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Blasting efficiency in granite aggregate quarry based on the combined effects of fragmentation and weighted environmental hazards

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Abstract

Purpose. Mine and quarry operators determine blasting efficiency by the sizes of fragments, while regulatory agencies evaluate the same from the level of environmental discomfort. Thus, a conflict of interest exists. This research distinguishes fragmentation efficiency from blasting efficiency. It proposes a new approach for evaluating blasting efficiency to break the conflict of interests between the quarry operators and the regulatory agencies.

Methods. Five blasting events in the FYS granite aggregate quarry have been studied, and design parameters have been obtained. As an indicator of blast-induced environmental discomfort, vibrations and air blasts are measured using a seismograph. The WipFrag desktop and Kuz-Ram model are used to assess the resulting fragmentations. Blasting efficiency is evaluated as a function of fragmentation and environmental constraints.

Findings. The powder factor affects the fragment size distribution and the environmental hazards of blasting but in a conflicting manner. Increased powder factor enhances good fragmentation but results in further environmental discomfort. Blast event 4 has the highest fragmentation efficiency of 46.53%, while 3 has the highest environmental control efficiency of 69.47%. Cumulatively, blast event 4 has the highest overall blasting efficiency of 45.43%. Future research is expected to standardise this novel approach and incorporate more blasting effects.

Originality. This work is the first attempt to quantify the efficiency of blasting operations in the aggregate quarry by combining the fragmentation produced and the resulting environmental hazards in a single model.

Practical implications. The model proposed in this research can be adopted by quarry operators and regulatory agencies for sustainable quarrying and mining to address identified conflicts of interest between them.

Keywords: *blasting efficiency, fragmentation efficiency, peak particle velocity, air blast, powder factor*

1. Introduction

Blasting and fragmentation efficiencies have always been used indistinctly. Industrialists and regulators have indiscriminately used the two terms to convey similar goals and concepts. It should be emphasised that fragmentation and blasting efficiencies are interrelated but differ in scale. Fragmentation efficiency is primarily related to the fragment size distribution of the muck piles. It affects downstream processes and does not consider the harmful effects on the environment, which require strict rules from various regulatory authorities. A blasting that produces few or no boulders with a high uniformity index is highly efficient for quarry and mine operators. Nevertheless, such blasting may result in very high levels of ground vibration and air blast exceeding acceptable limits, resulting in lower blasting efficiency value in the assessments of regulatory authorities.

On the contrary perspectives of regulatory authorities, a blast with very low vibration levels and air pressure below acceptable limits is highly efficient. To them, it does not matter if the blast produces rock fragments that are entirely boulders and cannot be handled by available equipment or machine. This situation is an impasse that needs to be addressed [1]. Consequently, a point of balance jointly acceptable by the industrialists and regulators must be established for sustainable mining and stone quarrying.

Blast efficiency can be evaluated using various approaches. The chosen method depends mainly on the further use of quarried products. Blasted muck pile can be assessed by counting boulders, shovel loading rate, visual observation, fragment size distribution, cost analysis and the effects of the blasting operation on the environment.

Blasting breaks the in-situ rocks into sizeable fragments that can be handled and manoeuvred by the available loading

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and haulage equipment. A substantial proportion of the resulting fragments must be reasonably smaller than the feed size of the primary crusher without unnecessarily producing excessive fines for efficient operation [2]. Thus, blasting is technically the first stage of comminution. Blast fragmentation must be continuously evaluated and tailored to suit specific production requirements while ensuring efficient further downstream operations [3], [4].

The mechanism of rock fragmentation by explosives accounts for the level of disturbance to the people living within the vicinity and the damage to surrounding structures [5]. During blasting, an initiated or detonated explosive changes rapidly within a few thousandths of a second to a gaseous state at a very high temperature and pressure. This quick reaction can produce a pressure of 18000 atmospheres that is exerted against the walls of the blast hole [6]-[9]. The resulting energy is then transmitted as a compressive strain wave into the circumferential rock mass at a velocity of between 2000 to 6000 m/s, causing rock breakage.

Blasting and explosive usage are potential sources of many human and environmental hazards. Actual rock breakage effectively utilised only about 5 to 15% of the total available explosive energy released during blasting [10], [11]. Sanchidrian et al. [12] studied energy efficiency in the single-hole confined blast and concluded that available fragmentation energy is 2 to 6% of the total energy. The remaining energy causes various environmental disturbances [13], [14]. These adverse effects of blasting are unavoidable and cannot be eliminated but can be mitigated to permissible levels to avoid human and environmental discomforts. Among the negative impacts of blasting, ground vibration and airblast take topmost priority to engineers and regulatory agencies.

The economy, productivity, and operational cost of mining and quarrying are significantly influenced by the particle size distribution of a muck pile [15], [16]. A well-designed blast gives rise to good fragmentation and minimal environmental disturbances. Sastry and Chandar [17], [18] have emphasised that the prime objectives of blasting should be centred on optimal fragmentation and safety. In designing a blast, the blast geometry, explosive properties, geological factors, the quantity of explosives, delay timing sequence, conditions and extent of available free surfaces are vital factors influencing fragmentation and blast efficiency [19]. Fundamentally, the controllable blast parameters are designed to accommodate the non-controllable ones to obtain anticipated outcomes.

