The thin line between accuracy and bias in characterisation of ore grindability

F Faramarzi[1,4]*, R Morrison*[2] *and T G Vizcarra*[3]

1. Global Senior Mining Industry Consultant, Dassault Systemes, Brisbane Qld 4000.
   Email: farhad.faramarzi@3ds.com
2. Honorary Professor, JKMRC, The University of Queensland, Brisbane Qld 4068.
   Email: r.morrison@uq.edu.au
3. Senior Consultant, JKTech Ltd Pty, Brisbane Qld 4068. Email: t.vizcarra@jktech.com.au
4. Alumnus, JKMRC, The University of Queensland, Brisbane Qld 4068.
   Email: f.faramarzi@uq.net.au

ABSTRACT

In comminution, grindability or 'hardness' indices are used to describe ore resistance to ball milling. The most commonly used measure is the Bond ball mill work index (BBMWi). The implicit assumption underlying this test is that the distribution of mineral hardness within the sample is uniform, or at least falls within a narrow range of variation. This paper considers cases where that assumption is not valid.

In actual industrial practice, feed is subjected to multiple breakage mechanisms and several stages of classification. These may introduce biases in the hardness of material that is actually processed by the ball mill. That is, the actual hardness of feed presented to the ball mill may differ from the fresh circuit feed, especially when transition/weathered ore types are processed. Such ore types tend to exhibit variable breakage characteristics, and separation of their different hardness components is likely during different stages in comminution processes. The result is that harder minerals will tend to concentrate in the ball mill recirculating load. Another example is when crushed SAG pebbles (which are generally comprised of harder minerals) are diverted to the ball milling stage with the aim of improving SAG mill throughput. In this case, ball mills will process material which may be significantly harder than the circuit feed. In both cases, the ball milling stage may become an operational bottleneck. For these milling strategies, results from standard test work conducted on fresh ore samples should be treated with caution.

In addition to proposing a model for describing attrition breakage behaviour, this paper also tests one approach to measuring the extent and impact of ore hardness variability not reflected in standard test work protocols. It presents the results and discusses implications from a laboratory test method, developed at the Julius Kruttschnitt Mineral Research Centre (JKMRC), to investigate the distribution of hardness within samples that would each otherwise be considered 'uniform'. The results from testing three different samples characterised by standard and modified Bond ball tests confirmed that up to a 10 per cent under-estimation in evaluating ore grindability is possible. Under-estimation of ball milling feed hardness increases the risk of ball mills with limited capacity during periods of processing transitional ore domains or when a modified circuit configuration is required for debottlenecking and improvement purposes.

INTRODUCTION

Review of literature

In mining and mineral processing, particle size reduction commences with drilling and blasting operations, continuing through to the comminution circuit where rocks are subjected to different types of breakage environments. The breakage environment depends on the objectives of rock breakage, which varies from transportation in mining, to liberation in milling.

The intrinsic variability of an ore can cause instability in SAG mill throughput (Faramarzi *et al*, 2018, 2019) and inefficient classification, ultimately compromising grind size and recovery (Putland, 2006). To mitigate these risks, comminution characterisation can be undertaken to spatially model the hardness of different regions in a deposit.

In general, comminution characterisation can be conducted as single – or multi-particle test work. The former refers to tests in which individual particles are broken separately at pre-defined levels of energy; these include the JK Drop Weight (Brown, 1992, personal communication; Napier-Munn *et al*, 1996) and SMC tests (Morrell, 2004). The latter refers to tests that require batches of material to be processed in pilot or laboratory mills. Some widely-used batch test examples are the JK abrasion mill test (Leung, 1988), the Bond tumbling mill tests (Bond, 1952), the MacPherson autogenous grindability test (MacPherson and Turner, 1978), and the SAG power index test (Starkey *et al*, 2006). It is important to note that these tests usually are undertaken on 'fresh' circuit feed.

The focus of this paper is to highlight the possibility of problematic changes in ore hardness between the fresh circuit feed and the ball mill feed, that are not necessarily detected with standard testing procedures. Depending on the mineralogical composition of the ore, minerals of higher resistance to grinding would likely accumulate in the ball milling recirculating load (Maxson *et al*, 1933). However, in variable ore types, it is likely that SAG milling preferentially disintegrates softer minerals in the ore which would in turn preferentially exit the grinding circuit, further exacerbating the accumulation of hard minerals in the ball milling recirculating load. It is expected that this effect would be most prominent in weathered ores, which often exhibit the largest degrees of hardness variability in a deposit. But since standard test protocols are applied to fresh circuit feed, this phenomenon would likely remain undetected during comminution test work programs.

The Bond ball mill work index (BBMWi) is the industry-standard measurement of resistance to ball mill grinding. However, low-energy attrition events are applied to the feed during stages as early as crushing, and remain significant contributors to size reduction in both SAG and ball milling. In this context, the review of the literature focuses on the understandings gained from batch attrition test work studies, and how this impacts subsequent grindability.

Implications from attrition breakage characterisation

Previous workers have undertaken experiments to identify key variables in low-energy breakage events, often with a view to incorporating these modes of breakage into comminution models.

Bemrose and Bridgwater (1987) categorise some variables affecting attrition into particle-related and environment-related properties:

- Particle properties include size, shape, surface, porosity, hardness and cracks.
- Breakage environment properties include time, velocity, pressure, shear and temperature.

It has been observed that the rate of attrition decreases with time (Dietz, 1979; Forsythe and Hertwig, 1949). This phenomenon may be due to the initial loss of mass in the form of fines, and then gradual smoothing of particles which are less susceptible to attrition (Bemrose and Bridgwater, 1987).

The importance of this topic in mineral processing has encouraged some researchers to investigate breakage characteristics of ores at low levels of energy, conventionally called 'abrasion' or 'chipping'. Austin *et al* (1986) defined abrasion as the steady removal of relatively small progenies broken from the particle surface as it tumbles in the mill. They conducted dry tests using -63 + 53 mm material, tumbled over a period of 35 minutes in a 600 mm diameter mill. In their experiments, the undersize was screened out and replaced with the same weight of fresh feed at pre-defined time intervals. Test results were plotted as percent weight in the top size fraction versus grinding time, from which the following conclusions were made:

- At the beginning of the test, the rate of mass loss for the fresh feed is high, leading to a steep downward slope. This is probably due to initial chipping and rapid removal of asperities from particle surfaces.
- Percent mass in the oversize decreases gradually as the coarse particles are further abraded over time. This reduces the slope as the test progresses.

