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Limitations of Fragmentation Assessment in the Hadjar Lamis Rhyolitic Massif (Chad): An Aggregate Quarry Case Study

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ABSTRACT

Rock fragmentation by blasting remains a critical challenge in quarrying operations, as it directly affects downstream efficiency, energy consumption, and overall production performance. In structurally complex volcanic massifs, conventional fragmentation assessments based solely on post-blast granulometry often fail to account for the control exerted by pre-existing discontinuities. Thus, this study investigates the effectiveness and practical limits of blast-induced fragmentation by explicitly linking in situ rock mass structure to post-blast fragment size distributions. The proposed approach combines systematic discontinuity mapping, stochastic simulation of block geometry, and comparative granulometric analyses of in

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ARTICLE INFO

Received: 8 May 2026 | Revised: 21 June 2026 | Accepted: 26 June 2026 | Published Online: 29 July 2026
DOI: <https://doi.org/10.30564/jees.v8i7.13481>

CITATION

Ahmat, M.M., Bada, A.M., Ateib M.A., et al., 2026. Limitations of Fragmentation Assessment in the Hadjar Lamis Rhyolitic Massif (Chad): An Aggregate Quarry Case Study. *Journal of Environmental & Earth Sciences*. 8(7): 281–298. DOI: <https://doi.org/10.30564/jees.v8i7.13481>

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situ blocks and blasted rock piles. The methodology was applied to the Hadjar Lamis rhyolitic massif (Chad), characterized by persistent and well-connected fracture networks. Results show that two dominant discontinuity families, mainly oriented NW–SE and NE–SW, govern in situ block geometry, with characteristic block sizes ranging from approximately 43–96 cm. Comparative analyses reveal that fragmentation efficiency is strongly site-dependent, with fragmentation indices (IF) varying between 1.25 and 2.25 and fragmentation quality factors (FQF) reaching values up to 0.73 when blast geometry and charge distribution are consistent with the dominant structural fabric. Conversely, misalignment between blast design and fracture orientation results in heterogeneous fragmentation and a high proportion of oversized blocks, despite comparable explosive energy input. These findings highlight the dual role of natural fracturing, which both facilitates breakage and limits fragmentation through stress-wave attenuation and gas escape. Overall, the study demonstrates that effective blast optimization cannot rely on explosive parameters alone but must integrate detailed geological characterization. The proposed framework provides a robust and transferable tool for improving fragmentation control and defining the structural limits of blasting performance in hard-rock quarries.

Keywords: Analysis; Discontinuity; Fragmentation; Block Size; Granulometry; Hadjar Lamis (Chad)

1. Introduction

Rock fragmentation by blasting remains a critical operation in surface mining and quarrying, as it directly governs downstream performance, including loading efficiency, communication energy consumption and overall operational costs^[1,2]. Despite significant advances in explosive formulations and blast design techniques, only a limited portion of the explosive energy is effectively converted into useful rock breakage, while the remainder is dissipated through vibrations, air blast and unintended damage to the surrounding rock mass^[3,4]. Consequently, improving fragmentation efficiency continues to be a central challenge in mining engineering.

Recent studies have shown that blast outcomes are not solely governed by explosive parameters but are strongly conditioned by the geological structure of the rock mass, particularly the orientation, spacing and persistence of natural discontinuities^[5,6]. In highly fractured volcanic and crystalline formations, discontinuity networks may either enhance fragmentation by preconditioning the rock or, conversely, attenuate stress waves and gas pressure, leading to heterogeneous fragment size distributions^[7,8]. This dual role of discontinuities introduces significant uncertainty in blast performance prediction.

Traditional fragmentation assessment approaches largely rely on post-blast granulometric analyses or empirical blast design rules that do not explicitly account for the initial block size distribution of the in situ rock mass^[9,10].

While modern developments incorporating image analysis, numerical modelling and machine learning have improved post-blast characterization, these methods often treat the rock mass as an equivalent continuum and neglect the structural control exerted by pre-existing fracture systems^[11,12]. As a result, the relationship between the geological fabric of the massif and the effectiveness of blasting remains insufficiently quantified.

In this context, there is a clear need for methodologies that explicitly link in situ block geometry derived from discontinuity networks to post-blast fragment size distributions, allowing for a more physically meaningful evaluation of fragmentation efficiency. Addressing this gap is particularly relevant in volcanic rhyolitic massifs, where strong anisotropy and fracture connectivity significantly influence explosive energy transmission.

The present study proposes a comparative fragmentation assessment framework based on the systematic characterization of natural discontinuities and the quantitative comparison between in situ block size distributions and blasted rock piles. By introducing fragmentation indices that explicitly relate pre- and post-blast granulometries, the proposed approach aims to evaluate both the efficiency and the practical limits of blasting performance under structurally controlled conditions.

The objectives of this work are therefore to: characterize the structural geometry of the rhyolitic rock mass through detailed discontinuity analysis; quantify in situ block size distributions using statistical and geometrical

methods; assess post-blast fragmentation through granulometric measurements; and evaluate the influence of geological structure on fragmentation efficiency and its operational implications.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods employed for structural characterization and fragmentation analysis. Section 3 presents and discusses the results. Finally, Section 4 summarizes the main findings and outlines the limitations and perspectives of the proposed approach.

2. Materials and Methods

2.1. Geographical Setting of the Study Area

The Hadjar Lamis Province is located in western Chad, between latitudes 13°00' N and longitudes 15°44' E, and is one of Chad's 23 administrative provinces. The province is administratively divided into four departments and nine municipalities, with Massakory as its capital city. It is bounded to the north by the Kanem region, to the northeast by Bahr el Ghazal, to the east by Batha, to the southeast by Guéra, to

the south by Chari-Baguirmi, to the west by Cameroon, and to the northwest by Lake Chad. The total surface area of the province is approximately 31,426 km² (**Figure 1**).

2.2. Geomechanical Context of the Study Area

Rock masses naturally undergo fracturing through shear deformation zones or brittle failure mechanisms. These fracture modes have been extensively documented over several decades, leading to substantial empirical and qualitative knowledge^[13,14]. Quantitative and mechanical approaches have further enhanced the understanding of fracture initiation and propagation in rock masses^[15].

Discontinuities are generated under a common stress field at a given geological time and tend to form characteristic angular relationships that depend on both lithological properties and stress regimes. These physical discontinuities significantly influence the mechanical, hydraulic, and thermal behavior of rock masses^[16]. The subdivision of a rock mass into partially or fully detached blocks resulting from the spatial arrangement of discontinuities represents a fundamental geometric property of fractured media^[17,18].

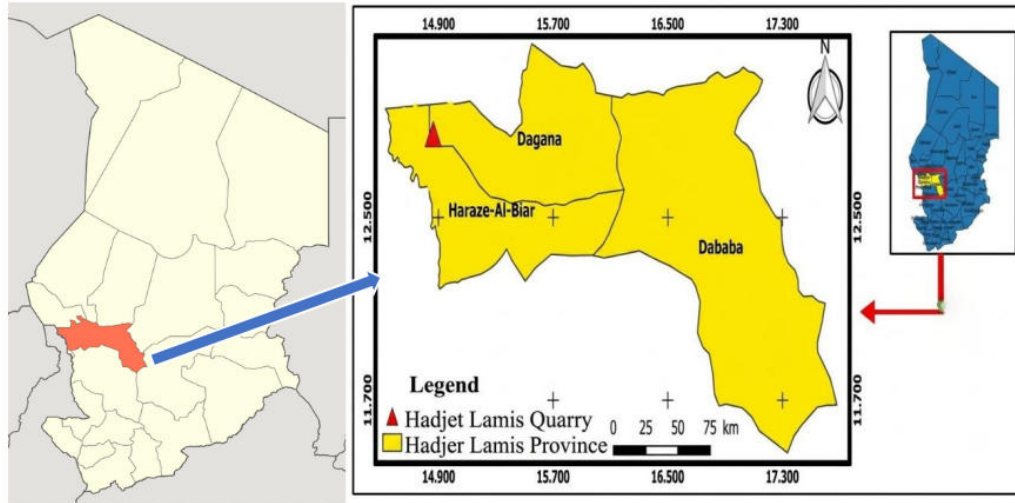


Figure 1. Location map of the study area.

