INTRODUCTION

The purpose of blasting in a mine is to convert the in situ rock mass into a muck pile that can be efficiently excavated and transported, placed as waste, stockpiled for later processing or fed to an ore treatment process. It is clearly an advantage to the mining operation if the fragmentation targeted for different classes of material has been defined to optimise the efficiency of this overall process. Blasts should then be designed to achieve these fragmentation targets.

A mining operation quickly develops a history of performance that can be used to guide future blast designs, although often on a qualitative rather than quantitative basis. This can be particularly effective in consistent geological environments where surprises tend to be minimal; however, this process is always ‘chasing its tail’ when conditions change or the required blasting outcomes need to be varied. Industry experience can be of some assistance when designing for a greenfield development, but this experience is unlikely to apply to the detailed characteristics of the ores found in a new mining area.

Older literature abounds with texts providing blast design guidelines and rules (e.g. DuPont, 1977; ICI Explosives, 1996; Konya and Walter, 1990; Hustrulid, 1999). Although sometimes contradictory because of the diverse background of the authors, general trends that have served the industry well are contained in these design rules; however, it is the authors’ contention that the rock and its properties are given insufficient prominence in most blast design rules and guidelines.

A problem with many design rules is that they offer advice on how to develop blast designs that generate ‘satisfactory’ or ‘good’ fragmentation when blasting the type of rock in which the author has experience, rather than generating specific blasting outcomes to optimise the performance for a specific operation. To do this it is necessary to predict what the particle size distribution of the blasted muck will be when a particular blast design is applied to a particular rock mass. This requires the provision of an adequate description of the blasting properties of the rock mass to a suitable fragmentation model.

MODELLING BLAST FRAGMENTATION

Approaches

In general, blast fragmentation models have followed one of two approaches (Scott, Chitombo and Kleine, 1993):

- an empirical or engineering approach that captures and extrapolates measured relationships between rock mass properties, blast designs and the fragmentation achieved
- a mechanistic or fundamental approach that focuses on the underlying physics describing the behaviour of the explosive and the response of the rock mass.

Characterising Rock Mass Properties for Fragmentation Modelling

A Scott¹ and I Onederra²

ABSTRACT

A great deal of technical and research effort has been applied to the development of models to predict fragmentation from rock blasting. A number of quite useful empirical or engineering models are currently available to blasting engineers and consultants, while more sophisticated approaches using mechanistic and numerical descriptions of rock breakage continue to be developed and applied by researchers and explosives companies.

The fragmentation resulting from any blast will be heavily dependent on the properties of the rock mass being blasted; however, most empirical models rely on ‘rock factors’ generated from simple rock mass properties to describe the influence of the rock on the blasting outcome. In contrast, mechanistic models need explicit rock mass properties that require sophisticated laboratory measurements and detailed structural data if realistic outcomes are to be generated. The fragmentation modeller is caught between excessively simple rock mass descriptions for the empirical models and excessively complex data requirements for the mechanistic models.

This paper briefly reviews the basis of a range of fragmentation models and the rock mass properties on which they rely. Shortcomings in the way that the mining industry tends to characterise the blasting properties of rock are discussed and some practical approaches are described to quantify these properties in both operating and greenfield mining environments. Case studies are presented where specific additional breakage properties and modelling features have been needed to generate a useful description of the fragmentation achieved.

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Current empirical approaches to fragmentation modelling were initially derived from experiments on blocks of intact rock or controlled blast benches (Kuznetsov, 1973; Bergmann, Riggle and Wu, 1973; Rustan, Vutukuri and Naaritjarvi, 1983) and crater studies (Just and Henderson, 1971). Parameters such as critical burden, critical charge, break-out angle and the resulting fragmentation were measured. The resulting relationships were extrapolated to apply to full-scale blasts and modified to match observed field performance using calibration factors.

Mechanistic models focus on specific mechanisms of the fragmentation process (eg radial crack formation) that are responsible for rock breakage. Relationships describing each mechanism are based on a description of the underlying physics, drawing on the relevant rock mass properties and perceived action of the explosive charge. Equations describing each of the relevant breakage mechanisms are then combined into a framework to represent the observable behaviour of the rock under the action of the explosive.

