Estimation of fines generated by blasting – applications for the mining and quarrying industries

I. Onederra, S. Esen and A. Jankovic

This paper introduces an engineering approach to estimate the proportion of fines generated during the blasting process. The proposed framework is based on the combination of two Rosin-Rammler based distribution functions to model the full range of fragments expected to be produced during this process. This particular approach, which has been successfully applied for a number of years by the Julius Kruttschnitt Mineral Research Centre (JKMRC), has been improved with the introduction of a new model to predict the potential volume of crushed material resulting from the crushing and shearing stages of blasting. Other sources of fines including liberation of infilling from discontinuities, particle collisions and post-blast processes have been excluded to simplify the modelling process. Validation analysis of the proposed framework has shown that there is good agreement between model predictions and the measured distribution of fines. In three distinct cases, results verified the hypothesis that a single index of uniformity can be used to describe the distribution of fragments in the range of 1 mm through to the expected post-blast mean fragment size ($x_{50}$). Although some limitations have been noted, the approach appears to provide useful approximations for continuous improvement analysis and applications. The practical application of the proposed modelling framework is demonstrated with an engineering study aimed at assessing the impact of blast fragmentation on the overall production of fines in a hard rock quarry. Results from simulations showed that less crushing requirements due to an overall increase in fragmentation contribute to a decrease in the specific crushing energy and hence a reduction in power consumption requirements. This analysis helped demonstrate the importance of addressing the impact of blast fragmentation distribution on overall quarry productivity requirements; and highlights the importance of adopting a holistic approach when addressing the blast optimisation problem.

INTRODUCTION

Blasting activities in mines and quarries have been placing significant emphasis on the ability to tailor fragmentation to improve downstream processes. In many of these operations, the impact of fines has been clearly identified. For example, the generation of excessive fines in operations adopting in situ leaching as the main ore processing method, may hinder recovery as certain fines tend to affect the permeability of leaching pads. Leaching performance may be affected if the proportion of material that is less than 150 μm exceeds 12% in the feed to the agglomerators. Similarly, the efficiency of coal processing is strongly related to the generation of fines of less than 0.5 mm. Increased fines content in run-of-mine feed leads to higher handling and processing costs, low yields, increased product moisture content, and in many cases a reduced product value. The same can be said of quarry operations where material of less than 2.4–15 mm in size may be considered to be of no value and hence wasted.

Whilst fines may be detrimental to some operations, in large-scale metalliferous mining there is evidence to suggest that by providing an appropriate size distribution to crushing and grinding circuits, a measurable increased throughput and/or reduced power draw can be obtained. This may entail a requirement to increase the proportion of finer material in production blasting activities.

The need to be able to predict the amount of fines from blasting has driven the development of an improved engineering model. The model being proposed is based on findings from both model-scale and full-scale data. Model-scale data were obtained from a comprehensive experimental programme, whilst full-scale studies have been compiled from surveys conducted over a number of years by researchers of the Julius Kruttschnitt Mineral Research Centre (JKMRC).

FRAGMENTATION MODELLING FRAMEWORK

For a number of years, the JKMRC has been applying two empirical models to estimate muckpile fragmentation distributions in surface blasting operations.
These empirical models are the two-component model (TCM) and the crushed zone model (CZM). These models are a hybrid between the well-known Kuz-Ram approach and two specific fines predictive models. A comparison of these two models conducted by Hall and Brunton has highlighted some deficiencies in their predictive capabilities, due principally to some limitations in their estimations of fines and intermediate size fractions. Their conclusions indicated that there was a need to review and further improve ways of predicting the distribution of fines and, in particular, estimations of crushing in the vicinity of detonated blastholes. This study has been part of that process.

Building on the hybrid approach incorporated in the CZM model, the expected distribution of fragments in the fines and coarse regions is modelled by two separate functions. These two functions are based on the well-established Rosin-Rammler distribution and given by:

\[ R(x) = 1 - e^{-0.693 \left( \frac{x}{x_{50}} \right)^n} \]  
Eq. (1)

for values of \( x \) less than or equal to \( x_{50} \)

\[ R(x) = 1 - e^{-0.693 \left( \frac{x}{x_{f}} \right)^n} \]  
Eq. (2)

for values of \( x \) greater than \( x_{50} \)

where \( R(x) \) is the proportion of the material passing a screen of size \( x \), \( x_{50} \) is the post-blast mean fragment size, \( n_c \) is the uniformity index for the coarse end of the distribution and \( n_f \) is the fines uniformity index which is given by:

\[ n_f = \frac{\ln \left( \frac{x}{-0.693} \right)}{\ln \left( \frac{1}{x_{50}} \right)} \]  
Eq. (3)

where \( f_c \) is the proportion of the material passing a screen of size 1 mm or the fines inflection point.

