

RELIABILITY OF SOME ORE CHARACTERIZATION TESTS

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ABSTRACT

Ore characterization is integral to any flowsheet development and equipment selection. There are risks to the overall flowsheet development if sufficient feed material is not characterized adequately representing the overall mine plan. The paper highlights some potential issues and opportunities to improve some of the commercial characterisations test procedures when macro-scale fractures, such as those apparent in RQD (Rock Quality Data); the response of friable ores with altered (argilic material) and remanent unaltered and hard / competent rock; and as well as variable rock shapes that make up the feed to a comminution circuits are considered.

KEYWORDS

Ore characterization, comminution, drop weight testing, RQD, friable ores

INTRODUCTION

Quantifying ore characterization is integral to any mine-project development. Over the years, a number of ore breakage characterization tests have been developed specific for each comminution stage. These specific tests were developed based on the understanding of machine dynamics and energy-size relationship of the ore to be comminuted. However, there is no single ore characterization test that cover all aspects of comminution (i.e. from blasting to fine grinding). The insight obtained between energy and crushed product (quantity and size) was a leap in comminution understanding and model development, (Hukki, 1961).

Lane et al. (2013), provided a comprehensive summary of various power-based comminution models that are currently used in design and circuit optimisation studies; the authors highlighted that the comminution power calculations are dependent on the consistency and reliability of the various commercial ore characterization tests that aim to model each comminution stage.

A number of technical reviews have been completed on the small-scale comminution methods for the application of flowsheet development and comminution modelling (Angove and Dunne, 1997), Mosher and Bigg (2002), Bailey et al. (2009) and Morrell (2009)). These reviews highlighted important issues pertaining to some commercial tests, especially the tests aimed at AG / SAG mill size selection, where the results can be biased by the various test laboratories for the same ores (Bailey et al., 2009). There are risks in the design and flowsheet, if ore characterization results and data of these tests are not well understood. An example of this is the coarser ore strength measurement procedure determined using the drop weight tester. The calculated A_{xb} strength parameter can be skewed by 10% due to misinterpretation of the test work data, hence leading to incorrect SAG specific energy calculations for competent rocks or A_{xb} values < 30 (Bailey et al., 2009). These variations in the calculated A_{xb} can either be due to: the operation of the drop weight tester; representative coarse particle selection; and or due to the calculation method used to determine A_{xb} from the t_{10} vs. Ecs data. Additionally, Bailey et al (2009), commented that the variability of the feed size distribution may also have impact on the measured SAG specific energies.

Other highlighted issues pointed out by Bailey et al. (2009) pertain to the suitability of some tests for competent ores. The authors commented that the SPI test is more suitable for less competent ores and whereas the JK drop weight tests are better suited for more competent ores. Additionally, the SPI test may be biased by sampling for multicomponent ore. This issue was recognized by Starkey et al. (2006) who later developed and improved the SPI test with the SAG Design Test for competent ores.

This paper presents a review of some commercial tests and highlights potential issues when interpreting comminution testwork data for the purpose of flowsheet development. The review specifically focused on the issues of:

- Representative sample selection – particle shape
- Influence of macro scale rock fracture on competency and SAG feed size
- The response of soft friable ores in comminution tests – Bond grindability test

SUMMARY OF ORE CHARACTERIZATION TEST WORK METHODS AND POWER BASED MODELS

When Bond first developed his comminution law, crushers, rod mills and ball mills were common equipment in the flowsheet. These tests were developed for the basis of scale-up of staged crush, rod and ball mill circuits (Bond, 1952). With the introduction of AG/SAG milling, HGPR and fine grinding in the flowsheet, specific comminution tests followed to suit these devices. Table 1 shows a summary-list of commercial comminution tests used in various comminution models. The applicability of these tests for the purpose of comminution circuit development in various comminution models was summarised by Lane et al. (2013).

Table 1 – Summary of small-scale comminution tests (modified after Mosher and Bigg (2002))

Test Name / Reference	Top Size (mm)	Sample Requirement (kg)	Type / Steady-state	Comminution Device Test Aim
Advanced Media Competency Test (Siddall et al., 1996)	165	300	Batch / No	AG / SAG Mills
UCS (Ulusay and Hudson, 2007)	NX, HQ, PQ cores with 1:~2.5 diameter / core length ratio	Min 10 cores	Core / No	Crushers
Point Load (Ulusay and Hudson, 2007), (ASTM, 1985, Bearman, 1999)	40 – 30	20	Single particle / No	Crushers
Bond Crusher Test (Bond, 1952)	75	10	Single particle / No	Crushers
JK Drop Weight Test (Napier-Munn et al., 2005)	64	75	Single particle / No	Crushers, AG / SAG mills
SMCC Test (Morrell, 2004)	31.5	5	Single particle / No	AG / SAG mills
SAG Design Test (Starkey et al., 2006)	F80 = 152	10	Batch / No	AG / SAG mills
MacPherson Test (MacPherson and Turner, 1978)	32	100	Continuous / Yes	AG / SAG mills
SAG Power Index (SPI) (Starkey and Dobby, 1996)	19	5	Batch / No	AG / SAG mills
Lab HPGR Test (Daniel, 2007)	12.5	25	Continuous / No	HGPR
Bond Rod Test (Bond, 1952)	13	10	Locked-cycle / Yes	Rod Mills, AG / SAG mills
Bond Ball Test (Bond, 1952)	3.5	10	Locked-cycle / Yes	Ball Mills
Stirred milling Test ¹	~1.5	10 – 20	Continuous / No	Stirred mills
ISAmill Test ²	~1.5	10 – 20	Continuous / No	ISA mills

Tests such as the Unconfined Strength (UCS) and Point Load Index (PLI) measure the bulk and tensile strength of the ore. The degree of broken product is not quantified in these tests. Whereas, tests such as the JK drop weight and the SMCC tests quantify the strength of ore using product size-energy relationship. The Advanced Media Competency, SPI, SAG design and MacPherson tests aim to quantify the specific energy required for AG / SAG milling by using lab-scale mills. For rod and ball mill tests, the standard Bond rod and ball mill tests are followed. The HGPR and fine grinding tests use customized lab-scale units to quantify the machine performance under variable operating conditions.

¹ Stirred milling tests are machine specific

² ISA milling tests are machine specific

As reported by Lane et al. (2013), some comminution models use a combination of JKSimMet (JKTech, 2007) and in-house empirical models developed from plant data to predict the power and throughput requirements of various comminution circuits. The AusGrind calculation is one such power-based model used extensively by Ausenco, (Lane et al., 2013). The calculation relies on empirical relationships obtained from +20 years of pilot and actual plant data to predict the comminution energies and throughputs for various circuits.

The use of AusGrind in flowsheet development follows an initial assessment and analysis of the test work data, review of project scale and geology and benchmarking other similar projects and risk assessments (**Error! Reference source not found.**). The aim of test work is to address the key risks and opportunities as a function of project scale and geology. The most common parameters and their associated test methods used by AusGrind for throughput and comminution power calculations are:

- DWi from SMCC tests
- Axb from JK drop weight tests
- CWI from Bond Crusher tests
- RWI and BWI from the Bond rod and ball mill tests
- Other testwork data such as the Advanced Media Competency tests, SPI and SAG Design test empirical relationships benchmarked against DWi or Axb results are used.