A higher level of fragmentation improves productivity, while a low level of vibration and airblast ensures human and structural safety [20]. However, fragmentation and environmental effects are influenced by the amount of powder factor [21], [22]. A higher amount of powder factor improves fragmentation and, thus, productivity [23]. Nevertheless, the blast-induced vibration and airblast also increase with an increase in the powder factor [24], [25]. This impasse calls for an optimum powder factor for sustainable blasting operations.

Segarra et al. [23] investigated the effects of powder factor on different percentage passing and concluded that fragmentation improves with powder factor. The most common tool for evaluating the impacts of blasting on structures and human beings is the Peak Particle Velocity (*PPV*) [26]-[29], as shown in Equation 1 [30], [31]. The vibration (*PPV*) level increases with the maximum quantity of explosives per delay. Thus, a higher amount of explosives ensure finer rock fragments but causes more vibration and airblast [32]. However, optimal fragmentation can be judiciously obtained without undermining safe environmental limits:

$$PPV = k\left(\frac{\sqrt{Q}}{R}\right)^{a}, \quad (1)$$

where:

PPV – the peak particle velocity;

Q – the maximum quantity of explosives detonated per delay;

R – the distance between the blast point and the measuring point;

K and *a* – site constants related to the rock feature and blasting conditions.

This research distinguished fragmentation efficiency from blast efficiency and proposed an approach for evaluating the two terms relatively. The study evaluates blast efficiency as a function of desired fragmentation size, environmental effects, and regulatory constraints. Thus, fragmentation efficiency is viewed as a component of blast efficiency. The proposed approach can be adopted by both mine operators and the regulatory authorities by setting a common standard limit to break the conflicts of interest.

2. Methodology

Blast design parameters were obtained for five blast operations of the FYS granite aggregate quarry in Bukit Mertajam, Pulau Pinang, Malaysia. The powder factor and the rock factor were calculated for each blast. From the closet residential building, each of the blasts was monitored. The peak particle velocity and airblast overpressure were obtained using a seismograph. The resulting fragmentation distributions of the muck pile were evaluated using WipFrag photo analysis software [33]. The 50% passing of each muck pile was obtained using the Kuz-Ram empirical model [34]. The fragmentation indicator, fragmentation efficiency, the level of environmental compliance, and overall blast efficiency were evaluated for each blast using new approaches based on weighted averages.

2.1. Bench blast design data

The blast design data for the studied quarries were obtained for various events. A total of five blast events were analysed. The spacing (*S*), burden (*B*), hole diameter (*D*), number of holes (*n*), hole depth (*L*), subdrill length (*S.D.*), bench height (*B.H.*), stemming length (*S.L.*), charged length (*Q.L.*) and the average weight of explosive per hole (*W*) were recorded for each blast event. The applied powder factor (*P.F.*) was evaluated for each blast using established standard procedures [35], [36].

2.2. Measurement of ground vibration and airblast overpressure

Seismograph Mini-SEIS II (Fig. 1) was used to monitor each blast at the closet residential building. The levels of blast-induced ground vibration and airblast overpressure were recorded. The seismograph Mini-SEIS II consists of the collector unit, the geophone, three spikes, the microphone, the microphone stand, and the windscreen. A vibration monitoring program requires measurements of peak particle velocity at the nearest residential or structural distance. Alcudia et al. [37] posited that the geological factors, the nature of the seismic source, and the wave type affect the magnitude of ground vibrations.

Figure 1. Seismograph Mini-SEIS II

Air vibrations are conveyed through the air; thus, weather conditions substitute geological factors as a primary variable [38]. For each documented blast event, the maximum particle velocity over the total recorded time was taken as the peak particle velocity (*PPV*), as shown in Figure 2. This maximum velocity is of paramount interest to the regulatory authorities irrespective of its direction of occurrence.

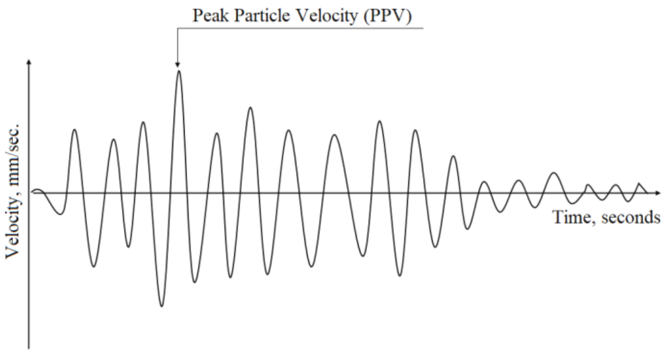


Figure 2. Illustration of Peak Particle Velocity (PPV)

Open and accessible locations are located near the closest residential structures to the blast points. The seismograph is mounted a few minutes before blasting. Holes are dug about 5 cm to remove topsoil, and the excess soil is scrapped. The three spikes are fixed to the geophone. The geophone was fixed firmly to the ground with the indicated arrow pointing to the direction of the blast as the seismic source for proper orientations of the three axes – vertical, horizontal and longitudinal. The sensor was levelled to obtain accurate readings as recommended by ISRM [39].

The geophone and the microphone cables are firmly fastened to the collector (the measuring unit). This process automatically activated the device, which was ready to acquire readings. The windscreen was fitted to the microphone to prevent the acoustic readings from the influence of wind [39]. The microphone was then fixed to its stand, positioned on top of the collector, and pointed to the blast direction. The peak particle velocity (mm/s) and the airblast overpressure (dB) were read immediately after blasting.

