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ORIGINAL PAPER

INVESTIGATION OF THE RELATIONSHIP BETWEEN THE SPECIFIC CHARGE AND BOND WORK INDEX: A CASE STUDY

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ABSTRACT

Research on blasting efficiency typically focuses on analyzing particle size distribution to evaluate blast fragmentation by examining blasting parameters. However, studies investigating the impact of blasting on downstream processing steps, particularly grinding efficiency, remain limited. This study emphasizes the effects of blast fragmentation on the efficiency of limestone processing and grinding operations. To achieve this, seven distinct blasting events were monitored in a limestone quarry, with specific charge values ranging from 0.33 to 0.49 kg/m³. The particle size distribution of the blasted material was assessed by capturing muck pile photographs and analyzing them using Wipfrag software. For each blast, the average particle size was calculated. Additionally, samples collected from the post-blast muck piles were subjected to laboratory-based Bond work index tests, yielding Bond work index values ranging from 7.8 to 13.8 kWh/T. The effects of specific charge on mean particle size and Bond work index were analyzed through regression analyses. The results revealed a strong correlation, with an 88 % correlation between specific charge and average particle size and an 80 % correlation between specific charge and Bond work index. The findings of this study clearly demonstrate the interrelationship between blasting and grinding processes.

1. INTRODUCTION

In open-pit mining, production typically involves drilling and blasting, followed by loading, transportation, crushing, and grinding. These unit operations are interconnected, making it crucial to optimize drilling and blasting to minimize grinding costs, the final stage of production. Reducing costs in the drilling and blasting phases alone does not eliminate the possibility of increased expenses in subsequent stages. Therefore, a comprehensive cost evaluation must consider both blasting at the beginning of production and grinding at the end. Traditionally, blasting aimed primarily at preparing the in situ rock mass for excavation and transportation, often overlooking its impact on downstream milling processes (Kanchibotla et al., 1998).

During crushing and grinding, reducing energy consumption in crushers and mills improves economic efficiency. Herbst and Pate (1998) estimated that blasting accounts for only 1 % of the total size reduction cost, which includes all stages from blasting to final grinding. While primary crushers contribute 2 % and secondary crushers 20 %, grinding represents a substantial 77 % of the total cost. This highlights the significant financial burden associated with grinding operations. Numerous researchers have developed mathematical models to estimate grinding energy consumption, with Bond's theory (Bond, 1952) being the most widely recognized. The theory is expressed by the following equation:

$$W = 10 \times W_i \times \left(\frac{1}{\sqrt{k_{p80}}} - \frac{1}{\sqrt{k_{F80}}}\right) \text{ (Bond, 1952)}$$

W = Grinding energy consumption (kWh/T)
W_i= Work index (kWh/T)
k_{p80} = the sieve size at which 80 % of the crushed product passes through. (micron)
k_{F80} = particle size at which 80 % of the feed material passes through (micron)

The particle size distribution resulting from blasting operations formed the foundation of production activities and significantly influenced the final stage of production–the grinding process. The work index (W_i) determination method, developed by Bond in 1960, remained a valid and effective approach. A key advantage of Bond's third theory was the widespread availability of measured and reported W_i values for various rock types. A significant portion of energy expenditures was attributed to grinding processes. Therefore, transferring variations in rock fragment characteristics from blasting to the grinding stage could lead to substantial cost savings (Ouchterlony, 2003).

Assessing the potential downstream effects of blasting on the entire production workflow was crucial for process optimization (Esen, 2013; Grundstrom et al., 2001). The cost of blasting operations was generally associated with the degree of fragmentation (Hoek and Bray, 1991; Mackenzie, 1967) (Fig. 1). A comprehensive evaluation of unit costs was necessary to analyze the impact of blasting on fragmentation costs (Fig. 2).

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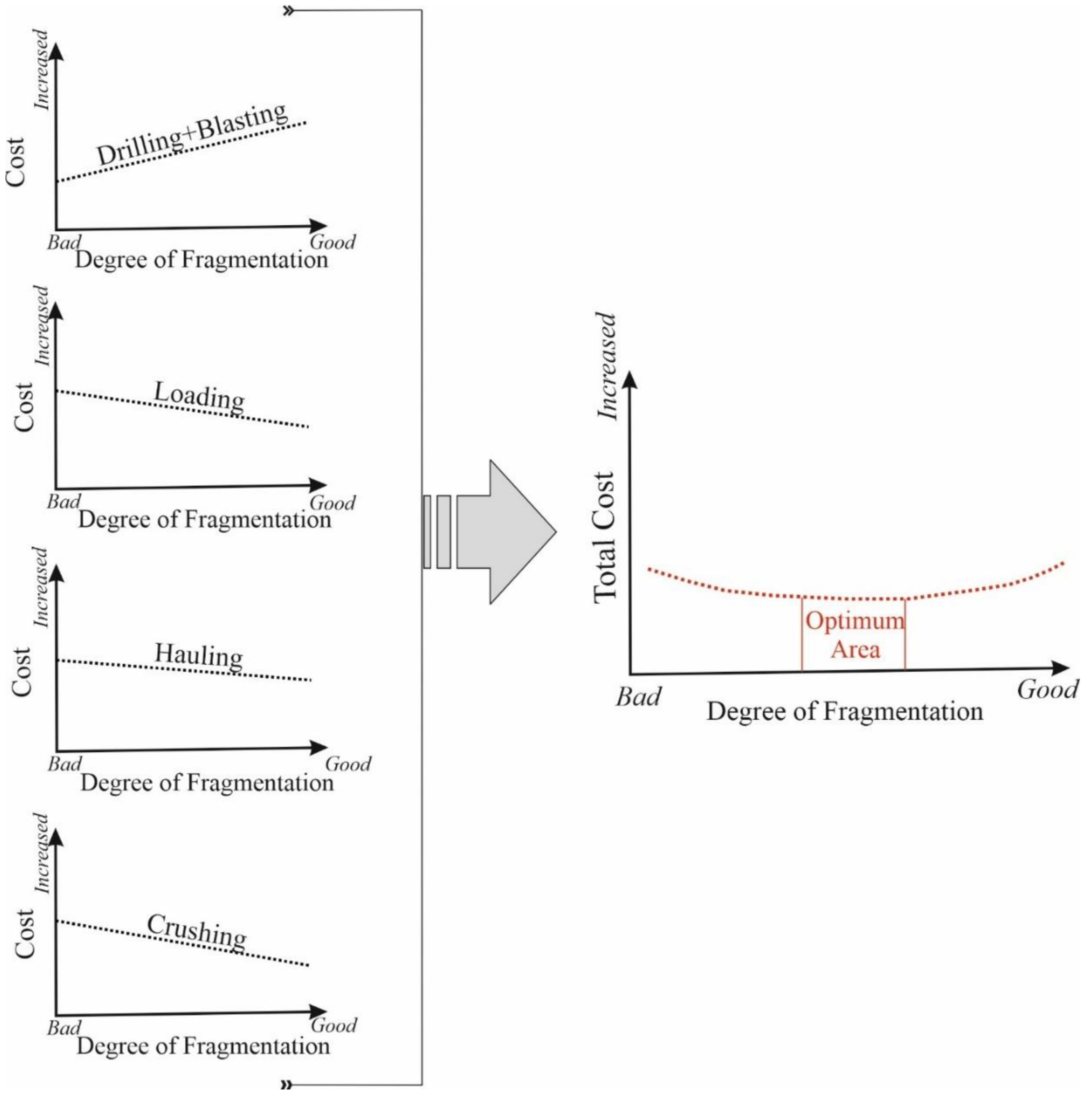

Fig. 1 Relationship between the degree of fragmentation and cost (revised from Mackenzie, 1967).

