Fragmentation Modelling and the Effects of ROM Fragmentation on Comminution Circuits

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ABSTRACT This paper reviews the blast fragmentation models developed to date and discusses the effects of the run-of-mine (ROM) fragmentation on the comminution circuits. The fragmentation model developed by the author is presented in detail. Its use in numerous mine-to-mill projects is briefly discussed. The fragmentation modelling framework is based on the combination of Kuz-Ram model to model the coarse end and an engineering approach to model the fines. It is well-known that the Kuz-Ram model underestimates the fines generated by blasting. The model is further validated by new data sets (actual sieving data). It is shown that the model is rather robust in estimating the fines generated by blasting. The mine-to-mill studies have shown that -10mm size generated by blasting can be considered a key performance index as this fraction has a significant effect on mill throughput. The mine sites have increased their powder factors significantly which resulted in mill throughput increases of 5 to 30%. Two case studies were presented as examples of the use of the fragmentation model in mine-to-mill projects. Some of the opportunities to further reduce the energy consumed by mining processes are also highlighted.

1 INTRODUCTION

Traditionally the mining industry manages the units of operations (drill&blast, load&haul, crushing and grinding) separately by adopting extreme control measures in operational and capital expenditure. Costs are generally managed separately for mining and milling cost centres. Cost minimisation is achieved through focussing on achieving production targets at minimum cost. This approach does not necessarily result in the reduction of the total mine operating cost (mining and milling). Investigations by several researchers to date have shown that all the processes in the mine to mill value chain are inter-dependent and the results of the upstream mining processes (especially blast results such as fragmentation, muckpile shape and movement, rock damage) have a significant impact on the efficiency of downstream milling processes such as crushing and grinding (Eloranta 1995, McKee et al. 1995, Kojovic et al. 1998, Kanchibotla et al. 1998, Simkus and Dance 1998, Scott et al. 1999, Kanchibotla et al. 1999, Valery et al. 1999, Valery et al. 2004, Dance et al. 2006, Esen et al. 2007, Valery et al. 2007, Kanchibotla and Valery, 2010).

Numerous mine-to-mill projects to date resulted in mill throughput increases of between 5 and 30% depending on the ore strength and communition properties. Fragmentation is the most significant component of the mine-to-mill value chain. It was shown that the effect of finer fragmentation on mill throughput is more significant than changing the operational parameters of the grinding circuit (Dance et al. 2006, Esen et al. 2007).

Drill and blast is understood to be the most energy efficient and cheapest way of reducing particle size compared to downstream operations, as shown in Table 1. The use of greater energy input in the blasting unit operation is less costly than expending the energy downstream.

Table 1. Energy and cost calculations by unit operations at a hard rock gold mine (Esen, 2010)

	Specific energy kwh/t	Energy factor	Cost factor
Drill and Blast	0.1 – 0.25	1	1
Load and haul	0.2 – 0.5	1 - 5	2 - 10
Crushing	1 – 2	4 -20	2 - 10
Grinding	10 – 20	40 - 200	8 - 20

Fragmentation can also have a notable impact on the economics of recovery in heap leaching as demonstrated by Sheikh and Chung (1987), in a study conducted at the Denison mine (Ontario, Canada). They concluded that the viability of heap leaching processing in this operation depended upon the alternative of maintaining stockpiles of broken ore for long periods of time, or adopting blast fragmentation optimisation strategies through the implementation of appropriate blast designs.

This paper discusses the fragmentation modelling which is used in carrying out the mine-to-mill simulations, the effect of feed size on crusher and SAG mill, and the application of the author's fragmentation model in mine-to-mill projects with two case studies.

2 BLAST FRAGMENTATION MODELLING

2.1 Background

The need to provide engineering solutions to full scale blasting problems such as those involving the optimisation of Run-of-Mine (ROM) fragmentation, has driven the development of several fragmentation models. These include empirical as well as advanced numerical techniques. Appendix 1 gives a chronological summary of the developments in applied fragmentation modelling over several decades.

The most commonly used empirical models are those based on the determination of parameters to fit functions that can adequately describe the expected distribution of rock fragments for a given set of conditions. In these approaches, the most widely applied fragmentation distribution function has been the Rosin-Rammler distribution or simplified versions of the same (Rosin and Rammler 1933, Kuznetsov 1973, Cunningham 1983, Yalun 1987, Rollins and Wang 1990, Aler et al. 1996). The Rosin-Rammler function has been recently replaced by the Swebrec function (Ouchterlony 2003,2005). This is a more refined representation of the size distribution of fragmented rock materials.