Perhaps the most successful empirical blast fragmentation model has been the Kuz-Ram model introduced by Cunningham (1983). An example of the more sophisticated mechanistic models is the Hybrid Stress Blasting Model (HSBM) described by Furtney, Cundall and Chitombo (2009) and Onederra et al (2013). Between these two ends of the modelling spectrum there have been a wide range of approaches developed.

**Which is the best approach?**

A suitable fragmentation model for any given situation is one that has been formulated to address the situation being studied and utilises the rock mass, explosive and blast design properties that have most influence on the blasting outcome.

Mechanistic models struggle to adequately represent the rock mass properties that genuinely control rock breakage under the action of an explosive charge. The explosive–rock interaction that controls the velocity of detonation, the dynamic breakage behaviour of the rock substance under supersonic and subsonic loading conditions, and the actual distribution and characteristics of rock mass discontinuities make the provision of these explicit parameters for a mechanistic breakage model extremely challenging in practical blasting situations. The most sophisticated model available will be of little use if the data used to describe the properties of the rock mass are not available, appropriate or representative of the rock to be blasted.

Modelling blast fragmentation for the mining industry requires an approach that can deal with large blast volumes and the inevitable variability in rock mass properties. Most fragmentation modelling undertaken for the mining industry uses empirical models while the mechanistic models tend to be applied to specific smaller scale problems usually associated with research activities.

**Rock mass properties used in models**

Tables 1, 2 and 3 provide a brief description of some of the more successful blast fragmentation models and the rock mass properties on which they depend. The tables do not constitute an exhaustive list of the models that have been developed, but are intended to represent the types of models that are available.

Table 1 describes the evolution of a number of empirical models based on the Kuz-Ram approach. Table 2 describes some mechanistic models and the rock mass properties they use and Table 3 describes some alternative empirical modelling approaches.

### TABLE 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Basis</th>
<th>Rock mass description</th>
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</table>
| Kuznetsov (1973) | Relationship derived from experimental data between the explosive charge and volume of rock broken by each blasthole and the particle size, for which 50 per cent of the muck pile by weight is finer. | A rock factor was included in the formula for the mean fragment size based on allocating:  
  - 7 for medium rocks  
  - 10 for hard, highly fissured rocks  
  - 13 for very hard, weakly fissured rocks. |
| Cunningham (1983) | Consistent with work by Holmberg (1974), Cunningham extended the output of Kuznetsov's model by describing the full fragment size distribution by fitting this to a Rosin Rammler curve. | Maintained Kuznetsov rock factor. |
| Lilly (1986)     | Lilly developed a 'blastability index' that Cunningham (1987) incorporated into the Kuz-Ram model to replace Kuznetsov's simple rock factor. Lilly's work was based on conditions encountered in open pit iron ore mines. | Lilly's blastability index was based on a series of ratings based on the field observation of the rock mass character (frangible, blocky or massive), joint plane spacing, joint plane orientation, strength and density. |
| Cunningham (1987) | Cunningham extended the inputs to the Kuz-Ram model to derive the shape factor for the Rosin Rammler fragment size distribution curve from basic blast geometry inputs. | Cunningham replaced Kuznetsov's rock factor with Lilly's blasting index. |
| JKMR Mine to Mill | A number of model developments were driven by projects during the 1990s exploring the impact of blasting on downstream processing. These focused on improving the description of the fine end of the fragmentation curve and required a departure from the Rosin Rammler size distribution to represent a higher proportion of fines. This was accounted for by merging two size distribution curves—one for the coarse end and one for the fine end. | Rock strength (unconfined compressive strength and tensile strength), Young's modulus, rock density, rock quality designation, fracture frequency. |
| Ouchterlony et al (2006) | A different curve (the Swebrec function) was proposed to describe the full fragment size distribution to replace the Rosin Rammler equation in the Kuz-Ram model. The Swebrec function has been successfully fitted to detailed sieved size distributions from carefully managed field experiments and confirms the increase in fines compared with the Rosin Rammler curve. | Ouchterlony applied the new size distribution curve to the 1987 Kuz-Ram model but also explored definitions for the top fragment size based on fracture spacing and blast geometry. |
| Scott and Onederra (2015) | A highly modified Kuz-Ram model has been successfully been applied in consulting assignments dealing with blasts in a wide range of rock types and blasting situations. Each of the three Swebrec parameters required to define the full size distribution are estimated by the model. | A rock factor is defined based on rock strength, fracture frequency and density. Statistical distributions of these data are utilised. |
CHARACTERISING ROCK MASS PROPERTIES FOR FRAGMENTATION MODELLING

