Ore Hardness Mapping of Batu Hijau Ore Deposit Using the Hardness Index Tester

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Abstract

Quantifying ore hardness in terms of impact resistance for crushing and grindability for milling plays an important role in an effective mine-to-mill program both for long-term strategic and daily operational planning. Two well-known standards for crushing and milling applications in the mining industry are the SMC drop weight index and Bond ball mill work index. To be practically implemented for high-volume testing and rapid turnaround, these tests have many challenges.

Batu Hijau has embarked on a campaign to characterize their ore deposit hardness. This was required to assist with the process operational performance and to update the mill throughput model. To execute this task a newly developed device called the Hardness Index Tester (HIT) was acquired. HIT is a device SimSAGe developed and engineered which offers some advantages over traditional devices. For example, it offers a simple test procedure, reduced sample requirement compared to the classic drop weight test, and a rapid turnaround. In addition, economic benefits were also anticipated. The program was performed and completed in house in under six months, and involved the testing of 326 drill core samples, allowing for fully characterizing the ore deposit hardness.

Keywords

Batu Hijau, Amman Mineral, ore hardness, HIT, DWi, BWi

Introduction

The Batu Hijau porphyry copper–gold deposit is in the southwestern part of the island of Sumbawa, Nusa Tenggara Barat Province, Indonesia. Amman Mineral manages the deposit; at the time of writing Amman is the second-largest copper-and-gold mining company in Indonesia. Amman Mineral has vision to be a transformative organization creating a legacy of best and has mission for providing commodities to the world in a responsible and sustainable way by thinking bravely and acting with intent to bring out the best of Amman Mineral, communities, and environment. The deposit is processed through an open pit method followed by crushing, semi-autogenous grinding (SAG) milling, ball mill–cyclone, pebble crusher-screening, flotation, and submarine tailings placement. Figure 1 shows the deposit's geographical location.

Figure 1—Location of the Amman Mineral Batu Hijau mine in Indonesia

The Batu Hijau deposit has a large variation of ore hardness in both impact resistance and grindability. The ore impact resistance represented by the drop weight index (DWi), and grindability represented by the Bond ball mill work index (BWi), are well-mapped in the deposit through the past geometallurgy program. For BWi, the geological block model is considered to be a very accurate representation of the actual ore grindability, since the BWi deposit mapping involved intensive sampling and direct measurement through laboratory Bond tests. However, for DWi, metallurgists have observed deviation between the geological block model estimates and the actual ore impact-resistance measurements. This is possiblly because the DWi deposit map was based on an empirical model in which DWi is a function of the ore's copper content.

In March 2021 Amman Mineral engaged SimSAGe and applied the Hardness Index Tester (HIT) device to update the DWi mapping of the Batu Hijau deposits of Phase-7AC and Phase-8. Considering the fast laboratory process, HIT device utilization then expanded to daily DWi and BWi monitoring for ore fed to the SAG Mill and to developing throughput modelling for milling performance evaluation.

Description

Three main aspects are involved for mapping the ore hardness of Batu Hijau deposit and its relation to the crushing and milling performance. The three aspects are the deposit, the processing plant, and the HIT device which are described in the sections below.

DEPOSIT DESCRIPTION

The Batu Hijau porphyry copper–gold deposit lies along the tectonically active east–west-trending Sunda–Banda magmatic arc that marks the convergence of three major tectonic plates, the Indian–Australian, Eurasian, and Pacific Plates. The southern part of Sumbawa is underlain by Late Oligocene to Middle Miocene low-potassic (low-K) calc–alkaline to weakly alkaline andesitic volcanic and interbedded volcaniclastic rocks, associated with low-K intermediate intrusions and minor shallow marine sedimentary rocks and limestones (Garwin, 2002; Maula & Levet, 1996).

A series of Miocene to Pliocene (15 to 2.5 million years ago [Ma]) intrusions were emplaced within a Late Oligocene to Middle Miocene andesitic volcano-sedimentary succession on the island. These intrusions include porphyritic andesite, hornblende diorite, quartz diorite, feldspar porphyry, tonalite, and intrusive diatreme breccia, in that approximate chronological order. The early hornblende–plagioclase–phyric andesite intrusions in the Batu Hijau district are constrained in age from 15 to 17 Ma (Garwin, 2002). Felsic intrusive events commenced with quartz diorite plutons and late-stage granodiorite to tonalite dikes at 5.9 Ma, and continued through tonalite intrusions at 3.7 Ma (Garwin, 2002). Diatreme breccia is exposed at some localities and marks a late Phase of magmatic activity post-dating the hydrothermal alteration.

The pre-mineralization rocks in Batu Hijau consist of interbedded andesite volcaniclastic rocks, porphyritic andesite, and quartz diorite intrusive bodies. These rocks are intruded by multiple phases of tonalite porphyry in Figure 2. The tonalite porphyry intrusions are classified as intermediate tonalite and young tonalite. These tonalite intrusions are similar in composition and phenocryst content, but are distinguished on the basis of cross-cutting contact relationships and the abundance and size of quartz phenocrysts (Proffett, 2001). Emplacement of the tonalite porphyry complex was rapid (<100,000 years) from 3.7 to 3.6 Ma (Garwin, 2002).

