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Full Length Research Article

Optimized Blasting Techniques For Enhanced Rock Breakage In Hard Rock Metal Deposits

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ABSTRACT
Blasting operations in hard rock metal deposits represent a critical phase in mining activities, directly influencing downstream processes and overall mine productivity. This study examines optimized blasting techniques aimed at enhancing rock breakage efficiency in hard rock metal deposits through comprehensive analysis of blast design parameters, rock properties, and fragmentation outcomes. The research investigates the relationship between controllable blast parameters including burden, spacing, powder factor, and stemming with resultant rock fragmentation. Field investigations conducted across multiple hard rock mining operations revealed that optimization of blast design parameters can significantly improve fragmentation quality while reducing operational costs. Results demonstrate that optimal burden values ranging from 3.5-4.2 m combined with spacing ratios of 1.2-1.4 achieved superior fragmentation with mean fragment sizes between 250-350 mm. Statistical analysis indicates strong correlation between powder factor optimization and downstream productivity improvements. The study establishes that integrated approaches combining rock mass characterization, precise explosive energy distribution, and controlled initiation sequences yield enhanced breakage efficiency. Findings provide valuable insights for mining professionals to optimize blasting operations, reduce production costs, and improve overall mining efficiency in hard rock metal deposit extraction.
Keywords: *Blasting optimization, Hard rock fragmentation, Powder factor, Blast design parameters, Metal deposits.*

1. INTRODUCTION

The extraction of metallic ores from hard rock deposits constitutes one of the most challenging operations in modern mining industry, where drilling and blasting serve as the primary method for rock fragmentation. The effectiveness of blasting operations directly influences the efficiency of subsequent mining processes including loading, hauling, crushing, and milling, thereby affecting the overall economics of mining operations (Nikkhah et al., 2022). In hard rock metal deposits, characterized by high compressive strength, complex geological structures, and varying mineralogy, achieving optimal fragmentation through blasting remains a persistent technical challenge that requires systematic optimization of multiple interdependent parameters. Rock blasting with explosives has evolved significantly since its inception, transitioning from empirical approaches to sophisticated, technology-driven methodologies incorporating advanced understanding of rock mechanics, explosive chemistry, and energy transfer mechanisms (Dotto & Pourrahimian, 2024). The fundamental principle of blasting involves rapid conversion of chemical energy into mechanical work through detonation of explosives, generating stress waves and high-pressure gases that induce fracturing in the surrounding rock mass. However, studies indicate that only 5-15% of the explosive energy is effectively utilized for rock fragmentation, with substantial energy dissipated as ground vibrations, air blast, heat, and noise, highlighting the critical need for optimization strategies (Tao et al., 2020). The quest for optimized blasting techniques in hard rock metal deposits is driven by multiple factors including increasing mining depths, rising operational costs, stricter environmental regulations, and the imperative to maximize resource recovery while minimizing dilution. Traditional blast design approaches, often based on simplified empirical relationships, frequently fail to account for the complex interplay between rock properties, explosive characteristics, geometric parameters, and site-specific geological conditions. Contemporary research emphasizes the necessity of integrated approaches that combine detailed rock mass characterization, precise explosive energy distribution, advanced initiation systems, and comprehensive fragmentation analysis to achieve superior blasting outcomes. Recent advancements in blasting technology encompass improvements in explosive formulations, electronic detonation systems, blast modeling software, and fragmentation measurement techniques using digital image analysis (Wang et al., 2021). These technological developments, coupled with enhanced understanding of blast-induced rock damage mechanisms, provide unprecedented opportunities for optimizing blasting operations in challenging hard rock environments. Numerical simulation techniques, particularly finite element and discrete element methods, have emerged as powerful tools for investigating blast-induced fracture propagation, stress wave behavior, and fragmentation patterns under variable geological and operational conditions. The significance of blast optimization extends beyond immediate fragmentation quality to encompass broader implications for mine productivity, equipment performance, energy consumption, and environmental impact. Studies have demonstrated that optimizing blast-induced fragmentation can lead to substantial improvements in loading efficiency, reduction in secondary breaking requirements, decreased crusher throughput time, and lower specific energy consumption in downstream comminution circuits. Furthermore, proper blast design minimizes adverse effects including excessive ground vibration, flyrock generation, and damage to surrounding rock mass, thereby enhancing safety and environmental performance.

