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Research Article

Rock Fragmentation Evaluation towards Blast-To-Mill Concept of Blast Optimization in Hard Rock Mines

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Abstract

Traditional blast optimisation studies ensure efficient mining operation but ignore potential impact of blasting on primary crushing. The performance of the primary crusher is key to the ore beneficiation process. Optimisation studies conducted through the mining operations to the comminution circuit is vital to the mine-to-mill concepts in the mining industry. In this approach, an innovative approach to the assessment of in-situ blasting is proposed and evaluated. This approach focuses on the acceptability of rock fragments on the Run-of-Mine (ROM) pad as opposed to the pits. Fragmentation analysis was conducted in the pit and on the ROM pad. A correlation efficiency of 0.92 was realized between the measured rock fragments in the pit and that on the ROM pad. About 10% of the rock fragments in the pit were classified as boulders while about 30% of the same rock fragments deposited on the ROM pad were classified as boulders. However, about 30% of the rockpile on the ROM pad was estimated to be lower than the Close Side Setting (CSS) of the primary crusher. It is recommended that future research evaluates the energy consumption and its related cost at the primary crusher in comparison to in-pit fragmentation and mucking cost performance.

Introduction

Drilling and blasting operation is one of the most critical activities that affect production in hard rock mining. Extensive production of boulders and fines associated with in-situ blasting are the main challenges of hard rock mining. Poor blast outputs considerably affect downstream operations including loading, hauling, crushing, and processing. Blast optimization strategies have often been used to find the optimum rock fragment sizes that reduce the quantity of boulders, toes/humps, and excessive fines produced to maximize the performance of the mining operations. Boulders and toes disrupt loading/mucking and the smooth operation of the primary crusher while excessing fines increases the loading time of the loader. These optimization strategies focus on minimizing total mining cost, toes/humps formation and boulders, maximizing the performance of in-pit loading and hauling, and maintaining Run-of-Mine (ROM) fragmentation characteristics [1-3]. Traditional blast optimisation studies focus on the efficiency of mining operations (drilling, blasting, loading and hauling activities) but often ignore the potential impacts on primary crushing. The primary crusher is the first stage of the comminution process at the processing plant. The performance of this primary crusher is significant to the ore beneficiation process. Optimizing blasts to increase the performance of the crushing and grinding operations will enhance the overall efficiency and profitability of the mine. Assessment of a blast on the performance of the primary crushing as part of the blast optimization strategy is an added step to the blast-to-mill concepts of the fragmentation process of hard rock mining. The blast-to-mill concept of fragmentation is the total appreciation of ensuring the achievement of optimal benefits from in-situ rock blasting on surface mining benches or in underground mining stopes through the various mining operations to the comminution process.

This paper evaluates the fragmentation of in-situ rock blasting, and further introduces a unique approach to evaluate rock fragmentation on the ROM pad and the impact of rock fragmentation on the performance of the primary crusher. Traditionally, blast performance assessment in terms of fragmentation analysis have always been done in the pit or stope and not on the ROM pad. This paper presents an innovative way of assessing rock fragmentation from in-pit blasting to the mill. The importance of blast optimization to the mine-to-mill concept of the extractive industry has also been discussed. Data was obtained from an open pit hard rock gold mine to validate the proposed options. The next section of this research paper discusses blast optimization with highlights on fragmentation analysis and downstream effect of blasting. Section 3 describes the materials and method used for the study with explanation on the data collection procedure and rock fragmentation assessment. Section 4 provides the results and discussions of rock fragmentation analysis and its performance in the pit, on the ROM pad and on primary crushing while Section 5 documents the research conclusions and recommendations.

Summary of Literature Review on Blast Optimization

Blasting is an important phase in the fragmentation process of hard rock mining. It constitutes the genesis of rock excavation and the principal element in optimum fragmentation and muckpile profiling. Two main factors, controllable and uncontrollable factors, influence every result or performance of a blast. In recent times, deterministic factors have also been defined [2,4]. Controllable factors are parameters which engineering, and bench crew can exercise control and balance them to achieve the desired results. Controllable factors are grouped into geometric parameters (bench and blast geometry such as drillhole diameter, burden, sub-drill, bench height); physicochemical parameters (including type of explosive, powder factor, strength of explosive, primer); and time parameters (such as type of initiation and detonation systems, initiation sequence of the blast). Uncontrollable factors are those geological parameters that define the properties and structures of the in-situ rock formation. Uncontrollable factors include fissures, faults, fractures, joint planes, cavities and mud-seams, compressive and tensile strengths, density and porosity. The blaster has no direct control on these uncontrollable factors. Deterministic factors are external parameters that directly and/or indirectly influence the design and performance of a blast. These deterministic factors include human influences, technical knowledge of professionals, environmental constraints, operational factors, and blast performance requirements. Optimizing a mine blast is greatly influenced by the appreciation of these notable factors.

Blast fragmentation evaluation

Fragmentation analysis describes the group of methods and techniques used to measure, estimate, and characterize rock fragments of a blast. Fragmentation measurement mainly involves the quantification and characterisation of the size distribution of rock fragments of a muckpile. Models and formulae are available in estimating and characterizing the size distribution of blasted rocks. The characteristics of these fragments are very important due to their effect on the efficiency and cost of downstream processes including loading, hauling and processing [5]. Some of the measurement techniques employed in rock fragmentation analysis include sieving or screening, oversize boulder count method, explosive consumption in secondary blasting method, shovel loading rate method, bridging delays at the crusher method, visual analysis method, photographic or manual analysis method, conventional and high-speed photogrammetric method and high-speed photography or image analysis method. Descriptions of these techniques have been discussed [6-9]. Recently, high speed photography or digital images processing and analysis systems have emerged with the advancement in technology and are increasingly becoming popular in fragmentation measurements [10]. The prediction of rock fragmentation with blast optimization models is very common. A review of existing empirical and mechanistic models for predicting rock fragmentation in the mining industry have been discussed [4,11,12]. Some fragmentation models applicable to surface blasting operations include Artificial Neural Networks (ANN), Bond-Ram model, Chung and Katsabanis model, Crushed Zone Model (CZM), Energy Block Transition (EBT) model, Kou-Rustan equation, Kuz-Ram model, Kuznetsov–Cunningham–Ouchterlony (KCO) model, Larson model, Modified Kuz-Ram model, Rosin-Rammler model, Swedish Detonic Research Foundation (SveDeFO) model, and Two Component Model (TCM) [1-3,11-18].

