Predicting SAG/AG Mill and HPGR Specific Energy Requirements Using the SMC Rock Characterisation Test

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Abstract. The SMC Test is described together with the sample requirements necessary to carry it out. The test is able to use very small sample quantities making it ideal for use with drill core. It generates a Drop-weight Index (DWi), which is shown to be correlated to the JK drop-weight test parameters A and b. The DW_i can also be incorporated in an equation that predicts the specific energy and transfer size of AG/SAG circuits. Its accuracy is demonstrated using data from a wide range of plants. The DW_i has been found to be correlated to the point load index, which makes it valuable for Mine-to-Mill projects. It is also correlated with the operating work index of HPGR circuits and in conjunction with pilot and/or laboratory scale HPGR testwork can be used to determine specific energy requirements for such circuits.

1 INTRODUCTION

It is generally recognised that the most accurate means for predicting the specific energy of grinding circuits is to pilot them. However, one of the major drawbacks of this approach is that a relatively large sample is required to do so. Collecting such a sample is expensive and in cases where the deposit is at depth, not practicable. Even if a sufficiently large sample could be obtained the question still arises as to whether the sample is representative of the orebody as a whole. In cases where the deposit is highly variable this is a particular problem. Ideally under these conditions it would be valuable to obtain samples of all of the major ore types and pilot these independently. However, such an approach would be even more prohibitive than treating a single sample. An alternative is to carry out laboratory rock breakage characterisation tests on drill core and use these results either on their own or in conjunction with one pilot test, which provides a baseline performance. The drill core data are then referenced against this result. One of the big advantages of this approach is that many core samples can be tested and a much more detailed picture of the comminution characteristics of the orebody can be obtained than would be the case if a single bulk sample were used. One of the potential drawbacks, however, is the extent to which laboratory tests are able to provide accurate predictions of comminution circuit performance. An important question that needs to be answered, therefore, is: “What is the most appropriate laboratory test to conduct and how should its results be used?”

Although drill core is much less expensive to obtain than bulk samples, drilling campaigns are still expensive and hence as far as possible the drill cores are put to multiple uses. This usually means halving or quartering it, with the result that only very small quantities may be available with which to carry out comminution testwork. The laboratory rock breakage test must therefore be able to accommodate this limitation.

With these problems in mind the SMC Test was developed together with a variety of approaches that use the results from the test to predict AG/SAG mill and HPGR circuit performance.

2 TEST DESCRIPTION

The test (referred to as the SMC Test) was developed to make use of relatively small samples, both in terms of quantity and particle size and to be versatile so as to make as much use as possible of whatever sample(s) is/are available for testing. As a result it is able to accommodate a wide range of particle sizes either in core or crushed form. The test is applied to particles of a particular size, the size chosen depending on the type and quantity of sample available. The choices of particle size that can be used in the SMC Test is shown in Table 1. Sample sources can be from a range of core sizes as given in Table 2. Typically either the 31.5+26.5mm or –22.4+19mm sizes are chosen as these are easily extractable from HQ and NQ cores respectively, and these tend to be the most popular core sizes used. When sample availability is very limited, quartered (slivered) core samples are cut using a diamond saw (Figures 1-3). This results in sample mass requirements as low as 2-2.5 kgs in total. However, where core is available in sufficient quantity (10-15 kgs) it can be crushed and the appropriate size fraction extracted eg quartered PQ core or half HQ or whole NQ could be crushed to extract (say) –22.4+19mm specimens suitable for testing etc.

Table 1 – Particle Size Ranges

Particle size (mm)
-45+37.5
-31.5+26.5
-22.4-19
-16+13.2

Table 2 – Core Sizes

Core	Nominal diam. mm
PQ	85
HQ	63.5
NQ	47.6
BQ	36.5
AQ	27

Once the core has been cut or crushed/sized into the chosen particle size range, 100 specimens are selected and divided into five equal lots. Each lot is then broken in an impact device using a range of closely controlled energies. A suitable impact device is the JKMRC's drop-weight tester (Napier-Munn et al, 1996), a picture of which is shown in Figure 4. After breakage the products are collected and sized on a sieve whose aperture is related to the original particle size. The % of undersize from sieving the broken products is plotted against the input energy. A typical plot from a test is given in Figure 5 and shows the expected trend of an increasing amount of undersize as the input energy is increased. The slope of this plot is related to the strength of the rock, a slope with a larger gradient being indicative of a weaker rock. The gradient of the slope is used to generate a so-called Drop-weight Index (DW_i). The DW_i has the units of kWh/m^3, which in turn has the same dimensions as strength and hence it is not surprising that the DW_i is correlated with direct strength measurements such as the point load index (see later).

