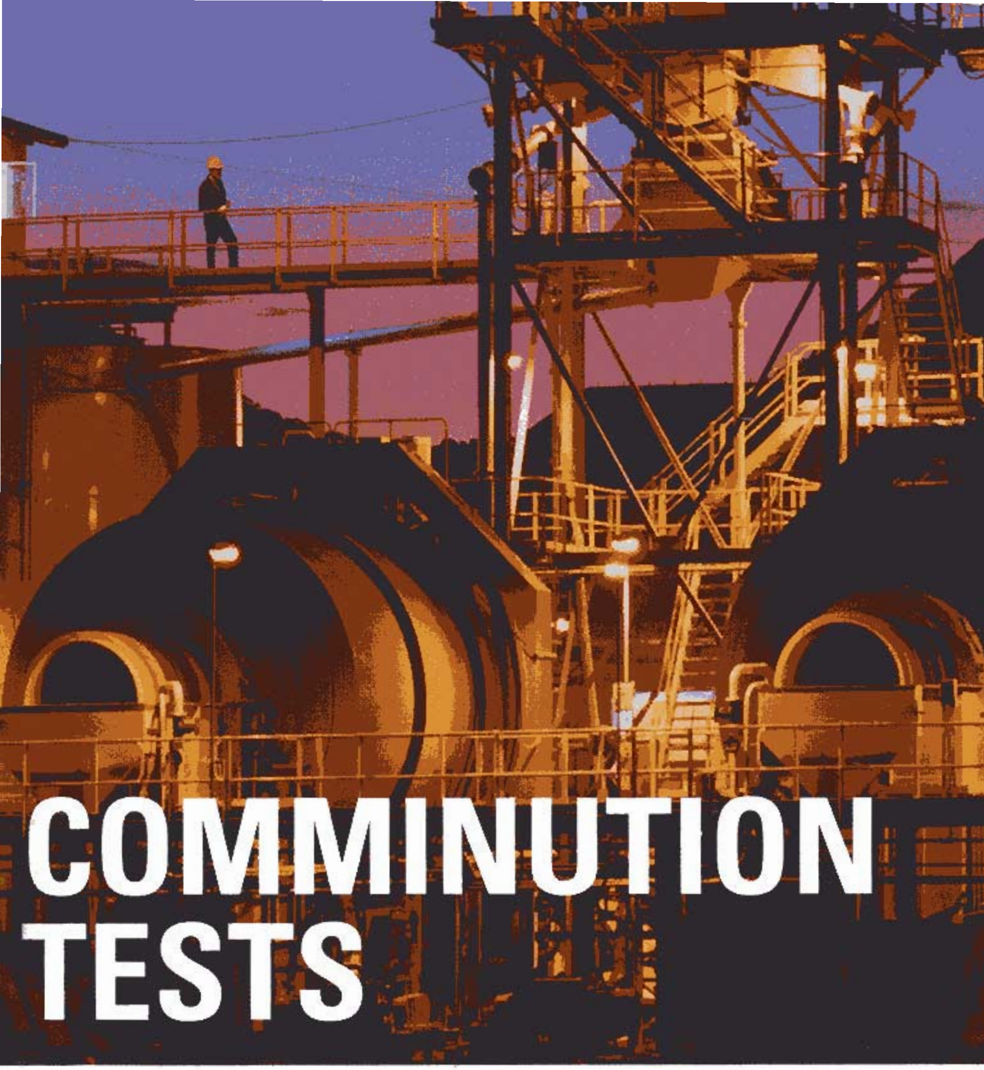

COMMINUTION TESTS

MINERALS SERVICES

SGS

SGS is proud to present the fourth edition of the Glossary of Comminution Terms. It provides factual definitions of the variety of grinding, comminution and hardness tests in the market today. Such tests reduce risk as they provide a comprehensive way to sample ore variability. Understanding the strengths and weaknesses of the tests available ensures a disciplined approach to circuit design and troubleshooting. To this end, we have included a technical paper from the SAG 2006 conference which compares a variety of current tests.

For additional copies of this glossary, please go to www.met.sgs.com and use the "contact us" tab.

SGS Minerals Services
September 25th, 2006

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ABRASION TEST

The test determines the Abrasion Index which can be used to determine steel media and liner wear in crushers, rod mills, and ball mills. There does not appear to be a correlation that can be used for autogenous grinding. Bond developed the following correlations giving the wear rate in lb of metal wear/kWh of energy used in the comminution process.

Wet rod mill	Rods	lb/kWh	=	$0.35(Ai - 0.020)^{0.2}$
	Liners	lb/kWh	=	$0.035(Ai - 0.015)^{0.3}$
Wet ball mill	Balls	lb/kWh	=	$0.35(Ai - 0.015)^{0.33}$
	Liners	lb/kWh	=	$0.026(Ai - 0.015)^{0.3}$
Dry ball mill	Balls	lb/kWh	=	$0.05Ai^{0.5}$
	Liners	lb/kWh	=	$0.005Ai^{0.5}$
Crushers (gyratory, jaw, cone)	Liners	lb/kWh	=	$(Ai + 0.22)/11$
Roll crushers	Roll shell	lb/kWh	=	$(0.1Ai)^{0.667}$

The abrasion test was developed by Allis-Chalmers* using a method and apparatus used by the Pennsylvania Crusher Division of Bath Iron Works Corp. The equipment consists of a rotating drum, into which the dry ore samples are placed, with an impact paddle mounted on a centre shaft rotating at a higher speed than the drum. The paddle is made of a standard alloy steel hardened to 500 Brinell. The abrasion index is determined from the weight loss of the paddle under standard operating conditions.

FEED SAMPLE REQUIREMENTS:

- 1.6 kg of minus ¾" plus ½" ore. This can normally be obtained by taking 5 kg of ore crushed to minus ¾" and screening at ½".

* Bond F. C., "Metal Wear in Crushing and Grinding", Allis-Chalmers Publication 07P1701, Dec 1963.