2.3. Image analysis of fragmentation distribution

Version 2.7.28 of WipFrag photo analysis software was used. WipFrag is a granulometry-based software that creates digital images to assess the size distributions of rock fragments [33]. WipFrag recognises distinct blocks using automatic algorithms and generates netting or outlines of blocks using edge or boundary identification techniques. WipFrag measures the two-dimensional net of the surface of the muckpile and transforms the same into a three-dimensional block size using geometric probability [40].

For higher accuracy, the horizontal axis of the camera should be at 90º to the muck piles surface to be captured. In actual practice, deviation from this recommended standard is involuntarily unavoidable. Therefore, images were captured with the horizontal axis of the camera at some angles different from 90º muck pile faces. Thus, scaling objects were used in capturing images of the blasted rock fragments [33], [41].

Honor 5X of 13 megapixels with a resolution of 1080×1920 rear camera was used to capture the images of the blasted rock fragments. Two 1-meter lengths of polyvinyl chloride (PVC) pipes with a diameter of 2 inches were used as scaling objects. Each pipe was placed at the top and bottom of the muck pile to be captured. This dual scaling was done for "tilt correction" [33], [42]. Multiple images were obtained for a single muck pile, and the separate analyses merged for enhanced precision.

The images of captured muck piles were transferred into the computer, and the image to be analysed was opened using the file menu of the WipFrag software. The idea was scaled, and the nets were generated to represent a network of block boundaries for each image using the default automatic edge detection menu. These boundaries delineated the edges of the fragments. The auto-generated nets were further improved by manually adjusting the edge detection parameters using the inbuilt editing tools. The block sizes were then measured, and the percentage passing curve was generated by virtual sieving. The virtual sieve also created a cumulative size table for each analysed image. These procedures were repeated for other images from the same muck pile, and the results were merged for improved precision.

2.4. Kuz-Ram estimation of 50% passing

The Kuz-Ram equation [34] is the most common empirical model for assessing surface blasting [43]. It evaluates blast fragmentation using design parameters – explosive characteristics, blast geometry, amount of explosive used, and rock factors. The Kuz-Ram model evaluates blast fragmentation by measuring the 50% passing (X_{50}) block size of a muckpile. The 50% passing size of the muck pile was evaluated using Equation (2) [34], [44]-[46]:

$$X_{50} = X_{KR} = AK^{-0.8} \cdot Q^{0.1667} \cdot \left(\frac{115}{RWS}\right)^{0.6333}, \quad (2)$$

where:

A – a constant representing rock factor which depends on the characterisation of the rock mass relative to structural discontinuity, rock strength, density, and hardness. Its value varies from 0.8 to 22 [47];

K – the powder factor (kg/m^3);

Q – the average mass of explosive per hole (kg);

RWS – the weight strength of the used explosive relative to ANFO.

The rock factor *A* was evaluated as Gheibie et al. [47] recommended by incorporating the rock mass property, joint plane spacing, joint plane orientation, specific gravity influence and hardness factor defined by Lilly [48].

2.5. Fragmentation efficiency

The fragmentation efficiency was assessed using two principal parameters; the actual size of the 50% passing muck pile obtained from the particle size distribution of image analysis (X_{bm}); and the 50% passing size derived from the Kuz-Ram model (X_{KR}). A new term called fragmentation indicator (*FI*) [49] was used to evaluate the level of deviation of the 50% passing of image analysis from that of the Kuz-Ram 50% passing as given in Equation (3):

$$FI = \frac{X_{KR}}{X_{bm}}, \tag{3}$$

where:

FI – fragmentation indicator;

X_{KR} – expected ideal 50% passing size of the blasted material from the Kuz-Ram model;

X_{bm} – 50% passing of blasted muck pile from particle distribution analysis.

If the fragmentation index (*FI*) is less than 1, the actual 50% passing obtained is coarser than the ideal size evaluated from the Kuz-Ram model. This situation happens if the ideal rock strength and rock factor constant (*A*) envisaged by the Kuz-Ram model is higher. A fragmentation index greater than one shows that the 50% passing is finer than the ideal size.

Fragmentation efficiency (Frg_{eff}) was further evaluated as an inverse negative exponential function of the fragmentation indicator and expressed in percentage (Equation (4)). The negative exponent makes the fragmentation efficiency directly proportional to the fineness of the 50% passing and, thus, the fragmentation indicator. Accordingly, the less coarse the muck pile, the higher the fragmentation efficiency:

$$Frg_{eff} = \exp^{-\left(\frac{1}{FI}\right)} \cdot 100\% = \exp^{-\left(\frac{X_{bm}}{X_{KR}}\right)} \cdot 100\%. \tag{4}$$

The exponential function shows the deviation of the 50% passing of Kuz-Ram from that of the image analysis. Exponential functions are used as solutions to real and simple dynamical systems. The 50% passing is a non-zero positive real number. The function accounts for the diverse complexity of the rock as represented by the rock factor constant (*A*) in the Kuz-Ram model. The negative exponent designates the fragmentation indicator (*FI*) as a quotient function.

2.6. Blast efficiency

The efficiency of a blast consists of fragmentation performance and the unintended but unavoidable environmental effects as regulated by the government. This research used a fragmentation indicator to define blast performance. The level of blast-induced ground vibration and airblast overpressure were assumed to represent the efficiency of environmental control measures of a blast. Equation (5) was used to evaluate blast efficiency:

$$Bla_{eff} = \pm\sqrt{\left|\left(Frg_{eff} \cdot Env_{eff}\right)\right|}, \tag{5}$$

where:

Bla_{eff} – blast efficiency;

Frg_{eff} – fragmentation efficiency;

Env_{eff} – efficiency of environmental control measures.

