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Optimization of Blasting Practices for Enhanced Rock Fragmentation and Environmental Control at a Granite Quarry in Northwestern Nigeria

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ABSTRACT

Efficient rock fragmentation is central to sustainable quarry operations, influencing downstream processing, operational costs, and environmental performance. This study evaluates and optimizes blasting practices at Sunshine Quarry, Kaduna State, Nigeria, where persistent challenges of poor fragmentation, excessive fines, and environmental hazards have been observed. Field data were collected on blast design parameters including burden, spacing, charge weight, hole depth, and delay timing, alongside rock properties such as density, porosity, tensile strength, and uniaxial compressive strength (UCS). Fragmentation outcomes were analysed using the Kuz–Ram model, while environmental impacts were assessed through vibration and dust measurements. Results indicate that the granite formation exhibits high density (2.58 g/cm³) and UCS (61.86 MPa), requiring optimized explosive energy distribution for effective breakage. Existing blasting practices produced oversized fragments and excessive fines, increasing secondary blasting costs and environmental risks, including dust levels (≈350 µg/m³) and vibration intensity (≈1.2 mm/s). Optimization of blast parameters—particularly charge weight, spacing, and delay sequencing improved predicted mean fragment size to 84.23 mm, enhancing fragmentation uniformity. The study demonstrates that integrating geotechnical characterization with empirical fragmentation modelling significantly improves blasting efficiency while reducing environmental impacts. The findings provide a practical framework for cost-effective, environmentally sustainable quarry blasting in developing mining contexts.

1. Introduction

Blasting remains the most widely used and cost-effective method for rock breakage in quarrying and mining operations globally (Singh et al., 2019; Kumar et al., 2022). Efficient blasting directly influences the entire mining value chain, including excavation, hauling, crushing, and milling processes. Poor fragmentation leads to increased operational costs, excessive energy consumption, and reduced productivity (Hasanipanah et al., 2016). In recent years, the integration of advanced blasting technologies such as electronic detonators, numerical modelling, and real-time monitoring systems has improved blast design precision and environmental compliance (Tang et al., 2021; Zhou et al., 2023).

Rock fragmentation is governed by complex interactions between explosive energy, blast geometry, and rock mass properties. Geological heterogeneity, joint orientation, and anisotropy significantly influence stress wave propagation and fracture development (Hoek & Brown, 2018). Consequently, achieving optimal fragmentation requires site-specific blast design tailored to local geomechanical conditions. Empirical models such as Kuz–Ram have been widely adopted to predict fragment size distribution and guide blast optimization (Chakraborty & Mishra, 2021).

Despite technological advances, many quarries in developing countries, including Nigeria, still rely on conventional blasting practices with limited optimization. This often results in suboptimal fragmentation, increased secondary blasting, and elevated environmental impacts such as ground vibration, dust emission, and fly rock hazards (Khandelwal & Singh, 2020; Monjezi et al., 2020). At Sunshine Quarry, located in Kaduna State, inefficient blasting has led to oversized boulders, increased operational costs, and safety concerns for nearby communities.

Furthermore, there is a lack of localized studies integrating rock properties with blast design optimization in Nigerian quarry environments. Most existing models are developed under different geological conditions, limiting their applicability without calibration. This gap highlights the need for site-specific research that combines empirical modelling, field data, and environmental assessment.

This study aims to evaluate and optimize blasting practices at Sunshine Quarry by integrating rock property characterization, field blasting data, and fragmentation modelling. Specifically, it;

- assesses existing blasting parameters and outcomes,
- analyses environmental and safety impacts,
- examines geomechanical properties influencing fragmentation, and

- proposes optimized blasting parameters for improved performance.

The research contributes to sustainable quarry operations by providing a practical, data-driven framework for blast optimization in similar geological settings.