Discontinuity orientation provides essential information on block geometry and mechanical anisotropy, which is critical for evaluating blast-induced fragmentation efficiency. In the Hadjar Lamis massif, altered volcanic rocks are intersected by numerous faults with thicknesses ranging from millimeters to meters. Some of these structures are likely of syn-volcanic origin; however, their continuity,

orientation, and relationship with alteration processes remain poorly constrained to date. Reconstructing the primary volcanic architecture of the Hadjar Lamis massif therefore requires an integrated petrographic, textural, and geochemical characterization of the rhyolitic formations. Mechanical characterization indicates that Hadjar Lamis aggregates exhibit relatively high resistance to abrasion and wear^[14].

2.3. Methodological Framework

Blasting fragmentation efficiency is assessed through a comparative analysis of in situ and post-blast block size distributions. The adopted methodology consists of three main stages:

- Characterization of the rhyolitic rock mass, aiming at a quantitative estimation of in situ block size distribution. A two-dimensional stochastic model is used to simulate discontinuity networks based on statistical analysis of field-measured structural data.
- Characterization of blasted rock piles, providing a quantitative estimation of post-blast fragment size distributions.
- Evaluation of fragmentation efficiency is achieved by comparing granulometric curves of the in situ rock mass and the corresponding blasted material, allowing assessment of blast design parameters.

2.3.1. Field Data Acquisition

Structural and microstructural analyses were conducted through systematic surveys of rock mass discontinuities using the scanline sampling technique. The parameters recorded for each discontinuity include orientation, dip, trace length, spacing, aperture, roughness, termination type, as well as physical attributes such as infilling material, wall alteration, and water presence. These parameters were quantified and compiled in standardized data sheets for subsequent statistical processing (Tables A1–A2).

All natural fractures exceeding 15 cm in length were recorded across the two investigated sites. Measurements were performed on vertical quarry benches, where fracture traces were accurately mapped onto scaled support planes (Figures 2). This approach enabled the evaluation of fracture orientations, density, spatial distribution, and clustering patterns.

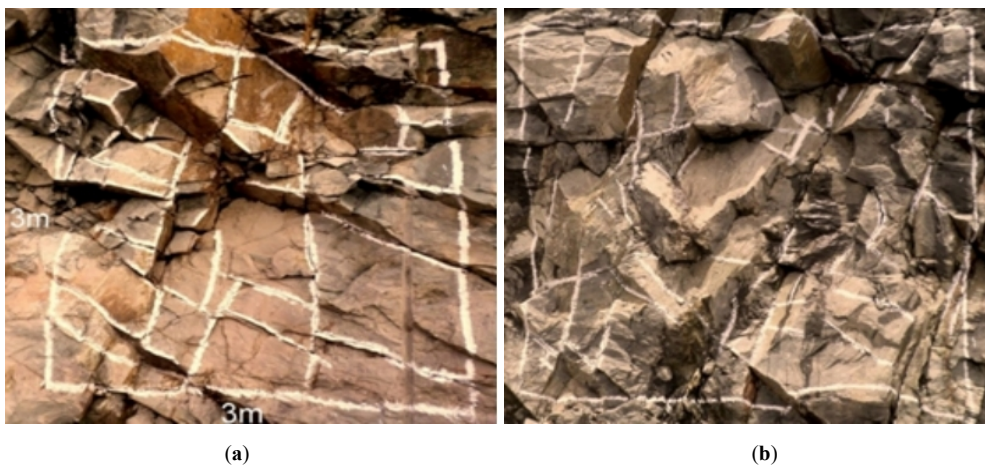


Figure 2. Mapping of fracture traces in (a) Sector 1, and (b) Sector 2, of Site 1.

To minimize overestimation of fracture density inherent to scanline bias, each measurement site was defined as a homogeneous block measuring $10\text{ m} \times 10\text{ m} \times 10\text{ m}$, regardless of scanline length. Site preparation involved careful surface selection, grid marking using paint, and systematic labeling of fracture traces (Figure 2).

2.3.2. Image-Based Measurement and Discontinuity Simulation

The image-processing approach involves reproducing the mapped rock surface onto a planar grid from which successive image treatments are applied to identify surface elements (Figure 3a,b). Discontinuities are simulated by frac-

ture families generated independently, allowing the incorporation of statistical distributions for fracture density, spacing, and aperture derived from field measurements.

Intersecting fracture traces define polygonal blocks, whose dimensions are extracted through geometrical analysis. The identification and stability assessment of blocks follow the key block theory framework^[7].

Measurement acquisition consists of two steps. First, two-dimensional geometric parameters are extracted for stochastic simulation of discontinuity networks and estimation of block size distributions for selected quarry sites^[7]. Fracture traces were digitized within square sampling areas of 9 m^2 and 16 m^2 .

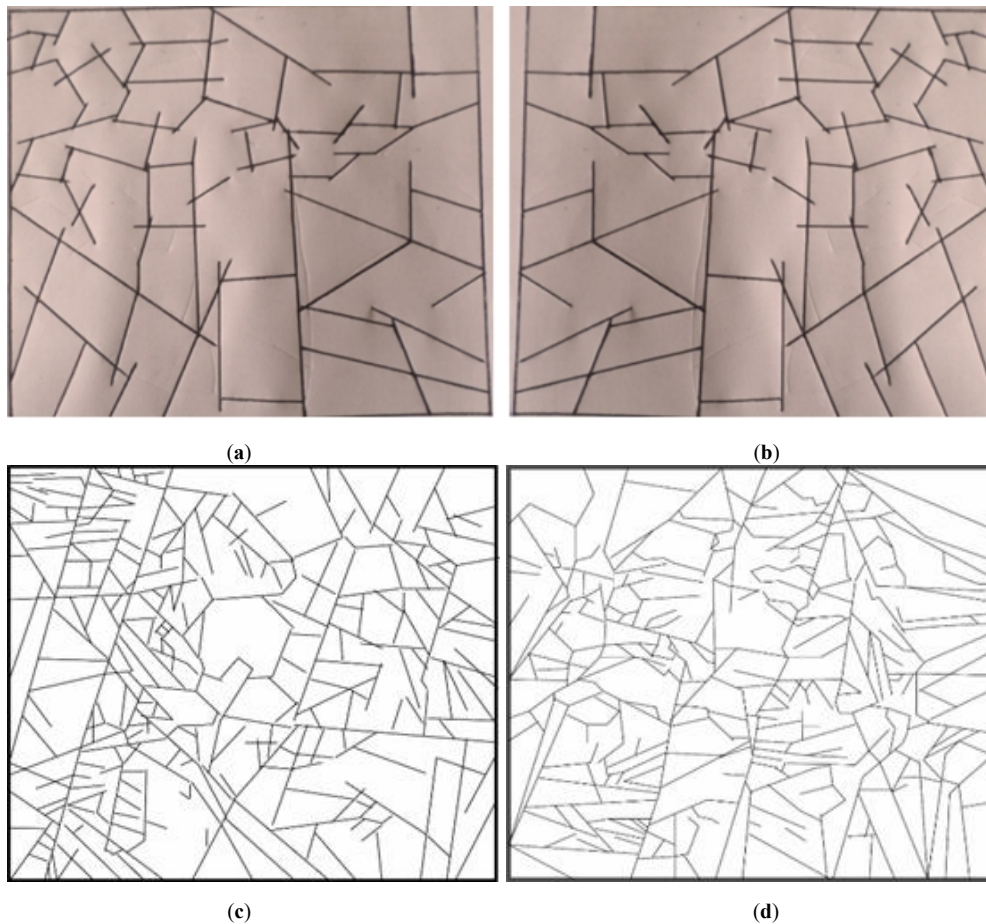


Figure 3. Individual fracture lengths and network-related lengths for: (a) Sector 1 and (b) Sector 2; Measurement of discontinuities in the in-situ massif: (c) Sector 3 and (d) Sector 4 of Site 2.