Equation (5) gives equal importance to both the fragmentation that affects process efficiency and the environmental hazards of blasting. The expression shows the mutual dependency of the environmental effects of blasting on the resulting fragment size distribution.

By this, a common standard acceptable to the mine/quarry operators and the regulatory authorities can be established. The established blast efficiency for each mine or quarry can be used for assessment and sustainable production.

Furthermore, the efficiency of environmental control measures was assessed based on the weighted average levels of blast vibration and noise compared to the maximum permissible limits (Equation (6)):

$$Env_{eff} = x\left(Vib_{eff}\right) + y\left(Aop_{eff}\right), \tag{6}$$

where:

Env_{eff} – efficiency of ground vibration control measures;

Aop_{eff} – efficiency of airblast overpressure control measures;

x – weighted value assigned to vibration;

y – weighted value assigned to airblast.

Equation (6) gives a weighted average of *x* % to ground vibration and *y* % to airblast overpressure (noise). The weighted priority assigned to vibration and airblast will be the sole decision of the regulating authority. This work was done in an aggregate granite quarry with very close residential buildings. The government and residents of this region give much importance to vibration over airblast. Therefore, a priority of 80% was assumed for vibration, while airblast takes 20%. This assumption puts the values of *x* and *y* used in this study to be 0.8 and 0.2, respectively.

However, if vibration and airblast have the same priority level (50% each), then *x* and *y* will have the same value of 0.5. The values of *x* and *y* can be adjusted as required in a blasting project. In actual practice, vibration is more challenging to control and causes more human and structural hazards than airblasts [50]. The global regulatory authorities use the levels of vibration and airblast overpressure to assess and grade blasting operations.

The efficiencies of ground vibration and airblast overpressure (noise level) control measures were further evaluated using Equations (7) and (8), respectively:

$$Vib_{eff} = \left(1 - \frac{V_{ppv}}{V_{\max}}\right) \cdot 100\%; \tag{7}$$

$$Aop_{eff} = \left(1 - \frac{N_b}{N_a}\right) \cdot 100\%, \tag{7}$$

where:

V_{ppv} – peak particle velocity of the blast (mm/s);

V_{max} – maximum permissible level of vibration (mm/s);

N_b – noise level generated from the blast (dB);

N_a – maximum permissible noise level (dB).

For this research, the maximum permissible level of vibration ($V_{\max}$) and that of airblast overpressure (N_a) as approved for FYS Quarry by the Department of Mineral and Geoscience of Malaysia are 5 mm/s and 120 dB, respectively. A negative value of either Equation (7), (8), or both implies that the permissible limits of ground vibration, airblast overpressure, or both have been violated. If any of these three conditions occurred, the blast efficiency (Equation (5)) assumes a negative value. In such a situation, the blast must be redesigned for environmental sustainability. The blast efficiency would be positive if none of the three circumstances occurred.

3. Results and discussion

3.1. Blast design parameters

The design parameters for the five studied blast events are shown in Table 1. No two or more designs are precisely the same though some common standard parameters exist. Only the hole diameter and the subdrill were maintained for all the designs. The variations are necessary to account for the different bench heights and disparity in geological conditions that may be encountered. The highest powder factor used is 0.51 kg/m^3, corresponding to a bench height of 11.89 m in blasts 1 and 2, while the smallest powder factor is 0.41 kg/m^3 corresponding to a bench height of 8.84 m in blast event 3.

3.2. Blast monitoring and efficiency of environmental control

The recorded ground vibration level was the highest peak particle velocity, a common practice amongst regulators [51]. Table 2 shows the vibration and noise levels and the efficiency of the environmental control measures for each blast. The maximum ground vibration (*V*max) and noise (*Na*) recorded in the five blast events were within the permissible limits of 5 mm/s and 120 dB, respectively. Thus, the efficiencies of the environmental control measures were all positive. Blast event 3, with the least peak particle velocity of 0.76 mm/s, has the highest environmental efficiency of 69.47%.

Table 1. Blast design parameters

Blast events	*S* (m)	*B* (m)	*D* (mm)	*n*	*L* (m)	*S.D.* (m)	*S.L.* (m)	*B.H.* (m)	*W* (kg)	*Q.L.* (m)	*P.F.* (kg/m^3)
Blast 1	3.66	3.05	89	40	12.19	0.30	3.05	11.89	68.20	9.14	0.51
Blast 2	3.66	3.05	89	40	12.19	0.30	3.66	11.89	68.20	8.53	0.51
Blast 3	3.66	3.05	89	40	9.14	0.30	3.66	8.84	40.92	5.48	0.41
Blast 4	3.05	2.44	89	40	9.14	0.30	3.66	8.84	40.92	5.48	0.62
Blast 5	3.05	2.44	89	22	6.10	0.30	3.66	5.80	18.20	2.44	0.42

Table 2. Blast monitoring and efficiency of environmental control

Blast events	Distance (m)	V_{ppv} (mm/s)	N_b (dB)	V_{max} (mm/s)	*Na* (dB)	$Vibe_{ff}$ (%)	$Aope_{ff}$ (%)	Env_{eff} (%)
Blast 1	589	1.37	113.50	5.00	120.00	72.60	5.42	59.16
Blast 2	539	1.52	118.00	5.00	120.00	69.60	1.67	56.01
Blast 3	848	0.76	110.00	5.00	120.00	84.70	8.33	69.47
Blast 4	419	2.29	114.00	5.00	120.00	54.20	5.00	44.36
Blast 5	334	1.52	110.00	5.00	120.00	69.60	8.33	57.35

Blast events 2 and 5 have the same vibration level of 1.52 mm/s but with different noise levels of 118.00 and 110.00 dB, respectively. The efficiency of event 5 (57.35%) with a smaller noise level is higher than that of event 2 (56.01%). Thus, the lower the vibrations and noise levels, the higher the efficiency of environmental control measures.

