

Application of HIT in Orebody Hardness Domaining Using Exploration Samples

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ABSTRACT: One of the challenges in orebody domaining in early exploration stage characterization programs, is availability of meaningful metallurgical data to target exploration drilling on prospects with a higher confidence of return. The HIT device has been successfully deployed in early metallurgical testing programs globally to help focus early resource definition and progress project development. During drilling programs however, access to larger sample fragments for ore hardness testing, especially related to parameters relevant to crushing and SAG/AG mill grinding, is generally not possible. To this end, an experimental study has been initiated at the Brisbane Metallurgical Laboratory in Australia to understand if HIT testing on -2 mm fragments could provide a solution. The proof-of-concept trial focused on 7 distinct rock samples selected to have a wide range of hardness ranging from 30 to 330, as defined by the well-known JKDWT Axb index. The standard HIT test protocol was modified to suit the small fragment constraint, and a wide range of test parameters was investigated aiming to find the most viable option to estimate the Axb index from tests on an unconfined bed of narrowly sized fragments below 2 mm. The preliminary results indicate that it is possible to reliably estimate the Axb index from testing less than 15g of the same material below 2 mm using the modified HIT test. This paper describes the initial trial and the results obtained for standard and small fragment HIT tests.

INTRODUCTION

The mining industry has for the longest time been testing ore hardness requiring significant investment in cost and time, typically Bond ball mill Work Index and SMC test[®] / JKDWT Axb (Bond, 1961; Morrell, 2004). The Axb index has become well known in the mining industry as a reliable measure of ore hardness in impact or crushing, evident in the numerous case studies reported at mining conferences since the late 1980s. Experimental determination of Axb using the above devices/tests requires samples, with sufficient mass, to be sent to designated laboratories, registered to conduct such tests. This protocol is accepted for

bankable and commercial testing, where material characterisation data is used in conjunction with machine specific data in modelling and simulation, and power-based calculations. However, for geometallurgical or orebody domaining in early exploration stage characterization programs, SMC tests simply do not provide a timely, viable and cost-effective solution. There is generally insufficient material available in the required coarser fragment sizes, typically between 22.4 and 13.2 mm for SMC tests, to perform such tests. For example, Bond testing typically requires at least 5kg of -3.35 mm material.

In order to address this void, a new device has been developed, exploiting a central feature of single particle impact testing—that the Axb can be reliably estimated using one precise low energy test, and that the Bond grindability can be linked to the breakage response at one precise high energy test. This device, called the Hardness Index Tester (or HIT), has been precision engineered to allow users to break narrowly sized fragments at a set specific energy, in a safe and easy manner. On pre-sized fragments, a single test using 20 fragments takes less than five minutes to complete, and the results are immediately available. Details of the HIT development and successful applications can be found in technical papers by Kojovic (2016), Bergeron et al (2017), Leetmaa et al (2019) and Varianemil et al (2023).

However, even the HIT device was seen as unsuitable for exploration stage ore characterization since the standard HIT test protocols required fragments coarser than 10 mm. This limitation was discussed in industry exploration forums regarding HIT applications for small fragments to infer Axb and BWi hardness.

Rio Tinto Exploration initiated a small proof-of-concept trial supplying 7 rock samples with expected wide range of hardness. The extension of the standard HIT test to particles with chosen fraction size less than two millimetres followed the work described by Whiten (2020) in which the JKDWT tester was used to break a bed of particles. Whiten's test breaks a bed of about 10 grams of particles in a narrow size fraction. Typical bed size is about 35 millimetres in diameter and 3 millimetres deep. The bed is retained by ring made of Scotch strapping tape, which has longitudinal strength but crosswise requires minimal energy to collapse.

The question whether bed breakage tests using the HIT can align with single particle breakage tests was addressed at the Brisbane Metallurgical Lab who completed the sample preparation, crushing & screening, standard HIT Axb tests and new small fragment HIT tests using a bed of narrowly sized particles.

This paper focuses on the application of the HIT device in unconfined bed impact breakage tests using fragments below 2 mm, and correlation of results with Axb measurements on coarser fragments. This work is seen separate to the significant research conducted on confined particle bed compression breakage tests (Schönert, 1988 and 1996) and more recent development of Piston & Die bed breakage tests at UBC (Davaanyam, 2015). The latter tests are much slower and require equipment that is not readily available for rapid application at the exploration phase.

HIT DESCRIPTION

SimSAGE Pty Ltd developed the HIT for rapid rock-hardness determination at the mine site, allowing on-the-spot determination of rock hardness variability. The HIT exploits a central feature of single particle impact testing, by which the Axb can be reliably estimated using one precise low-energy test (Kojovic, 2016; Napier-Munn et al., 1996). Results from several industrial trials confirmed the HIT was able to align with the Axb derived using the JK Drop Weight Test or SMC Test, providing the same fragments were used in both test methods, including the initial fragment selection and product sizing protocol. Figure 1 shows the second generation HIT device, which comprises a frame, a sample cup to hold the fragment to be crushed, crusher hammer assembly, and dual lever mechanism



Figure 1. Image of HIT device and close-up of broken rock in cup

to trigger the hammer's release onto the fragment in the cup. The sample cup sits in a dedicated grooved inset on the base-plate's top surface and comprises a handle allowing a user to easily remove the sample cup from the frame during testing.

