Insights From 30 Years of Breaking Rocks – The JK Drop Weight Tester and the SMC Test

*B. Wong[1], Matthew Weier[1], & Stephen Morrell[2]

[1]JKTech Pty Ltd
40 Isles Road Indooroopilly Queensland Australia 4068

[2]SMC Testing
https://www.smctesting.com/

*Corresponding author: b.wong@jktech.com.au

Abstract

Thirty years ago, the first JK Drop Weight Tester (JKDWT) was commissioned at the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Brisbane, Australia. Many years of thinking, testing, failing, testing and thinking went into the question: How to perform a standard laboratory scale test to replicate rock breakage inside autogenous mills?

Thirty years later and the JKDWT is still the world's benchmark rock characterisation test to determine their resistance to impact breakage, with impact breakage being the main breakage mechanism in crushers and semi-autogenous grinding (SAG) mills. Two tests are conducted on the JKDWT: the JK Drop Weight Test and the SMC Test. These have become the standard in the industry, with the number conducted to date over 6,000 and 70,000, respectively. The world's largest database of ore characterisation results has provided significant insights and lessons for the industry and contributed to the optimising and design of thousands of mineral processing plants.

These tests are designed to replicate the same breakage mechanism, and at the same energy levels that rocks experience in crushers and SAG mills. The high control of these two tests on the impact energy applied, and on the rock particle sizes, gives precise results characterising rock behaviour over the size and energy range of interest.

This paper describes the development history of the JKDWT, the advent of the JKDW Test and subsequent development of SMC Test; the importance of knowing and understanding the A and b parameters; and current and future developments to ensure that the precision and accuracy of the tests are maintained or improved.

Keywords

JK Drop Weight Tester, SMC Test, breakage, Axb

Introduction

The JK Drop Weight Tester (JKDWT) was developed at the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Brisbane, Australia**;** it has become the world's benchmark rock characterisation test to determine the resistance to impact breakage which is the main breakage mechanism in crushers and autogenous (AG) and semi-autogenous grinding (SAG) mills. The test was designed to replicate the same breakage mechanism (impact breakage), at the same energy levels, that rocks experience inside mills. The high control of these tests on the impact energy applied, and on the rock particle sizes, gives precise results characterising rock behaviour over the size and energy range of interest.

The JKDWT is now over 30 years old, and two tests are conducted: the JK Drop Weight (JKDW) Test and the SMC Test. These have become the standard in the industry, with the number conducted to date over 6,000 and 70,000, respectively. The world's largest database of ore characterisation results has provided significant insights and lessons for the industry and contributed to the optimising and design of thousands of mineral processing plants.

The objective of the JKDW Test and SMC Tests is to establish the relationship between energy input and the degree of breakage of ore particles as it occurs in crushers, AG and SAG mills. This is done by breaking a range of particles sizes with energies replicating those found in those comminution processes. The best-known relationship between breakage energy and degree of breakage (Eq 1) was developed in the 1980s (Narayanan and Whiten, 1988) from which the industry recognised Axb parameter is derived and routinely used to describe the ore hardness for AG and SAG mills:

$$t10 = A\,(1-e^{-b.Ecs}) \qquad \text{(Eq 1)}$$

Where:

- t10 is the percent of product passing one-tenth of the original particle size, used to quantify the amount of breakage,
- A is the asymptote of the t10 and specific energy curve,
- b is related to the overall slope of the t10 vs Ecs curve at the lower energies,
- Ecs is the specific energy of comminution.

A and b are parameters which describe the response of the ore under test to increasing levels of input energy in single impact breakage. A typical t10 v Ecs curve resulting from a JKDW Test is shown in Figure 1. The Axb represents the slope at the origin of the curve and has been universally accepted as the parameter which represents an ore's resistance to impact breakage. Over the years the Axb parameter has been benchmarked according to the JK Database shown in Figure 2.

While the Axb parameter has been a large part of the industry focus, it is important to recognise that the A and b parameters are not the only outputs of the JKDW Test and SMC Tests. The JKDW Test also produces crusher energy and appearance functions matrices which are associated with the models incorporated in JKSimMet, a comminution modelling and simulation software package. The crusher energy details the relationship between particle size, amount of breakage and energy requirement; and the appearance functions detail the relationship between amount of breakage and the product size distribution. It is these that allow the accurate modelling of crushers, AG and SAG mills, characterising the relationships between feed, energy consumption, and product for a given feed size distribution and feed rate. Similarly, the SMC Test produces the parameters for use in the Morrell power calculations (Morrell, 2009).