ALLIS CHALMERS DRUM MEDIA COMPETENCY TEST

The test was developed by Allis Chalmers. The test measures the quality of the ore to be grinding media. The combined quantity and quality of the ore can be used to determine which type of grinding circuit can be used, and therefore reduce the scope and cost of pilot plant testing.

The batch test is run in a 6' x 1' drum. The coarse fraction of primary crushed ore is ground for a specified time and the size distribution and mass of the product studied.

FEED SAMPLE REQUIREMENTS:

- 750 kg of minus 7" plus 4" ore.

* Rowland C. A., "Testing for Selection of Autogenous and Semiautogenous Grinding Mills and Circuits", in Advances in Autogenous and Semiautogenous Grinding Technology, Mular A.L., Agar G.E., eds., 1989.

ALLIS CHALMERS HIGH ENERGY IMPACT TEST

The test determines the Crushability Index*, which is analagous to the Bond work index, and can be used with Bond's Third Theory of comminution to calculate net power requirements for sizing crushers.

The impact apparatus consists of two free swinging pendulum mounted hammers, one being the hammer and the other larger one being the anvil. Only the hammer is raised and the specimen is mounted in contact with the anvil. The system is designed so that by raising the hammer to a fixed level there is excess energy for breakage. Any energy used in excess of breakage is imparted to the anvil and by measuring the movement of the anvil the energy imparted to breakage can be determined by difference.

FEED SAMPLE REQUIREMENTS:

- At least 10 pieces of minus 1.5" plus 0.75" ore (20 pieces recommended).

* Flavel M. D., "Selection and Sizing of Crushers," Chapter 21 in Design and Installation of Comminution Circuits, Mular A. L. and Jergensen II G. V., SME 1982.

AMDEL-ORWAY ADVANCED MEDIA COMPETENCY TEST

This test was developed by Orway Mineral Consultants and Amdel*. It consists of a tumbling test in a 6' x 1' mill on rocks in the range 104 to 165 mm, followed by size-by-size low-energy impact testing on the surviving rocks.

A plot is made of impact work index against size fraction. Comparison with previous data and interpretation of the curve shape will indicate the competency of the ore. The test has been used to predict the build-up of critically sized material in SAG grinding.

* 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, 1989.

* 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.

BOND BALL MILL GRINDABILITY TEST

The test determines the Bond Ball Mill Work Index which can be used with Bond's Third Theory of comminution to calculate net power requirements*. Various correction factors may have to be applied.

$$W = Wi \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}} \right)$$

Where W = Net power consumption in kWh/t

Wi = Bond work index (either Imperial or Metric units)

P = The 80% passing size of the ground product in μm

F = The 80% passing size of the feed in μm

The test is a closed circuit dry grindability test run in a standard ball mill, and can be performed at mesh sizes ranging from 28 mesh to 400 mesh. The normal finishing size is 100 mesh.

FEED SAMPLE REQUIREMENTS:

- 10 kg of minus 6 mesh ore.

* Bond F. C., "Crushing & Grinding Calculations," Reprint from British Chemical Engineering, Allis-Chalmers Publication 07R9235B

BOND LOW ENERGY IMPACT TEST

The test determines the Bond Impact Work Index which can be used with Bond's Third Theory of comminution to calculate net power requirements for sizing crushers*. It can also be used to determine the required open sized settings (jaw crushers and gyratory crushers) or closed sized settings (cone crushers) for a given product size.

$$P_{80} = 25400 \times Oss \times (0.04Wi + 0.40)$$

$$P_{80} = 25400 \times Css \times 7Ecc \times \frac{(0.02Wi + 0.70)}{(7Ecc - 2Css)}$$

Where Oss = Open side setting in inches

Css = Closed side settings in inches

Ecc = Eccentric throw in inches

The impact apparatus consists of two pendulum mounted hammers mounted on two bicycle wheels so as to strike equal blows simultaneously on opposite sides of each rock specimen. The height that the pendulum is raised is increased until the energy is sufficient to break the specimen.

FEED SAMPLE REQUIREMENTS:

- At least 10 pieces of minus 3" plus 2" ore (20 pieces recommended).

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

BOND ROD MILL GRINDABILITY TEST

The test determines the Bond Rod Mill Work Index which can be used with Bond's Third Theory of comminution to calculate net power requirements for sizing ball mills*. Various correction factors may have to be applied.

The test is a closed circuit dry grindability test run in a standard rod mill, and can be performed at mesh sizes ranging from 4 mesh to 65 mesh. The normal finishing size is 14 mesh.

FEED SAMPLE REQUIREMENTS:

- 15 kg of minus ½" ore.

* Bond F. C., "Crushing & Grinding Calculations", Reprint from British Chemical Engineering, Allis-Chalmers Publication 07R9235B

BREAKAGE & SELECTION FUNCTIONS

Detailed modelling of rod and ball mill circuits requires the determination of the breakage and the selection function.

The breakage function (also referred to as the "breakage distribution function" or the "appearance function") describes the size distribution of particles produced by a one-time breakage of a single particle. This function is assumed to be ore specific and independent of the grinding equipment. The function can incorporate variations in the relative size distributions for different original particle sizes, or can be simplified by assuming that the size distribution relative to the original particle size will be constant.

The selection function (also referred to as the "breakage function") describes the number of breakage events per time unit for the various time fractions. This function is ore and grinding equipment specific. It incorporates the probability of a particle encountering an impact event, and the probability of breakage occurring.

The ore specific breakage function is measured in the laboratory. The SPOC* procedure is carried out in a laboratory ball mill of at least 25 cm diameter with a specified ball distribution filling 35% to 40% of the mill volume, running at 70% of critical speed. Three to four feeds with narrow size ranges and different top sizes are used. Two tests are run on each size fraction. The grinding time for the second test is determined from the findings of the first test with the objective of reducing the top size fraction by 30% to 50%. The test results are fed into a computer program (FINDBS), which calculates the breakage function.

A sampling survey of the plant grinding circuit, combined with the breakage function, allows the calculation of the equipment specific selection function.