2. Location of the Study Area

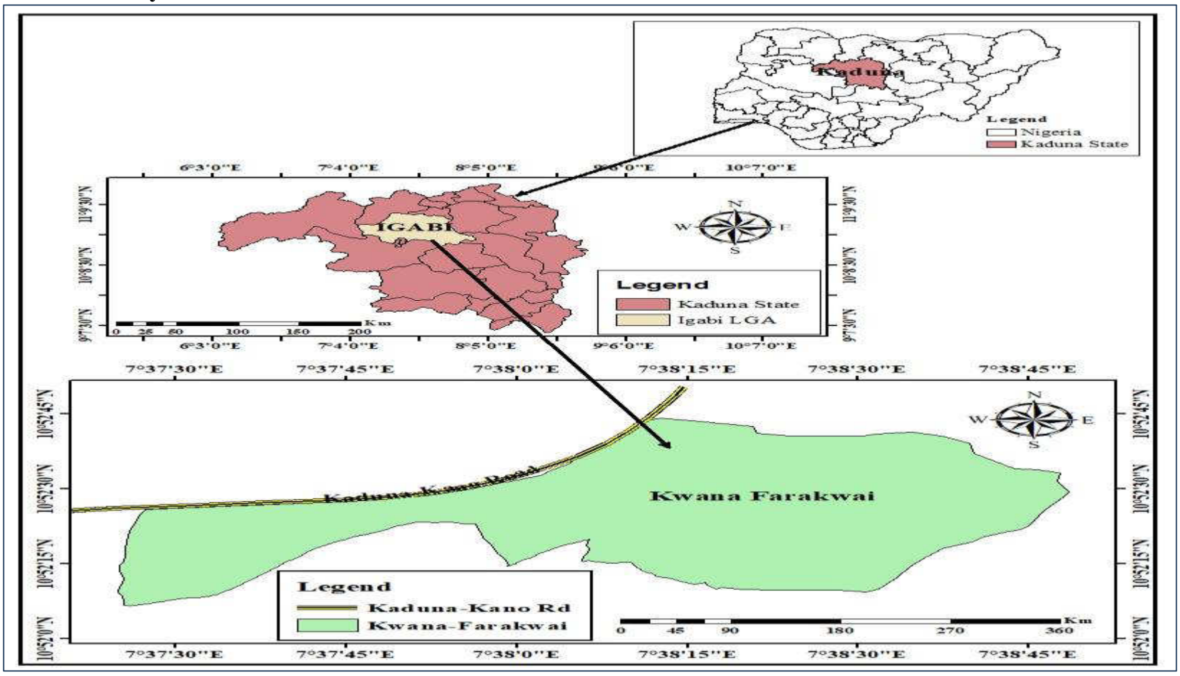

Figure 1.1: Map of Kaduna Showing the Study Area

Kwanar Farakwai is strategically located along the Kaduna-Zaria Expressway, about 30 km northeast of Kaduna city. The village's location along the Kaduna-Zaria Expressway, a major highway connecting Kaduna to Zaria and other northern regions, ensures ease of transportation and accessibility. This strategic positioning facilitates the movement of goods and people, contributing to the local economy and connectivity with larger urban centers. Additionally, the proximity to Kaduna city, a significant transportation hub with rail and road junctions, further enhances accessibility to Kwanar Farakwai. While specific coordinates for Kwanar Farakwai are not readily available, it is positioned near Kaduna city, which has coordinates approximately at latitude 10.5104642° N and longitude 7.4165053° E.

3. Materials and Methods

The study was conducted at Sunshine Quarry, Kaduna State, characterized by granitic rock formations. Field investigations included data collection on blast design parameters such as burden, spacing, hole depth, charge weight, and delay timing. Rock samples were collected from multiple locations and subjected to laboratory testing.

