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Optimization of the powder factor during rock masses blasting according to their intrinsic properties

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ABSTRACT

The primary aim of mining enterprises is to extract commodities that can be sold commercially. As a result, it is always essential to look for technological solutions to minimize production costs with the most optimized working results. Optimizing rock blasting parameters is one of the technological solutions used. These parameters differ from one mine to another, as each mine has different conditions. The present work was carried out at the Kef Essenoun phosphate mine in northeastern Algeria, with the main aim of optimizing the powder factor when blasting rock massifs according to their intrinsic characteristics to attain optimal outcomes from both technical and economic perspectives. To achieve this objective, we carried out field measurements to understand the characteristics of rock mass discontinuities. These measurements were then mapped using DIPS software. Laboratory studies were conducted to examine the physical and mechanical properties of the rock matrices (limestone and phosphate). Fragmentation results were analyzed using the Kuz-Ram model to compare the firing plans proposed by the company with those actually carried out. The results obtained by the Kuz-Ram model were validated using Wip-Frag software. The results show great convergence on the technical side (degree of fragmentation) and a significant difference on the economic side. This difference corresponds to the extraction cost of limestone and phosphate rock, which could be reduced approximately 812,000 USD per year through the optimization of the amount of explosives used in the proposed blasting plans. The optimization also diminishes the vibrations linked to blasting, leading to improved safety and enhanced slope stability.

Keywords: *Fragmentation, Powder factor, Discontinuities, Image analysis, Kuz-Ram.*

1. Introduction

Mining is a significant industry that influences the economic and technological advancement of nations globally [1]. This industry faces many challenges, including the analysis and evaluation of mining performance and productivity, especially in open-pit mining. This activity is crucial for attaining optimal operational efficiency, minimizing expenses, and maximizing revenues [2]. The management of blasting operations during ore extraction is crucial, as the efficiency of all mining activities utilizing drilling and blasting relies on it. Increasing blast energy does not necessarily improve fragmentation. The economic assessment of high-budget projects involving drilling and blasting necessitates a thorough investigation of explosive performance and blasting process management [3]. The execution of blasting in multiple open-cast mines demonstrates that a mere fraction of the explosive energy is utilized in the rock fragmentation process, while the remainder is lost as seismic vibration, air-blast, and heat [4, 5]. It is, therefore, necessary for blasting designers to evaluate the performance of the blasting result in order to control the energy use of the explosive charge to obtain optimal working results [6]. In open-pit mining, blasting efficacy can be evaluated based on the extent of fragmentation, dislodged-rock volume, spoil-pile displacement and configuration, intact-rock damage, ground vibration, air-blast, fly-rock, toxic gases, and ore dilution [7]. Rock fragmentation is among the most frequently optimized outcomes of blasting [8]; it influences the efficiency and expenses of subsequent mining operations, including loading, crushing, grinding, etc. [9, 10]. Both direct approaches (e.g. sieve analysis) and indirect methods (e.g. observational, experimental, or image-based techniques) can be employed to examine and assess rock fragmentation (Figure 1) [11].

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An efficient blasting operation is characterized by a maximum proportion of fragments within the specified size range that may be transported by handling equipment and utilized by the consumer for subsequent operations without additional processing [12]. Optimal blasting is linked to the most effective utilization of blasting energy in the rock fragmentation process. This minimizes blasting expenses by decreasing the usage of explosives and minimizing the dissipation of explosive energy during detonation, decreases the projection of materials, and reduces vibrations associated with blasting, leading to higher degrees of safety and greater stability for adjacent structures [13]. To achieve these objectives, it is necessary to identify the factors that affect blasting efficiency [14]. There are two categories of factors influencing rock fragmentation: controllable and uncontrollable factors [15]. Controllable factors are aspects that engineering and the site crew can regulate and adjust to attain the intended outcomes. These elements are categorized into geometric parameters, specifically bench and blast geometry (Figure 2); parameters include borehole diameter, load, sub-drilling, and bench height; physico-chemical factors encompass explosive type, powder factor, explosive strength, and primer; temporal aspects involve initiation type and detonation systems, as well as the blasting initiation sequence. Uncontrollable variables are geological parameters that determine the properties and structures of the rock formation in situ. They include cracks, fractures, faults, joint planes, cavities and mud veins, density and porosity, compressive and tensile strengths [16, 17]. Various studies indicate that precise monitoring of the powder factor is crucial for optimizing explosive consumption in blasting operations and for forecasting efficient and optimal blasting conditions in mines [18-20]. This factor indicates the amount of explosives necessary to fragment one cubic meter of rock [21]. An appropriate powder factor for minimizing total costs is characterized by its ability to provide effective fragmentation, reduced projection, and less ground vibration [22]. Many researchers have reported that the study of rock mass characteristics facilitates the selection and optimal use of explosives during bench blasting [23, 24]. All evidence clearly indicates that the attributes of the blasted rock mass significantly influence blasting outcomes [25-27]. In Algeria, blasting operations at the Kef Essenoun phosphate mine utilize a nearly uniform blasting plan across various rock formations, particularly regarding the powder factor, without accounting for the primary intrinsic characteristics of the rock formations that substantially affect the technical and economic outcomes of the blasting. This study seeks to establish a method for optimizing the powder factor for blasting in this mine, with the objectives of minimizing blasting costs and mitigating vibration issues within the mine. This methodology, which involves the characterization of limestone and phosphate rock formations, including their physical and mechanical qualities as well as the mapping of discontinuities (fissures), seeks to ascertain the appropriate quantity of explosives required. This facilitates the creation of blasting plans customized to the unique characteristics of each rock formation, rather than employing a standardized approach. We examined the fragmentation outcomes utilizing the Kuz-Ram prediction model to compare the blasting plan executed by the corporation with the intended plans. The outcomes derived from the Kuz-Ram model were corroborated by image analysis utilizing the Wip-Frag software.

