual test.

Most of the grindability tests are supported by a large database, in which the sample can be positioned. Examples of such databases are presented in a separate paper of this conference [3].
Bond Ball Mill Grindability

The Bond ball mill grindability 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 [7]. The crusher work index (CWI) or impact work index is calculated as follows:

$$\text{CWI} = \frac{53.49 \times d \times (1/\text{mm})}{\text{S.G.}}$$

Where $d$ is the energy at which the specimen broke, mm is the thickness of the rock specimen, and S.G. is the specific gravity of the ore. The J/mm are transformed in kVt/h as follows:

$$\text{kVt/h} = \frac{45.5 \times \text{Joules/mm}}{\text{Specific Gravity}}$$

**Table 1: Summary of Grindability Test Procedures**

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample</th>
<th>Top Size</th>
<th>Closing Size</th>
<th>Sample Requested</th>
<th>Sample Consumed</th>
<th>Type</th>
<th>Steady-State</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond Ball Mill</td>
<td>0.305</td>
<td>3.3</td>
<td>Any</td>
<td>0.145</td>
<td>10 5</td>
<td>Locked-cycle</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>SPI Test</td>
<td>0.305</td>
<td>38</td>
<td>N/A</td>
<td>10</td>
<td>2</td>
<td>Batch</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>SMC Test</td>
<td>N/A</td>
<td>32</td>
<td>Any</td>
<td>20</td>
<td>5</td>
<td>Single Particle</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Bond Rod Mill</td>
<td>0.305</td>
<td>13</td>
<td>Any</td>
<td>1.2</td>
<td>15</td>
<td>8</td>
<td>Locked-cycle</td>
<td>Y</td>
</tr>
<tr>
<td>Bond Low-energy Impact</td>
<td>N/A</td>
<td>75</td>
<td>PO</td>
<td>N/A</td>
<td>25</td>
<td>10</td>
<td>Single Particle</td>
<td>N</td>
</tr>
<tr>
<td>Drop-weight Test</td>
<td>N/A</td>
<td>63</td>
<td>HQ</td>
<td>N/A</td>
<td>75</td>
<td>25</td>
<td>Single Particle</td>
<td>N</td>
</tr>
<tr>
<td>MacPherson Autogenous</td>
<td>0.45</td>
<td>32</td>
<td>NO</td>
<td>1.2</td>
<td>175</td>
<td>100</td>
<td>Continuous</td>
<td>Y</td>
</tr>
<tr>
<td>Media Competency</td>
<td>1.83</td>
<td>165</td>
<td>-</td>
<td>N/A</td>
<td>750</td>
<td>300</td>
<td>Batch</td>
<td>N</td>
</tr>
<tr>
<td>Pilot Plant</td>
<td>1.75</td>
<td>150-200</td>
<td>Various</td>
<td>&gt;60000</td>
<td>10000</td>
<td>Continuous</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>LABWAL HPGR</td>
<td>0.25</td>
<td>12.5</td>
<td>BO</td>
<td>N/A</td>
<td>250</td>
<td>25</td>
<td>Continuous</td>
<td>Y</td>
</tr>
</tbody>
</table>

**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 [7]. The crusher work index (CWI) or impact work index is calculated as follows:

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**MINNOVEX SAG POWER INDEX (SPI) TEST**

The Minnovex SAG power index (SPI) [8], expressed in minutes, is defined as the time (t) necessary to reduce an ore sample from a $K_w$ of 12.5mm to a $K_w$ of 1.7mm. The batch test is carried out in a laboratory mill of 12” diameter x 4” length, loaded with 15% steel balls of 1” diameter. The SPI test itself requires 2kg of ore with a top size of 1/4” (19mm), but a total of 10kg of 1/16” is generally preferred, which allows for the determination of a crusher index (the crusher index is used to estimate the size distribution of the primary crusher). The sample is prepared to have an $F_80$ of 12.5mm, and the test is run to determine the time required to reach an $P_80$ of 1.7mm.

$$\text{SPI} = \frac{62}{t \times (G_S)^{0.6} \times \text{Gpr} \times \text{CWSI}}$$

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 (12.5mm for RWI and 3.3mm for BWI), and/or grain size properties. The Bond rod mill work index is used to calculate the power requirement at intermediate size, i.e. from 12.5mm to about 1mm. 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 (BW and CWI) for SAG mill design using semi-empirical relationship [6].

$$\text{BBW} = \frac{3.15 \times (G_S)^{0.6} \times \text{Gpr} \times t}{(F_80) \times (F_80) \times (F_80)}$$

Where $P$ 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 Bond mill work index is computed with an equation very similar to that of the ball mill test, as follows:

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$\text{BBW} = \frac{3.15 \times (G_S)^{0.6} \times \text{Gpr} \times t}{(F_80) \times (F_80) \times (F_80)}$
10 values will increase with rock size, which means that the hardness of the ore actually decreases, which is often the effect of the increased frequency of cracks in the coarser rocks. For very competent ore, the lines will be nearly horizontal, while non-competent fractured ore will show a high gradient of 10 with increasing size. Decreasing trends of 10 by size are fairly rare. These curves can be used to infer the competency of the ore at coarser size for those ores that are carried out on finer material, at the low end of the size spectrum.