2.3.3. Block Size Analysis of the Mass

The equivalent size of the blocks thus delimited can be represented either by the diameter of the sphere, by the stopping point of the equivalent cube, or by the maximum distance separating any two vertices. The granulometric analysis method consists of numerically simulating the numerical sieving simulation. Starting from the surface of the delimited mass, the surface is reproduced on a collared plane with increasing sizes, the thresholds of which are determined manually using a reference frame.

The transition from surface area distribution to volume distribution is based on the assumption that the measured blocks can be approximated as spheres. The result takes the form of a classic block size distribution curve; the block size distribution exhibits certain structural characteristics, and the frequency or volume distribution of blocks within a given equivalent size interval can then be represented (**Figure 4**).

Measuring the block size distribution of rhyolites from

blasting allows for the characterization of the blast's outcome and thus constitutes one aspect of the blasting process from a technical standpoint^[19]. The methods are based on heap sampling. String granulometry is equivalent to a sampling line stretched across the heap, along which the length of blocks intercepted by the line (l) and their longest visible length (L), weighted by the length of intercepted blocks, are recorded. This technique was selected for its operational simplicity and reproducibility (**Figure 5**). However, to be able to study the entire pile of crushed stone, the maximum measurement length is 18 m, theoretically more than 18 times the maximum dimension of the largest block. The measured values are recorded in a program to obtain a block size distribution curve, with the x-axis representing the value of the largest visible dimension of the block and the y-axis representing the percentage of passing material. The average block size distribution of the measurement, as well as the curve's shape coefficient, can be determined to assess the homogeneity of the crushed material^[20].

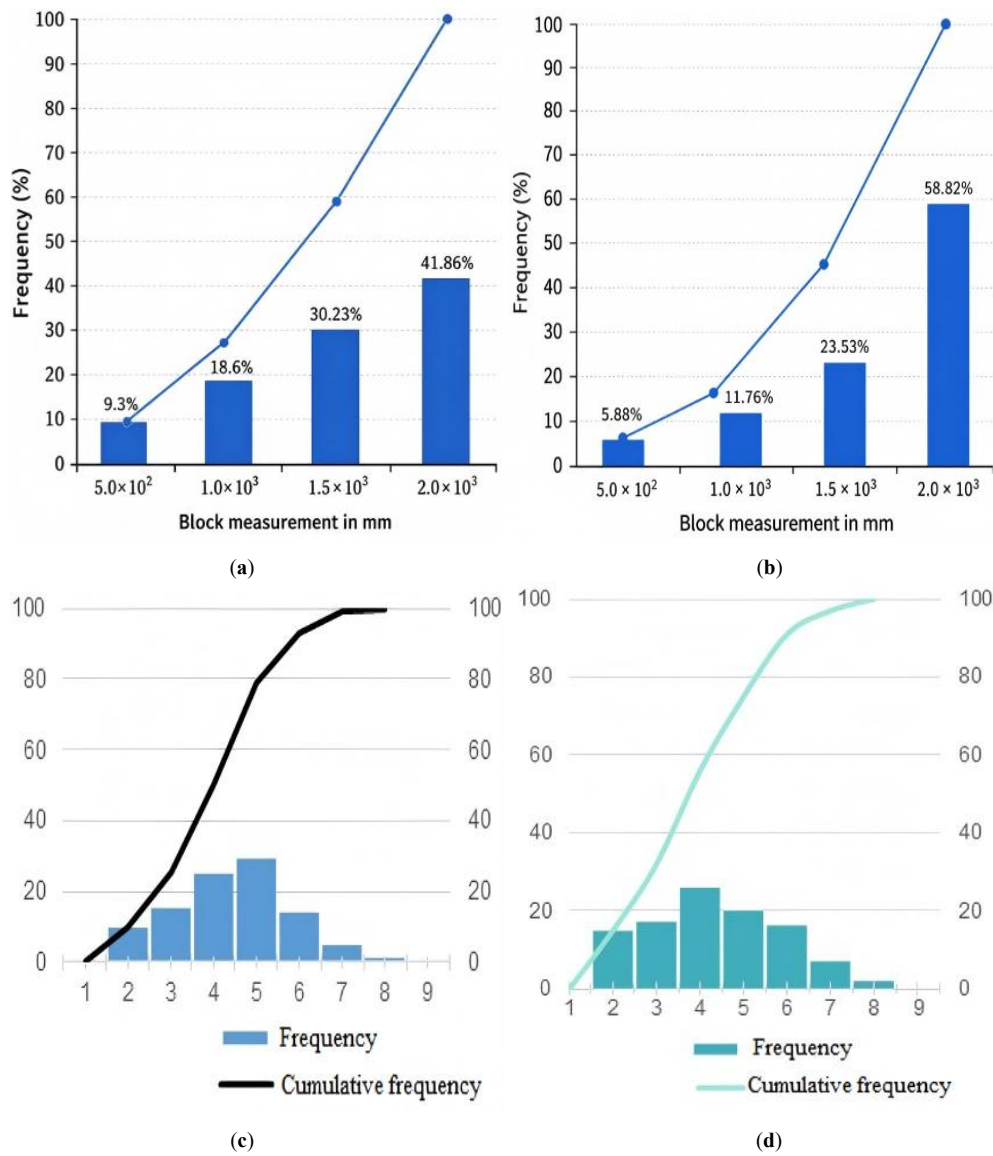


Figure 4. In situ block size histogram: (a) Sector 1; (b) Sector 2. Frequency distribution of in situ blocks of Site 2: (c) Sector 1; (d) Sector 2.



Figure 5. The photograph of the block size measurement using the line method.

2.3.4. Analysis of the Blasted Rock Piles

This analysis simulates the effect of a sieve on the blocks. Before taking the photograph, two standards of perpendicular length are placed in the field of view to correct for distortions due to the viewing angle. The procedure involves successively opening the sieve for blocks of increasing sizes and calculating the corresponding surface areas^[21]. Opening the sieve to a given size effectively isolates the blocks.

By proceeding with measurements at various sizes, we can approximate the surface distribution of the different blocks in the image. The transition to a volumetric distribution is based on the assumption that the measured blocks can be approximated as spheres. To compare the block size distribution of the blasted rock pile with that of the in-situ rhyolitic massif, the block size data is converted into three dimensions using corrective methods selected according to the average block shape index^[22]. This yields the block size distribution of the blasted rock pile, the results of which are shown in the following figures.