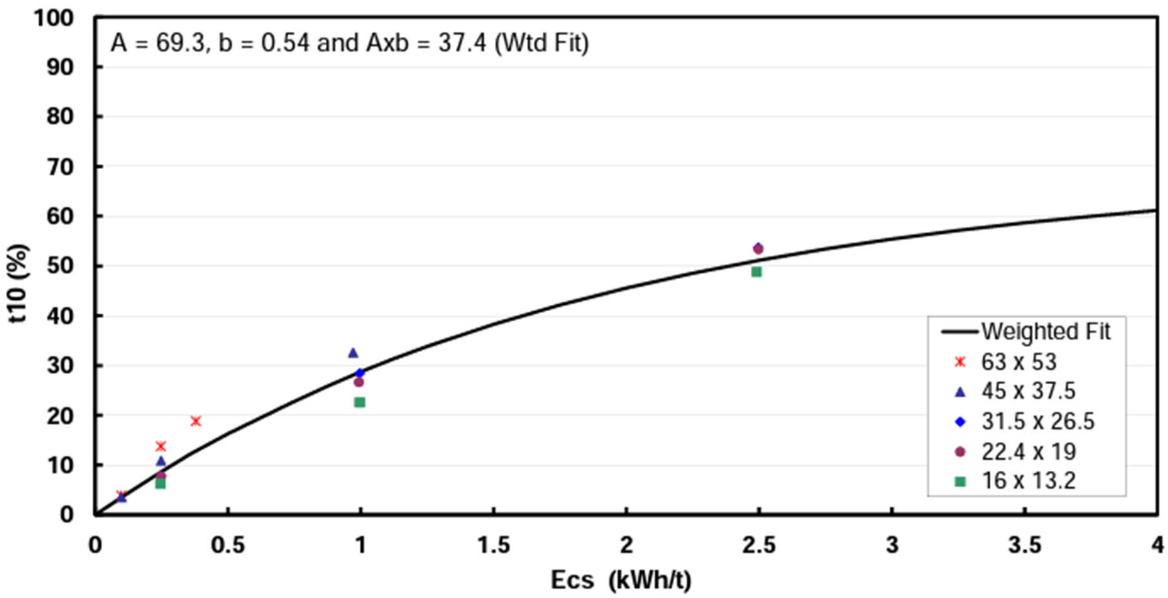


Figure 1—A typical t10 v Ecs curve from a JKDW Test

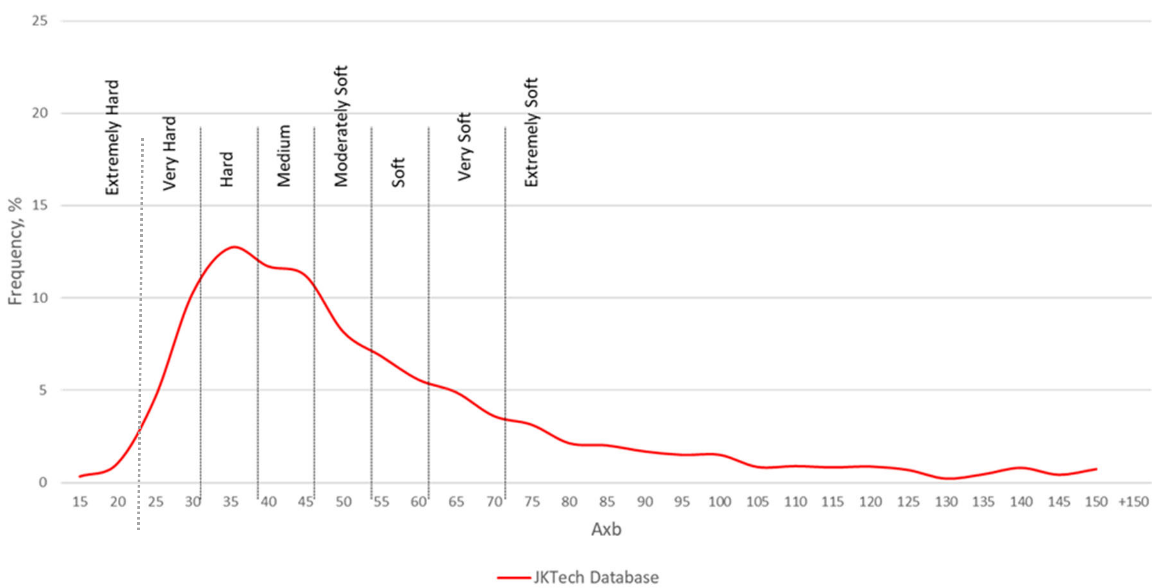


Figure 2—Benchmarking of Axb parameter

Development History

The JKMRC has long been a pioneer and leader in comminution and developing particle breakage testing machines. Since the 1980s, a number of impact breakage testing devices have been developed at the JKMRC for comminution research and commercial service. The twin pendulum (Narayanan, 1985; Narayanan and Whiten,

1988) was the first single particle breakage testing device developed at the JKMRC. This was designed originally for ball and rod mill modelling—hence relatively small particle sizes were used in the testing, with outputs used in simulation models that required appearance functions (size distributions) and their relationship to breakage energy for ball mills. Subsequent to this, Leung (1988) upgraded the pendulum test to become larger which could break larger particles and was more for use with tertiary crusher modelling (Anderson and Whiten model).

Then the JKMRC, through Doug Brown and Bob Marshall, designed the JK Drop Weight Tester as a replacement for the pendulum, shown in Figure 3 and Figure 4. The design principle was kept simple, and hence the JKDWT is relatively easy to use, it has a higher energy level control and the ability to break a wider range of particle sizes more applicable to AG and SAG modelling. The tester's simplicity with minimal sensors and electronics has led to its robustness and lack of issues.

Figure 3—Doug Brown and the JKDWT

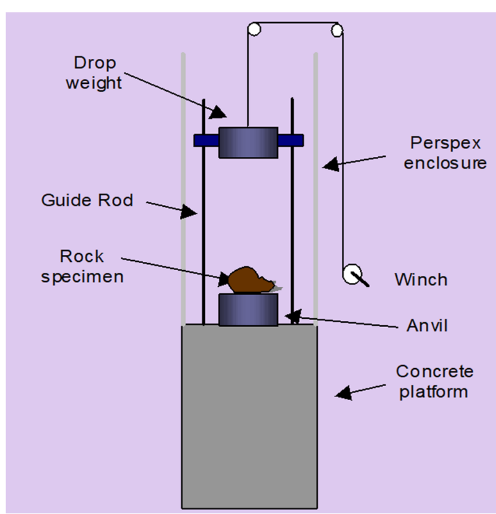


Figure 4—Schematic of the JKDWT

However, it was quickly recognised that the relationship described in Eq. 1 did not include anything related to the particle size being tested, and that particle size can have a significant impact on the relationship. Initial steps towards accounting for this included using Eq. 1 for characterisation of each individual particle size in the JKDW Test, and this remains a part of the JKDW analysis. George Banini's PhD work at the JKMRC (Banini, 2000) went a great way to showing the possible changes in t10 vs Axb relationships over various particle sizes, with the particle size affecting not just the Axb but also the A parameter. Later models were developed, such as the Mpq (Shi and Kojovic, 2007), which have been incorporated into the analysis of JKDW Test results. This work over the past decades has highlighted the importance of understanding how breakage characteristics change over the particle size range, especially when considering the comminution processes of interest involves particles over a significant size range.