Tests at low-energy levels produce a bimodal size distribution that is typical of attrition. Leung (1988) conducted extensive experiments to obtain low-energy appearance functions from bimodal product size distributions by designing two types of tumbling tests (multi-particle and single-particle tumbling tests). It was observed that the product size distributions generated in either test regime were identical. Additionally, he conducted a series of low impact-energy (2.4×10^{-4} kWh/t) tests. The results of this comparative program, applied to samples from four different mines, indicated that product size distributions from individually tumbled particles, multi-particle tumbling, and low-energy impact tests, were effectively identical.

These experiments also showed that the amount of fine product mainly depends on grind time, mass of charge and the particle size of the charge. Leung's findings formed the basis of the now-standard JK abrasion test that measures the abrasiveness of a given rock sample, expressed in terms of a 't_a' parameter (Napier-Munn *et al*, 1996).

Later, Devasahayam (2013) adopted the standard JK abrasion mill testing approach to investigate the effect of grind time and particle size on the produced bimodal product size distributions. Three kg of -55 + 37.5 mm, -37.5 + 26.5 mm, -26.5 + 22.4 mm and -22.4 + 16 mm size fractions from five different rock samples were prepared. Tests were run up to 10 minutes, and results largely aligned with the findings of Leung (1988) – specifically, that a longer grind time and a smaller size fraction produces a finer product, while the relative shape of the product size distributions remains identical. Devasahayam (2013) concluded that the shape factor of the particles was also a key parameter in abrasion, which varied with particle size and rock type.

Faramarzi (2020) argued that the current abrasion tests, being dry experiments, do not capture the likely effect of water upon attrition or low-energy breakage events that predominate in SAG milling. It is likely that water has an important role in low-energy comminution especially when milling highly altered or weathered ores, which are generally rich in aluminosilicate minerals (eg clays) that can more readily deteriorate in water. Additionally, several other testing issues were highlighted:

- The standard JK abrasion mill test is a dry procedure.
- The test scrubs the surface of the particles for a short period of time, and quantifies rock attrition with a single 't_a' value after 10 minutes of tumbling. Therefore, time-dependencies are not considered in the procedure.

Faramarzi (2020) developed an extended attrition mill testing approach with the aim of capturing the role of ore variability in ore breakage behaviour under low-energy levels in dry and wet modes. The experiments were conducted on eight rock types, and showed that different rock types exhibit different attrition characteristics in wet compared to dry environments. To an extent, this reflected the degree of alteration or weathering of the rock. Preliminary results showed that the role of water might either improve or suppress attrition, depending on the rock type. The outcomes of the attrition tests in wet vs. dry environments led to a suite of experiments that tested the hardness of actual ball milling circuit feed, which was shown to sometimes be harder than fresh circuit feed.

The point is further discussed in the following sections of this paper.

Implications from grindability characterisation

The Bond ball mill test is a batch laboratory test in which the circuit is closed with a limiting screen, to simulate the effect of hydrocyclones that are commonly used to classify ball milling discharge. It is the industry-standard measure of ore grindability, and ultimately is used in ball mill design and geometallurgical modelling. The interaction between the ball mill and classifier drives the material composition in the mill, with harder minerals accumulating in the re-circulating load. The Bond test targets a 250 per cent re-circulating load which is a typical value in conventional ball milling circuits (Man, 2002).

The Bond ball mill has smooth liners to facilitate emptying the mill after each cycle. Additionally, liner packing is avoided with the use of smooth liners. Conversely, most industrial ball mills have lifters and rotate at typical speeds ~72–76 per cent (Morrell, 1996). The charge motion inside the laboratory mill must attain a profile similar to its industrial analogues, and thus with smooth liners the test is undertaken at 91 per cent critical speed.

Blending is common practice to improve feed consistency during production. Yan and Eaton (1994) tested whether the average of grindability of different components is a reliable indicator for ore blends. They carried out experiments on samples of hard rock, soft rock and three differing blends of the two components. It was observed that ore blend grindabilities were weighted more heavily towards the harder rocks. This suggests that the harder components were accumulating in the circulating load.

Fuerstenau and Venkataraman (1988) showed that minerals of different hardness interact with each other, with harder minerals improving the breakage rates of softer minerals, and with their own breakage rates decreasing with time. It has also been reported that in grinding multi-component feeds, the breakage rate functions of individual minerals change with variations in the composition of the mill hold-up (Fuerstenau and Venkataraman, 1988; Yan and Eaton, 1994).

Yan and Eaton (1994) asserted that in grinding a blend of hard and soft components in closed-cycle, the harder components break at slower rates and eventually predominate in the recirculating load. Accumulation of the harder components in the mill was evident during the Bond ball tests as well. They concluded that Bond ball testing may not be appropriate on ores of widely differing grindability, since the composition of the mill hold-up material may not represent the composition of the starting blend. This finding is analogous to the changes in composition that can take place between SAG milling and ball milling.

Implications from the extended attrition mill tests

Details of the extended attrition mill testing are provided in the Appendix A of this paper. The 'M10' variable (%) is the amount of material passing 1/10th of the geometric mean size of the original size interval (Faramarzi, 2020). Figure 1, shows the samples tested as well as the colour of their progenies after a comminution test; Table 1 summarises their comminution properties as a reference.