SAMPLE INVENTORY

Seven lump rock samples were selected for the small fragment HIT test trial with the total mass ranging from 1.95 to 5.93kg. Table 1 and Figure 2 show the samples and quantity as received.

Table 1. Summary of Samples Received by BML


 SAMPLE INVENTORY						
Project Ref	B2318	Page	1	Notes:		
PM	AL	Received Date	5/30/2023			
Client's Ref	Rio Tinto					
Item Label	Description	Condition	Comments	Wet/Dry	GROSS (kg)	Nett DRY (kg)
11202601	Vesiculated Basalt	good		Dry	2.45	
11202602	Basalt	good		Dry	5.93	
11202603	Siltstone	good		Dry	2.92	
11202604	Weathered Siltstone	good	Some breakage occurred in transit.	Dry	2.92	
11202605	Milky Quartz	good		Dry	1.99	
11202606	Greyish Quartz	good		Dry	2.01	
11202607	Granite	good		Dry	1.95	



Figure 2. Images of seven samples supplied for proof-of-concept tests

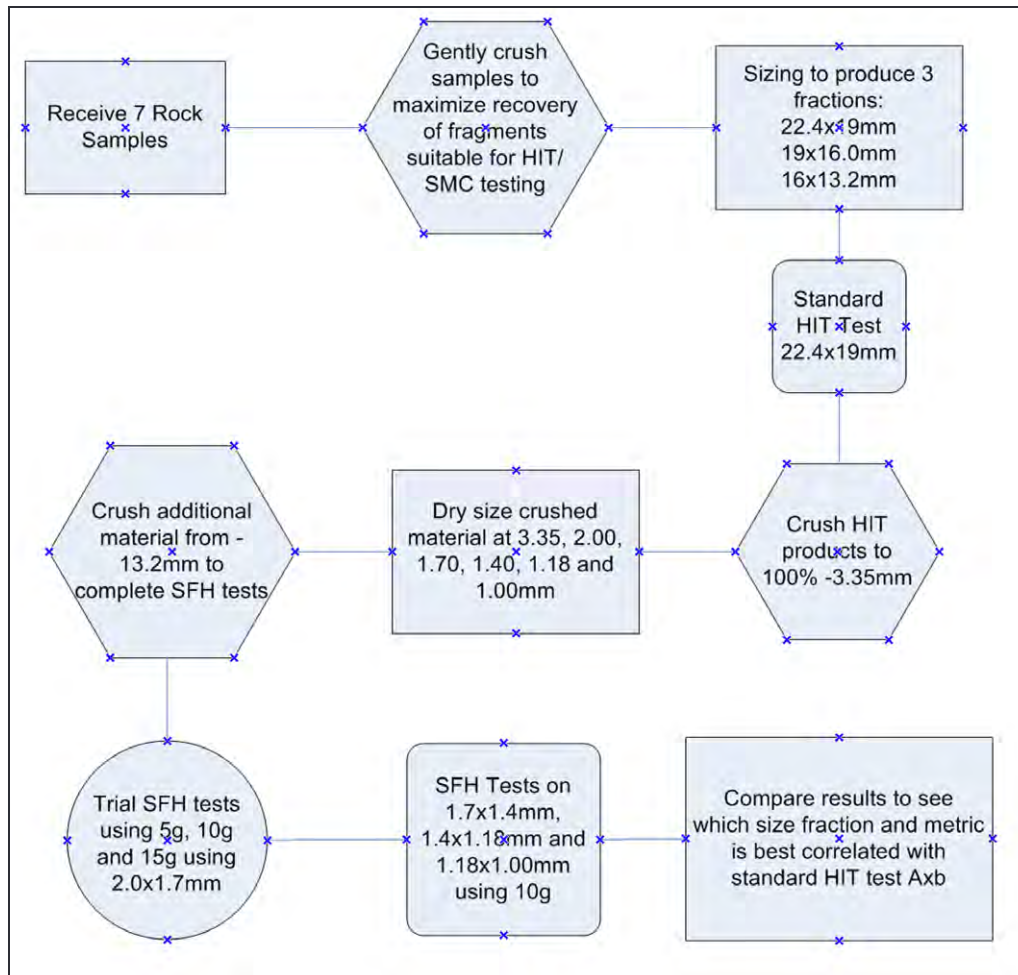


Figure 3. Flowsheet showing workflow applied to all 7 samples

SCOPE OF WORK

The seven samples were all treated in the same way, aiming to provide fragments suitable for standard and small fragment HIT testing using selected size fraction in the target -2 mm range. Figure 3 shows the key steps of the workflow employed by BML. A description of these steps follows.

Sample Selection for Standard HIT Axb Tests

After reviewing the available material post initial crushing of the lump samples it was clear that there would be sufficient fragments to undertake standard HIT Axb tests using triplicate splits of fragments in the 22.4x19 mm size fraction. Figure 4 shows one split of 10 fragments for all seven samples supplied for the trials.

