

THE DEVELOPMENT OF A SMALL-SCALE TEST TO DETERMINE **WORK INDEX FOR HIGH PRESSURE GRINDING ROLLS**

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ABSTRACT

The use of High Pressure Grinding Rolls is gaining significant interest as a replacement for SAG milling in the comminution of hard rock ores because of the potential for reduced costs in terms of energy and grinding ball consumption. Estimation of expected energy consumption for full-scale operations has conventionally involved the testing of a few fairly large samples in pilot scale HPGRs. This paper describes the development of a small-scale batch test method for determining a work index for HPGR of a large number of samples that can be used to show the variability of the ore as an integral part of a geometallurgical approach to circuit design and production forecasting.

The test equipment that was developed comprises a hydraulic press with adjustable pressure operating on small batches of ore in a locked cycle test procedure. A work index measurement was determined that links the specific energy consumed in the test to the breakage achieved such that the index can be used to predict comminution energy requirements.

The measurements were calibrated against laboratory scale HPGR equipment to develop a model for design and forecasting that includes crushers, HPGRs and ball mills in a complete comminution circuit.

INTRODUCTION

Estimation of the expected energy consumption for full-scale HPGR operations has conventionally involved the testing of a few fairly large samples in laboratory and pilot scale machines (Danilkewich, 2006). With the financial input of five mining corporations, SGS has developed a small scale test capable of providing relevant information on the variability of energy consumption and size reduction from drill core samples. It is our intention that the values measured in the test will be scaled up, through benchmark comparison with pilot sized and full sized HPGR units, to allow plant design and throughput forecast on a block by block basis of the mine plan using a new CEET program. CEET® (an acronym for Comminution Economic Evaluation Tool) is an advanced grinding design and performance predicting tool that uses energy relationships to model the performance of SAG / Ball mill circuits.

This paper describes the development of the equipment and a small scale static test that measures specific energy for compression breakage through the calculation of mechanical energy consumed and breakage achieved. We refer to this test as the Static Pressure Test, or SPT.

Tests were conducted to measure reproducibility, the effects of feed moisture, feed particle size and feed volume. A locked cycle test procedure was developed to calculate a High Pressure grindability index, HPI that is used to predict the specific energy requirements of HPGR laboratory units of 0.25 m and 0.71 m diameters.

TEST EQUIPMENT

Since the objective is to have a small scale test that can handle large numbers of samples to describe variability across the ore body, equipment was selected to handle only 1 to 2 kg of broken ore sample in a static pressure mode rather than continuous throughput. A

conventional 50 ton workshop hydraulic press was selected, as shown in Figure 1 that can apply high pressure in a controlled manner to the ore confined in a cylinder. A steel cylinder of 100mm inner diameter, shown in Figure 2, was selected such that the maximum applied pressure was 55 MPa, estimated to be similar to the working pressure on hard rock within the breakage zone of a continuous HPGR. The height of the cylinder was selected at about 200 mm to hold the desired volume of broken ore and suit the stroke length of the hydraulic press. The base of the cylinder was easily removable to allow the broken rock to be pressed out after crushing. The rate of movement of the press piston as supplied was 3.4 mm/

sec under load. The piston moves against increasing resistance until the limit of the stroke or maximum set force (e.g. 50 tons) is reached.

Figure 1: 50 t hydraulic press assembly

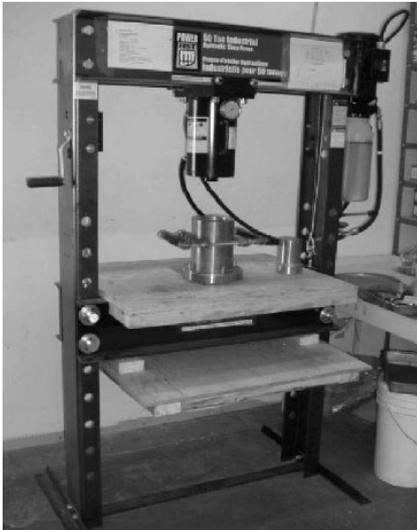
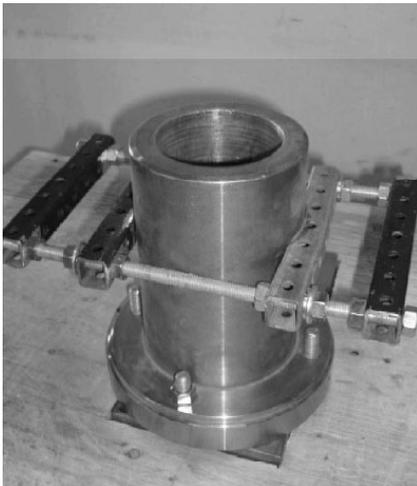


