RESEARCH ARTICLE

JENER Journal of Empirical and Non-Empirical Research
Volume 2, Issue 5, Page 345-348 | Article No. 39
DOI: 10.4898/jener.v2i5.a39
ISSN: 7895-9216
Journal homepage: https://jenerjournal.com
Journal email: editor@jenerjournal.com

JENER Journal
JENER Journal of Empirical and Non-Empirical Research

Integrated Geomechanical, Statistical and GIS-Based Evaluation of Drilling and Blasting Inefficiencies on Aggregate Production: a Case Study of NBHH Quarry, Northwestern Nigeria

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ARTICLE INFORMATION

Article history:
Published: May 2026

Keywords:
Drilling And Blasting
Rock Fragmentation
Kuz-Ram Model
Quarry Optimization
Aggregate Production

ABSTRACT

Efficient drilling and blasting operations are fundamental to achieving optimal rock fragmentation, cost efficiency, and environmental sustainability in quarrying systems. This study investigates the impact of poor drilling and blasting planning on aggregate production at NBHH Quarry, Talata-Mafara, Zamfara State, Nigeria, using an integrated geomechanical, statistical, and geospatial approach. Field observations were combined with laboratory analyses and empirical modelling to evaluate blast performance and identify optimization strategies. Granite samples collected from the quarry were analyzed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) to determine mineralogical and geochemical composition. Mechanical properties were evaluated using uniaxial compressive strength (UCS), point load strength index (PLSI), Brazilian tensile strength, and density tests. Results indicate that the rock mass is silica-rich, dominated by quartz (47%), orthoclase (34%), albite (7%), and muscovite (13%), with SiO_2 content of approximately 65.2%. UCS values ranged from 17.9–18.7 MPa, tensile strength averaged 9.35 MPa, and density ranged from 2.62–2.66 g/cm³, confirming a strong and brittle lithology. Field assessment revealed significant deficiencies in blasting practices, including improper burden and spacing, inconsistent charge distribution, and poor delay timing. These issues resulted in uneven fragmentation, excessive fines, oversize boulders, and increased operational costs. Statistical analysis using Pearson correlation and Principal Component Analysis (PCA) showed strong relationships among rock strength parameters, with the first principal component accounting for over 80% of the total variance. GIS-based spatial mapping further highlighted variability in rock properties across the quarry. Optimization using the Kuz-Ram model improved fragmentation uniformity and reduced inefficiencies. The study demonstrates that integrating geomechanical characterization, statistical tools, and spatial analysis into blast design significantly enhances productivity and sustainability in quarry operations.

1. Introduction

Drilling and blasting operations constitute the primary mechanism for rock fragmentation in surface mining and quarrying activities, directly influencing downstream processes such as loading, hauling, crushing, and grinding. Efficient blast design is essential for optimizing fragmentation, reducing energy consumption, minimizing operational costs, and ensuring environmental compliance. In well-managed quarry operations, blasting contributes significantly to productivity by producing uniformly sized rock fragments that enhance crusher efficiency and reduce the need for secondary breakage. However, poorly planned blasting operations often result in suboptimal fragmentation, leading to increased operational costs, reduced productivity, and heightened environmental risks.

Globally, advancements in blasting technologies—including the development of empirical models, numerical simulations, and artificial intelligence-based prediction systems—have improved the understanding and control of rock fragmentation processes. Models such as the Kuz-Ram fragmentation model have been widely applied to predict fragment size distribution based on rock properties and blast design parameters. Despite these advancements, many quarry operations in developing countries, including Nigeria, still rely heavily on traditional and experience-based blasting practices. This reliance often results in inefficient energy utilization, poor fragmentation, and increased operational challenges.