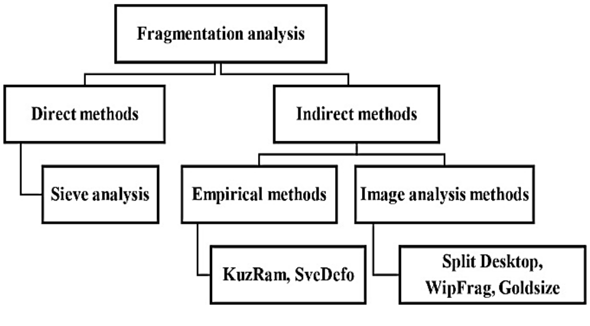


Figure 1. Flowchart of fragmentation analysis techniques.

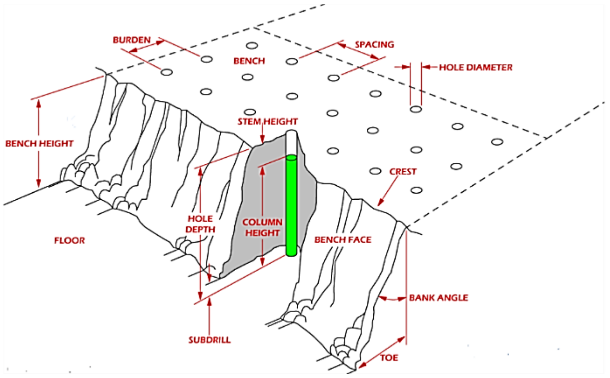


Figure 2. Geometry of bench blasting.

2. General setting

Phosphates from Algeria's DjebelOnk basin are associated with Tertiary marine deposits. This mining basin comprises five phosphate deposits: Djemi-Djema, Dj. Onk Nord, Kef Essenoun, Bled El Hadba, and OuedBetita [28-30]. The Kef Essenoun deposit is situated in southeastern Algeria, 100 km from the Wilaya of Tébessa and 20 km from the Algerian-Tunisian border, along the route between Tébessa and El Oued (Figure 3).

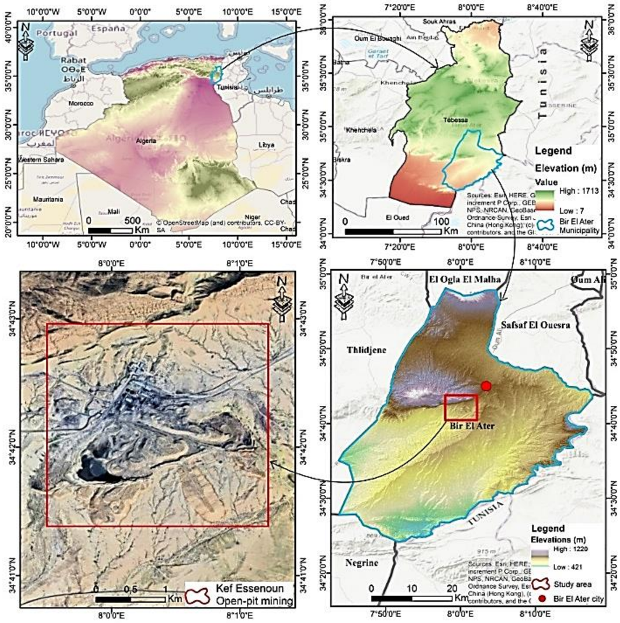


Figure 3. Location map of the study area.

The Kef Essenoun deposit is situated near the southern base of the Djebel Onk mountain range. The latter is a limestone massif about 20 km in length and 3 km in width, aligned from east-west to east-northeast-west-southwest to an elevation of 1192 m at Djebel Tarfaya. The summit of the Kef Essenoun deposit surpasses 900 m in elevation and predominantly consists of limestone, descending gradually to the mining site at 700 m. This mountain features a substantial Maestrichtian limestone cliff almost 100 m in height [31]. The deposit area is influenced by a trio of significant NNW-SSE transverse faults, exhibiting no substantial modification of its geometry [32]. The Kef Essenoun deposit comprises the subsequent lithological sequence arranged from bottom to top (Figure 4). [33]: The bottom Thanetian formations, constituting the phosphate beam's wall, are characterized by dark, laminated marls that locally incorporate two sub-metric layers of dolomitic phosphates in the bottom section;

- The phosphate beam from the Upper Thanetian comprises a singular phosphate layer devoid of sterile intercalation;

- At the summit of the phosphate beam, the Ypresian flinty calcareous-dolomitic series is present, upon which Lutetian limestones are occasionally superimposed, succeeded by Miocene sands and, ultimately, recent Quaternary deposits predominantly including alluvium. The overall thickness of the sterile overburden ranges from 40 m in the north to 198 m in the south.

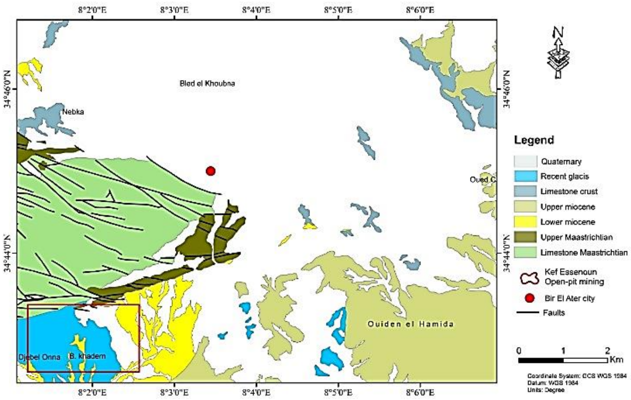


Figure 4. Geological map of the research region.