The breakage function and selection function can be used in computer simulation programs to model rod mill and ball mill circuits.

* Simulated Processing of Ore and Coal, CANMET publication SP85-1/7.2E

BRINELL INDENTATION MICROHARDNESS

Used for defining hardness of metals and alloys*. Indentation is done by bringing a 10mm diameter steel ball, subjected to a load of 3000 kg, in contact with the specimen surface. The load is reduced to 500 kg for soft metals. The load is applied for 30 seconds. The diameter of the indentation is measured and the Brinell hardness is given by the formula:

$$HB\ (\text{in kg/mm}^2) = \frac{2F}{\pi D \times \left(D - \sqrt{D^2 - d^2}\right)}$$

Where F is the applied load in kg·Force
D is the diameter of the ball in mm
d is the diameter of the indentation in mm

FEED SAMPLE REQUIREMENTS:

- Flat face on specimen. Thickness must be 10 times the depth of the impression, and the indentation must be at least 2.5 times the diameter of the impression away from the edge of the specimen.

* ASTM E 10-96, "Test Method for Brinell Hardness of Metallic Materials", 03-01.

COMPRESSION CRUSHABILITY TEST

This test determines the unit crushing strengths of individual rock pieces. It is used to predict load bearing strengths under slow compressive forces. The test can be performed either on prepared samples, cubes or cylinders, or on natural shaped particles. Since crusher pressures are applied to randomly oriented particles, most crushability tests use unprepared particles. Particles are weighed and then placed between a stationary plate and a movable head attached to a hydraulic cylinder with a power source. The pressures at which the particles fail are recorded. Plots are made of particle weight against force to break rock.

Compression crushability index (Cci)

$$= \frac{0.0073 \times \text{Force F}}{\left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right)} \times wt^{0.667} \times SG^{0.333}$$

Where P = The 80% passing size of the crushed product in μm

F = The 80% passing size of the crusher feed in μm

Force F = Force required to break particle of size F

Wt = Weight of rock with diameter F

SG = Specific gravity of rock

$$Cc = Cci\left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right)$$

= Compression crushability kWh/t

FEED SAMPLE REQUIREMENTS:

- At least 20 rock pieces with sizes spanning the crusher feed K_{80} size.

Flavel M. D., "Selection and Sizing of Crushers", Chapter 21 in Design and Installation of Comminution Circuits, Mular A. L. and Jergensen II G. V., SME 1982.

DORRY HARDNESS TEST

The test determines the coefficient of hardness. It is used by the aggregate industry.

A 1"Ø x 1" cylinder of sample is subjected to the abrasive action of quartz and fed upon a revolving steel disc. The weight loss (W) after 1000 rpm is determined and this gives the coefficient as follows:

$$\text{Coefficient of hardness} = 20 - (W/3)$$

FEED SAMPLE REQUIREMENTS:

- A 1"Ø x 1" cylinder of sample.

HARDGROVE GRINDABILITY TEST

The test* determines the Hardgrove Grindability Index (HGI). The index is used in dry grinding and mostly by the coal industry. Its usefulness is limited by the fact that it only ranks materials on a relative grindability scale. However, Bond has suggested a relationship that can convert it to the Bond ball mill work index:

$$Wi = 435/HGI^{0.91}$$

The test is performed in a roller mill that has been calibrated using four standard coal samples. Hardgrove mills are manufactured by a number of companies, each differing slightly. The fixed weight of charge is ground for a fixed number of revolutions at a fixed rotational speed.

FEED SAMPLE REQUIREMENTS:

- 50 g of minus 14 mesh plus 28 mesh sample.

* ASTM D-409-93a, "Test Method for Grindability of Coal by the Hardgrove-Machine Method". 05.05.

JK BALL MILL DROP-WEIGHT TEST

Similarly to the standard drop weight test, this test*, developed at the Julius Kruttschnitt Mineral Research Centre, generates energy vs. breakage for ore particles. This test uses three size fractions between 5 and 13 mm; as such, it is more applicable to ball mill sized particles than the standard drop weight test. The primary result of this test is the calculation of the ball mill appearance function, which can be used for ball mill simulation. The data from this test is interpreted to calculate A and b parameters as in the standard test. These parameters can be compared to the parameters from a standard test to provide insight into varying energy requirements for breakage at different sizes.

FEED SAMPLE REQUIREMENTS:

- 10 kg of minus 0.53" (13.5 mm) ore is prepared by the testing facility.

* Mineral Comminution Circuits – Their Operation and Optimisation, Napier-Munn T. J., Morrell S, Morrison R. D., Kojovic T, Chapter 4, JKMRC Monograph Series in Mining and Mineral Processing 2.

JK DROP-WEIGHT TEST

The JKTech drop-weight test*, developed at the Julius Kruttschnitt Mineral Research Centre, measures the appearance function of the ore for five sized fractions in the range 13 to 63 mm, at various energy inputs (0.1 to 2.5 kWh/t). The results are subsequently reduced to two parameters: A and b. The apparatus consists of a system for dropping a variable weight onto various size rock specimens from various heights. As part of the procedure, the abrasion characteristic of the sample (t_a) is also measured using a tumbling test.

These ore-specific parameters can be used in grinding circuit modelling and simulation using the JKSimMet software. Combinations of crushing, AG or SAG grinding, classification, and secondary grinding can be modelled and simulated. Crushing energy requirements can be estimated from the drop-weight test, and AG/SAG energy requirements can be estimated from the simulation.

Results can be used in the simulation of operating plants to test changes in ore types, classification sizes, ore feed size distribution, ball load, grate apertures, use of pebble crushers, etc. Simulation can also be used in new circuit design to examine various circuit configurations and to refine equipment selection and performance.

FEED SAMPLE REQUIREMENTS:

- 65 kg of minus 4" ore is prepared by the testing facility to minus 2½"

* Mineral Comminution Circuits – Their Operation and Optimisation, Napier-Munn T. J., Morrell S, Morrison R. D., Kojovic T, Chapter 4, JKMRC Monograph Series in Mining and Mineral Processing 2.