Swebrec function contains three parameters, x_{50}, x_{max} (mean and maximum fragment size, respectively) and an undulation parameter b. It has been shown that this function can describe the sieved data with a coefficient of determination R^2 better than 0,995 in 95% of the fragmentation data encountered (Ouchterlony 2003,2005). This function has been tested against hundreds of sieved size distributions from bench blasts in quarries, reef blasting, model blasting and crushing.

The Swebrec function is as follows:

$$P(x) = 1/\{1+[\ln(x_{max}/x)/\ln x_{max}/x_{50})]^b\} \quad (1)$$

In the late 1990s, developments in fragmentation modelling saw the introduction of the two component modelling approach which mainly allowed for improvements in the prediction of fine fragmentation (Kanchibotla et al. 1999, Djordjevic 1999, Thornton et al. 2001). Subsequently Onederra and Esen (2004) developed a more accurate way of estimating the potential volume of crushed material resulting from the crushing and shearing stages of blasting.

Above fragmentation models have been successfully used in numerous projects to date. There are also significant advances made with the numerical models (Minchinton and Lynch 1996, Ruest et al. 2006, Dare-Bryan et al. 2010); however, their use is not widespread and only used at a high-level research/consulting projects. This paper doesn't attempt to review these models as it is not within the scope of this paper.

2.2 Onederra and Esen's (2004) fragmentation model

Fines (usually -10mm term) in blasting is considered as one of the most important KPIs in the mine-to-mill concept. Mine-to-mill projects to date showed us that operations that require higher mill throughputs should maximize a maximum amount of fines (-10mm fraction). These projects required an accurate estimation of fines and complete ROM fragmentation size distributions.

The Kuz-Ram model's poor ability to describe the fines was one of the major reasons why the Two Component Model (Djordjevic 1999), the Crush Zone Model (Kanchibotla et al. 1999) and Onederra and Esen's (2004) model were developed at the JKMRC. All combine two Rosin-Rammler distributions or components, one for the coarse part of the curve and one for the fines. Onederra and Esen (2004) showed that the Kuz-Ram model is not able to satisfactorily predict the complete size distribution of fragments, particularly in the fine and intermediate size fractions (Figure 1). The need to be able to predict the amount of fines from blasting has driven the development of a new engineering model.

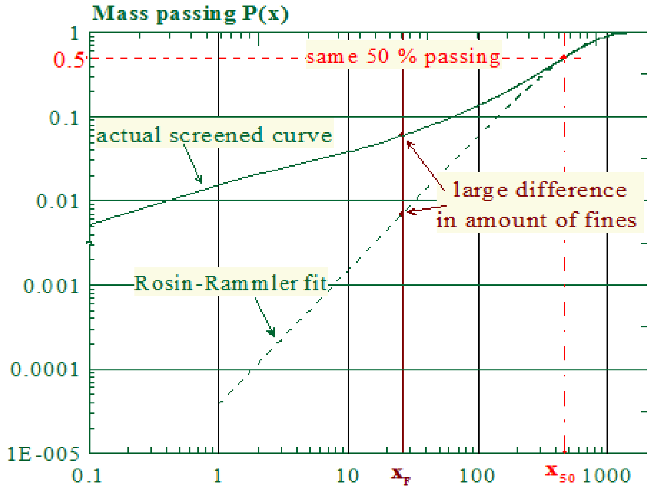

Figure 1. Kuz-Ram's limitation in predicting the fines and intermediate regions (Ouchterlony, 2005)

Onederra and Esen's (2004) model is detailed in their paper. Their framework is based on the combination of a new model to predict the radius of crushing around a blasthole with a model to predict the volume of crushed material resulting from major radial cracks (Figure 2). Other sources of fines including liberation of infilling from discontinuities, particle collisions and post-blast processes are excluded to simplify the modelling process. Based on the analysis of a number of full scale blasting surveys, their study has confirmed that upon detonation of an explosive, the region of crushing around a blasthole is not the only source of fines. However, the proportion of fines generated by the crushed zone in low strength rocks is relatively greater than in medium to high strength rock types, and therefore should not be neglected.