The modelling framework is graphically illustrated in Figure 1 by comparing the standard Rosin-Rammler or Kuz-Ram based distribution with the proposed combined distribution functions. This figure also highlights the main modelling parameters, namely the fines inflection point \( f_c \), the expected mean fragment size \( x_{50} \) and the ‘coarse’ uniformity index \( n_c \), also referred plainly in literature as the uniformity index \( n \). In this paper, a thorough description of a revised approach to determine the fines inflection point \( f_c \) is given. The determination of the other two key modelling parameters (i.e. the mean fragment size, \( x_{50} \) and the ‘coarse’ uniformity index, \( n_c \)) follows the well-documented Kuz-Ram approach and is, therefore, not covered here.

The fines inflection point \( f_c \)

Literature indicates that fines present in a muckpile tend to originate from the near field crushing zone, fracturing (shearing) zones as well as possible liberation from rock mass discontinuities. The fines inflection point is introduced to consider these sources and is given by:

\[ f_c = \%Fines_{(-1.0)} = \left( \frac{V_c + V_b}{V_t} \right) \times 100 + [F_r] \]  
Eq. (4)

where \( V_c \) is the volume contribution of the crushed zone, \( V_b \) is the volume contribution from breakage (major radial cracks), \( V_t \) is the total volume being blasted and \( F_r \) is a rock mass fines correction factor.

The fines inflection point is based on the hypothesis that, for most conditions, the coarsest particle size expected to be generated during the crushing and shearing stages of blasting would be 1 mm, and that the percentage passing fraction would be directly proportional to the volume of crushed and/or sheared rock material surrounding a detonated blasthole.

As depicted in Figure 2, the estimation of the volume of crushed and/or sheared rock material follows simple geometric calculations given by (i) the radius of crushing and thus the volume of a cylinder of crushed rock; and (ii) the distribution of major

1 Key parameters of the proposed fragmentation modelling framework
radial cracks, which are assumed to be evenly distributed around a borehole, planar and also continuous along the length of the explosive charge. These two components define the total volume of a ‘star’-shaped crushed region (i.e. \( V_c + V_b \)).

In the proposed modelling framework, a rock mass correction factor (\( F_r \)) has been introduced to address the hypothesis that fines may also be liberated from rock mass discontinuities. However, an approach to determine this parameter has not been developed, as there is insufficient quantifiable evidence to support this. To simplify the modelling structure, the \( F_r \) parameter is, therefore, currently disregarded and the modelling process involves only the determination of \( V_c \) and \( V_b \).

The crushed zone model to determine \( V_c \)

The determination of \( V_c \) is based on an improved model to predict the radius of crushing generated by a detonated blasthole reported by Esen et al. This model is given by the empirical relationship:

\[
r_c = 0.812 r_o (CZI)^{0.219}
\]

where \( r_c \) is the crushing zone radius (mm), \( r_o \) is the borehole radius (mm) and \( CZI \) is defined as the crushing zone index. This is a dimensionless index that identifies the crushing potential of a charged blasthole and is calculated from:

\[
CZI = \left( \frac{P_b}{K \times \sigma_c} \right)^3
\]

\( T \), tensile strength; \( \rho \), density.

\[
F_r = \frac{E_d}{1 + \nu_d}
\]

where \( P_b \) is the borehole pressure (Pa), computed from non-ideal detonation theory, \( K \) is the rock stiffness (Pa) and \( \sigma_c \) is the uni-axial compressive strength (Pa). Rock stiffness \( K \) is defined assuming that the material within the crushing zone is homogeneous and isotropic and is given by:

\[
K = \frac{E_d}{1 + \nu_d}
\]