Figure 2: Steel cylinder with 100mm I.D



It was demonstrated that the specific energy used in breakage can be measured during the test and related to the breakage that occurred. However, energy measurements were difficult to make since they required the concurrent reading of distance traveled for the piston and increasing pressure applied over a testing period of some 20 seconds. It was recognized that such data acquisition needed to be made by better instrumentation and gathered into a computer for calculations. These modifications were completed and the equipment is shown in Figures 3 and 4. The data is now very easy to collect,

with readings every 0.25 sec, and allows for speedy and reliable test work. The pressure is increased until the set point is reached and then pressure is automatically released.

Figure 3: 50 ton piston with distance measurement rheostat

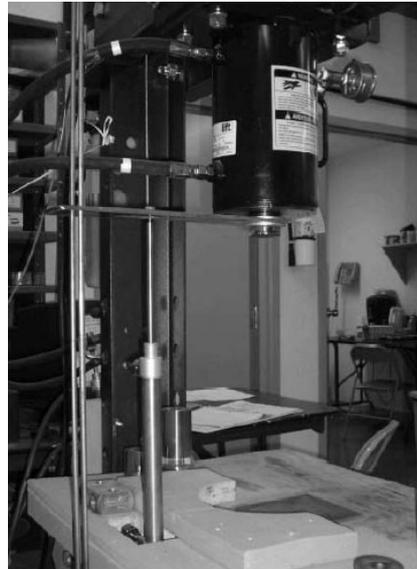


Figure 4: Operator station with display monitor and input/output signal box (top left)



The computer data collection system allows accurate plots of distance vs. time, Figure 5 and force vs. time, Figure 6. The "knee" that occurs low down on the force vs. time plot appears to be the force needed to achieve full packing of the ore sample before any breakage begins, typically about 7.5 tons i.e. about 9 MPa in the 100mm diameter cylinder.

The 100mm steel cylinder allows pressures of up to 55MPa to be applied

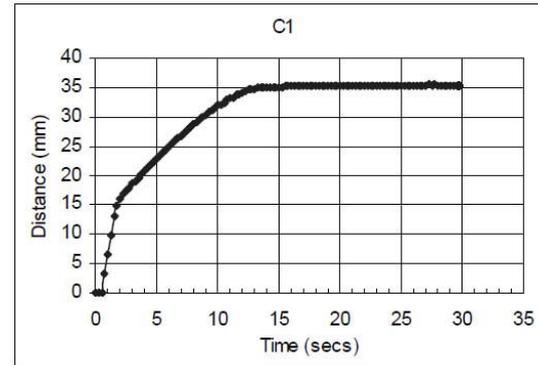


Figure 5: Distance traveled by piston vs. time

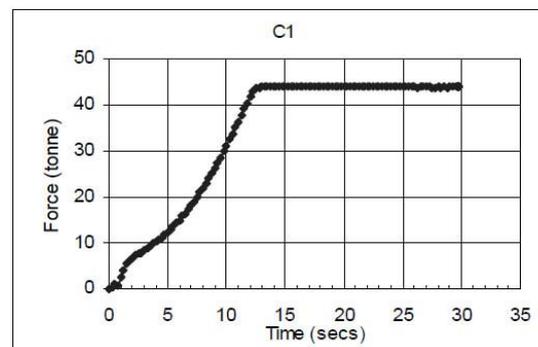


Figure 6: Force used by press vs. time

directly to the ore sample. A 70mm cylinder was added to allow pressures up to 110MPa to be used. This allows testing at the estimated (between roll) pressures that are available on the laboratory scale Polysius Labwal HPGR machine. These pressures were chosen since the resultant cake is similar in bulk density to that produced in testing using the Labwal machine.

DEVELOPMENT OF TEST PROCEDURE - THE STATIC PRESSURE TEST, SPT

Conventional primary grinding technology uses a semi- or fully autogenous mill and the accepted small scale test to determine the specific energy requirement is the SAG Power Index, SPI test. Ore samples are typically prepared for SPI testing as part of any design or forecasting study using CEET technology. This preparation requires crushing a sample to 100% minus ¾ inch, with 80% minus ½ inch. Consequently such a sample is available for static pressure testing and for comparison with SPI values and their use in CEET studies.

The testing was initially conducted in open-circuit using 2 passes of the sample through the press. After this procedure exhibited certain shortcomings, the test was changed to a locked cycle technique as described below.