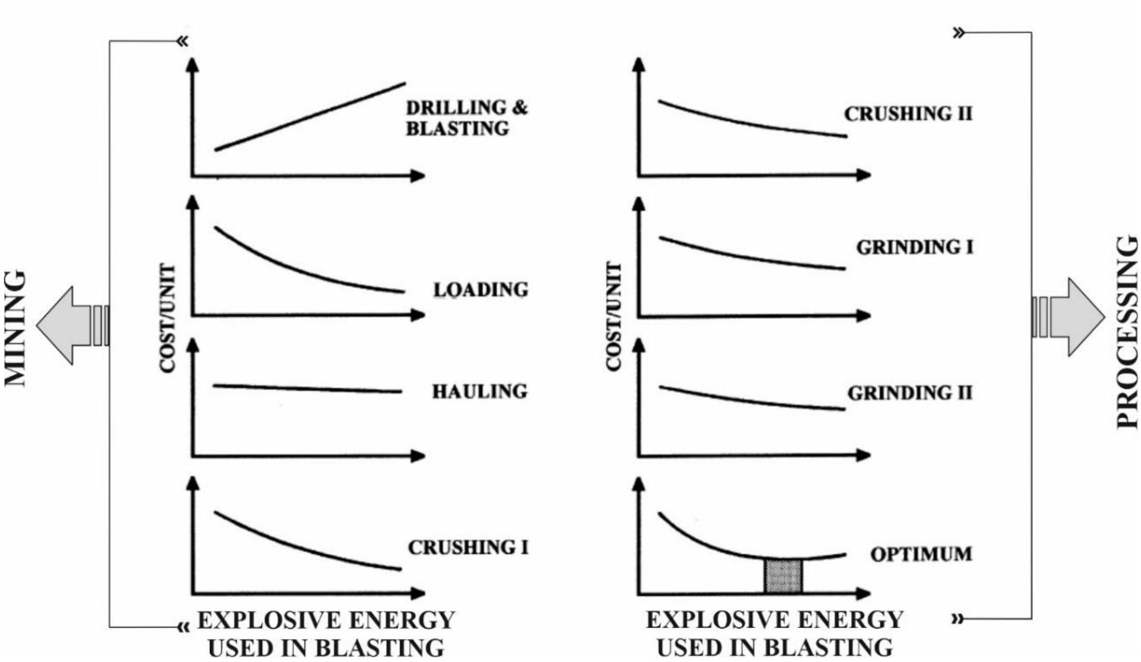

Fig. 2 Relationship between the unit costs of mining operations and the blasting effort (revised from Nielsen and Kristiansen, 2020).

Rock fragmentation was one of the most optimized outcomes of blasting due to its significant impact on downstream processes (Grundstrom et al., 2001; Kim, 2010; Ouchterlony, 2003). Optimized blasting, which ensured an appropriate particle size distribution, reduced energy consumption and lowered the costs associated with crushing and grinding. Moreover, effective sizing enhanced product quality by ensuring that final specifications met desired standards. Inadequate fragmentation placed additional strain on secondary and tertiary crushing stages, as a smaller proportion of material could bypass these stages. This negatively affected both productivity and energy consumption. The post-blast size distribution directly influenced the feed size distribution of the primary crusher and, consequently, all subsequent crushing stages (Workman and Eloranta, 2003). Blasting was the first step in the crushing and separation process and played a critical role in optimizing the value chain from the mine to the processing plant. For this approach to be successful, understanding the effects of blasting outcomes–such as fragmentation, movement, dilution, damage, and rock softening–on overall process efficiency was essential (Kanchibotla, 2014). As the amount of explosive energy used in blasting increases, finer rock fragments are produced. However, the resulting particle size is influenced not only by the energy input but also by the initial size and structure of the rock. In widely jointed rock formations, the average block size is larger, necessitating higher explosive energy to achieve the desired fragmentation. In contrast, thinly bedded rock formations require less explosive energy to produce a similar particle size. In highly fractured rock masses, fragments tend to separate along existing joints rather than undergo significant breakage. This indicates that the stress wave primarily facilitates the detachment of rock fragments rather than their complete fragmentation (Chakraborty et al., 2004).

The degree of rock fragmentation significantly affects factors such as the efficiency of excavators and loaders, the capacity of crushers and mills, the energy consumption of crushing equipment, and the cost of final crushed products, including industrial minerals and construction aggregates (Sanchidrian et al., 2012). The energy used in blasting fragmentation is measured by evaluating fragment sizes before and after blasting. In open-pit mining, the desired fragmentation is defined based on the intended end use of the rock and the available resources. The assessment of fragmentation has become considerably easier and faster with the use of digital image analysis techniques, employing various hardware and software tools (Chakraborty et al., 2004).

The effects of blasting on fragmentation can be categorized into two main aspects: (i) the size distribution of bulk material fragments and (ii) the formation of microcracks within these fragments (Asgari et al., 2015; Khademian and Bagherpour, 2017; Ouchterlony, 2003; Shehu and Hashim, 2020). The first aspect is directly observable and can be estimated using sieve analysis or imaging techniques. In contrast, the second aspect is not visible to the naked eye and requires magnification for measurement. Therefore, the degree of rock fragmentation resulting from blasting was evaluated based on both the produced fragment size distribution and the extent of microcrack formation (Nielsen and Malvik, 1999; Ouchterlony, 2003; Seccatore, 2019; Workman and Eloranta, 2003). Cracks induced by blasting can be classified into two types based on size: macrocracks and microcracks (Anders et al., 2014; Khademian and Bagherpour, 2017; Ouchterlony, 2003; Parra et al., 2015). Macrocracks are visible to the naked eye and range in size from millimeters to centimeters (Parra et al., 2015). Microcracks, however, are only observable under magnification and typically measure less than 1 mm in length and less than 0.1 mm in width (Anders et al., 2014).