The authors are involved in the use of fragmentation models to estimate and manage fragmentation in practical blasting situations, usually applied to mining operations. In these applications there are significant opportunities to:

- extend conventional rock characterisation data to tackle specific blasting issues.
- utilise data from other disciplines (eg geology, metallurgy) to enhance and extend data used for fragmentation modelling etc.

The Kuz-Ram based models rely on an index to describe the ‘blastability’ of the rock mass. These indices range from a simple allocation of a value based on the general character of the rock (eg seven for medium rocks etc) to complex algorithms combining basic properties such as strength, density and fracture frequency. The mechanistic models rely on more fundamental characteristics that may include dynamic properties that require sophisticated laboratory testing.

The authors are involved in the use of fragmentation models to estimate and manage fragmentation in practical blasting situations, usually applied to mining operations. In these applications there are significant opportunities to:

- avoid the adoption of standard or nominal values for rock mass properties to represent large volumes of rock
- reflect the variability of rock mass properties and the impact that this has on the likely range of blasting outcomes
- improve the description of rock mass structure
- utilise data from other disciplines (eg geology, metallurgy) to enhance and extend data used for fragmentation modelling

ROCK MASS CHARACTERISATION FOR A GREENFIELD SITE

Requirements

Blast modelling is required for a greenfield mining project so that suitable blast designs can be derived to guide:

- the types and quantity of explosives that will be required so that supply logistics and costs can be estimated...
domains are sometimes defined as areas within the deposit where the properties of the ore will provide similar mining and processing performance. Such a classification may assist in the definition of appropriate blasting domains but more specific blasting properties may be required to develop the most appropriate classification.

Advice from resource geologists should be helpful in identifying zones within the deposit that are of similar lithology, alteration or structural disturbance. Geometallurgical domains are sometimes defined as areas within the deposit where the properties of the ore will provide similar mining and processing performance. Such a classification may assist in the definition of appropriate blasting domains but more specific blasting properties may be required to develop the most appropriate classification.

By definition, a greenfield site does not have access to local operating experience to form a basis for these estimates. The blast design requirements and expected blast performance must be estimated based on the rock mass properties that can be identified from the exploration and preproduction-site investigations.

It is a relatively simple matter to formulate ‘typical’ or ‘representative’ blast designs based on limited rock mass data. These may satisfy the very earliest and simplest mine planning activities; however, before a project can progress to a bankable level of feasibility it is necessary to be able to address each of the points above in terms, not only of the average or typical situation, but in terms of the full range of situations, designs and performance that are likely to be encountered.

**Potential data sources**

Potential sources of data for a greenfield site include surface geological mapping, surface and aerial geophysics and their interpretation; however, the vast majority of useful data will be derived from drill core. The core itself should be logged by both resource geologists and geotechnical personnel and photographed prior to samples being removed for resource, geotechnical or metallurgical testing. Scott, Onederra and Chitombo (2006) addressed how various requirements for rock characterisation from geologists, metallurgists, geotechnical and blasting engineers vary and identified specific areas where the needs of the blasting engineer should receive increased focus. In particular, the management of rock mass data should be changed from the structure shown on Figure 1 to that of Figure 2, so that all parties can benefit from the work of the other disciplines. This requires the creation of a rock characterisation database that is maintained as a live entity, accepting data from a number of sources and being structured to generate information in the form best suited to each discipline.