2.3.5. Evaluation of Fragmentation Effectiveness

This evaluation is based on comparing the block distribution within the rock mass to that of the blocks after blasting. This assessment of fragmentation effectiveness is only possible after plotting both curves for the same site. The quality of the fragmentation is determined by comparing the block size distribution curve of the blasted rock pile to that characterizing the initial state of the rock mass. The result takes the form of two juxtaposed conventional block size distribution curves. A parameter called the fragmentation index has been introduced. The fragmentation index is defined as the ratio of the block size in the rock mass in situ to the size of the blocks in the blasted rock piles.

$$IF = \frac{X_{cr}}{X_{cm}} \quad (1)$$

The *IF* (Fragmentation Index) is very explicit because it takes into account the characterization of the in-situ rock mass by a block size distribution curve and the characterization of the blasted rock pile by another block size distribution curve. It is a ratio of size reduction applied to the blocks after blasting. When the fragmentation index is equal to 1,

it means that there was no fragmentation during blasting. A fragmentation index greater than 2 indicates that the characteristic size of the in-situ rock mass was reduced by more than half.

To facilitate comparison of the block size distribution in the rock mass with that of the corresponding blast pile, the Rosin-Rammler distribution law is fitted to the data obtained from the block size analysis of the rock mass and the blast pile. The distribution law is expressed by the following relationship: Characteristic size (X_c), which corresponds to the size of the blocks with 63.2% passing, (X) the largest dimension of the block, (X_m) the average block size in the blast pile, and n is the shape coefficient of the distribution. For the same characteristic size, a large value of n would indicate uniformity^[23].

$$F(X) = 1 - \exp\left(-\frac{X}{X_c}n\right) \quad (2)$$

where X is the block size, X_c the characteristic size (63.2% passing), and n the uniformity index. If we consider only the frequencies, we observe that the work done by explosive energy is very significant at the Hadjar Lamis quarry. The analysis must be limited to the interpretation of the influence of blasting parameters other than the in-situ rock mass structure^[24]. In general, fragmentation efficiency is essentially a delayed measurement; we have introduced another parameter based on comparing the shape index of the block distribution curve for the respective in-situ rock mass and blasted rock piles^[25]. This parameter is capable of globally evaluating fragmentation efficiency, which depends on the blasting objectives. It is called the fragmentation quality factor and is calculated using the formula^[26]:

$$F_{QF} = N_r / N_m \quad (3)$$

N_r and N_m respectively denote the shape index of the block size distribution curve in the in-situ rock mass and in the pile of quarried rock. The aim is to verify its validity and establish the limits of its application. This representation on a plane allows us to synthesize the directional families. By studying the fracture networks, we observed that short fractures terminate at intersections of long fractures; thus, the segments are cut when they reach the boundaries of the polygons (**Figure 3**).

3. Results and Discussion

3.1. The Geological Structures of the Quarry

The geological overview showed that the heterogeneity of the Hadjar Lamis massif, as well as its continuous nature, identified by a certain density of fractures, poses a problem of scale effect. The system exhibits scale-dependent behavior of 15-m-thick steps on a large scale. Although the major directional families are those indicated by the fracture analysis (**Tables A1–A2**), the analyzed bench will not reveal all the discontinuity associations, and the hypothesis of a continuous medium is not realistic. It is necessary to address the problem site by site (**Figures 2–3**) and then its general implications.

At the quarry scale, initial field observations allowed for the identification of geological features likely to pose major problems during extraction. Indeed, geological structures control the block size distribution of the extracted material and the stability of the slopes, and consequently influence the extraction method. In-depth geotechnical investigations are necessary to perform a failure analysis, as the unique characteristics of Hadjar Lamis, compared to other forma-

tions in Chad, also necessitate a detailed structural study to determine its dimensions and behaviour. The Hadjar Lamis massif has been characterized petrographically and geotechnically^[14]. The families of discontinuities defined are those already identified and observed in the field; the block size distribution of the extracted material must then be studied.

3.2. Statistical Analysis of Data

The statistical analysis of discontinuities revealed that each characteristic family studied confirms the considerable influence of two directional families that are present at all scales (**Tables A1–A2**). These characteristics are represented by the histograms of the measured data, either in frequency or cumulative form (**Figures 6–15**). The tests carried out at the two sites show that the amplitude of variation is very small, at 1.17 and 1.84, which demonstrates the high homogeneity of the rock mass and its strong cohesion. The optimal ratio was found to be approximately 20%. The charge ratio varied considerably during the tests. The bottom charge, nitramines, primarily generates shock waves, while the column charge, mainly composed of ANFO, generates gases upon detonation.

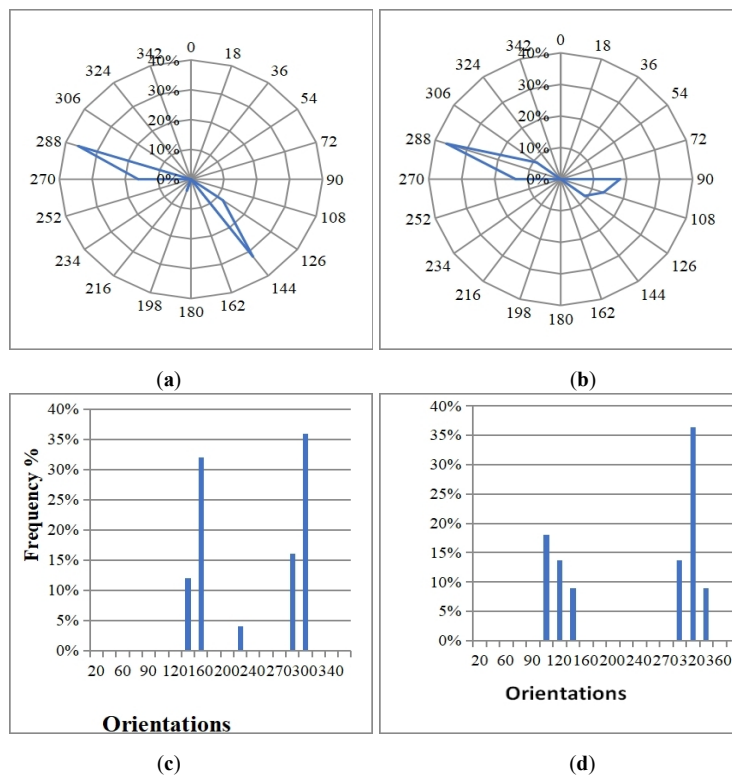


Figure 6. Azimuth rose diagrams ((a) Sector 1 and (b) Sector 2) and the corresponding frequency histograms ((c) Sector 1 and (d) Sector 2) for Site 1.

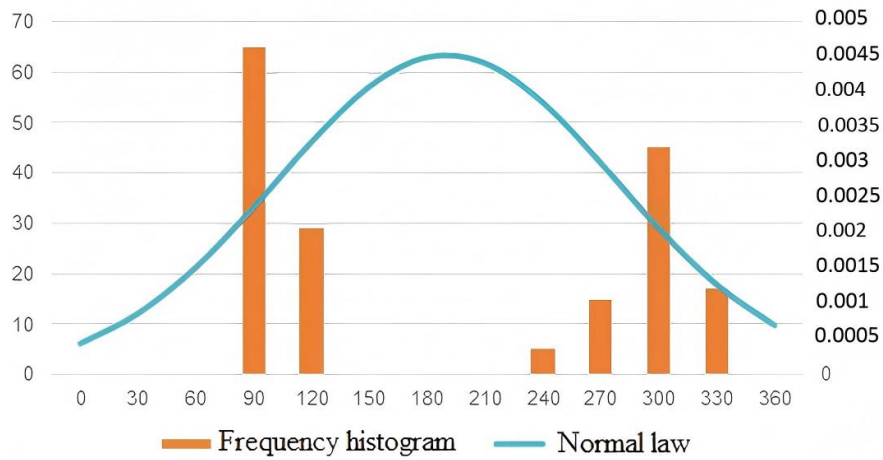


Figure 7. Frequency distribution of block orientations at Site 1 (Sector 2).