The mechanism behind rock fragmentation and microcrack formation during blasting is complex and not yet fully understood (Khademian and Bagherpour, 2017). The most widely accepted theory suggests that rock breakage due to explosive detonation in blast holes occurs in two stages. First, shock waves propagating from the blast hole generate radial cracks around it. Next, gases produced by the explosion penetrate these cracks, further expanding and extending them (Khademian and Bagherpour, 2017; Olsson et al., 2002). While shock waves primarily contributed to microcrack formation, the movement and displacement of rock fragments were mainly driven by the explosion gases (Olsson et al., 2002). Microcracks played a crucial role, particularly during the grinding stage (Workman and Eloranta, 2003). Microcrack formation began in the initial stage of size reduction, which was blasting. As the material passed through primary and secondary crushers, the number of microcracks increased. Consequently, during the final stage of size reduction–fine grinding–energy consumption decreased. The presence of microcracks enhanced grinding efficiency and reduced the energy required for further size reduction (Nielsen, 1999).

Many studies have demonstrated that optimizing blasting operations can improve mill efficiency by up to 40 % (Brent et al., 2013). Below is a summary of key research conducted on this topic.

Nielsen and Kristiansen (2020) investigated the impact of bulk material size distribution on crushing and grinding processes field and laboratory-scale blasting experiments.

Fuerstenau et al. (1995) conducted plant-scale tests at a porphyry copper operation and found that reducing the blast spacing and burden from 9 meters to 8 meters increased semi-autonomous grinding (SAG) mill efficiency by 5–10 %.

Paley and Kojovic (2001) focused on optimizing the blasting process to enhance the performance of a SAG mill at a lead and zinc mine. Through extensive testing and modeling, they determined that increasing

Table 1 Energy and cost calculations by unit operation (Workman and Eloranta, 2003).

	Feed size (cm)	Product size (cm)	Work input (kWh/T)	Energy cost ($/t)
Explosives		40	0.24	0.087
Primer crushing	40	10.2	0.23	0.016
Seconder crushing	10.2	1.91	0.61	0.043
Grinding	1.91	0.0053	19.35	1.35
Total			20.43	1.50

Table 2 Effect of blasting on the crushing and grinding operations (Nielsen, 1999).

	A blasting operation with a specific charge of 1.2 kg/m^3			A blasting operation with a specific charge of 1.56 kg/m^3		
Status	Size of the feed material (mm)	Particle Size (mm)	Energy Consumption (kWh/T)	Size of the feed material (mm)	Particle Size (mm)	Energy Consumption (kWh/T)
Blasting		840	0.3−0.4		470	0.4−0.5
Primer crusher	840	150	0.3	470	135	0.2
Sekonder crusher	150	20	2.8	135	19.05	2.2
Coarse grinding	20	0.21	6.8	19.05	0.21	6.1
Fine grinding	0.21	0.045	18.2	0.21	0.045	17.3
cost. NOK/ton	04	24	35	5.2	22.2	33

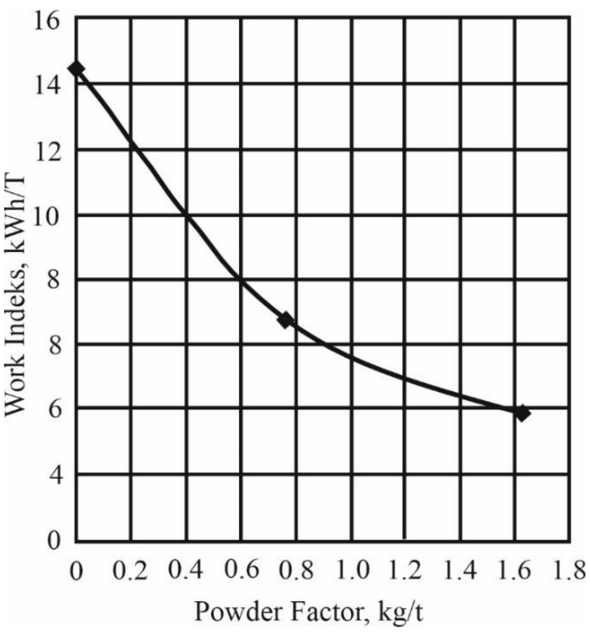

Fig. 3 Work index as a function of the powder factor (Workman and Eloranta, 2003).

the powder factor from 0.29 kg/t to 0.72 kg/t yielded an annual net benefit of $30 million, primarily due to increased concentrate production. A key factor in this success was the identification of the optimal blast fragmentation that maximized mill performance.

Workman and Eloranta (2003) examined the impact of particle size distribution on crushers and mills. They conducted energy and cost analyses based on average particle size and found that a significant portion of total expenditures occurred during the grinding stage (see Table 1). They emphasized the importance of determining the optimal particle size distribution in blasting operations.

Workman and Eloranta (2003) estimated that blasting with a powder factor of 0.45 kg per ton could reduce the work index (W_i) for taconite from 14.87 kWh/T to 10.4 kWh/T. If this reduction persisted through the grinding stage, the work input would decrease by 30 %, leading to a reduction in total energy costs. They emphasized that the economic benefits of this reduction would be substantial. Additionally, they demonstrated the relationship between work index and powder factor (specific charge) for taconite, as shown in Figure 3.

Similarly, Nielsen (1999) found that using a higher specific charge reduced energy consumption during both the crushing and grinding stages (Table 2). Nielsen (1999) also examined the impact of microcracks in the particle mass created during blasting on the crushing and grinding processes. In his study, increasing the specific charge from 1.2 kg/m³ to 1.56 kg/m³ resulted in a 30 % reduction in energy consumption at the primary crusher, a 20 % reduction at the secondary crusher, and a 15 % reduction during the grinding stage.

As shown in Table 2, increasing the specific charge and reducing the reduction ratio led to lower energy consumption, particularly in the fine grinding stage. This effect was primarily due to the formation of microcracks within the particles.

Table 3 summarizes some of the studies detailed above, providing a clear view of the impact of specific charge on the Bond work index.

In blasting operations, specific charge is one of the most important parameters influencing the efficient fragmentation of rock and the particle size

Table 3 Some of the studies aimed at increasing the grinding efficiency.

Researchers	Mine Site	Variable Parameter	Result
Fuerstenau et al. (1995)	Copper	The spacing and the burden have been reduced from 9 m to 8 m.	The efficiency of the SAG mill increased from 5 % to 10 %.
Nielsen (1999)	Taconite	The specific charge increased from 1.2 kg/m³ to 1.56 kg/m³.	The energy consumption in grinding decreased by 15 %.
Paley and Kojovic (2001)	Lead-zinc	The specific charge was increased from 0.29 kg/t to 0.72 kg/t.	Annual benefit of $30 million in SAG costs.
Grundstrom et al. (2001)	Gold	The specific charge increased from 0.66 kg/m³ to 0.85 kg/m³.	The efficiency of the SAG mills increased by 25 %.
Workman and Eloranta (2003)	Taconite	The specific charge was increased from 0.33 kg/t to 0.45 kg/t.	The Bond work index decreased by 30 %.

distribution after blasting. This factor is also related to the Bond Work Index, which directly affects energy consumption and efficiency in ore preparation processes in mining. Although the effects of specific charge on the particle size distribution after blasting have been widely studied in the literature, its impact on the Bond Work Index has been addressed to a limited extent. To fill this gap, this study aims to investigate the effects of specific charge on both the particle size distribution and the Bond Work Index in a limestone quarry. For this purpose, data obtained from various blasting operations were analyzed to determine the relationship between specific charge and the resulting mean particle size, as well as its effects on the Bond Work Index. Additionally, the study evaluates the potential of optimizing energy consumption in mining operations through the influence of specific charge on mean particle size.