**Domains**

A blasting domain is an area or subset of the deposit where the rock mass properties display similar blasting properties. An example might be a surface-weathered zone, blocky but otherwise competent waste, the ore itself or an area of the mine affected by an intrusion or other geological feature. It is common practice for geotechnical engineers to identify domains based on stability or reinforcement requirements but appropriate blasting domains may or may not align well with these geotechnical domains.

Advice from resource geologists should be helpful in identifying zones within the deposit that are of similar lithology, alteration or structural disturbance. Geometallurgical domains are sometimes defined as areas within the deposit where the properties of the ore will provide similar mining and processing performance. Such a classification may assist in the definition of appropriate blasting domains but more specific blasting properties may be required to develop the most appropriate classification.

Analysis of data describing the key blasting parameters of strength, structure and density is likely to reveal systematic differences in blasting characteristics between domains. It is likely that most deposits will contain a number of identifiable blasting domains. A typical delineation of geotechnical and blasting domains is given in Figure 3.

**Blasting properties**

**Intact rock strength**

Geotechnical engineers will tend to describe rock substance strength in terms of unconfined compressive strength (UCS) in MPa. UCS needs to be measured in a laboratory using sophisticated equipment and carefully prepared samples. The failure of a cylinder of rock under compressive load with no lateral confinement does not really represent the conditions under which the rock is expected to break under the action of an explosive; however, most blasting models use UCS as the principal parameter representing rock strength. This is acceptable if it is understood that this is really just providing a ‘strength index’ to the model and that it has been formulated, adjusted or calibrated to respond sensibly to this index.

Point load strength (PLS) can be measured using a portable hydraulic machine to test the strength of appropriately sized samples or sections of core (Brook, 1985) as shown on Figure 4. The sample is compressed between two conical platens and the failure load used to calculate the PLS in MPa. While the results are generally subject to some scatter, a sufficient number of tests can result in indices that correlate with blasting, crushing and milling performance (Scott, Morrell and Clark, 2002). For instance, the JKMRC drop weight rock breakage parameters A and b are widely relied upon to estimate the energy requirements and throughput expected from grinding operations and these parameters are found to correlate well with PLS.
UCS is often estimated by multiplying PLS by a constant. This multiplier will vary for different rock types and it is desirable to compare any available data pairs to establish a local relationship. Table 4 shows an example from a metalliferous mine.

Geophysical data can also be used to estimate rock strength, especially if they can be calibrated using data from local strength measurements (Read and Stacey, 2009).

Field strength indices like those summarised on Table 5 are often recorded based on surface scratch tests or the response of the rock to a hammer blow. While inevitably crude, these qualitative tests can be useful. It is, however, critical that they are performed to consistent criteria and are not subject to excessive individual bias.

**Rock mass structure**

In any rock mass the rock substance may be disrupted by a number of types of discontinuities. These may range from faults, joints, bedding planes and foliation to more subtle healed fractures. In terms of blasting, all of these type of discontinuities are important because they provide distinct planes of weakness that assist in the generation of blast fragments.

Structures within a rock mass are generally not continuous, but they do tend to occur in geometric patterns or sets that share common characteristics such as orientation and frequency. While not always intersecting to form free blocks within the rock mass, inspection of muck piles generally reveals a large number of blocks (usually the larger fragments within the muck pile) that are bound by joints on several sides. Blasting extends the existing discontinuities to complete the definition of these blocks which are then freed by the movement of the blast burden to form the muck pile. The coarse end of the fragment size distribution is strongly influenced by the size of these *in situ* blocks.

Geotechnical engineers concerned with the failure of a slope are inclined to ignore structures that cannot contribute to the failure of that slope. Engineers concerned with the stability of a development drive are only concerned with the structures that affect the stability or reinforcement requirements of that drive. Blasting is affected by all structures, large and small.