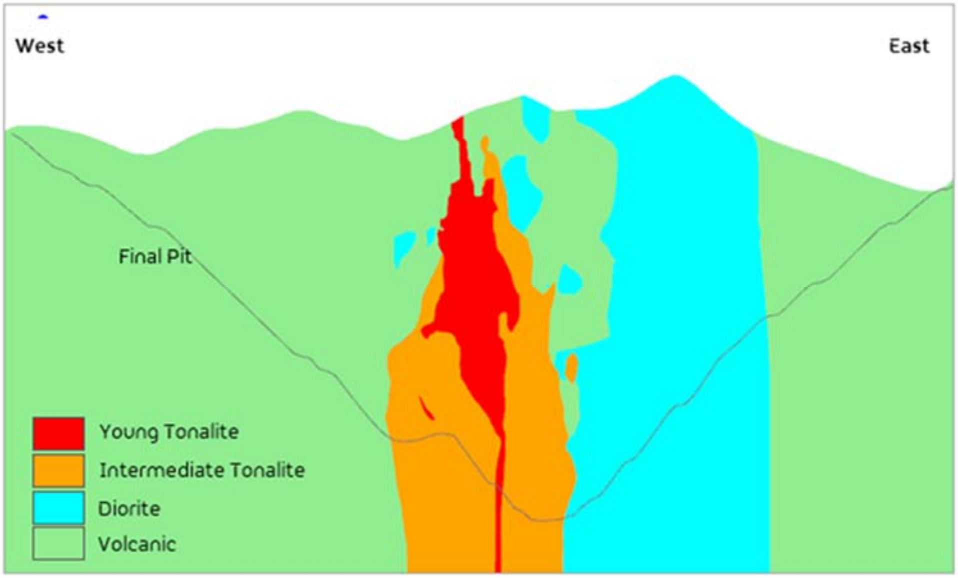


Figure 2—Typical geologic section 090 facing north

PROCESS PLANT DESCRIPTION

Batu Hijau has a dual-line grinding mill circuit, two SAG mills, followed by two closed-circuit ball mills per SAG mill and a combined pebble crusher circuit. The SAG mill is fed with crushed ore from the mine with 80% passing (F_{80}) 50 to 70 millimetres (mm). The typical throughput capacity of Batu Hijau's grinding circuit is 4,000 to 6,000 tonnes per hour depending on ore hardness. The typical cyclone overflow product reporting to the flotation circuit has a P_{80} between 180 and 250 microns. The main sections of Batu Hijau's operation, shown in Figure 3, are as follows:

- Primary crushing circuit: two 60–89 gyratory crushers with 600 kilowatt (kW)-rated motor power followed by a 5 kilometre overland conveyor feeding the SAG mill stockpile.
- SAG circuit: two gearless 36-foot (ft) SAG Mills with 14 megawatt (MW)-rated motor power followed with trommel screen and dewatering screen.
- Ball mill circuit: four 20 ft ball mills with 7.4 MW rated motor power followed by 15 hydrocyclones.
- Pebble crusher circuit: four pebble crushers with 750 kW-rated motor power followed by two vibrating screens. The pebble crusher screen undersize reports to the Ball Mill discharge pump box.

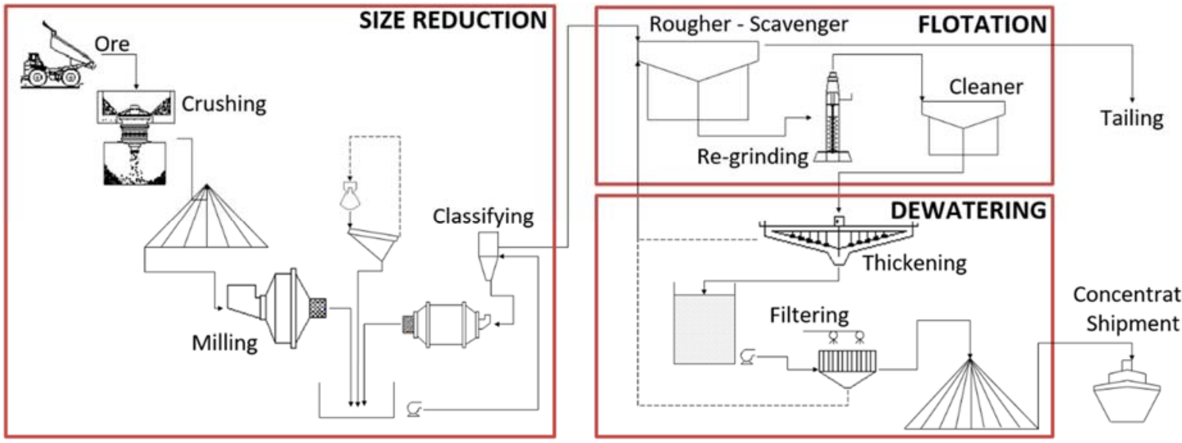


Figure 3—Amman Mineral’s Batu Hijau simplified processing flowsheet

Batu Hijau’s ore hardness is very dependent on the ore lithology and copper content. In general, the ore competency decreases as the ore copper content increases. This is because the main copper mineralization appears in the intermediate tonalite core’s internal fractures, surrounded by quartz diorite intrusive and volcanic lithic breccia rocks.

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). The HIT has been precision-engineered to allow users to break narrowly sized fragments at a set specific energy, in a safe and easy manner. Figure 4 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 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. The device is supplied with a novel quality assurance and quality control (QA/QC) feature, to ensure that the targeted potential energy is consistently delivered.

HIT users are provided access to online software for Axb and BWi calculations—eliminating the need to send the raw data off site for analysis (further details of HIT development and applications can be found in technical papers by Bergeron et al., 2017; Kojovic, 2016; Kojovic et al., 2019). Opportunities to automate HIT are being considered.

As of April 2023, 16 machines are in use: 12 at operating mine sites and 4 at commercial laboratories. Since the HIT's commercial release in August 2017, HIT usage statistics across all 16 users indicate approximately 47,000 tests (31,500 Axb tests and 15,500 Bond proxy tests), representing almost 683,000 rocks. Industrial feedback has confirmed the HIT mechanical integrity is very good, requiring only replacement of impact plates and bearing at service. The user feedback confirms the established QA/QC is important to sustain test result integrity.