Validation results based on seven case studies have shown that there is good agreement between model predictions and the measured proportion of fines, at the assumed cut off point of 1mm.

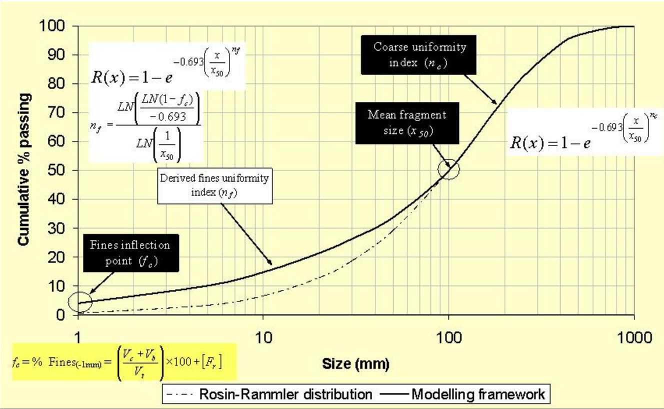

Figure 2. Onederra and Esen's model

3 FEED SIZE EFFECT ON CRUSHERS AND SAG MILLS

Primary crushers are sensitive to oversize rocks because they cause hang-ups and also increase the power draw. It is generally accepted that the primary crushers reduce only the top size of run of mine and most of the fines (- 10mm) are generated through blasting. The Key performance Index (KPI) is the Closed Side Setting (CSS) of the primary crusher. If the ROM fragmentation is finer, then there is a scope to minimize the CSS to deliver finer SAG feed.

It is important to highlight that any mine-to-mill optimization work focuses on feed size to the SAG Mills (Dance et al. 2006). SAG mills require a certain ore feed size distribution to operate efficiently. This feed is supplied to the mill by the Primary Crusher, which is also influenced by the size distribution achieved from blasting. Significant effort has been spent at a number of operations to relate SAG mill throughput with SAG mill feed size. Very good correlations have been obtained demonstrating that the finer the topsize and F80 of the mill feed, the higher the mill throughput. Figure 3 shows correlations between SAG mill feed size as measured by on-line image analysis systems and SAG mill throughput and specific energy consumption (kWh/t) at a copper ore operation (Dance et al. 2006).

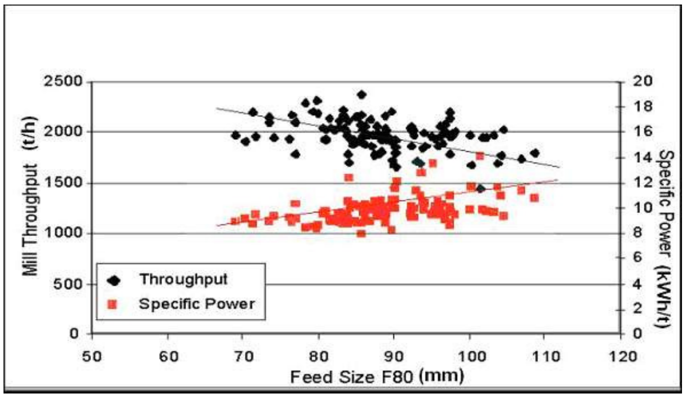

Figure 3. SAG feed size versus throughput & specific energy at a copper operation (Dance et al. 2006)

The ideal size distributions, which result in maximum mill throughput and performance, will depend on the breakage characteristics of the ore (rock strength) as well as the operating conditions of the mill (lifter design, grate design, mill speed and rock charge). In general terms, higher throughput for these harder domains may be achieved when the SAG mill feed has (Dance et al. 2006):

- as fine a top size as possible;
- the smallest possible amount of 25 to 75mm intermediate size material and
- a maximum amount of –10 mm fines.

Figure 4 gives a general indication of the strategy required to achieve an ideal SAG mill feed size distribution. The SAG mill feed topsize is mostly controlled by the Primary Crusher. The intermediate size material which is usually in the size range between 25 to 75mm (this range will vary according to ore hardness) is reduced both by appropriate fragmentation in the mine and optimal operation of the Primary Crusher. Fines (-10mm material) are largely generated by blasting. Depending on ore hardness, some fines can be also generated by inter-particle breakage in the crusher, especially when it is choke fed. The more fines in the feed, the higher the SAG mill throughput: a relatively simple relationship.