Results from Standard HIT Axb Tests

The results from the standard HIT Axb tests completed by BML are shown in Table 2. The format shows the results for

each split of 10 rocks across the 7 samples supplied by RT, including the average fragment mass in the 22.4x19 mm size fraction, specific comminution energy and Axb.

The table also shows the average Axb for each of the seven samples and standard deviation indicating variability within each sample. The standard HIT Axb tests suggest sample 4, weathered siltstone, has the lowest impact resistance with an Axb of 331. The sample with the highest impact resistance is sample 3, siltstone, having an Axb of 32. The variability within each of the 7 samples, as defined by the coefficient of variation (CoV) or SD/Mean, ranges from 3% for sample 5, milky quartz, to 20% for sample 2, basalt. The average Axb CoV is around 11%, compared to only 6% for the average fragment mass. The fragment mass CoV ranges from 4% to 10% across the seven samples. There is no evidence to suggest variation in fragment mass translates to variation in impact hardness as expressed by Axb.



Figure 4. Images of 10 fragments in the 22.4×19 mm size fraction used in HIT Axb tests

Table 2. BML HIT Axb Test Report

Sample ID	HIT sizes	Sample Split	Number of Particles	Average Mass (g)	Ecs (kWh/t)	HIT - Axb*	Average Sample HIT - Axb*	Standard Deviation of Sample HIT - Axb*	Crushing Hardness Ranking
11202601	-22.4 / 19.00 mm	1 of 3	10	13.5	0.2	70	74	6	soft
		2 of 3	10	11.9	0.3	81			
		3 of 3	10	12.5	0.2	71			
11202602	-22.4 / 19.00 mm	1 of 3	10	13.7	0.2	56	61	12	medium soft
		2 of 3	10	12.4	0.2	53			
		3 of 3	10	11.6	0.3	75			
11202603	-22.4 / 19.00 mm	1 of 3	10	12.4	0.2	29	32	4	hard
		2 of 3	10	11.5	0.3	32			
		3 of 3	10	11.7	0.3	36			
11202604	-22.4 / 19.00 mm	1 of 3	10	12.8	0.2	354	331	29	very soft
		2 of 3	10	11.7	0.3	298			
		3 of 3	10	13.1	0.2	340			
11202605	-22.4 / 19.00 mm	1 of 3	10	12.8	0.2	104	107	3	soft
		2 of 3	10	11.7	0.3	111			
		3 of 3	10	14.2	0.2	107			
11202606	-22.4 / 19.00 mm	1 of 3	10	13.0	0.2	85	96	12	soft
		2 of 3	10	12.0	0.2	109			
		3 of 3	10	12.5	0.2	95			
11202607	-22.4 / 19.00 mm	1 of 3	10	16.0	0.2	126	130	21	very soft
		2 of 3	10	14.5	0.2	112			
		3 of 3	10	14.7	0.2	153			

Comparison of HIT Axb Tests with Rio Tinto Geological Classification

The results from the standard HIT Axb tests were compared with RT's geological classification and nominal crushing hardness ranking, as shown in Table 3 and Figure 5. Though the overall trend is consistent, the geological classification is unable to clearly distinguish the samples in the intermediate hardness range, which is critical to define the energy requirements for crushing in industrial operations.

Generation of Small Fragments

The aim of the trial was to determine the applicability of the HIT for smaller size fractions by comparing the breakage response of a bed of -2 mm material with the breakage response of single coarser fragments using the seven samples supplied for the tests. To this end, the product from the HIT Axb tests were scalped at 3.35 mm, and the

-3.35 mm material screened to determine the mass distribution, specifically the +2.0 mm, 2.0x1.7 mm, 1.7x1.4 mm, 1.4x1.18 mm, 1.18x1.0 mm and -1.0 mm. The +3.35 mm material was further crushed and scalped at 3.35 mm to reduce the coarser material to essentially 100% -3.35 mm. The workflow is depicted in Figure 6.

The trials required generation of at least 30g of material from each of the seven samples, sufficient to undertake at least three repeat HIT tests using 10g per split. However, the initial preparation indicated that the HIT products alone could not provide sufficient mass, as shown in Table 4, requiring a small proportion of the initial -13.2 mm material generated in the initial crushing of the rock lumps to be subjected to a similar protocol as used on the HIT products. The final mass distributions across the seven samples were consistent with an average 66:34 split at 1 mm for the HIT products and 65:35 for the -13.2 mm material.

Table 3. Geological Classification of 7 Samples

RT_Sample_ID	Sample	Description	Crushing Hardness Ranking	Crushing Hardness Ranking	Average Sample HIT Axb*	SD of Sample HIT - Axb*
11202603	Siltstone	amorphous gray siltstone	hard	6	32	4
11202602	Basalt	amorphous, fine-grained basalt	medium soft	3	61	12
11202601	Vesiculated basalt	Vesiculated basalt	soft	2	74	6
11202605	Milky Quartz	White milky quartz	soft	2	107	3
11202606	Grayish Quartz	Grayish, slightly weathered quartz	soft	2	96	12
11202607	Granite	Compacted, biotite granite/granodiorite	very soft	1	130	21
11202604	Weathered Siltstone	weathered, slightly friable siltstone	very soft	1	331	29