3.3. WipFrag fragmentation distribution

Figure 3a-e shows the captured muckpile images and the digitised fragment boundaries from WipFrag. Depending on the lateral spread of the blasted fragments, two or three muck piles were captured, processed, and the results merged for a blast event. The merged results of the fragmentation distribution for each of the five blast events are shown in Figure 4a-e, respectively. The average 50% passing sizes (X_{bm}) for the five blast events are 384.90, 359.74, 490.09, 200.42, and 397.86 mm, respectively. All the blast events produced a size fraction greater than 1000 mm except for blast event D.

3.4. Fragmentation and blast efficiencies

Table 3 shows the efficiency of each of the evaluated blast events. Blast event 4, with a fragmentation efficiency value of 46.53%, has a blast efficiency of 45.43%. The reduction was caused by its low efficiency of environmental control measure (44.36%), being the blast event with the highest vibration level of 2.29 mm/s. Similarly, blast event 3, with a fragmentation efficiency of 25.59%, has a cumulative blast efficiency of 42.17%. The increase was due to its higher efficiency of environmental control measure (69.47%) being the blast with the lowest vibration level of 0.76 mm/s. This result proved the validity of the proposed model and clearly illustrated its interdependency on 50% passing size and the hazards caused to the environment.

Table 3. Fragmentation and blast efficiencies

Blast events	*P.F.* (kg/m^3)	X_{bm} (mm)	X_{KR} (mm)	*FI*	Frg_{eff} (%)	Env_{eff} (%)	Bla_{eff} (%)
Blast 1	0.51	384.90	326.83	0.85	30.80	59.16	42.69
Blast 2	0.51	359.74	324.32	0.90	32.98	56.01	42.98
Blast 3	0.41	490.09	359.61	0.73	25.59	69.47	42.17
Blast 4	0.62	200.42	261.97	1.31	46.53	44.36	45.43
Blast 5	0.42	397.86	308.12	0.77	27.49	57.35	39.71

Figure 5a-c displays the relationship between the effects of powder factor on the 50% passing size (X_{50} or D_{50}) and the efficiencies of fragmentation and environmental control measures. The graphs show that an increase in powder factor will produce smaller and finer fragment sizes, thereby increasing fragmentation efficiency. However, such an increase in the powder factor will conversely result in more vibration and noise levels, thus, giving rise to low efficiency of environmental control measures. This outcome also goes in agreement with previous studies [16], [23], [52].

Figure 6a, b illustrates the influence of the average 50% passing size on the efficiencies of fragmentation and environmental control measures. It is evident from the plots that fragmentation efficiency improves with a smaller average fragment size. A larger 50% passing size implies a reduction in the mass of explosive used per unit volume of blasted rock (powder factor) and, thus, low vibration and noise levels. The plots' trends also agree with Segarra et al.'s work [23]. This decrease in the mass of explosives used will consequently lead to enhanced efficiency of environmental control measures but a decrease in fragmentation efficiency.

An increase in the powder factor increases the available energy for rock fracturing, thereby enhancing fragmentation and efficiency.