Table 1 Physical and mechanical properties of rock types

<table>
<thead>
<tr>
<th>Case study</th>
<th>Rock type</th>
<th>( s_c ) (MPa)</th>
<th>( T ) (MPa)</th>
<th>( \rho ) (kg m(^{-3}))</th>
<th>( E_d ) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Coal blasting(^9)</td>
<td>Coal</td>
<td>20</td>
<td>2.0</td>
<td>1440</td>
<td>9.6</td>
</tr>
<tr>
<td>2. Mount Coota(^9)</td>
<td>Hornfeld</td>
<td>200</td>
<td>16</td>
<td>2730</td>
<td>83.0</td>
</tr>
<tr>
<td>3. Ok Tedi Mine(^9)</td>
<td>Monzodiorite</td>
<td>55</td>
<td>7.8</td>
<td>2600</td>
<td>34.0</td>
</tr>
<tr>
<td>4. Cadia Hill Gold(^9)</td>
<td>Monzonite</td>
<td>127</td>
<td>9.0</td>
<td>2600</td>
<td>77.0</td>
</tr>
<tr>
<td>5. Escondida Mine(^9)</td>
<td>Porphyry ore</td>
<td>22</td>
<td>3.0</td>
<td>2616</td>
<td>15.2</td>
</tr>
<tr>
<td>6. Porgera Gold Mine(^9)</td>
<td>Hornblende Diorite</td>
<td>138</td>
<td>13.0</td>
<td>2725</td>
<td>70.0</td>
</tr>
</tbody>
</table>

Results from this preliminary back analysis are given in Table 3. The analysis shows that following the ISRM rock classification system, categorised by Young’s modulus (<www.rockmass.net>), in the soft (low strength) rock types, the proportion of fines due to the crushed zone relative to the total amount of fines, are in the range of 9.1–19.6% (Cases 1, 3 and 5). In the medium-to-hard (high strength) rocks, the range is 8.5–9.2% (Cases 2, 4 and 6). This analysis
clearly supports the hypothesis that in full scale blasting operations, the crushed zone around a blasthole is not the only significant source of fines, and that in most cases, the contribution of breakage can be expected to be significant.

As the proposed approach seeks to estimate the proportion of fines only present in the muckpile, post-blast sources such as excavation, handling, mechanical sieving and crushing are not relevant to the modelling framework being proposed. However, fines generated by the breakage process itself must be considered. In order to address the issue of incorporating the contribution of overall breakage on the proportion of fines (i.e. \(V_b\) in the proposed framework), a simplistic crack model has been adopted. This model is proposed as a preliminary engineering tool to estimate the parameter \(V_b\) as discussed below.

**The crack model to determine \(V_b\)**

The following approach assumes that the source of fines from overall breakage is directly proportional to a volume of crushed material bounded by major blast induced fractures. The number of near field radial cracks \((C)\) around the blasthole is estimated following the approach proposed by Katsabanis:16

\[
C = \varepsilon_s \left( \frac{P_{eq}}{T_{ro}} \right) \quad \text{Eq. (8)}
\]

where \(\varepsilon_s\) is the strain at the blasthole and \(T_{ro}\) is the dynamic tensile strength of the rock (Pa), which is assumed to be in the range of 4–8 times the static value.

\[
\text{The strain at the blasthole wall, } \varepsilon_s \text{, can be approximated by Katsabanis:16}
\]

\[
\varepsilon_s = \frac{(1 - \nu)P_s}{2(1 - 2\nu)\rho v_P^2 + 3(1 - \nu)\gamma P_s} \quad \text{Eq. (9)}
\]

where \(P_s\) is the explosion or borehole pressure (Pa); \(\rho\) is the rock density (kg m\(^{-3}\)); \(v_P\) is the P-wave velocity (m s\(^{-1}\)); \(\gamma\) is the adiabatic exponent of the detonation products; and \(\nu\) is the Poisson's ratio of the rock.

The length or radial extension of cracks is determined empirically with the stress attenuation function proposed by Liu and Katsabanis,19 assuming that the crack will arrest when the induced stress is equal to the static tensile strength or the rock material. In this case, the following relationship is proposed:

\[
C_i = r_c \left( \frac{T_{s}^2}{T_{ro}} \right)^{\phi} - r_c \quad \text{Eq. (10)}
\]

where \(T_s\) is the static tensile strength of the rock (Pa), \(r_c\) is the blasthole radius (m), \(r_c\) is the radius of crushing (m), \(\phi\) is the pressure decay factor and \(P_{eq}\) is the equilibrium pressure (Pa), or the pressure experienced at the end of the crushing zone which is given by:

\[
P_{eq} = P_s \left( \frac{\rho v_P}{\rho_{s}} \right)^{\phi} \quad \text{Eq. (11)}
\]