JKTech Pty Ltd (JKTech) commercialised the JKDWT in 1992; there are now 81 machines at metallurgical laboratories in commercial environments (60), at mine sites (18), and at research facilities (3) around the world. The first mine site tester was sold to Teck in Canada, and the first commercial tester (besides JKTech) was sold to SGS Lakefield in Canada. The JKDW Test requires about 65 kilograms (kg) of rock sample. The main reasons to perform the JKDW Test is to generate the parameters for use in creating a JKSimMet model to simulate different conditions of a comminution circuit, or for ore hardness benchmarking purposes.

Stephen Morrell developed the SMC Test, which was commercialised in 2004. Since 2004 it has become the most popular and versatile laboratory ore hardness test in the world. It is routinely used in design, optimisation and geometallurgical (ore body profiling) projects. Relatively small amounts of drill core are required to provide work indices that are used in power-based equations for predicting the specific energy of comminution circuits. The SMC Test produces the drop weight index (DWi) parameter, conventional crushing circuits (Mic parameter), and high-pressure grinding roll circuits (Mih parameter). Used in combination with the Bond ball mill work index test, the total comminution circuit (Mia, Mib parameters) and ball mill circuit (Mib parameter), the total comminution circuit energy requirement can be predicted. As of the date of this paper, over 70,000 SMC Tests have been conducted. Performed on the JKDWT it produces similar ore hardness results for benchmarking purposes and design using the Morrell method. The SMC Test uses a 30 kg sample of core or rock, making it useful for geometallurgical projects to know the ore hardness variability knowledge across an orebody.

The JKDWT is reliable. In more than 30 years only minor repairs have been needed and only once has a machine been decommissioned and replaced commercially due to its' age. Operator safety is a priority for JKTech, with a number of redesigns made over the life of the tester to decrease the risk of injury to the operator. The JKDWT is currently in its sixth iteration and earlier versions have been retrofitted with safety kits to bring them in line with the newer version.

The JK Rotary Breakage Tester (JKRBT) was developed during the AMIRA P843 project. It was designed as a faster test that provides similar results to those of the JKDW Test. Although faster and a more robust test unit, it could not be commercialised successfully due to the much higher production cost.

Two of the more recent changes have been the following;

- The SAG Circuit Specific Energy (SCSE) parameter (Matei, 2015): this was a step away from using Axb as the hardness parameter. This was driven by an understanding of some issues around the use of the Axb parameter, and the desire to introduce one which was more intuitive for engineers who are using these parameters. As such the SCSE is the expected power draw, in kWh/t, of a basic comminution circuit processing the ore in question.
- The Integrated Test: this was created to combine the JKDW Test and SMC Test into a single test for use in characterising ore under AG and SAG milling conditions. This was released in 2016 to minimise

sample requirements for clients' requiring the parameters from both tests. Over 200 samples have been tested to date.

Since JKTech commercialised the JKDWT and SMC Test, it has committed to ensuring quality and consistent results. To maintain and improve test standards, since 2007 JKTech has co-ordinated regular comparative testing programs known as Round Robin programs, involving all commercial JKDWT and SMC Test licensed laboratories. The Round Robin program has been conducted four times. These programs are labour intensive and involve sending the laboratories testing samples pre-prepared by JKTech. These tests are conducted to determine the conformity of the laboratories, the JKDWT's correct functioning, as well as providing some measure of their precision using robust statistical methods. Due to the program's design, it has been possible to investigate the amount of test variance arising from variation within the repeatability of the test procedure as well as the variance arising from the reproducibility of the test procedure. This information is used to improve the quality of testing by identifying and correcting any reasons for variance at laboratories with unusual results. This ensures that all laboratories obtain results within acceptable statistical limits. Clients can have confidence that the same results can be obtained at any laboratory. Figure 5 shows the most recent Round Robin results in 2018 with most laboratories conducting tests in duplicate. This shows that most laboratories were within the range of an Axb of 31.3 and 37.8. Laboratories 6 and 28 were classed as being an outlier and having a high error (poor duplication). JKTech worked with these laboratories to investigate the causes of these errors and to subsequently re-perform the tests until acceptable results are achieved.