JK PENDULUM TEST

This test was the original test*, developed at the Julius Kruttschnitt Mineral Research Centre, used to determine the JK ore specific parameters. However, it has now been mainly superseded by the drop-weight test. It is similar to the standard drop-weight test but, among other disadvantages, uses a top size particle of only 1¼", due to energy input limitations. The results are interchangeable with those of the drop-weight test.

The impact apparatus consists of two free swinging pendulum mounted hammers, one being the hammer and the other larger one being the anvil. Only the hammer is raised and the specimen is mounted in contact with the anvil. Any energy used in excess of breakage is imparted to the anvil and by measuring the movement of the anvil the energy imparted to breakage can be determined by difference.

FEED SAMPLE REQUIREMENTS:

- 30 kg of minus 4" ore is prepared by the testing facility.

* Mineral Comminution Circuits – Their Operation and Optimisation, Napier-Munn T. J., Morrell S, Morrison R. D., Kojovic T, Chapter 4, JKMRC Monograph Series in Mining and Mineral Processing 2, 1996.

KILBORN PEBBLE COMPETENCY TEST

The test was developed by Bunting S. Crocker of Kilborn Engineering. The test gives a relative measure of pebble competency for use in a pebble mill. The rate of breakdown of the pebbles is compared with the rates from other ores of varying competency. A pebble consumption rate in kg/kWh is also determined.

Pebbles and coarse sand are ground wet on a batch basis in a 36"Ø x 24" mill. Pebble level, pulp level and pulp density are checked on a regular basis and adjusted as necessary. The test is continued until 100% of the pebbles have been replaced or until the rate of replacement is steady over a five hour period.

FEED SAMPLE REQUIREMENTS:

- 500 kg of minus 4" plus 1½" ore.

KNOOP INDENTATION MICROHARDNESS

Used for defining hardness of metals, alloys, minerals, ceramics, glass, etc.*. Indentation is done by bringing a diamond point in contact with the specimen surface and then applying a known load (0.1 g to 500 g). The Knoop indenter is pyramid shaped with a diamond-shaped base. The Knoop hardness is given by the formula:

$$KV \text{ (in kg/mm}^2\text{)} = 14230P/l^2$$

Where P is the test load in grams and l is the long diagonal in μm. Hardness is a vectoral property and a range of values can be obtained depending on the crystal alignment.

FEED SAMPLE REQUIREMENTS:

- Flat face on specimen. Can be used on grains as small as 1 μm in diameter.

* ASTM C 849-88(1994), "Test Method for Knoop Indentation Hardness of Ceramic Whitewares," 15.02.

* ASTM C 730-85(1995), "Test Method for Knoop Indentation Hardness of Glass," 15.02

LABORATORY COMPARATIVE WORK INDEX

The test gives an approximate work index for an ore sample which can be used with Bond's Third Theory of comminution to calculate net power requirements. The test depends on laboratory batch grinding using a comparison with the grinding of an ore of known Bond work index, in the same mill.

The test is used where insufficient material is available, or the sample is not coarse enough for a Bond grindability test.

FEED SAMPLE REQUIREMENTS:

- Dependent on the size of mill and amount of material available.

LIMESTONE GRINDABILITY TEST

The test* determines the Grindability Index of limestone. Its usefulness is limited by the fact that it only ranks materials on a relative grindability scale. It is a simple test and is often used for quality control in the limestone industry.

The sample is wet ground in a ceramic jar mill for a specific number of revolutions and the amount of minus 200 mesh material produced is determined*.

FEED SAMPLE REQUIREMENTS:

- 20 g of minus 20 mesh plus 40 mesh ore.

* ASTM C110-96a, "Test Methods for Physical Testing of Quicklime, Hydrated Lime, and Limestone", 04.01.

LOS ANGELES ABRASION TEST

The test* determines a value reported as the percent loss. It is used in the aggregate industry as an indicator of the relative quality or competence of various sources of aggregate having similar mineral compositions. There are two procedures, one for small-size coarse aggregate, and one for large-size coarse aggregate.

The test is a batch test run in a standard 28" x 20" ball mill with one 3½" lifter bar to give a combination of abrasion and impact. The sample is screened at the end of the test at 1.7 mm to determine percent loss.

FEED SAMPLE REQUIREMENTS:

- 5 kg of various graded samples from 1½" to 4 mesh for ASTM C131-96.
  10 kg of various graded samples from 3" to 1" for ASTM C535-96.

* ASTM C131-96, " Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine", 04.02.

* ASTM C535-96, "Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine", 04.02.

MacPHERSON AUTOGENOUS GRINDABILITY TEST

The test determines the MacPherson correlated autogenous work index*. This can be used in conjunction with the Bond rod and ball mill work indices to determine power requirements, and to suggest circuit configurations, for AG/SAG circuits. Bond's Third Theory of comminution is used to calculate net power requirements.

The test is a closed circuit dry grindability test run in a small standard SAG mill using mill charge level control and air classification to give a -14 mesh product. A correlation has been determined between the operating work index, determined from full scale and pilot plant operations, and the gross work index determined from the small scale tests.

FEED SAMPLE REQUIREMENTS:

- 175 kg of minus 1¼" ore. Preparation from minus 4" feed by the testing group is preferred since the feed size distribution is critical.

* MacPherson A. R., and Turner R. R., "Autogenous Grinding from Test Work to Purchase of Commercial Unit", Mineral Processing Plant Design, A.L. Mular and R.B. Bhappu, eds., AIME, New York, 1978, pp. 279-305.

MILLER ABRASIVITY TEST

The test determines the Miller Number of slurries*. The number has two components, abrasivity and attrition, although the abrasivity is the commonly used number. The abrasivity represents the rate of weight loss from a metallic wear block, and the attrition represents the effect of slurry breakdown as measured by a loss of abrasivity as the test progresses. The number is relative to other materials for which commercial operating data are available. The test was developed for pump and pipeline wear determinations.

The slurry sample is placed in a tank and the metallic wear block is moved in a reciprocating motion along a neoprene block placed in the bottom of the tank for a total of 4 x 4 hours.