2. EXPERIMENTAL STUDIES

As part of this research, the material produced from the monitored blasts in the quarry was fed to crushers and transported to either a cement factory or gravel plants near the quarry, depending on the material properties. It was crucial for the particle size distribution of the heap after blasting to be homogeneous and meet specific size requirements for effective downstream processes. The aim was to demonstrate the efficiency of blasting and determine the effect of specific charge consumption and blast muck pile size distribution on the efficiency of the excavation, loading, transportation, crushing, screening, and grinding processes that follow blasting.

A total of seven blasting operations were monitored. Size distribution analyses were conducted after blasting, and samples were collected from the blasting heap for laboratory experiments to determine the Bond Work Index and assess the effect of blasting efficiency on subsequent ore preparation processes at a limestone quarry. The details of the studies conducted are provided below under the respective headings.

2.1. STUDY AREA

The limestone quarry studied in this research is located near the Bornova district in İzmir province, Türkiye (Fig. 4). The quarry is situated between residential areas in the northeastern part of Bornova. An overview of the study area is shown in Figure 5.

2.1.1. GEOLOGICAL SETTINGS

The foundation of the region consists of the Bornova Mélange, which includes Upper Cretaceous–Paleocene-aged sandstone and shale sequences. The Bornova Mélange rocks are highly folded and fractured. The Neogene-aged Mudstone-Claystone unit and the Clayey Limestone unit unconformably overlie the Bornova Mélange. The Upper Cretaceous–Paleocene Bornova Mélange rocks exposed in the Izmir Metropolitan area primarily consist of conglomerate, micritic limestone, Bornova Flysch, and limestone olistoliths. Flysch serves as the matrix of the Bornova Mélange. The Bornova Mélange unit overlies the basement rocks in the Izmir region. This unit was subjected to intensive tectonic deformation during and after sedimentation (Erdoğan, 1990; Kıncal, 2005; Koca, 1995). The study area comprises Mesozoic rocks, including the Lower Limestone Unit, Middle Limestone Unit, Upper Limestone Unit, and bauxite deposits between them, in chronological order.

2.1.2. DOMINANT ROCK PROPERTIES OF THE STUDY AREA

To assess the physical and mechanical properties of the rock in the limestone quarry where blasting operations were observed, block samples were collected from the site. Core samples were extracted in the laboratory, and various physical and mechanical tests were conducted to analyze the rock properties. The results are presented in Table 4.

2.2. MONITORING AND EVALUATION OF THE BLASTING OPERATIONS

During the initiation stage of the study, fieldwork was conducted to monitor seven blasting operations. Technical data related to the blasting operations, including the location of the blasts, hole diameter, burden thickness, spacing, hole depth, stemming

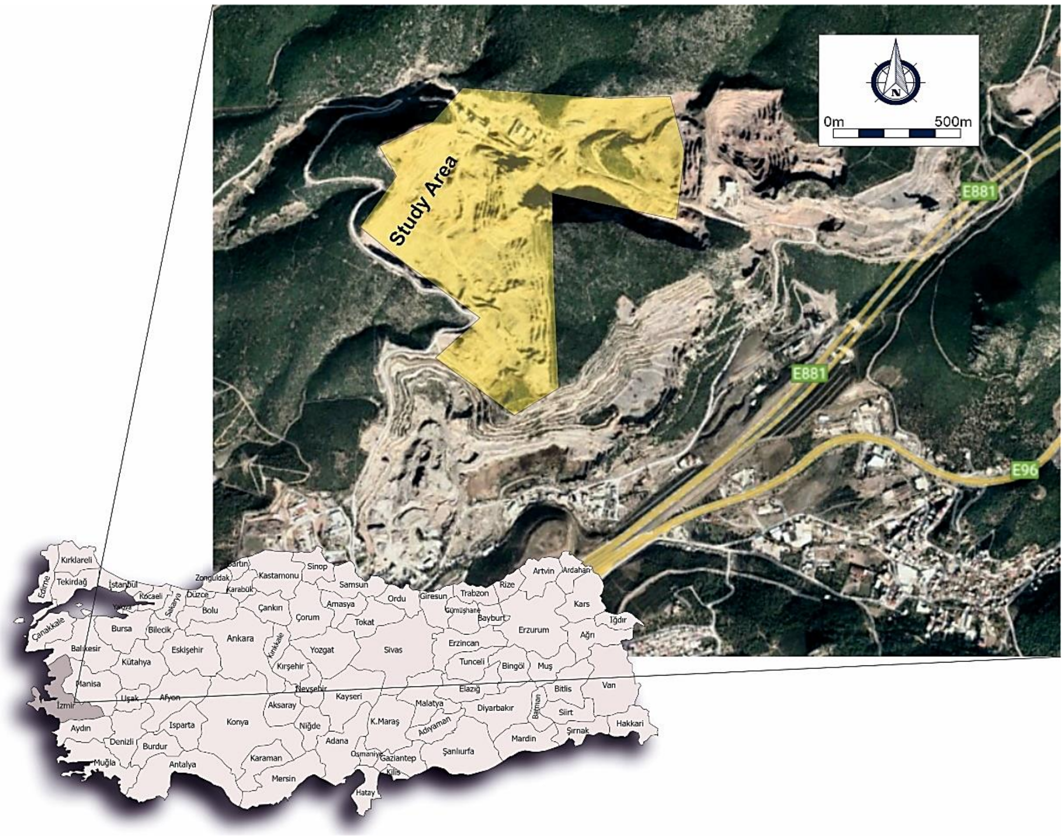

Fig. 4 The location map of the study area.

Fig. 5 Overview view of the study area.