The HIT device can be used to generate quantitative estimates of Axb and BWi using relatively small samples of ore (<500 grams [g]) from the mine or mill feed. It is thus ideal for routine testing of mill feed samples to monitor performance and adjust mill settings for optimum performance or a geometallurgical program.

Figure 4—Image of HIT device at Batu Hijau and close-up of broken rock in cup

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. If the selection and sizing protocols are not followed in the HIT testing, calibration against standard tests may be required. Figure 4 shows a recent comparison using drill-core samples from a copper deposit in Canada, highlighting a strong agreement between the SMC and HIT Axb results across a wide range of hardness (Axb 30 to 120).

The industrial trials also demonstrated the possibility of using HIT for Bond BWi estimation via a calibration between the breakage response at high specific-energies and actual full Bond BWi results on the same ore. This concept is based on historical work, including the studies in coal breakage linking the Rosin–Rammler curve slope and intercept to the coal hardness. As the specific energy required in HIT testing is of the same order as that delivered during one cycle in the BWi laboratory mill, the fragment size used in the HIT BWi proxy tests needs to be around 8 to 10 mm. Results from industrial trials with over 400 samples covering 20 ores suggest that this approach can be used to estimate the BWi within an acceptable certainty for geometallurgical applications. In some cases, the approach has yielded very reliable estimates using less than a 50 g sample. Figure 5 shows a recent example of a wide range of hardness (BWi 7 to 23 kilowatt hours per tonne [kWh/t]), with an average relative error better than 5%.

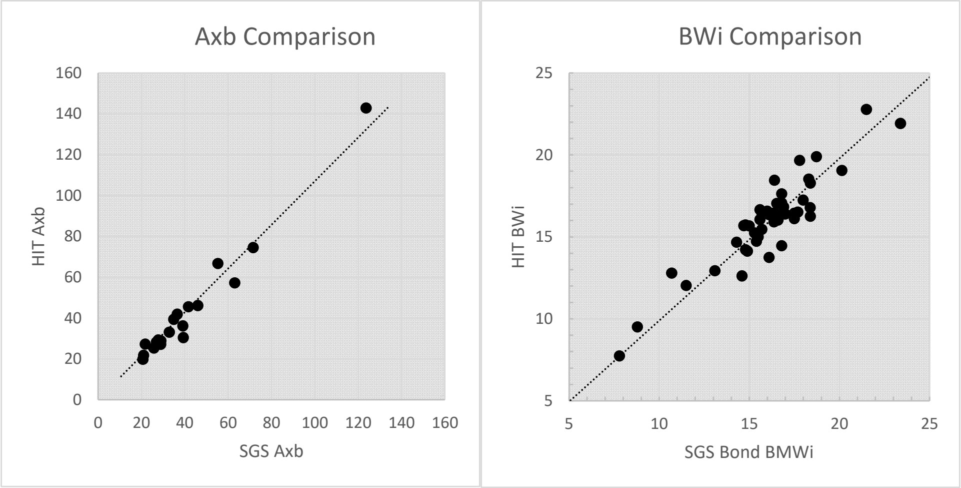


Figure 5—Example of correlations between HIT and standard DWi and BWi Results (62 drill core samples)

Feedback from users has confirmed that the HIT device provides an inexpensive and rapid solution for measuring ore hardness at site, in the lab or in the field. The industrial applications have confirmed the device's integrity, both mechanical and technical, and its potential for generating high-volume Axb and Bond proxy information. HIT testing can easily show the difference in ore hardness, and the extent of the inherent variability within the ore samples. Applying HIT testing to SAG feed and blasthole samples is viable as a routine process—akin to assaying samples—providing valuable knowledge on the ore hardness variability and its impact on SAG throughput. This example is discussed further below.

Batu Hijau Phase 7AC and Phase 8 DWi Mapping

At Batu Hijau, ore hardness characteristics are used to predict mill throughput, design an appropriate milling circuit configuration, and provide a baseline for future plant optimization. Considering the importance of the deposit's ore hardness information, Batu Hijau developed robust ore-hardness mapping, including DWi and BWi mapping. Note that the DWi is a direct function of ore specific gravity (SG) and 1/Axb index.

BWi in geological mapping is based on laboratory testing of representative core samples from the pit; hence, the actual BWi for ore delivered to the mill should be close to what is estimated from the geological deposit map. For DWi, the geological mapping is based on a model in which DWi is predicted based on copper content in the feed. The actual DWi works well in general for ore delivered to the mill. However, a discrepancy is observed for ore with feed grade 0.3% to 0.5% Cu, as the uncertainty in the DWi vs. feed grade relationship is higher, as shown in Figure 6.