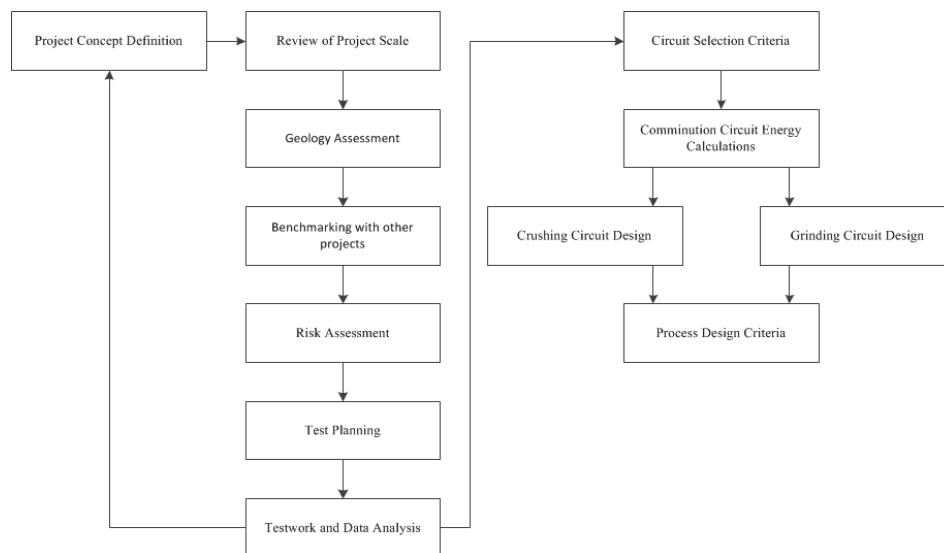


Figure 1 – Ausenco’s comminution design methodology (modified after Lane et al. (2013))

Misinterpretation of the above mentioned ore breakage characteristics can lead to inaccurate comminution energy calculations and throughput predictions. Circuit energy and throughput calculations should be benchmarked against actual plant performance and based on breakage characterization tests that are reliable. Also, the impact of ore variability on calculated comminution power need to be well understood. Some of the factors that impact on the comminution and throughput calculations can be attributed to:

- Sample representation
 - Extreme sample variability with a mix of extreme hard and soft ores

- Inadequate coarse ore particle selection
 - The interpretation of rock fracture, fracture in-fill type and macro-size competency, (Barratt, 2009).
 - High particle shape variability

In order to minimise the risk in flowsheet development, pilot plant trials are required to provide deeper insight into the comminution performance prior to defining the process design criteria. These can be used to assess ore variability but the use in this context is limited due to the high cost associated to pilot plant sampling and operation. These trials can highlight some of the potential sensitivities and risks that are not captured in the ore characterization tests. A typical (SABC) small-scale pilot plant trial may require a 20-tonne representative sample to achieve steady-state operation, which can be difficult to obtain especially if trials are conducted to evaluate the circuit performance for variable ore feed. Therefore, the reliability of small-scale comminution tests require careful interpretation to (a) select ore feeds to be tested and (b) reduce potential project risks.

REPRESENTATIVE SAMPLE SELECTION – PARTICLE SHAPE

The comminution strength parameters such as the A_{xb} (from the JK drop weigh test method) or DW_i (from the SMC test method) rely on non-linear regression analysis to fit empirical models to the t_{10} vs. E_{cs} data. Chandramohan (2010), (2011) and (2013) emphasized that the interpretation of the JK drop weight data can be misleading when biased sample shapes are selected to calculate the A_{xb} parameter. Figure 2 shows sample test work data for non-flaky and flaky particles orientated horizontally and vertically on the drop weight anvil.

Sample shapes were selected according to the techniques developed by Nakajima et al. (1978). Table 2 shows the calculated A_{xb} values for varying particle shapes for the same ore. According to the standard t_{10} calculation method (Narayanan and Whiten, 1988), the t_{10} value is considered to be the $1/10^{\text{th}}$ passing of original parent particle mean dimension. For simplicity, the t_{10} value is calculated from the mean retained mesh screens, which is based on the assumption that the selected particle is ‘blocky’ or non-flaky in shape. Therefore, when flaky rock shapes orientated horizontally were corrected for the actual particle thickness, the corrected A_{xb} values are reduced, indicating a more competent shape than the non-flaky samples. No clear protocols are in place to minimize the shape biases when selecting particles according to the standard JK drop weight procedure. Stark et al. (2008) noted the importance of operator training and monitoring when conducting the JK drop weight tests, where biased sample selection could lead to uncertainty in the final result.

Table 2 – Calculated A_{xb} values based on particle shape and orientation

Shape	A_{xb}
Non-flake	63.7
Flake vertical	59.0
Flake horizontal	91.7
Flake horizontal (corrected)	53.4

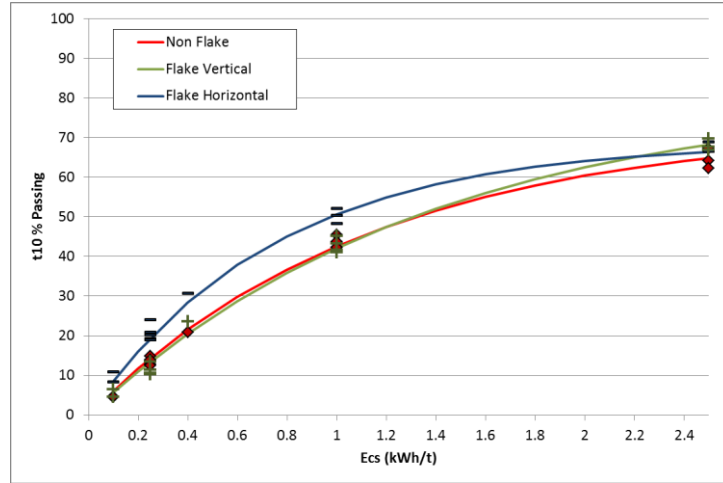


Figure 2 – Data for samples tested based on shape (Chandramohan (2013))

To minimise the variances in the JK drop weight result, Chandramohan et al. (2013) proposed a mechanistic model to predict the Axb value for any rock shape. The mechanistic model, shown in equation (1) and (2), uses known-controlled shapes, in this case biased blocky or non-flaky shapes, to calibrate the shape factor for any rock shapes. In equation (2), the σ_{UCS} is the UCS strength value; θ is the internal friction angle of rock (typically 31 degrees for most rocks); μ and μ_R are related to the internal friction and angle and dynamic friction; and Y is the particle thickness resting on the anvil.

$$Axb_{Flake} = Axb_{Nonflake} \left(\frac{ModelFlake F_n}{ModelNonFlake F_n} \right) \quad \text{Equation (1)}$$

$$F_n = \frac{\left[\frac{\sigma_{UCS}(1 - \sin \theta)}{1 + \sin \theta} \right] Y}{\left[\mu + (1 + \mu)\mu_R \right]} \quad \text{Equation (2)}$$

Chandramohan (2013) recommended using the SMCC test protocols to deliberately bias the non-flaky samples for model calibration. The particle-selection criteria in the SMCC test is tightly controlled by the mean density. Therefore, the sample-shape biases are minimized (Morrell, 2004). Using the knowledge of variable competencies for variable rock shapes, Chandramohan et al. (2011) presented potential opportunities to take advantage of rock shapes for the benefit of AG/SAG optimisation. This work showed the potential application to control grind and throughput by maintaining optimum flaky and non-flaky shape-ratio in the SAG feed. Figure 3 illustrates the steps to remove the bias in the calculated Axb values based on particle shape. The flaky shapes are removed from the sample using slotted screens that are 42% of the passing screen-mesh size. The production of flaky-shapes is dependent on crusher operation, (Bengtsson and Evertsson (2006), (2009)). Therefore, for flowsheet development, it is useful to quantify the amount flaky product produced from crushers. For higher proportion of flaky product, the overall Axb value should be calibrated to match the likely SAG feed competency based on the proportion of particle shape when sizing AG / SAG milling equipment.

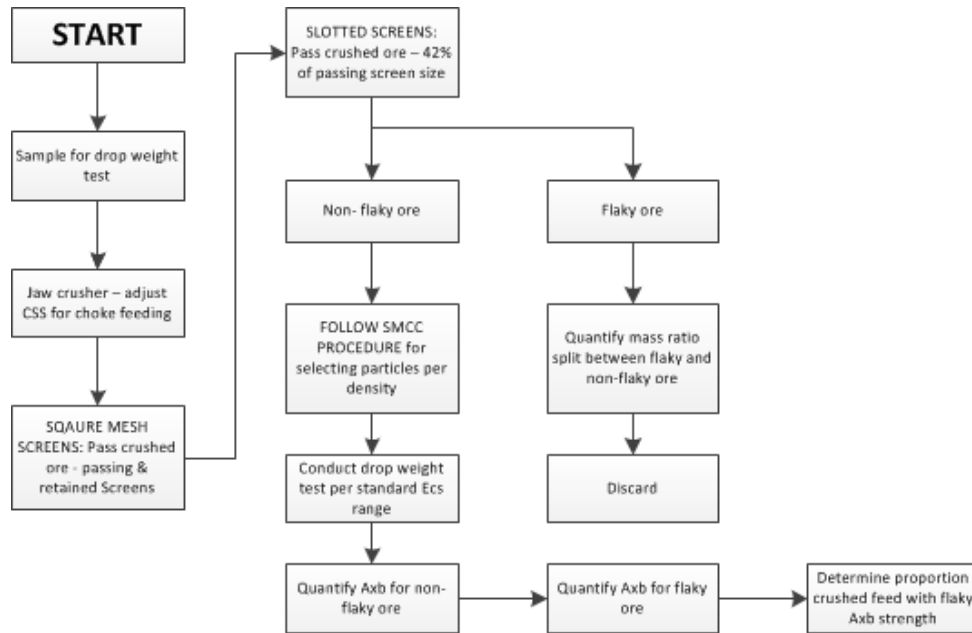


Figure 3 – Decision tree for selecting particle shape and quantifying Axb strength, (Chandramohan, 2013)

THE INFLUENCE OF ROCK FRACTURE ON COMPETENCY AND SAG FEED SIZE

The RQD measurements from drill core logging are an indicator of the ore profile rock quality down a drill hole. **Error! Reference source not found.** shows an example of the procedure for measuring RQD in cores. High RQD values indicate broken core and low RQD values indicate unbroken core.