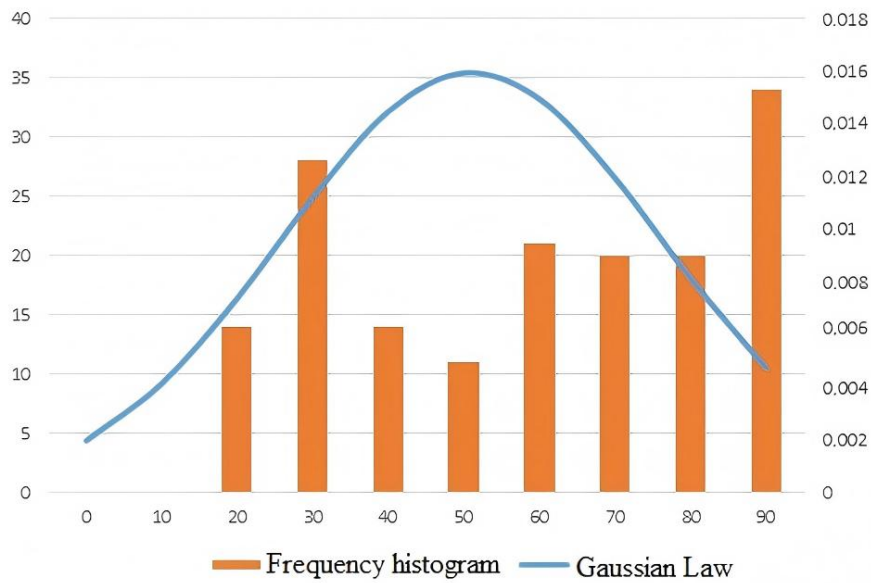


Figure 8. Frequency distribution of block dip angles at Site 2 (Sector 2).

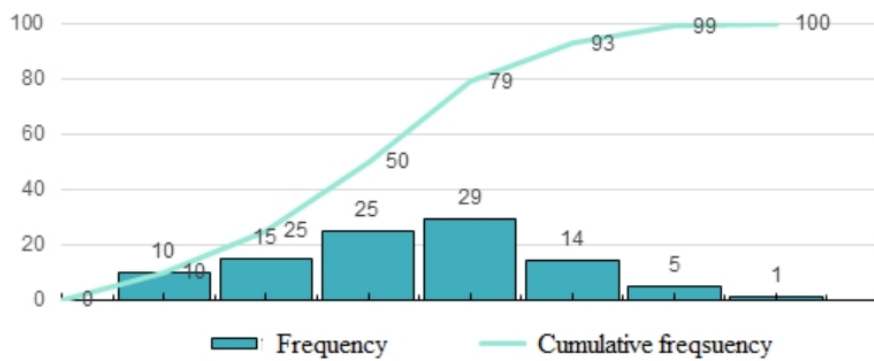


Figure 9. Block size distribution of the in situ rock mass at Site 2 (Sector 1).

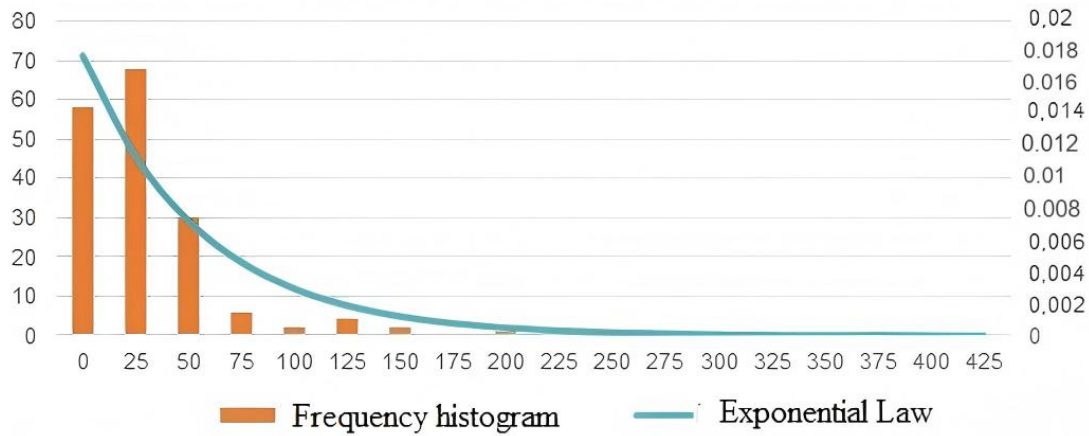


Figure 10. Weighted block size distribution based on block length at Sector 2.

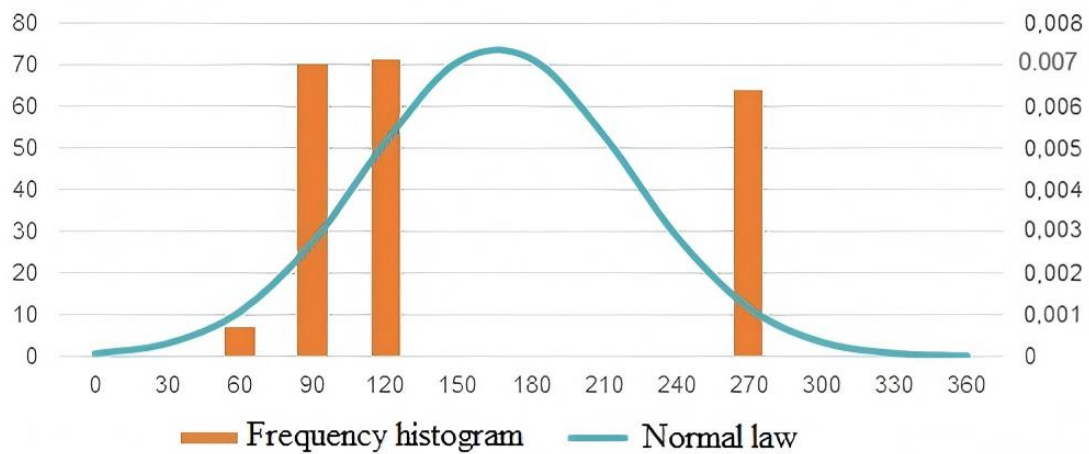


Figure 11. Frequency distribution of block orientations at Site 2 (Sector 2).

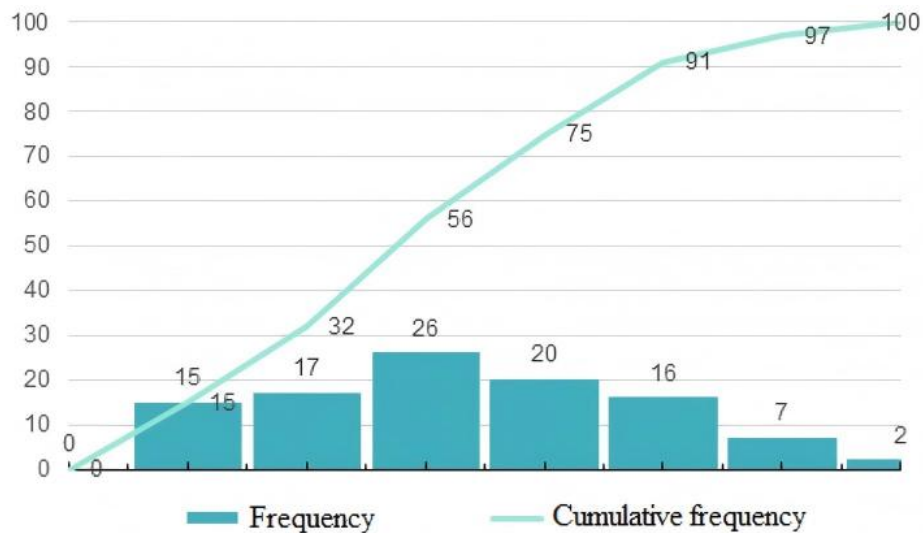


Figure 12. Granulometric curve and block size distribution of the blasted rock pile at Site 2.