The pressure decay factor \(\phi\) is a function of rock and explosive properties. It is a negative number that has been found to be in the range of –1·24 to –1·65 for a wide range of explosive and rock combinations.\(^{19}\) A

### Table 3 Role of the crushed zone in the generation of fines

<table>
<thead>
<tr>
<th>Case study</th>
<th>(r_c) (mm)</th>
<th>(V_c) (m(^3))</th>
<th>Blast volume ((\text{m}^3))</th>
<th>Percentage –1 mm (crushed zone)</th>
<th>Percentage –1 mm (measured total fines)</th>
<th>Measurement technique</th>
<th>Relative proportion of fines from the crushed zone (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Coal blasting(^{26})</td>
<td>746</td>
<td>9·34</td>
<td>465·5</td>
<td>2·00</td>
<td>17·0</td>
<td>Mobile screening after excavation and handling</td>
<td>11·8 ((V_{c}, F_1, E&amp;H, S))</td>
</tr>
<tr>
<td>2. Mount Cootha(^{18})</td>
<td>122</td>
<td>0·45</td>
<td>197·23</td>
<td>0·21</td>
<td>2·3</td>
<td>Primary crusher product</td>
<td>9·1 ((V_{c}, F_1, E&amp;H, C))</td>
</tr>
<tr>
<td>3. Ok Tedi Mine(^{1})</td>
<td>573</td>
<td>9·83</td>
<td>944·6</td>
<td>1·00</td>
<td>11·0</td>
<td>Split* with fines correction from crusher product</td>
<td>9·1 ((V_{c}, F_1, E&amp;H, C))</td>
</tr>
<tr>
<td>4. Cadia Hill Gold(^{15})</td>
<td>301</td>
<td>2·92</td>
<td>631·8</td>
<td>0·46</td>
<td>5·0</td>
<td>Split with fines correction from crusher product</td>
<td>9·2 ((V_{c}, F_1, E&amp;H, C))</td>
</tr>
<tr>
<td>5. Escondida Mine(^{7})</td>
<td>1085</td>
<td>27·3</td>
<td>944·6</td>
<td>2·90</td>
<td>18·0</td>
<td>Split with fines correction from crusher product</td>
<td>16·1 ((V_{c}, F_1, E&amp;H, C))</td>
</tr>
<tr>
<td>6. Porgera Gold Mine(^{4})</td>
<td>229</td>
<td>0·71</td>
<td>406·6</td>
<td>0·17</td>
<td>2·0</td>
<td>Split with fines correction from crusher product</td>
<td>8·5 ((V_{c}, F_1, E&amp;H, C))</td>
</tr>
</tbody>
</table>

\* Split refers to the Split Engineering image analysis technique.\(^{17}\)

\(V_c\), contribution from the fracturing or breakage process; \(F_1\), contribution of fines liberated from rock mass discontinuities; E&H, excavation and handling; S, mechanical sieving; C, crushing.
first approximation can be obtained with the following empirical relationship:

\[
\phi = - \left( 0.0085 E_j + 0.9955 \right) \left( \frac{V_p}{V_{OD}} \right)^{0.13}
\]

Eq. (12)

where \( E_j \) is the dynamic Young's modulus (GPa), \( v_p \) is the p-wave velocity (m s\(^{-1}\)) and \( V_{OD} \) is the confined velocity of detonation of the explosive charge.

In order to make preliminary verifications of the proposed crack model, all of the case studies described in Table 3 have been reanalysed and new crushed volume predictions have been made and summarised in Table 4.

As shown in Table 4, there is now better agreement between the measured and the modelled proportion of fines at the assumed cut-off point of 1 mm. Discrepancies are within the expected errors associated with sampling and modelling assumptions. In general, in all rock types, the predicted fines inflection point is lower when compared to the measured total fines. This is more pronounced in the weaker rock types where further degradation can be expected from handling, transportation and crushing, as has been previously demonstrated by Djordjevic et al.\(^{29}\)

### VALIDATION OF THE PROPOSED FINES MODELLING FRAMEWORK

The approach to predict the fines inflection point \( f_c \) and the derivation of a single index of uniformity \( n_f \) to describe the distribution of fines between this point and the mean fragment size is validated in this section. A comparison between model predictions and measurements conducted in three full-scale blasts outside the original database has been carried out.