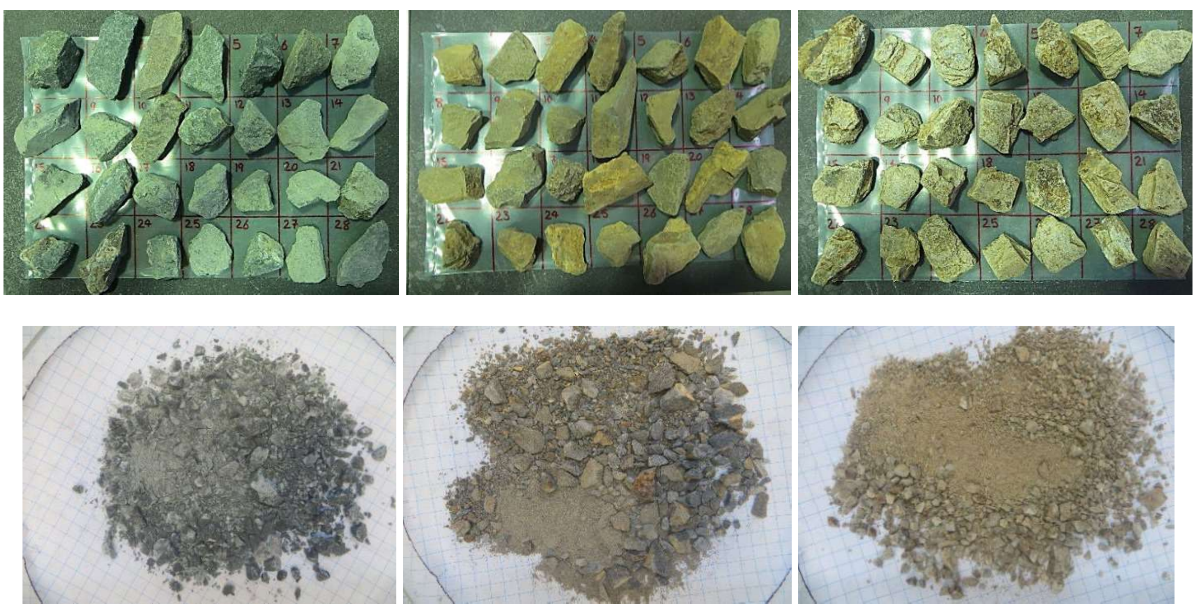

FIG 1 – Left to Right (Top): Sample A: Cadia Block Caved Gold Mine; Sample B: Maaden Gold Mine; Sample C: Weathered JK Site Rock; Left to Right (Bottom): Progenies for Samples A, B and C.

TABLE 1

Standard comminution and physical properties of tested samples.

Description	ta*	A×b	BBMWi (kWh/t)	Density (t/m^3)
Sample A	0.23	30	19.7	2.74
Sample B	0.30	30	12.7	2.70
Sample C	0.91	71	11.9	2.55

*Abrasion ore parameter.

Figure 2 shows the results of the extended attrition mill test for the three samples. The rate of mass loss for Sample A is low and is similar in both dry and wet modes. The rate of mass loss for Sample B is higher and the difference between dry and wet modes is more evident. Figure 3 shows that the rate of mass loss is very high for Sample C in both dry and wet modes.

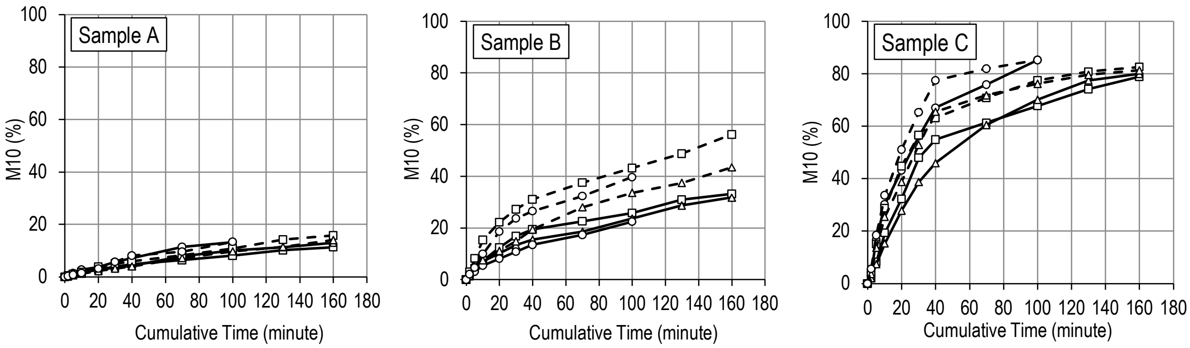

FIG 2 – Experimental results for three samples, with each sample tested three times (solid line for dry and dashed line for wet experiments).