The high degree of control imposed on both the size of particles and the energies used to break them means that the SMC Test is very precise and is largely free of the repeatability problems which plague tumbling mill rock characterisation tests (Angove and Dunne (1997), Kaya (2001)). Such tests usually suffer from variations in feed size, which is often not closely controlled, as well as energy input, which although is often assumed to be constant per mill revolution is often highly variable (Levin, 1989).

Figure 1 – Sample Pieces Cut from 50mm Quartered Core

Figure 2 – Sample Pieces Cut from Whole 50mm Core

Figure 3 – Sample Pieces Cut from Half 50mm Core

3 USES OF THE DW$_i$

3.1 Modelling and Simulation of AG and SAG Mill Circuits

The use of modelling and simulation has become routine in the design and optimisation of AG and SAG mill circuits. One of the most widely used models for this purpose is the so-called “variable rates” model (Morrell and Morrison, 1996). A more up-to-date version has also been developed with enhanced predictive capabilities (Morrell, 2004). This uses a two-parameter description of rock breakage that is developed from data obtained from a drop-weight test (Napier-Munn et al, 1996). The two parameters (A and b) are ore specific and relate the t_{10} (a size distribution index) to the applied specific energy (Ecs). The equation used for describing the relationship between the t_{10} and Ecs is given below.

$$t_{10} = A\,(1 - e^{-b.Ecs}) \qquad (1)$$

The specific comminution energy (Ecs) has the units kWh/t and is the energy applied during impact breakage. As the impact energy is varied, so does the t_{10}. Higher impact energies produce higher values of t_{10}, which is reflected in products with finer size distributions. The A and b parameters, in conjunction with equation 1, are used in AG/SAG mill modelling for predicting how rocks break inside the mill. From this description the model can predict what the throughput, power draw and product size distribution will be.

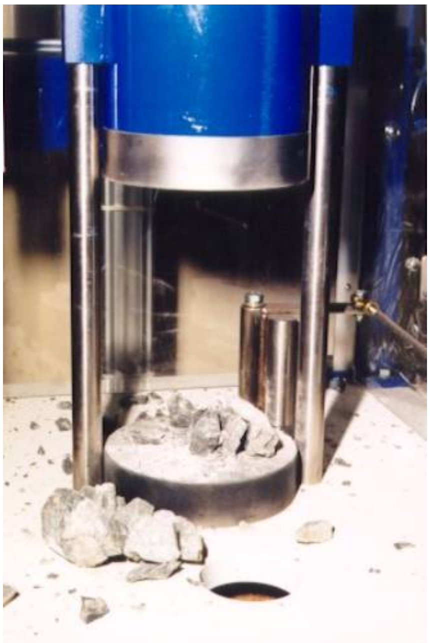

Figure 4 – Drop-weight Tester

The standard JK drop-weight test normally needs at least 75 kgs of raw material and hence normally precludes its use for small drill core samples. However, the DW$_i$ is highly correlated with the A and b parameters and therefore can be used to estimate their values very accurately. Figure 6 illustrates this using data from 40 different ore types. The scatter apparent in the figure has an associated standard deviation of 6.5%. This is related to the differences in the variation of strength with particle size that different rocks exhibit. This scatter can be reduced by carrying out full drop-weight tests on selected samples from the orebody in question to better define the size-by-size relationship and hence refine the DWi – A,b correlation. Such drop-weight tests are usually referred to as SMC Test “calibrations”, though from the previous comments they can be dispensed with if the 6.5% precision of the data base correlation is deemed acceptable.