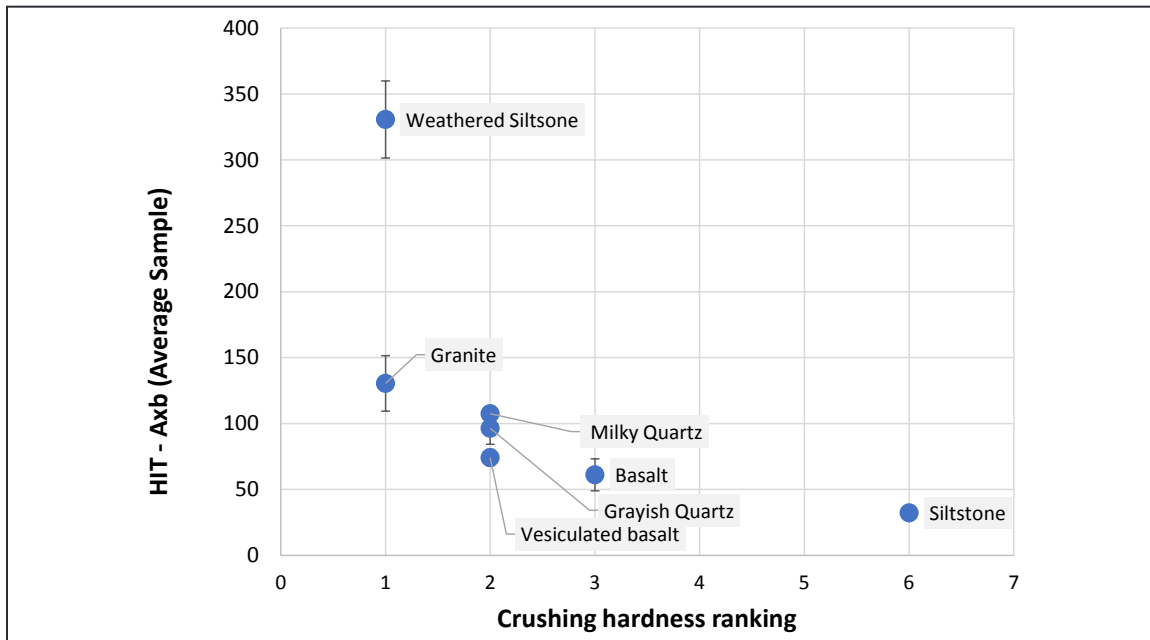


Figure 5. Relationship between geological hardness classification ranking and HIT Axb test results

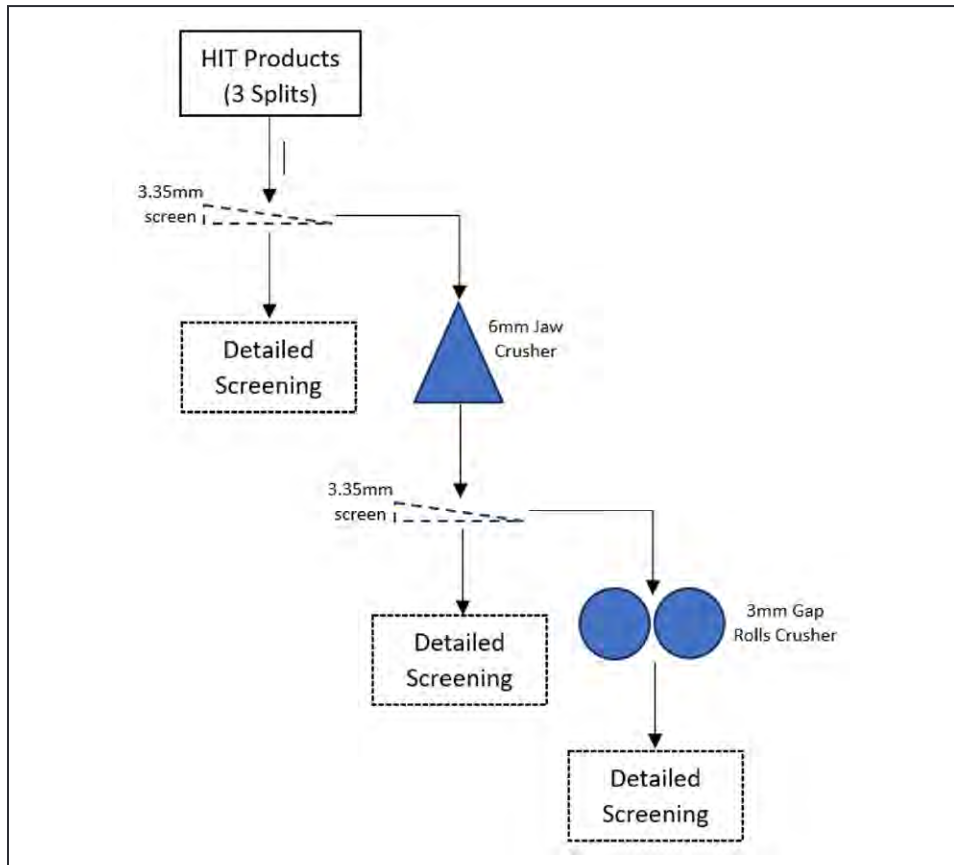


Figure 6. Workflow in reducing the HIT products to 100% -3.35 mm

Table 4. Mass Distributions from Sample 11202601 (Vesiculated Basalt)