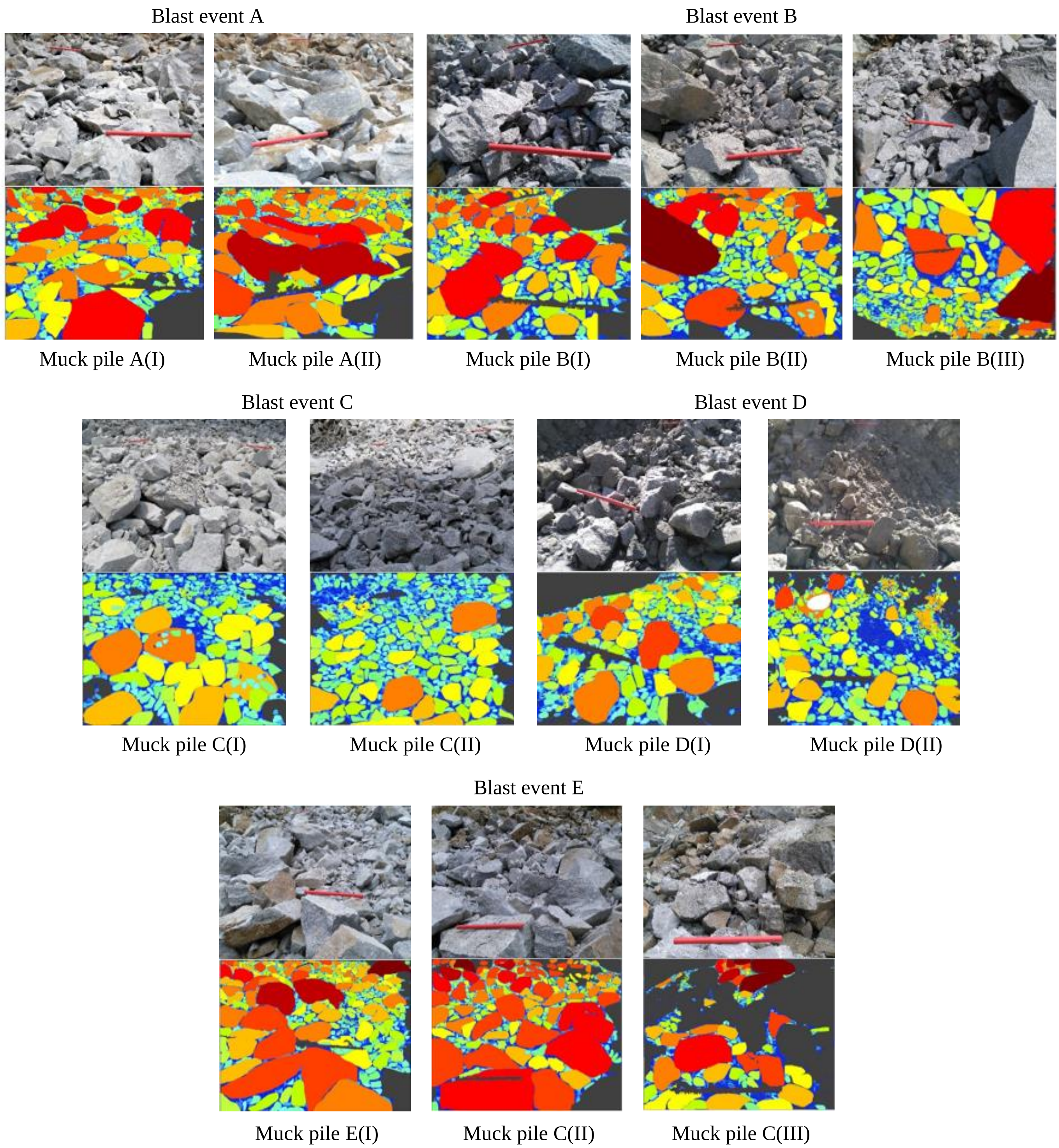
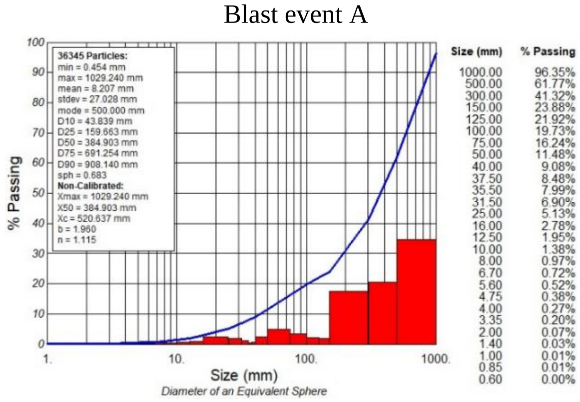
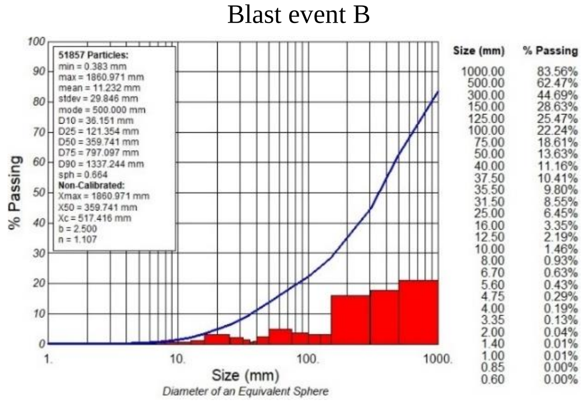


Figure 3. Muck pile photos and digitised WipFrag nettings of the studied five blast events A, B, C, D, and E