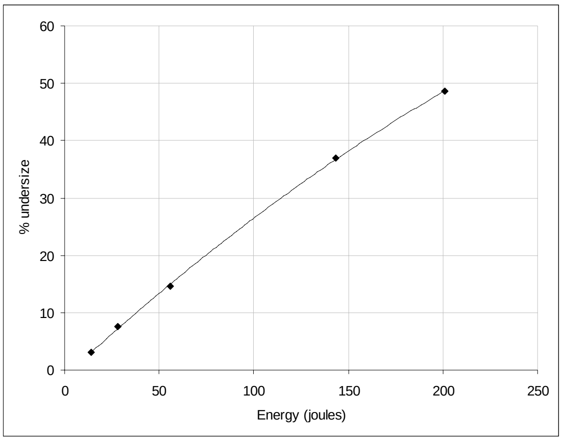

Figure 5 – Typical Results from a SMC Test

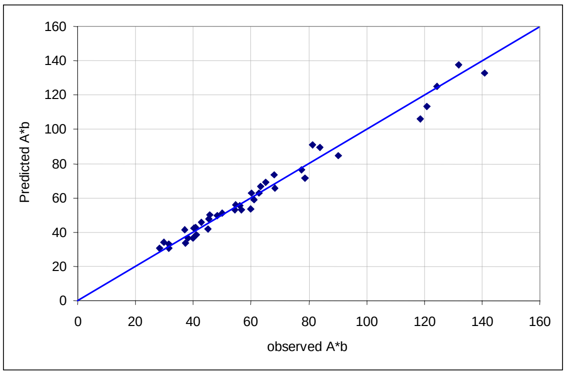

Figure 6 – Observed vs Predicited Values of A x b Using the DW$_i$ Data Base Correlation

Apart from being able to predict throughput and power draw of AG/SAG mills, modelling and simulation also enables a detailed flowsheet to be built up of the comminution circuit response to changes in ore type. It also enables optimisation strategies to be developed to overcome any deleterious changes in circuit performance that are predicted. This is particularly useful during the design stage as the chosen circuit can be tested under a range of conditions to see whether the circuit will meet its production targets. Strategies can then be developed to overcome any potential problems. These can include both changes to how mills are operated eg ball load, speed etc but also changes to feed size distribution through modification to blasting practices and primary crusher operation – so-called Mine-to-Mill approach.

3.2 Mine-to-Mill

The feed size to AG and SAG mill circuits has been demonstrated to have a significant impact on throughput with effects such a that illustrated in Figure 7, being commonplace. Modifying blast design and primary crusher operation can significantly influence AG/SAG mill feed size, hence giving a potentially cost effective way to increase comminution circuit throughput. Trial and error experimentation in this field, however, can be very costly and thus it is usual to rely on blast fragmentation modelling and grinding circuit simulations to determine what the optimum blast design should be. This will vary with ore type and hence it is important not only to have appropriate blast models but also rock breakage descriptions. Blasting models require information on rock mass competence such as provided by the point load strength (Scott et al, 2002). The DW_i is correlated with the point load strength (Figure 8) and hence can also be used in blast fragmentation modelling where direct measurements of point load strength are not available. Conversely, where a significant data base of point-load tests are available these can be used to augment the comminution description of the orebody by using the correlation in Figure 8 in reverse.

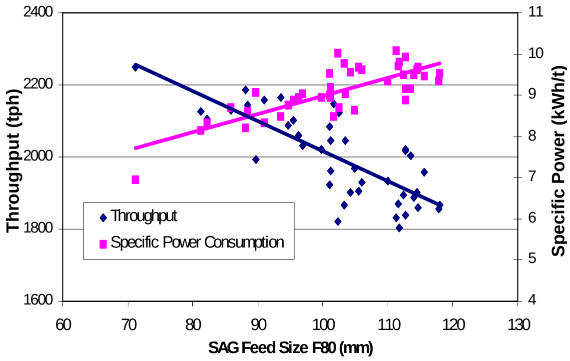

Figure 7 - Influence of Feed Size on SAG Mill Performance (after Hart et. al., 2001)

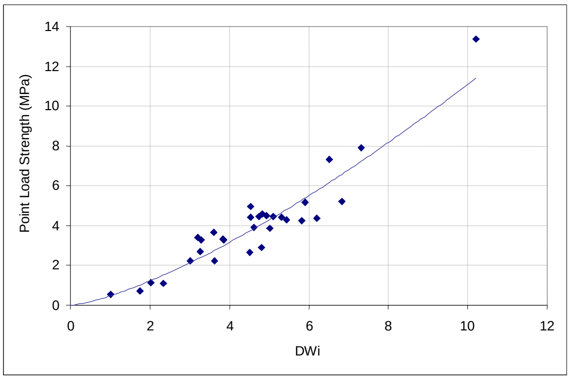

Figure 8 – Correlation Between Point Load Strength and the DW_i for a Copper Ore

3.3 Power-based Calculations

3.3.1 AG/SAG Mills

The power-based approach to design uses a methodology which, given certain ore breakage characteristics, predicts the specific energy for a particular AG/SAG mill circuit. The multiplication of the specific energy by the target throughput gives the required power draw of the mill. A mill is then selected which can draw the required power under the chosen operating conditions eg ball charge and speed.