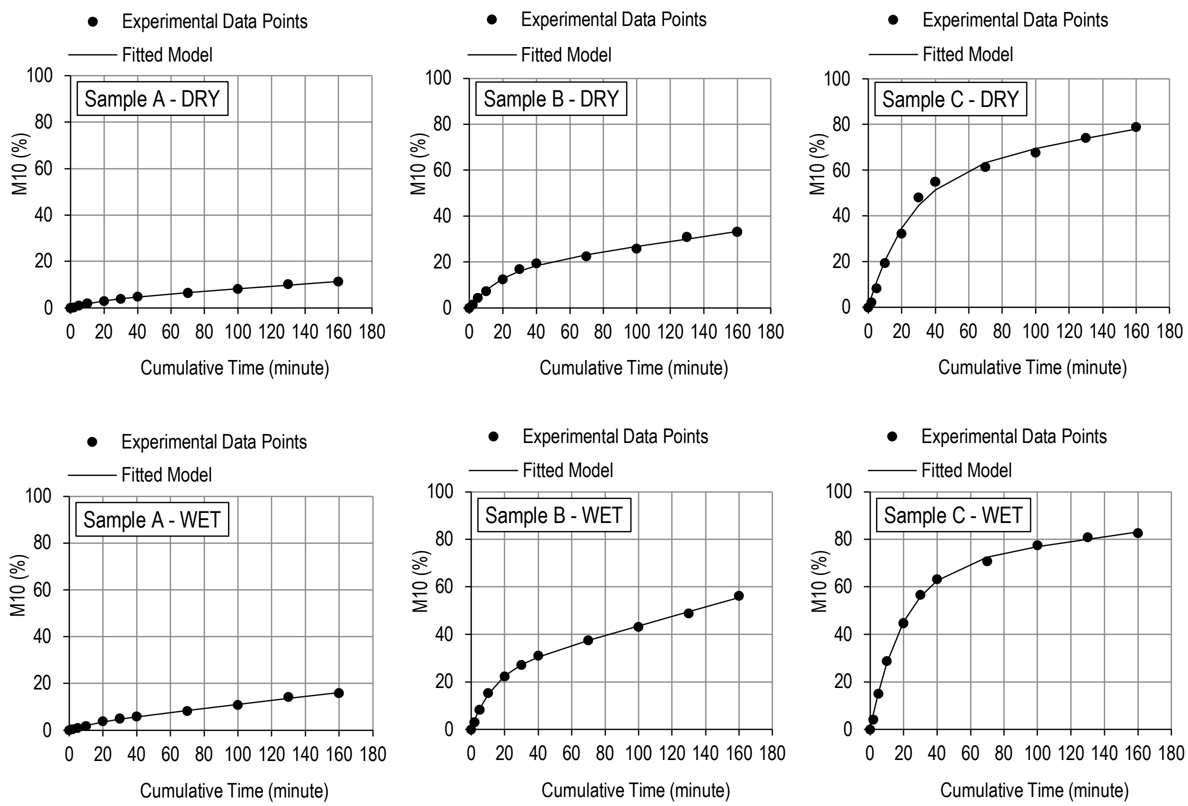

FIG 3 – Equation 2 fitted to the experimental data points of Test 1 – as an example.

The observed difference between dry and wet modes for Samples B and C may have been a consequence of their altered or weathered nature. Figure 2 shows that as expected, a rapid rounding and smoothing process occurs first followed by an almost constant rate of mass loss while the grinding environment remains more or less constant. It also indicates that water can promote the effect of low-energy breakage events.

Faramarzi (2020) used an exponential model which provided a good description of the rapid mass loss phase. However, we can combine the two relationships for a wider range estimate of M10 at time t minutes:

$$M10 = C + mt - C(1 - \exp(-Tt)) \quad (1)$$

where m is the slope of the linear processes, that is the rate of mass loss and C is the projected intercept at t = 0. The second term is an exponential decay which is equal to – C at t = 0. The rate of decay T controls how quickly the rounding process occurs and is the rate constant.

The model can be further simplified:

$$M10 = mt + C(1 - \exp(-Tt)) \quad (2)$$

Figure 3 shows that this model is a good match to the measured data. Tables 2 and 3 show the derived parameters and the standard error of the model fit or the estimate.

TABLE 2

Parameter estimates from model fitting and standard error – Dry mode.

Description	Test 1			Test 2			Test 3		
	m	***C***	***T***	***m***	***C***	***T***	***m***	***C***	***T***
Sample A	0.055	2.739	0.060	0.000	18.967	0.007	0.000	18.993	0.012
SE	0.173			0.302			0.378		
Sample B	0.109	15.936	0.055	0.141	9.612	0.085	0.151	7.209	0.073
SE	0.704			0.508			0.360		
Sample C	0.125	58.117	0.040	0.096	66.355	0.025	0.215	63.663	0.052
SE	2.598			0.853			2.098		

*SE: Standard Error of the estimate = $\sqrt{SS/_{N-3}}$ where N is the sample size.

*SS: Sum of Squares of difference = $\sum_{i=1}^{n}(M_i - P_i)^2$ where M and P are measured and predicted values of i.

TABLE 3

Parameter estimates from model fitting and standard error – Wet mode.

Description	Test 1			Test 2			Test 3		
	m	***C***	***T***	***m***	***C***	***T***	***m***	***C***	***T***
Sample A	0.083	2.727	0.061	0.050	8.496	0.008	0.027	14.226	0.013
SE	0.333			0.179			0.729		
Sample B	0.200	23.559	0.077	0.155	18.558	0.032	0.160	23.194	0.050
SE	0.585			0.907			1.014		
Sample C	0.097	67.597	0.051	0.034	75.564	0.039	0.000	86.340	0.048
SE	1.257			2.122			2.141		

*SE: Standard Error of the estimate = $\sqrt{SS/_{N-3}}$ where N is the sample size.

*SS: Sum of Squares of difference = $\sum_{i=1}^{n}(M_i - P_i)^2$ where M and P are measured and predicted values of i.

Observations based on the model parameters

Sample A which is appreciably harder than samples B and C shows very similar parameters for wet and dry attrition. The intercept C at 2.7 per cent suggests that only a small amount of rounding and smoothing occurs.

The grinding rate m for Sample A is much lower than for Sample B. Surprisingly m for Sample C is lower again. However, that may be because with a C value of 58 per cent, the intensity of the grinding environment will have been substantially reduced.

Sample B has a much lower C value of 15.9 per cent and should enjoy a more constant grinding environment. However, an m which correlates better with mill performance may need to be normalised with an estimated or measured mill power draw.

The Bond test overcomes these issues by using a well-controlled ball charge and restoring the ore loading before each cycle.

The initial rapid wear phases enjoy a much more similar grinding environment and should offer more valid comparisons. The two harder ores A and B have similar dry rate constants *T*, but the altered Sample C has a much lower value. As noted earlier, fresh ore Sample A shows similar parameters, but oxidised/altered Samples B and C show appreciably increased rates of initial loss and intercept when milled wet.

Overall, this model provides a way to estimate M10 over time and to compare how quickly and how much rounding will occur. However, as noted earlier, the *m* parameter may need to be normalised against power draw to be useful for prediction of attrition in other environments.

As the Bond test is based on grams of new product per revolution, the presence of or absence of -106 µm material in the feed sample makes little difference.

The modified feed does allow a little more of the new volume for grinding – about 25 per cent, but as the volume of feed is matched to the interstitial ball space, it does not make much difference.

Concluding remarks on attrition breakage behaviour

The rounding of Sample A is just that and does not imply a multicomponent feed. This is consistent with the C value of 2.7 per cent wet and dry, which suggests that ore A is also highly uniform with respect to hardness. The measured work indices overlap at less than two standard deviations.

Samples B and C have much broader distributions of hardness losing around 30 per cent of the soft feed hardness distribution as -425 µm. Hence the remaining feed material should be harder on average than the standard feed as suggested by the C values of 16 and 58 per cent respectively for Samples B and C. Their measured work indices do not overlap at two standard deviations.