The adopted criteria for validation involved a direct comparison between the measured and predicted 10% and 20% passing fractions (i.e. P10 and P20). The adoption of P10 and P20 values as a comparison benchmark is justified by their common use as input parameters in comminution simulation tools for the design and optimisation of crushing and grinding circuits. Table 5 gives a summary of the input parameters available and used in the analysis.

In case study 1, fragmentation assessment and blast monitoring work have been reported by Hall\(^{19}\) and involved the application of image analysis techniques for material greater than 258 mm. Below this size, the material was initially screened in the field, followed by subsampling and laboratory screening down to 0.36 mm.

In case studies 2 and 3, reported by Onederra and Corder,\(^{22}\) two important blasting/ore domains were identified and surveyed in benches 2755S1 and 2875N11 of the pit. In both of these domains, the proportion of fragments less than 1 mm in size (i.e. fines inflection point) was measured from laboratory sieving of the primary crusher product or what is referred to as bell cut sampling.

For the conditions described above and following the procedures outlined earlier, the zones contributing to crushing given by the \( V_p \) and \( V_{OD} \) parameters were calculated and the fines inflection point \( f_c \) determined in each case. Table 6 summarises the model results together with the measured values.

As shown in Table 6, in all three cases the predicted fines inflection point values are reported below the measured values. This is considered to be a logical outcome, as the proposed fines modelling framework does not consider the contribution of fines given by

### Table 4 Comparison between new modelled results and measured values

<table>
<thead>
<tr>
<th>Case study &amp; rock type</th>
<th>( r_i ) (mm)</th>
<th>Number of cracks (C)</th>
<th>Volume crushed ( V_p + V_c ) (m(^3))</th>
<th>Blast volume (m(^3))</th>
<th>%–1 mm (model)</th>
<th>%–1 mm (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Coal</td>
<td>746</td>
<td>43</td>
<td>38.1</td>
<td>465.5</td>
<td>8.2</td>
<td>17</td>
</tr>
<tr>
<td>2. Hornfled</td>
<td>122</td>
<td>2</td>
<td>2.81</td>
<td>197.23</td>
<td>1.43</td>
<td>2.3</td>
</tr>
<tr>
<td>3. Monzodiorite</td>
<td>573</td>
<td>6</td>
<td>6.05</td>
<td>944.6</td>
<td>6.4</td>
<td>11</td>
</tr>
<tr>
<td>4. Monzonite</td>
<td>301</td>
<td>3</td>
<td>29.3</td>
<td>631.8</td>
<td>4.6</td>
<td>5</td>
</tr>
<tr>
<td>5. Porphyre ore</td>
<td>1085</td>
<td>23</td>
<td>107</td>
<td>944.6</td>
<td>11.3</td>
<td>18</td>
</tr>
<tr>
<td>6. Hornblende Diorite</td>
<td>229</td>
<td>2</td>
<td>4.85</td>
<td>406.6</td>
<td>1.2</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 5 Descriptive parameters of case studies

<table>
<thead>
<tr>
<th>Case study</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quarry blast(^{13})</td>
<td>Open pit – Blast 2755S1(^{22})</td>
<td>Open pit – Blast 2875N11(^{22})</td>
</tr>
<tr>
<td>Explosive</td>
<td>Emulsion</td>
<td>Heavy ANFO</td>
<td>Heavy ANFO</td>
</tr>
<tr>
<td>Hole diameter (mm)</td>
<td>109</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>VOD (m s(^{-1}))</td>
<td>5345</td>
<td>5100</td>
<td>5100</td>
</tr>
<tr>
<td>Explosive density (kg m(^{-3}))</td>
<td>1150</td>
<td>1250</td>
<td>1250</td>
</tr>
<tr>
<td>Charge length (m)</td>
<td>11.3</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Burden × spacing × bench height (m)</td>
<td>3.6 × 4.2 × 13.5</td>
<td>6.5 × 6.5 × 16</td>
<td>7.0 × 7.0 × 16</td>
</tr>
<tr>
<td>Rock type</td>
<td>Foliated phyllite</td>
<td>Porphyre ore</td>
<td>Porphyre ore</td>
</tr>
<tr>
<td>( \sigma_c ) (MPa)</td>
<td>71 (parallel to foliations)</td>
<td>58</td>
<td>61</td>
</tr>
<tr>
<td>( T ) (MPa)</td>
<td>11.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>( \rho ) (kg m(^{-3}))</td>
<td>2700</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>( E_j ) (GPa)</td>
<td>30.0</td>
<td>37.0</td>
<td>37.0</td>
</tr>
</tbody>
</table>
particle collisions and degradation of the rock material from loading, handling, transportation, and dumping.