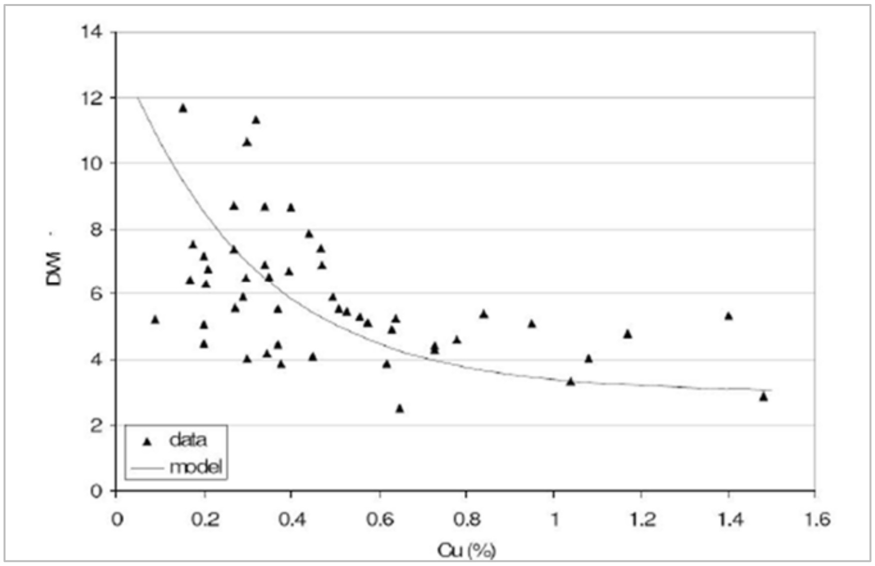


Figure 6—Batu Hijau DWi and %Cu relationship (SMCC Pty. Ltd., 2006)

Amman Mineral sees an opportunity to improve the accuracy of DWi mapping by changing the approach from a model to a laboratory measurement. With SimSAGe's HIT technology this is possible because the test mimics the JKMRC Drop Weight and SMC Test work, but HIT requires fewer samples and the test procedure is much simpler. The output from a HIT test is the Axb value, which is later converted to DWi by using a well-known mathematical formula to calculate DWi from the Axb and ore specific gravity.

In total, 326 drill core samples (PQ, NQ, and HQ) with 10 centimetre intervals from the Phase 7 additional cut (P7AC) and Phase 8 (P8) Batu Hijau deposits were HIT tested (Figure 7).

Figure 7—Batu Hijau P7AC and P8 core samples selected
for Axb measurement using HIT

Overall, the program was completed in six months, from May to October 2021, and Amman Mineral tested all samples in house. The test begins with drying the core samples for 12 to 24 hours in a laboratory oven at 100°C to remove moisture from the samples. The test then continues with crushing the core samples into a specific size range (−22.4+19.0 mm). Figure 8 illustrates the crushed drill core samples ready for HIT Axb measurement.

Figure 8—Crushed fragments from P7AC and P8 core samples
ready for Axb measurement using HIT

The Axb test requires 30 rock specimens. The rock specimen is carefully selected to remove any unlikely shapes such as pencil-like, and thin shapes which can lead to bias in measurement (Figure 9).

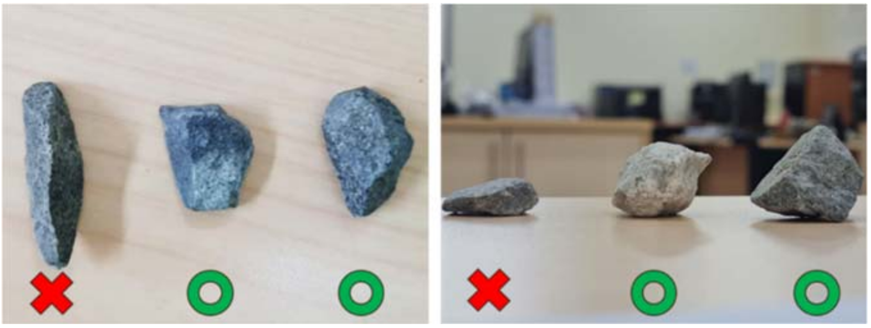


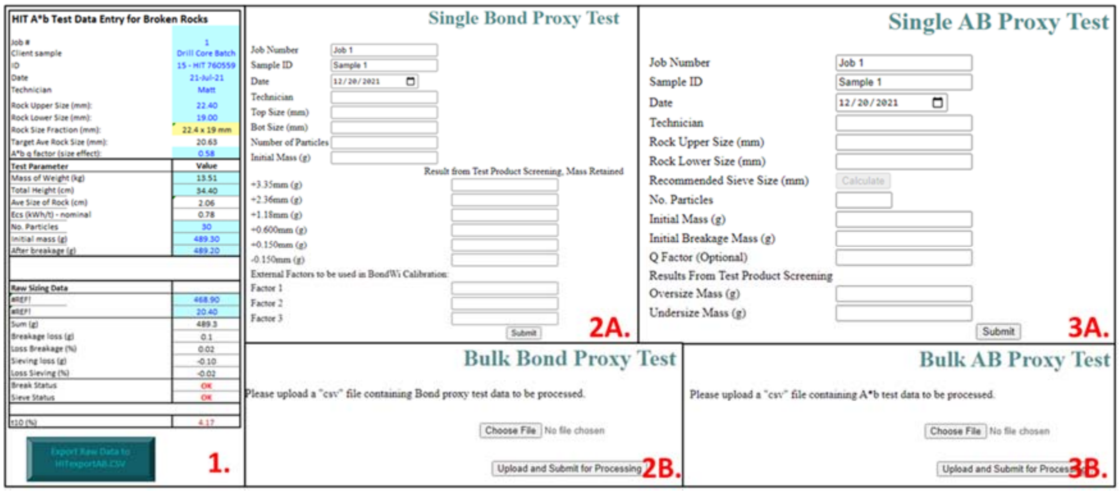
Figure 9—Example of rejected and accepted 22.4 x 19 mm fragments
for Axb measurement through HIT

The selected specimens are then placed into the HIT seated cup and sampled individually. Then, the drop weight is released by pulling the HIT's two hand levers simultaneously. The broken specimen is removed and the process is repeated until all 30 rock specimens are broken. Figure 10 shows the rock in the HIT cup before and after the test. All broken products are then collected and combined for laboratory sieving using a single screen (Figure 11).