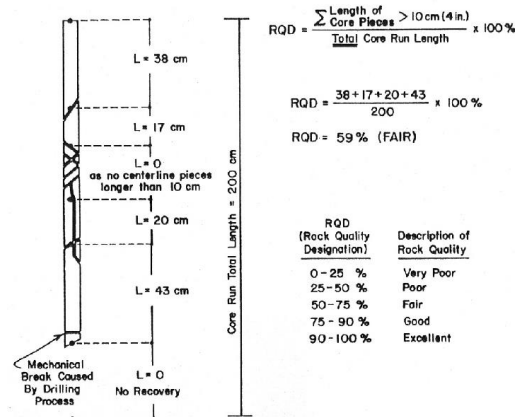


Figure 4 – Procedure for measuring and calculating RQD (after Deere and Deere (1988))

Examples of lower and higher RQD values cores are shown in **Error! Reference source not found.**. In this example, the lower RQD value is 53 % and the higher value is 87%. As shown in the figure, the sample with lower RQD comprises of significantly fractured cores and fines. The sample with higher RQD value contains less fractured material. The estimated RQD for the cores are based on visual

inspection; therefore the measured values are subjective and are susceptible to errors in the estimating method.



Figure 5 – Examples of core RQD

In regards to hardness measurements, to-date there has been no conclusive evidence to suggest that RQD has any significant impact on measured coarse-ore competency parameters such as the JK drop weight's Axb and SMCC's DWi values. Wirfiyatal and McCaffery (2011) developed a throughput-relationship model based on geotechnical measurements such as PLI, RQD, Rock Mass Rating (RMR) and comminution parameters such as JK drop weight and Bond tests for Batu Hijau operation. In their work, Wirfiyatal and McCaffery (2011) commented on the considerable limitation of the throughput relationship prediction when using RQD benchmarked against PLI. The main issue with using PLI as a proxy for hardness (fracture toughness) for SAG throughput calculation was the limitation in the size fraction tested. The PLI test uses 35 – 65 mm size rocks, which account for approximately 15% of SAG mill energy consumption, (Wirfiyatal and McCaffery, 2011). In order to determine the overall SAG energy consumption, representable SAG feed size distribution is required. The single particle drop weight tests used to calculate DWi and Axb parameters, incorporate wider representable SAG feed distribution. It was suggested by Wirfiyatal and McCaffery (2011) for the Batu Hijau geology, that the quartz-vein density drives the mineralogy and hardness. Therefore, for homogenous mineralisation, larger particles have similar hardness to smaller particles. As the quartz density decreases, so does the mineralisation, hence reducing the similarity in hardness between large and smaller rock particles. Since the drill cores are either crushed or cut into test pieces prior to competency tests, it is hypothesized that mineralogy and density of fractures between coarse and fine particles heavily influences the measured Axb or DWi values, rather than the RQD values of the cores (Barratt, 2009, Wirfiyatal and McCaffery, 2011). Therefore, the SAG throughput and power predictions are mainly influenced by the SAG feed due to the inherent macro scale rock fractures and densities.

IMPACT OF PARTICLE SELECTION ON COMPETENCY

Figure 6 and Figure 7 illustrate two examples of drop weight data for low and high RQD samples and the analysis of the data shown in Table 3 and

Table 4. Fitted curves of lower bound, upper bound and best-fit curves are shown using the Narayanan and Whiten t_{10} equation, (Narayanan and Whiten, 1988). The t_{10} value is not constant for varying particle sizes as shown by the variability in the specific energy graphs (t_{10} vs. Ecs), especially for high impact specific energy tests (above 1 kWh/t). The t_{10} values are higher for the coarser particles than for the finer particles. For the high scatter sample (low RQD), the distribution of the t_{10} data for high-energy impact is significant (standard deviations shown in Table 3). These observations were also noted by Morrell in his earlier works (2004) and (2009). For the low scatter sample (high RQD), in which the t_{10} distribution for high-energy impact is low (standard deviations shown in

Table 4).

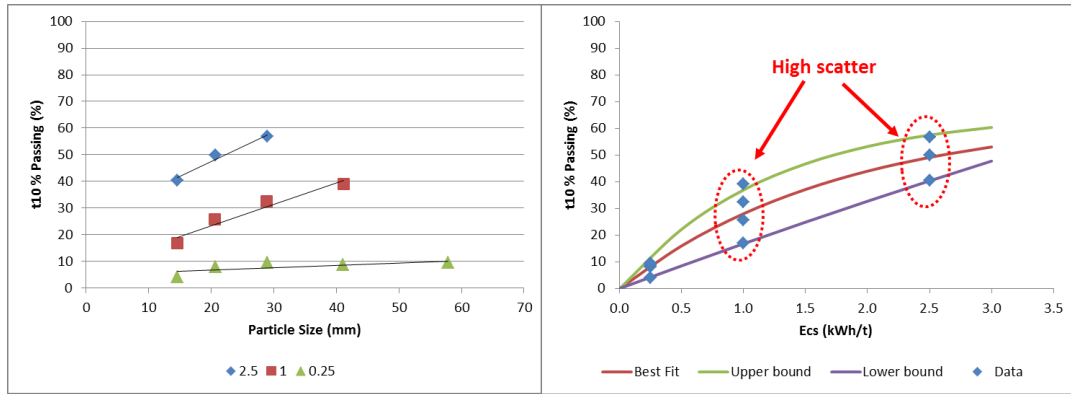


Figure 6 – Low RQD sample (high scatter) drop weight data, Best fit Axb = 36.7

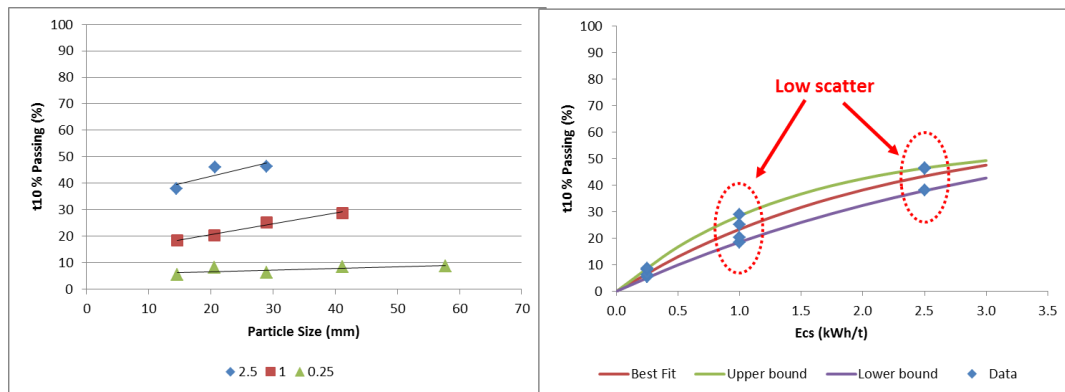


Figure 7 – High RQD sample (low scatter) drop weight data, Best fit Axb = 29.2

In this example, Axb values are calculated using Narayanan and Whiten equation and shown in the analyses data, (Table 3 and

Table 4). The calculated lower and upper bound Axb show significant variability when compared with the estimated best-fit values. The upper bound Axb values, estimated from the highest t_{10} values per tested specific energies are higher, indicating a less competent ore. The lower bound Axb values estimated from the lowest t_{10} values per tested specific energies are lower, indicating a more competent ore. The best-fit Axb values lie between lower and upper bound range. To determine extent of t_{10} scatter on the calculated Axb values, 75th and 25th percentile values of the t_{10} data for the three energies are used to calculate the Axb values.