Some other key observations during the test work were:

- The slow rate of attrition for the hard rock samples in dry and wet modes, producing more rounded particles. The colour of the product after each cycle was similar to the final product in both the dry and wet modes.
- The fast separation and disintegration of the soft components (likely to be clays and oxides) from the hard components (probably quartz) during the early stages of tumbling, particularly when wet. This was especially the case for Sample C (see Figure 2).
- Changes to the colour of the product in dry and wet modes. For example, in the case of Sample C, as the test proceeded the product colour changed from dark brown to light brown, ending with an almost white, silica-rich material.
- Decreasing viscosity of the slurry product in the wet tests, probably due to further removal of the clay minerals from the original sample after each cycle. This was particularly the case for Sample C.

The outcomes from this suite of experiments formed the basis of the hypothesis in the next section.

Statement of problem

The results of the extended attrition mill test in dry and wet modes lead to the following question and hypothesis:

- When a typical SAB or SABC circuit processes a transition ore type, a considerable amount of the softer material grinds out the SAG mill and reports directly to the hydrocyclone overflow; consequently, the harder (and coarser) material with a truncated particle size distribution (PSD) is introduced to the ball mill which accumulates in the recirculating load and ultimately constrains milling capacity.

  This potentially results in a change in BBMWi between the fresh circuit feed hardness, and the actual hardness introduced to the ball mills (see Figure 4).

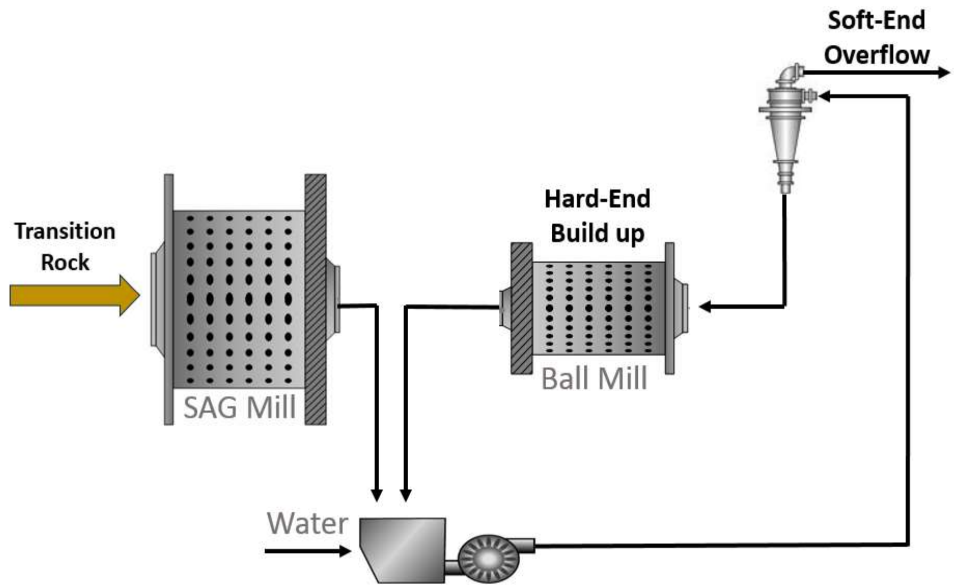

FIG 4 – Typical SAG – ball milling circuit configuration.

EXPERIMENTAL DESIGN

A test work program was designed to mimic the effect of attrition of rocks prior to introduction into ball milling circuits. It was assumed that scrubbing the material in a wet environment would remove some soft minerals in the feed, similarly to what occurs inside SAG mills. Additionally, a classification stage was introduced to mimic the duty of a hydrocyclone and generate a 'truncated' feed size distribution. The sample preparation process was as follows:

1. Material was crushed to -3.35 mm.
2. 4000 g of -3.35 mm material was fed to the JK abrasion mill (300 mm diameter × 300 mm length with four 10 mm lifter bars).
3. 1.5 L fresh water was added to the mill.
4. The mill was operated for 20 minutes at 53 rev/min.
5. The mill was emptied, and the product wet-sieved on a 425 μm screen.
6. The +425 μm material was oven-dried, and the undersize discarded.
7. After drying, the +425 μm material was re-sieved on a 425 μm screen to ensure good separation of fines.
8. This process was repeated several times to collect sufficient -3.35 mm + 425 μm material.
9. The standard Bond ball mill test was undertaken on the prepared samples.

For each ore type (shown in Figure 1), three samples were prepared based on the modified approach and three samples were prepared with the standard Bond procedure.

The closing screen sizes for Sample A were 106 μm for four experiments, and 150 μm for the other two which is reflected in a coarser product PSD for 'modified tests 1 and 2' shown in Figure 5. All experiments on Samples B and C were conducted with a closing size of 150 μm. The feed and product PSDs show good consistency in the experimental work.