LOCKED CYCLE TESTS

The preferred test procedure is a locked cycle test akin to the Bond Ball mill work index determination. The first cycle starts with minus 6 mesh ore removed since it is believed that the fines content can fill most of the voids allowing little room for rock breakage and piston movement. Without adequate piston movement there is little measurable energy used and therefore very little breakage.

The test procedure requires that the plus 6 mesh material is weighed (typically about 1600 grams), placed in the cylinder and tamped down. The piston is brought to rest against the surface of the sample. The press is started and concurrent observations taken of pressure and piston distance moved until the piston stops at the required maximum set pressure. The piston movement lasts for about 15 seconds. After withdrawing the piston the base of the cylinder is removed and the sample pushed out (using the piston) as broken rock and agglomerates as shown in Figure 7.



Figure 7: Broken rock with cake agglomerates

The minus 6 mesh produced in the 1st cycle is removed and replaced by fresh ore (the whole sample including minus 6 mesh) for the 2nd cycle. Cycles are continued until a consistent amount of minus 6 mesh is produced. This can take as little as 5 cycles. The whole ore

sample is used to determine the F_{80} and the minus 6 mesh product from the last cycle is used to determine the P_{80} .

The average specific energy for the last 3 cycles is now used to calculate the locked cycle HPI, similar to the Bond Work Index value, where:

$$E = 10 * HPI * (\sqrt{1/P_{80}} - \sqrt{1/F_{80}})$$

Bond is preferred to the Rittinger equation proposed by others (Klymowsky, 1997) since the use of the square root (0.5 exponent) for the product goes some way in accounting for the additional energy consumed in generating more fine material than would be expected at the same P_{80} in a conventional crusher. An alternative exponent as suggested by Morrell (2004) may prove to be suitable after gaining more experience.

The mechanical energy consumed in each test is calculated from the concurrent force and distance measurements. Force is plotted against distance moved as shown in Figure 8. The key aspect of the test is that the work or energy used is calculated by force multiplied by distance moved at any small unit of time such that total mechanical energy (joules) used is the integration under the curve in Figure 8. Mechanical energy is converted to equivalent electrical energy (kWh) and divided by the product weight (minus 6 mesh) to determine a specific energy used in breakage, in conventional units of kWh/t. Average energy and product weights from the last three cycles are used to determine HPI. The results can then be compared from one ore sample to another to investigate variability across an ore body.

The locked cycle test should be reliable in establishing figures for use in scale-up to plant operation, since the product size, P_{80} , in the region of 2 to 3mm, is reasonably close to actual plant operation.

Shortened version of Locked Cycle test

The locked cycle test is a relatively lengthy procedure requiring 6 to 7kg of sample. HPI is calculated from the average specific energy determined from

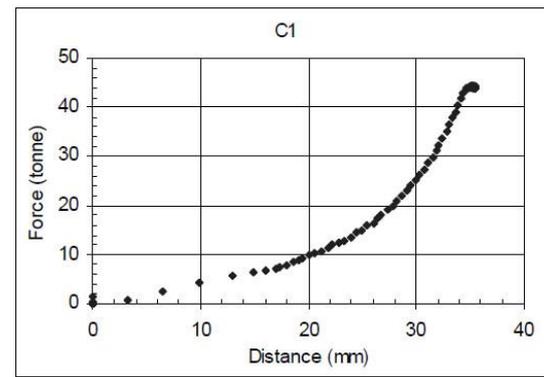


Figure 8: Force used by press vs. Distance traveled by piston

the last 3 cycles, the 80% passing size of fresh feed, and the 80% passing size of the -6# fraction (the product) of the last cycle. Examination of the results suggests that a good estimate of locked cycle test result can be obtained after only the 2nd cycle as shown in Figures 9 and 10. Specific energy and final product can therefore be measured after Cycle 2 to supply a good estimate of HPI. However, this should be calibrated by conducting the full locked cycle test on a proportion of the tests from any full ore body study.

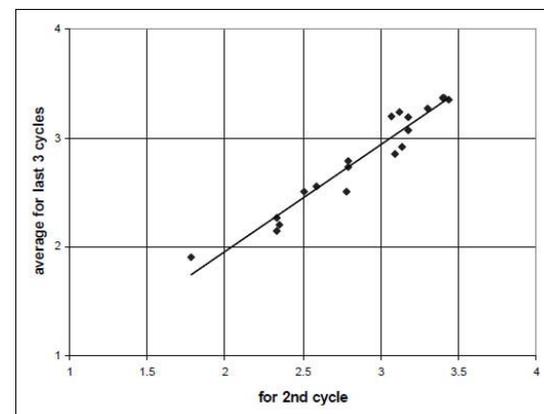


Figure 9: Relationship between specific energy (kWh/t) used in Cycle 2 and the average of last 3 cycles