The Kef Essenoun phosphate deposit contains 168 million tonnes (Mt) of confirmed reserves, with ore containing 26.53% P_2O_5 and 2.16% magnesium oxide [34]. The deposit is mined by an open-pit method involving drilling and blasting to extract the phosphate and overlying rocks (limestone). Holes parallel to the slope of the step are drilled and charged with two types of explosives: Anfomile, in bulk, is used as the primary explosive, while Marmanite III, in cartridges, is used for priming. Two blasts are fired each day, one for limestone and one for phosphate ore.

3. Materiel and methods

3.1. Rock fragmentation process

Rock fragmentation through blasting is a multifaceted dynamic process associated with the interaction between the rock mass and explosives [35]. This process can be delineated into several stages: the decomposition of explosives into gas under elevated pressure and temperature, the transmission of shock waves through the rock mass, the fracturing or damage of the rock, the expansion of gases through the newly formed zones of weakness, the formation of cracks, and subsequently, the displacement and ejection of fragments (Figure 5).

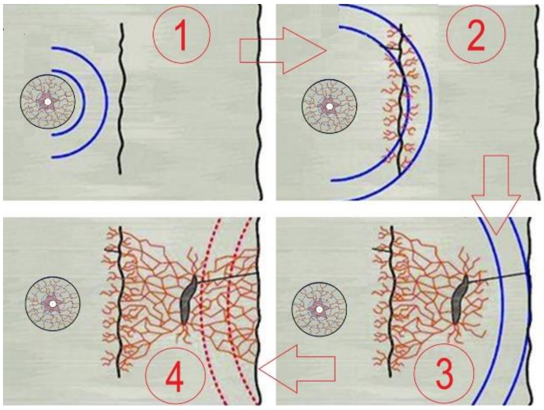


Figure 5. An illustrative diagram summarizes the essential steps of blasting in rocks: 1. hole radius; 2. radial cracking; 3. elastic limit; 4. ductile deformation and fragmentation [36].

Numerous scholars have experimentally and numerically examined the damaged regions surrounding a single-hole blast, showing that the extent of these areas is primarily controlled by both explosive properties, such as detonation velocity, density, and detonation pressure, and the mechanical resistance of the rock mass, including uniaxial compressive strength, tensile strength, Young's modulus, and Poisson's ratio. The heterogeneous and anisotropic nature of the rock, intersected by fractures, joints, and other structural features, further modifies the distribution of explosive energy and crack propagation, potentially causing partial propagation, reflection, or complete cessation of stress waves depending on the structural characteristics and the stress intensity. Wang et al demonstrated that stress intensity factors at the tips of pre-existing cracks are governed by blasting-induced displacements [37], while Fatehi Marji et al confirmed that radial crack propagation around blast holes can be effectively modeled using displacement discontinuity methods [38]. Sarfarazi et al showed that blasting-hole spacing, free-surface proximity, rock texture, and temperature strongly influence crack growth, energy dissipation, and the size of the damage zone [39, 40]. Haeri further demonstrated that interactions among neighboring cracks significantly alter stress intensity factors and crack growth paths under compressive loading [41], and Sarfarazi et al. reported that microscopic tensile breakages dominate fracture propagation and that the semi-circular bend test provides fracture toughness values closely matching direct measurements [42].

3.2. Assessment of powder factor utilizing rock mass characteristics

The determination of blasting and drilling parameters for open-cast mining relies on Vauban's volumetric hypothesis, which establishes a relationship between the volume of the blasted block V and the requisite quantity of explosive Q:

$$Q = q \times V \tag{1}$$

where q: specific consumption of the explosives, kg/m^3.

This assumption is crucial for calculating the amount of explosives needed in the borehole and for the entire block. The primary objective is to ascertain the optimal specific consumption of explosives, the principal energy metric for blasting [43]. In the majority of scientific publications in this field, specific explosive consumption is expressed by the term powder factor (K) [44]:

$$K = \frac{\text{mass of explosive (Q)}}{\text{Volume of rock blasted (v)}} \tag{2}$$

Diverse methodologies and combinations have been employed by various researchers to ascertain the powder factor, predominantly considering the attributes of the rock mass, which are the most critical factors of rock-explosive interaction [45].

Ashby [46] posits that the powder factor necessary for efficient blasting can be ascertained as a function of fracture density (fracture frequency) and the effective friction angle, which denotes the resistance of the broken rock mass.

Lilly [47] established a formula to calculate the powder factor (q) based on the blastability index (BI). Lilly [48] proposed the blastability index (BI) as the aggregate of representative values from five rock mass parameters: rock mass description (RMD), joint plane spacing (JPS), joint plane orientation (JPO), specific gravity influence (SGI), and Mohs hardness (H) [49].

$$q = 0.004BI \tag{3}$$

Lilly [47] reanalyzed the Block Index (BI) and adapted it to various rock mass conditions prevalent in open-pit mines, utilizing uniaxial compressive strength (UCS) in lieu of Mohs hardness (H).

$$BI = 0.5\,(RMD + JPS + JPO + SGI + 0.05\,UCS) \tag{4}$$

Agyei and Nkrumah [50] examined the diverse methodologies for calculating the powder factor in both surface and underground blasting operations, including estimation based on Bond's Work Index, fragmentation theory, artificial neural network models, and regression models. The researchers examined the influence of undisturbed rock attributes on powder factor selection and investigated the implications of this choice on blast design.