The choice of an appropriate measure of the ore breakage characteristics and an associated technique for predicting the specific energy are obviously very important for this approach to work. The DW_i has been found to provide a good indication of the breakage characteristics of ores wrt AG and SAG mills and when combined with equation 2 is able to predict the specific energy of a wide range of circuits with a high degree of accuracy.

In the form shown in equation 2 it is suitable for operations in closed circuit with trommels or screens with apertures typically in the 10-20 mm range. It is combined with equation 3, which gives the associated transfer size of the circuit. For circuits where the AG/SAG mill is closed by a fine screen or cyclone, equation 2 is used to obtain the specific energy to reach the transfer size indicated by equation 3 and SMCC's comminution equation used to estimate the additional energy required to grind from this transfer size to the target grind of the fine screen/cyclone (see equation 4). In equation 4 the data from conventional Bond ball work index tests are used to represent the relevant ore properties (M_i). It should be noted that the Bond ball work index itself is not used. In stead the raw data from the Bond test are used to calculate an M_i value so that it is compatible with equation 4. The energies from the two calculations are then added together to obtain the total energy requirement for the AG/SAG circuit. The accuracy of the equations is illustrated in Figure 9, which shows the observed and predicted specific energies for over 30 different plants (46 different data sets). The range covered by these plants is given in Table 3. The precision of the equation as indicated by these data is 8.2% (1 sd).

$$S = K.F_{80}^{a}.DW_i^{b}.(1+c(1-e^{-dJ}))^{-1}.\phi^{e}.f(A_r) \qquad (2)$$

$$T_{80} = f - \frac{g.S}{DW_i^{b}} \qquad (3)$$

where
S = specific energy at the pinion
F_{80} = 80% passing size of the feed
T_{80} = 80% passing size of AG/SAG mill circuit
DW_i = drop-weight index
J = volume of balls (%)
ϕ = mill speed (% of critical)
$f(A_r)$ = function of mill aspect ratio
a,b,c,d,e,f,g = constants
K= function whose value is dependent upon whether a pebble crusher is in-circuit

$$W = M_i K\left(x_2^{f(x_2)} - x_1^{f(x_1)}\right) \qquad (4)$$

where
W = Specific energy (kWh/tonne)
K = Constant chosen to balance the units of the equation
M_i = Index related to the breakage property of an ore (kWh/t)
x_2 = 80% passing size for the product
x_1 = 80% passing size for the feed

The specific energy predicted from the above equations is used in conjunction with a model that predicts the power drawn by a mill with given dimensions, ball load, total load and speed (Morrell, 1996). In a design situation the throughput would be specified and hence the mill dimensions would be adjusted until the required power was obtained. Where a circuit already exists and a drilling programme is undertaken to determine how well future ores would be handled by the AG/SAG circuit, the throughput would be predicted by dividing the power draw of the existing mill by the predicted specific energy. Each drill core tested can therefore be assigned a throughput. Thus, in conjunction with the Mine's block model, it is possible to build a detailed picture of the most likely future performance of the AG/SAG mill circuit as the mine is developed further.

Table 3 – Range of Conditions Covered by Eq 2

variable	**max**	**min**
A	81.3	48
b	2.56	0.25
sg	4.63	2.5
DWi	14.2	1.8
Bond ball Wi (kWh/t)	26	9.4
F80 (mm)	176	19
P80 (microns)	600	54
Diameter (m)	12	3.94
Length (m)	8.3	1.65
Ball load (%)	25	0
Speed (% critical)	86	68
Aspect ration (L/D)	1.5	0.3
SAG kWh/t	29.2	2.4

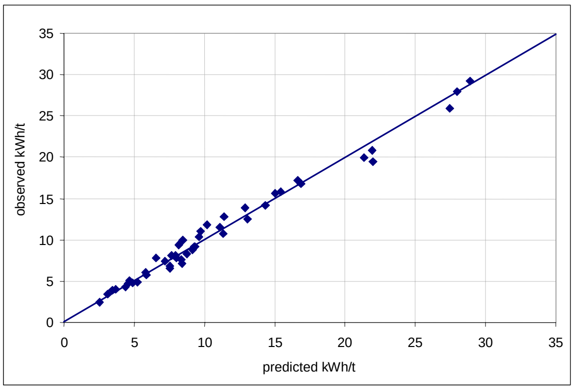

Figure 9 – Observed vs Predicted Specific Energy of 46 Different Full-scale AG/SAG Circuits Using the DW_i