Reported Abrasivity:	Oil well mud	10	Backfill <100 mesh	180
	Potash brine	11	Pyrite	194
	Limestone	27	Corundum <400 mesh	241
	Magnetite	67	Corundum <200 mesh	1040
	Cu concentrate	128		

FEED SAMPLE REQUIREMENTS:

- Approximately 10L of dry solids or the equivalent amount of slurry.

* ASTM G 75-94, "Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)", 03.02.

MINNOVEX 'MODBOND' GRINDABILITY TEST

Similar to a comparative work index, this test is an open circuit dry batch grindability test run in the standard Bond ball mill for a set time and can be used at mesh sizes from 65 to 200 mesh (normally 100 mesh). The test requires calibration against the standard Bond ball mill work index test to estimate the work index. It is used to show the ore body hardness profile and to predict throughput in a ball mill circuit.

FEED SAMPLE REQUIREMENTS:

- 1.2 kg of minus 6 mesh ore.

MINNOVEX SPI TEST

The test* determines the MinnovEX SAG Power Index. It is used to show ore body hardness profiles for operating or potential mines. The SPI values are used to predict throughputs for SAG/AG mills and in the determination of power requirements for such mills in potential mines via the Minnovex CEET program. The test is a batch test, run with 2 kg of ore in a standard 12" x 4" SAG mill, and it measures the time (in minutes) required to grind a sample from 80% passing ½" to 80% passing 10 mesh.

The test is run in conjunction with a Minnovex crusher index that uses the breakage characteristics during sample preparation to minus ¾" to predict the SAG mill feed size using the CEET program.

FEED SAMPLE REQUIREMENTS:

- At least 2 kg of passing ¾" ore for the SPI mill feed (with no more than 80% passing ½"). 10 kg is required for the crusher index determination.

* Dobby G, Kosick G, and Starkey J, "Application of the Minnovex SAG Power index Test at Five Canadian SAG Plants", in International Autogenous and Semiautogenous Grinding Technology 1996, Mular A.L., Barratt D.J., and Knight D.A., eds.,1996.

MOH'S HARDNESS

A relative scale of hardness developed by mineralogists for mineral identification. The minerals do not advance in any definite or regular scale of hardness. The hardness of a clean rock specimen is determined by attempting to scratch the minerals enumerated in the standard list with the specimen. The hardness of the specimen, for instance, is quoted as being between 4 and 5 if it will scratch fluorspar but not scratch apatite.

Moh's Hardness:
1 – Talc
2 – Rock Salt/Gypsum
3 – Calcite
4 – Fluorspar
5 – Apatite
6 – Orthoclase Feldspar
7 – Quartz
8 – Topaz
9 – Corundum
10 – Diamond

FEED SAMPLE REQUIREMENTS:

- Clean mineral specimen.

POINT-LOAD TEST

The test measures the Point Load Strength Index ($I_{s(50)}$) of rock specimens, and their Strength Anisotropy Index ($I_{a(50)}$), which is the ratio of Point Load Strengths in directions that give the greatest and least values. Rock specimens in the form of core (diametral and axial tests), cut blocks (block test), or irregular lumps (irregular lump test) are broken by application of a concentrated load through a pair of spherically truncated, conical platens. The required testing apparatus is light and usually portable. A standard testing procedure has been suggested by the International Society for Rock Mechanics*.

Core specimens with length/diameter ratio greater than 1.0 are suitable for diametral testing.

Core specimens with length/diameter ratio of 0.3 to 1.0 are suitable for axial testing.

Block or irregular lump specimens, with a length/height ratio greater than 1.0, and a height/width ratio of 0.3 to 1.0, are suitable for these tests.

FEED SAMPLE REQUIREMENTS:

- At least 10 specimens for each sample, more if the sample is heterogeneous or anisotropic.

* International Society of Rock Mechanics, "Suggested Methods for Determining Point Load Strength," International Journal of Rock Mechanics, Mineral Sciences, & Geomechanics Abstr. 22, 53-60 (1985).

SAG MILL COMMINUTION (SMC) TEST

The SMC test* is an abbreviated version of the drop-weight test, which can be performed at lower costs on small rocks or drill cores. Cores are cut into ¼ cylinders using a diamond saw and the test is subsequently performed as per the standard drop-weight test procedure, except that only one size fraction is tested. The test generates the A and b parameters, which are used in the JKSimMet simulations, and a drop-weight index in kWh/t. The test uses a single (and finer) size fraction, as well as a lower number of specimens (100), which limits its accuracy. Normally, the main ore zone(s) in the deposit is tested using the full procedure to calibrate the SMC test, which can then be used to generate detailed mapping information at lower costs on localized samples, providing they have comparable geological characteristics.

FEED SAMPLE REQUIREMENTS:

- The test procedure requires 100 rocks (minimum 60), or quarter core 'cubes', in any given size fraction of the drop-weight test procedure. For the standard size (27-32 mm), this can be obtained by stage-crushing approximately 20 kg to passing 32 mm. Lower weight (5 kg) is often sufficient, if the test is performed on smaller rocks.

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

STATIC PRESSURE TEST

The SGS MinnovEX Static Pressure Test (SPT) is used to estimate the energy requirement to achieve a specific level of size reduction of an ore by High Pressure Grinding Rolls (HPGR). The test measures the energy consumed in crushing a dry sample of ore in a steel sample container using a hydraulic press. The test is run in closed circuit to a product that is 100% passing 6 mesh (3.35mm). A High Pressure Grinding Index is determined from the 80% passing value of the feed and product sizes and energy used in breakage. The index can be determined at a range of pressures and is used to show the ore body hardness profile. Throughput in commercial units is predicted after plant calibration.

FEED SAMPLE REQUIREMENTS:

- At least 7 kg of passing ¾" ore (with no more than 80% passing ½").