2. LITERATURE REVIEW

Extensive research has been conducted on blasting optimization in hard rock mining, with scholars investigating various aspects of blast design, rock breakage mechanisms, and fragmentation prediction. The foundational work in blast design established relationships between explosive properties, rock characteristics, and geometric parameters that continue to inform modern practices. Lilly (1986) developed the blastability index concept, providing a systematic framework for assessing rock mass resistance to blasting based on rock density, structure, and strength properties. This work laid the groundwork for subsequent refinements in blast design methodologies tailored to specific rock types and mining conditions. Research on powder factor optimization has demonstrated its critical role in achieving desired fragmentation while controlling costs (Adesida, 2022). Powder factor, defined as the mass of explosive per unit volume of rock blasted, serves as a fundamental parameter influencing fragmentation quality, blast-induced vibration, and operational economics. Empirical studies across diverse mining operations have established powder factor ranges for different rock types, with hard rock metal deposits typically requiring values between 0.7-0.8 kg/m³ for adequate fragmentation. However, optimal values vary significantly depending on rock properties, blast geometry, and desired fragmentation specifications.

The Kuz-Ram model, initially proposed by Kuznetsov and subsequently refined by Cunningham, represents one of the most widely adopted empirical approaches for predicting blast fragmentation. This model incorporates rock factor, explosive characteristics, and geometric parameters to estimate the fragment size distribution of blasted material. Despite its widespread application, the Kuz-Ram model has limitations in accounting for complex geological conditions, variable rock properties, and advanced initiation sequences, prompting researchers to develop modified versions and alternative approaches. Recent studies have integrated machine learning algorithms with traditional fragmentation models to enhance prediction accuracy under diverse operational conditions (Gebretsadik et al., 2024). Investigation of blast design parameters has revealed the critical importance of burden and spacing optimization. Burden, defined as the distance from a blast hole to the nearest free face, fundamentally determines the volume of rock influenced by each explosive charge. Research indicates that burden values should be proportional to explosive diameter and rock density, with typical relationships suggesting burden = 25-30 times explosive diameter for hard rocks. Spacing, the distance between adjacent blast holes, should be optimized relative to burden to ensure uniform energy distribution and minimize toe problems. Studies have established optimal spacing-to-burden ratios ranging from 1.2 to 1.5 for most hard rock applications, though specific values depend on rock properties and blast objectives.

Stemming, the inert material placed at the top of the blast hole, plays a crucial role in confining explosive gases and directing energy downward into the rock mass. Insufficient stemming results in premature venting of explosive gases, reducing fragmentation effectiveness and increasing air blast and flyrock risk (Zhang et al., 2021). Research suggests optimal stemming lengths of 0.7-1.0 times the burden value, with crushed stone or drill cuttings serving as effective stemming materials. Recent innovations include composite stemming structures designed to enhance confinement while facilitating controlled gas release. Studies on timing and initiation sequences have demonstrated their profound influence on fragmentation quality and blast-induced vibration. Electronic detonation systems enable precise inter-hole delay times, allowing optimization of stress wave interaction, fracture propagation, and rock displacement. Research indicates that proper delay timing creates favorable stress conditions for successive detonations, enhancing overall fragmentation while reducing peak vibration levels. Investigations into shock wave interaction and fracture coalescence mechanisms have provided insights into optimal delay selection strategies for various geological settings.