3.3.2 High Pressure Grinding Rolls (HPGR)

Although HPGR technology has become commonplace in the cement and diamond mining industries and of late has been making significant inroads in the processing of iron ore, it has yet to make a major impact in the gold, platinum and base metals sectors. However, interest in the technology is now such that general expectations are that rapidly increasing numbers of HPGR machines are soon likely to find their way into these sectors. Due to their operation, the more established techniques for breakage characterisation, design and scale-up that have been developed using tumbling mills, are not applicable for HPGRs. Simulation has helped in this regard, JKSimMet containing a model that has been shown to have good scale-up capabilities (Morrell et al,1997, Daniel and Morrell, 2004). This model needs HPGR data to calibrate it, and although it has been shown that laboratory-scale HPGR results are suitable, separate tests need to be conducted on every different ore type, as the size reduction and throughput parameters of the model are ore dependent. Ore characterisation therefore remains a problem, though it is being currently researched in the AMIRA P9 project.

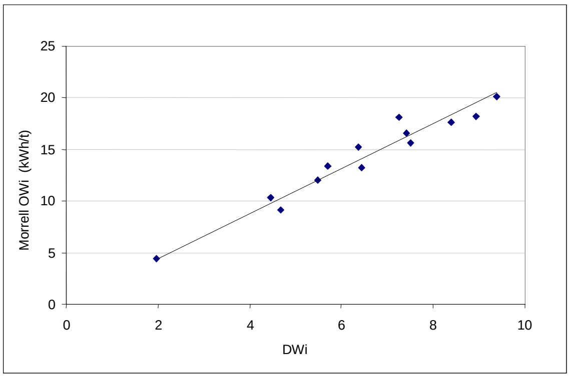

Figure 10 – DW_i vs HPGR Operating Work Index

The DW_i may provide at least part of the answer as it has been found that it is correlated with the operating work index of HPGR's as Figure 10 indicates. The data in this figure have been obtained from 13 different ore types. It is valid for machines operating with a working pressure in the range 2.5-3 N/mm^2. This qualification with respect to the applicability of the correlation in Figure 10 is very important as the operating work indices of HPGR machines are a strong function of their working pressure. This is illustrated in Figure 11, which shows the typical response of an increase in the operating work index as the working pressure increases. This result implies that operating at higher pressures (and hence higher specific energies) is less energy efficient than at lower pressures.

The correlation in Figure 10 is not intended for design purposes but can be used in conjunction with pilot and/or laboratory-scale HPGR test results to predict the specific energy requirement of rock samples that cannot be tested in an HPGR. Its value for orebody profiling is obvious. Also the fact that the DW_i is both applicable to AG/SAG and HPGR circuits makes the SMC Test particularly attractive in greenfield design projects as its use for characterising drill core does not compromise the ability of the designer when subsequently evaluating the response of AG/SAG and HPGR circuits to changes in ore type.

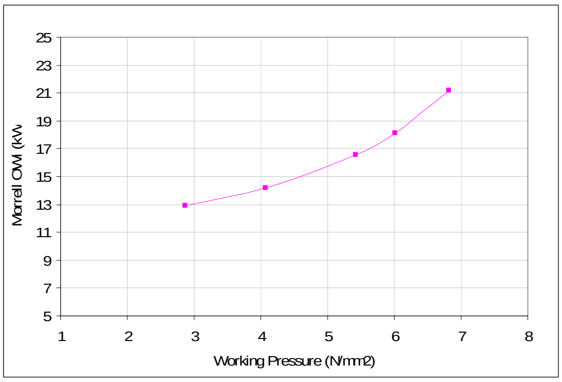

Figure 11 – Working Pressure vs HPGR Operating Work Index

4 CONCLUSIONS

The SMC rock breakage characterisation test has been developed to make use of very small quantities of sample, such as quartered drill core. The test generates a strength index (DW_i) which, via modelling and/or power-based techniques, can be used to predict the specific energy of AG and SAG mills as well as HPGR circuits. Its applicability for modelling stems from its correlation with the JK rock breakage parameters (A and b). For power-based calculations an equation has been developed which relates it and operating variables such as feed size, ball load and speed to AG/SAG mill specific energy.

The usefulness of the DW_i also extends to rock mass characterisation in mining applications, as it is correlated with the point load index/UCS. It is therefore ideally suited for mine-to-mill studies as it can be simultaneously used as an input to both comminution circuit and blast fragmentation models, where independent point load/UCS measurements are not available.

HPGR operating work indices have also been found to be strongly related to the DW_i making it a valuable tool for orebody profiling not only for AG/SAG mill circuits but HPGR ones as well.

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