THOMPSON TEST

The test* determines relative grindability in terms of relative surface area (RSA), which, when used with standard tables, allows rod or ball mill power and size to be determined. A standard 4.55 kg (10 lb) of sample is stage ground, dry, at five minute intervals, for a total time chosen for fineness of end point, and small samples removed for screen analyses. The mill is a 12" x 24" Marcy batch rod mill. The test has the advantage of obtaining data to the fineness of grind to be used in the plant operation, as opposed to fixed screen size end points for the Bond work indices.

FEED SAMPLE REQUIREMENTS:

- 30 kg to 90 kg of minus ¾" ore.

* Reed W. M., "Thompson Procedure – A Contrast for Mill Size Selection", Chapter 13 in Design and Installation of Comminution Circuits, Mular A. L. and Jergensen II G. V., SME 1982.

UNCONFINED (UNIAXIAL) COMPRESSION TEST

The test determines the unconfined compressive strength of a rock specimen according to the standard procedure*. Drill core specimens with length to diameter ratio greater than 2:1 are cut with a diamond saw to achieve nearly parallel end faces within ± 0.025 mm. The cylinder is then submitted to UCS measurements within an electronic-servo controlled Material Test System (MTS) at loading rates of approximating 10^{-5} s^{-1}, until failure of the specimen. The loading data and other test parameters are recorded with a computer-based data acquisition system, and the UCS is reported. Axial force, axial deformation and circumferential deformation variables can also be recorded as part of the procedure to generate the Young's Modulus and Poisson's ratio.

FEED SAMPLE REQUIREMENTS:

- Drill core specimens with length to diameter ratios greater than 2.

* ASTM D2938-95, "Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens", 04.08.

VICKERS INDENTATION MICROHARDNESS

Used for defining hardness of metals, alloys, minerals, ceramics, glass, etc.*. Indentation is done by bringing a diamond point in contact with the specimen surface and then applying a known load (0.1 g to 500 g). The Vickers indenter is pyramid shaped with a square base. The Vickers hardness is given by the formula:

$$HV \text{ (in kg/mm}^2\text{)} = 1854.4P/d^2$$

Where P is the test load in grams and d is the mean diagonal in mm. Hardness is a vectoral property and a range of values can be obtained depending on the crystal alignment.

FEED SAMPLE REQUIREMENTS:

- Flat face on specimen. Can be used on grains as small as 1 μm in diameter.

Young B. B., Millman A. P., "Microhardness and Deformation Characteristics of Ore Minerals", Trans. I.M.M., April, 1964, vol. 73, pp. 437-466.

VOLUMETRIC HARDGROVE GRINDABILITY TEST

This test is a modification of the Hardgrove Grindability Index using a fixed volume of feed rather than a fixed weight. This grindability index (GI) is used in dry grinding and was developed more for the non-coal industries*. When using the Preiser-type Hardgrove machine it is related to the Hardgrove Grindability Index by the following relationship:

$$HGI = 6.97GI + 15.93$$

Good correlation has been shown with the Bond ball mill work index using the Preiser-type machine with the equation:

$$Wi = 87.5/GI^{0.93} \quad \text{for } Wi > 8.5$$

Or $$Wi = 1622/HGI^{1.08} \quad \text{for } Wi > 8.5$$

No relation has been established for work index lower than 8.5.

The test is also performed in a roller mill that has been calibrated using four standard coal samples. The fixed volume of charge is ground for a fixed number of revolutions at a fixed rotational speed.

FEED SAMPLE REQUIREMENTS:

- 36 mL of minus 14 mesh plus 28 mesh sample.

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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 circuits 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. Pilot plants 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 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 reutilized in Table 1.

It is obvious that the ability of testing 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 2.8 g/cm^3. 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).

Table 1: Summary of Grindability Test Procedures

Small-scale Test	Mill Dia. (m)	Top Size (mm)	Top Size (Core)[3]	Closing Size (mm)
Bond Ball Mill	0.305	3.3	Any	0.149
SPI Test	0.305	38[3]	NQ	N/A
SMC Test	N/A	32	Any	N/A
Bond Rod Mill	0.305	13	Any	1.2
Bond Low-energy Impact	N/A	75	PQ	N/A
Drop-weight Test	N/A	63	HQ	N/A
MacPherson Autogenous	0.45	32	NQ	1.2
Media Competency	1.83	165	-	N/A
Pilot Plant	1.75	150-200	-	Various
LABWAL HPGR	0.25[4]	12.5	BQ	N/A

[1] Weight requested for the test, for typical ores (S.G. = 2.8 g/cm^3). Denser samples require more weight, proportional to the S.G.

[2] Approximate weight consumed in the test for typical ores (S.G. = 2.8 g/cm^3).

[3] Minimum core size for a complete test. Partial results can sometimes be obtained with smaller cores

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].

GRINDABILITY TESTS

BOND BALL MILL GRINDABILITY

The Bond ball mill grindability test is performed according to the original Bond procedure [4]. It requires 10 kg of minus 6 mesh (3.35 mm) material that is preferably prepared at the testing facility, by stage-crushing the sample to 100% passing 6 mesh, but normally less than 5 kg are actually used in the test. The test is closed with a fine screen (typically in the range 65 mesh to 270 mesh), and the size of the screen is normally

Sample Requested[1] (kg)	Sample Consumed[2] (kg)	Type	Steady-state (Y/N)	Database (Y/N)
10	5	Locked-cycle	Y	Y
10[4]	2[4]	Batch	N	Y
20[6]	5[5]	Single Particle	N	Y
15	8	Locked-cycle	Y	Y
25	10	Single Particle	N	Y
75	25	Single Particle	N	Y
175	100	Continuous	Y	Y
750	300	Batch	N	Y
>50000	10000	Continuous	Y	Y
250	25	Continuous	Y	N

[4]The recommended wieght for an SPI test is 10 kg of 38 mm, but the test itself only requires 2 kg minus 19 mm.

[5]The recommended top size for an SMC test is 32 mm, but the test can be performed on smaller rocks or drill core, requiring smaller weights.

[6]Rol. Diameter of the LABWAL HPGR.

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:

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

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 relies widely 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 [5].