OPEN-CIRCUIT TESTING

Initial development of the SPT involved the use of an open-circuit 2-pass test that was used for checking test reproducibility, and the effect of varying feed size and feed volume. The 2-pass test procedure involved the use of 2 kg of minus ¾" ore, screened to remove the minus 6 mesh and pressed in the 100mm steel cylinder. The minus 6 mesh material produced in the first pass was removed and the over-size returned to the cylinder for a 2nd pressing. The total

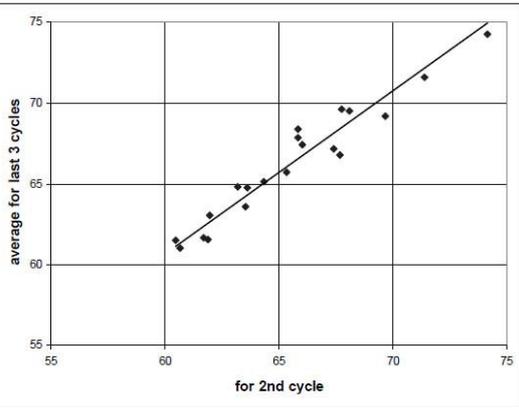


Figure 10: Relationship between -10# in the product from Cycle 2 and the average of last 3 cycles

energy used over the 2 passes was measured. Total energy and the feed and product sizes were used to compute a High Pressure index, HPI (for the open-circuit test).

Reproducibility

The test appeared to be very reproducible supplying similar results from duplicate samples of ore. Test results on samples from different ore bodies are summarized in Table 1.

Effect of Moisture content

Laboratory HPGR test programs conducted on the 0.25m diameter by 0.1m Labwal and 0.71m diameter by 0.21m Regro machines supplied by Polysius consider the effect of low levels of moisture content of the feed. SPT work is normally conducted on air dry samples. A series of tests were conducted on a sample after air and oven drying and at 2 and 4% moisture content.

The results are presented in Table 2 showing similar changes in the HPI with moisture as pilot machine testing. These changes need to be investigated on more samples before using the data in plant design.

Effect of particle size of the feed

Typically tests were conducted on minus 3/4 inch feed with the minus 6 mesh removed to allow space in the cylinder for breakage to occur. A series of tests were conducted to investigate the effect on the calculated HPI of changing the top

Table 1: Repeat SPT results

Test	Sample	Pressure MPa	Energy Input	F ₈₀ microns	P ₈₀ microns	Product -6#	HPI
A	Gold ore	55	1.26	12900	9000	45.6	16
B	Gold ore	55	1.17	12500	9000	45.4	15.4
A	Au/Ag ore	54.7	1.21	14450	9250	47.2	14.3
B	Au/Ag ore	54.7	1.11	13450	9850	46	15.1
C	Au/Ag ore	54.8	1.23	14400	10150	45.1	16.1
A	Copper ore 1	55	1.23	14100	9400	45.2	15.1
B	Copper ore 1	54.9	1.19	14175	10000	44.9	15.7
A	Copper ore 2	55	1.21	15150	8500	49.3	12.8
B	Copper ore 2	54.8	1.27	14200	9000	48.9	14.9
A	Nickel ore 1	54.6	1.07	13275	10200	33.7	15.6
B	Nickel ore 1	55.3	0.91	12900	10400	32.4	14.5
A	Moly ore 1	54.5	1.31	8425	5500	60.2	14.2
B	Moly ore 1	54.7	1.31	8650	5550	59.7	14.1
A	Nickel ore 2	55	0.97	13500	8000	37.1	10.5
B	Nickel ore 2	55	1	13750	8125	37.9	10.8
A	Moly ore 1	55	0.91	8000	2750	65.9	6.3
B	Moly ore 1	55	0.9	7600	3050	60.9	6.7

Table 2: Repeat tests conducted at different moisture content

Sample moisture	Pressure MPa	Energy Input kWh/t	F ₈₀ microns	P ₈₀ microns	HPI	Product -6#
Air dry	55	1.31	8425	5500	14.2	60.2
Air dry	55	1.31	8650	5550	14.1	59.7
Oven dry	55	1.28	8775	5450	13.3	60.5
4% moisture	55	1.2	8550	5400	12.6	59
2% moisture	55	1.25	8670	5600	13.5	59.3

size of the feed and the effect of allowing the minus 6 mesh to remain in the feed. The results from two ore samples are shown in Figures 11 with the HPI

declining with increase in feed size when the minus 6 mesh is retained in the feed and increasing after the fine fraction was removed.