At NBHH Quarry in Talata-Mafara, Zamfara State, preliminary observations indicate persistent inefficiencies in drilling and blasting operations. These inefficiencies are manifested through improper burden and spacing, inconsistent drilling depths, inadequate explosive charge distribution, and poor timing sequences. Such deficiencies not only affect fragmentation quality but also increase the occurrence of oversize boulders and excessive fines, both of which negatively impact aggregate production. Oversize materials require secondary blasting or mechanical breaking, leading to increased operational costs, while excessive fines reduce the quality of aggregate products and may result in material wastage.

Furthermore, environmental concerns associated with poor blasting practices—such as ground vibrations, flyrock, air overpressure, and dust emissions—pose significant risks to workers, nearby communities, and infrastructure. The magnitude of these impacts is strongly influenced by rock properties, including strength, density, and mineral composition. However, in many quarry operations, these geomechanical characteristics are rarely integrated into blast design, leading to inefficient and potentially hazardous blasting outcomes.

Previous studies have emphasized the importance of incorporating rock mass properties into blast design to improve fragmentation efficiency and reduce environmental impacts. However, limited research has been conducted on integrating geomechanical, statistical, and spatial analyses in small- to medium-scale quarry operations in Nigeria. This study addresses this gap by combining laboratory characterization, statistical modelling, and GIS-based spatial analysis to evaluate drilling and blasting inefficiencies at NBHH Quarry.

1.1 The objectives of this study are to:

- characterize the mineralogical, geochemical, and mechanical properties of the rock mass;
- assess the impact of poor drilling and blasting practices on fragmentation and aggregate production;
- analyse relationships between rock properties and blast performance using statistical tools; and
- propose optimized blast design strategies using empirical models. The findings are expected to contribute to improved quarry productivity, cost efficiency, and environmental sustainability.

2. Description of the Study Area

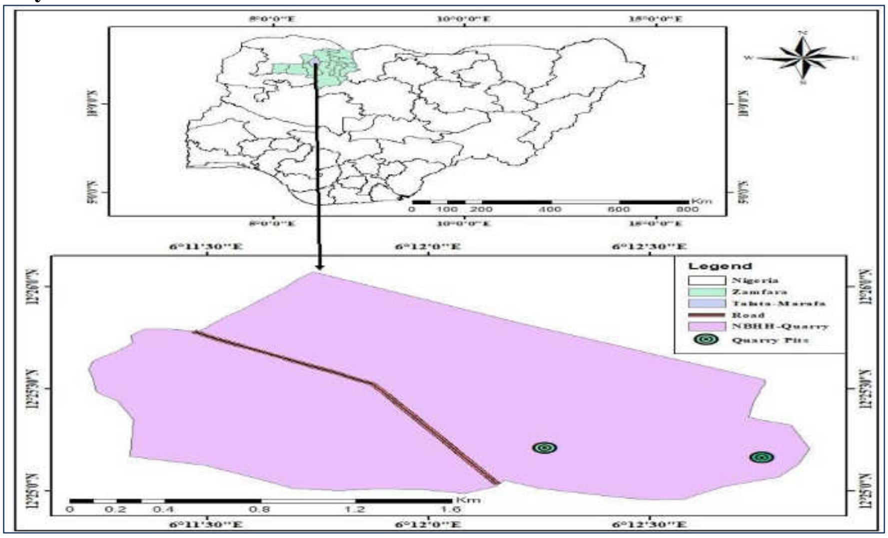

Figure 1 Map of the Study Area

The study was conducted at NBHH Quarry, located in Talata-Mafara Local Government Area of Zamfara State, Northwestern Nigeria. The quarry lies within the coordinates approximately 12°25′29.21″N latitude and 6°12′6.15″E longitude. The region is part of the Nigerian Basement Complex, which is characterized by crystalline igneous and metamorphic rocks of Precambrian age. The dominant lithology in the study area is porphyritic biotite granite, which exhibits coarse-grained texture and significant mineralogical variability.