SAG MILL COMMINUTION (SMC) TEST

The SAG mill comminution (SMC) test was developed by Steve Morrell [11]. It is an abbreviated drop-weight test, which can be performed at low cost on small rocks or drill cores. Cores are normally cut into ½ cylinders using a diamond saw and the test is performed similarly to the standard drop-weight test procedure, except that a single size fraction is tested. The test can be performed at various rock sizes, the minimum acceptable top size being 16mm. The recommended rock size is 26.5-31.5mm, which requires preparing about 20kg of samples, but only 5kg is actually tested, and all the products and unused material can be reused for metallurgical testing. Testing of smaller rocks or drill core requires significantly smaller weight. A bulk sample, or essentially any size of drill core, is adequate for the 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 ta and crusher parameters, which must be obtained through a full drop-weight test. Normally, the main ore zones/ types in the deposit are submitted to the full drop-weight test procedure and the SMC test is used to measure the variability within the main ore zones/ types. When the gradient of hardness is 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 for AG/SAG mills. The A and b values can be used directly in JKSimMet for plant design, expansion and optimisation.

MacPherson et al [13], as a continuous test, uses a drop-weight mill with an 8% ball charge. A draft fan supplies the airflow required to remove the ground material from the mill, which is collected via a Cyclone and a dust collector (baghouse). The Cyclone is 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 1/14", 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 100kg, but typically, a 175kg sample is requested to allow for left 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. 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 as well as a size-by-size S.G. determinations. This allows the evaluation of any preferential coarse build-up or particle density concentration in the mill charge. The mill power drawn, throughput and product size distribution are used to compute a specific energy input and the MacPherson autogenous work index (AWI).

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 grindability 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.

MEDIA COMPETENCY TEST

There have been some variations of media competency tests developed over the years. The principal objective of these tests is the assessment of media competency of the AG/SAG mill. The most successful media competency tests is the Advanced Media Competency Test (AMCT), developed by Orvay Mineral Consultants and AusWADE (15), which features a ‘tumble test’ in a 6 x 1’ mill using ten large rocks in five size fractions in the range 104 to 165mm. The mill is rotated at 10-16 revolutions and the charge is dumped and size analyzed. The surviving rocks are subjected to the fracture energy test procedure, which consists of a series of Bond low-energy 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 Bond indices (rod and ball), and database support. With a top particle size of 165mm, 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 [16], [17]. For autogenous mills, the traditional methodology for testing and scale-up of HPGRs consisted of processing a large sample in a pilot mill (normally performed by the supplier). This has the disadvantage of requiring a large quantity of material. Bench-scale units, requiring a minimum of about 250kg per test are available and may eventually be used as an alternative to a pilot plant, providing suitable scale-up methodologies are developed. Other testing procedures 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 HPGRs is their 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 K80’s inadequate, unless appropriate corrections are made [18]. (This problem is shared by AG/SAG mills.) 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. This requires a fair quantity of material and the difficulties inherent to performing such a pilot plant make it difficult to come up with reliable conclusions.

The use of a small locked-cycle scale test, such as the Bond ball mill grindability test is proposed as a cheap alternative to achieve the same objective in a more controlled manner, and more importantly, with a smaller sample size. SGS has developed a simple methodology that is based on the 0.25m LABWAL HPGR from Polysius, which has a top size of 12.5mm. 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 4. The power requirement normally increases linearly with the pressure of operation. The K80 typically decreases with a higher pressure of operation, until it reaches a plateau. The HPGR protocol, corresponding to the best condition, is compared 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 ignored in the analysis and the results are assessed in terms of throughput rate or specific energy requirement. Assuming one Bond ball mill revolution draws constant power, the kWh/t is inversely proportional to the ‘gross’ gram per revolution in the Bond test. 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 of the feed that is coarser than the closing screen size, thus ignoring the benefit of the additional fines. This power can be added to that of the LABWAL to come up with a total requirement from 12.5mm to final product size.

The total power for the HPGR system can be compared to that of a conventional circuit, based on the rod and ball mill work indices and the Third Theory of comminution. The power

Figure 1: Drop-weight Test Interpretation

Figure 2: Relative Density of Rock Particles

Figure 3: Variation of Hardness by Size from a Drop-weight Test

Figure 4: Relative Density of Rock Particles

Figure 5: Variation of Hardness by Size from a Drop-weight Test

Figure 6: Drop-weight Test Interpretation
2. The main ore types should also be considered. But the following guidelines should be different, so there is no standard recipe for the design of a test program, which is based on their variability testing and geometallurgical factors. 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 geological mapping of an ore deposit, but they have to compromise on the deliverables. The more sophisticated tests provide 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 for all major ore types. This can be measured in the range 13.2 to 63 mm using the JK Tech drop-weight test. The results may be used to extrapolate potential problems at coarser size or 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. In AG/SAG milling, a hard component can always build up and modify the mill performance over time. The MacPherson Autogenous Grindability test can be performed on 175 kg of drill core, so it offers a cost-effective alternative to pilot plant. The test will show if a hard component of the ore builds up over time, and it can cause high throughput problems. If autogenous and/or pebble milling is contemplated, the test procedure can produce pebbles for analysis.

3. Variability in the ore deposit should be addressed through a proper program. SPI and/or SMC tests can be both used to test SAG mill variability, while the Bond ball mill grindability test remains the most appropriate way to test ball mill hardness. The number of samples to be tested will largely depend on the project size and economics, as well as the level of acceptable risk. High throughput/low grade projects will require the highest amount of testing.

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 evaluations.

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. All the tests described in this paper have both strengths and weaknesses, and none of the tests produce all the desirable “deliverables.”

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 scalups. Pilot testing sits at the far end of the sampling effort, but it will also offer the most detailed set of deliverables. It is always desirable to perform a pilot test 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 in the market. The discussion was limited to the most common and accepted test procedures, but this list is far from being exhaustive, and may change as new methodologies are being developed. 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


CONTAT INFORMATION

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