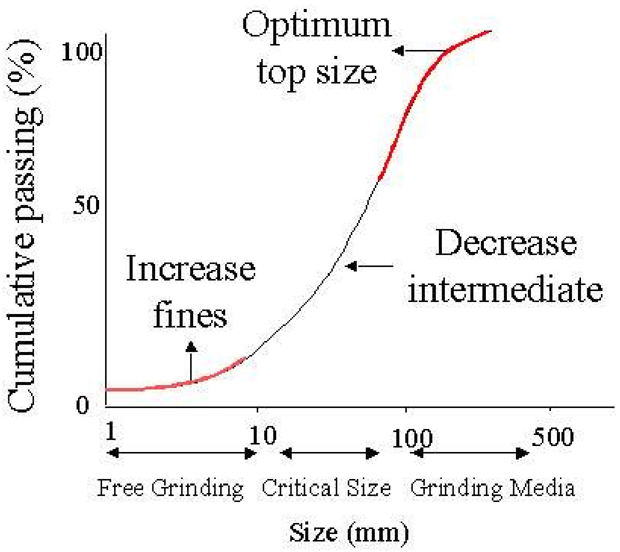

Figure 4. SAG mill feed size distribution (Dance et al. 2006)

4 UPDATE WITH THE FRAGMENTATION MODEL AND ADDITIONAL VALIDATION DATA

Given the success of Swebrec function in fitting the fragmentation data, it was decided to use the modelling results (x_{50},x_{70}, x_{80} and % passing at 1mm data) and force Swebrec function to pass through these four data sets using below simplified Swebrec function:

$$P(x)=\frac{1}{1+\left[\dfrac{\ln(x_{\max}/x)}{\ln(x_{\max}/x_{50})}\right]^{a}} \tag{2}$$

where xmax and a are fitting parameters.

Figures 5 to 8 show the application of this approach to four cases in which fragmentation data is partially or fully sieved. It is shown that the updated model compares well with the experimental data.