Figure 10—Example of 22.4 x 19 mm fragment before and after breakage in the HIT

Figure 11—Sieving of HIT breakage products post breakage test

The sieving results are then uploaded to the SimSAG online calculator to interpret and convert the laboratory test results into Axb values. Figure 12 illustrates the HIT testing sheet with the raw laboratory sieving data, and example interfaces for the SimSAG online calculator, depending on the form of data input.



HIT A*b Test Data Entry for Broken Rocks

Job #	1
Client sample	Drill Core Batch
ID	15 - HIT 760559
Date	21-Jul-21
Technician	Matt
Rock Upper Size (mm):	22.40
Rock Lower Size (mm):	19.00
Rock Size Fraction (mm):	22.4 x 19 mm
Target Ave Rock Size (mm):	20.63
A*b q factor (size effect):	0.58
Test Parameter	**Value**
Mass of Weight (kg)	13.51
Total Height (cm)	34.40
Ave Size of Rock (cm)	2.06
Ecs (kWh/t) - nominal	0.78
No. Particles	30
Initial mass (g)	489.30
After breakage (g)	489.20
Raw Sizing Data	
#REF!	468.90
#REF!	20.40
Sum (g)	489.3
Breakage loss (g)	0.1
Loss Breakage (%)	0.02
Sieving loss (g)	-0.10
Loss Sieving (%)	-0.02
Break Status	OK
Sieve Status	OK
t10 (%)	4.17

Single Bond Proxy Test

Job Number: Job 1
Sample ID: Sample 1
Date: 12/20/2021
Technician:
Top Size (mm):
Bot Size (mm):
Number of Particles:
Initial Mass (g):

Result from Test Product Screening, Mass Retained
+3.35mm (g):
+2.36mm (g):
+1.18mm (g):
+0.600mm (g):
+0.150mm (g):
-0.150mm (g):
External Factors to be used in BondWi Calibration:
Factor 1:
Factor 2:
Factor 3:

Single AB Proxy Test

Job Number: Job 1
Sample ID: Sample 1
Date: 12/20/2021
Technician:
Rock Upper Size (mm):
Rock Lower Size (mm):
Recommended Sieve Size (mm):
No. Particles:
Initial Mass (g):
Initial Breakage Mass (g):
Q Factor (Optional):
Results From Test Product Screening
Oversize Mass (g):
Undersize Mass (g):

Bulk Bond Proxy Test

Please upload a "csv" file containing Bond proxy test data to be processed.

No file chosen

Bulk AB Proxy Test

Please upload a "csv" file containing A*b test data to be processed.

No file chosen

Figure 12—1, HIT Axb test data entry spreadsheet; 2A & 2B,
calculator for single and bulk Bond proxy test; 3A & 3B,
calculator for single and bulk Axb proxy tests.

From the 326 drill core samples tested, the HIT Axb results were used to classify the samples as follows:

- 106 cores (32%) were classified “Very Hard”(Axb index <28.5)
- 103 cores (31%) were classified “Hard” (Axb index between 28.5 and 37)
- 33 cores (10%) were classified “Medium Hard” (Axb index between 37 and 42)
- 41 cores (13%) were classified “Medium” (Axb index between 42 and 54)
- 31 cores (9%) were classified “Medium Soft” (Axb between 54 and 65)
- 13 cores (4%) were classified “Soft” (Axb index higher than 65).

The Axb distribution of Batu Hijau P7AC and P8 hardness is diagramed in Figure 13, while the spatial distribution of Axb data is shown in Figure 14.

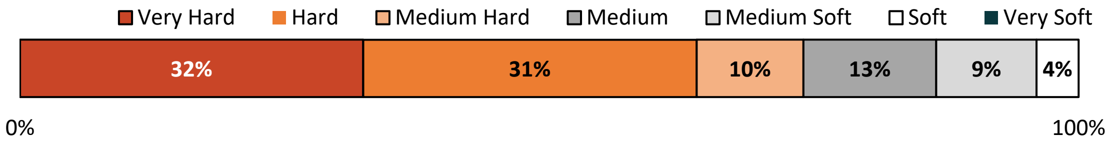


Figure 13—Batu Hijau P7AC and P8 Axb distribution

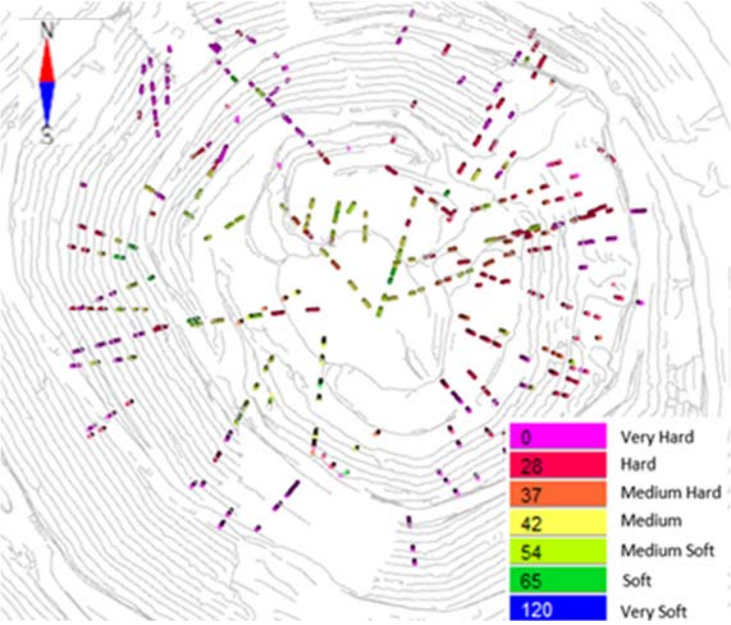


Figure 14—Plan view of composited Axb data for
P7AC and P8 Batu Hijau deposit

If the Axb value distribution in the P7AC and P8 is integrated with the ore lithology, then it can be concluded that intermediate tonalite and young tonalite have less impact resistance compared to diorite quartz and volcanic breccia rock, as shown in in Table 1 and in the boxplot graphs in Figure 15.