**TABLE 4**

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Unconfined compressive strength / point load strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuff</td>
<td>19.6</td>
</tr>
<tr>
<td>Microdiorite</td>
<td>18</td>
</tr>
<tr>
<td>Mudstone</td>
<td>26</td>
</tr>
<tr>
<td>Porphyry</td>
<td>9.1</td>
</tr>
<tr>
<td>Andesite</td>
<td>20</td>
</tr>
</tbody>
</table>
Anything that provides a plane of weakness through the rock mass might be exploited by the blast fracture mechanisms to form fragments; however, it is common for material logged for geotechnical (stability) purposes to overlook the smaller, but often quite common discontinuities.

Most geological core logs include an assessment of the observed fractures. There is a strong tendency to reduce these data to report the rock quality designation (RQD), which is defined as the percentage of the core length that is longer than 100 mm. Higher values of RQD indicate higher quality rock (ie fewer fractures) but experience indicates that similar RQD values can arise for rock masses of quite different structural properties. RQD is therefore not particularly useful as a quantitative guide to blasting requirements or blasting performance. Fracture frequency (the number of fractures observed per metre of core) can be related more effectively to the likely in situ block size distributions and has been found by the authors to be a much more useful input to blast design.

For example, Figures 5, 6 and 7 show examples of core from a copper deposit exhibiting different fracture frequencies and Figure 8 compares the estimated in situ block size distribution for each of these fracture frequencies using a relationship suggested by White (1977).

More sophisticated geometric models have also been developed to describe the three dimensional structure of a rock mass (eg Brown, 2007). Most geotechnical logging programs would capture the location and orientation data required for each fracture to generate such a model; however, the technical effort involved to generate such models is not generally made available during the prefeasibility or feasibility stages of a new project.

**Rock material density**

The density of drill core is routinely measured during most exploration programs as it drives the conversion between volume and mass for the estimation of mining quantities and

<table>
<thead>
<tr>
<th>Code</th>
<th>Descriptor</th>
<th>Unconfined compressive strength (MPa)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>Extremely weak</td>
<td>0.25–1.0</td>
<td>Breaks in hand</td>
</tr>
<tr>
<td>R1</td>
<td>Very weak</td>
<td>1.0–5.0</td>
<td>Cuts with knife</td>
</tr>
<tr>
<td>R2</td>
<td>Weak</td>
<td>5–25</td>
<td>Pick readily indents</td>
</tr>
<tr>
<td>R3</td>
<td>Moderately strong</td>
<td>25–50</td>
<td>Readily fractures with blow from hammer</td>
</tr>
<tr>
<td>R4</td>
<td>Strong</td>
<td>50–100</td>
<td>Requires firm hammer blow to break</td>
</tr>
<tr>
<td>R5</td>
<td>Very strong</td>
<td>100–200</td>
<td>Requires several hammer blows to break</td>
</tr>
</tbody>
</table>
while the measurement of density is generally straightforward, care is required if the rock displays porosity in which case measurements may be required for both sealed and unsealed core samples. The density of the rock affects its inertial characteristics and hence how the rock mass will move in response to the forces applied during blasting. High porosity rocks may be slow to respond to the action of explosion gases and generate less muck pile movement.

Many hard, brittle rocks display densities in the range of 2.7 to 2.9 t/m$^3$ and the precise density value is unlikely to have a material effect on blasting performance. Some sedimentary strata may only display densities around 2.0 t/m$^3$ and some iron ores may record densities of 3.6 t/m$^3$. Variation on this scale will have a significant impact on blast performance and needs to be included in an effective fragmentation model.

**Rock material stiffness**

Young’s modulus is a measure of stiffness and is usually recorded during the measurement of UCS from a prepared core sample. Dynamic Young’s modulus and Poisson’s ratio can also be obtained using seismic techniques in which the velocities of compression and shear waves are determined. These elastic constants can be determined if the density of the rock is known. Relationships have been proposed between static and dynamic Young’s modulus (Eissa and Kazi, 1988).

**Blastability indices**

The inputs required for most blastability indices or factors referred to in Table 1 and Table 3 are a subset of the parameters discussed previously. These are also the properties that drive most empirical fragmentation models.