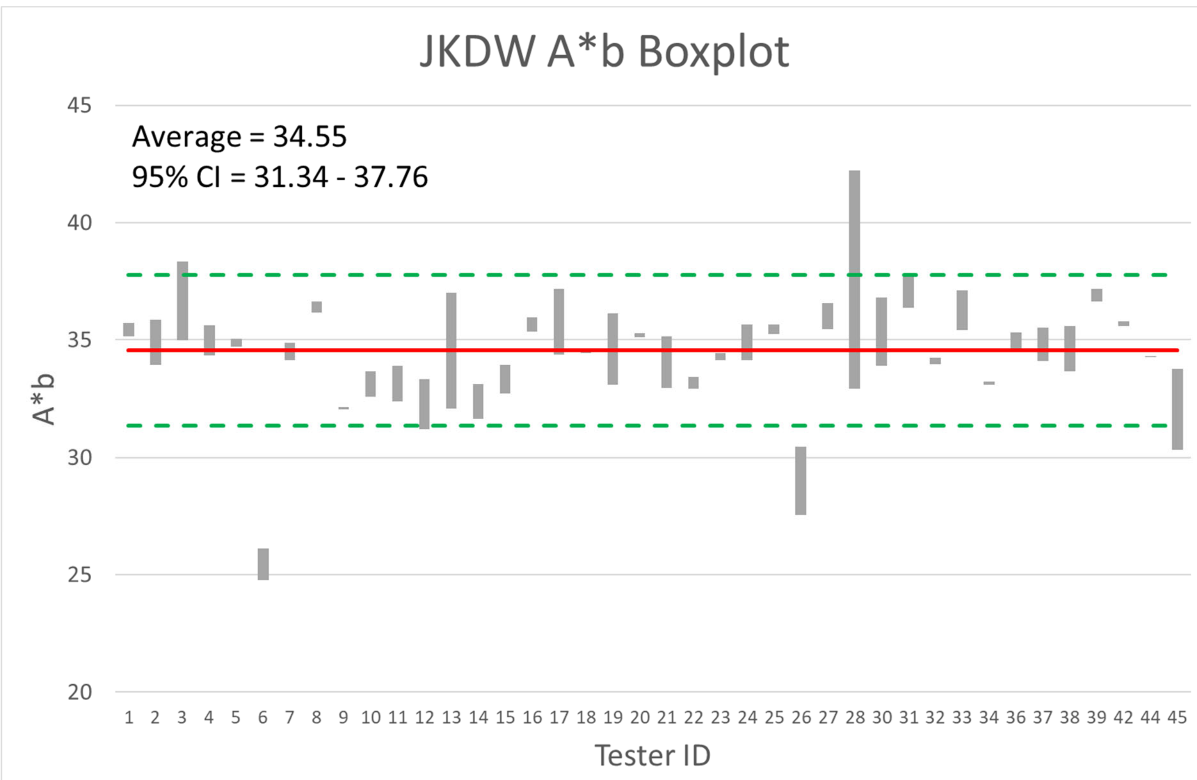


Figure 5—Round Robin Results for 2018

Insights Over the Years

After thirty years several insights have been learnt related to ore hardness characterisation; how it relates to other parameters in the mine, how the use of hardness has evolved, who is conducting the SMC Test, and while Axb is common—do not forget the importance of A and b separately.

The current JK Database of Axb can be summarised by the following (remembering that high values of Axb indicate a soft ore),

- Minimum: 12.9
- Median: 45.3
- Mean: 62.2
- Maximum: 962.0.

JKTech and SMC Testing have collated a large amount of operating data through comminution optimisation projects and Mine-to-Mill style projects with corresponding ore characterisation results. Leveraging these data has been key to ensuring the industry can make accurate decisions. Three of the key uses of this data have been:

- Design modelling using JKSimMet: since the late 1980s the JKDW Test and SMC Test ore-specific characteristics results have been used in the SAG Mill and Crusher mathematical models in JKSimMet. In conjunction with a relevant database of operational data, this has become a standard methodology. The JK Database has continually evolved with industry trends to ensure that the parameters used are relevant. Many other companies that design comminution circuits utilise JKSimMet and leverage their own databases for this use. The size, relevance and diversity of the database is very important in ensuring a valid outcome.
- Prediction of Run-Of-Mine Particle Size Distribution (ROM PSD): there is good agreement between Axb and ROM PSD in the JK Database to be able to provide an estimation for this data which is not readily available at many operations or for feasibility studies (or similar). This can be used for JKSimMet simulations; or for validation purposes for operations with ROM PSD data (Figure 6).
- Benchmarking of comminution circuit efficiency in optimisation to assess “Site X” performance against the industry: using Figure 7 as an example, the SMC Test results can be used to estimate the specific comminution energy requirements of a particular ore in kWh/t. This is taken from comparable operations in the industry, with the same circuit configuration, dealing with the same ore hardness, and achieving the same size reduction. Based on the comparison - actual kWh/t vs predicted kWh/t - “Site X” does it better than 34.8% of the comparable operations in the industry (and not as good as the other 65.2%). Therefore “Site X” has room for improvement.

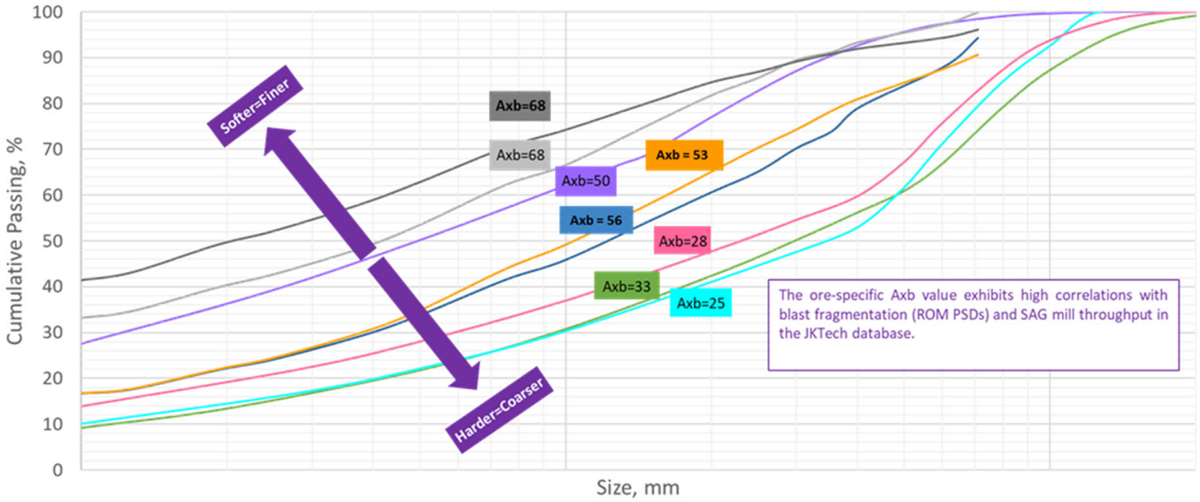
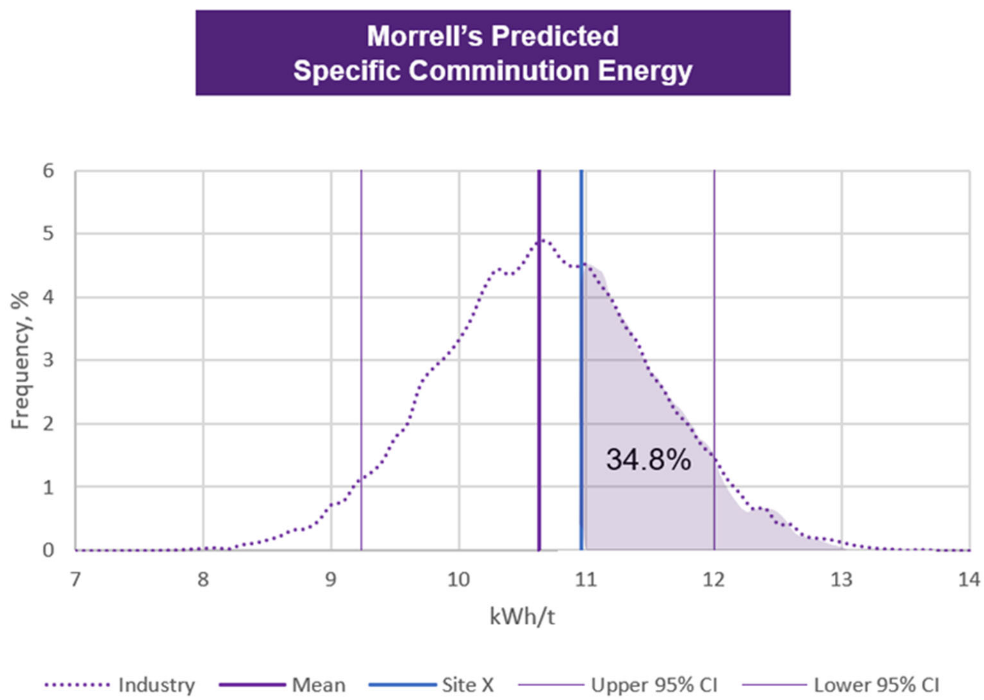