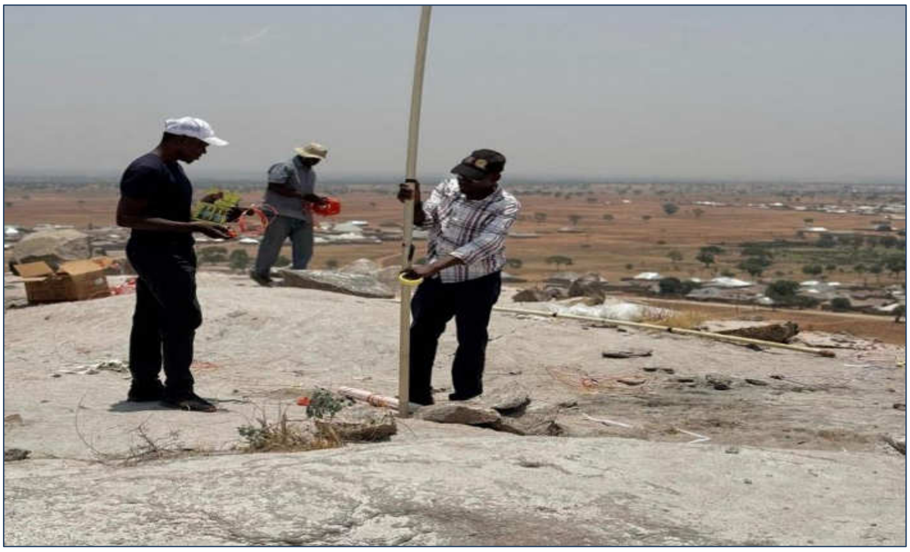

Plate 1: Charge Weight Optimization

Geotechnical analyses included determination of density, porosity, tensile strength (Brazilian test), and uniaxial compressive strength (UCS). Mineralogical composition was analysed using X-ray diffraction (XRD), while chemical composition was determined via X-ray fluorescence (XRF).

Plate 2: Density Test Determination

Fragmentation analysis was conducted using the Kuz–Ram model, which predicts mean fragment size based on rock factor, explosive energy, and blast geometry. Environmental parameters, including vibration levels and dust concentration, were measured during blasting operations.

Statistical analysis was performed to establish relationships between blasting parameters and fragmentation outcomes. Optimization scenarios were developed by adjusting key variables such as charge weight, spacing, and delay timing to achieve improved fragmentation.

4. Results and Discussion

Results indicate that the granite formation possesses high strength characteristics, with an average density of 2.58 g/cm³ and UCS of 61.86 MPa. These properties significantly influence blasting efficiency, requiring higher energy input for effective fragmentation. Current blasting practices resulted in poor fragmentation, characterized by oversized boulders and excessive fines. This inefficiency increased secondary blasting requirements and operational costs. Fragmentation analysis using the Kuz–Ram model showed that existing blast parameters were not optimized for the rock mass conditions.

Table 1: Evaluation of the Blasting Parameters

Parameter	Value	Remarks
Hole Diameter	60mm	Suitable for granite, but could accommodate a larger charge for better fragmentation.
Hole Depth	25 meters (avg.)	Adequate for effective blasting, but adjustments to charge weight and delay timing can improve results.
Total Holes per Blast	68	Sufficient for wide blast area; however, adjustments may be needed to reduce oversized boulders.
Spacing	2m by 2m	Standard spacing, but could be optimized for better fragmentation.
Burden	2m by 2m	Appropriate but may need further optimization to improve uniform fragmentation.
Explosive Material	Gelatine Explosives	Effective for granite, but further adjustments in charge weight and delay timings are necessary.
Delay Times	500ms, 17ms, 42ms	Need optimization to improve fragmentation efficiency and minimize oversized boulders.
Total Detonators	103	Adequate, but adjustments to detonator placement and delay synchronization could improve results.
UCS	61.86 MPa	High UCS indicates the need for increased charge weight and optimization of blast design.
Weight of Explosives	690kg	Adequate charge weight, but may need optimization based on blast design and rock resistance.
Rock Density	*2.60 g/cm³*	Relatively high density; requires sufficient explosive energy for effective fragmentation.

(Ehinze, F. 2025)

Environmental assessment revealed significant dust pollution (≈350 µg/m³) and ground vibrations (≈1.2 mm/s), posing risks to nearby communities. These findings align with previous studies highlighting the environmental impacts of uncontrolled blasting (Khandelwal & Singh, 2020).