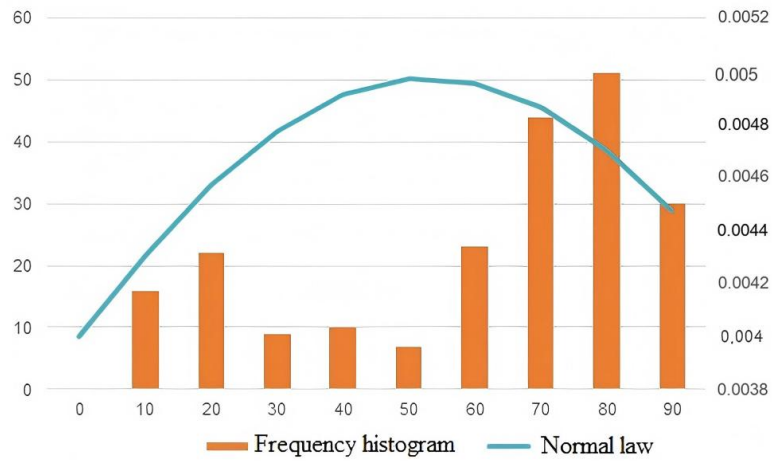
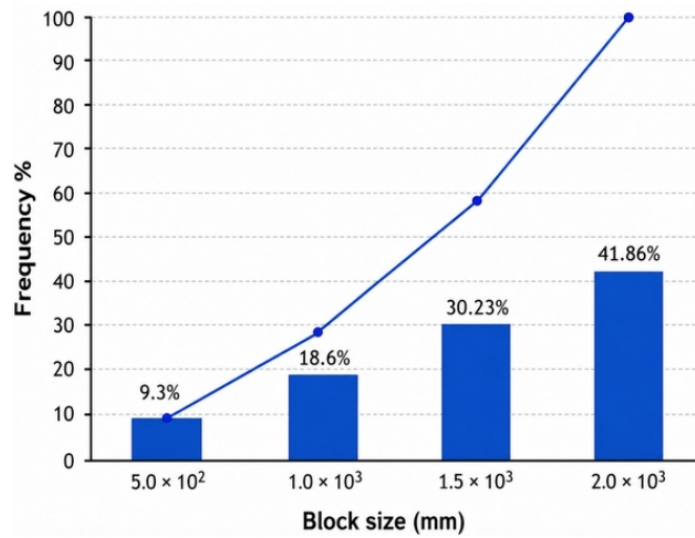
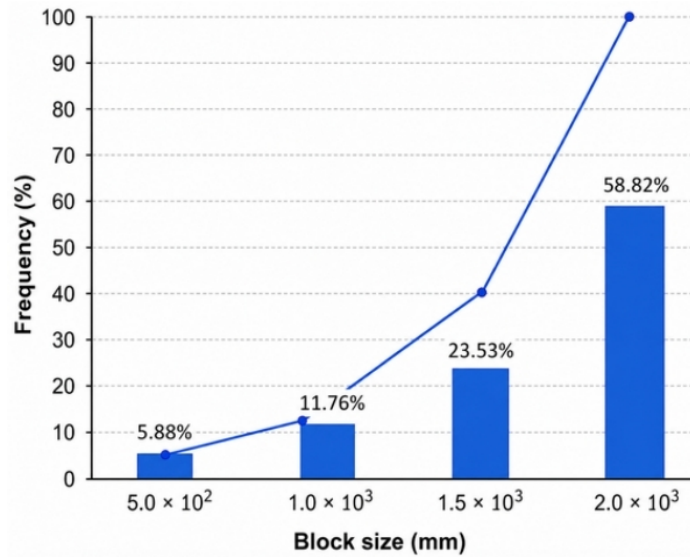


Figure 13. Granulometric curve and block size distribution of the blasted rock pile: dip angle analysis.



(a)



(b)

Figure 14. Distribution of block sizes in the rhyolitic massif in situ, Site 1.

Note: Bars: Frequency (%). Line: Cumulative frequency (%).

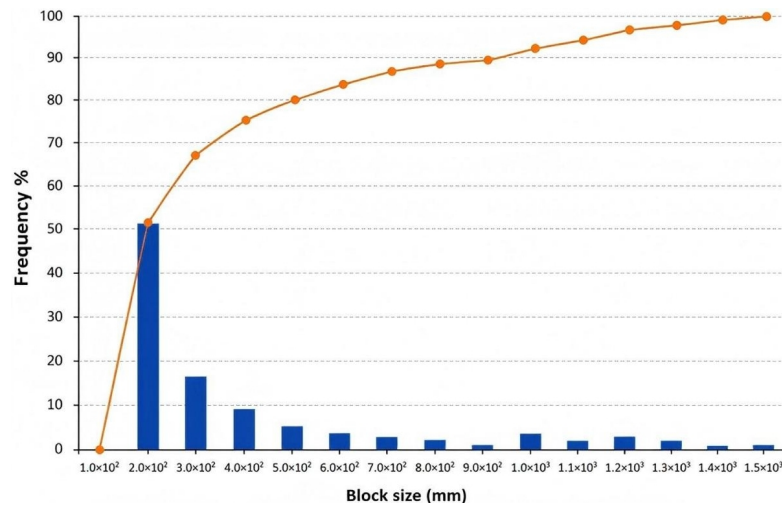


Figure 15. Block size distribution curve and block size distribution of the blasted rock pile: Site 1.

Note: Bars: Frequency (%). Line: Cumulative frequency (%).

These experimental distributions are examined to deduce the most suitable theoretical distribution laws (Figures 7–13). Following these analyses, simulations of the natural discontinuity system of the rock mass are performed, based on fracturing studies carried out before blasting. These simulations are grouped by family in Tables A1–A2, along with the results of the statistical calculations. The average block size is coarse and regular, with variable characteristic sizes X_c of 96, 87, 65, 49, and 43 cm. The block size distribution of the blasted rock pile is then evaluated using the line method, which consists of stretching a sampling line across the pile. The length of the blocks intercepted by the line and their maximum visible length in the plane of the pile surface are recorded along this line (Figure 5). This technique was selected for its operational simplicity and reproducibility. The results obtained during these firing tests show that the size of the block is linked to the petrography of the rhyolite of the Lamis d’Hadjjar.

The results are expressed in the form of classical granulometric curves, which are widely used to describe the fragmentation characteristics of rock masses. Block size can be estimated using several geometric parameters, including block volume, mean diameter, and average polyhedral size. For a rhyolitic rock mass, the block size distribution can be described by a function $F(x)$, which reflects the structural characteristics of the massif.

This distribution can be represented either as a frequency distribution or as a volume-based distribution for blocks within a given size interval. Each investigated site is

therefore characterized by its own granulometric curves, as illustrated in Figures 7–11.

The frequency-based block size distribution represents the relative number of blocks within each size class. However, the function $F(x)$ mainly emphasizes numerical abundance and does not adequately reflect the actual importance of block size in terms of volume within the rhyolitic rock mass.