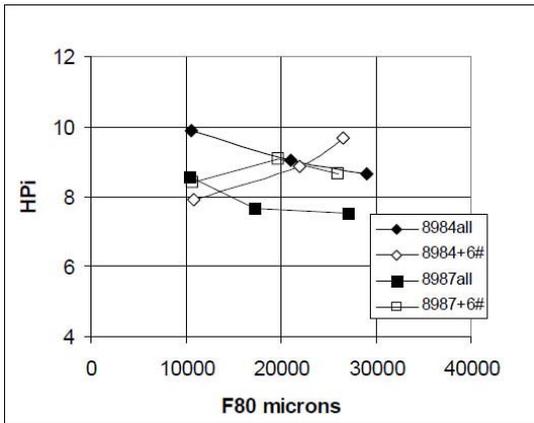


Figure 11: HPI vs. Feed size for two samples

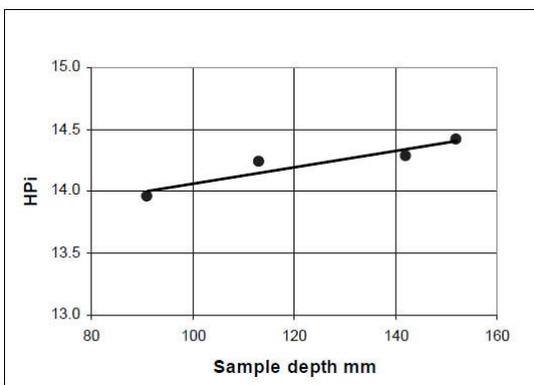


Figure 12: HPI vs. Sample depth for one sample



Figure 13: Unbroken rock seen at the bottom of the 100mm diameter cylinder after testing

Such inconsistency of results point to the need for standardized feed size F_{80} and size distribution in the open-circuit test to ensure the reliability of data needed for hardness comparison between samples and use in a scale-up model. This became a motivation for using the locked cycle approach to testing.

Effect of feed volume

It was noticed that changing cylinder diameter while applying the same pressure (i.e. force divided by area) caused changes to the results. It was at first suspected that the difference may be a result of edge effect in the cylinder, but then it became apparent that the changes in results are due to having different depths of ore in the cylinder (equivalent to changing the gap size in an HPGR). This can be seen in a series of tests conducted on a sample at the same pressure with a resultant small increase in HPI with depth shown in Figure 12.

Close observation revealed a layer of rock at the bottom of the cylinder that was completely unbroken when depth of ore was too great or pressure was low, as shown in Figure 13. All of the energy was absorbed in breakage at the higher levels with insufficient force being applied to allow further movement of the piston against the resistance due to inter-particle friction in the broken rock.

It appeared that the variation in volume of +6 mesh available from sample to sample and used in the open circuit test could introduce some error into the HPI value. This was further motivation for the change in procedure to a locked cycle test.

SPT RESULTS

EFFECT OF PRESSURE

It is obvious that increasing HPGR pressure will result in more breakage while consuming more energy. This can be seen from test work with both the Labwal and Regro pilot scale HPGR machines. The pressure used in an HPGR is normally quoted as "Specific grinding force" (quoted in N/mm^2 or MPa) defined as the total hydraulic force exerted on the rolls divided by the projected area of the rolls (Klymowsky, 2006). The

exerted force (in kN) is a product of the pressure on the hydraulic pistons and the piston area. The results of varying the pressure or "specific grinding force" used in single pass tests conducted on a Labwal at Lakefield and a Regro in Germany using the same minus 1/2" feed material are shown in Figures 14 and 15. In Figure 14 the increase in energy (measured as net electrical energy) consumed is approximately proportional to the pressure applied. Note that all test results conducted at various % moistures are presented and may explain the scatter in the results.

In Figure 15 the % minus 6 mesh produced is plotted against net electrical kWh/t consumed. It appears that there is a declining return in terms of breakage achieved from the extra energy used i.e. the pressure applied. Calculation of the HPI i.e. energy used per unit of breakage, would show an increase of HPI with pressure (specific grinding force) applied. Machine suppliers such as Polysius are aware that beyond a certain input, energy is absorbed and wasted as friction generating heat. This is known as the "saturation energy". This situation was noted in the development of the Cerro Verde project (Vanderbeek, 2006) and others in the literature.