Some of the formulae used to characterize the size distribution of rock fragmentation are the Rosin-Rammler uniformity index, uniformity or Hazen coefficient (Cu), and coefficient of gradation or coefficient of curvature (Cg). The Rosin-Rammler and uniformity expressions are respectively shown in Equations (1) and (2) have well been discussed [2,3,13,14,19]. The Rosin-Rammler uniformity index is mostly used to estimate the general size distribution of the blasted muckpile including fines. The uniformity index usually ranges between 0.7 (very non-uniform) and 2.0 (very uniform).

$$R_X = \exp\left[-0.693\left(\frac{X}{X_m}\right)^n\right] \quad (1)$$

$$n = \left(2.2 - \frac{14B}{d}\right)\sqrt{\left(\frac{1+{S}/{B}}{2}\right)}\left(1-\frac{W}{B}\right)\left(abs\left(\frac{BCL-CCL}{L}\right)+0.1\right)^{0.1}\frac{L}{H} \quad (2)$$

Where: R_x = mass fraction retained on screen opening x; n = uniformity index; B = burden (m); S = spacing (m); d = hole diameter (mm); W = standard deviation of drilling precision (m); L = charge length (m); BCL = bottom charge length (m); CCL = column charge length (m); H = bench height (m).

The uniformity index is a different measurement compared to work index. Uniformity index defines the measure of the particle size range, and it is used to determine whether the material (blasted muckpile) is uniformly graded or well graded, while work index is a measure of the blasted muckpile (ore) resistance to crushing and grinding. Work index is determined using Bond grindability test, a value used to establish the blasted muckpile (ore) characteristic usually used to design the comminution plants of the mine. The equations of the Uniformity Coefficient and the Coefficient of Gradation are respectively shown in Equations 3 and 4. The Uniformity Coefficient (Cu) defines the measure of the particle size range, and it is used to determine whether a material is uniformly graded or well graded. The Coefficient of Gradation (Cg) is a measure of the shape of the particle size curve. The Cu < 5 indicates a very uniform size distribution, Cu between 5 and 15 indicates the distribution is medium uniform while Cu > 15 indicates the distribution is non-uniform. Values of Cg from 1 to 3 indicate the distribution is well graded or desired.

$$C_u = \frac{D_{60}}{D_{10}} \quad (3)$$

$$C_g = \frac{D_{30}^2}{D_{60} \times D_{10}} \quad (4)$$

where: Dx = Fractional number of particle size above x% (x = 10, 30, and 60).

Downstream effect of blasting

There have been several discussions on blast optimization and the effect of blasting on downstream mining operations [7,10,20,21]. These operations are mainly loading or excavation or mucking, hauling, dewatering, drilling, and processing. However, the effect of blasting on the comminution process is the focus of this research study. Comminution is the term applied to the process by which the particle size of an ore stream is progressively reduced. It is the first step in processing the ore from the mine. Blasting is considered as the first stage of the comminution process on the mine field. Comminution takes place as a sequence of crushing and grinding processes. Crushing reduces the particle size of the Run-of-Mine (ROM) ore to a level that grinding can be carried out until the valuable mineral (e.g., gold) and gangue are substantially produced as separate particles. A primary crusher receives the run-of-mine ore after blasting and produces the first reduction in size after mine field blasting. The output of the primary crusher is fed through the grinding and milling process of the processing plant. An increase in the degree of fragmentation gives lower crushing costs as more material passes through as undersize. Liner costs, repair and maintenance, and bridging time will decrease, and the crushing rate will increase. One other major effect of blast performance which has become a major concern in the mining industry is the reduction in the stroke or throw of the primary crusher. Stroke of a crusher is the difference between the Open Side Setting (OSS) and the Close Side Setting (CSS). This increases the crushing time, reduces capacity and thereby affecting crusher throughput. This problem is more pronounced when boulders find their way through the grizzly due to their shape or the rock orientation upon arrival on the grizzly. Under severe conditions, crusher breakdown may occur which reduces crusher availability and thus affect crusher throughput [7].

Materials and Methods

Data collection

Mining operations of a gold mine was considered for four weeks and the major parameters influencing the blasting operations were carefully garnered for this research study. Details of the blasting operations have not been discussed in this paper but has been thoroughly described by Eshun et al. [10]. Drilling is done using Sandvik Panterra 1500i Drill Rigs. Production holes are marked out in staggered pattern to a specified depth with specific hole diameter drilled with button bits. The drill holes are mostly drilled with a 102 mm diameter bit at an angle of 90° for production blasting. A 250 g pentolite booster, an emulsion blend explosive of composition – 70% pure Emulsion and 30% Ammonium Nitrate Porous Prills (ANPP) are used for blasting in the mine. Ammonium Nitrate Fuel Oil (ANFO) explosives is only used in dry hole conditions. As an effort for improving the quality of blast fragmentation, the mine periodically conducts studies and evaluates the Velocity of Detonation (VOD) of the explosives and other key drilling and blasting parameters. Detailed description of the VOD studies has been discussed by Eshun et al. [10]. Due to the sporadic nature of blasting in the pit, the effect of data collection exercise on operational delays was undertaken timely, and the clarity of photographic images were ensured. To ensure the reliability and quality of the research findings, blurred photographs of blasted rocks in the pit and on the ROM pad for the fragmentation assessments were screened-off from the pool of data collected during the field study period. This reduced the total number of effective blasts to four.

Table 1 shows a summary of the collected data on the blasts used for this study. All the data were collected from blasting the same type of fresh rock (Tonalites and Dolerites) with density ranging from 2.5 g/cm^3 to 2.7 g/cm^3. Production blasting is restricted to fewer blastholes to minimize the blast impacts on neighbouring communities. Apart from Shot 3 which was a single-bench blast (hole depth of 6.0 m), all the blasts were conducted on double benching (hole depth of 9.0 m).

Table 1: Summary of results for each shot.

Drill and Blast Parameters	Shot 1	Shot 2	Shot 3	Shot 4
Burden (m)	4	4	3.4	4
Spacing (m)	4	4	3.4	4
Hole depth (m)	9	9	6	9
Drill hole diameter (mm)	115	115	115	115
Stemming height (m)	3.5	3.5	2	3.5
Meters Drilled (m)	792	765	960	855
No. of Blastholes	88	85	160	95
Explosive quantity (kg)	6 725	6 800	7 940	6 950
Powder factor (kg/m^3)	0.53	0.55	0.58	0.59
Total BCM	12,672.00	12,240.00	11,097.60	13,215.00

Several photographic images of the muckpile in different angles of view (in regular grids) were carefully obtained to ensure a good representation of the entire muckpile. Photographic overlaps, which is a common error in fragmentation analyses studies, were avoided to prevent double processing of data. Similarly, after loading the top-flitch of the muckpile, series of different photographic images were again taken on the same muckpile to ensure good representation of rock fragments from the surface through to the bench floor. These images were obtained from the blasted rocks in the pit and the same blasted rocks dumped on the ROM pad. Samsung digital camera 14.2 M pixel and 5x optical zoom was used to capture these images. A measuring rule of 300 mm length was used as a standard for determining the scaling factor during the image capturing and processing. The education version of Split-Desktop 3.1 photographic analysis software was used for evaluating the rock fragments of the muckpile.