Table 3 – High scatter (low RQD) breakage data

Size fraction (mm)	Ecs (kWh/t)	Best fit t_{10} (%)	Upper bound t_{10} (%)	Lower bound t_{10} (%)	t_{10} 75th Percentile (%)	t_{10} 25th Percentile (%)
16 x 13.2	2.5	40.4	56.7	40.4	53.3	45.1
22.4 x 19	2.5	49.9				
31.5 x 26.5	2.5	56.7				
Average		49.0				
SD		8.2				
16 x 13.2	1	16.9	39.0	16.9	34.1	23.4
22.4 x 19	1	25.6				

31.5 x 26.5	1	32.4				
45 x 37.5	1	39.0				
Average		28.5				
SD		9.5				
16 x 13.2	0.25	4.1				
22.4 x 19	0.25	7.9				
31.5 x 26.5	0.25	9.4	9.4	4.1	9.4	7.9
45 x 37.5	0.25	8.6				
63 x 53	0.25	9.4				
Average		7.9				
SD		2.2				
Axb		36.7	54.2	17.3	46.8	29.6

Table 4 – Low scatter (high RQD) breakage data

Size fraction (mm)	Ecs (kWh/t)	Best fit t ₁₀ (%)	Upper bound t ₁₀ (%)	Lower bound t ₁₀ (%)	t ₁₀ 75 th Percentile (%)	t ₁₀ 25 th Percentile (%)
16 x 13.2	2.5	37.9				
22.4 x 19	2.5	46.1	46.3	37.9	46.2	42.0
31.5 x 26.5	2.5	46.3				
Average		43.4				
SD		4.8				
16 x 13.2	1	18.4				
22.4 x 19	1	20.2				
31.5 x 26.5	1	25.2	28.8	18.4	26.1	19.8
45 x 37.5	1	28.8				
Average		23.2				
SD		4.7				
16 x 13.2	0.25	5.4				
22.4 x 19	0.25	8.0				
31.5 x 26.5	0.25	6.1	8.6	5.4	8.3	6.1
45 x 37.5	0.25	8.3				
63 x 53	0.25	8.6				
Average		7.3				
SD		1.4				
Axb		29.2	39.8	21.4	34.3	22.8

Figure 8 shows the calculated Axb values from Table 3 and Table 4. Boxes and whisker plots are used to show the variability Axb data. The whiskers show the calculated lower and upper bound values. The boxes show the calculated 75th and 25th percentile values. The scatter in the calculated Axb value for both samples is significant. The Axb ranges from 17.3 - 54.2 for the high scatter (low RQD) sample and ranges from 21.4 – 39.8 for the low scatter (high RQD) sample. The 75th and 25th percentile Axb values show wider distributed hardness range for the high scatter (low RQD) sample, indicating similar proportion of soft and hard particles were selected for the JK drop weight tester. Whereas the 75th and 25th percentile Axb values for the low scatter (high RQD) sample, show a skewed hardness distribution, indicating a higher proportion of competent particles were selected for the JK drop weight tester.

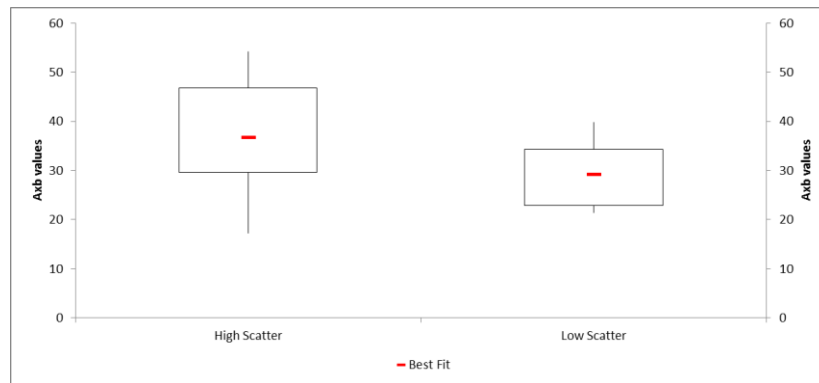


Figure 8 – Analysis of the t_{10} data for low and high scatter samples

Figure 9 and Figure 10 **Error! Reference source not found.** show more examples of the variability in the measured t_{10} vs. particle size and calculated t_{10} vs. Ecs curves for eight JK drop weight samples. The scatter in the measured t_{10} is significant for varying tested specific energies, hence having an impact in the measured Axb values (shown in Figure 11).

Samples 1 to 4 show variable t_{10} values at different particle sizes for energies tested greater than 1 kWh/t. Hence, these differences in the measured t_{10} values have an impact on the calculated t_{10} vs. Ecs curves which are then used to determine the Axb values of the ore sample. For samples 5 to 8, the measured t_{10} variability is mainly between the 0.25 to 2.5 kWh/t tested energy range. For these samples, the particles tested at the 1 kWh/t energy show considerable t_{10} variability, hence having an impact on the calculated Axb values.

In Figure 11 for the calculated Axb value distribution, samples 1, 6, and 8 have wider percentile distributions and the rest with lower percentile distribution between the 75th and 25th. For samples that have wider percentile distribution, it is probable that the samples comprised of even distribution of hard and soft particles, which was observed earlier for the high scatter sample (low RQD) shown in Figure 6. For samples with narrower and skewed percentile distributions about the best-fit Axb value, it is probable that biased particle selections were used for the tests (samples 2, 5, and 7).

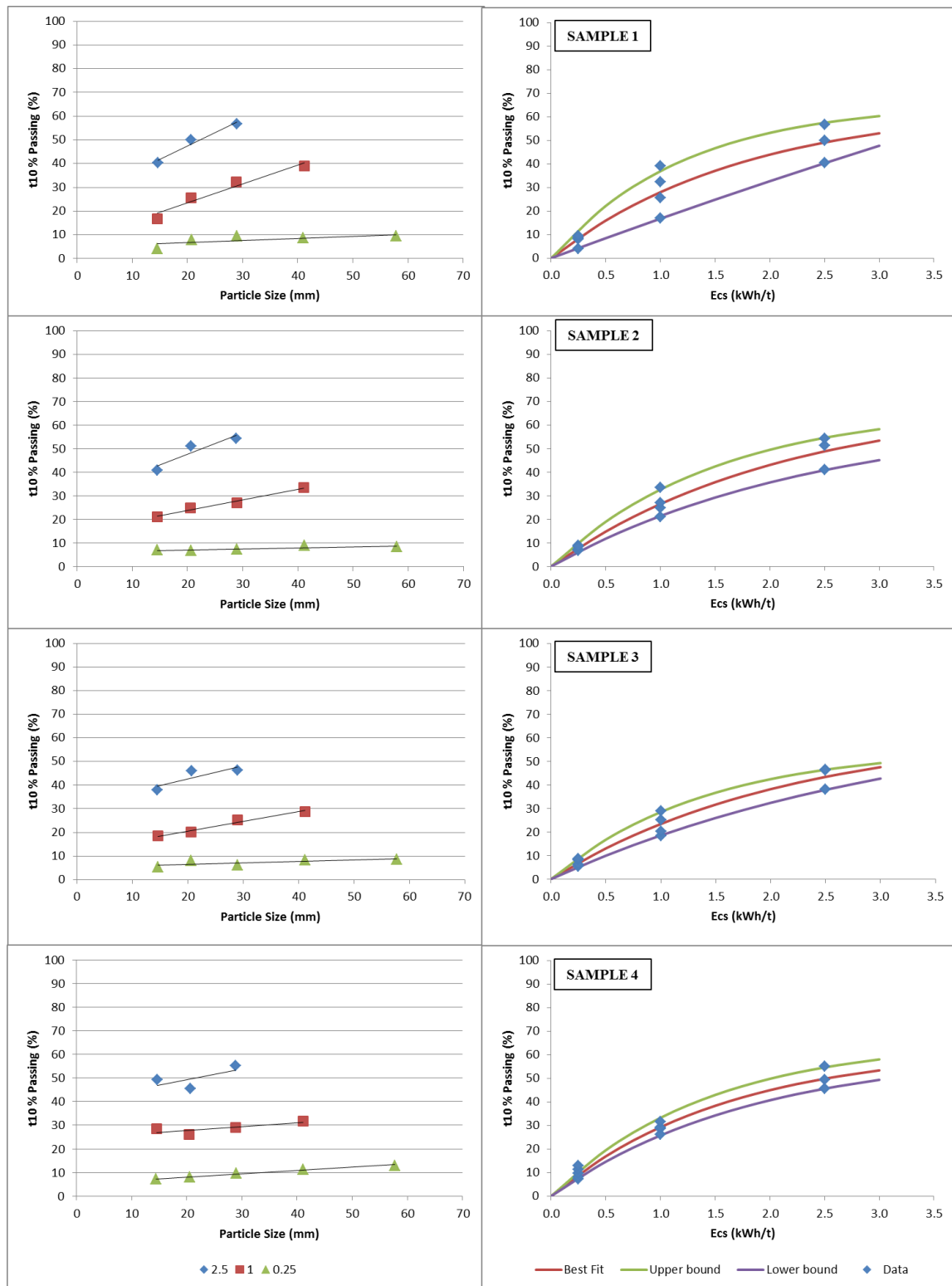


Figure 9 – Examples of best fit, upper and lower bound Axb data for variable samples (samples 1 to 4)