3.2.1. Discontinuities characteristics

A rock mass is primarily characterized by its heterogeneity, complicate the planning and execution of a blasting strategy. The heterogeneity will influence the massifs structure; contingent upon the tectonic stresses experienced (presence of discontinuities) and its characteristics [51]. Therefore, comprehending the attributes and positioning of discontinuities is crucial for enhancing blasting operations [52]. Characterizing rock mass discontinuities (fissures, fractures and faults, etc.) involves identifying their geometric characteristics (orientation, extension and density, … etc.) and their mechanical characteristics such as filling, roughness and, in particular, shear strength [53]. The network of major families of discontinuities, including stratification planes, foliation, and fractures, influences blast energy and fragment size distribution, as these discontinuities represent zones of weakness [54]. Furthermore, fractured rocks offer lower fragmentation than non-fractured rocks due to stress wave attenuation and gas escape through joints. Geological discontinuities also create an imbalance in load distribution, resulting in uneven fragmentation and fracture. Moreover, fractured rocks exhibit less fragmentation compared to non-fractured rocks as a result of stress wave attenuation and gas egress through joints. Geological discontinuities induce an imbalance in load distribution, leading to irregular fragmentation and fracturing [55]. According to Merabet et al [56], a good knowledge of crack characteristics (density and spacing) can optimize blasting design and improve fragmentation quality. These characteristics are considered key factors in determining explosive charge values.

3.2.2. Rock matrix characteristics

Multiple studies have demonstrated that the characteristics of undamaged rock, particularly its physical-mechanical qualities, are among the most significant factors affecting blasting outcomes. The primary properties encompass cohesiveness and the internal friction angle of the rock [57], tensile strength [58], compressive strength, and rock density [59]. Cohesion and internal friction angle are two fundamental strength criteria commonly employed to define the shear strength of rock. They can be acquired immediately through laboratory procedures (triaxial tests) [60]. Ashby concluded that fracture density and the strength of the organized rock mass, shown by the angle of friction, significantly influenced blasting performance [61]. The compressive strength of a rock is described as the most significant stress that a rock sample can endure when unidirectional stress is applied, typically axially, to the ends of a cylindrical specimen [62]. The compressive strength of a rock mass can endure the compressive force generated by the explosion. Uniaxial compressive strength (UCS) is a vital factor affecting the dynamic ability of a rock mass. The UCS values quantify the energy necessary for fragmentation following the detonation of natural rock blocks [63]. Tensile strength is a critical mechanical property of rock mass in rock engineering [64]. The predominant technique for assessing tensile strength is the Brazilian method. In this experiment, rocks break under biaxial stress, with one primary stress being tensile and the other compressive. During blasting, the rock is fragmented by the interplay of two waves: one compressive and one tensile. Tensile fracture transpires when the reflected tensile wave surpasses the rock's tensile strength, leading to subsidence [58]. The density of rock is a crucial determinant in calculating the quantity of explosives necessary to displace a specific volume of rock. The charge-to-diameter ratio of the charge fluctuates with rock density, hence altering the powder factor. Low-density rocks necessitate a reduced explosive charge to fragment a unit volume, but high-density rocks demand a greater specific explosive charge for detonation [50].

This investigation involved the characterization of the rock massifs at the Kef Essenoun mine bleachers, which was conducted in two primary stages. The initial phase entailed in situ assessments of discontinuity attributes utilizing a geological compass on two-step sides, one composed of limestone (sterile) and the other of phosphate (ore). These measurements include the direction, dip, intensity, and spacing of discontinuities. A stereographic program (Dips) was then used to process and map these measurements. In the second stage, we determined a range of physical and mechanical properties of the intact rock formations (limestone and phosphate) constituting the rock massifs. The properties were determined using laboratory testing conducted on samples obtained from identical research fronts (Figure 6).

Figure 6. Example of a compression test performed on a phosphate specimen.

On the basis of this characterization, we have calculated the powder factor for each blasting operation on these types of rock mass. We based our calculations on formulas (3) and (4), which consider the primary attributes of a rock mass, including density, compressive strength, shear strength, tensile strength, and rock fracturing. The findings are presented in the results section.

$$K = q_{et} \times K_{ex} \times K_{fiss} \times K_d \times K_c \times K_v \times K_{sd} \tag{5}$$

where: q_{et}: rock extractability (kg/m^3), K_{ex}: transformation index of the standard explosive, K_{fiss}: fractured index that takes into account the fracturing of the mass, K_d: index that takes into account the degree of fragmentation, K_c: index that takes into account the extent of actual load concentration, K_v: Index that takes into account the impact of the volume of blasted rock for the stairs, K_{sd}: Index that considers the arrangement of the load and the surface number of the mass attracted by the case on two free surfaces [65]. The pullability of the rock can be found using the following equation [66]:

$$q_{et} = 0.02 \times (\sigma_{comp} + \sigma_{sh} + \sigma_t) + 2\gamma \tag{6}$$

where: σ_{comp}: Compressive strength of rocks (Mpa); σ_{sh}: Shear strength of rocks (Mpa)

σ_t: Tensile strength of rocks (Mpa); γ: Density (t/m^3).