Size Fraction	HIT Products	-13.2 mm Material	Sufficient Mass?
2.0×1.7 mm	65.8g	178.8g	Yes (> 30g)
1.7×1.4 mm	38.6g	89.1g	Yes (> 30g)
1.4×1.18 mm	24.3g	52.6g	No (< 30g)
1.18×1.0 mm	21.8g	65.0g	No (< 30g)

The question of whether the HIT products and -13.2 mm material had similar breakage characteristics was addressed by comparing the response of 2.0×1.7 mm fragments for three samples, namely 11202603 (Axb=32), 11202604 (Axb=331), and 11202606 (Axb=96). The HIT tests were conducted using 5g, 10g and 15g of fragments in the cup. The size distribution of the products suggest the fragments in the HIT products were similar to the -13.2 mm material, within expected variation within each sample. The energy applied to the bed can be expressed in kWh/t or J/g, as defined in the JKDWT (Napier-Munn et al., 1996), assuming the HIT drop hammer falls onto a solid base:

$$E_{sb} = 2.72 H M / m \quad (1)$$

where

E_{sb} = specific energy to bed (kWh/t) = 9.81 H M / m (J/g)

H = drop height (m)

M = mass of dropped mass (kg)

m = mass of particles in bed (g)

For example, in the HIT device, the E_{sb} is effectively 0.31 kWh/t for a 10g of sample, 4.51kg drop mass and 25.4cm drop height.

The sizing of the products from crushing and HIT testing was completed using 200 mm diameter sieves and RoTap sieve shaker. As the HIT sample sizes were small, the sieves were kept clean between tests. Table 5 shows the expected number of fragments in the HIT cup for 10g samples greatly exceed the typical numbers of fragments used in SMC (100) or even standard HIT tests (30). The shape factor was assumed to be 0.75. Hence the bed testing is likely to be significantly more representative of the whole sample, avoiding bias that is possible in SMC and HIT sample selection.

Table 5. Expected Number of Fragments in HIT Bed Breakage Tests (10g, Ore SG 2.6 t/m³)

Size Fraction	# Fragments
2.0×1.7 mm	815
1.7×1.4 mm	1400
1.4×1.18 mm	2415
1.18×1.0 mm	4000

SFH Test Evaluations using 2.0×1.7 mm

One of the key uncertainties was which size fraction to use in the small fragment HIT (SFH) testing, given the protocol was moving from single particle to bed impact breakage, as per Whiten (2020). To this end three samples were tested using 5g, 10g and 15g as noted previously. As the HIT cup diameter was approximately 80 mm, these masses nominally represented 1 layer, 1 to 2 layers and 2 to 3 layers, depending on the size fraction, as illustrated in Figure 7.

Figure 8 shows the specifications of the HIT cup.

The 15g samples were prepared in two ways, 1) as deposited in the cup, and 2) compacted by the weight of the HIT drop hammer carefully lowered on top of the material in the cup. There was no significant difference in the breakage response, evident in the similar product size distributions observed for the 15g as-is and compacted results.

The aim of the initial experiment was to compare the product size distributions (PSD) and correlations of the PSD metrics with the HIT Axb for the three 3 different masses tested. Two initial PSD metrics were selected,

1. the mass percent unbroken (%Unbroken), and
2. mass percent passing ½ of the initial mean particle size (%passing 0.5 RS) of the broken material.

The two metrics (%Unbroken and %Passing 0.5 RS) were plotted against the HIT Axb for each of the three samples selected in the 2.0×1.7 mm size fraction. Figure 9 compares the charts for 5g, 10g and 15g, suggesting that 10g



Figure 7. Images of 1.7×1.4 mm sample 11202602 in HIT cup (5, 10, 15 and 15g compacted)