Assessment of rock fragmentation

The analyses of the captured photographs were carried out using single and combined image analyses methods. For the single image analysis method, the photographs of rock pile sample from 1 to 20 were independently analysed. A medium rated fine correction factor of 50% was used for images obtained in the pit. However, due to the dusty environment blurring the images obtained from the ROM pad, a fine correction factor of 70% was appropriately used during the fragmentation assessment. The single image analysis was conducted for all the images obtained from the pit and ROM pad for each blast. To obtain the optimum rock size fragmentation from a blast, all the images for each blast or muckpile were combined and analysed. This is the concept of the combined image analysis method of photographic evaluation of rock fragmentations. All images obtained from the pit for a blast was combined while images obtained from the ROM pad pertaining to that same blast shot was also combined separately. Images pertaining to the same blast shot but obtained separately from the pit and the ROM pad were later combined and analysed to obtain the fragmentation from each unique blast shot.

Results and Discussions

Fragmentation analysis

In this section, the evaluation of the blasted in-situ rocks in the pit and the Run-of-Min (ROM) pad have been discussed. The photographic imaging technology for assessing rock fragments was used for this research study.

Fragmentation analysis of blasted in-situ rocks in the pit

Sample results of photographic analytical process of the individual images from muckpiles in the pit and on the ROM pad, used for assessing the rock fragments are shown in Figures 1a-1d. The scaled, delineated, manually edited and the final output of the size distribution of the rock fragments as shown in Figures 1a-1d describe the process of the photographic analysis of the muckpiles from each blasting shot.

Figure 1a: Fragmented material and scaled object.

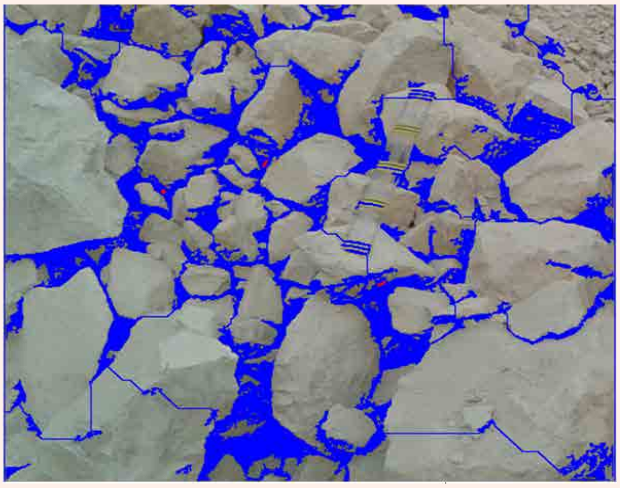


Figure 1b: Auto delineated image.

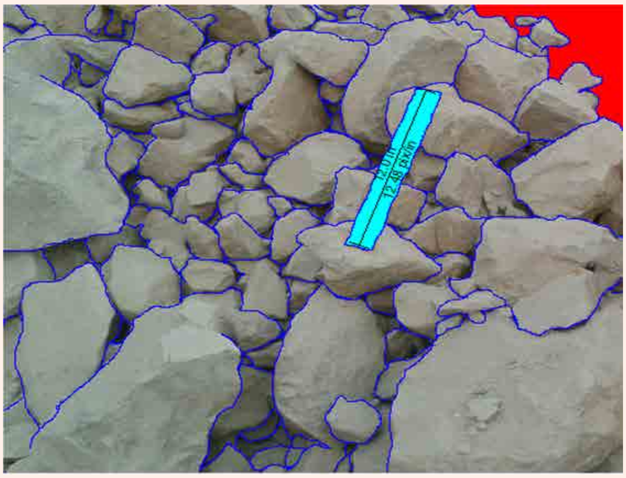
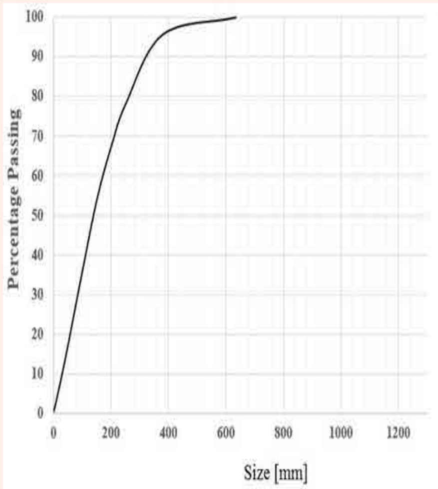


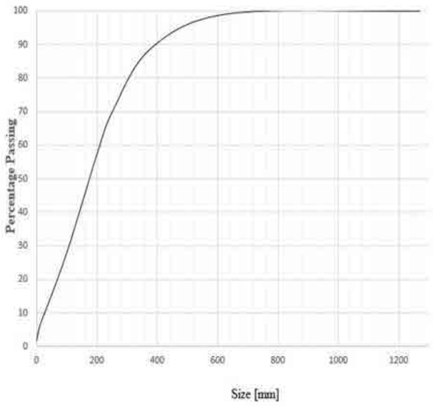
Figure 1c: Manually Edited Delineated Image.



Size (mm)	% Passing
635	100
381	95.7
254	78.56
203.2	67.87
152.4	54.31
101.6	36.21
50.8	17.23
25.4	8.29
19.05	6.16
12.7	4.07
9.53	3.04
6.35	2.03
4.75	1.53
2	0.66
% Passing	**Size (mm)**
F10	30.39
F30	85.49
F60	171.43
Top Size (99.95%)	456.4
RosRam Uniformity	1.31

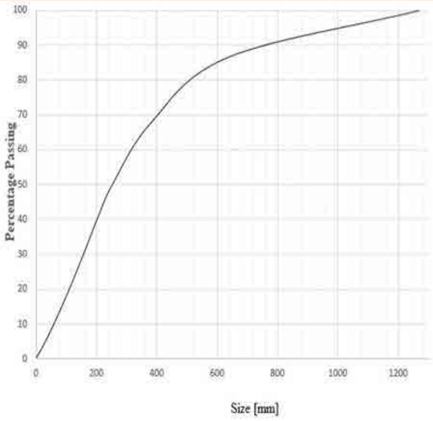
Figure 1d: Output Results of Analysis

The blast performance assessment of the size distribution of the rock fragments from each blasting shot is shown in Figures 2-5. According to mine management, a good blast performance is realised when percentage boulders in the blast are about 10% or lower, and about 90% of the blasted material passes through the grizzly size of 650 mm. In Figures 2-5, the average rock fragment sizes corresponding to 10%, 30%, and 60% of the quantity of the measured rocks are indicated as F10, F30, and F60 respectively. Similarly, the Rosin-Ramler uniformity index for the muckpile of each blasted shot is also indicated on Figures 2-5.