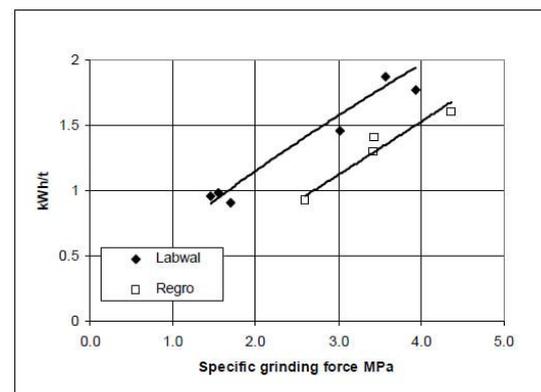


Figure 14: kWh/t vs. Specific grinding force (MPa) for laboratory HPGR machines

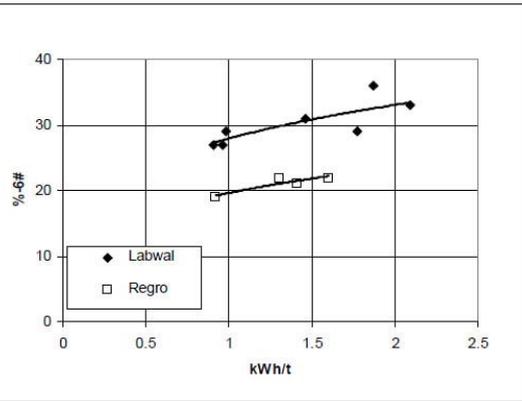


Figure 15: %-6# produced vs. specific energy consumed (kWh/t)

The same situation can be seen in testing samples by SPT. The HPI, a measure of hardness (or energy used per unit of breakage achieved) can be seen to increase disproportionately as the applied pressure is increased for samples from a single ore body in Figure 16.

$$HPI = a \times (MPa)^b$$

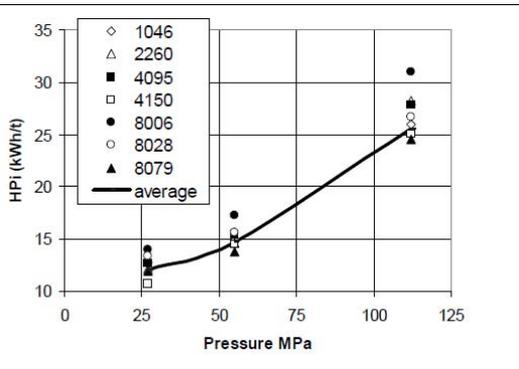


Figure 16: HPI vs. applied pressure for samples from the same ore body

Over the range of pressures used in the test, the relationship can be considered to take the form:

$$HPI = a \times \exp(b \times MPa)$$

Where 'a' and 'b' are functions of the HPI at a set standard pressure (55 MPa in the case of these tests).

These functions may change for different ore bodies as can be seen in Figure 17 where the letters in the legend (B, E, etc.) indicate different ore bodies.

The SPT will therefore indicate when there is an excess of pressure (achieving minimal extra breakage), while conducting the test in locked cycle will also indicate when there is insufficient pressure (resulting in a high circulating load).

The set standard SPT pressure (55 MPa) appears to be in reasonable agreement with the actual pressure utilized between the rolls of a Labwal machine under typical operating conditions. This can be determined by calculating a "force acting angle" under typical operating conditions (Klymowsky, 2006) and determining the projected area (length of arc formed by twice the angle multiplied by length of rolls). Dividing the exerted force (kN) by this projected area (mm²) supplies a pressure (MPa) similar to that used in the SPT.

COMPARISON OF HPI WITH SAG AND BALL MILL WORK INDICES

Comparison of the HPI values measured using the locked cycle test at a pressure of 55 MPa with SPI values (used to determine energy required for SAG milling) and with Bond Ball mill work indices, BWi are shown in Figures 18 and 19 below.

The correlation of HPI with both SPI and BWi in Project C is surprisingly strong, but not so surprising if we consider that BWi also correlates very well with SPI. This is an ore with consistent comminution energy requirement throughout a large size range.

Comparison of HPI with SPI and BWi for other ore bodies shows greater scatter over all the samples tested.

Plotting the cumulative frequency distribution of HPI values for these ore bodies in Figure 20 illustrates the value of the SPT in variability testing required for plant design and production forecasting.