Table 1—Axb value across four ore lithologies

Rock Type	**Minimum**	**Maximum**	**Mean**	**Median**	**Standard Deviation**
Volcanic	17.6	91.6	32.5	2797.0	13.6
Diorite	21.9	76.4	35.0	33.7	8.5
Intermediate Tonalite	25.3	67.9	51.4	52.5	10.1
Young Tonalite	41.4	54.1	47.8	47.8	6.3
Total	**17.6**	**91.6**	**36.9**	**33.5**	**13.3**

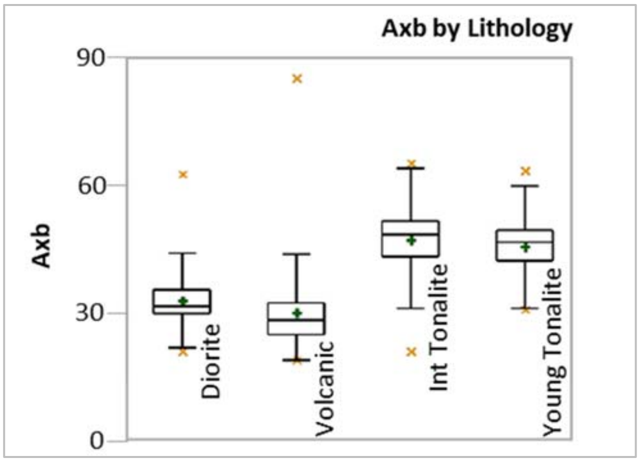


Figure 15—Axb value across four ore lithologies

The Axb values HIT measured were converted to DWi indices using a well-known relationship (Doll, 2023) calibrated using historical SMC DWi, ore SG, and Axb results:

$$DWi = \frac{\rho \ x \ 96.703}{(Axb)^{0.992}} \tag{1}$$

where DWi = SMC DWi (t/m^3)

ρ = rock specific gravity (t/m^3)

Axb = impact resistance index determined using the HIT

Ordinary Kriging was used to estimate Axb for a 25 x 25 x 15 metre (m) block. For interpolation, a maximum of 14 composites were used, with a maximum of four per drill hole, and a minimum of six composites. Search strategies were selected based on the ratio of ranges for domains, as defined from the variograms, and are unique to each domain.

As seen from the cross-section view of Axb estimations facing north (Figure 16), the hardness index in the center of the Batu Hijau pit ranges from hard to soft. In addition, the rock index tends to be harder outward of the pit. A hard to soft rock index can be associated with the distribution of tonalite intrusions that have higher veining density compared to volcanic and diorite. A similar pattern also occurs for the calculated DWi (Figure 16).

To evaluate the difference between DWi resulting from Axb measurement through the HIT device and DWi resulting from a model as a function of ore %Cu, a frequency distribution for those two populations is plotted in the same graph, as shown in Figure 17. The peak of DWi from HIT is two points higher than the DWi from the ore %Cu model, and the distribution of DWi derived from HIT tests is wider than the distribution of DWi from the ore %Cu model. The implications of these differences are significant, as the empirical model would tend to overestimate the milling capacity through the SAG mills.