The intersection of randomly oriented discontinuities may generate a very large number of small-sized blocks (Figure 5). Although these blocks may dominate in number, their individual volumes are generally small. Consequently, their influence on rock mass stability or fragmentation processes is not as significant as might be inferred solely from their numerical proportion, as illustrated by the orientation frequency distribution at Site 1 (Figure 7).

To address this limitation, the weighted block size distribution, denoted $K(x)$, was adopted. This approach is defined as the percentage of the total block volume composed of blocks with diameters smaller than a given value relative to the total volume of blocks within the system. The weighted distribution therefore provides a more realistic representation of the true granulometric structure of the rock mass (Figure 10).

Two major granulometric cases are identified, with a considerable proportion of materials ranging between 1,000 and 1,500 mm, indicating a relatively homogeneous block size distribution. For Site 1, a significant proportion of blocks belong to the granulometric class exceeding 2,000 mm, rep-

representing approximately 58.13% of this upper size class. In contrast, for Site 2, the block size distribution is mainly concentrated between 1,500 and 2,000 mm.

The stochastic simulation framework, derived from the analysis of different statistical parameters and the structural configuration of the sampled sites, shows that when the number of discontinuity families is less than or equal to two, the effects of their orientations on block size distribution are significant and cannot be neglected.

The granulometric curve obtained for the blasted rock pile at Site 2 (**Figure 12**) illustrates the redistribution of block sizes induced by blasting operations. Compared with the in-situ rock mass, the blasted material exhibits a broader dispersion of block sizes.

The corresponding dip angle distribution of the blasted blocks (**Figure 13**) is characterized by a mean value of approximately 53° and a high standard deviation, indicating a strong variability in block orientations resulting from blast-

ing and post-blast rearrangement processes.

3.3. Fragmentation Assessment

The proposed method for assessing fragmentation was applied repeatedly to verify its validity and establish the limits of its application. We will analyze the four experimental blasts shown in **Table A3**, which summarizes the distribution of the blasts studied at the two sites and their respective results. We observe that this approach to studying blast effectiveness, based on comparing the size distribution of the blocks in situ and the block size distribution of the blasted rock pile, fully incorporates the influence of the initial structure of the rock mass on the blast results (**Figures 16–18**). Thus, the results indicate that each site, characterized by its geological structure and corresponding petrography, requires appropriate techniques or modifications to achieve the desired fragmentation.

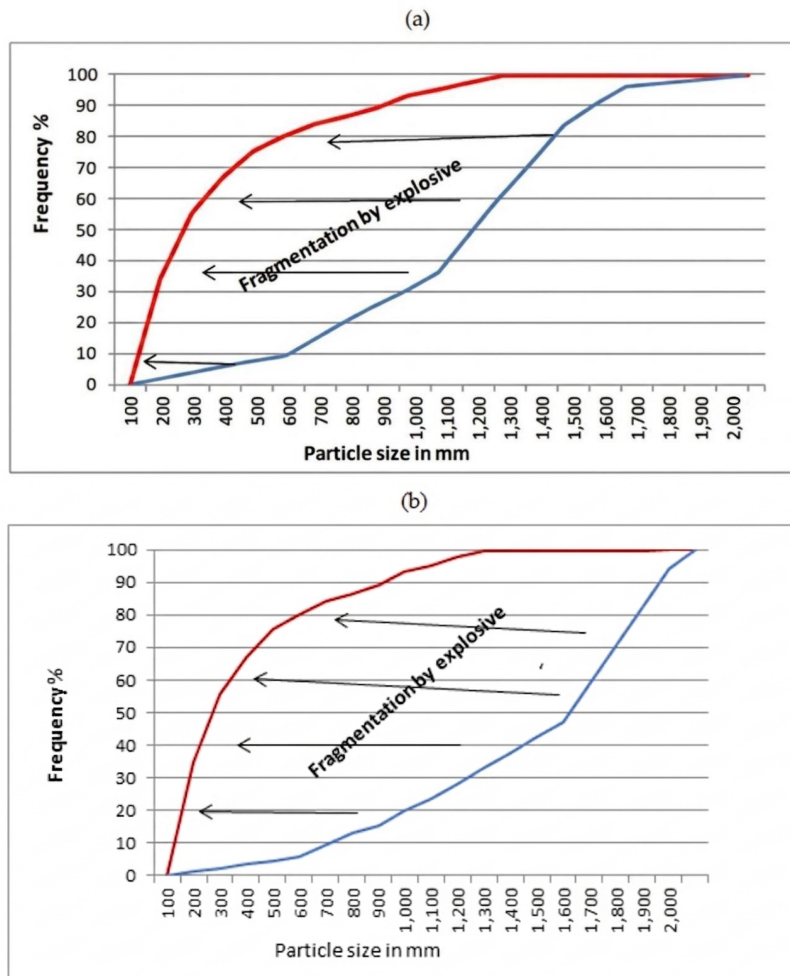


Figure 16. Comparison of block size distribution curves for the blasted rock pile at Site 1: (a) Sector 1; (b) Sector 2.

Note: Blue curve: in situ rock mass (before blasting). Red curve: blasted rock pile (after blasting). The arrows indicate the shift in the block size distribution after blasting, highlighting the reduction in characteristic block size.

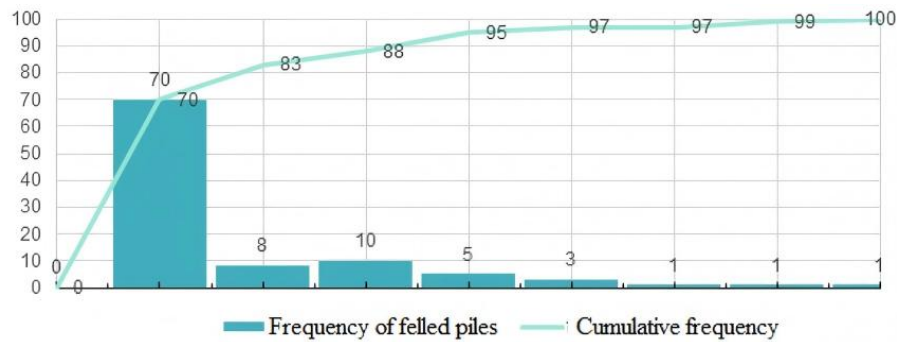


Figure 17. Distribution of block size of the blasted rock pile: Site 2.

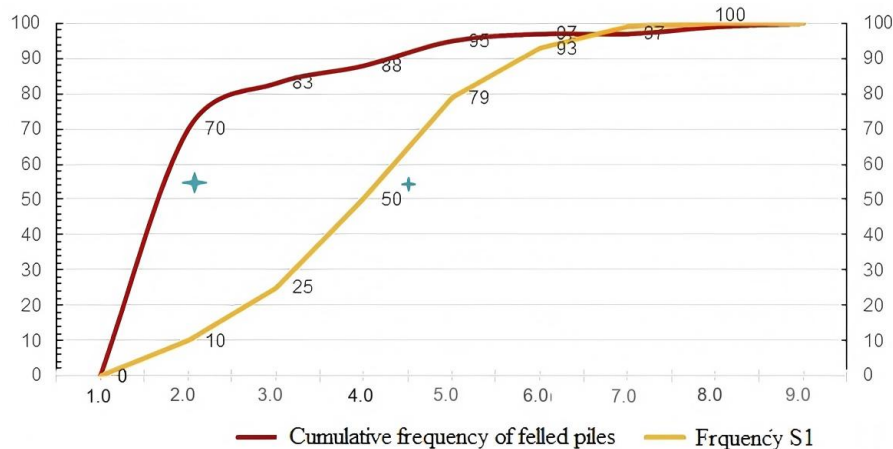


Figure 18. Comparison of the block-size distribution curves for the in situ rock mass and the blasted rock pile at Site 2, before and after blasting.