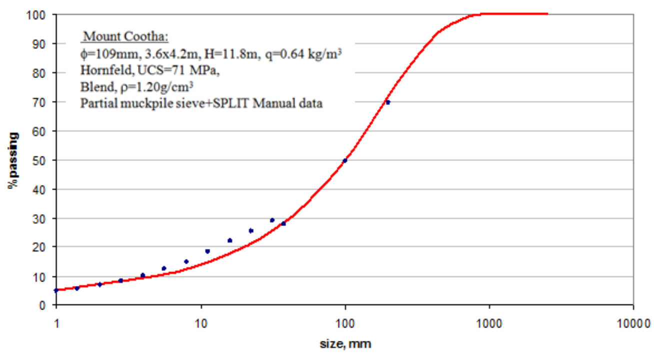

Figure 5. Mount Cootha Quarry fragmentation data – experimental vs model fit

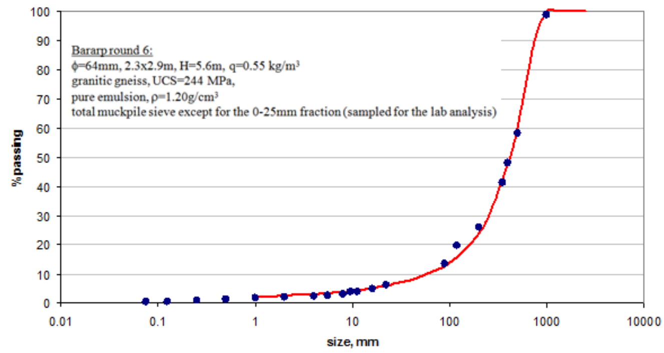

Figure 6. Bararp Quarry fragmentation data – experimental vs model fit

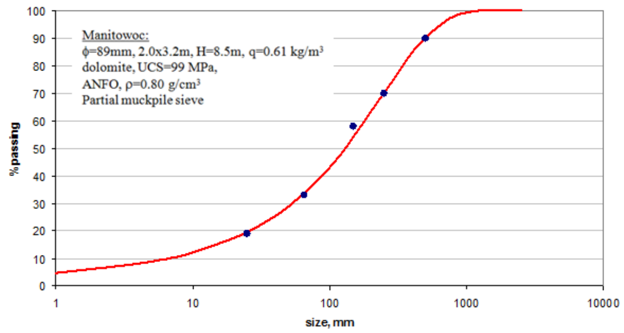

Figure 7. Manitowoc Quarry fragmentation data – experimental vs model fit

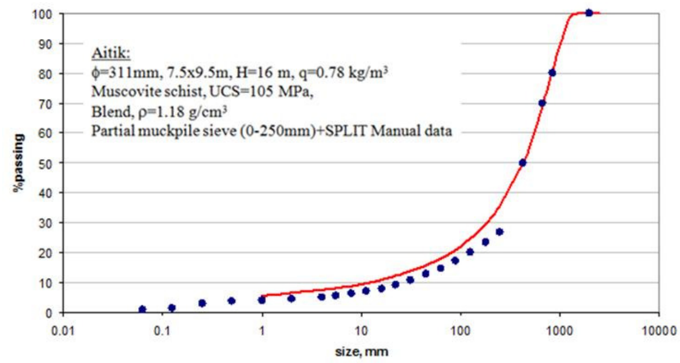

Figure 8. Aitik copper/gold fragmentation data – experimental vs model fit

Some sieve data were collected from a large open pit gold mine in Australia. The sieve sizes were 10mm and 30mm. Image analysis was also conducted to determine the size distribution of the blasted muckpile. Figure 9 shows the comparison of the sieve data versus fragmentation model. It is shown that the results compare well at 10 and 30mm sizes where the sieve data is available (Esen, 2010).

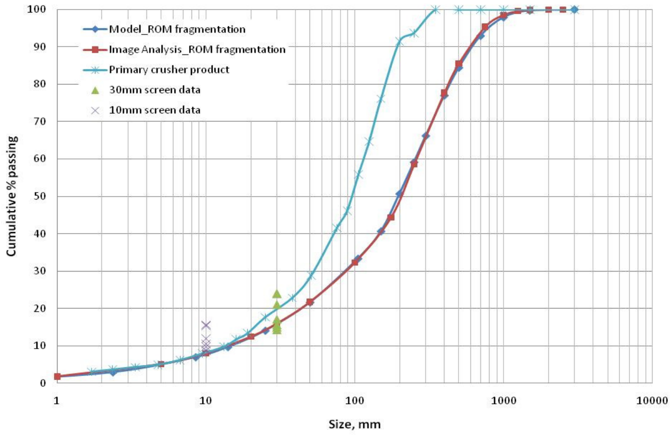

Figure 9. Comparison of the sieve data at 10 and 30mm with the model

5 THE APPLICATION OF THE FRAGMENTATION MODEL IN MINE-TO-MILL PROJECTS

The fragmentation developed by the author has been used in numerous mine-to-mill projects globally. Two of the case studies are discussed in detail to demonstrate the application of the model.

The first case study is from a large copper-zinc operation in South America. This operation wanted to increase the throughput of a particular ore type that historically processed between 2,300 and 3,300tph. The study revealed a number of opportunities for improving ROM fragmentation through blast design changes (Table 2).

Table 2. Baseline and modified blast design parameters at a large copper-zinc operation in South America (Esen et al. 2007)

Design	Hole Dia (mm)	Burden x Spacing (m)	Powder Factor (kg/m³)	Predicted % -25mm	Predicted P80 (mm)
Current	311	7 x 8	1.15	30.7	401
Modified	311	6 x 7.5	1.62	44.4	175

A trial blast was conducted on material containing this ore type and resulted in significantly finer fragmentation. Figure 10 shows a trend of SAG mill tonnage over time before, during and after this modified blast material was processed. For the entire period shown, the ore type was the same and was mined from a similar area of the pit. The values in Figure 7 show the mill tonnage increased from 3,500 to 4,000tph before to around 5,000tph for the modified blast material. With the stockpile depleted and normally blasted material sent to the concentrator, tonnage returned to below 4,000tph. The increase in mill throughput was 25 to 40%, exceeding all expectations and more than compensated for the 8¢/tonne higher blasting costs. The mine-to-mill trials conducted after this work included pebble crusher, grate open area, SAG mill ball charge, a slight change in the blast pattern. This helped the mine consistently achieve SAG mill throughputs above 4000tph for this specific ore type.