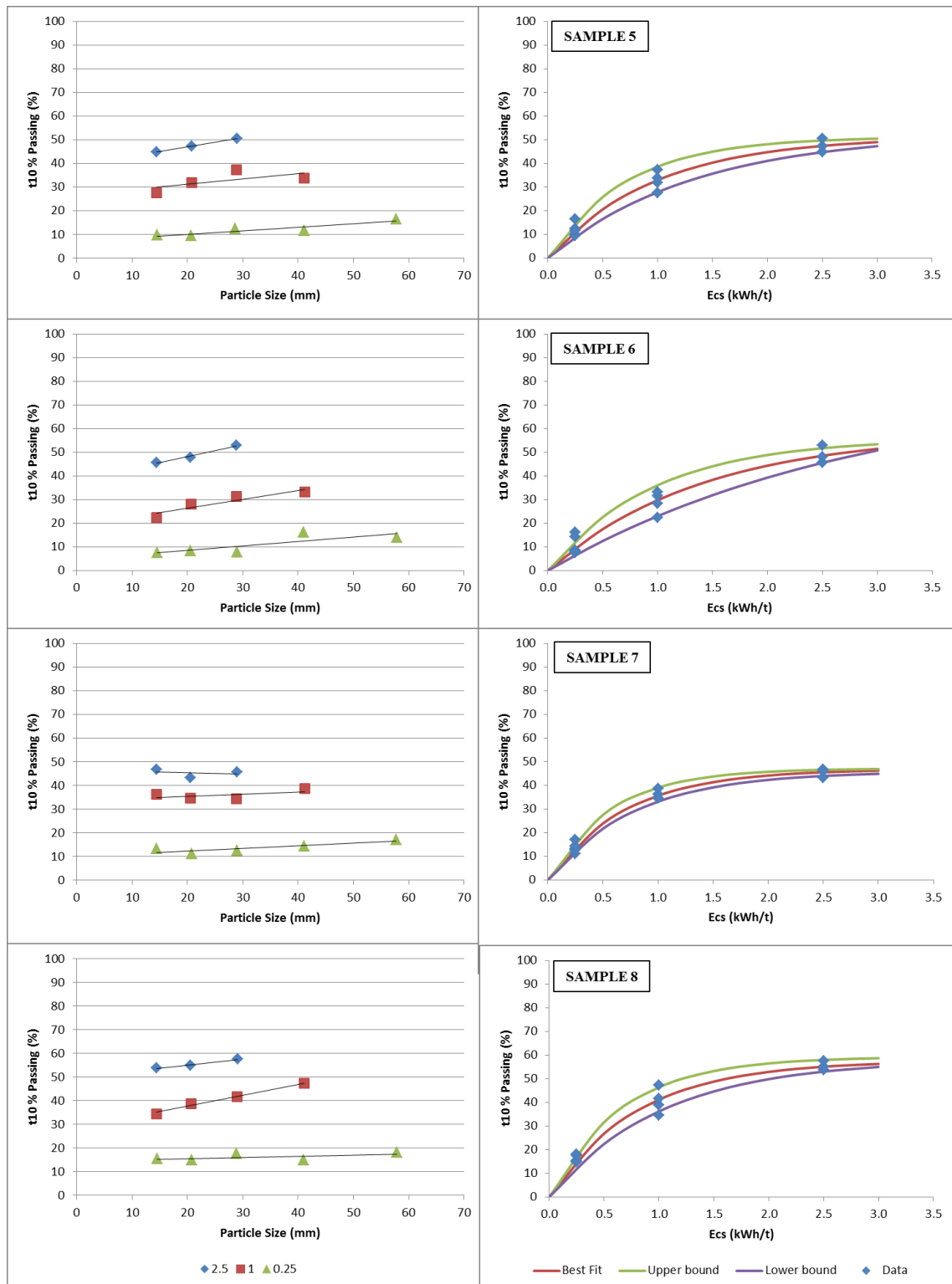


Figure 10 – Examples of best fit, upper and lower bound Axb data for variable samples (samples 5 to 8)

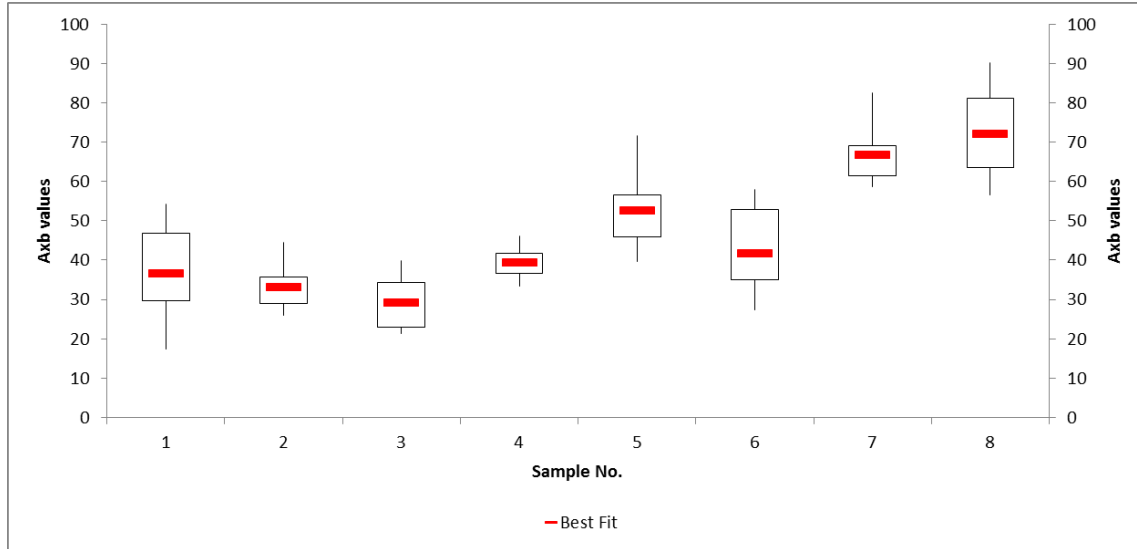


Figure 11 – Calculated Axb values for samples 1 to 8

As shown in the analysis above, representable and controlled particle selection is critical to the analysis and calculation of Axb values. The distinct variability shown for the measured t_{10} values at each tested energy for varying particle sizes have an overall impact on the calculated Axb range for each sample. These variabilities in the calculated Axb values for each tested samples can have detrimental impact on the overall SAG throughput and power calculations.

According to Burger et al. (2006), Barratt (2009) and Wirfiyatal and McCaffery (2011) fracture densities in the sample have a significant impact on the measured hardness values. The coarser ore have higher fracture densities, and therefore have higher Axb values indicating a less competent ore, and finer ore particles comprising of lower fracture densities are considered to be more competent. Therefore controlled particle selection protocols are required. Controlled particle selection method based on ore SG, such as used in the SMCC test, will be useful to reduce the extreme particle selection biases (currently the JK drop weight procedure do not use ore SG as a proxy for sample selection).

IMPACT OF RQD ON SAG FEED SIZE

Bailey et al. (2009) used Morrell's equation (3), to determine the SAG feed (F80) or primary crusher product based on ore competency and crusher closed side setting.

$$F80 = 0.2 \times CSS \times DWi^{0.7} \quad \text{Equation (3)}$$

Once the F80 of the comminution circuit is known, a suitable combination of equipment is selected to achieve the desired design throughput. Bailey et al. (2009) commented on cases where the predicted F80 from the above equation did not match crusher P80 for the desired CSS. In most of the observed cases, the SAG mill feed was finer than expected and actual F80s were significantly lower than the predicted ones. This mismatch in the predicted vs. actual SAG mill feed F80 can be either due to:

- unaccounted inherent macro-scale rock fracture, or
- reduced size distribution caused by higher intensity blasting or fragmentation during mining - for the purpose of this paper, the influence of intensive blasting on ore competency is not investigated.

The DWi is a measure of hardness based on ore SG and drop weight test data (Bailey et al., 2009). It is the main factor in equation (3) that has an effect on the overall SAG F80 prediction. The DWi and/or Axb values³ are important for AG/SAG mill power and throughput prediction. Therefore, the reliability of the energy-based models is heavily dependent on representative competency measurements.