Figure 6—JK Database Axb and Run-Of-Mine particle size distribution relationship



Industry Mean (kWh/t)	10.63
Upper 95% confidence limit (kWh/t)	12.00
Lower 95% confidence limit (kWh/t)	9.24
Site X Actual (kWh/t)	10.96

Figure 7—Benchmarking Example Using the SMC Test

Morrell (2015) presented the global trends in ore hardness based on the SMC Tests conducted up to that time from 82 countries, which included 35,000 tests from 1,300 deposits covering 30 commodities. The number of tests has now doubled to over 70,000. An update of the distribution by continent and commodity is shown in Figures 8 and 9 respectively. It should be noted that for each SMC Test the primary commodity has been recorded, e.g., Copper for Copper/Gold ore etc.

South and Central America still dominate the distribution, accounting for over 47% of total tests which has increased since 2015 at 43%. However, North America has decreased to 16% from 23%, and Oceania has decreased from 17 to 16%. There has been an increase in the total tests performed in Africa, up to almost 11% from 8%, while the other regions remain similar.

The commodity distribution has stayed relatively consistent since 2015. Dominated by copper and gold ore tests, these have stayed at 58% and 22% respectively. These results are relatively unsurprising due to the importance of copper production in South and Central America and the increased activity in this region with regards to new mining projects and optimisation of current mines.

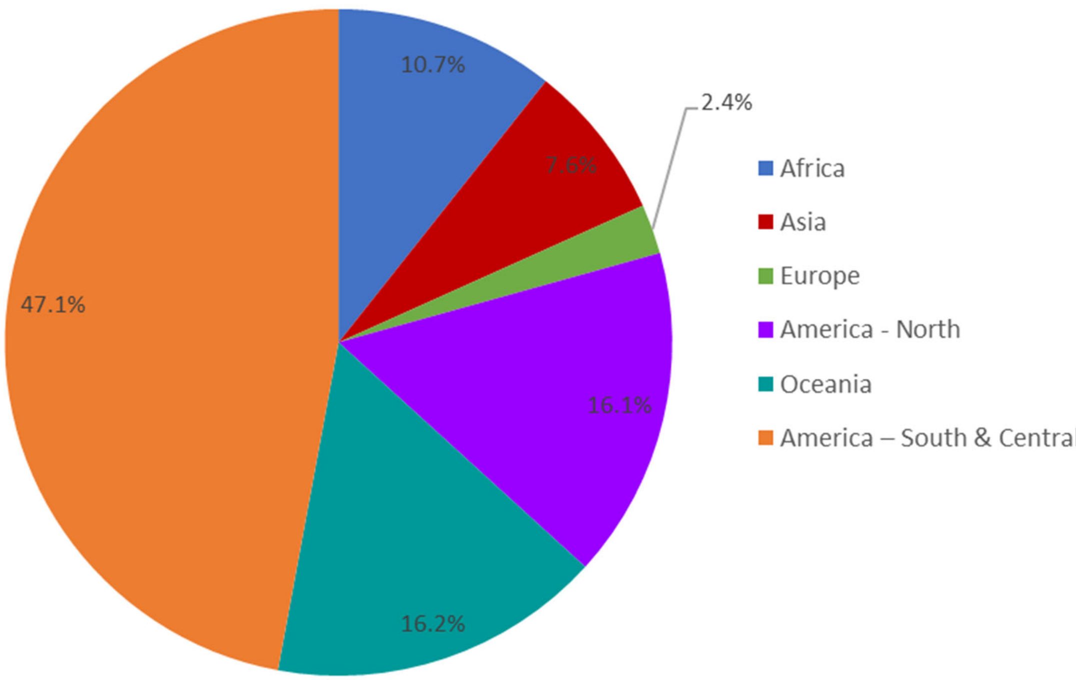


Figure 8—Distribution of SMC Tests by Continent (2023)