A blasting index can be an effective way to identify how blasting properties vary throughout a deposit. They can then be used to assist in the definition of individual blasting domains. Figures 9 and 10 compare a blasting index for two different domains in a metalliferous mine. The fact that the domains differ significantly is obvious from the difference in the distribution of the indices. The plots also indicate that the domain represented by Figure 9 predominantly consists of material that should require relatively low powder factors while that represented by Figure 10 will require more intense blasting; however, the distributions of these data indicate that about a third of the rock from Figure 9 will have similar blasting requirements to the rock represented on Figure 10. The distribution of these properties can be used to understand the range of blasting outcomes that is likely.

**Technical challenges**

There are a number of challenges faced when dealing with the characterisation of a rock mass for a greenfield site. The first is to acquire an adequate appreciation of the variability of each of the properties that are being studied. It is tempting
to deal with ‘average’ properties and to ignore outlying data values. Most sampling and testing programs will reveal a population of results and the average may not be the most useful representation of the population. For example, the frequency with which the strength of a particular rock lithology was reported is shown in Figure 11. It is a simple matter to report the average strength to be 70 MPa, but this ignores the fact that about a quarter of the rock tested demonstrated a strength less than half this value. Similarly, a small, but appreciable proportion of the test results indicated the presence of much stronger rock. Modelling can respond to these different strength parameters to provide a better estimate of the range in fragmentation outcomes than can be achieved by simply working with an average value.

Similarly, it can be very misleading to deal with average values of fracture frequency when the intensity of fractures is likely to vary with location within the deposit. Figure 12 shows a frequency distribution for fracture frequency from a copper-gold deposit. There are clearly at least two populations of fracture frequency contributing to this plot. Figure 13 shows a plot of fracture frequency from an individual drill hole and shows how the hole passes through zones of massive, blocky and fractured ground, each of quite different blasting properties. Plotting the fracture frequency (FF) with depth demonstrates that there are at least two quite different classes of rock and how they are distributed. Clearly significant proportions of the deposit are highly fractured (FF > 20/m) and significant proportions display FF values distributed around an average value of about 6/m.

It is challenging to gain an adequate three dimensional appreciation of the distribution of the rock mass properties when working predominately with core. A 3D model that displays the lithology, major structures and blasting parameters should enable:

- a better understanding of the distribution of the available data
- the ability to assess patterns and trends in the data
- designs and modelled output to be generated for different areas of the proposed operation.
When viewed in conjunction with lithology and alteration, useful relationships between these properties and the blasting properties can often be developed and used to extend the modelled blasting properties throughout the deposit.

**ROCK MASS CHARACTERISATION IN AN OPERATING MINE**

**Opportunities**

An operating mine provides much better access to the rock mass than is available for a greenfield mining venture; however, operational issues and mine schedules may limit opportunities for the safe personal inspection, sampling or testing of rock in the next production blast. In an underground mine, access to the rock to be blasted may be little better than provided by exploration data, although mapping and sampling the walls of adjacent openings and monitoring blasthole drilling performance can provide opportunities for improved rock mass characterisation.

**Rock mass data**

The same rock mass data are required in an operating mine as needed to predict the blasting properties of a greenfield deposit; however, the acquisition and management of the data needs to be efficient and timely if blasting is to meet the required production schedules.

When access is available, rock can be inspected from faces and bench surfaces. Geological properties can be noted and field strength tests conducted. Hand samples can also be taken for PLS or other breakage tests.

Remote sensing systems such as laser mapping and terrestrial photogrammetry can be used to map lithologies and discontinuities in a rock mass without the need for personnel to be close to rock exposures (Poropat, 2006). The captured data can add to the detailed rock mass model to improve the understanding of the trends in rock mass properties.

The performance of blasthole drills can be monitored to identify changes in hardness, drilled chips can be logged to identify geological boundaries within the bench and blastholes can be geophysically logged for more detailed interrogation. Surface and inter-hole seismic tests can be conducted if required. While data captured during and after drilling is too late to affect the chosen blast pattern, there is still scope to vary the charge and initiation designs to allow for variation in blasting properties identified from these investigations.