In cases 2 and 3, differences between predicted and measured \( f_c \) values of 3.4% and 5.1% may be perceived as gross underestimations of the proposed model. However, the friable nature of the complex porphyry ore was expected to be subject to further degradation from loading, handling, and dumping prior to crushing. This susceptibility to degradation was confirmed by the measured differences between the primary crusher product and SAG mill feed fragmentation. This difference was of the order of 5–8% for the \(-1\) mm size fraction in the N11 and S1 domains, respectively.\(^{22}\)

Figure 3 shows a comparison between the predicted and measured fines, highlighting the 10% and 20% passing fractions. A parity chart of measured versus modelled cumulative percentage passing for fragments in the range of 1–63 mm is also included. It should be noted that, in all cases, the fines uniformity index \((f_O)\) and the subsequent modelled distribution of fines was determined with the measured post-blast mean fragment size \(x_{50}\). This was considered adequate in order to assess the validity of the hypothesis proposing that a single index of uniformity can be used to describe adequately the distribution of fragments from 1 mm through to the expected post-blast mean fragment size \(x_{50}\).

### Table 6  Comparison between modelled and measured fines inflection point values for three full scale blasts

<table>
<thead>
<tr>
<th>Case study</th>
<th>( r_c ) (mm)</th>
<th>Number of cracks (C)</th>
<th>Volume crushed ( V_c ) (m(^3))</th>
<th>Blast volume (m(^3))</th>
<th>Fines inflection point</th>
<th>% –1 mm (model)</th>
<th>% –1 mm (measured)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarry blast</td>
<td>240</td>
<td>5</td>
<td>8.36</td>
<td>202.95</td>
<td>4.1</td>
<td>4.9</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Blast 2755S1</td>
<td>606</td>
<td>8</td>
<td>54.2</td>
<td>676</td>
<td>8.0</td>
<td>11.4*</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Blast 2875N11</td>
<td>592</td>
<td>8</td>
<td>60.2</td>
<td>833</td>
<td>7.2</td>
<td>12.3*</td>
<td>5.1</td>
<td></td>
</tr>
</tbody>
</table>

*Primary crusher product (belt cut sampling).

### Table 6  Comparison between modelled and measured fines inflection point values for three full scale blasts

<table>
<thead>
<tr>
<th>Case study</th>
<th>P10 (mm)</th>
<th>Difference (mm)</th>
<th>% Error</th>
<th>P20 (mm)</th>
<th>Difference (mm)</th>
<th>% Error</th>
<th>Model Measured</th>
<th>Model Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarry blast</td>
<td>4.5</td>
<td>4</td>
<td>-0.5</td>
<td>12.5</td>
<td>15.5</td>
<td>13*</td>
<td>-2.5</td>
<td>-19.2</td>
</tr>
<tr>
<td>Blast 2755S1</td>
<td>1.7</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>8.5</td>
<td>9.8</td>
<td>1.3</td>
<td>13.3</td>
</tr>
<tr>
<td>Blast 2875N11</td>
<td>2.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>9.5</td>
<td>11*</td>
<td>1.5</td>
<td>13.6</td>
</tr>
</tbody>
</table>

*Laboratory sieving; *calibrated SPLIT image analysis system.
As shown in Figure 3, the proposed fragment size distribution function appears to be an adequate descriptor of the expected distribution of fines generated in full-scale blasting conditions. The parity chart shows that although the model may in some cases underestimate and overestimate the proportion of fines generated by blasting, overall trends are being captured by this single uniformity index. In terms of the predictive errors associated with specific size fractions such as P10 and P20, for case 1, the error is of the order of –12.5% and –19.2%, respectively, whilst for cases 2 and 3, the average predictive error for P20 is about 13.5%. This is considered adequate for engineering design purposes given the expected variability of rock material and explosive performance within the blasted volume.