Table 4 Properties of the rock in the limestone quarry

Density	2.73 g/cm^3
Unit weight per unit volume	2.65 g/cm^3
Uniaxial compressive strength	29.5 MPa
Shore hardness	42.8

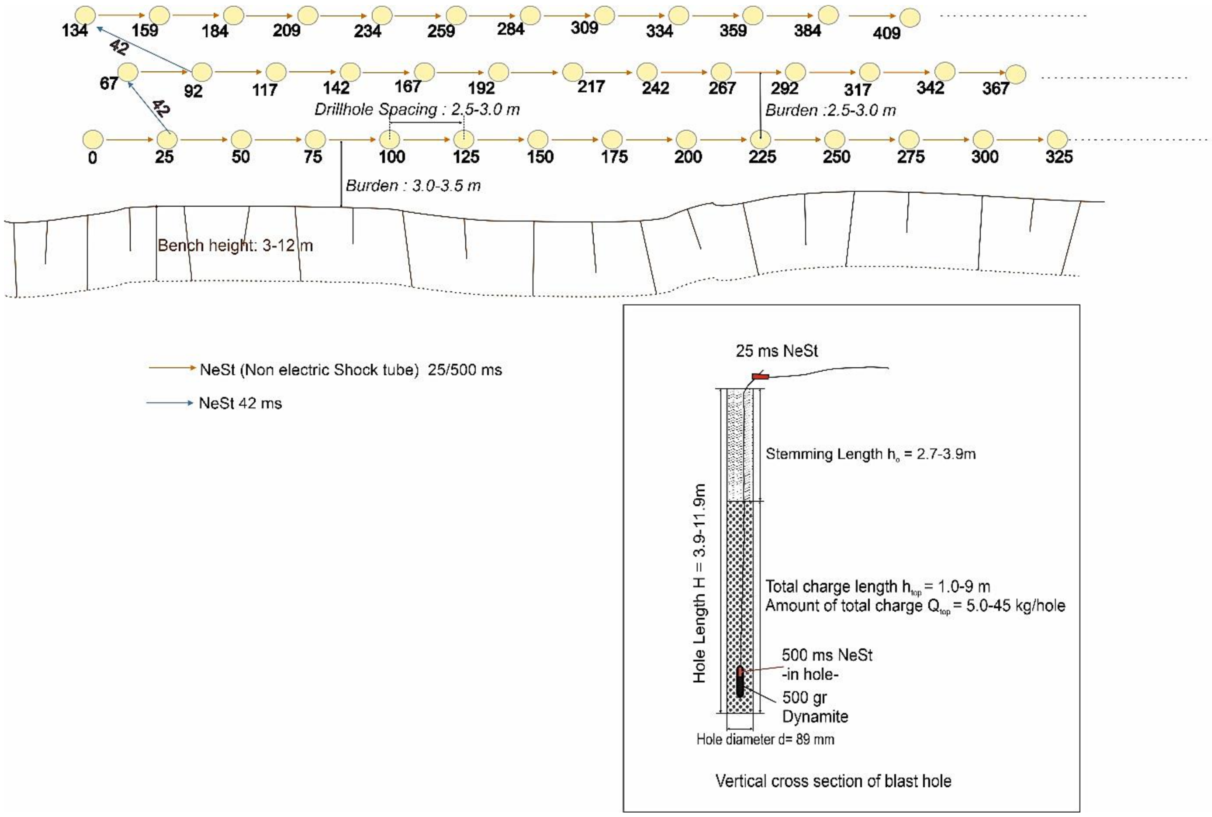

Fig. 6 Plan view of the Blast-1 initiation system and the blast hole profile.

Fig. 7 Blasting area of Blast-1.

length, delay intervals, stemming material, and the amount of explosive ammonium nitrate fuel oil (ANFO) per delay, as well as the total amount of ANFO, were recorded. In the blasting operations using non-electric delay detonator technology, the hole diameter ranged from 89 mm, and the spacing was between 2.5 and 3.5 m. The burden ranged from 3.0 to 3.5 m. Non-electric delay detonators with delay times of 500 ms inside the hole, 25 ms on the surface, and 42 ms on the surface were used. The bench height in the study area varied between 3 and 12 m. The hole geometry and initiation system plan for Blast-1, along with the vertical section of the hole, are provided in Figure 6 as an example. An image of the blasting area is shown in Figure 7.

To determine the particle size distribution of the muck pile after blasting, the resulting piles were divided into sections and photographed at a scale for analysis. Multiple images were captured from the pile to ensure the accuracy of the results. Photographs were taken after each blast, with an average of 15 images per blast. The images for each muck pile were analyzed using WipFrag Image Analysis Software (WipWare, 2020), and size distribution curves were generated for each blast. The steps of the size distribution analysis for a muck pile photograph from one of the monitored blasts are shown in Figure 8. Average particle sizes, the number of blocks affecting k_{50}, and specific charge values are provided in Table 5

The effect of specific charges on the distribution can be observed by consolidating the size distribution graphs of the seven blasts into a single graph (Figure 9).

2.3. LABORATORY STUDIES

In this study, work indices were calculated using the Bond Method on samples collected from the muck piles after each of the seven blasting operations. Sampling was conducted at both the inlet and outlet points of the tertiary crusher within the crushing plant. This procedure was repeated for each of the seven blasting events. The samples from the crushing plant were then reduced to approximately 6 kg through various sample reduction methods in the laboratory.

The samples were crushed to a particle size of less than 3.35 mm to facilitate controlled Bond testing.

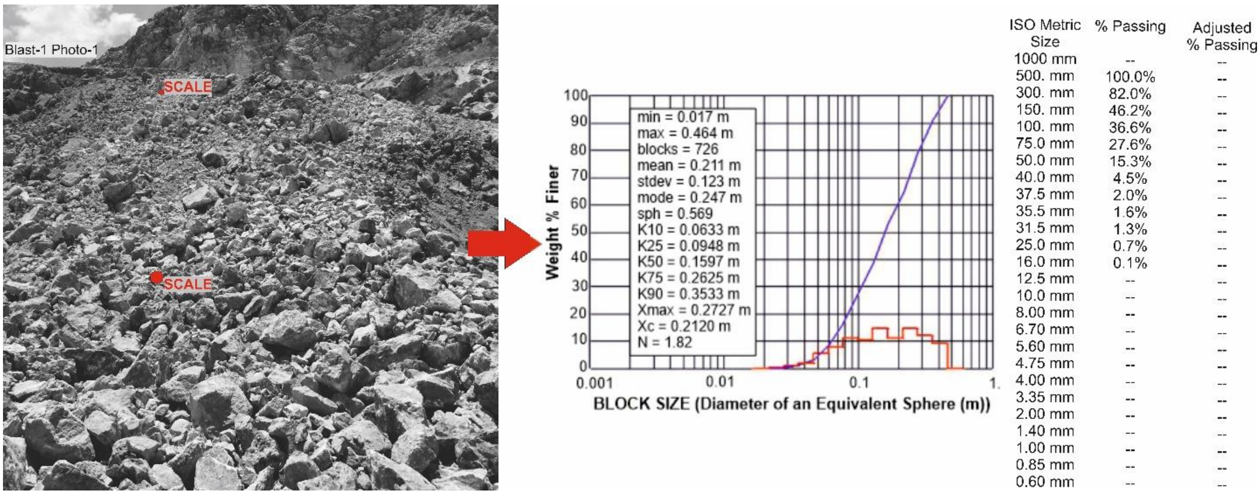

Fig. 8 Analysis steps of a photograph from the muck pile of Blast-1.

Table 5 Average particle sizes, number of blocks affecting k_{50}, and specific charge values.