The influence of rock mass properties on blasting outcomes has been extensively investigated, with researchers developing various classification systems and indices to characterize rock blastability. Rock mass rating, joint spacing, rock density, compressive strength, and elastic properties all significantly affect blast performance. Verma et al. (2018) conducted field investigations examining blast-induced damage in rocks with varying quality ratings, elucidating relationships between rock mass characteristics and explosive energy requirements. Understanding these relationships enables tailored blast designs that account for specific geological conditions encountered in hard rock metal deposits. Recent research has increasingly focused on numerical simulation approaches to investigate blast-induced rock fragmentation. Xie et al. (2016) utilized finite element simulation to explore effects of in-situ stress and boundary conditions on cut-hole blasting, providing valuable insights into optimal practices under high-stress environments. Liu et al. (2019) proposed improved methods for addressing challenges in deep hole blasting, examining stress characteristics and rock mass raising mechanisms. These numerical investigations complement field studies by enabling systematic exploration of parameter variations and mechanisms difficult to observe in practice.

3. OBJECTIVES

The primary objectives of this research are:

1. To evaluate the influence of blast design parameters on rock fragmentation quality in hard rock metal deposits
2. To establish optimal parameter ranges for enhanced blasting efficiency
3. To investigate the correlation between rock properties and blasting performance
4. To provide practical recommendations for improving blast design in hard rock metal mining operations

4. METHODOLOGY

This study adopted a comprehensive methodological framework integrating field investigations, laboratory testing, data collection, and statistical analysis to optimize blasting techniques in hard rock metal mines. Research was conducted across five operational sites, including copper, iron ore, and polymetallic deposits, selected based on rock hardness, operational scale, and existing blasting practices. Detailed geological mapping and rock mass characterization were performed to assess lithological variations, structural features, and rock quality designation. Representative rock samples underwent laboratory testing to determine uniaxial compressive strength, tensile strength, Young's modulus, Poisson's ratio, and density, with point load tests providing comparative strength estimates. Experimental blast rounds systematically varied key design parameters such as burden (3.0–4.5 m), spacing (3.5–5.5 m), powder factor (0.65–0.85 kg/m³), and stemming length (2.5–4.0 m). Explosives used included ANFO, emulsions, and heavy ANFO blends, with detailed documentation of hole dimensions, charge distribution, and initiation timing. Fragmentation analysis was conducted using WipFrag digital image processing to determine size distribution parameters relative to operational targets.

Blast performance monitoring involved measurement of ground vibration, air overpressure, and visual assessment of throw and heave. Statistical tools, including correlation and multiple regression analysis, were applied to establish relationships between design variables and fragmentation outcomes. All activities were performed under strict safety standards, adhering to regulatory guidelines for explosives handling, exclusion zones, and on-site personnel safety.

5. RESULTS

The research generated comprehensive data on blast performance across varied parameter combinations and geological conditions. Analysis of 91 experimental blast rounds provided statistically significant results regarding the influence of design parameters on fragmentation quality and operational efficiency. The following tables present key findings from the investigation.

Table 1: Rock Mass Properties of Study Sites

Mine Site	Rock Type	Density (kg/m³)	UCS (MPa)	Tensile Strength (MPa)	Young's Modulus (GPa)	RQD (%)
Site A	Copper Ore (Magnetite)	3,250	125	8.5	68	72
Site B	Iron Ore (Hematite)	3,680	142	9.2	75	68
Site C	Polymetallic Ore	2,950	108	7.8	62	65
Site D	Copper-Gold Ore	2,840	98	7.2	58	70
Site E	Iron Ore (Banded)	3,420	135	8.8	72	74

Table 1 presents comprehensive rock mass properties from the five study sites representing diverse hard rock metal deposit types. The data reveals substantial variability in rock density ranging from 2,840 to 3,680 kg/m³, with iron ore deposits exhibiting highest densities consistent with their mineralogical composition. Uniaxial compressive strength values span 98 to 142 MPa, classifying all sites as hard to very hard rock requiring robust blast designs. Tensile strength measurements correlate positively with compressive strength, ranging between 7.2 and 9.2 MPa. Young's modulus values indicate relatively stiff rock behavior with measurements from 58 to 75 GPa. Rock quality designation percentages demonstrate moderately fractured to good quality rock masses, influencing explosive energy distribution and fragmentation mechanisms.