Whilst the above cases support the hypothesis that in full-scale blasting conditions the use of a single index of uniformity is appropriate to describe the distribution of fragments from the fines inflection point \((f_c)\) to the mean fragment size \((x_{50})\). Recent large-scale field trials conducted in more massive and competent rock masses have shown that an approach based on a single uniformity value may produce an overestimation of the proportion of fines, particularly in the range of 10–100 mm. Results from sieved muckpiles under these environments have shown that in the fines region there could be at least two marked changes in uniformity which describe the natural breakage characteristics of the rock material. A preliminary comparison of these data with the proposed fines distribution function has confirmed this. However, it is important to highlight that for the repeatable documented cases, the proposed star-shaped crushed model was able to estimate the fines inflection point \((f_c)\) adequately. Further work is being conducted to address the above limitation and refine the overall predictive capabilities of the model.

APPLICATION OF THE PROPOSED FRAGMENTATION MODELLING FRAMEWORK

To demonstrate the practical application of the proposed fragmentation modelling framework, fragmentation distributions for two blasts have been modelled and used as input to processing simulations. This cross-disciplinary modelling work was aimed at assessing the impact of blast fragmentation on the overall production of fines in a hard rock quarry. The analysis focused on quantifying the relative contribution of blasting to the total production of fines or waste material and it is based on conditions found at the Mount Cootha Quarry summarised in Table 1 and documented by Kojovic et al.

Quarry processing simulations were conducted following two specific requirements. The first related to the production of fine aggregates (product range, 18 mm to 2.4 mm), with waste considered to be any material less than 2.4 mm. This required the implementation of three stages of crushing similar to that illustrated in Figure 4. The second simulation considered the production of coarser aggregates (product range 32 mm to 10 mm), with waste considered to be any material less than 10 mm. This required the implementation of only two stages of crushing.

Table 7 describes the blast design parameters adopted in this modelling exercise. Geotechnical properties measured at the Mount Cootha Quarry are described in Table 1. Results of the expected muckpile

Table 7 Blast design parameters for simulated conditions

<table>
<thead>
<tr>
<th></th>
<th>Blast 1</th>
<th>Blast 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosive</td>
<td>Emulsion</td>
<td>Emulsion</td>
</tr>
<tr>
<td>Hole diameter (mm)</td>
<td>109</td>
<td>109</td>
</tr>
<tr>
<td>Detonation velocity (m s(^{-1}))</td>
<td>4968</td>
<td>4968</td>
</tr>
<tr>
<td>Explosive density (kg m(^{-3}))</td>
<td>1180</td>
<td>1180</td>
</tr>
<tr>
<td>Charge length (m)</td>
<td>11.3</td>
<td>11.3</td>
</tr>
<tr>
<td>Burden × spacing × bench height (m)</td>
<td>3.6 × 4.2 × 13.5</td>
<td>3.0 × 3.5 × 13.5</td>
</tr>
<tr>
<td>Powder factor (kg m(^{-3}))</td>
<td>0.61</td>
<td>0.88</td>
</tr>
</tbody>
</table>

4 Example of a three stage crushing circuit at the Mount Cootha quarry (after Kojovic et al.18)
fragmentation distributions given by the proposed fragmentation modelling framework are shown in Figure 5.

As discussed earlier, the results of the blast fragmentation model shown in Figure 5 have been used as input into two quarry processing simulation options using the JKSimMet program. This program has been developed from extensive JKMRC experience in the field of comminution and has now become an industry standard tool for design and optimisation of mineral processing activities. A summary of the simulation results for both blasting scenarios and the two processing options are shown in Table 8 and Figures 6 and 7.

The application of the proposed fines modelling framework in conjunction with quarry processing simulation models have shown that any increase in the proportion of fines generated during the blasting process does not translate directly into an equivalent increase in the amount of fines or waste product downstream (i.e. after crushing). This is because a significant proportion of fines may be generated during the crushing stages of the production of the required products.

As shown in Figure 6, the impact of crushing on fines (waste) generation is more pronounced in the finer quarry processing circuit, where three stages of crushing are required. The amount of fines generated in crushing is about 1.6–2.6 times of that produced by blasting for blasts 2 and 1, respectively. In the coarser processing circuit (Fig. 7), fines generated from blasting have a more significant contribution to the total production of waste material. As shown, the amount of fines produced in crushing are about 0.8–1.3 times of that produced by blasting for blasts 2 and 1, respectively.