The climate of the area is tropical, with distinct wet and dry seasons. The wet season typically occurs between May and October, while the dry season extends from November to April. These climatic conditions influence weathering processes and may affect rock strength and blasting efficiency. The terrain is generally undulating, with exposed rock outcrops suitable for quarrying activities. Geologically, the granite in the study area is composed predominantly of quartz, feldspar, and mica minerals. The high quartz content contributes to the hardness and brittleness of the rock, making it resistant to fragmentation. Structural features such as joints and fractures are present and play a significant role in controlling rock breakage during blasting.

The quarry is actively engaged in the production of construction aggregates, including crushed stones of various sizes. Drilling and blasting operations are carried out periodically to loosen rock material for subsequent processing. However, variations in rock properties across the quarry site necessitate site-specific blast design approaches. Understanding the spatial distribution of these properties is therefore critical for optimizing blasting performance.

3. Materials and Methods

This study employed a combination of field investigation, laboratory analysis, statistical modelling, and geospatial techniques to evaluate drilling and blasting inefficiencies at NBHH Quarry. Fieldwork involved direct observation of drilling and blasting operations, measurement of blast parameters such as burden, spacing, and hole depth, and documentation of fragmentation outcomes. Rock samples were collected systematically from different locations within the quarry to ensure representativeness.

Laboratory analyses were conducted to determine the mineralogical, geochemical, and mechanical properties of the rock samples. X-ray diffraction (XRD) was used to identify mineral phases, while X-ray fluorescence (XRF) analysis provided information on chemical composition. Mechanical properties were evaluated using uniaxial compressive strength (UCS), point load strength index (PLSI), Brazilian tensile strength, and density tests.

Statistical analysis was performed using Pearson correlation to evaluate relationships among rock properties and their influence on fragmentation. Principal Component Analysis (PCA) was applied to reduce data dimensionality and identify dominant factors controlling blast performance. Data were standardized prior to PCA to ensure comparability.

Geographic Information System (GIS) techniques were used to map the spatial distribution of rock properties across the quarry. Coordinates of sampling points were recorded using a GPS device and imported into GIS software. Spatial interpolation methods, such as Inverse Distance Weighting (IDW), were applied to generate distribution maps for key parameters.

The Kuz-Ram empirical model was used to estimate fragment size distribution and evaluate blast efficiency. This integrated approach enabled a comprehensive assessment of the factors influencing drilling and blasting performance.

4. Results and Discussion

Table 1: Mineralogical Analysis of Sample Rock

Mineral Phase	Chemical Formula	Weight Fraction (wt%)	PDF Card No
Quartz (syn)	SiO_2	47 ± 8	01-085-0865
Orthoclase	$KAlSi_3O_8$ (represented as $Al_2O_3 \cdot K_2O \cdot 6SiO_2$)	34 ± 10	00-002-0534
Albite	$NaAlSi_3O_8$	7 ± 6	00-001-0739
Muscovite	$H_2KAl_3(SiO_4)_3$	13 ± 6	00-001-1098

The mineralogical analysis revealed that the granite is predominantly composed of quartz (47%), orthoclase (34%), albite (7%), and muscovite (13%), indicating a silica-rich composition. XRF results confirmed high SiO_2 content (~65.2%), which contributes to the rock's high strength and to fragmentation. Mechanical tests showed UCS values ranging from 17.9 to 18.7 MPa, tensile strength averaging 9.35 MPa, and density between 2.62 and 2.66 g/cm³, confirming a strong and brittle rock mass.

Field observations indicated significant deficiencies in blasting practices, including improper burden and spacing, inconsistent drilling depths, and poor explosive charge distribution. These issues resulted in uneven fragmentation characterized by the presence of oversize boulders and excessive fines. Such fragmentation patterns negatively affect crusher efficiency and increases operational costs.

Table 2: Correlation Matrix

Parameter	UCS	Tensile	Density
UCS	1.00	0.91	0.88
Tensile	0.91	1.00	0.85
Density	0.88	0.85	1.00

Correlation analysis showed strong positive relationships among UCS, tensile strength, and density, indicating that these parameters collectively influence blast performance.