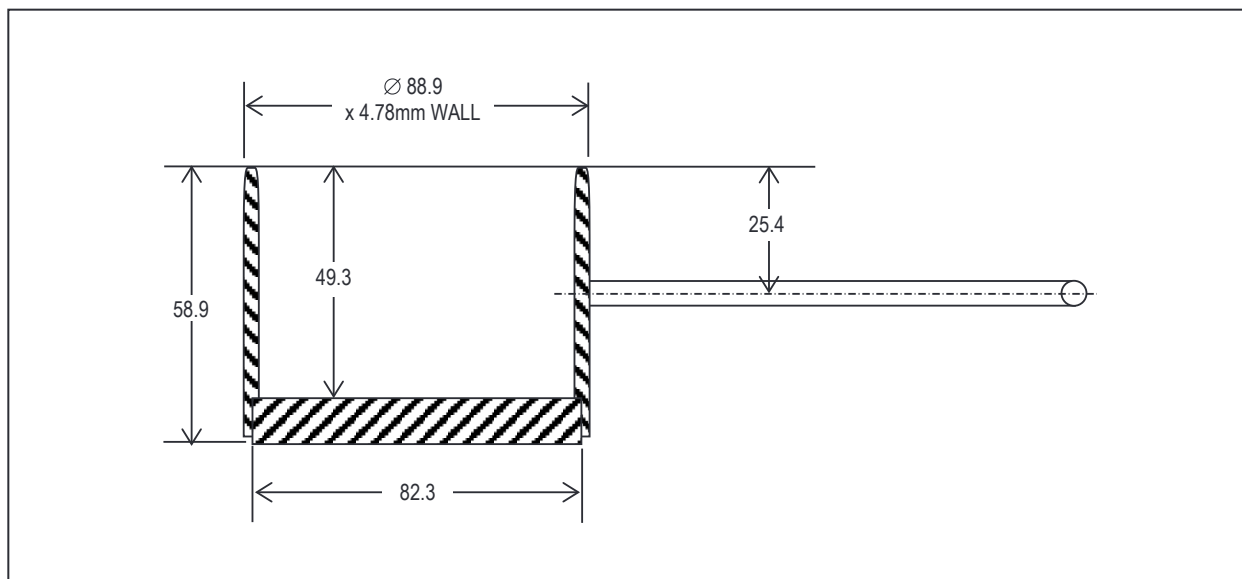


Figure 8. HIT sample cup specifications

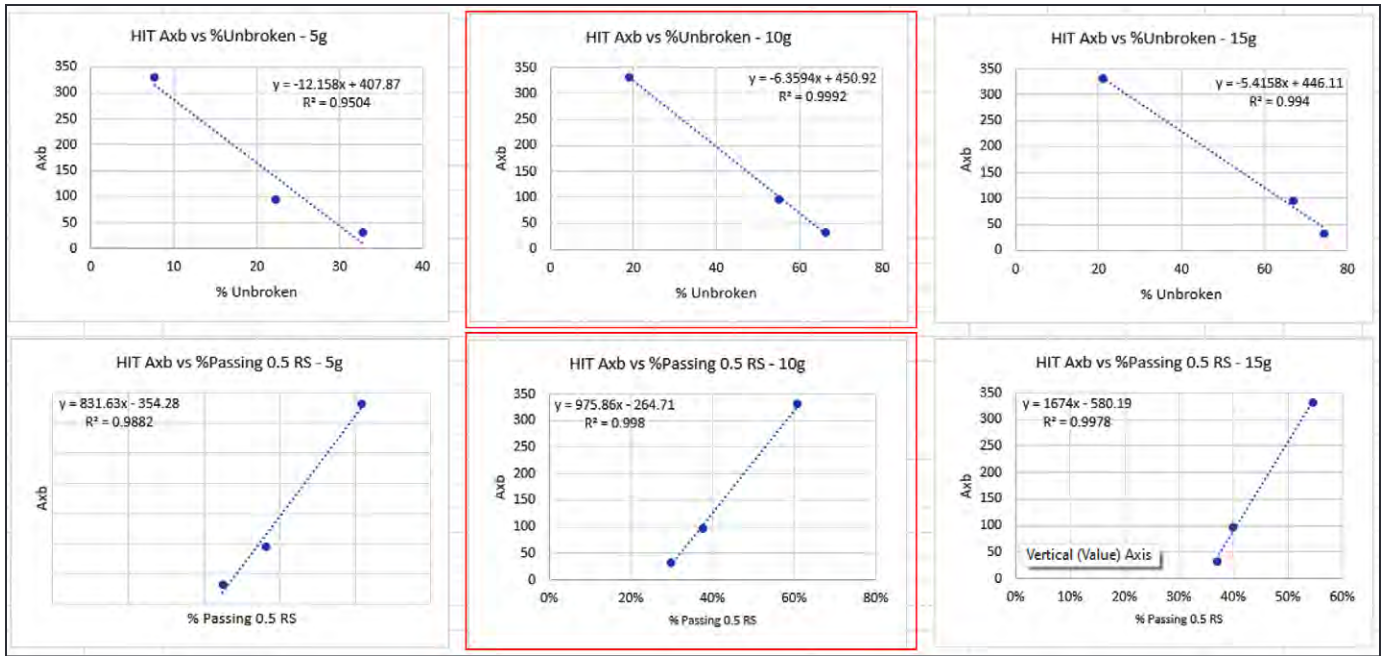


Figure 9. Charts for 2.0×1.7 mm samples (5, 10, and 15g), showing HIT Axb vs %Unbroken and HIT Axb vs %Passing 0.5 RS (10g highlighted in red as most reliable)

provided the most statistically significant and reliable correlations. Hence 10g was selected for the SFH test protocol and moved to the next phase of testing.

Comparison of SFH Test Size Distributions

The question of which size fraction below 2 mm to use in the SFH test protocol was addressed by comparing the size distributions of four separate size fractions and three samples, as follows:

Size Fractions

- 2.0×1.7 mm
- 1.7×1.4 mm
- 1.4×1.18 mm
- 1.18×1.00 mm

Samples

- 11202603 (Axb=32)
- 11202604 (Axb=331)
- 11202606 (Axb=96)

The size distributions shown in Figure 10 indicate that smaller fractions are not as good as far as distinguishing the samples in terms of the impact hardness (or Axb index). It appears the 1.7×1.4 mm size fraction is the best choice for the SFH protocol, based on the difference between size distributions for the three samples selected.