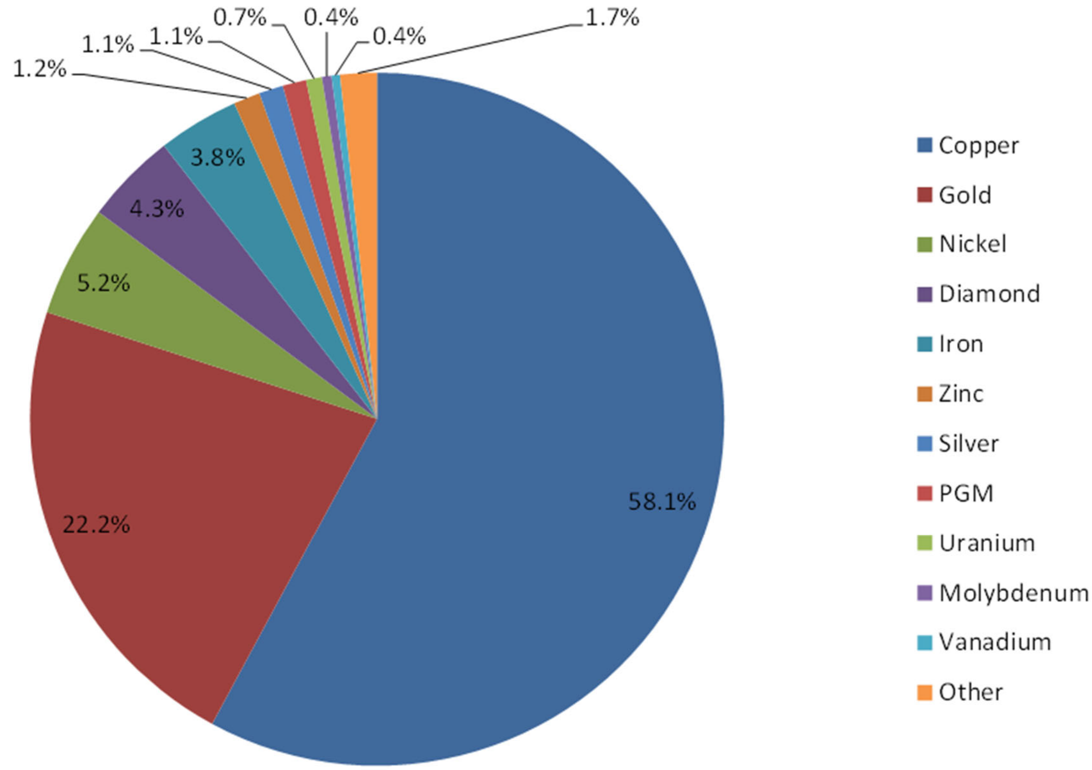


Figure 9—Distribution of SMC Tests by Commodity (2023)

The mean DWi values by commodity are shown in the histogram in Figure 10. Only commodities that account individually for more than 0.1% of total numbers of SMC Tests have been included. As can be seen there is a very large variation between commodities, with Tin ore topping the list with a mean DWi of over 10 kWh/m^3. This has replaced Tungsten ore from 2015 which was approximately 10 kWh/m^3. This has now dropped to 8 kWh/m^3 which is less than basalt. Bauxite remains the softest with a mean value of almost 2 kWh/m^3 with Graphite, Iodine and Phosphate ores also less than 3 kWh/m^3.

Other notable additions from 2015 include Manganese ore with a mean DWi of almost 6 kWh/m^3, and Lithium ore at almost 4 kWh/m^3.

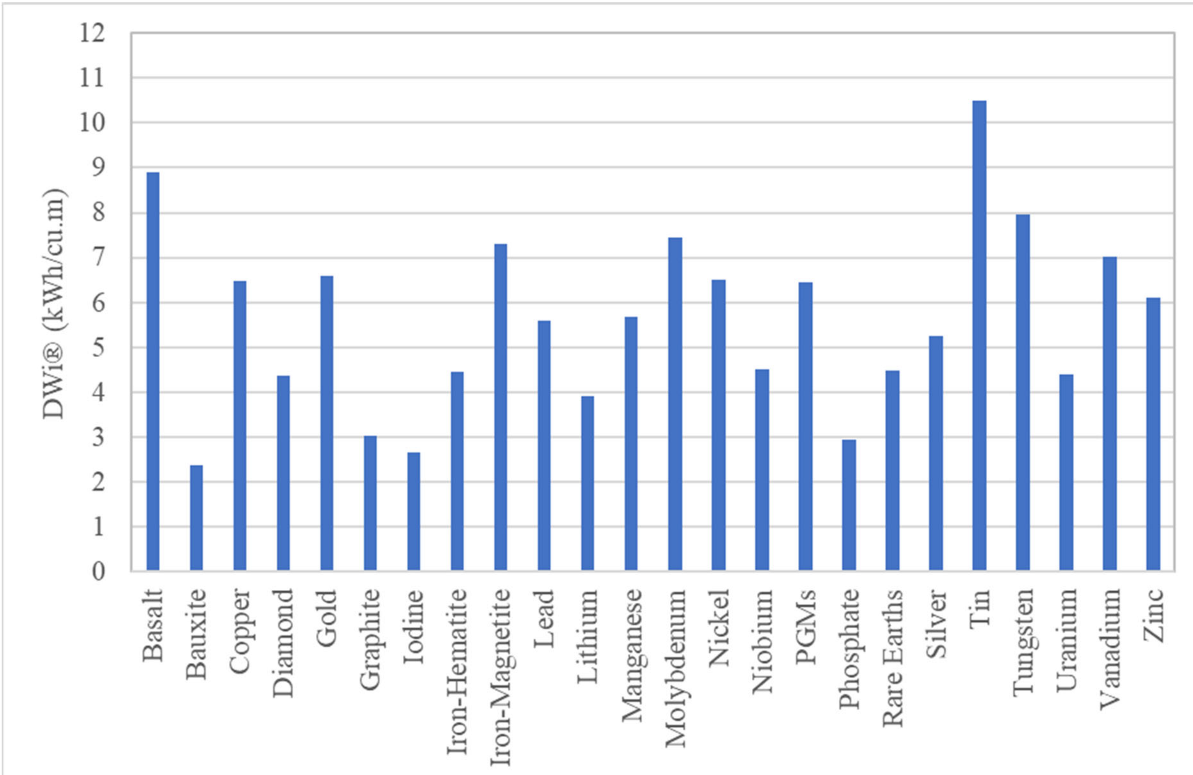


Figure 10—Mean DWi value by commodity (2023)