Blast No	Specific charge value (kg/m^3)	Total number of blocks analyzed	Average particle size (k_{50}) (m)
B1	0.43	2056	0.251
B2	0.49	2903	0.212
B3	0.35	1552	0.272
B4	0.33	1108	0.312
B5	0.43	3261	0.198
B6	0.33	689	0.369
B7	0.42	1322	0.225

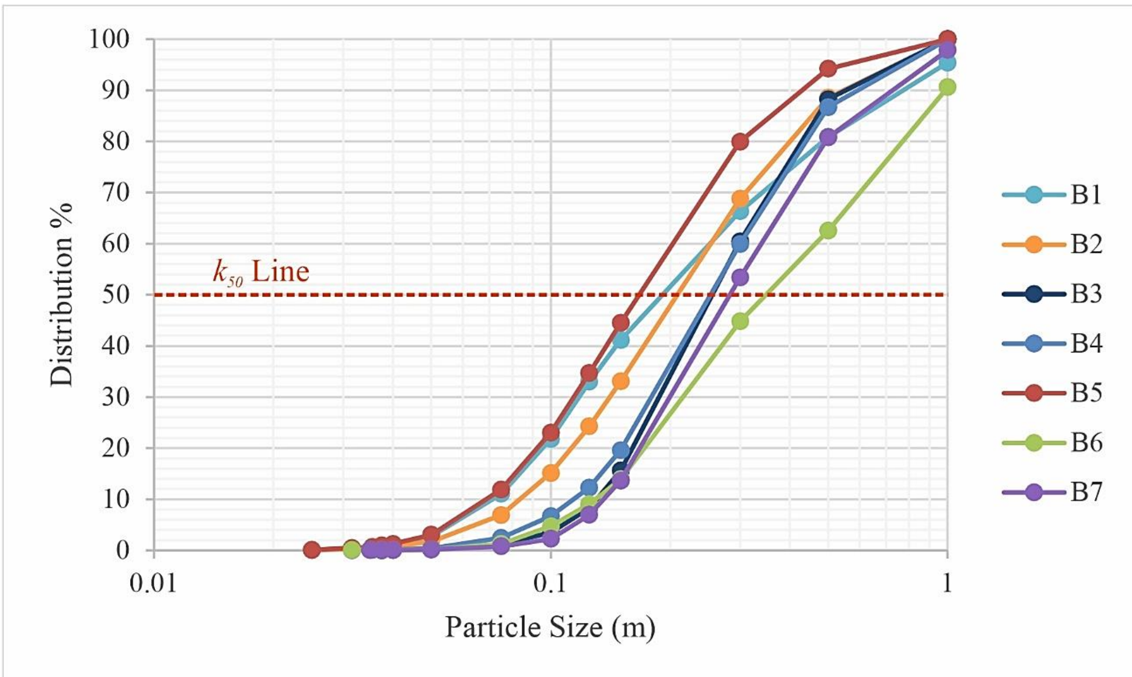

Fig. 9 Size distribution graphs of the seven blasts.

The feed sample for the Bond test was prepared, and a particle size analysis was conducted on the feed material. The sieve fractions of the feed material included sizes of 3.35, 2.36, 1.70, 1.18, 0.85, 0.60, 0.425, 0.300, 0.212, 0.150, and 0.106 mm. During the sieve analysis, the feed material samples were weighed, and both percentage and undersize values were determined. A total of 285 steel balls, weighing 20,125 grams, were used as the grinding media. After placing the Bond sample feed material into the mill, the initial speed was set to 100, and the grinding process began with the mill's rotation. The laboratory Bond mill used in this study is illustrated in Figure 10.

Fig. 10 Laboratory Bond mill used in this study.

The ground material was passed through a series of sieves with sizes of 0.600 mm, 0.425 mm, 0.300 mm, 0.212 mm, and 0.106 mm to determine the amount of material below 0.106 mm. The materials retained above 0.106 mm were combined and weighed. This weight was subtracted from the total weight of the Bond sample feed material to calculate the amount of additional material needed. Based on the percentage values of the samples (-3.35 mm, -2 mm, - 1 mm), the amount of material to be added to the portion above 0.106 mm was determined using sample reduction methods. The material was then prepared for grinding, made ready for milling, and fed into the mill.

The number of cycles for the second grinding process was determined by the amount of material produced below 0.106 mm during the first grinding. The grinding cycle was terminated when the circulating load reached 250 % and the values of the undersized product produced per cycle converged. The equation related to this process is provided below:

$$Circulating\ Load = \frac{(Bond\ Sample\ Feeding\ Material) - (material\ produced\ below\ 0.106\ mm\ per\ cycle)}{(0.016\ product\ obtained\ per\ cycle)}\ X\ 100$$

The average of the undersized product generated per cycle for the last three cycles provided the grindability value of the ore that could be ground in the ball mill, expressed as G_{bp}. The 0.106-mm sample from the last cycle was analyzed using sieves with sizes of 0.106, 0.075, 0.053, and 0.045 mm.

The work index (W_i) was calculated using the following equation. It incorporated three key size parameters: F, representing the particle size through which 80% of the sample feed passed; P, the size of the material that had been ground in the last cycle and passed through the sieve; and P_1, the size of the test sieve (Bond, 1952).

$$\mathrm{W_i} = \frac{44.5}{(P_1)^{0.23}\ x\ (G_{bp})^{0.82}\ x\ (\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}})}\ \mathrm{(kWh/T)}$$

W_i = Work index (kWh/T)
F = The particle size through which 80 % of the sample feed passed (micron)
P = The size of the material that had been ground in the last cycle and passed through the sieve (micron)
P_1 = The size of the test sieve (micron)
G_{bp} = The grindability value (g/rev)

In the experiments conducted in this study, P_1 was set to 106 microns. The results from the seven Bond work index tests, as described above, are presented in Table 6.

Table 6 Bond work index values obtained from the seven blasts.

Blast No	Bond Work Index (kWh/T)
B1	10.9
B2	7.8
B3	13.8
B4	11.8
B5	9.7
B6	13.7
B7	12.9