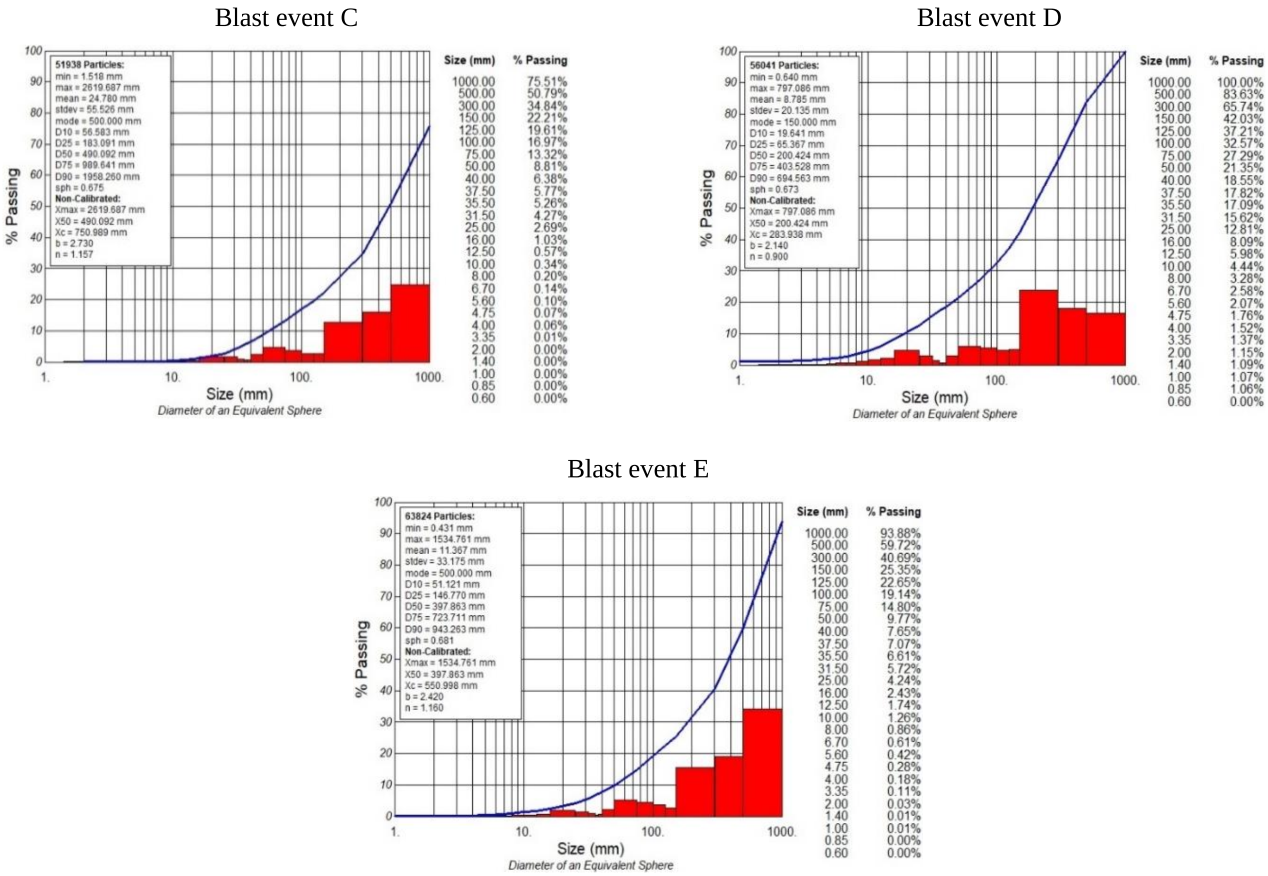


Figure 4. WipFrag distribution analyses for the five studied blast events A, B, C, D, and E

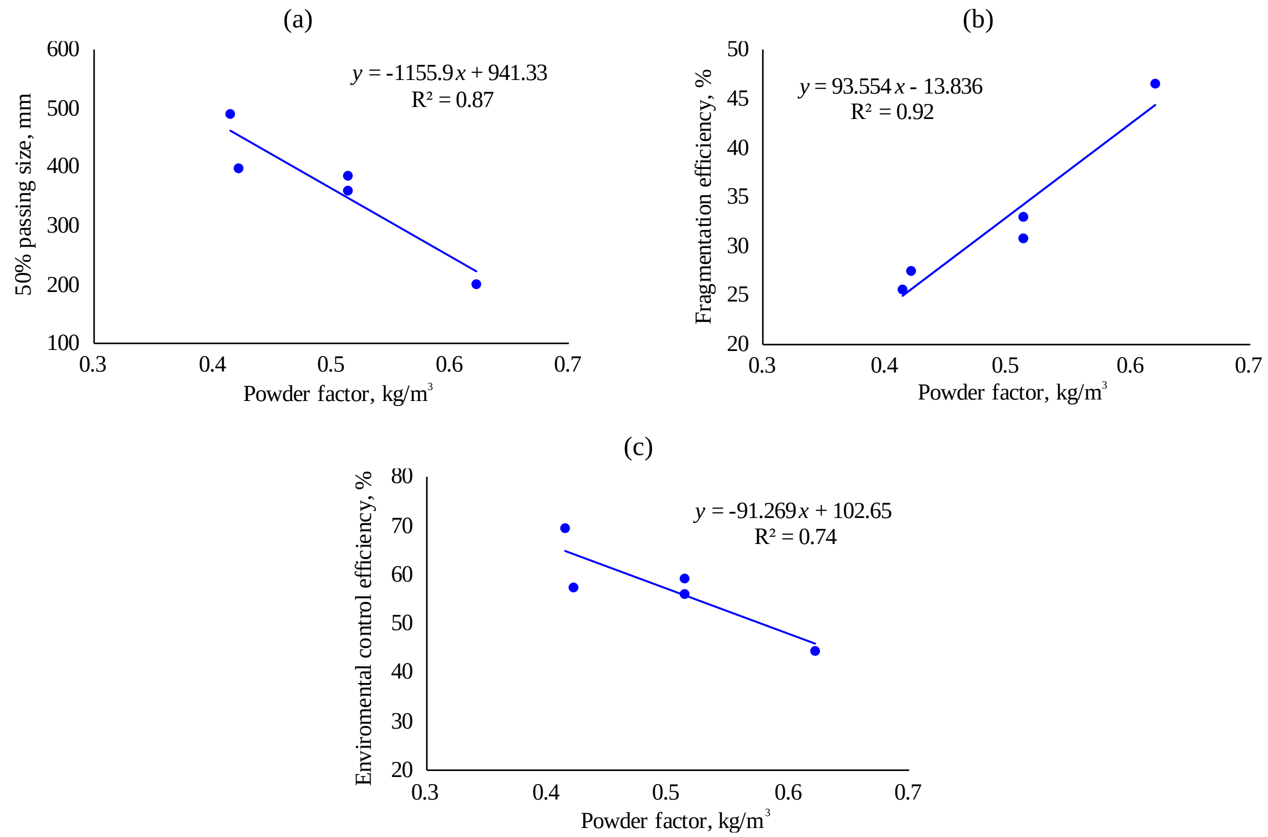


Figure 5. Effects of powder factor on 50% passing size, fragmentation efficiency and efficiency of environmental control measures: (a) 50% passing size vs powder factor; (b) fragmentation efficiency vs powder factor; (c) environmental control efficiency vs powder factor