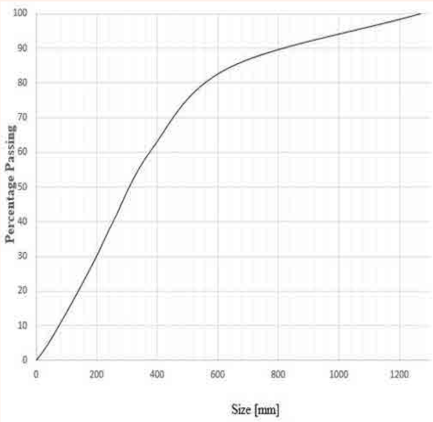
Size (mm)	% Passing
1270	100
635	99.16
381	89
254	70.41
203.2	57.97
152.4	42.96
101.6	28.16
50.8	15.51
25.4	9.64
19.05	8.13
12.7	6.54
9.53	5.54
6.35	4.26
4.75	3.54
2	2.07
% Passing	**Size (mm)**
F10	26.95
F30	108.41
F60	210.75
Top Size (99.95%)	697.39
RosRam Uniformity	1.19

Figure 2: Output results of Shot 1.



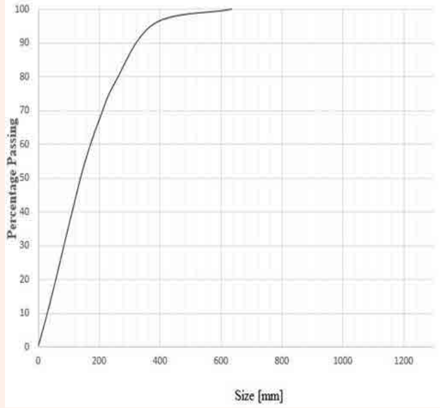
Size (mm)	% Passing
1270	100
635	86.5
381	67.74
254	50.1
203.2	40.08
152.4	28.83
101.6	18.13
50.8	8.35
25.4	3.96
19.05	2.93
12.7	1.94
9.53	1.46
6.35	0.99
4.75	0.75
2	0.34
% Passing	**Size (mm)**
F10	59.8
F30	157.67
F60	316.81
Top Size (99.95%)	1187.62
RosRam Uniformity	1.25

Figure 3: Output results of Shot 2.



Size (mm)	% Passing
1270	100
635	84.32
381	60.75
254	39.88
203.2	30.59
152.4	22.1
101.6	14.03
50.8	6.35
25.4	2.94
19.05	2.16
12.7	1.4
9.53	1.04
6.35	0.68
4.75	0.51
2	0.22
% Passing	**Size (mm)**
F10	75.69
F30	199.86
F60	375.31
Top Size (99.95%)	1155.08
RosRam Uniformity	1.37

Figure 4: Output results of Shot 3.

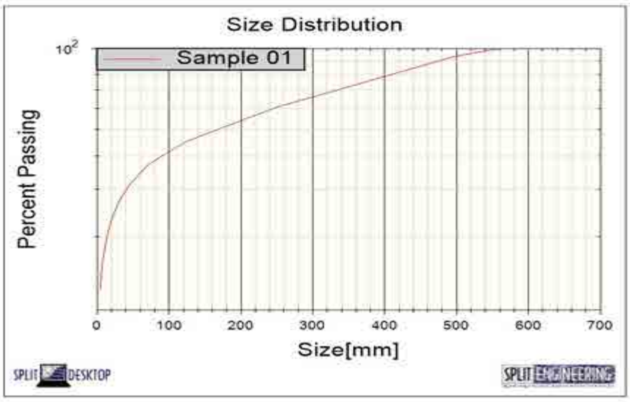


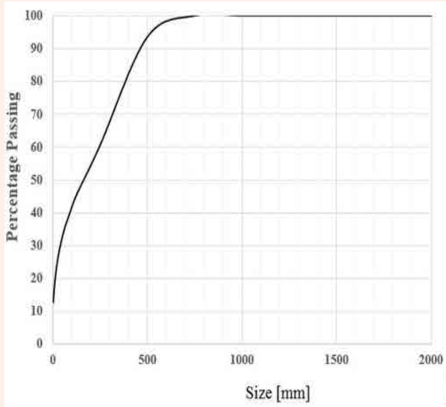
Size (mm)	% Passing
635	100
381	95.7
254	78.56
203.2	67.87
152.4	54.31
101.6	36.21
50.8	17.23
25.4	8.29
19.05	6.16
12.7	4.07
9.53	3.04
6.35	2.03
4.75	1.53
2	0.66
% Passing	**Size (mm)**
F10	30.39
F30	85.49
F60	171.43
Top Size (99.95%)	456.4
RosRam Uniformity	1.31

Figure 5: Output results of Shot 4.

Analysis of ROM pad material

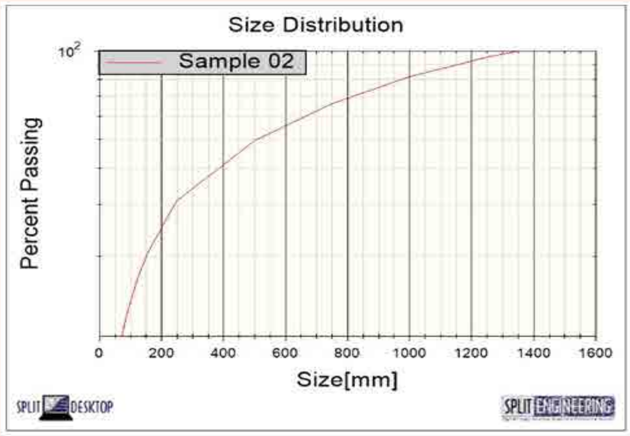
The image analysis process and assessment procedure for the pit muckpile was repeated on images of blasted rocks obtained from the ROM pad. Similarly, a single and combined image analyses were carried out with Split-Desktop software. Since the cumulative size obtained by individual images cannot be used to assess the fragmentation of the rock sizes of the entire ROM pad material, the concept of the combined image analysis method of fragmentation analysis was again used to obtain the optimum rock sizes of the entire rock material on the ROM pad. Figures 6-9 show the fragmentation analysis results of the corresponding blasts measured on the ROM pad.