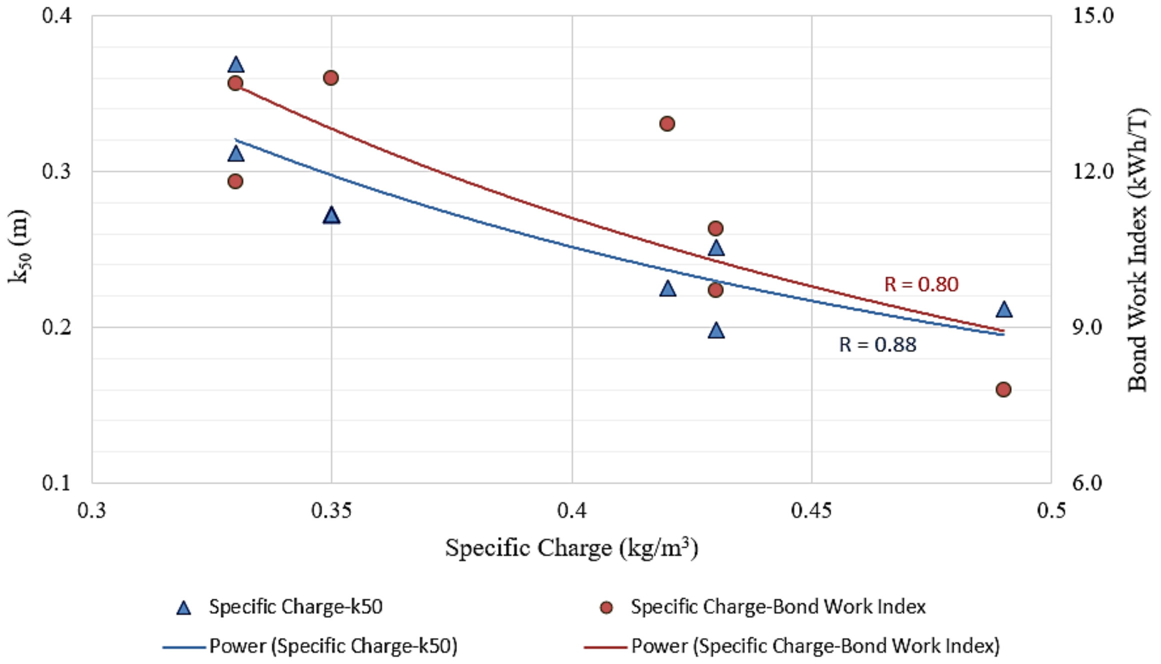

Fig. 11 Relationship between the Specific Charge, Mean Particle Size (k_{50}), and Bond Work Index.

Table 7 Model Summary.

	R	R^2	Adjusted R^2	Std. Error of Estimate
k_{50}	0.877	0.769	0.722	0.117
Bond Work Index	0.801	0.641	0.569	0.136

Independent variable: Specific charge

The experimental results from samples of the seven blasts showed that the lowest Bond work index value was obtained from the Blast-2 sample, while the highest value came from the Blast-3 sample, as shown in Table 6.

3. COMPARISON OF THE OBTAINED DATA

This study monitored seven blasting operations in a limestone quarry, recording relevant blasting parameters. The size distribution of the muck pile after blasting was determined using image processing techniques, and samples were taken from the pile during the feeding process to the crusher for laboratory Bond tests. Drilling-blasting, crushing, and grinding operations are directly interconnected. Achieving homogeneous fragmentation and preventing the formation of large blocks during blasting are crucial for reducing energy consumption in grinding. Additionally, the particle size fed into the primary crusher should be optimized to enhance the grinding process. Therefore, the relationship between the specific charge value, the muck pile's mean particle size, and the Bond work index for the seven blasting operations was examined using bivariate regression analysis.

As seen in Figure 11, an increase in the specific charge leads to a decrease in the average fragment size (k_{50}) and the Bond Work Index, indicating improved fragmentation and reduced grinding energy requirements. The relationship presented in the figure 11 has been analyzed using the SPSS software (SPSS Statistics, 2024), and the Model Summary table is provided in Table 7.

The average particle size (k_{50}) obtained from the muck pile after blasting is critical for the loading process and the material fed into the crushers. Maintaining the material within specific size ranges is essential for efficient feeding to the crushers. In the graph shown in Figure 11 (blue line), a numerical analysis was conducted to establish the relationship between specific charge and average particle size (k_{50}). The analysis revealed an 88 % correlation between the two variables. In other words, as the specific charge increased, the particle size decreased, with a regression coefficient of 0.88. A standard error of 0.117 suggests that the model effectively explains the relationship between specific charge and k_{50}, though it indicates a prediction error margin of roughly 11.7 %. As shown in Figure 11 (red line), the relationship between specific charge and the Bond work index was established with a regression coefficient of 0.80. It is evident that as the specific charge increased, the Bond work index decreased. A standard error of 0.136 indicates that the model explains the relationship between specific charge and Bond work index well, but there may still be an error margin of approximately 13.6 % in the predictions. These evaluations clearly demonstrated that optimizing the specific charge value in quarries, with consideration of economic factors, is crucial for both the initial production stage (blasting) and the final stage (grinding). Such optimization is essential for improving overall operational efficiency.

The relationship between specific charge and mean fragment size was examined, revealing an 88 % correlation. Specifically, as the specific charge increases, the mean fragment size (k_{50}) decreases, with a regression coefficient of 0.88. Furthermore, the relationship between the Bond Work Index, obtained from grinding experiments conducted with samples from seven different blasts and corresponding specific charge values, was established, yielding a regression coefficient of 0.80. The study concluded that as the specific charge increases, the Bond Work Index–an indicator of energy consumption during grinding–decreases. Both field and laboratory studies demonstrated that the specific charge value affects the fragment size distribution of the blasted pile, which in turn indirectly influences the grinding process.

4. CONCLUSION

This study investigated the relationship between the particle size distribution from blasting operations and the energy consumption required for grinding. Bond Theory was utilized for this purpose. The Bond work index measures a material's resistance to grinding and is widely used in the design of grinding circuits. On the other hand, the particle size distribution of the muck pile produced by blasting reflects the fragmentation efficiency. If the muck pile after blasting is larger or has an undesirable size distribution, grinding the material becomes more difficult, increasing the Bond work index. Therefore, controlling the size distribution of the muck pile produced after blasting to reduce energy consumption during grinding–i.e., optimizing blast fragmentation–is crucial for achieving optimal grinding performance and overall energy efficiency.

Drilling, blasting, crushing, and grinding processes are directly interconnected. Ensuring homogeneous fragmentation and preventing the formation of large blocks during blasting is critical to reducing energy consumption during grinding. Additionally, the particle size fed into the primary crusher plays a significant role in optimizing the overall grinding process.

To analyze this relationship, bivariate regression analyses were conducted using specific charge values ranging from 0.33 to 0.49 kg/m^3, mean particle sizes of muck piles from each of the seven blasts, and their corresponding Bond work indices. A significant correlation of 88 % was found between specific charge and mean particle size (k_{50}), indicating that the mean particle size decreases as the specific charge increases. Furthermore, the relationship between specific charge and the Bond work index was determined with a regression coefficient of 0.80. As the specific charge increases, the Bond work index, which represents the energy required for grinding, decreases. This demonstrates that higher specific charge values lead to finer fragmentation, reducing grinding resistance and lowering energy consumption.

As the specific charge increases, the number of microcracks formed during blasting increases. These microcracks are further enhanced as the material passes through primary and secondary crushers, reducing energy consumption during the final stages of fine grinding and size reduction. A higher Bond work index indicates that the size distribution of the muck pile is larger, suggesting that an appropriate specific charge value was not used and that insufficient microcracks were formed. The relationship between these parameters helps optimize blasting operations to produce particle sizes that are conducive to lower energy consumption in grinding.