3.3. Fragmentation analysis using digital image processing and empirical KuzRam model

Digital image processing is highly advantageous for fragment analysis and is extensively utilized in industry due to its rapid execution and minimal error rate across several images [67]. It handles images from several sources, including camcorders, still cameras, photographs, or digital data [36]. In recent decades, several image analysis software packages, including Split-Online, Split-desktop, Gold-Size, and Wip-Frag, have been developed and documented for use in the mining industry. The primary benefit of these software packages is their integration and lack of disruption [68]. WipFrag is a prevalent software application utilized to study blasting imagery in mining and quarrying operations. WipFrag employs sophisticated image processing algorithms to precisely evaluate photos of blasted materials, yielding critical data on particle size, shape, and distribution [69]. For numerous years, empirical models have been employed to optimize detonations. These encompass the Kuznetsov-Cunningham-Ouchterlony (KCO) model and the modified Kuz-Ram model (MKM) [70]. These empirical models provide a predicted value for the fragmentation size distribution per explosion, the uniformity index, and additional parameters to determine the optimal fragment size. The Kuz-Ram model is a globally acknowledged predictor of rock fragmentation [71, 72]. The empirical

Kuz-Ram model's input data comprises critical blast design parameters, including rock characteristics, explosive attributes, pattern design specifications, and desired fragmentation criteria. This unique characteristic renders the concept and tool outstanding for fragmentation computations [73].

- **Mean size fragments of muckpile (Xm= X50), m**:

$$X_{50} = A[PF]^{-0.8} Q^{0.167} \left(\frac{115}{RWS_{ANFO}}\right)^{0,633} \quad (7)$$

- **Size distribution curve**:

$$R(X) = 1- e^{-\left(\frac{x}{x_c}\right)^n} \quad (8)$$

- **Uniformity index:**

$$n = \left(2,2 - 14\,\frac{B}{D}\right)\left(\frac{1+\left(\frac{S}{B}\right)^{0,5}}{2}\right)\left(1 - \frac{E_p}{B}\right)\left(\frac{L}{BH}\right) \quad (9)$$

where:

A: Rock factor; PF: Powder factor in kg/m^3; Q: Charge mass per blast holes, kg; RWS$_{ANFO}$: weight strength of explosive relative to ANFO, %; Ep: Deviation of blast holes.

This work evaluated the particle size distribution of fragmented rocks using two methods: the Kuz-Ram prediction model and image processing with WipFrag (Figure 7). The combined use of these two methods enables a more comprehensive assessment of rock fragmentation, from prediction to field validation.

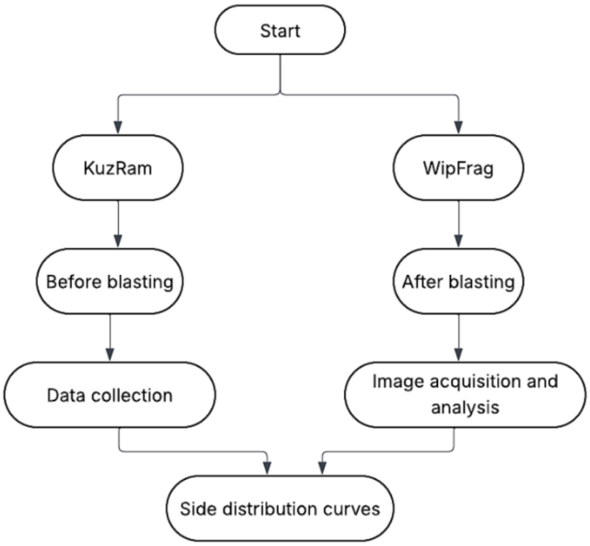


Figure 7. Steps for Fragmentation Analysis.

KuzRam was used to predict fragmentation on the basis of existing shot plans (the one used by the company) and proposed plans. Wip-Frag was used to analyze the actual fragmentation of existing plans, to validate the results produced by the Kuz-Ram model.

The proposed approach is broadly applicable to open-pit blasting across diverse geological settings. Nonetheless, a comprehensive site analysis is necessary to ascertain the inherent properties of the rock mass designated to be blasted. The methodology must be tailored to these attributes to enhance fragmentation and reduce expenses.

4. Results and discussion

4.1. Analysis of discontinuity characteristics

As previously stated, measured data on discontinuity features are analyzed using a stereographic program (Dips), allowing for the identification of the primary families of discontinuities within each rock mass. The findings are displayed in Table 1 and Figure 8.

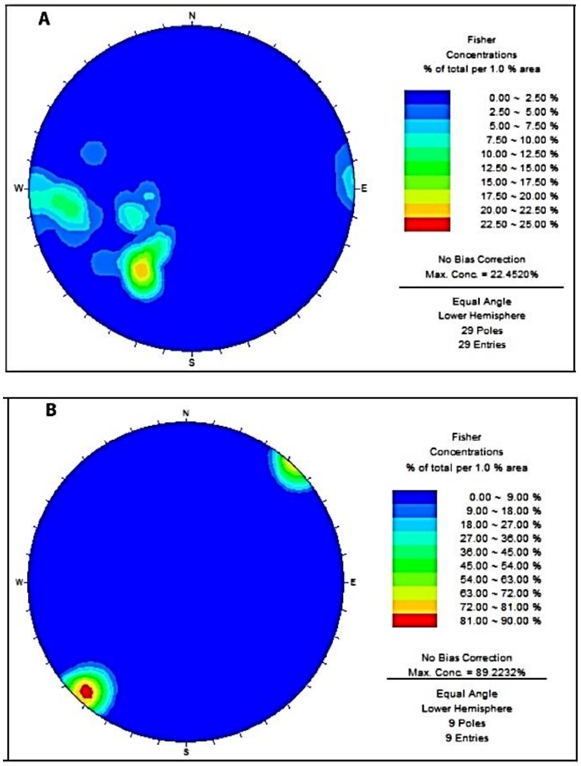


Figure 8. Stereographic projection; A) limestone bedrock, B) phosphate bedrock.

Table 1. Discontinuity Characteristics of Rock Masses.