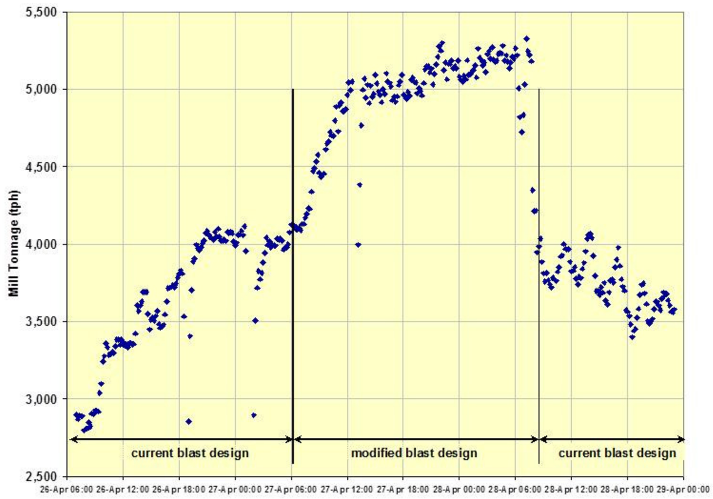

Figure 10. Trend of concentrator tonnage during modified blast trial (Dance et al., 2007)

Another case study was from a gold mine in Ghana. The mine-to-mill project was conducted on November/December 2010 period. This mine used to operate at a powder factor of 1.20kg/m^3 (Table 3) and having a SAG mill F80 of 40mm. An alternative blast design (Table 3) was suggested at a powder factor of 1.40kg/m^3 with some other design changes. The mill F80 decreased to 30mm as shown in Figure 11 and the mill throughput increased by 23% (from 475tph to 587tph) with the alternative blast design (Esen and Crosby, 2011).

Table 3. Blast design parameters for the base case and modified blasts at a gold mine in Ghana

	Baseline	Alternative blast design
Hole diameter, mm	165	165
Bench height, m	9	9
Powder factor, kg/m^3	1.2	1.4
F80, mm	284	251
% -10mm	20.4	22.6

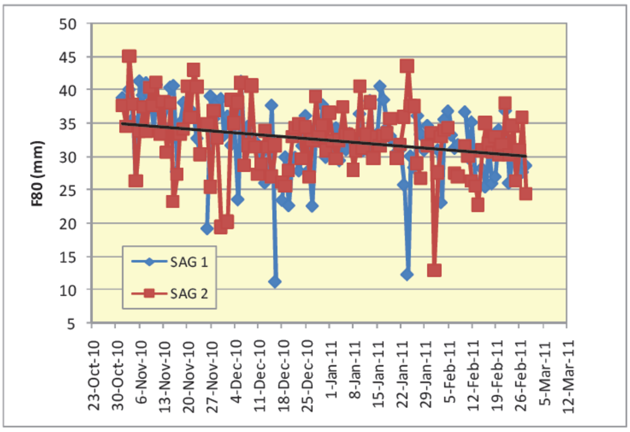

Figure 11. Mill feed F80 data for SAG1 and SAG2 Mills

6 CONCLUSIONS

This paper reviewed the existing empirical fragmentation models including the author's model which is currently updated using Swebrec function. The model was validated with four case studies. The updated model appears to compare well with the measured data sets.

The fragmentation model was used in numerous mine-to-mill projects in which mill throughput increased between 5 and 30%. In these projects, -10mm fraction that is generated by blasting appear to be the most important KPIs in any mine-to-mill project.

Two case studies were presented to demonstrate the benefits of the mine-to-mill. The first case study was from a large copper-zinc operation. This operation increased their throuhput with the modified blast by 25-40% exceeding all expectations.

Another case study was from a gold mine in Ghana. The optimised blast design resulted in the reduction of the mill feed (mill F80 decreased from 40mm to 30) and increased the mill throughput by 23% (from 475tph to 587tph).

The threat of global warming, increased cost of energy, limited availability of water resources and social and legislative pressures are creating a need in the mining industry to reduce energy and water consumption. Many mining companies are now routinely accounting for the energy and water consumed and greenhouse gases produced per unit of final product and are making special efforts to operate in a more sustainable manner.

Recent reviews to date have shown the value of the use of the high-intensity blasting, HPGRs in comminution circuits and pre-concentration in future mining circuits.

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Appendix 1. Development of empirical blast fragmentation models.