The findings of this study underscore the strong interconnections between blasting and grinding processes. Optimizing specific charge values not only ensures a more efficient fragmentation process but also reduces energy consumption during grinding, thereby enhancing the operational efficiency of mining operations. These results demonstrate the strong link between blasting and grinding processes. Optimizing specific charge values not only facilitates a more efficient fragmentation process but also reduces energy consumption during the grinding stage, thereby enhancing the operational efficiency of the quarry.

REFERENCES

Anders, M.H., Laubach, S.E.and Scholz, C.H.: 2014, Microfractures: A review. J. Struct. Geol, 69, 377–394. DOI: 10.1016/j.jsg.2014.05.011, 2014

Asgari, A.R., Farshad, N. and Norouzi, S.: 2015, Blast-induced rock fracturing and minimizing downstream comminution energy consumption. 41st Annual Conference on Explosives and Blasting Technique, New Orleans, LA.

Bond, F.C.: 1952, The third theory of comminution. Transact. Am. Inst. Min., Metall., Petrol. Eng, 193, 484–494.

Brent, G., Rothery, M., Dare-Bryan, P., Hawke, P., Gomez, R. and Humeres, I.: 2013, Ultrahigh intensity blasting for improved ore comminution. Fragblast,10, 163–169.

Chakraborty, A.K., Raina, A.K., Ramulu, M., Choudhury, P.B., Haldar, A., Sahu, P. and Bandopadhyay, C.: 2004, Parametric study to develop guidelines for blast fragmentation improvement in jointed and massive formations. Eng. Geol., 73, 105–116. DOI: 10.1016/j.enggeo.2003.12.003

Erdoğan, B.: 1990, Tectonic relations between İzmir–Ankara zone and Karaburun belt. Bull. Miner. Res. Explor., 110, 1–15.

Esen, S.: 2013, Fragmentation modelling and the effects of ROM fragmentation on comminution circuits. 23rd International Mining Congress & Extibition of Turkey, 251–260.

Fuerstenau, M., Chi, G. and Bradt, R.: 1995, Optimization of energy utilization and production costs in mining and ore preparation processes. 19. international mineral processing congress, San Francisco.

Grundstrom, C., Kanchibotla, S.M., Jankovich, A. and Thornton, D.: 2001, Blast fragmentation for maximising the SAG mill throughput at Porgera gold mine. ISEE 27th Ann. Conf. Expl. & Blasting Techn., 1, 383–399.

Herbst, J.A. and Pate, W.T.: 1998, Dynamic simulation of size reduction operations from mine to mill. Proceedings Mine to Mill Conference, 4, 98, 243–248.

Hoek, E. and Bray, J.D.: 1991, Rock Slope Engineering: Third Edition, CRC Press, 368 pp.

Kanchibotla, S.S.: 2014, Mine to mill value chain optimization: role of blasting. In: Anderson, C.G., Dunne R.C. and Uhrie, J.L. (Eds.), Mineral Processing and Exractive Metallurgy: 100 Years of Innovation. ~~Uhrie,~~ Society for Mining, Metallurgy & Exploration, 51–64.

Kanchibotla, S., Morrell, S., Valery, W. and O'loughlin, P.: 1998, Exploring the effect of blast design on SAG mill throughput at KCGM. Mine to Mill Conference, Brisbane, 153–158.

Khademian, A. and Bagherpour, R.: 2017, Alteration of grindability of minerals due to applying different explosives in blasting operation. Min. Eng., 111, 174–181. DOI: 10.1016/j.mineng.2017.06.016

Kim, S.J.: 2010, An experimental investigation of the effect of blasting on the impact breakage of rocks. Master Thesis, Department of Mining Engineering, Queen's University.

Kıncal, C.: 2005, Engineering geological evaluation of the geological units exposed in the Inner Bay Area (Izmir vicinity) using Geographical Information Systems and remote sensing techniques. Ph.D Thesis, Dokuz Eylul University, Izmir, 342 pp., (in Turkey).

Koca, M.Y.: 1995, Slope stability assessment of the abandoned andesite quarries in and around the Izmir city centre. Ph.D Thesis, Dokuz Eylul University, Izmir, Turkey.

Mackenzie, A.S.: 1967, Optimum blasting. Proceedings of the 28th Annual Minnesota Mining Symposium, 181–188.

Nielsen, K.: 1999, Economic effects of blasting on the crushing and grinding of ores. -In: Proc. 6th Int. Symp. on Rock Fragmentation by Blasting, 251–256.

Nielsen, K. and Kristiansen, J.: 2020, Blasting-crushing-grinding: Optimisation of an integrated comminution system. Rock Fragmentation by Blasting. In book: Rock Fragmentation by Blasting, 269–277. DOI: 10.1201/9781003078104-38

Nielsen, K. and Malvik, T.: 1999, Grindability enhancement by blast-induced microcracks. Powder Technol., 105, 1–3, 52–56. DOI: 10.1016/S0032-5910(99)00117-5

Olsson, M., Nie, S., Bergqvist, I. and Ouchterlony, F.: 2002, What causes cracks in rock blasting? Fragblast, 6, 2, 221–233. DOI: 10.1076/frag.6.2.221.8668

Ouchterlony, F.: 2003, Influence of blasting on the size distribution and properties of muckpile fagments: a state-of-the-art review. MinFo project P2000-10: Energy optimisation in comminution, Luleå University of Technology.

Paley, N. and Kojovic, T.: 2001, Adjusting blasting to increase SAG mill throughput at the Red Dog mine. Proc. of 27th Annual Conf. on Explosives and Blasting Research, Orlando, 65–80.

Parra, H., Onederra, I., Michaux, S., Kuhar, L., McFarlane, A. and Chapman, N.: 2015, A study of the impact of blast induced conditioning on leaching performance. Miner. Eng., 74, 1–12. DOI: 10.1016/j.mineng.2014.12.032

Sanchidrian, J.A., Ouchterlony, F., Moser, P., Segarra, P. and L´opez, L.M.: 2012, Performance of some distributions to describe rock fragmentation data. Int. J. Rock Mech. Min. Sci, 53, 18–31. DOI: 10.1016/j.ijrmms.2012.04.001

Seccatore, J.: 2019, A review of the benefits for comminution circuits offered by rock blasting. REM-Int. Eng. J, 72, 141–146. DOI: 10.1590/0370-44672017720125

Shehu, S.A. and Hashim, M.H.M.: 2020, Evaluation of blast fragmentation and its benefits: a review of the paradigm and ambiguity. Int. J. Min. Miner. Eng., 11, 338–358. DOI: 10.1504/ijmme.2020.10034283

SPSS Statistics. (30.0.0): 2024, IBM.

WipFrag Image Analysis Software, WipWare.: 2020.

Workman, L. and Eloranta, J.: 2003, The effects of blasting on crushingand grinding efficiency. ISEE 29th Explosives and Blasting Technique Conference, Nashville, Tennessee.