**Calibration**

Closing the feedback loop between rock mass properties, detailed blast design (and its implementation) and the resulting excavation and fragmentation performance allows fragmentation models to be effectively calibrated. These models can then be used to guide the design changes needed to not only avoid poor fragmentation outcomes, but to ‘tune’ the resulting fragmentation towards the targeted performance.

Even simple indications of performance such as boulder counts and qualitative feedback from field staff can be useful. Ideally, routine fragmentation measurements are needed using scanning or photographic tools, supplemented by excavation, crushing and milling performance for the blasted material as it is tracked through the chain of production processes. Advanced techniques using high resolution 3D laser scanning have recently been demonstrated (Onederra, Thurley and Catalan, 2015).

It is the authors’ experience that the more advanced empirical fragmentation models described in Table 1 are capable of guiding the blast design changes required to steer fragmentation outcomes towards the targeted performance if adequate rock mass and blast performance data can be made available on a timely basis.

**MANAGING FINES GENERATION**

The fine end of the muck pile size distribution can be important for two reasons:

1. the operation might seek to increase the proportion in fines generated by the blast in order to improve downstream crushing and milling performance
2. the objective may be to limit fines in the blasted muck to improve post mining mineral extraction; for instance, in a heap leaching operation.

Most blast fragmentation models estimate the extent of breakage based on the strength allocated to the rock and some measure of the strength and concentration of the explosive charge – perhaps the expected detonation pressure and powder factor. The value of rock strength is likely to be the UCS or some simpler measurement converted to UCS.

A more detailed analysis might focus on energy–breakage relationships for the rock as used in comminution models (JKMRC, 1996). While it is not possible to directly relate the energy deemed to be required to achieve a targeted level of breakage to the energy contributed by the explosive (Torrance and Scott, 2015), such tests will identify the patterns of breakage inherent to different rock types. Some rocks tend to break to finer sizes than others given the same energy input. If a particular proportion of fines is targeted for a blasted muck pile it would be helpful to understand the inherent patterns of breakage for the different rock types encountered by the operation. Rocks that tend to produce fewer fines will need to be blasted at higher intensity than rocks that tend to break to finer particles if a targeted proportion of fines is to be achieved.

The characterisation of inherent breakage behaviour is critical if the task is to limit the generation of fines from a blast. Lower blasthole pressures and reduced confinement are the usual recommendations for blasts to generate fewer fines. The result will be influenced by the rock strength but also by the inherent energy–breakage relationships.

An example of this was reported by (Scott et al, 1998), which described a program of fines reduction at the Cerro Colorado...
heap leach copper operation in northern Chile. After blasting, the run-of-mine ore was reduced to -12.7 mm particle size in three stages of crushing and screening. The crushed material was then agglomerated and stacked out on prepared leaching pads where they were continuously irrigated. The ultimate recovery of copper and rate of leaching achieved on the pads is affected by the size distribution of the agglomerated product. The operation suffered from excessive fines in the heap leach feed material which resulted in reduced leaching rates and poor metal recoveries.

A detailed evaluation of the fines generated in production blasts and during crushing was undertaken by JKTech. This study identified that while both blasting and crushing practices could be improved, neither could be attributed with the generation of the level of fines that was causing the problem. Individual assessment of each metallurgical domain revealed that the Andesite ores with sericitic alteration were the most prone to generating fines. Mineralogical assessment revealed that these ores contained a significant proportion of bound clay minerals that were being liberated during breakage. These bound clay minerals were identified and described differently by geologists and mineralogists, as shown in Figure 14 and 15.

In order to characterise the additional fines potential of different ores, the proportion of liberated clay was measured using a site laboratory test specifically developed for this project. Having characterised the vulnerability of different ores to fines generation, blasting and crushing guidelines were developed that treated the most vulnerable ores with the lowest possible energy and largest feasible particle size to enhance leaching performance. Less vulnerable ores could be blasted and crushed more conventionally.

The Cerro Colorado experience demonstrates that if the mechanisms behind a particular fragmentation problem can be adequately identified then a focused characterisation process can be designed. This may require an approach that is outside the usual or conventional rock characterisation for modelling blast fragmentation.