The analysis shows that in both cases, less crushing requirements due to an overall increase in fragmentation contribute to a decrease in the specific crushing energy and hence a reduction in power consumption requirements. This suggests that, in the case where finer aggregate products are required, the environmental and cost benefits of decreased power consumption must be weighed against the penalty of increasing the amount of fines generated after processing. As shown in Figure 6, a 2.7% increase in the amount of fines due to the higher intensity blast translates only to a 1% increase in the total amount of waste, but at the same time a 4% reduction in the power consumption requirements. For the coarse

<table>
<thead>
<tr>
<th>Table 8 Processing simulation results</th>
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<tbody>
<tr>
<td>Processing method</td>
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<tr>
<td></td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>Blasting scenario</td>
</tr>
<tr>
<td>ROM P80 (mm)</td>
</tr>
<tr>
<td>ROM –2.4 mm (%)</td>
</tr>
<tr>
<td>ROM –10 mm (%)</td>
</tr>
<tr>
<td>PCP P80 (mm)</td>
</tr>
<tr>
<td>PCP –10 mm (%)</td>
</tr>
<tr>
<td>PCP –2.4 mm (%)</td>
</tr>
<tr>
<td>Primary crusher (kW)</td>
</tr>
<tr>
<td>SCP P80 (mm)</td>
</tr>
<tr>
<td>SCP –10 mm (%)</td>
</tr>
<tr>
<td>SCP –2.4 mm (%)</td>
</tr>
<tr>
<td>SCP, secondary crusher (kW)</td>
</tr>
<tr>
<td>Secondary crusher (kW)</td>
</tr>
<tr>
<td>Total (kWh t⁻¹)</td>
</tr>
<tr>
<td>ROM, run-of-mine; PCP, primary crusher product SCP, secondary crusher product.</td>
</tr>
</tbody>
</table>

5 Modelled fragmentation distributions for blast 1 and blast 2

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aggregate production option (Fig. 7), higher intensity blasting results in a 2.1% increase in waste product but a 6% reduction in power consumption. Because of the finer fragmentation in blast 2, there would be an increase in loading and hauling productivity which has not been quantified in this paper. It is important to add that this will have an impact on the total cost of production as documented by Kojovic et al.18

CONCLUSIONS
An engineering approach to predict the proportion of fines generated during blasting has been presented. The improved ‘hybrid’ approach introduces a new model to predict the potential volume of crushed material resulting from the crushing and shearing stages of blasting. Other sources of fines including liberation of infilling from discontinuities, particle collisions and post-blast processes have been excluded to simplify the modelling process.

Based on the back analysis of a number of full-scale blasting surveys, this study has confirmed that upon detonation of an explosive, the region of crushing around a blasthole is not the only source of fines. This has justified the inclusion of a factor that considers the contribution to fines by the overall fracturing process.

The overall modelling framework has been validated with three distinct case studies. Results from this analysis have shown that there is good agreement between model predictions and the measured distribution of fines, verifying the hypothesis that a
single index of uniformity can be used to describe the
distribution of fragments in the range of 1 mm
through to the expected post-blast mean fragment size
\( (x_m) \). Some limitations have been noted, particularly
with regards to the possible overestimation of fines in
more massive and competent rock types. However, the
approach appears to provide useful approximations for
continuous improvement analysis and engineering
applications. Further work is continuing to identify
other possible limitations and thus improve the
framework’s predictive capability.

The practical application of the current framework
has been demonstrated with a cross-disciplinary
modelling study. The study was aimed at assessing the
impact of blast fragmentation on the overall
production of fines in a hard rock quarry. Results have
indicated that any increase in the proportion of fines
generated during the blasting process does not
translate directly into an equivalent increase in the
amount of fines or waste product downstream (i.e.
after crushing). This is because a significant
proportion of fines may be generated during the
crushing stages of the production of the required
products. The impact of blasting will depend on the
final product requirements. Further analysis also
showed that less crushing requirements due to an
overall increase in fragmentation contribute to a
decrease in the specific crushing energy and hence a
reduction in power consumption requirements.

The application case study has helped demonstrate
the importance of addressing the impact of blast
fragmentation distribution on overall quarry
productivity requirements. This highlights the
importance of adopting a holistic approach when
addressing the blast optimisation problem and the key
role that engineering modelling tools, such as those
proposed in this paper, can play in this process.

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