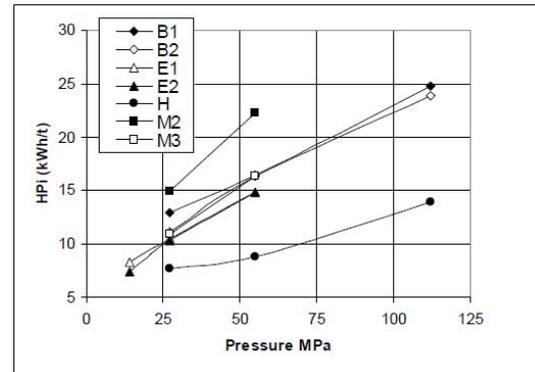


Figure 17: HPI vs. applied pressure for different ore bodies

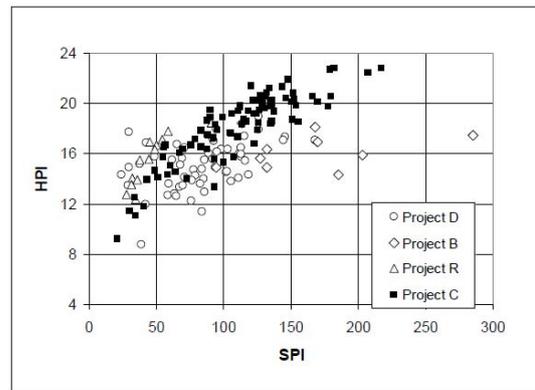


Figure 18: HPI vs. SPI for four ore bodies

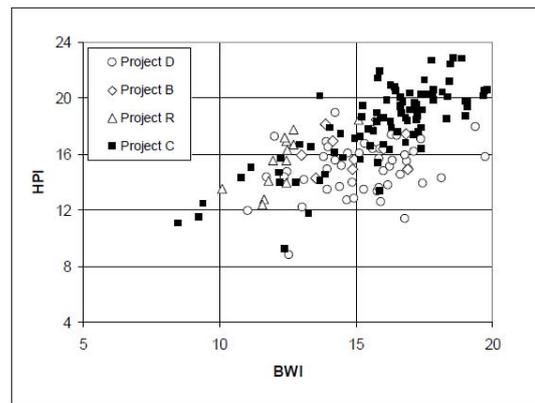


Figure 19: HPI vs. BWi for four ore bodies

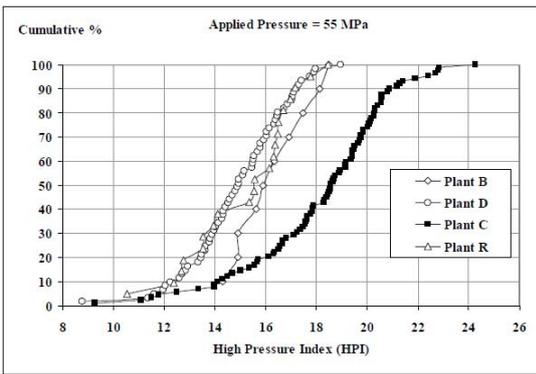


Figure 20: HPI frequency distribution for four ore bodies

EFFECT OF HPI ON TEST PRODUCT SIZE

The variation in HPI value between samples in locked cycle tests has an impact on the P_{80} of the finished product as shown in Figure 21, and on the amount of finished product (i.e. the % -6 mesh) from each cycle as shown in Figure 22. This data is of value in a scale-up prediction of the size of material to be treated in a subsequent Ball milling operation and the amount of circulating load at the HPGR.

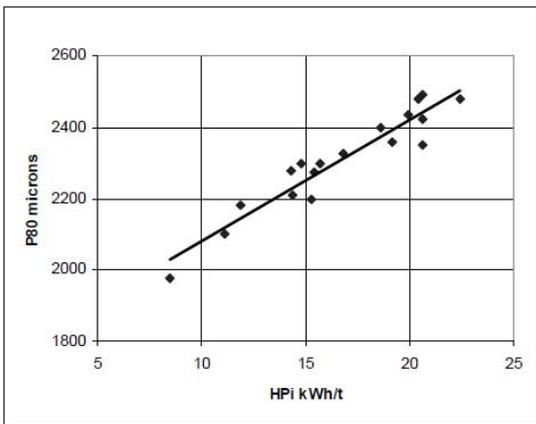


Figure 21: Variability between samples in the P_{80} of -6# product at a pressure of 55 MPa

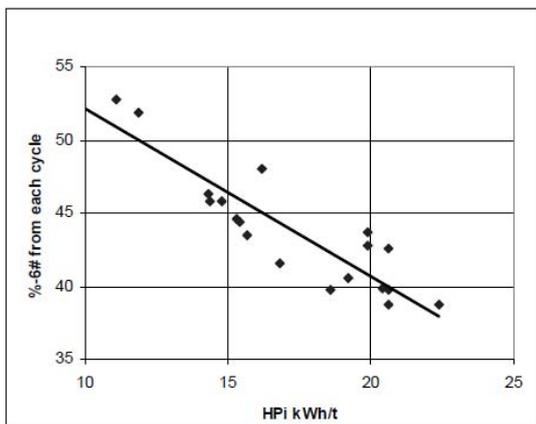


Figure 22: Variability between samples in % of -6# material from each cycle at a pressure of 55 MPa

Size distributions of closed circuit SPT products are shown in Figure 23 for three samples with one sample showing the response to changing pressure. They are similar to size distributions presented in the literature for laboratory and pilot plant testing of hard rock.