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" (12.5 mm) and the test is run under a 100% circulating load. 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:

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

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 (12.5 mm for RWI and 3.35 mm 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 12.5 mm to about 1 mm. 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 [6].

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:

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

Where J 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 kWh/t as follows:

$$kWh/t = \frac{45.5 \times Joules/mm}{Specific\ Gravity}$$

The test is generally performed on 20 rocks, which is relatively small, resulting in poor statistics. 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. The test requires > 3" rocks or PQ core, although relevant numbers may be obtained from HQ core.

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_{80} of 12.5 mm 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. The SPI test itself requires 2 kg of ore with a top size of ¾" (19 mm), but a total of 10 kg of 1½" 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 12.5 mm, and the test is run to determine the time required to reach a P_{80} of 1.7 mm.

Higher grinding time indicates higher resistance to grinding, thus a harder ore. The SPI is transformed into kWh/t and is used for production forecast and circuit design using the CEET software [9], which was developed with the technical and financial support of 13 major mining companies. The SPI has the advantage of requiring a low weight, 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 profile.

JKTECH DROP-WEIGHT TEST

The JKTech drop-weight test, as shown by Napier-Munn et al [10], 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 30 particles is measured to assess the ore average density and 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 to 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. About 25 kg of material is actually consumed in the test, and all the products and unused material can be re-used for metallurgical testing.

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, which 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.

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 1. The t_{10} increases with higher energy inputs and reaches a plateau, which corresponds to Parameter A.

$$t_{10} = A\left(1 - e^{-b \cdot E_{cs}}\right)$$

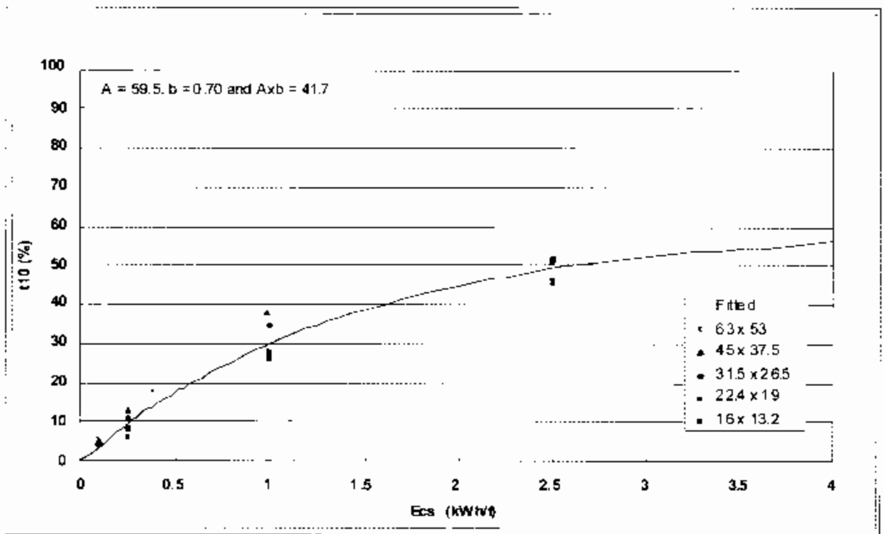

Figure 1: Drop-weight Test Interpretation

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 for a particle size analysis. By convention, the abrasion parameter (t_a) is equal to 1/10 of the t_{10} achieved in the abrasion test.

The density determination is performed on 30 rock specimens, using a water displacement technique. An example is presented in Figure 2, for an ore showing a bimodal distribution of densities. The density distribution of the ore is important for AG/SAG milling evaluation, as it will ultimately affect the bulk density of the mill charge and associated power draw. In this example, the steady-state density of the AG/SAG mill charge will be largely affected by the relative hardness between heavy and light components. The hardest of the two will dominate the mill charge, so the resulting steady-state density of the rocks in the mill charge may end-up anywhere between ~2.7 and 3.9. This is a significant range, which could make the power draw projections inaccurate, especially if the AG/SAG mill is designed for a low steel charge.

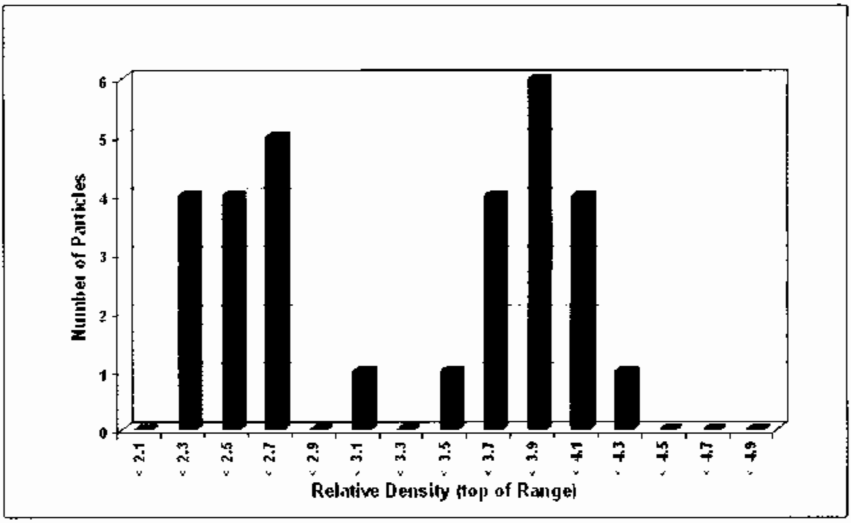

Figure 2: Relative Density of Rock Particles

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 3 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, 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 t_{10} with increasing size. Decreasing trends of t_{10} by size are fairly rare. These curves can be used to infer the competency of the ore at coarser size for those tests that are carried out on finer material, at the low end of the size spectrum.