Size (mm)	% Passing
2000	100
1750	100
1500	100
1250	100
1000	100
750	100
500	93.48
250	60.43
125	45.28
88	39.4
63	35.22
44	30.89
31	27.18
22	23.96
16	21.31
11	18.56
7.8	16.34
5.5	14.36
4	12.76
RosRam Uniformity	0.64

Figure 6: Output results of Shot 1.



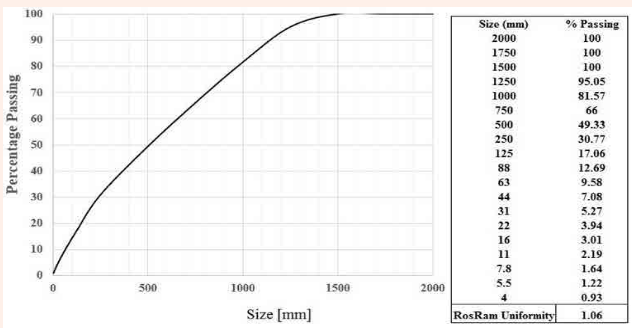
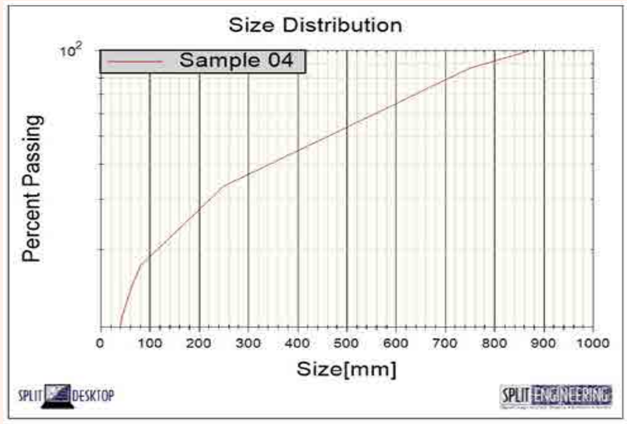


Figure 7: Output results of Shot 2.



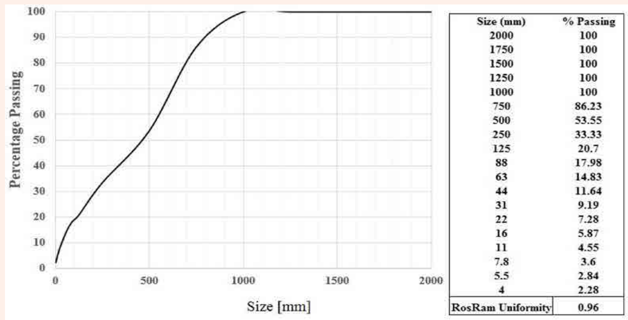
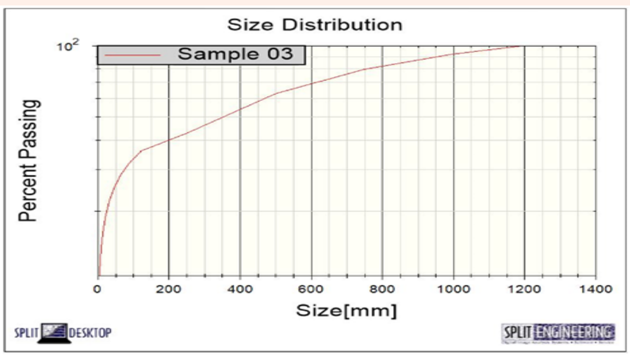


Figure 9: Output results of Shot 4



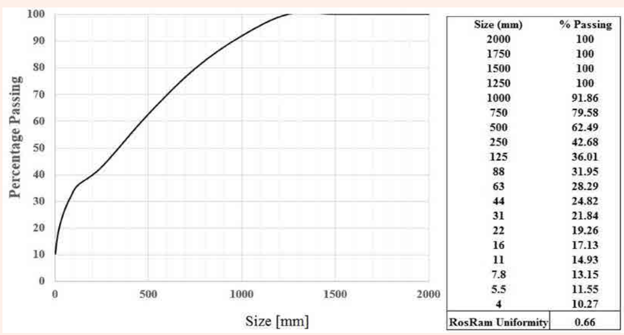


Figure 8: Output results of Shot 3.

Performance evaluation of blast and primary crushing

Blasting results are measured by the performance of downstream processes including loading, hauling, and ultimately the performance of the primary crusher [22,23]. The performance of the primary crusher is also the focus of this research study. Based on the size of the grizzly, the primary crusher installed at the mine accepts a feed of maximum size 650 mm before the rocks are reduced or crushed down below the Close Side Setting (CSS) or gape of 150 mm.

Blast performance assessment in the pit

The blast fragmentation analyses for Shots 1, 2, 3 and 4 respectively indicate that about 42%, 28%, 22%, and 53% of the rock fragments are less than the 150 mm. Thus, these percentages of the rock fragments from each blast shot do not require crushing and will freely pass through the CSS of the primary crusher without being crushed. Table 2 is a summary of the analysed in-situ rock fragmentation results in the pit.

Table 2: Blast performance in the pit based on mine requirement.

Blast	Material (%) < 150 mm	Material (%) ≤ 650 mm	Material (%) > 650 mm	Remarks
Shot 1	42.26	99.18	0.82	Good Blast Performance
Shot 2	28.32	86.82	13.18	Poor Blast Performance
Shot 3	21.72	84.69	15.31	Poor Blast Performance
Shot 4	53.45	100	0	Excellent Performance
Combined	32.1	90.12	9.88	Good Blast Performance

From Table 2, about 32% of the blast fragments in the mine would not require crushing by the primary crusher. The jaws of the primary crusher will do no work on the 32% of the blasted rocks fed into it when it constantly swings with the attempt to reduce the size of the rock fragments. Based on this study, the total Bank Cubic Metre (BCM) for all the four blasts is 49,224.6 m3. It can be deduced that, about 32% of energy consumption of the primary crusher, corresponding to about 17,700 m3 of rock material fed into the primary crusher is lost to no work done. Analyses of the data also shows that about 57%, 59%, 63%, and 47% of blasted rocks respectively from Shots 1, 2, 3 and 4 had rock fragment sizes ranging from 150 mm to 650 mm. Thus, the primary crusher would be engaged to averagely crush about 56% of the blasted rocks fed into it. The remaining 1%, 13%, and 15% of the blasted rocks respectively from Shots 1, 2, and 3 constitute boulders, since they measured above 650 mm. No boulder was photographically measured for Shot 4. The boulders detected during the study period were either screened-off by the grizzly during the feeding process or passed through the grizzly, thereby, blocking the jaw of the crusher. The rock boulders that were screened-off by the grizzly were further reduced into smaller rock fragments using the rock breaker.