Database on RQD vs. SAG feed F80 was used to develop relationships to modify equation (3), (Burger et al., 2006, Wirfiyatal and McCaffery, 2011, Morrell, 2014). Therefore equation (4) can be re-written as for two conditions:

$$\begin{aligned} F80_{RQD} &= (0.2 \times CSS \times (DWi)^{0.7}) \times (0.1 \times RQD^{0.5}) & \text{If } RQD > 25\% \\ F80_{RQD} &= (0.2 \times CSS \times (DWi)^{0.7}) \times (0.5) & \text{If } RQD < 25\% \end{aligned} \quad \text{Equation (4)}$$

The best fit Axb values calculated in Table 3 and

Table 4 were used to estimate the impact of RQD on SAG mill feed F80 using equation (4), (Table 5 and Table 6). For calculation purposes, a crusher CSS of 110 mm was used. As shown, the RQD reduces the calculated SAG Feed F80 value but does not change the measured ore competency.

Table 5 – Estimating SAG F80 for Lower RQD data with best fit Axb data

Value	Unaltered data (100% RQD)	53% RQD
Axb	36.7	36.7
DWi (kWh/t)	7.4	7.4
SAG F80 (mm)	89	65

Table 6 – Estimating SAG F80 for Higher RQD data with best fit Axb data

Value	Unaltered data (100% RQD)	87% RQD
Axb	29.2	29.2
DWi (kWh/t)	9.2	9.2
SAG F80 (mm)	104	97

Figure 12 shows the decision tree for applying the techniques presented in this section. The RQD factor is only applied to core samples. For core samples with varying RQD, the SMCC test recommended to minimise sample selection variability. For crushed ore, either JK drop weight test or SMCC is preferred. To estimate the SAG feed F80 for the core samples, equation (4) is recommended.

³ DWI is roughly proportional to the inverse of the Axb value for a given sample

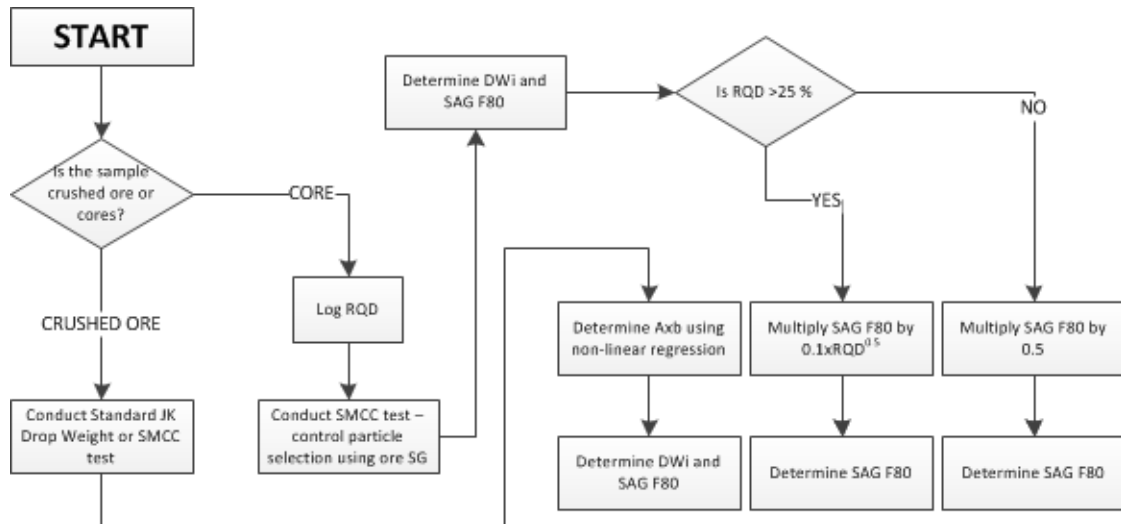


Figure 12 – Decision tree for determining DWi and SAG mill feed F80 for throughput calculations of hard ores

THE RESPONSE OF SOFT FRIABLE ORES IN COMMINATION TESTS

For friable ores, the size distribution is usually skewed to include high amounts of fines particles in the feed. For competent and blocky ores, the size distribution is usually skewed with fewer fines. Typically friable ore types have low competency in the coarse size fractions ($A_{xb} > 80$). Low competency ores are usually expected to have high throughput through the SAG mill and are circuits are constrained by the secondary and tertiary grinding stages. Therefore, the risk in process design for the treatment of friable ore is greater in the secondary or tertiary grinding stages.

The standard Bond ball mill work index test is conducted under dry milling conditions. For ores with Bond work indexes greater than 12 kWh/t, dry locked cycle tests are suitable as they have low difference in hardness between wet and dry milling. However, for friable ores that present high proportions of clays, dry locked cycle tests may results inaccurate work index values and, therefore, either modifications to dry test or wet milling is recommended. Man (2002) provided a detailed review on the reasons of why the Bond grindability test is conducted the way it is. Man described the reasons for conducting dry milling tests were mainly due to logistics of the test which may otherwise require cyclones or other wet classifiers and pumps. Furthermore, Man (2002) noted that the effects of slurry viscosity may bias the Bond grindability results. Dry milling tests are simpler and easier to carry out than wet milling. However, in recent test work managed by Ausenco of soft ore project, the grindability result varied as much as 20% between dry and wet milling; where the wet milling work index result was significantly lower than that for dry milling and consistent with continuous milling pilot tests that were carried out.

To prevent “over-grinding”, rod milling is more suited than ball milling for friable ores that contain high amounts of clays. Figure 13 shows an example of the product response in the standard Bond rod and ball mill grindability tests. The ball mill tends to over-grind feed with a potential increase in slimes production. A slimes increase of 5% in the $-10 \mu\text{m}$ fraction is estimated for ball milling compared to rod milling, (Figure 13). Excess slimes or fines in the product can be detrimental in the flotation response; thus decreasing the overall recovery. However, rod milling capacities are limited by the size of the mill. For high throughput, lower operating costs, ball milling is preferred over rod milling.

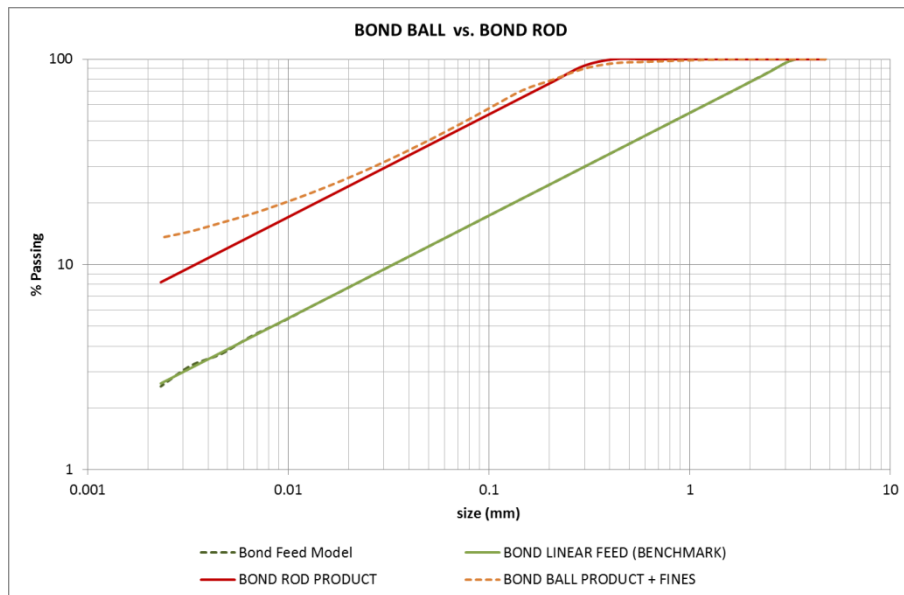


Figure 13 – Example of Bond rod and Bond ball mill grindability test product for the same ore and feed size distribution

For ores that have excessive fines, a modified Bond grindability test is required. This is because, the fine in the feed may bias the Bond milling work index. Therefore a pre-screened feed, shown in Figure 14, is suitable for the modified Bond grindability test. Key aspects of the tests are:

- closing screens 1 and 2 have the same aperture.
- ratio of fresh split is quantified between pre-screened feed to the locked cycle circuit and pre-screened product.
- test is conducted on the pre-screened feed targeting a circulating load of 250%.
 - locked cycle tests have similar procedures as the Bond ball or rod mill tests for wet and dry milling.
 - for wet milling, a solids density of 70 % w/w is recommended. However, this can change based on slurry viscosity impact on milling performance.
- steady-state specific power of the locked cycle circuit is determined after a number of cycles
- total specific power of the circuit based on fresh feed is then calculated from the ratio of pre-screened feed and product.
- the circuit Bond milling work index is calculated from the fresh feed F80 and the combined product P80.