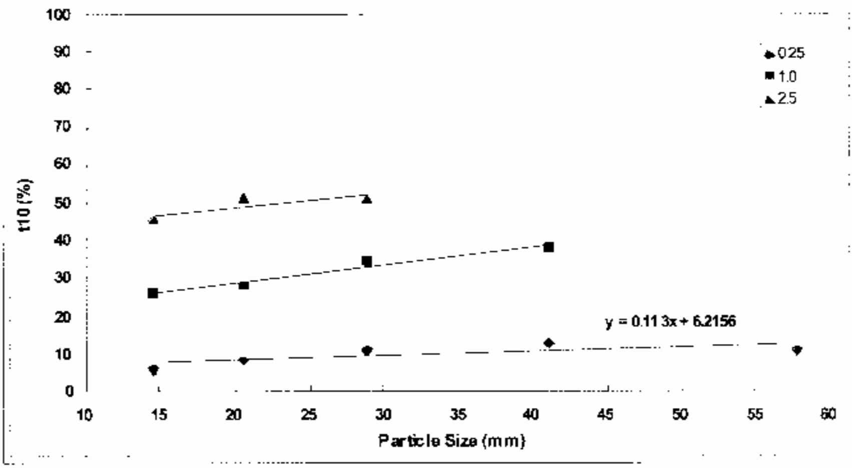

Figure 3: Variation of Hardness by Size from a Drop-weight Test

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 ¼ 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 16 mm. The recommended rock size is 26.5-31.5 mm, which requires preparing about 20 kg of sample, but only 5 kg is actually tested, and all the products and unused material can be re-used 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 t_a 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.

The advantage of the SMC test is that it generates the energy versus breakage relationship with a relatively small quantity of sample. Because the test can be performed on small rocks, it is well suited for variability testing.

MACPHERSON AUTOGENOUS GRINDABILITY TEST

The MacPherson autogenous grindability test is described in great detail in a separate paper from this conference [12]. The test was developed by Arthur MacPherson et al [13], as 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 1¼" 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.

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 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 draw, 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 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.

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 survival in autogenous milling. The most successful media competency tests is the Advanced Media Competency Test (AMCT), developed by Orway Mineral Consultants and Amdel [14], [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 165 mm. The mill is rotated for 500 revolutions and the charge is dumped and size analyzed. The surviving rocks are submitted to a 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 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 [16], [17]. As for autogenous mills, the traditional methodology for the testing and scale-up of HPGR has 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 25 kg 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 HPGR 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} inadequate, unless appropriate corrections are made [18]. (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 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. SGS 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 performance of the HPGR 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 K_{50} typically decreases with a higher pressure of operation, until it reaches a plateau.

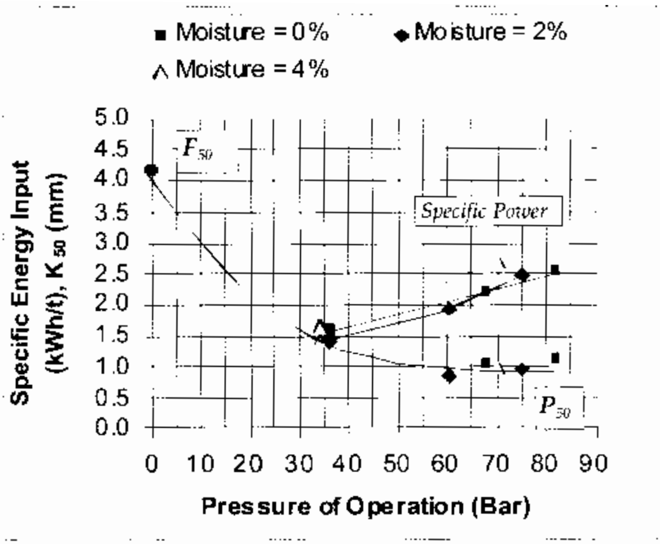

Figure 4: LABWAL HPGR Testing

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 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 are 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 12.5 mm 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 comparison can also be done against AG/SAG mills. This methodology has only been used to scope the potential energy savings of HPGR at small-scale.

CONCLUSION

For AG/SAG mills, grindability testing is always a compromise between the testing/sampling effort and the test deliverables. The cost of testing generally increases with the deliverables and the 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 on the deliverables. 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 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 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 if it causes 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 both be 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 weak nesses, 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 scale-up. 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 plant, before proceeding with the sizing of a commercial AG/SAG mill or HPGR, 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.

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CONVERSION FACTORS

US STANDARD TEST SIEVE SERIES

AMERICAN ASTM	TYLER STANDARD SCREEN	INTERNATIONAL
INCH OR SIEVE	INCH OR SIEVE	MILLIMETERS OR MICRON
1.06 inch	1.05 inch	26.50mm
1	-	25.00
7/8	0.883	22.40
3/4	0.742	19.00
5/8	0.624	16.00
0.53	0.525	13.20
1/2	-	12.50
7/16	0.441	11.20
3/8	0.371	9.50
5/16	2 1/2 mesh	8.00
0.265	3	6.70
1/4	-	6.30
3 1/2 sieve	3.5	5.60
4	4	4.75
5	5	4.00
6	6	3.35
7	7	2.80
8	8	2.36
10	9	2.00
12	10	1.70
14	12	1.40
16	14	1.18
18	16	1.00
20	20	850µm
25	24	710
30	28	600
35	32	500
40	35	425
45	42	355
50	48	300
60	60	250
70	65	212
80	80	180
100	100	150
120	115	125
140	150	106
170	170	90
200	200	75
230	250	63
270	270	53
325	325	45
400	400	38
450	-	32
500	-	25
635	-	20

DRILL CORE SPECIFICATION

	DIAMETER		VOLUME LENGTH	
	(MM)	(INCH)	M^3X10^{-3} / M	$INCH^3$/FOOT
AQ	27.0	1.062	0.57	10.6
TT	35.0	1.378	0.96	17.8
BQ	36.4	1.433	1.04	19.3
NQ	47.6	1.875	1.78	33.1
HQ	63.5	2.500	3.17	58.9
BQ3	33.5	1.320	0.88	16.4
NQ3	45.1	1.775	1.60	29.7
HQ3	61.1	2.406	2.93	54.6
PQ3	83.1	3.270	5.43	100.8