The Axb parameter is the most commonly known rock hardness benchmark and is referred to in many process design and optimisation reports throughout the minerals industry. While Axb has proven to be a useful hardness indicator, by itself it does not capture all the details of ore breakage behaviour. It is easy to forget that the A and the b parameters by themselves are equally important. The ore behaviour is characterised by both A and b, and it is the correct determination of both parameters that allows the determination of the Axb value. The influence of A is the most significant as this plays an important role in determining product size-distribution coming from AG and SAG operations, which of course influences downstream behaviour.

While there is a desire to estimate Axb using a single low-energy data point, there are significant issues with fitting a multi-parameter curve using a single data point, most importantly is that one of the parameters must be assumed. This can be highlighted by looking at the variation in estimated Axb caused by changes in assumed value of the A parameter (Table 2). The values in the table are from an example single low-energy data point Ecs = 0.25 and t10 = 15, with the b parameter fitted using various assumed A values. The estimated Axb varies between 65.0 and 75.2. This is a significant difference and could cause issues in throughput predictions or misleading benchmarking data. Using the linear fit results in an Axb of 60, again the difference with the estimated Axb can be considered high.

Table 2—Example of effect of A on Axb

assumed A	b	Axb
40	1.88	75.2
50	1.43	71.3
60	1.15	69.0
70	0.96	67.5
80	0.83	66.4
90	0.73	65.6
100	0.65	65.0
		60.0

The importance and influence of A in JKSimMet modelling was determined by modelling a SAG mill using a variety of A and b parameters such that for each Axb value examined a number of A and b combinations were used. These simulations show SAG throughput can vary by up to almost 4% in the simulated cases (Figure 11), and that the product size (T80) from the SAG mill can vary by up to 220 µm (Figure 12) which is likely to cause downstream challenges from misleading predictions of performance.

In summary, it is very important to know the A and b parameters by themselves, only then can you be confident of the reported Axb value and know how the result can be used. If the Axb value is generated from the JKDWT via the JKDW Test and SMC Test, then it can be used in any capacity—benchmarking, design, and optimisation. If not, it should be used with caution.