As shown in the method above, the calculated the Bond milling work index was based on fresh feed; therefore a reverse closed circuit classifier is required for the circuit design.

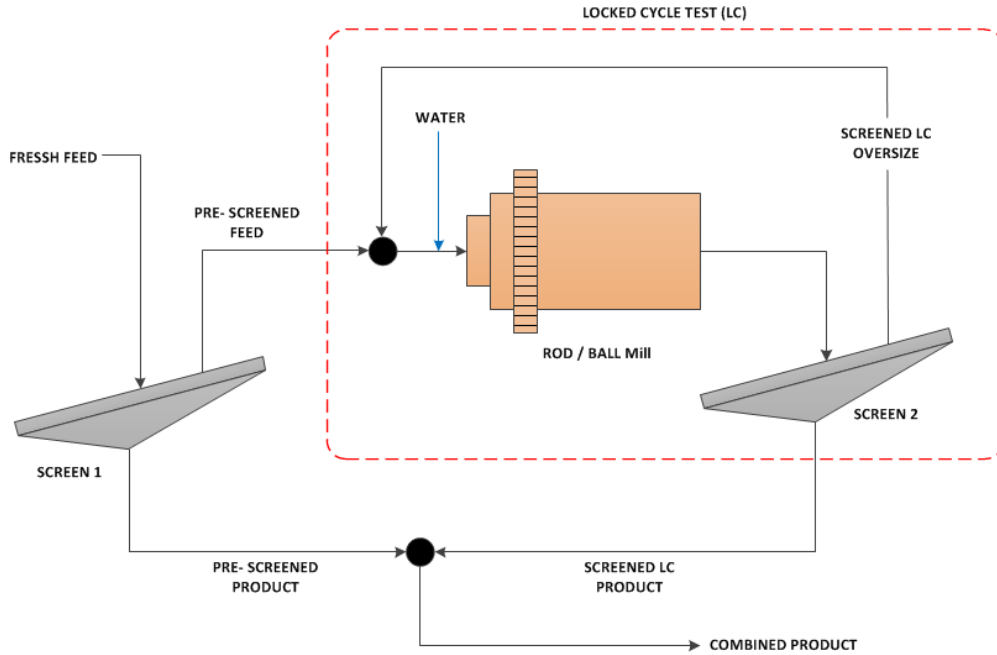


Figure 14 – Locked cycle procedure for fresh feed with excess fines

As pointed-out by Man (2002), slurry viscosity has a significant impact the Bond work index grindability value. Shi and Napier-Munn (1996), (1999), (2002) conducted extensive work on the impact of slurry viscosity on ball milling performance. They developed a criterion for milling performance based on the quantity of $-38 \mu\text{m}$ in the feed and product of the secondary and tertiary grinding circuits, shown in equation (5).

$$\text{Grinding Index} = \left(\frac{S_D - S_F}{100 - S_F} \right) \times 100 \quad \text{Equation (5)}$$

Where:

- S_D is the percent passing $-38 \mu\text{m}$ in the mill discharge
- S_F is the percent passing $-38 \mu\text{m}$ in the mill feed

According to Shi and Napier-Munn, the aim of the grinding index is to capture the inefficiencies of the grinding and classification circuit. A high grinding index indicates higher events of particle-breakage occurring inside the mill and a low grinding index indicates less efficient breakage occurring inside the mill either due to inefficient cyclone classification (i.e. high circulation load) or due to high slurry viscosity. Therefore, the grinding index can be used as a performance indicator to select correct cyclone spare parts dimension (i.e. spigot and vortex finder) and operating pressures.

Figure 15 shows the logical setups required for selecting the type of test for friable ores. The aim of the decision tree is to quantify and select the correct test procedure based on the proportion of fines in the crushed product which may have an impact on the Bond milling work index and slurry viscosity.

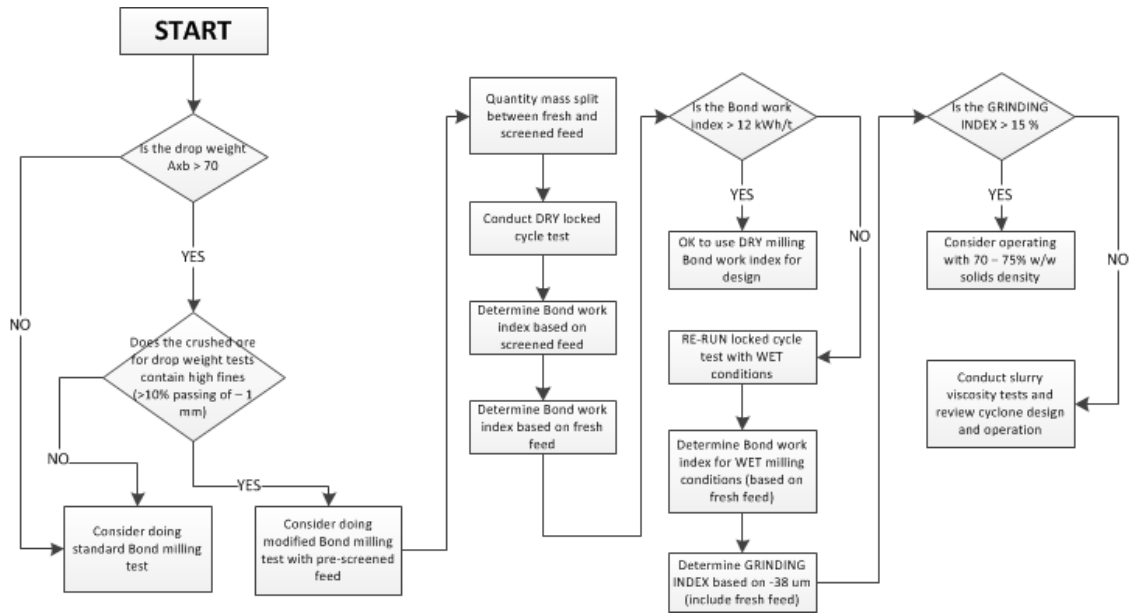


Figure 15 – Decision tree for conducting Bond milling test on soft ores

CONCLUSION

The paper presented a review of some common commercial test work for coarse and friable ores. The reliability of these tests and the understanding of the test outcome are pertinent for flowsheet development. Tests such as the JK drop weight, SMCC and the Bond ball / rod grindability tests were developed based on the necessity of comminution equipment selection. Therefore careful consideration and understanding of the test work data is an important step in the design process. The main conclusions of analysis of comminution tests sensitivities influence on flowsheet development are:

- In the drop weight test procedure, it is assumed that sample selection for single particle tests is random. However, a biased sample selection by shape can significantly change overall strength index. As crusher product is considered to be representative of typical a SAG mill feed during flowsheet development, particle selection for drop weight tests should reflect the variability in the feed. If the crusher produces increased quantity of flaky ore, then the drop weight strength index should be calibrated to reflect the proportion flaky and non-flaky shapes in the SAG mill feed.
- Analysis of the t_{10} data showed significant scatter when uncontrolled sampling procedure is followed when selecting particles for the drop weight tests. Coarser particles had higher Axb values indicating less competent materials. Finer particles had lower Axb values, indicating more competent samples. Commentary by Burger et al. (2006), Barratt (2009) and (Wirfiyatal and McCaffery (2011), Burger et al., 2006) indicated that fracture density controls the hardness distribution between coarse and fine particles. In terms of core RQD and its impact on ore competency, particle selection is main driver for hardness variability. High and low t_{10} data for each tested energy calculates the maximum and minimum range of Axb values. The 75th and 25th percentile values indicate the distribution of the data about the best fit value based on particle selection. A wider distribution indicates an uncontrolled distribution of particle selection. To minimise the uncontrolled bias in the sample selection for cores, it is highly recommended that the SMCC test procedures and protocols should be followed to control the particle selection using ore SG as a proxy. However, as the case with most commercial tests, obtaining representable sample

selection to determine overall ore competency will be a challenge, if the cost of the test is a decision factor during the PFS.