Table 2: Blast Design Parameters and Performance Metrics

Blast ID	Burden (m)	Spacing (m)	S/B Ratio	Powder Factor (kg/m³)	Stemming (m)	Hole Diameter (mm)	Bench Height (m)
B-15	3.5	4.2	1.20	0.75	3.0	165	12
B-23	4.0	4.8	1.20	0.72	3.2	165	12
B-34	3.8	5.0	1.32	0.78	2.8	152	13
B-47	4.2	5.5	1.31	0.68	3.5	165	14
B-56	3.7	4.5	1.22	0.80	3.0	152	12
B-68	4.0	5.2	1.30	0.73	3.3	165	13

Table 2 documents representative blast design parameters implemented during experimental trials across study sites. Burden values ranged from 3.5 to 4.2 meters, systematically varied to evaluate influence on fragmentation. Spacing adjustments produced spacing-to-burden ratios between 1.20 and 1.32, within the optimal range identified in literature for hard rock applications. Powder factor variations from

0.68 to 0.80 kg/m³ reflected different explosive loading strategies tested during the research. Stemming lengths between 2.8 and 3.5 meters provided adequate confinement while varying as proportion of burden. The table demonstrates systematic parameter manipulation enabling statistically valid comparison of outcomes across different design configurations in similar geological settings.

Table 3: Fragmentation Analysis Results

Blast ID	Mean Fragment Size (mm)	X_{50} (mm)	X_{80} (mm)	Uniformity Index	Oversize >800mm (%)	Fines <50mm (%)
B-15	285	265	520	1.52	8.5	12.3
B-23	310	295	565	1.48	11.2	10.8
B-34	245	228	475	1.58	6.8	14.5
B-47	365	348	685	1.45	15.4	8.2
B-56	235	220	450	1.62	5.2	16.8
B-68	295	280	545	1.50	9.8	11.5

Table 3 presents comprehensive fragmentation analysis results quantified through digital image processing of post-blast muck piles. Mean fragment sizes ranged from 235 to 365 mm across experimental blasts, reflecting significant variation attributable to parameter modifications. The X_{50} values, representing median fragment sizes, closely tracked mean values with range of 220 to 348 mm. X_{80} measurements, indicating the size below which 80% of material passes, ranged from 450 to 685 mm, critical for crusher feed specifications. Uniformity indices between 1.45 and 1.62 indicate relatively consistent fragmentation distributions. Oversize percentage varied substantially from 5.2% to 15.4%, directly impacting secondary breaking requirements. Fines generation ranged from 8.2% to 16.8%, with implications for dust control and material handling efficiency.

Table 4: Correlation Between Powder Factor and Fragmentation

Powder Factor (kg/m³)	Mean Fragment Size (mm)	Loading Time (min/truck)	Specific Energy (kWh/t)	Boulder Frequency (per 100m³)
0.65	395	8.5	1.82	12.5
0.70	342	7.2	1.68	9.8
0.75	288	5.8	1.52	6.5
0.80	248	5.2	1.45	4.2
0.85	225	4.9	1.40	3.8

Table 4 demonstrates the strong correlation between powder factor optimization and multiple performance indicators in hard rock blasting operations. As powder factor increased from 0.65 to 0.85 kg/m³, mean fragment size decreased systematically from 395 to 225 mm, representing a 43% reduction in fragment size. Loading time per truck decreased from 8.5 to 4.9 minutes, indicating substantial improvement in loading efficiency attributable to better fragmentation. Specific energy consumption in downstream crushing declined from 1.82 to 1.40 kWh/t as fragmentation improved, demonstrating the mine-to-mill benefits of blast optimization. Boulder frequency decreased dramatically from 12.5 to 3.8 instances per 100 cubic meters, significantly reducing secondary breaking requirements and associated delays.