From the results shown in Table 2 and the afore discussions, it can be deduced that Shot 4 demonstrated an excellent blast performance with about 100% of all the blasted rock not containing any boulder. The blast performance is followed by Shot 1 which demonstrated a good blast performance with about 99% of blasted rocks within the accepted feed size of the crusher and boulders (1%) above the mine's maximum allowable boulder count of 10% for any blast. Shots 2 and 3 exceeded the allowable boulder count of 10% and therefore demonstrated poor blast performance. Figure 10 is the fragmentation profile of the overall blast output in the pit. The overall output results of the entire muckpile indicate that 32.1% are less than 150 mm, 32.1% to 90.1% are less than or equal to 650 mm and 9.9% are greater than 650 mm. From the combined analyses, the overall blast in the mine has a good blast performance.

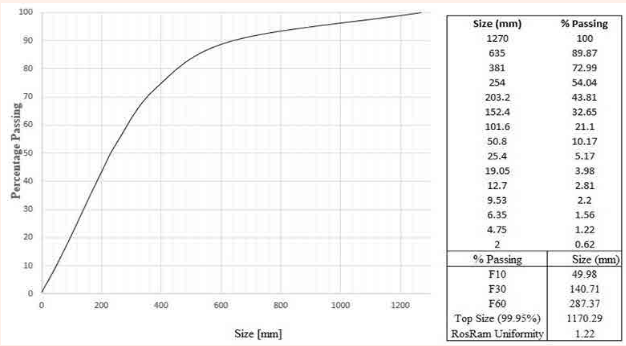


Figure 10: Blast fragmentation profile in the pit.s of Shot 3.

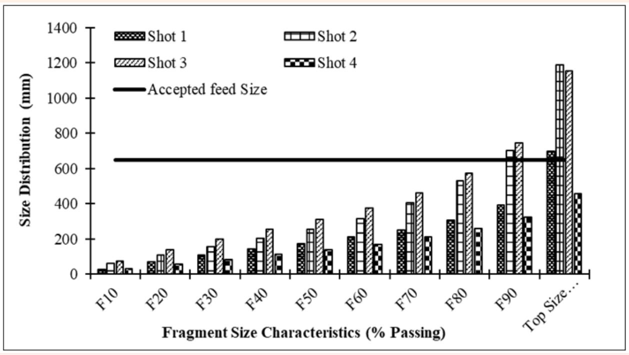


Figure 11: Comparison of blast fragmentation characteristics in the pit

The output results of all the four shots for fragment size characteristics were also compared and shown in Figure 11. About 80% of particle sizes (rock fragments) of all the shots under study were below the accepted feed size of the crusher installed at the mine compared to the expected 90%.

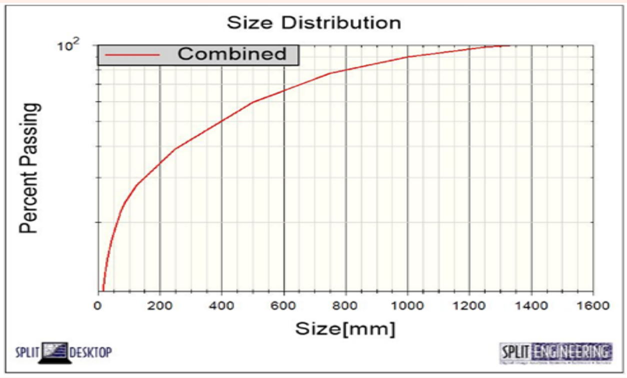
To further assess the blast performance of the gold mine, the uniformity index, uniformity coefficient, and coefficient of gradation were computed and analysed. Table 3 shows a summary of the analysed blast performance based on the uniformity index, uniformity coefficient and coefficient of gradation of the fragmentation of the blasted in-situ rock. From Table 3, all the rock fragments resulting from the blasts were non-uniform but well graded. However, based on the uniformity coefficient, Shot 3 was very uniform while Shots 1, 2, and 4 were medium uniform. It can therefore be concluded that, Shot 3 demonstrated a good blast performance when compared to the rest of the shots based on the uniformity index, uniformity coefficient, and coefficient of gradation.

Table 3: Blast performance in the pit based on rock fragments distribution.

Blast	Uniformity Index	Remarks	Uniformity Coefficient	Remarks	Coefficient of Gradation	Remarks
Shot 1	1.19	Non-uniform	7.82	Medium uniform	2.07	Well graded
Shot 2	1.25	Non-uniform	5.3	Medium uniform	1.31	Well graded
Shot 3	1.37	Non-uniform	4.96	Very uniform	1.41	Well graded
Shot 4	1.31	Non-uniform	5.64	Medium uniform	1.4	Well graded
Overall Blast	1.22	Non-uniform	5.75	Medium uniform	1.38	Well graded

Blast performance assessment on the ROM pad

The blast performance profile of the muckpile on the ROM pad is shown in Figure 12. The fragmentation analysis of the blast material at the ROM pad indicates that about 30% of the material to be fed to the primary crusher are less than 150 mm compared to 32% of the muckpile analysis in the pit; 30% to 70% are less than or equal to 650 mm compared to the 32% to 90% of the muckpile analysis in the pit; and 30% greater than 650 mm compared to 9.9% of the muckpile analysis in the pit. The muckpile on the ROM pad has been evaluated based on the uniformity index, uniformity coefficient, and coefficient of gradation and the results are shown in Table 4.



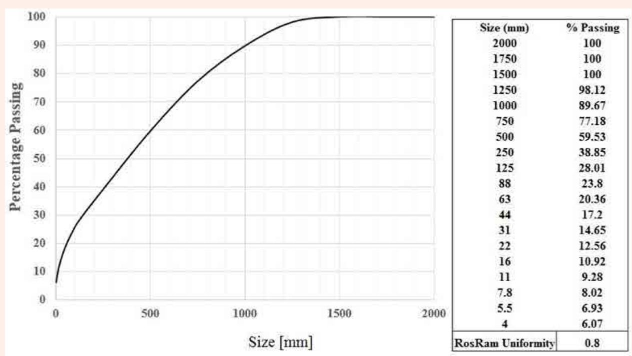


Figure 12: Blast performance profile on the ROM pad.

Table 4: Blast performance on the ROM pad based on distribution of rock fragments.