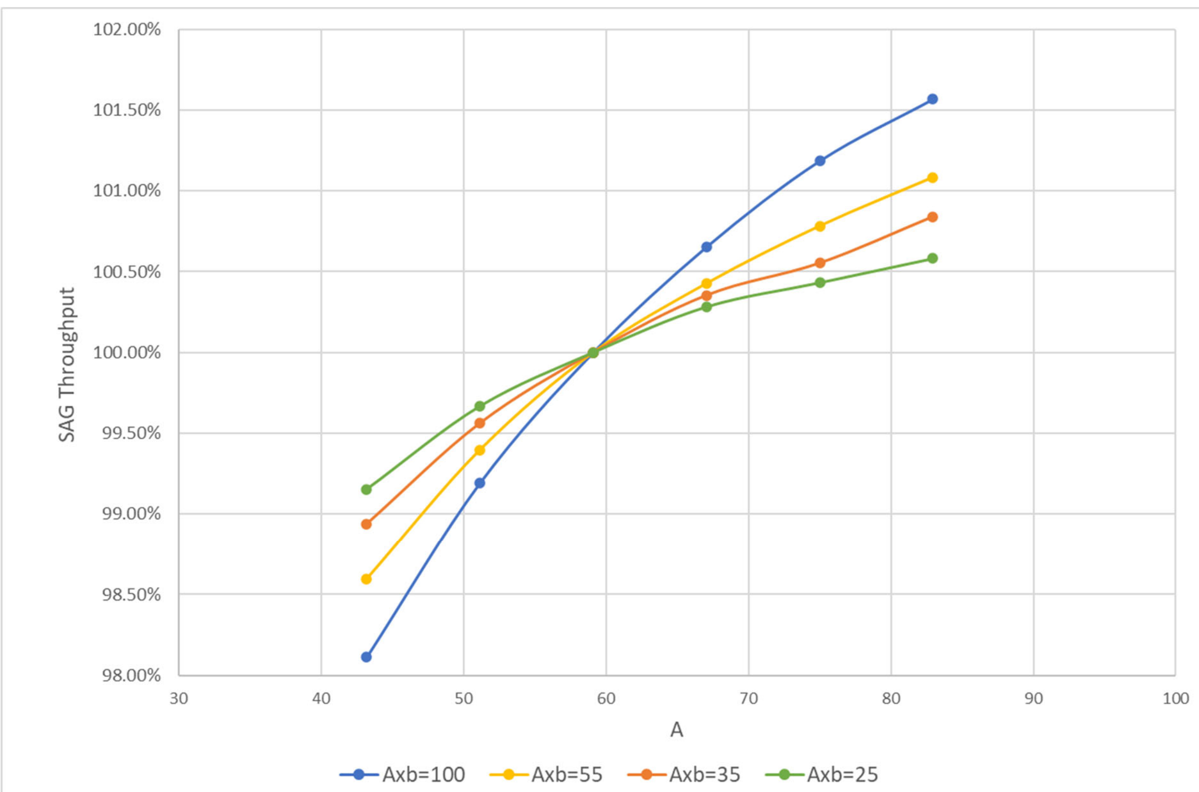


Figure 11—Modelled changes in SAG throughput with changes in A

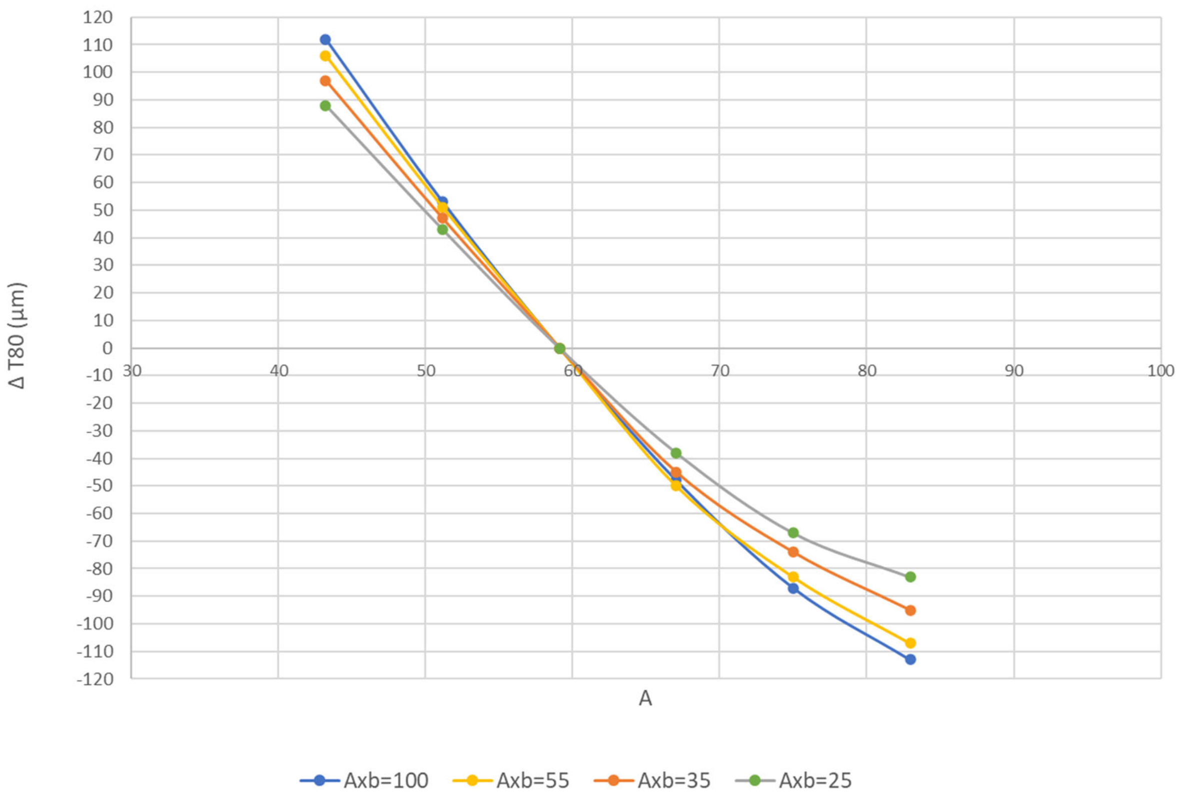


Figure 12—Modelled changes in SAG T_{80} values with changes in A

Future Developments

Future developments of the machine and test methodologies are currently being progressed, and simplicity of use is still a primary objective. Many planned improvements are aimed at continuously improving safety considering the manual nature of the machine. The following major developments are being considered,

- Round Robin – The next Round Robin will be prepared from late 2023 for distribution in 2024. This Round Robin program will also involve the Bond Ball Mill Work index test, as in a previous program, to determine the quality assurance and quality control,
- Improving the efficiency of the JKDW Test methodology by reducing the number of combinations for determining mass / heights parameters,
- Investigating the potential for the JKDWT to widen the energy range through addition of lighter mass and heavier mass heads. This could lead into a greater particle size range being available for testing,
- Looking at other quality (laser diode for speed check) and ease of use improvements.

Conclusions

The JKDWT is now over 30 years old and has become the standard ore hardness testing machine in the industry by performing the JK Drop Weight Test and the SMC Test. Development of the machine and the methodology has evolved over this period to ensure the safe operation and accuracy of results. Over 6000 and 70,000 JKDW Tests and SMC Tests respectively have been conducted to date with the resultant Axb parameter being used for process design of comminution circuits, benchmarking ore hardness and comminution circuit efficiency. JKTech and SMC Testing remain committed to ensuring high quality, accurate and consistent results from the JKDWT.

References

Morrell, S. (2015). *Global Trends in Ore Hardness*. SAG Conference 2015, Vancouver.

Matei, V., Bailey, C. W., & Morrell, S. (2015). *A New Way of Representing A and b Parameters from JK Drop-Weight and SMC Tests The "SCSE"*. SAG Conference 2015, Vancouver.

Shi, F. & Kojovic, T. (2007). *Validation of a model for impact breakage incorporating particle size effect*. Int. J. Miner. Process 82 156-163.

Banini, G. A. (2000). *An Integrated Description of Rock Breakage in Comminution Machines*. PhD Thesis, JKMRC.

Narayanan, S. Sankara (1985). *Development of a laboratory single particle breakage technique and its application to ball mill modelling and scale-up*. PhD Thesis, School of Engineering, The 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., Sect. C: Mineral Process. Extr. Metall., 97: C115-C124.

Leung, K. (1988). *An energy based, ore specific model for autogenous and semi-autogenous grinding mills*. PhD Thesis, School of Engineering, The University of Queensland.

Morrell, S. (2009). *Predicting the overall specific energy requirement of crushing, high pressure grinding roll and tumbling mill circuits*. Minerals Engineering.