Characteristics of the discontinuities	Rock mass		
	Limestone		Phosphate
Average distance of cracks (m)	1 ,00		1.60
Density of cracks (m^{-1})	1,6		1
Number of families of discontinuities	02		01
Direction of families of discontinuities (°)	240	260	220
Dip of families of discontinuities (°)	20	60	30

The limestone massif presents two different families of directional discontinuities: the first family is characterized by a direction of N240° and a dip of 20°, while the second family is characterized by a direction of N260° and a dip of 60°. The crack density in this massif is 1.6 m-1 with an average crack spacing of 1m. This indicates that cracks are closely spaced in this massif. The phosphate massif exhibits a series of discontinuities oriented at N220° with a dip of 30°. The crack density in this massif is 1m-1 with an average crack spacing of 1.60m. This indicates that cracks are more widely spaced than in the limestone massif.

4.2. Physico-mechanical characteristics laboratory findings

Table 2 presents the primary physical and mechanical characteristics of phosphate and limestone rocks, as ascertained via laboratory testing of specimens. The findings indicate that limestone rocks possess superior physical and mechanical qualities compared to phosphate rocks, including enhanced compressive and tensile strength. This indicates that limestones exhibit greater resistance to forces that challenge them, such as impact or stress.

4.3. Powder factor optimization

Optimizing powder factors for limestone and phosphate blasting requires adjustments to the explosive charge. including the quantity and length of the charge, as well as the length of the tamping in the proposed blasting plans. Table 3 summarizes the parameters of a blasting plan used by the Kef Essenoun mine company and the proposed plans. The results of the powder factor calculations, based on equations (5) and (6), indicate that the values obtained for phosphate and limestone are lower than those used by the company. The calculations give 0.37 kg/m³ for phosphate and 0.39 kg/m³ for limestone, while the company uses a fixed value of 0.42 kg/m³ for both. This difference implies that the company uses more explosives than necessary for both rock types, resulting in additional costs, stronger ground vibrations, and potentially environmental damage.

Minimizing the powder factor enhances slope stability by reducing vibration-induced stresses. A lower explosive quantity limits excessive rock fracturing and shear stress, thereby improving slope structural integrity and reducing the risk of rockfalls and degradation. Additionally, reduced vibration decreases damage and wear on mining equipment, leading to lower mechanical loads and improved durability of the mining infrastructure.

The difference between the calculated values and those used by the company is explained by the fact that the calculations take into account the specific properties of the rocks, which influence the optimization of the powder factor. Unlike the company's calculations, which do not take these properties into account, our calculations offer a more precise approach.

Table 2. Physical and Mechanical Characteristics of Rocks.

Properties	Rocks	
	Phosphate	Limestone
Density; (t/m³)	2,43	2,5
Compression strength (Mpa)	500-600	600-700
Tensile strength (Mpa)	40-72	72-84
Shear resistance (Mpa)	75-105	105-120
Internal friction angle (°)	37	37
Cohesion (Mpa)	1.15	1.80

Table 3. Parameters of blast design.

Parameters	Unites	Valeurs		
		Used	Proposed	
			Phosphate	Limestone
Hole Diameter	mm	125	125	125
Dip Direction	Degree	75	75	75
Burden	m	4.5	4.5	4.5
Spacing	m	4.5	4.5	4.5
Sub-drilling	m	1.65	1.65	1.65
Hole depth	m	16.65	16.65	16.65
Charge length	m	10.65	9.65	10
Stemming	m	6	7	6.65
Powder factor	Kg/m³	0.42	0.37	0.39
Charge/hole	Kg	131	113	119
Bench height	m	15	15	15
Holes numbers	/	Limestone 28 Phosphate 18	18	28

4.4. Analysis of rock fragmentation

Table 4 and Figure 9 present the distribution of particle sizes in blasted rock (limestone and phosphate) obtained by KuzRam analysis. These data quantify the distribution of fragment sizes in the blasted piles and the proportion of each size present.

The examination of the KuzRam model reveals that the magnitude of limestone fragments obtained after blasting will be similar, whether with the plan used by the company or the proposed plan. The model predicts a low percentage of oversized blocks, with 3.20% for the current plan and 4.60%. The proposed plan indicates that most blocks conform to the permitted size range, with the highest allowable fragment size for the primary crusher being 1400 mm. Similarly, for phosphate, the model predicts a low percentage of oversized blocks: 1.30% for the current plan and 1.90% for the proposed plan. Consequently, it can be said that the blasting process is efficient for both rock types, as it contains a maximum percentage of acceptable fragments that can be moved and processed efficiently during subsequent mining operations such as loading, transport, and crushing, enabling smoother, more productive operations.

The results can be corroborated through picture analysis with WipFrag, which assesses rock fragmentation resulting from blasting activities conducted as part of the company's strategy (real fragmentation outcomes). Figure 10 illustrates an example of two particle size distribution curves, one representing limestone and the other representing phosphate rock.

Table 4. Examination of rocks blasted by KuzRam.