Blast	Uniformity Index	Remarks	Uniformity Coefficient	Remarks	Coefficient of Gradation	Remarks
Shot 1	0.64	Very non-uniform	119.14	Non-uniform	3.23	Not well graded
Shot 2	1.06	Non-uniform	10.15	Medium uniform	1.33	Well graded
Shot 3	0.66	Very non-uniform	125.24	Non-uniform	3.16	Not well graded
Shot 4	0.96	Non-uniform	15.68	Non-uniform	2.47	Well graded
Overall Blast	0.8	Non-uniform	38.77	Non-uniform	3.35	Not well graded

Comparison of blast performance in the pit and on the ROM pad:

Table 5 shows a summary of the analysed rock fragment size distribution of the in-pit muckpile and rockpile on the ROM pad. The comparative analysis shows that the estimation of size ranges < 150 mm was fairly the same for both the pit muckpile and rockpile on the ROM pad but very different for the other size ranges. The inconsistency in the measured values may have been caused by the exposure of the boulders hidden within the in-pit muckpile which appeared on the surface of the rockpile when dumped on the ROM pad. Thus, boulders were observed on the ROM pad but not in the pit; a very rare information to the miner on the field. The comparable size ranges < 150 mm indicates that, there is a minimal interference of airborne dust particulates present on the ROM pad on photographic analysis of rock fragments. In this study, the interference can be valued at 5.8%.

Table 5: Comparative analysis of blast performance in the pit and on the ROM pad.

Size range	Muckpile in Pit (%)	ROM Pad Material (%)
< 150 mm	32.1	30.25
Average (150 mm to 650 mm)	90.12	70.12
> 650 mm	9.88	29.88

The correlation plot between the photographic size estimations of the rock fragments measured in the pit and on the ROM pad is shown in Figure 13. The correlation coefficient of 0.92 indicates a strong correlation between the estimated rock fragments in the pit and on the ROM pad.

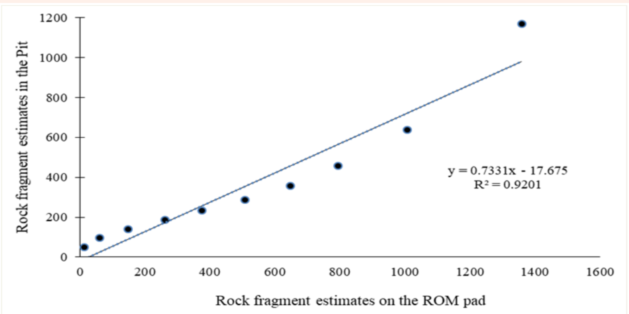


Figure 13: Correlation analysis of rock fragment estimates in the pit and on the ROM.

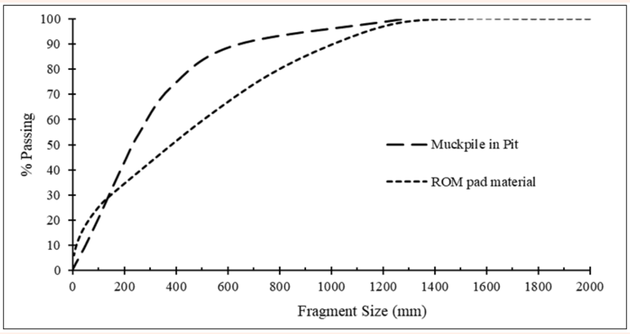


Figure 14: Size distribution curve of rock fragment estimates in the pit and on the ROM pad.

The estimated size distribution of the rock fragments in the pit and on the ROM pad are shown in Figure 14. In Figure 14, the shape of the size distribution of the rock fragments measured in the pit is different from that measured on the ROM pad. From the plot in Figure14, the shape of the size distribution of the rock fragments in the pit rises sharply at smaller size fragments of the rocks before flattening at the maximum rock fragment size. However, the plot of the rock fragments on the ROM pad shown in Figure 14 rises steadily to the same maximum fragment size. The rock fragmentation in the pit was estimated as smaller sizes while that on the ROM pad was widely spread.

Figure 15 shows the characteristics of the estimated size distribution of the rock fragments of the muckpile in pit and rockpile on the ROM pad compared to the expected rock fragment size from the blast (size requirement for the primary crusher is at most 650 mm). From the in-pit estimations, about 90% of the muckpile were below the rock fragment size requirement for the primary crusher. However, the blasted rock measured on the ROM pad indicates that, about 70% of the rock fragments from the blast were below the desired rock fragment size for the primary crusher. The discrepancies in the measurements of the rock fragments from the same blast often cause a lot of contentions between miners and the processing team.

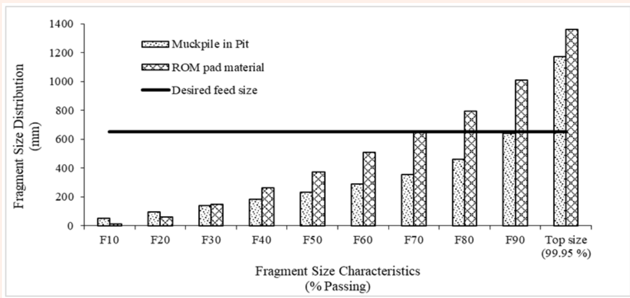


Figure 15: Size characteristics of rock fragment estimates in the pit and on the ROM pad.

Performance evaluation of blast on primary crusher

The performance of the primary crusher is evaluated based on the frequency and flow of rock movement on the ROM pad and the continuous crushing ability of the primary crusher. Rock material is fed into the primary crusher using the front-end loader. Operational delays of the front-end loader affect the continuous operation of the primary crusher. These delays occur when large rock fragments (boulders) are unable to pass through the grizzly to the primary crusher, reeling-off to the base of the mouth of the crusher and needs to be cleaned by the grader. The movement of the loader is reduced during the cleaning activity of the grader. Similarly, the inability of the loader to transport rock material from the ROM pad into the primary crusher due to the presence of boulders affect the operational time and hence, the continuous crushing activity of the primary crusher. It was observed that, the angle effect of the grizzly ensured that, near size rock fragments did not pass through it to bog the primary crusher.

A time-and-motion study was conducted on the operational movement of the loader in feeding the primary crusher on the ROM pad. The result of the study is shown in Table 6. With the known quantities of ore fed into the primary crusher (measured from a real time measuring device in the plant for each period), the productivity of the primary crusher was estimated. With a targeted primary crusher productivity of 580 tonnes per hour, an estimated average primary crusher productivity (or loader productivity) of 433.4 tonnes per hour was achieved within the study period. Thus, about 75% of the target for primary crushing is achieved, indicating an average lost productivity rate of approximately 25%. Figure 16 shows the productivity profile of the loader operation during the study period of the gold mine.

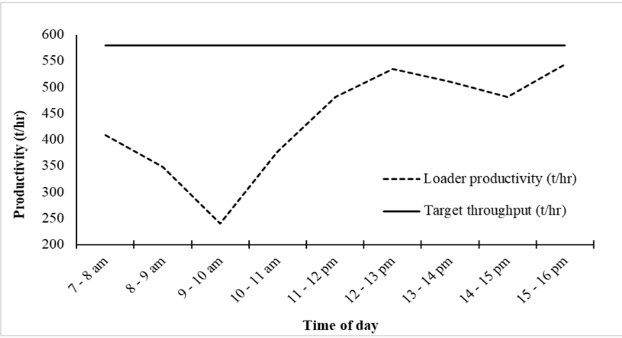


Figure 16: Loader productivity on the ROM pad of the gold mine.