Note: Green stars indicate the characteristic points of the red and yellow curves.

Drilling presents some deviation problems, and blasting results are heavily influenced by longitudinal fractures, entire tiers of which collapse under the effect of sliding. Fragmentation is very heterogeneous at Site 1, with a high proportion of large blocks exceeding 1.5 m in diameter. Sector 2 of Site 1 is characterized by minerals of a size proportional to the sparse fracture networks; the longitudinal and transverse fractures have exposed the slab-like rock mass. Fragmentation is homogeneous because the explosive effectively utilizes all the energy used to fragment and destabilize the rock mass. At Site 2, drilling is difficult, and blasting yields good results despite significant energy dissipation between the fractures.

Fragmentation is good; however, other parameters characterizing blast results, such as bulking and spreading, are less significant from the yield point to the processing level. Parameters such as the number of rows, the height of the blast face, and the initiation method influence block size distribution and the blast design we selected has some impact on block size distribution. This analysis focuses solely on frag-

mentation and, more specifically, the influence of geological characteristics on blast results. It should also examine other technical parameters that can be adapted to improve blast results. The results of the factor analysis of the components are almost identical and all lead to the same conclusion. Blast geometry and the rock matrix play a crucial role and have a significant influence on blast results for both sites.

After analyzing all possible causes (blast geometry, initial fracturing of the massif, shock wave effect, specific energy of the explosives, and initiation sequence), the analysis demonstrates that the characteristic size of the blocks in the Hadjar Lamis massif in situ plays a crucial role. Based on the modeling of discontinuities and their statistical analysis, it was demonstrated that the major fracture pattern was oriented NW–SE and exhibited a high degree of continuity. This network, due to its continuity, is connected to the transverse fractures. The modeling shows that longitudinal blasts facilitate the displacement of the blasted volume under gravitational influence, as well as the escape of gases toward the

free surface of the blast face. For transverse blasts, the fracture network extends inwards toward the massif; this tends to counteract the gas thrust effect, allowing gases to penetrate deeper into the massif, following the preferential drainage network represented by this open and interconnected fracture (Figures 3 and 5).

3.4. The Effectiveness of Blasting

From all these analyses, the initial fracturing of the rock mass induces two opposing effects: on the one hand, it weakens the mass and reduces its overall mechanical resistance; on the other hand, it counteracts the mechanical action of the explosive by attenuating the shock wave as it passes through discontinuities and by releasing gases in the cracks. The method chosen to compare the different results of all the test blasts is principal component analysis, which identifies the physical parameters of the blast that can influence the technical results. According to our correlation circles, the four main axes are:

Axis 1 related to the geometric parameters of the blast.

Axis 2 related to the characteristic size.

Axis 3 is defined by the percentage of active charge and the explosive distribution.

Axis 4 represents specific consumption and has little influence on the analysis.

This approach examines the degree of contribution of each parameter considered in the construction of the principal axes. It is observed that the shape index, characterizing the block size distribution of the spoil heaps, is well represented on axis 2, and that axis 1 is influenced by the characteristics of the explosion mass and the explosive used. Only the results of the variances applied to the correlation circles along axes 1 and 2 for the active and passive variables are presented (Table A4).

4. Conclusions

Thus, in this work, the effectiveness and practical limits of blast-induced rock fragmentation were examined by explicitly relating post-blast fragment size distributions to the structural characteristics of the in situ rock mass. Through

a comparative analysis combining discontinuity mapping, stochastic simulation of block geometry, and granulometric characterization of blasted rock piles, the study establishes a structure-based framework that overcomes the limitations of conventional post-blast fragmentation assessments.

The results show that fragmentation efficiency at the Hadjar Lamis rhyolitic quarry is predominantly controlled by the geological structure of the rock mass. Two persistent and well-connected discontinuity families, mainly oriented NW–SE and NE–SW, govern in situ block geometry, with characteristic block sizes ranging from approximately 43–96 cm. Comparative analyses reveal fragmentation indices (IF) between 1.25 and 2.25 and fragmentation quality factors (FQF) reaching up to 0.73 when blast geometry and charge distribution are consistent with the dominant fracture network. In contrast, misalignment between blast design and structural fabric leads to heterogeneous fragmentation and a high proportion of oversized blocks exceeding 1.5 m, even under comparable explosive energy conditions.

These findings emphasize the dual and antagonistic role of natural fracturing, which simultaneously promotes rock breakage and limits fragmentation efficiency through stress-wave attenuation and premature gas escape, thereby defining intrinsic bounds to blasting performance. The proposed framework, based on the combined use of structural analysis and quantitative indices, provides a robust tool for site-specific blast optimization. Beyond fragmentation, the approach can be extended to include slope stability, muck pile geometry, vibration control, and environmental constraints, highlighting the necessity of integrating detailed geological characterization into blast design for efficient, controlled, and sustainable quarrying in structurally complex rhyolitic massifs.

Author Contributions

Conceptualization, M.M.A. and F.K.; methodology, M.M.A., A.M.B. and F.K.; field investigation, M.M.A., M.A.A. and H.B.M.; formal analysis, F.K. and G.H.P.; writing—original draft preparation, M.M.A.; writing—review and editing, F.K., G.H.P. and M.H.T. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language editing, grammar correction, and improvement of readability. No AI tools were used for data collection, data analysis, interpretation of results, scientific reasoning, or the generation of scientific conclusions. All AI-assisted outputs were carefully reviewed, verified, and edited by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the content presented in this work.

Appendix A

Table A1. Classification of discontinuities by family, Site 1.

No. Families	Numbers Fractures	Orientations Means	Dips Means	Lengths Means	Density	Standard Deviations Orientations	Standard Deviations Dips
1	11	143.72° N	73.90° N	2.55	0.15	08.50	18.05
2	14	281.57° N	31.08° N	1.63	0.10	26.90	08.22
3	13	295° N	40.7° N	3.02	0.33	10.80	16.93
4	9	116° N	58.75° N	2.30	0.25	10.80	30.11

Table A2. Classification of discontinuities by family, Site 2.

No. Families	Numbers Fractures	Orientations Means	Dips Means	Lengths Means	Density	Standard Deviations Orientations	Standard Deviations Dips	Standard Deviations of Lengths
1	94	115° N	70	2.92	49	18.88	13	64
2	67	285° N	25	1.47	35	22.10	10	26
3	36	93° N	69	1.43	64	8.95	10.86	44.56
4	112	120° N	69	4.02	57	7.40	9.50	64.81
5	64	284° N	18	1.94	48	7.40	12.61	33.93

Table A3. Results of studied blasts.

No. Sites	No. Sectors	Xcl	Xc	n1	n2	IF	FQF
1	1	111.3	49.41	0.84	1.2	2.25	0.7
	2	89.49	60.01	0.41	1.06	1.5	0.4
2	1	89.5	71.9	0.7	1.21	1.25	0.58
	2	87.2	60.42	1.05	1.41	1.44	0.73

Note: X is the characteristic block size; N is the shape index; IF is the Fragmentation index; and FQF is the Fragmentation quality factor.

Table A4. Results of correlation circles along the principal component axis.

Hadjar Lamis	Number of Blasts	Axes	Applied Variance (%)
Site 1	13	1	73.7
		2	17.3
Site 2	13	1	74.8
		2	15.2

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