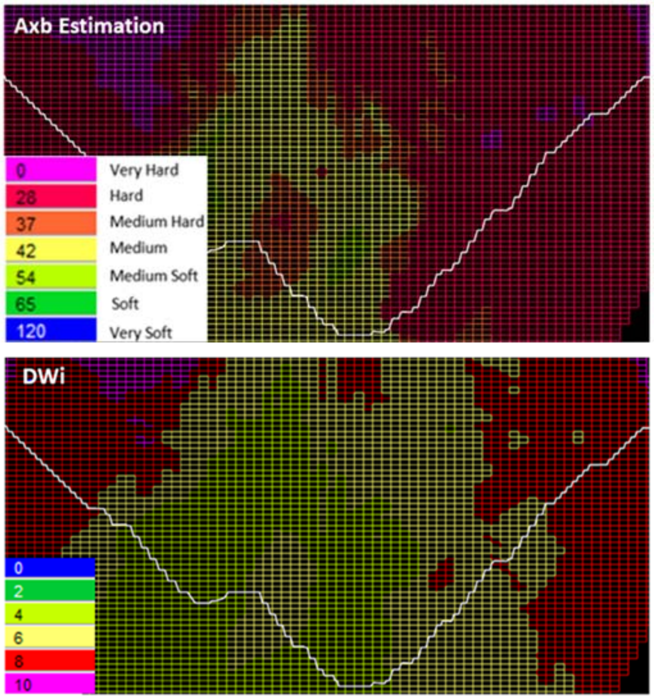


Figure 16—Cross-section facing north of Axb estimates and calculated DWi

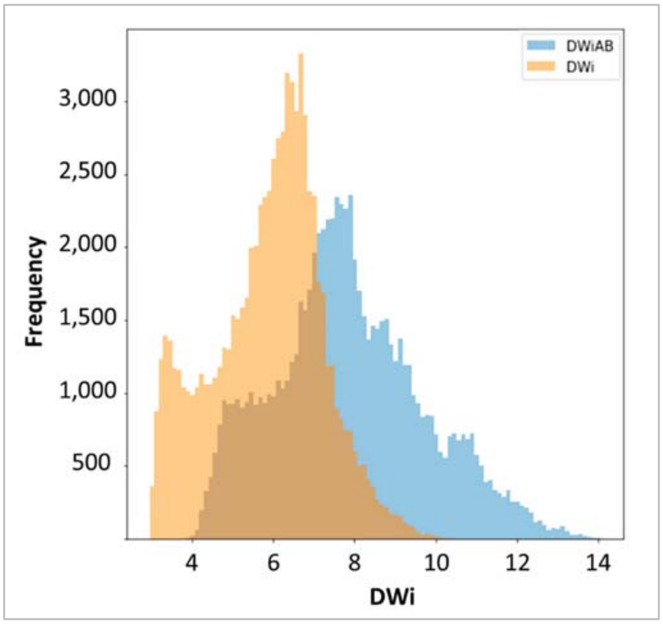


Figure 17—Comparison between Dwi from %Cu model (DWi) and DWi from HIT measurement (DWiAB) for P7AC and P8 of Batu Hijau Deposit

Daily Ore Hardness Measurement

Pursuing continuous improvement in geometallurgy and plant optimization, and having experienced the simplicity and cost- and time-effectiveness of ore hardness testing using HIT, Amman Mineral decided to extend HIT's utilization at their metallurgy laboratory to monitor the actual ore hardness (DWi and BWi) fed to Batu Hijau grinding circuit on a daily basis. To this end, in late 2021 Amman Minerals acquired a second HIT machine to provide 100% availability. Currently, 15 to 20 kg samples are taken from the SAG apron feeder via spot sampling. Though these samples may not represent the overall daily ore variation, the value of building a database of ore hardness feeding the grinding circuit is recognized at the time of writing.

The DWi derived through HIT measurement from the daily SAG feed monitoring follows the same laboratory testwork procedure discussed above. For the HIT BWi measurement, the procedure is quite similar, except for the sample amount and size selection of the rock specimen. For BWi, the size selection is −11.2+9.5 mm instead of −22.4+19.00 mm, and the amount of specimens per sample is 20 instead of 30 rocks.

The BWi measurement using the HIT device in Batu Hijau is developed by building a database through laboratory testing under two different methods for the same rock sample. The first method is BWi measurement through a standard Bond ball mill test, and the second method is BWi measurement using HIT. In total, 101 broken muck samples from Batu Hijau pit were tested, with the BWi ranging from 9 to 26 kWh/t. The actual BWi then plotted against the HIT BWi and a model line through statistical regression is drawn (Figure 18). The average relative error for samples below 20 kWh/t is 7.6% (which reflects the majority of the deposit). Ore types harder than 20 kWh/t need special attention, since the single HIT test on 20 fragments is struggling to explain the extremely high measured hardness. Duplicate tests might be necessary, or some external factor may be required as an input to correctly forecast the Bond BWi for such samples.

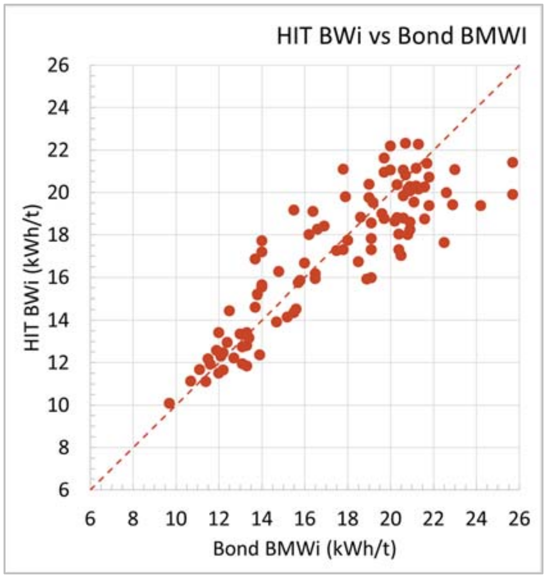


Figure 18—Comparison of actual BWi versus HIT BWi estimates for 101 pit samples (6 to 26 kWh/t)

Ore Hardness and Throughput Data Analysis at Batu Hijau

Conceptually, there are three major factors contributing to the milling rate and then throughput (Figure 19).

- Ore hardness
- Feed and product size
- Equipment power utilized.

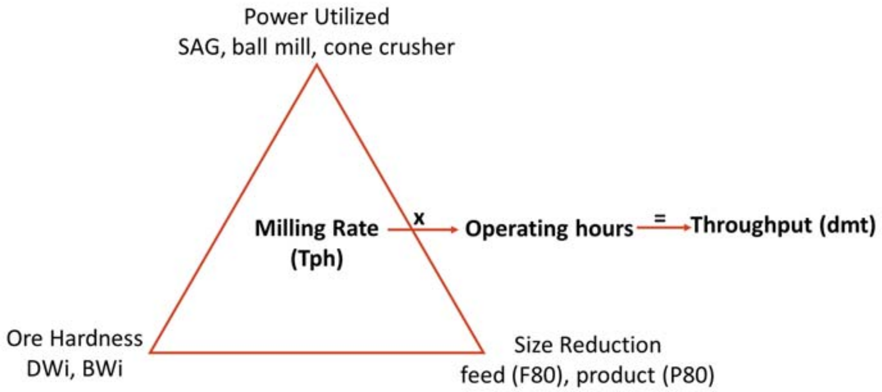


Figure 19—Triangle diagram of key variables affecting the milling rate.