Size (mm)	Passing (%)			
	KuzRam (Blast plan used)		KuzRam (Blast plan proposed)	
	Phosphate	Limestone	Phosphate	Limestone
0	0,00	0,00	0,00	0.00
3	0,00	0,00	0,00	0.00
7	0,00	0,00	0,00	0.00
15	0,60	0,50	1.00	0.70
30	2,70	2,30	3.70	2.80
60	6,60	5,70	8.10	6.40
90	11.10	9.50	12.60	10.30
100	12.60	10.90	14.20	11.70
200	28.70	25.10	29.00	25.20
400	57.20	51.50	53.70	49.30
600	76.60	71.10	70.90	67.30
800	88.10	83.70	82.20	79.70
1000	94.30	91.30	89.40	87.70
1200	97,40	95.50	93.70	92.70
1400	98,90	97.80	97.10	95.80
1600	100	99.50	99.20	97.60
1800	100	100	100	100

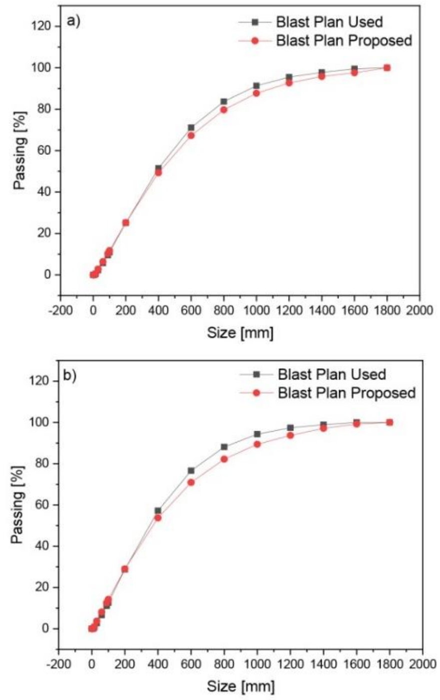
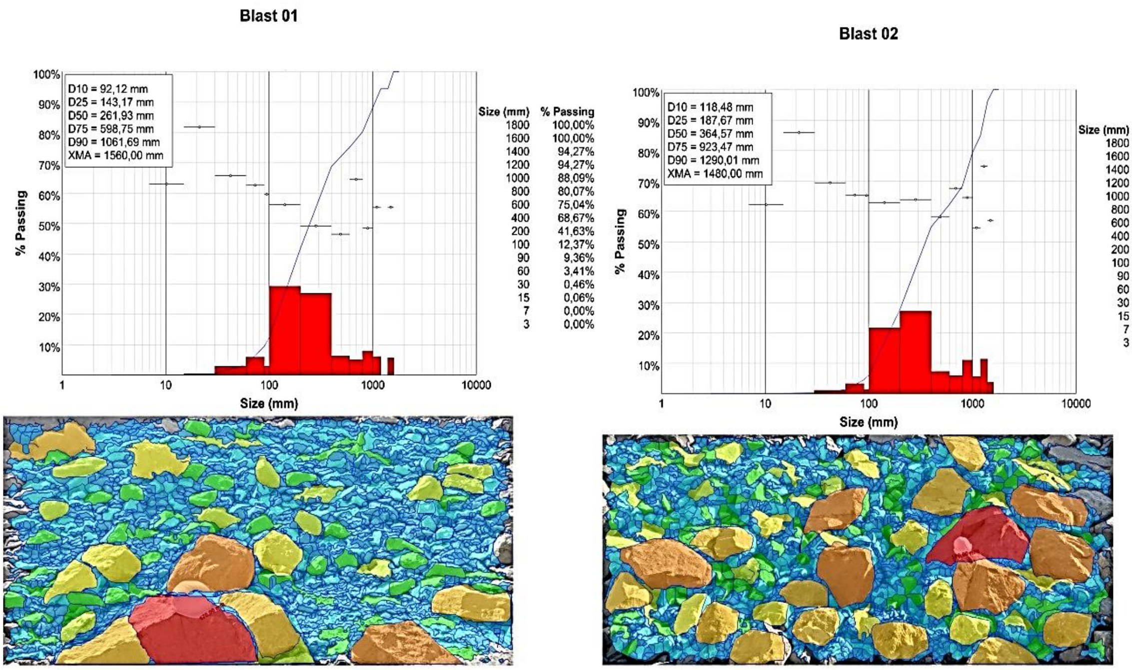


Figure 9. Fragmentation analysis utilizing KuzRam a) for limestone, b) for phosphate.



Blast 01

Size (mm)	% Passing
1800	100,00%
1600	100,00%
1400	94,27%
1200	94,27%
1000	88,09%
800	80,07%
600	75,04%
400	68,67%
200	41,63%
100	12,37%
90	9,36%
60	3,41%
30	0,46%
15	0,06%
7	0,00%
3	0,00%

Blast 02

Size (mm)	% Passing
1800	100,00%
1600	100,00%
1400	96,25%
1200	84,88%
1000	79,22%
800	68,19%
600	62,15%
400	54,81%
200	27,67%
100	5,99%
90	4,52%
60	1,26%
30	0,17%
15	0,04%
7	0,00%
3	0,00%

Figure 10. Wip-Frag examination of blasted rock (Blast1 limestone rock; Blast 2 phosphate rock).

The results show that a low percentage of oversized blocks were observed in the blasted rock pile (5.73% for limestone and 3.75% for phosphate), which means that the majority of blasted rocks fell within the acceptable size range (Figure 11).

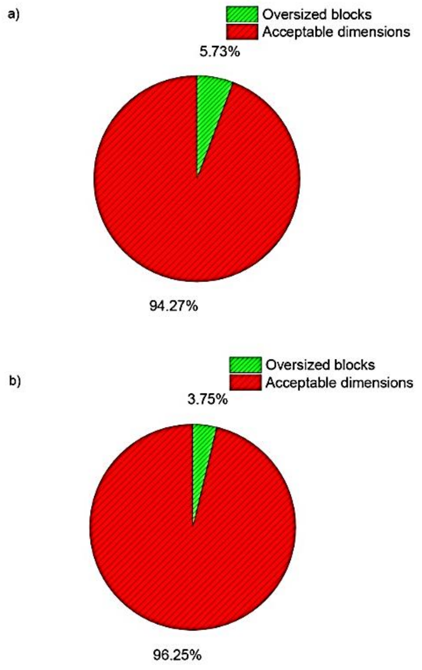


Figure 11. Fragment size percentages as determined by WipFrag analysis a) Limestone fragments; b) Phosphate fragments.