DUST GENERATION

A more extreme example of the need for a specialised approach to rock characterisation was reported by Scott, Michaux and Onederra (2009). Predicting the generation of dust from open pit mining operations is traditionally based on the use of ‘emission factors’ that describe the mass of dust expected to be generated from individual mining and materials handling processes (EPA, 1998). These emission factors are based on field measurements from ‘typical’ operations. Estimates of dust generation would have much greater credibility if they could be related directly to the characteristics of the rock at the particular site and the actual blast designs used. Available blast fragmentation models predict breakage down to perhaps 1 mm in size. The challenge was to be able to extend the fragment size estimate a further three orders of magnitude to dust-sized particles.

The size distribution of the material less than 1 mm in size is normally not addressed in blast modelling and so a new approach was required. Research undertaken by the JKMRC had demonstrated that rock breaks in distinctive patterns when the fragments concerned are unaffected by macro-structures such as jointing, bedding or foliation. How a rock breaks is governed by the magnitude and rate of the energy applied and the characteristics of the material properties of the rock.

A specialised test was developed to measure the breakage patterns from different rock types down to dust-sized particles. The selected sample for each rock type was crushed in several passes to generate enough fragments in each size fraction to show the distinctive fines generation pattern of each rock texture sample. Figure 16 shows the results of this approach. The graphs show size distributions from the crusher tests for a wide range of rock types. Breakage down to 1 mm follows an orderly relationship as this tends to involve breakage of material larger than the grain size of the rock. Quite distinctive breakage signatures are found for each rock type below 1 mm where breakage continues below the rock’s grain size.

A blast fragmentation model was used to estimate the fragmentation curve down to 1 mm. The distribution was then extended into the ultra-fine sizes by distributing the material passing 1 mm based on the relative fine size distribution for that rock type observed in the fine crushing tests. This allowed the proportion of ultra-fines generated by different blast designs to be estimated for different rock types.
The application of standard emission factors would have led to the same amount of dust being estimated for each ore type; however, the clear differences in fines generation between the different ores demonstrated by the crushing test allowed the differences in dust generation for the different rock types to be modelled.

CONCLUSIONS

The best fragmentation model for any given situation is one that has been formulated to address the situation being studied and that utilises the rock mass, explosive and blast design properties that have most influence on the blasting outcome. A critical requirement is that the rock mass properties and their variability are adequately quantified in a form that suits the assumptions that form the basis of the selected fragmentation model.

There are a wide range of fragmentation models available to the blasting industry. The rock mass data required for these models vary with the structure of the models and their underlying assumptions. While the properties that influence rock breakage behaviour during blasting can be identified, many of these properties are difficult to quantify, especially with the data density required to describe the variability that is common in practical blasting situations.

Rock mass data are collected and used by a number of disciplines working at a mine. Ideally, the data used by each of these groups should be shared, although care is required to ensure that the basis of the data is fully understood. Data collected to guide comminution and geotechnical design can be relevant to blasting operations and an understanding of the geological and mineralogical influences are invaluable to interpret trends in rock mass properties across a deposit.

Care is required to appreciate the variability in rock mass properties as well as their typical values. Fragmentation outcomes will not remain consistent as the rock being blasted varies from its nominal characteristics. Modelling can be adapted to respond to a range of input properties to generate a more realistic range of fragmentation outcomes.

Some models (eg the Kuz-Ram model and its derivatives) utilise blasting indices compiled from relationships between basic properties describing strength, density and structure. These indices can be an effective way of identifying how blasting properties vary throughout a deposit and can be used to assist in the definition of individual blasting domains.

Fragmentation models can be calibrated by closing the feedback loop between rock mass properties, blast designs and the resulting excavation and fragmentation performance. These models can then be used to guide the design changes needed to not only avoid poor fragmentation outcomes, but to ‘tune’ the resulting fragmentation towards the targeted performance.

Some fragmentation challenges may result from mechanisms outside those incorporated in the available fragmentation models. In such cases it may be possible to develop new or different characterisation tests and to modify the modelling process to adequately account for these mechanisms.

REFERENCES


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