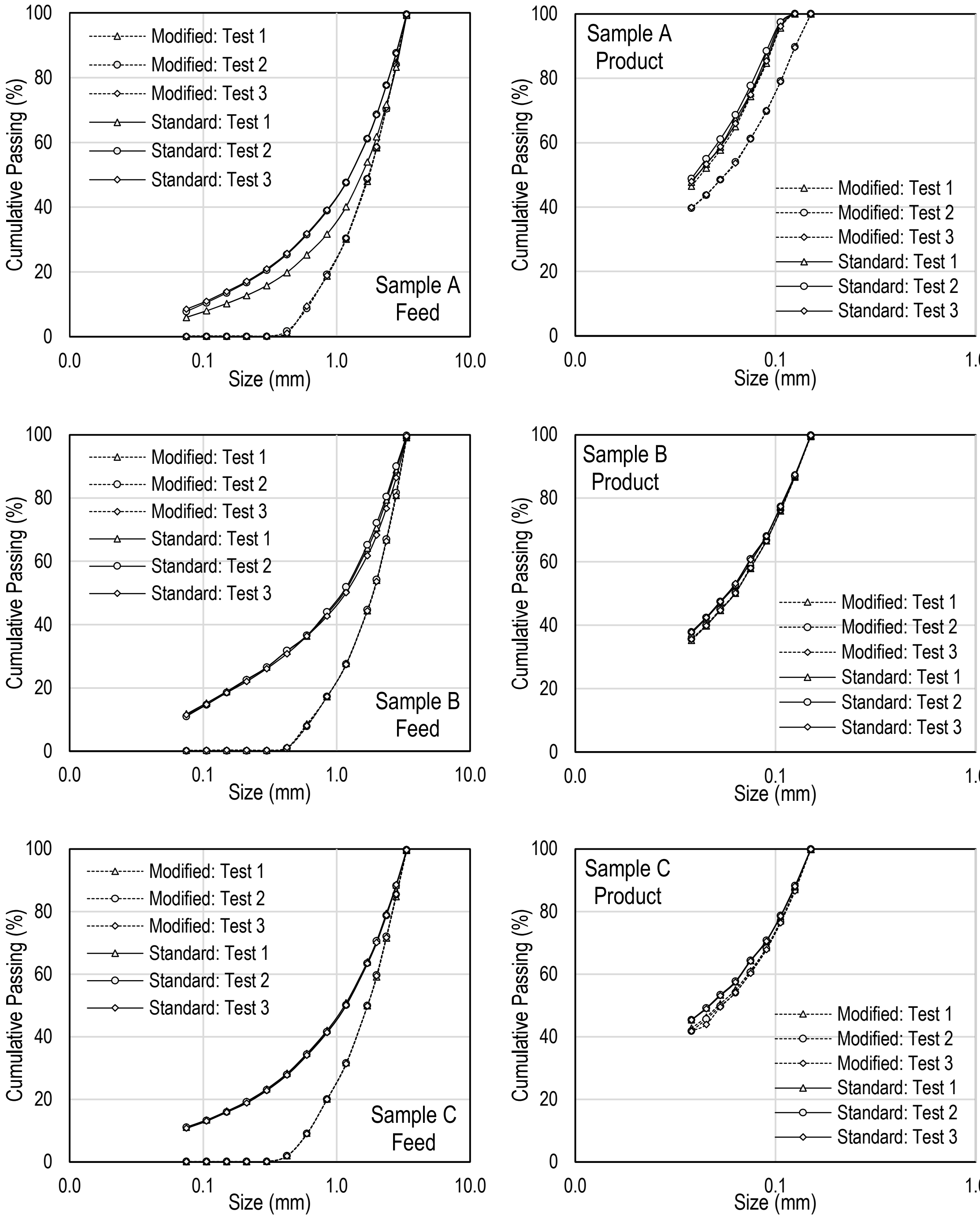

FIG 5 – Feed and product size distributions for all Bond ball mill tests.

RESULTS AND ANALYSIS

The Bond ball mill experiments (Standard versus Modified sample preparations) were undertaken three times on each sample. The measured BBMWi values as well as confidence limits (CL) are reported in Table 4.

The BBMWi values measured by the standard and modified Bond ball experiments are illustrated in Figure 6.

TABLE 4

Summary statistics of Bond ball mill tests (Standard versus Modified sample preparations).

Type of Test	Bond Ball Mill Test (Standard Sample Prep)			Bond Ball Mill Test (Modified Sample Prep)		
Measurable	**BBMWi (kWh/t)**			**BBMWi (kWh/t)**		
Sample	**Sample A**	**Sample B**	**Sample C**	**Sample A**	**Sample B**	**Sample C**
Test 1	19.8 (CS=106um)	12.8 (CS=150um)	11.9 (CS=150um)	20.6 (CS=106um)	14.0 (CS=150um)	13.1 (CS=150um)
Test 2	19.7 (CS=106um)	12.5 (CS=150um)	11.9 (CS=150um)	20.7 (CS=150um)	13.9 (CS=150um)	13.0 (CS=150um)
Test 3	19.6 (CS=106um)	12.7 (CS=150um)	11.9 (CS=150um)	21.0 (CS=150um)	13.9 (CS=150um)	13.4 (CS=150um)
Mean	19.7	12.7	11.9	20.8	13.9	13.2
SD	0.10	0.15	0.00	0.21	0.06	0.21
95% CL	0.25	0.38	0.00	0.52	0.14	0.52

SD: Standard Deviation, CL: Confidence Limit, CS: Closing Screen.

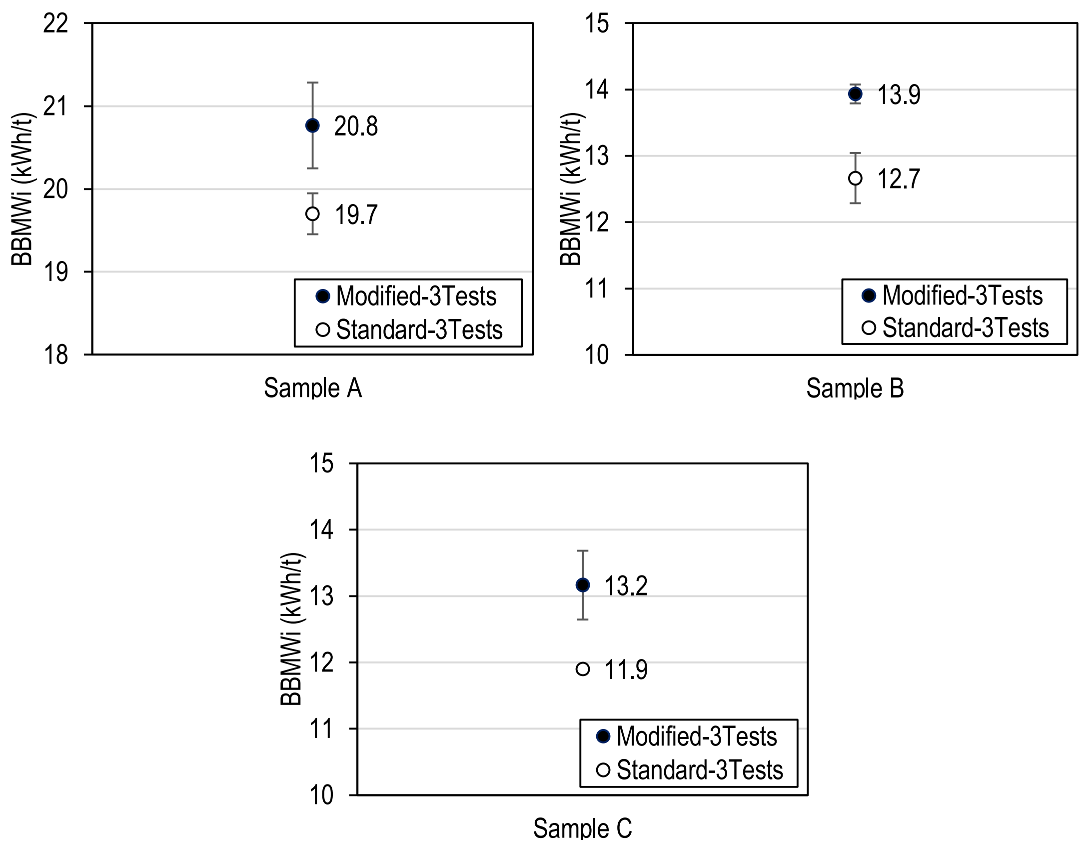

FIG 6 – Comparison of standard and modified BBMWi values.