Figure 12 depicts the various particle sizes (D10, D25, D50, D75, D90, and Dmax) produced by blasting. In limestone, D10 (88.98 ± 28.23 mm) denotes the minimum particle size, whilst D25 (139.35 ± 27.15 mm) and D50 (158.12 ± 29.34 mm) indicate the mean particle sizes. The largest particles are D75 (596.15 ± 32.65 mm), D90 (1071.11 ± 31.02 mm), and Dmax (1555.23 ± 30.51 mm). The phosphate results are as follows: D10 (120.13 ± 26.13), D25 (195.78 ± 28.45), D50 (371.12 ± 30.14), D75 (918.18 ± 32.95). The phosphate results are as follows: D10 (120.13 ± 26.13), D25 (195.78 ± 28.45), D50 (371.12 ± 30.14), D75 (918.18 ± 32.95), D90 (1298.73 ± 32.33), and Dmax (1485.79 ± 29.18). The observed Standard deviations in the blasts of each facies are minimal to moderate, signifying the uniformity of these particles for each rock type across the several blasts.

The results obtained by WipFrag are compatible with those of the KuzRam model, with a slight difference observed in the percentage of oversized blocks, which validates the use of the KuzRam model to estimate grain size after blasting. Based on the results presented, it is justified to conclude that the current blasting plans (the one used by the company) and the proposed plans are effective in achieving acceptable fragmentation. However, the current plans are not as cost-effective as the proposed plans. The latter reduces mining costs by using fewer explosives, which directly reduces the cost of purchasing explosives (Figure 13). Applying these plans would result in saving approximately 812,000 USD per year, of which 670,000 USD for limestone and 142,000 USD for phosphate (Figure 14).

5. Conclusion

This research aims to determine the ideal powder factor for rock fragmentation at the Kef Essenoun phosphate mine. It involves determining the optimal quantity of explosives for blasting various rock masses to minimize blasting expenses and mitigate environmental concerns, including gas emissions, dust dispersion, and ground vibrations.

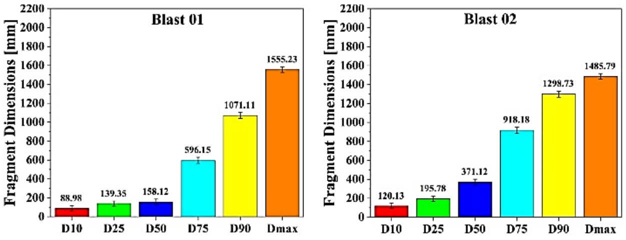


Figure 12. Standard deviations for WipFrag fragmentation curves; (Blast1 limestone rock; Blast 2 phosphate rock).

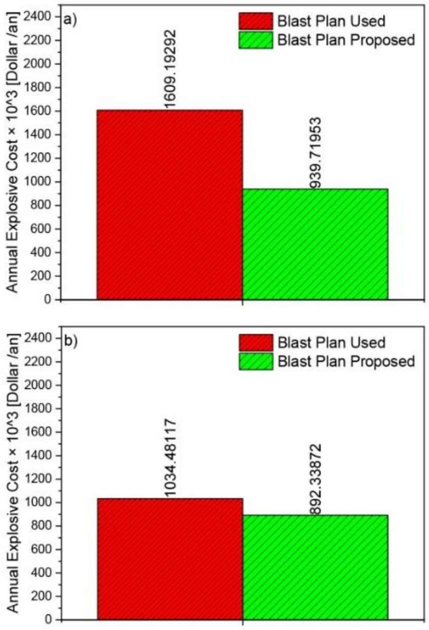


Figure 13. Annual expenditures on explosives; a) for limestone; b) for phosphate.

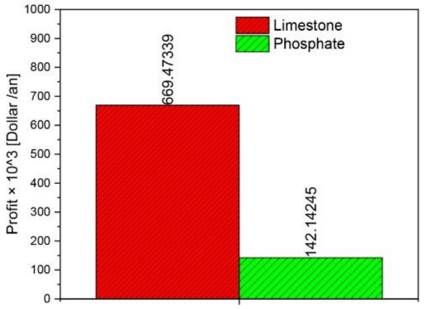


Figure14. Yearly Earnings.

The results demonstrate that a uniform powder factor is inapplicable to the blasting of limestone and phosphate because of their unique features and discontinuous characteristics. Blasters need to adjust the powder factor to each specific scenario, considering the inherent properties of the rock.

Examining discontinuities (fissures) and the inherent properties of the rock (strength, density) is crucial for comprehending the overall behavior of phosphate and limestone formations, which are discontinuous and anisotropic systems. Understanding these characteristics enables to anticipate the rock's behavior during blasting, highlighting regions of increased brittleness or resistance. Structural deficiencies, including cracks or joint zones, impact shock wave propagation and influence rock fragmentation.

By pinpointing these vulnerabilities and their attributes (such as crack spacing), one can focus blasting energy in areas that will most effectively fracture the rock. Consequently, precise estimation of the volume to be shattered and modification of the requisite explosives ensure the attainment of the intended outcomes. Alternative blasting strategies have been presented to attain these outcomes, minimizing the quantity of explosives while ensuring effective rock fragmentation through the utilization of the Kuz-Ram model and WipFrag software. These proposals are more economically feasible, projecting saving approximately 812,000 USD per year, which includes 670,000 USD from limestone and 142,000 USD from phosphate. This signifies a substantial enhancement in profitability, attributable to decreased extraction costs via the utilization of less explosive materials.

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