APPLICATION OF SFH TESTS TO ALL 7 SAMPLES

The selected SFH test protocol of 10g using 1.7×1.4 mm material was applied to all seven samples and results compared in charts of HIT Axb versus %Unbroken and HIT Axb versus %Passing 0.5 Initial Mean Size. Figure 11 shows the X-Y plot comparisons.

The plots suggest the %Unbroken metric and fractions smaller than 1.4 mm are not as reliable as 1.7×1.4 mm. The most significant correlation is for the 1.7×1.4 mm size fraction and %Passing 0.5 Initial Mean Size, showing an R² value of 0.97, expressed as follows:

$$\text{HIT Axb Index} = 1126.1 \times \%P - 332.4 \quad (2)$$

where %P = %Passing 0.5 Initial Mean Size (1.54 mm)

Clearly the dataset lacks softer samples, with Axb values in the 150 to 300 range. Hence more work is required to confirm the robustness of the relationship between Axb and %Passing 0.5 Initial Mean Size, if other metrics are more relevant, and to see if the relationship is ore specific or universal.

The initial results are very encouraging, suggesting the SFH tests provide a simple and quick method of testing the breakage properties of small particles which can be linked to the standard measures of impact hardness such as Axb.

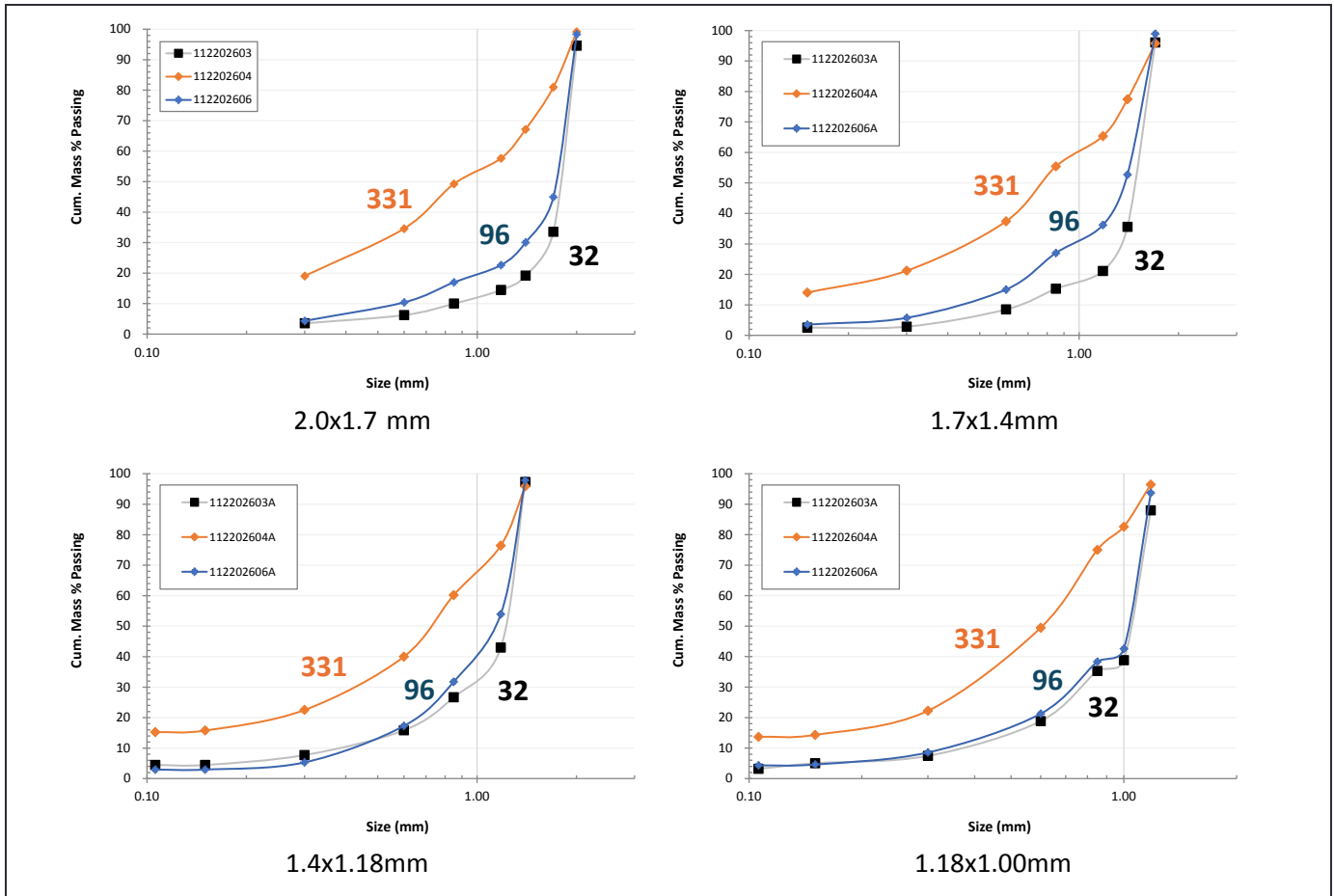


Figure 10. Size distributions of SFH test products for 4 size fractions and 3 samples