In each test, the modified procedure resulted in 'harder' BBMWi results. While the magnitude of this change differed between each sample, all increases in BBMWi from the baseline standard procedure to the modified procedure were statistically significant.

The differences in the BBMWi values between the standard and modified testing procedures are likely to be driven by ore mineralogy and texture, and to some degree the removal of the -425 µm fines. That is, in the case of variable ores, the feed prepared through the modified sample preparation is concentrated in harder minerals following the removal of softer minerals. However, the circulating load in the BBMWI test is truncated as the closed-circuit size as part of the standard test. This factor will reduce the sensitivity to using a truncated feed.

Figure 7 compares the grindability of all samples during the experiments. For Sample A (a fresh, competent, less heterogeneous rock type) it was difficult to differentiate between grindability rates of the standard (Mean = 0.863 g/rev) and modified (Mean = 0.876 g/rev) experiments. However, Sample B (a competent but more variable rock type) shows a significant difference in grindability between the standard (Mean = 1.547 g/rev) and modified (Mean = 1.785 g/rev) tests. Sample C (a weathered, soft and variable rock sample) shows similar patterns between the standard (Mean = 1.629 g/rev) and modified (Mean = 1.864 g/rev) tests.

As shown in Figure 7, the grindability rates for Sample A show no significant difference between standard and modified tests, which is characteristic of a competent ore type. It is interesting to note that for Samples B and C, standard and modified feeds resulted in significantly different grindability rates at all stages. A possible reason would be the presence of higher concentrations of hard minerals in the modified feed. That is, the attrition process in wet environments results in preferential disintegration and separation of 'softer' minerals from the initial feed. Mineralogical analysis is required for confirming possible changes in composition in these ore samples, which should be considered in future investigations.

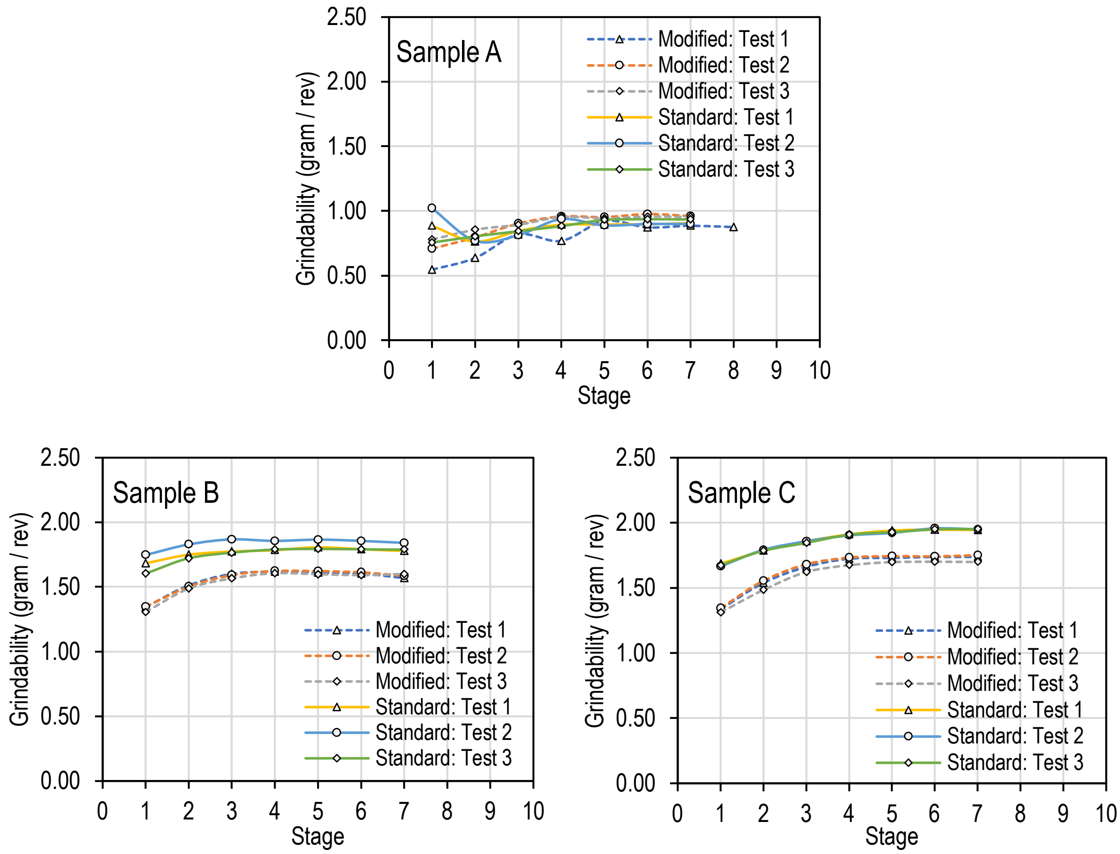

FIG 7 – Grindability rate per stage for all Bond ball mill tests.

DISCUSSION

A simple model of the process has been developed. The model parameters provide quantitative characterisation of the rounding phase and the more uniform rate of attrition phase after removal of asperities and altered material.

To further understand the implications of ore variability, the possibility of hardness/grindability changes through the comminution-classification process was examined by developing a suite of novel laboratory experiments. The outcomes are considered indicative and should assist future investigations in improving ore testing procedures.

Although standard 'average-based' comminution tests provide indicative measurements of ore hardness properties, not accounting for possible changes in material hardness at different stages of a flow sheet could render standard test outcomes as misleading. At worst, this may result in the selection of a ball mill which is too small.