Table 3: PCA Output

Component	Eigenvalue	Variance (%)
PC1	2.45	81.7
PC2	0.35	11.6
PC3	0.20	6.7

PCA results revealed that the first principal component accounted for over 80% of the total variance, highlighting the dominant role of rock strength in controlling fragmentation.

GIS mapping demonstrated spatial variability in rock properties across the quarry, suggesting that uniform blast design is inadequate. The application of the Kuz-Ram model indicated that optimized blast parameters could significantly improve fragmentation uniformity and reduce inefficiencies. These findings underscore the importance of integrating geomechanical, statistical, and spatial analyses in blast design.

5. Conclusion

This study has demonstrated that poor drilling and blasting planning significantly affects aggregate production efficiency at NBHH Quarry. The presence of strong and brittle granite, characterized by high quartz content and elevated mechanical strength, requires carefully optimized blast design parameters to achieve efficient fragmentation. However, field observations revealed that current blasting practices are inadequate, leading to uneven fragmentation, increased operational costs, and reduced productivity.

The integration of geomechanical characterization, statistical analysis, and GIS-based spatial mapping provided a comprehensive understanding of the factors influencing blast performance. Strong correlations among rock strength parameters and the dominance of the first principal component highlight the importance of considering these properties in blast design. The study also showed that spatial variability in rock characteristics necessitates site-specific blasting strategies rather than uniform approaches.

The application of the Kuz-Ram model demonstrated that optimized blast design parameters can significantly improve fragmentation quality and reduce inefficiencies. These findings emphasize the need for data-driven approaches in quarry operations to enhance productivity and sustainability.

Overall, the study provides a practical framework for improving drilling and blasting practices in quarry operations, particularly in developing regions where traditional methods are still prevalent. Implementing the recommended strategies will not only improve aggregate production but also reduce environmental impacts and enhance safety.

6. Recommendations

To improve drilling and blasting efficiency at NBHH Quarry and similar operations, several practical recommendations are proposed. First, blast design parameters such as burden, spacing, and hole depth should be optimized based on detailed geomechanical characterization of the rock mass. This will ensure efficient energy utilization and improved fragmentation.

Second, the use of empirical models such as the Kuz-Ram model should be adopted for predicting fragment size distribution and optimizing powder factor. Incorporating such models into routine operations will enhance decision-making and reduce reliance on trial-and-error methods.

Third, real-time monitoring systems should be implemented to measure blast-induced ground vibrations, air overpressure, and fragmentation outcomes. This will enable continuous evaluation and improvement of blasting practices.

Fourth, personnel involved in drilling and blasting operations should receive regular training on modern blasting techniques and safety practices. This will improve operational efficiency and reduce the risk of accidents.

Fifth, GIS-based mapping should be integrated into quarry management to monitor spatial variability in rock properties and guide location-specific blast designs. Finally, collaboration with research institutions and industry experts is recommended to facilitate the adoption of advanced technologies, including machine learning models for blast prediction.

7. Limitations and future studies

Despite its contributions, this study has several limitations. The statistical analyses were based on a limited dataset, which may not fully capture the variability of rock properties across the quarry. Additionally, the absence of real-time blast monitoring data limited the ability to validate predicted fragmentation and environmental impacts.

The use of empirical models such as Kuz-Ram, while effective, may not fully account for complex interactions between rock properties and blasting parameters. Furthermore, the GIS analysis relied on interpolation methods that may introduce uncertainties in areas with sparse data points.

Future studies should focus on collecting larger datasets to improve the reliability of statistical analyses and model predictions. The integration of advanced technologies such as machine learning and artificial intelligence is recommended to enhance the accuracy of blast performance prediction. Real-time monitoring systems should also be incorporated to provide continuous feedback on blasting outcomes.

Additionally, comparative studies across multiple quarry sites with different geological settings would provide broader insights into the applicability of the proposed framework. The use of drone-based photogrammetry and image analysis for fragmentation assessment is another promising area for future research.

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