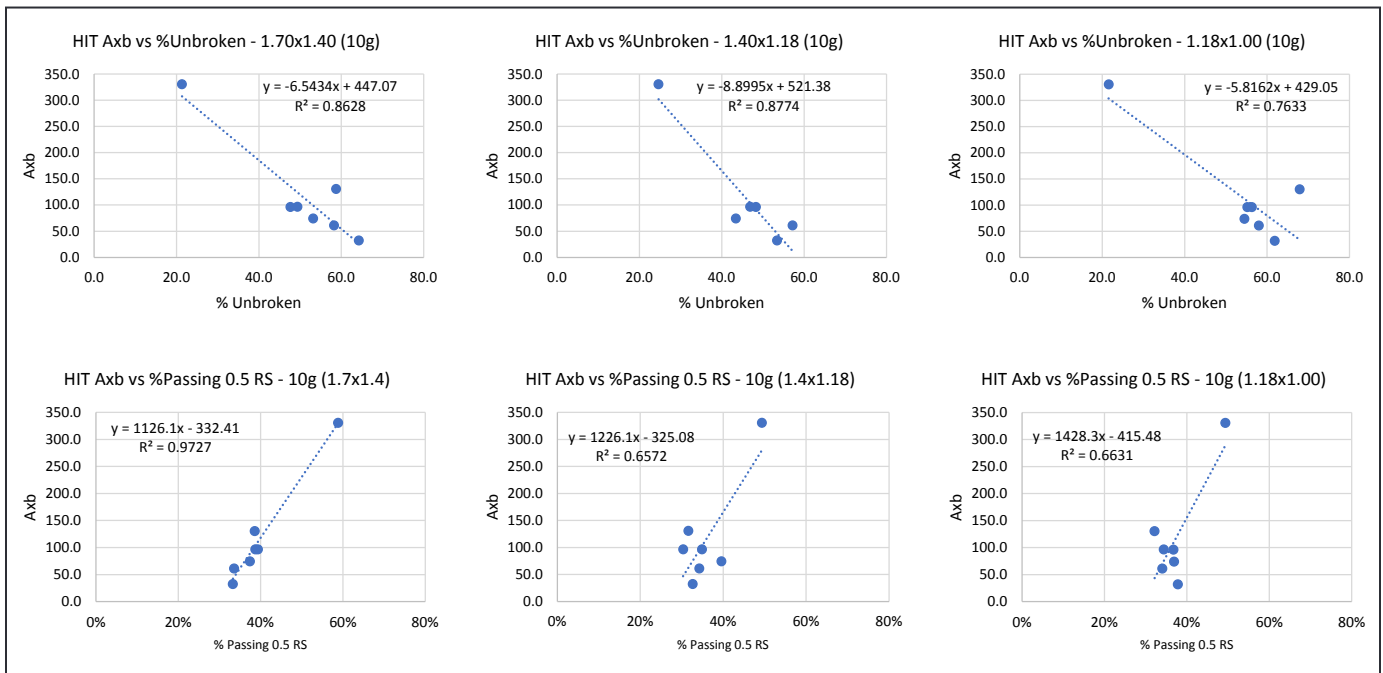


Figure 11. X-Y plots (7 samples) - 1.7x1.4 mm, 1.4x1.18 mm, 1.18x1.00 mm (10g)

CONCLUSIONS

The small fragment HIT test trial results are very encouraging, over a good range of rock impact hardness, as defined by the JKDWT Axb index. The trial results indicate that 10g of 1.7×1.4 mm material yields the most significant correlation with the HIT Axb index.

Of the two PSD metrics used in the analysis, the %Unbroken was less reliable, especially using the smaller fractions. The best option appears to be a normalized % passing metric, for example, the % passing 1/2 relative size. More work is required to determine whether there is a better metric for the SFH data analysis and subsequent modeling against standard ore hardness parameters.

The correlation for Axb with the % passing 1/2 relative size is very strong across the 7 samples, similar to initial 3 samples which bodes well for the robustness of the relationship. It is not clear whether the 2.0×1.7 mm fraction would be just as reliable or better. Further work is required to confirm.

The trial has yet to consider correlations with other hardness indices such as the Bond Work Index (BWi), but this will be part of validation analysis to see if the SFH test can also be used to reliably estimate the BWi.

The SFH test is much simpler and faster than single particle tests like JKDWT, SMC and standard HIT, and grinding tests such as the Bond Ball Mill Work Index test, and is considered an opportunity for early exploration programs to understand the deposit and target further drilling programs and areas for advanced metallurgical testing. The SFH test using 10g of 1.7×1.4 mm fragments quantifies the breakage response of approximately 1400 fragments, compared to only 100 fragments in the SMC test. Hence the SFH test is considerably more representative of the whole sample.

The SFH test requires only 10g, which is easily prepared without the problems of selecting typical coarse particles, particularly if they are not available as in exploration programs. The benefit is that the HIT can be deployed on samples finer than 2 mm generated from exploration drilling, offering the potential for targeted exploration drilling and focussed geometallurgy sampling, affording potential costs savings at the front end of a project/resource definition. The SFH test is a single impact on 10g of narrowly sized fragments, followed by screening of the product using 5 sieves starting with the top size of the fragments. The total SFH test time would be less than 10 minutes per sample.

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