The attrition tumbling mill testing approach in dry and wet modes characterises the amenability of rock samples to attrition. The difference between wet and dry attrition parameters to some extent indicates the degree of alteration or weathering of the rock (eg clay-rich samples). The indications from these experiments suggest that it would be beneficial if standard testing methods are improved to obtain more information on ore breakage behaviour on a stage-by-stage basis, particularly before and after classification steps where removal of fine particles from the circuit could bias the composition of recirculating loads towards harder minerals.

The results of this study suggest that it is likely that comminution characteristics (ie BBMWi) of fresh, competent ore types (eg Sample A) remain largely consistent through the milling process. That is, the BBMWi of fresh feed will be representative of ball milling feed. Conversely, for weathered samples where soft minerals are susceptible to rapid deterioration in the presence of water (eg Samples B and C), size reduction and classification processes might bias ball milling feed grindability towards harder minerals.

It is worth noting that this effect can, in other ways, offset the benefit of strategies that are otherwise intended to improve circuit performance. One example is when crushed SAG pebbles (which are generally comprised of larger percentages of hard minerals when compared to fresh feed) are diverted to the ball milling stage with the aim of improving SAG mill throughput. This can overload ball mills with material that may be significantly harder than the circuit feed.

Overall, the results of this study suggest that depending on the ore characteristics, ball mill feed hardness could increase by 10 per cent compared to fresh circuit feed, which is otherwise tested in conventional test work programs. This difference might be exacerbated with different circuit configurations, and should be investigated in future research.

CONCLUSIONS

The standard ore hardness test work procedures assume reasonably homogeneous feed. The test work approach detailed in this paper provides a way to quantify variability arising from non-homogenous feed. High variability will most likely increase the required ball milling power compared with traditional design techniques. Hence one way to reduce risk associated with high variability would be to increase contingency in ball mill selection.

The novel tests undertaken in this study showed that, depending on the degree of alteration/weathering of an ore, the rates of attrition in dry versus wet environments could differ, due to the preferential breakage (and removal from the grinding circuit) of soft minerals prior to ball milling. This has implications for the subsequent grindability of these types of rocks, as measured with Bond work index testing.

Key conclusions from this study are as follows:

- The results from this initial suite of experiments suggest that, depending on ore properties, up to a 10 per cent difference in hardness between circuit feed and the actual ball mill feed is possible. However, the difference may become more pronounced for highly variable ore types.
- Higher BBMWi values for samples prepared with the modified procedure are likely to be driven by ore mineralogy.
- Therefore, for orebodies of highly variable mineralogy, the standard Bond ball mill results should be treated with caution; for design purposes, higher risk factors should be considered when sizing mills.

Future experiments could compare Bond test results on circuit feed samples versus samples obtained from the hydrocyclone underflow of a full-scale production plant. Correlating these differences with mineralogical data will help operations better refine production strategies when dealing with highly variable/multicomponent ore types.

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APPENDIX A

The testing procedure is illustrated in Figure A1. The extended attrition mill testing approach steps are as follows (Faramarzi, 2020):

- A 300 mm diameter × 300 mm long tumbling mill with four 10 mm lifter bars.
- The mill speed is 53 rev/min.
- Sample requirement is 4000 ± 30 g.
- Particles suitable for this testing approach can be in either of -63 + 53 mm, -53 + 45 mm, -45 + 37.5 mm, -37.5 + 31.5 mm and -31.5 + 26.5 mm or a combination of two successive size fractions. However, it has to be noted that the experiments were conducted by using 4000 ± 30 g particles in the size range of -63 + 45 mm (2000 ± 15 g of -63 + 53 mm and 2000 ± 15 g of -53 + 45 mm). It was aimed to use very coarse particles, assuming that they should contain more elements of intrinsic variability.
- Accumulative grind time is 100 minutes. It includes time intervals/cycles at which tumbling stops to measure mass loss at a defined size criterion. In this study, the accumulative grind time was extended to 160 minutes for several experiments to further investigate the effect of time on attrition behaviour of the tested samples.
- The testing approach includes two separate experiments in the wet and dry modes. In the wet mode, 1.5 litre fresh water is used in the first cycle as well as each of the time intervals.

The measurable is mass loss at a certain size criterion at the end of each cycle. Therefore, two 'characteristic' sizes were chosen as size criteria as below:

- M2 size: It is used to separate the product at 1/2nd of the geometric mean size of the upper and lower apertures of the original size interval. All the particles smaller than M2 size are removed and coarser particles will be present in the next cycle.
- M10 size: The M10 variable expressible in percent is the amount of material passing 1/10th of the geometric mean size of the upper and lower apertures of the original size interval. This variable is used in the modelling.
- Additionally, mass of the particles that are still falling in the original size range is measured in each cycle. This variable shows percentage of mass loss within the original size range after each cycle.

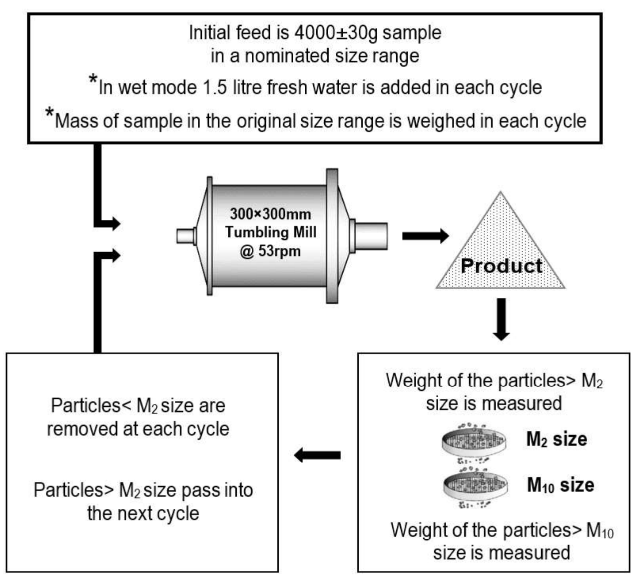

FIG A1 – The extended attrition mill testing approach procedure (Faramarzi, 2020).