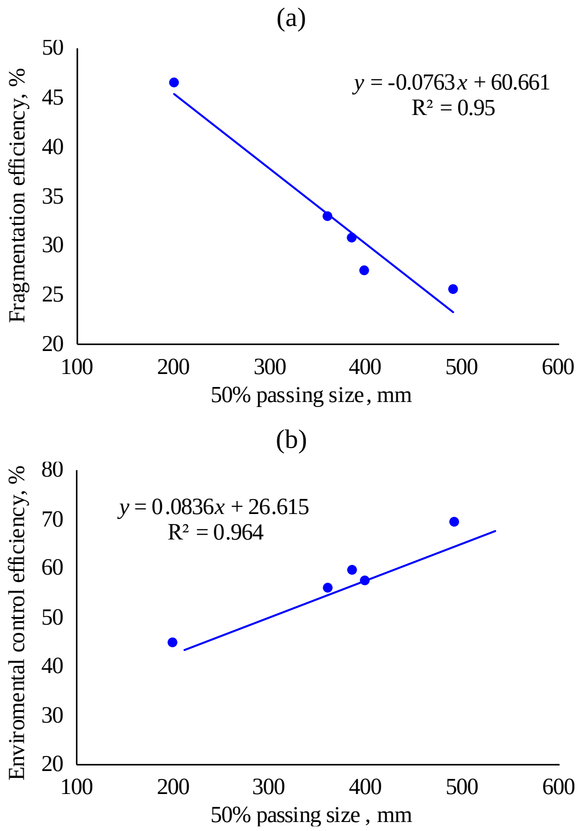


Figure 6. Effect of 50% passing size on the efficiencies of fragmentation and environmental control measures: (a) fragmentation efficiency vs 50% passing size; (b) environmental control efficiency vs 50% passing size

This increase in the specific charge of explosives to enhance fragmentation adversely leads to the generation of more blasting fumes and a higher amount of waste energy that increases the levels of ground vibration and airblast, consequently resulting in low efficiency of environmental control measures.

4. Conclusions

There are various methods and techniques for evaluating blast efficiency. However, due to conflicts of interest, no single common standard approach is currently accepted by both the industrialists and the regulatory authorities. The industrialists based their assessments on fragmentation performance, while the government regulators judge blast operations by the induced environmental hazards.

Fragmentation and blast efficiencies have been wrongly used to express the same ideals. This study acknowledged that the two terms are interrelated but vary in scope. Fragmentation efficiency is fundamentally concerned with the size distribution of the blasted materials. While effective fragmentation can be achieved with a higher powder factor, excessive utilisation of explosives to actualise this performance objective causes higher levels of vibration and airblast overpressure that may result in structural rattling, racking, pollution and human discomforts, amongst other damage. Thus, the necessity for differentiating fragmentation efficiency from blast efficiency.

This research proposed a model for evaluating the efficiency of blasting operations. The study assessed blast efficiency as a function of fragmentation performance and the effectiveness of environmental control measures. The established model can be discussed and adopted by the industrialists and the regulatory authorities for sustainable quarrying and mining to address the identified conflicts of interest.

Future study is expected to standardise and incorporate more effects of blasting into this novel integrated method of quantifying blast efficiency.

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Ефективність вибухових робіт у кар'єрі гранітної маси на основі комбінованих ефектів фрагментації та зваженої небезпеки для навколишнього середовища

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Мета. Встановлення різниці між ефективністю фрагментації підірваної гірської маси та ефективністю вибухових робіт на основі нового підходу до цієї оцінки, що долає конфлікт інтересів між операторами кар'єрів і регулюючими органами.

Методика. Було вивчено п'ять вибухових подій у кар'єрі гранітної маси FYS та отримано проєктні параметри. Як індикатор екологічного дискомфорту, спричиненого вибухом, за допомогою сейсмографа вимірюються вібрації та повітряні хвилі. Робочий стіл WipFrag та модель Kuz-Ram використовуються для оцінювання отриманих фрагментацій. Ефективність вибухових робіт оцінюється залежно від фрагментації та обмеження навколишнього середовища.

Результати. Встановлено, що пороховий фактор впливає на розподіл розміру уламків та небезпеку вибухових робіт для навколишнього середовища, але суперечливим чином. Визначено, що підвищений пороховий фактор сприяє ефективній фрагментації, але призводить до більшого дискомфорту навколишнього середовища. Вибух 4 має найвищу ефективність фрагментації 46.53%, тоді як третій – має найвищу ефективність контролю навколишнього середовища 69.47%. У сукупності вибух 4 має найвищу загальну ефективність вибухових робіт 45.43%. Очікується, що майбутні дослідження стандартизують цей новий підхід і будуть включати більше вибухових ефектів.

Наукова новизна. Вперше кількісно оцінено ефективність вибухових робіт у кар'єрі гранітної маси шляхом об'єднання утвореної фрагментації та небезпеки для навколишнього середовища в одній моделі.

Практична значимість. Модель, запропонована в цьому дослідженні, може бути прийнята операторами карєрів та регулюючими органами для його сталого розвитку та видобутку корисних копалин з усуненням виявлених конфліктів інтересів поміж них.

Ключові слова: *ефективність вибуху, ефективність фрагментації, максимальна швидкість часток, повітряна хвиля, пороховий фактор*