Optimization of blasting parameters improved fragmentation outcomes. Increasing charge weight, optimizing burden and spacing, and adjusting delay timing enhanced energy distribution and crack propagation. The optimized design achieved a predicted mean fragment size of 84.23 mm, indicating improved uniformity and reduced oversize material.

The results demonstrate that integrating rock property analysis with empirical modelling significantly improves blast performance. Similar findings have been reported in other studies emphasizing the importance of site-specific blast design (Chakraborty & Mishra, 2021).

5. Conclusion

This study evaluated blasting practices at Sunshine Quarry and identified key inefficiencies related to poor fragmentation and environmental concerns. The integration of rock property characterization with empirical modelling (Kuz–Ram) enabled the development of optimized blasting parameters tailored to the quarry's geological conditions.

The findings show that the granite formation, characterized by high density and compressive strength, requires precise energy distribution to achieve effective fragmentation. Existing blasting practices resulted in oversized fragments and excessive fines, increasing operational costs and environmental risks.

By optimizing charge weight, burden, spacing, and delay timing, the study achieved improved fragmentation uniformity with a predicted mean fragment size of 84.23 mm. Additionally, environmental impacts such as dust emission and ground vibration were reduced through better blast control.

The study concludes that site-specific blast design, supported by empirical modelling and geotechnical analysis, is essential for efficient, safe, and sustainable quarry operations. These findings provide a practical framework for improving blasting performance in similar geological environments.

6. Limitations and Future Research Directions

6.1 Limitations of the Study

While this study provides valuable insights into blasting optimization, several limitations must be acknowledged. The research is confined to a single quarry site in Kaduna State, Nigeria, which may limit the generalization of results to other geological environments. The granite-dominated lithology presents specific mechanical properties that differ from sedimentary or metamorphic formations, thereby influencing fragmentation behaviour differently.

The study relies primarily on the Kuz–Ram empirical model for predicting fragmentation. Although widely applied, this model has limitations in capturing complex geological variability, including anisotropy, joint persistence, and in-situ stress conditions. These factors can significantly influence blast outcomes but are not fully incorporated into the model framework.

Environmental analysis was restricted to dust concentration and ground vibration measurements. Other parameters such as air overpressure, noise pollution, and long-term ecological impacts were not comprehensively assessed due to instrumentation and logistical constraints. Additionally, the study is based on short-term field observations, which may not fully capture temporal variations in blasting performance.

The dataset used, although adequate for analysis, represents a limited number of blast events and may not fully reflect operational variability. Furthermore, advanced technologies such as drone-based fragmentation analysis, 3D photogrammetry, and real-time monitoring systems were not utilized.

Lastly, the economic implications of optimized blasting were not quantitatively evaluated. A detailed cost-benefit analysis would provide stronger justification for industrial adoption of the proposed optimization strategies.

6.2 Recommendations for Future Research

Future studies should expand the scope of investigation to multiple quarry sites with varying geological conditions to improve the generalizability of results. Comparative studies across different rock types would enhance understanding of fragmentation behaviour under diverse conditions.

Advanced modelling techniques, including finite element modelling (FEM), discrete element modelling (DEM), and machine learning approaches, should be integrated to improve prediction accuracy and account for complex rock mass behaviour. These approaches can better simulate stress wave propagation and fracture mechanics.

The adoption of modern monitoring technologies, such as drone-based imaging, laser scanning, and real-time vibration sensors, is recommended to improve data accuracy and enable dynamic blast optimization. Integration with Geographic Information Systems (GIS) would allow spatial analysis of blast impacts.

Future research should also incorporate comprehensive environmental assessments, including air overpressure, noise levels, and long-term ecological impacts. Longitudinal studies are particularly important for evaluating cumulative environmental effects.

A detailed economic evaluation of optimized blasting practices is essential. Future studies should quantify cost savings associated with improved fragmentation, reduced secondary blasting, and enhanced crusher efficiency.

Finally, research into sustainable blasting technologies—such as low-emission explosives, biodegradable stemming materials, and energy-efficient detonation systems—should be prioritized to align with global environmental sustainability goals.

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