Amman Mineral with SimSAGe internally adapted the SMC power-based throughput model in its approach to modeling the Batu Hijau grinding circuit throughput, based on the HIT DWi and BWi measurements. Following the SMC model structure (Morrell, 2009), the specific-energy requirement Wi (kWh/t) is:

$$\mathrm{Wi}= M_i 4\overset{\text{size reduction factor}}{\overleftrightarrow{\left(P_{80}{}^{f(P_{80})} - F_{80}{}^{f(F_{80})}\right)}} \tag{2}$$

where Wi = specific energy (kWh/t)

Mi = material comminution ore index (kWh/t)

P_{80} = the 80% passing size for grinding product (microns)

F_{80} = the 80% passing size for SAG feed (mm)

$f(P_{80}) = -(0.295 + P_{80}/1{,}000{,}000)$

$f(F_{80}) = -(0.295 + F_{80}/1{,}000)$

In the Batu Hijau-adapted SMC power model, the actual Mi is calculated for any given day by rearranging Equation 2, where the F_{80} and P_{80} terms are obtained from SAG feed image analysis and laboratory measurements, respectively. The actual Mi is then plotted against DWi and BWi resulting from the HIT measurements (Figure 20 and Figure 21).

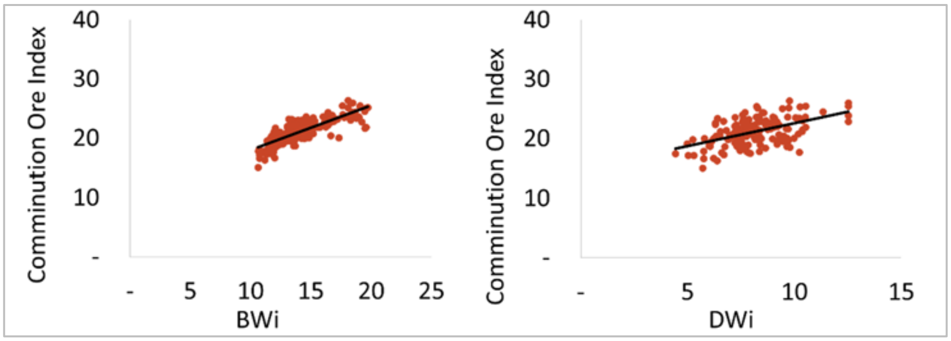


Figure 20—Mi (material comminution ore index) and
BWi relationship (left), and DWi relationship (right) for Batu Hijau grinding circuit

The Figure 20 plots suggest the SMC material comminution index is linearly related to both DWi and BWi, as expected, since they reflect the combined SAG, pebble crushing, and ball mill grinding circuits. Statistical analysis was performed to develop an empirical model for the Mi as a function of DWi and BWi,:

$$\text{Mi} = A + B \times DWi + C \times BWi \tag{3}$$

where Mi = predicted material comminution ore index (kWh/t)

DWi = calculated SMC DWi based on HIT measured Axb and rock SG (kWh/t^3)

BWi = Bond BWi determined using HIT (kWh/t)

A, B, C = equation coefficients determined from statistical regression analysis

By using Equation 3, the daily ore hardness can be estimated through the Mi. Then, by combining the Mi value with the daily feed size, F_{80}, product size, P_{80}, utilized power, and equipment availability, the expected throughput can be calculated. Figure 21 compares the actual throughput against the Batu Hijau-adapted SMC power model, showing a strong correlation, with an average relative error of ±4.7%. The bias at the higher throughputs has been associated with lower BWi samples, suggesting potential to improve the accuracy by decoupling the DWi and BWi in calculating the overall specific-energy requirement (Equation 2).

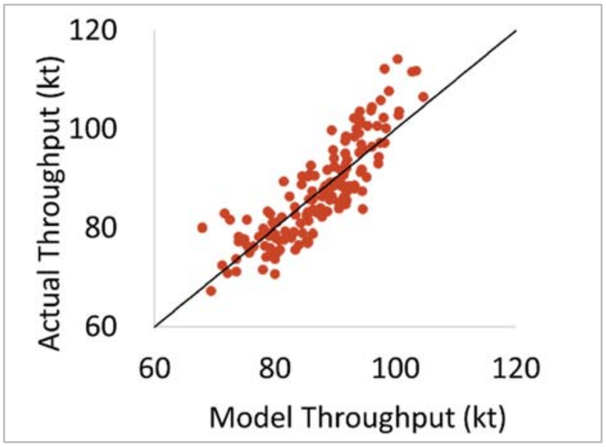


Figure 21—Comparison of 2021 Batu Hijau actual throughput vs. adapted SMC power model throughput

Conclusions

Amman Mineral have successfully integrated the HIT device as part of their geometallurgy and plant optimization programs. In summary, there were three objectives being sought from HIT utilization in the Batu Hijau deposit. They were as follows:

- To map the deposit's DWi of Phase-7AC and Phase-8 by using the Axb value from HIT testing on 326 drill core samples.
- To give a practical and acceptable daily DWi and BWi monitoring of ore feeding the SAG mill using spot samples from the apron feeder.
- To evaluate the milling performance through throughput modeling according to the ore hardness, feed and product size, and power utilized.

The revised DWi mapping of the deposit has provided a more reliable predictor of the pit’s ore hardness distribution, which is necessary for mine planning. In addition, the HIT daily ore hardness measurement, achieved via an dapted SMC power-based model (combining both DWi and BWi) by using HIT on SAG feed samples, has greatly improved the understanding of ore hardness's impact on overall grinding performance, and allowed metallurgist to initiate projects for optimizing throughput and griniding efficiency.

Future work considered to improve the model performance are as follows:

1. Split the material comminution index (Mi) into coarser grinding (Mia) and fine grinding (Mib).
2. Validate the model by using the hourly plant data just after the spot sampling at the SAG apron feeder is performed.
3. Explore options to improve the HIT BWi reliability for samples harder than 20 kWh/t.

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