The loader productivity profile for the study period indicates that the planned productivity of 580 tonnes per hour was not achieved and initial investigation shows that there were considerably high waiting times to allow the grader to clean-up the boulders and the rock breaker to reduce the boulders on the ROM pad. Although there were materials on the ROM pad, the loader could not work due to the relative number of boulders reported on the ROM pad and awaiting to be reduced and mucked. As discussed in Table 5, the estimated 29.9% boulders on the ROM pad might have increased the operational delays and hence affecting the productivity of the primary crusher. A regression analysis of the obtained data shown in Figure 17 was conducted with Minitab to evaluate the loader – crusher throughput productivity. From the regression model (Figure 17) of the obtained data (Table 6), the actual throughput of the crusher for the gold mine is related to the loader productivity by Equation 5.

$$Actual\,tones\left(t\right) = 34.85 + 0.8046 Loader\ productivity\left(\frac{t}{hr}\right) \quad (5)$$

Table 6: Average loader cycle time and productivity on the ROM pad during the study period.

Operational Time Period	Spot and Load (min)	Turn and Travel (min)	Dump Time (min)	Wait Time (min)	Total Cycle Time (hrs)	Quantity of Material Moved (t)	Loader Productivity (t/hr)
7 – 8 am	10.58	37.4	6.7	2.04	0.9453	387	409.38
8 – 9 am	8.64	30	5.21	7.01	0.8477	295	348.01
9 – 10 am	12.2	30.75	4.99	5.2	0.8857	216	240.04
10 – 11 am	11.42	35.78	7.34	3.71	0.9708	367.5	377.39
11 – 12 pm	10.48	31.8	7.81	2.18	0.8712	406	481.44
12 – 13 pm	12.99	34.46	6.76	2.24	0.9408	502	535.07
13 – 14 pm	10.02	32.87	5.78	3.85	0.8753	445	510
14 – 15 pm	12.49	32.05	5.93	3.6	0.9012	428	481.1
15 – 16 pm	8.31	31.34	4.82	3	0.7912	425.5	542.94

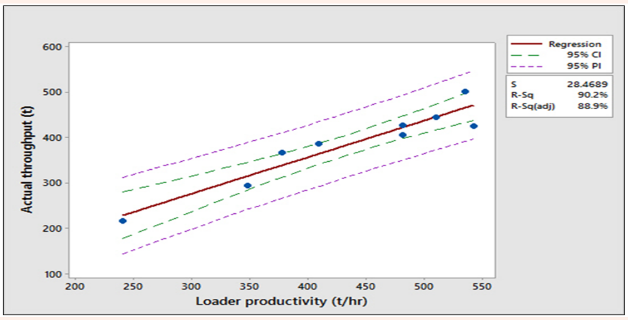


Figure 17: Regression analysis of the loader – crusher productivity on the ROM pad.

The regression plot shown in Figure 17 indicates that the model (regression equation) is a good fit for the obtained data. The results further indicate that at 95% Confidence Interval (CI), only one of the points lies outside the range of the confidence interval. The coefficient of determination of 90.2% also indicates that the actual throughput of the crusher corresponds well to the loader productivity. At 95% Confident Interval (CI), the regression model of the loader – crusher activities on the ROM pad will achieve at least 95% Prediction Interval (PI) for new observations.

Conclusion

Different photographic images of the blasted muckpile in different angles of view (in regular grids) of the muckpile for a good representation of the entire muckpile were carefully obtained for the fragmentation analysis. For the first time, fragmentation analysis was conducted on the same blasted rock in the pit and on the ROM pad. The analyses of the captured photographs were carried out using single and combined image analyses methods. The blasted rock in the pit and on the ROM pad after transportation from pit were further assessed with the empirical uniformity index, uniformity coefficient, and coefficient of gradation. The correlation of 0.92 was determined between the measured rock fragments in the pit and that on the ROM pad. Although the correlation was strong, there were minor discrepancies between the distribution curve of the fragmentation measurements in the pit and on the ROM pad. More boulders were measured on the ROM pad as compared to the pit; thus, the boulders might have been buried in the muckpile during the in-pit fragmentation assessment. About 9.9% of the rock fragments in the pit were classified as boulders while about 29.9% of the same rock fragments transported to the ROM pad were measured and classified as boulders.

The fragmentation analysis of the blast material on the ROM pad indicated that about 30% of the blasted rocks to be fed to the primary crusher was less than the Close Side Setting (CSS) of 150 mm. However, fragmentation analysis of muckpile in the pit is about 32.1% lesser than the CSS of the primary crusher. This indicates that, fragmentation analysis on the smaller fractions of the in-pit muckpile compares well with the rockpile on the ROM pad. A regression analysis on the loader – crusher activities on the ROM pad reveals that the productivity of the loader on the ROM Pad highly correlates to the performance of the primary crusher at a correlation coefficient of 90.2% for the gold mine. The research study shows that poor blast performance resulting in boulder formation affects the continuous operation of the primary crusher. The waiting time of the front-end loader, and thus, the primary crusher increased considerable since the estimated boulders of about 30% on the ROM pad occasionally must be reduced and cleaned by the rock breaker and the grader.

Recommendations

The authors recommend that extractive companies extend fragmentation analyses beyond the pit to the ROM pad. Information from the ROM pad, the final determinant of the nature of the blasted rock should be used to amend the continual drilling and blasting practices of hard rock mining. About 30% of the blasted rocks per analyses in the pit and on the ROM pad indicates that, the primary crusher does no work on the rock fragments. This percentage of the blasted rock moves freely through the CSS of the primary crusher since they are of comparable smaller sizes. Energy is expected to be lost for no work done on the blasted material. Initial investigation with operators of the mine's processing plant on the loss of energy by the primary crusher shows that, the cost of energy lost is comparatively better than the cost of explosives energy resulting from the drill and blast operations of the gold mine.

Spending more money on the explosives is preferably better than producing boulders that keep blocking the primary crusher and exponentially increasing the processing cost through stop-and-start action of the primary crusher. For better appreciation of this assertion, the authors recommend future mine-to-mill research to expand the study scope to assess the cost of energy consumption by the primary crusher and the drill and blast energy in the pit with regards to rock fragmentation. It is further recommended that where applicable (crushing or grinding), the crushing laws (Rittinger's law, kick's law, and Bond's law) should be used to compliment the assessment of the energy consumption and cost of the primary crusher in blast-to-mine optimization.

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