SCALE UP

To date there is only a short series of samples that were tested by the SPT and also in locked cycle tests on the Labwal pilot scale machine at Lakefield, and a further sample tested in the larger Regro pilot machine at Polysius in Germany. Most samples are tested in open circuit at these facilities and the data is not comparable to the SPT for scale up. The specific energy used in the laboratory machines is higher than that measured in the SPT, as would be expected since they are electrical power measurements that include machine efficiency compared with the mechanical energy calculation of the SPT. Any scale-up energy function used must take cognizance of this situation.

The scale up function based on these pilot results produces the comparison shown in Fig 24, where the open point is the Regro test. The scatter may be due to the lack of consideration of different pressures and moisture variation. As a first approximation, it was assumed that the pressure (specific grinding force) used in the pilot machines always relates to a fixed pressure of 55 MPa in the SPT, since (when measured) it produces a similar cake (or "flake" as agglomerates are sometimes called) density as shown in Table 3. Further data is required to eliminate the source of outliers in Figure 24 and tighten the forecasts.

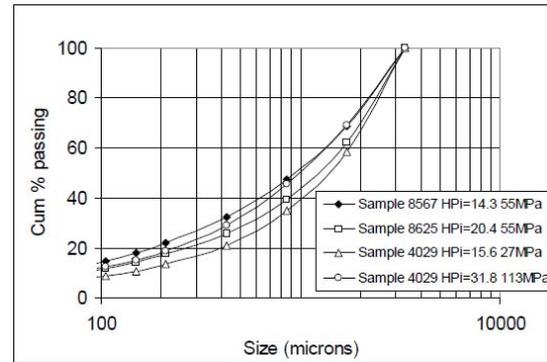


Figure 23: Locked cycle SPT product size distributions

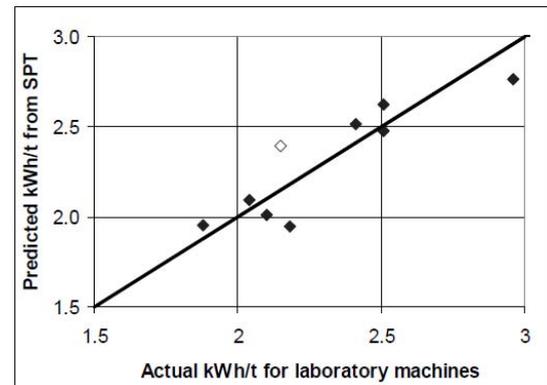


Figure 24 Predicted vs. Actual specific energy consumed on pilot machines

Table 3: Comparative cake densities for SPT and Labwal products

Sample	SPT		Labwal	
	Cake density	Pressure MPa	Cake density	Specific grinding force N/mm ²
PES	2.29	54	2.25	2.60
PEM	2.17	54	2.19	2.59
PEH	2.15	54	2.24	2.59
PWS	2.13	54	2.22	2.51
PWM	2.21	54	2.32	2.52
DS	2.27	55	2.26	2.92

CONCLUSIONS

A reasonable amount of laboratory test work has now been conducted on a variety of ore samples. Development of a small scale test that replicates the type of breakage achieved in HPGRs is at the point where it can be said that:

- This is a piece of equipment that can easily be used to generate reliable reproducible measurements of the energy used in the test.
- Test material feed and product sizes are measured so that a grindability "index", HPI can be calculated that relates energy consumed with breakage achieved.
- There is the potential for error in open-circuit tests due to variation in penetration of the breakage within the cylinder when the charge volume changes. A standard quantity is required for such a test feed.
- There is the potential for error in determining an index for feed material of variable size, F_{80} and size distribution. A standard size is required for test feed.
- A locked cycle test akin to the Bond Work Index test can be conducted to determine a grindability index for comparison of samples to show the variability of the ore body.

- Conducting tests at various pressures has shown that the HPI can be measured at a single pressure and the value estimated for other applied pressures for that ore body.
- A new version of CEET has been written to forecast throughput for a given Secondary Crusher, HPGR, Ball mill circuit, and conversely such a circuit can be designed to meet a specified production from a given ore body. Further scale up data is required to refine the models.

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