Morrell's (2009), SAG feed F80 calculation was modified to include variable RQD values. For RQD values greater than 25%, a factored power-function relationship is used to calibrate the SAG feed F80. For RQD values less than 25%, a constant factored multiplier is used. The conditional RQD calibration of the SAG feed F80 was based on Ausenco's RQD vs. SAG feed F80 database, (Ausenco, 2014).

- For friable ores, which contain high fines in the feed, careful operational consideration of the secondary and tertiary grinding equipment is required. Therefore the Bond work index tests (for ball and rod mill selection) should take into consideration of the high fines in the feed. A modified Bond grindability test is required fines in the fresh feed to be removed prior to the test. For ores with high amount of fines and Bond work indices less than 12 kWh/t, wet milling is recommended. From authors' experience, for these ores difference in the Bond work index of up to 20 % between dry and wet milling has been observed.

The use of (Shi and Napier-Munn (2002)) Grinding Index is useful to optimise the target slurry density of the ball milling circuit. They showed that the viscosity of the slurry has an impact on grinding performance. Therefore, the Grinding Index could be used as a proxy for cyclone / classification operating parameters.

Flowsheet development of comminution circuits must rely on representative testwork and good understanding of the test work data. Risk mitigation plans to improve test reliability were proposed for both hard and friable ores.

Three decision tree diagrams were developed as part of the procedure for comminution testing. These logic-diagrams are recommended to be used as decision guidance when dealing with peculiar ores such as the ones described in this paper.

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REFERENCES

- ANGOVE, J. E. & DUNNE, R. C. A Review of Standard Physical Ore Property Determination. World Gold Conference, 1997 Singapore. 139-144.
- ASTM 1985. Suggested Methods for Determining Point Load Strength ASTM D5731-08. *International Society for Rock Mechanics Commission on Testing Methods*, 22, 51 - 60.
- AUSENCO 2014. Internal Document - RQD database vs. SAG mill feed F80. *In: AUSENCO* (ed.).
- BAILEY, C., LANE, G., MORRELL, S. & STAPLES, P. 2009. What can go wrong wrong in comminution circuit design? *Tenth Mill Operators Conference*. Adelaide, South Australia: AUSIMM.
- BARRATT, D. J. 2009. Technical MEMO - Crushing Work Index Comparison Between Labs. *In: DJB CONSULTANTS, I.* (ed.).

- BEARMAN, R. A. 1999. The use of the point load test for the rapid estimation of Mode I fracture toughness. *International Journal of Rock Mechanics and Mining Sciences*, 36, 257-263.
- BENGTTSSON, M. & EVERTSSON, C. M. 2006. An empirical model for predicting flakiness in cone crushing. *International Journal of Mineral Processing*, 79, 49-60.
- BENGTTSSON, M., SVEDENSTEN, P. & EVERTSSON, C. M. 2009. Improving yield and shape in a crushing plant. *Minerals Engineering*, 22, 618-624.
- BOND, F. C. 1952. The third theory of comminution. *Transcript AIMME*, 193, 484-94.
- BURGER, B., MCCAFFERY, K., JANKOVIC, A., VALERY, W., MCGAFFIN, I. & LA ROSA, D. 2006. Batu Hijau Model for Throughput Forecast, Mining and Milling Optimisation. In: KAWATRA, S. K. (ed.) *Advances in Comminution*. Society for Mining, Metallurgy and Exploration.
- CHANDRAMOHAN, R. 2013. *Effect of Rock Shapes in Comminution*. PhD, University of Queensland.
- CHANDRAMOHAN, R., HOLTHAM, P. N. & POWELL, M. S. 2013. Development of a mechanistic breakage model to predict the strength of varying rock shapes. *European Symposium in Comminution and Classification*. Germany.
- CHANDRAMOHAN, R., POWELL, M. S. & HOLTHAM, P. N. The influence of particle shape in rock fracture. International Mineral Processing Conference 2010, 2010 Brisbane. AUSIMM.
- CHANDRAMOHAN, R., POWELL, M. S., HOLTHAM, P. N., LANE, G. & DANIEL, M. J. 2011. The Effect of Blends of Rock Shapes in AG / SAG Mills and Comminution Circuits. *Semi-Autogenous Grinding Conference 2011 - Fifth International Conference on Autogenous & Semiautogeneous Grinding Technology*. Vancouver, Canada: CIM.
- DANIEL, M. J. 2007. *Energy efficient mineral liberation using HPGR technology (PhD)*. PhD, University of Queensland.
- DEERE, D. U. & DEERE, D. W. 1988. *The Rock Quality Designation (RQD) INDEX in Practice*, Philadelphia, ASTM ST 984.
- HUKKI, R. T. 1961. Proposal for a Solomonic settlement between the theories of von Rittinger, Kick and Bond. *Trans SME / AIME*, 220, 403 - 408.
- JKTECH 2007. JK SimMet users manual - version 5.
- LANE, G. S., FOGGIATTO, B. & BUENO, M. P. Power-based Comminution calculations using AusGrind. In: PROCEMIN, ed. Procemin 2013, 2013 Chile.
- MACPHERSON, A. R. & TURNER, R. R. Autogenous grinding from test work to purchase of a commercial unit. In: MULAR, A. L. & BHAPPU, R. B., eds. *Mineral Processing Plant Design 1978* New York. AIME, 279 - 305.
- MAN, Y. T. 2002. Why is the Bond Ball Mill Grindability Test done the way it is done? *The European Journal of Mineral Processing and Environmental Protection* 2, 34 - 39.
- MORRELL, S. 2004. Predicting the specific energy of autogenous and semi-autogenous mills from small diameter drill core samples. *Minerals Engineering*, 17, 447-451.

- MORRELL, S. 2009. Predicting the overall specific energy requirement of crushing, high pressure grinding roll and tumbling mill circuits. *Minerals Engineering*, 22, 544-549.
- MORRELL, S. 2014. *RE: RQD vs. SAG Feed F80*.
- MOSHER, J. B. & BIGG, A. C. T. Bench Scale testing and pilot plant tests for comminution circuit design. *In: SME, ed. Mineral Processing Plant Design, Practice and Control*, 2002.
- NAKAJIMA, Y., WHITEN, W. & WHITE, M. 1978. Method for measurement of particle shape distribution by sieves. *Mineral Processing Extractive Metallurgy*, 87, 194 - 203.
- NAPIER-MUNN, T. J., MORRELL, S., MORRISON, R. D. & KOJOVIC, T. 2005. *Mineral Comminution Circuits - Their operations and optimisation*, University of Queensland.
- NARAYANAN, S. S. & WHITEN, W. J. 1988. Determination of comminution characteristics from single particle breakage tests and its application to ball mill scale up. *Trans Inst Min Metall*, 97, C115 - 124.
- SHI, F. N. & NAPIER-MUNN, T. J. 1996. A model for slurry rheology. *International Journal of Mineral Processing*, 47, 103-123.
- SHI, F. N. & NAPIER-MUNN, T. J. 1999. Estimation of shear rates inside a ball mill. *International Journal of Mineral Processing*, 57, 167-183.
- SHI, F. N. & NAPIER-MUNN, T. J. 2002. Effects of slurry rheology on industrial grinding performance. *International Journal of Mineral Processing*, 65, 125-140.
- SIDDALL, B., HENDERSON, G. & PUTLAND, B. Factors influencing sizing of SAG mills from drill core samples. *In: SME, ed. SAG Conference, 1996 Vancouver, BC*.
- STARK, S., PERKINS, T. & NAPIER-MUNN, T. J. JK drop weight parameters – a statistical analysis of their accuracy and precision, and the effect on SAG mill comminution circuit simulation. *In: METALLURGY, T. A. I. O. M. A., ed. MetPlant 2008, 2008 Perth*. 147 - 156.
- STARKEY, J. & DOBBY, G. Application of the SAG Power Index at five Canadian SAG Plants. *In: SME, ed. Autogenous and Semi-Autogenous grinding conference, 1996 Vancouver, BC*.
- STARKEY, J., HINDSTROM, S. & NADSDY, G. SAG Design Testing, What it is and why it works. *In: SME, ed. SAG Conference 2006, 2006 Vancouver, BC*.
- ULUSAY, R. & HUDSON, J. A. 2007. *The Complete ISRM Suggested Methods for Rock Characterisation, Testing and Monitoring: 1974 - 2006*, Ankara, Turkey, ISRM Turkish National Group.
- WIRFIYATAL, F. & MCCAFFERY, K. Applied Geo-Metallurgical Characterisation for Life of Mine Throughput Prediction at Batu Hijau. *Proceedings of the Fifth International Conference on Autogenous and Semiautogenous Grinding Technology, SAG 2011, 2011 Vancouver, Canada*.