Table 5: Burden and Spacing Optimization Results

Burden (m)	Spacing (m)	S/B Ratio	X_{50} (mm)	Backbreak Index	Toe Problems (%)	Ground Vibration (mm/s)
3.5	3.8	1.09	268	Medium	18.5	28.5
3.5	4.2	1.20	245	Low	12.2	24.2
4.0	4.8	1.20	285	Low	10.5	22.8
4.0	5.5	1.38	325	Medium	22.8	26.5
4.2	5.0	1.19	295	Low	11.8	21.5
4.5	5.4	1.20	338	Medium	20.5	25.8

Table 5 presents detailed analysis of burden and spacing optimization effects on fragmentation quality and blast performance indicators. The data reveals that spacing-to-burden ratios around 1.20 consistently produced superior results across multiple metrics. Median fragment sizes (X_{50}) varied from 245 to 338 mm depending on burden-spacing combinations. Backbreak indices, rated qualitatively as low or medium, indicate that excessive spacing relative to burden increased undesired breakage beyond designed limits. Toe problems, quantified as percentage of blast length experiencing inadequate bottom breakage, ranged from 10.5% to 22.8%, with lower values associated with optimal burden-spacing combinations. Ground vibration measurements demonstrated that larger burden values within practical limits slightly reduced vibration levels while maintaining adequate fragmentation.

Table 6: Comparison of Explosive Types and Performance

Explosive Type	Density (g/cm³)	VOD (m/s)	Energy (MJ/kg)	Fragment Size (mm)	Cost per m³ (USD)	Efficiency Index
ANFO	0.82	3,800	3.68	325	12.50	1.00
Emulsion	1.18	5,200	4.12	265	18.75	1.35
Heavy ANFO	1.05	4,500	3.95	285	15.25	1.22
Site Mixed	1.10	4,800	4.02	275	16.80	1.28
Packaged ANFO	0.85	3,950	3.75	312	13.80	1.08

Table 6 compares performance characteristics and outcomes for different explosive types utilized in hard rock metal mining applications. Bulk ANFO, with lowest density at 0.82 g/cm³ and velocity of detonation of 3,800 m/s, produced largest mean fragment sizes at 325 mm but offered lowest cost at $12.50 per cubic meter. Emulsion explosives, featuring highest density of 1.18 g/cm³ and VOD of 5,200 m/s, generated finest fragmentation at 265 mm mean size but with premium cost of $18.75 per cubic meter. Heavy ANFO blends provided intermediate performance with mean fragments of 285 mm at moderate cost. The efficiency index, calculated as ratio of fragmentation improvement to cost increase relative to standard ANFO, reveals that emulsion explosives provided best overall value despite higher unit cost, followed by site-mixed formulations and heavy ANFO blends.

6. DISCUSSION

The comprehensive analysis of blasting operations in hard rock metal deposits has yielded significant insights into optimization strategies and their practical implications for mining operations. The strong correlation observed between powder factor and fragmentation quality confirms theoretical predictions from energy-based fragmentation models while providing quantitative relationships applicable to operational decision-making. The systematic reduction in mean fragment size with increasing powder factor demonstrates that explosive energy density remains a primary controlling variable in hard rock breakage, consistent with findings from recent research on copper and iron ore mining operations (Ke et al., 2022; Leng et al., 2020). The optimal burden-spacing relationships identified in this research align closely with established empirical guidelines while refining specific parameter ranges for hard rock metal deposits. The consistent superior performance observed at spacing-to-burden ratios around 1.20 reflects optimal stress wave interaction and burden relief sequencing. Ratios significantly below 1.15 resulted in excessive confinement and elevated vibration, while ratios exceeding 1.35 produced weak fracture zones between holes and increased toe problems, as documented in Table 5. These findings complement numerical simulation studies that have demonstrated the critical role of geometric parameters in controlling blast-induced crack propagation patterns (Tao et al., 2020; Zhang et al., 2023).

The substantial variation in rock properties across study sites, as documented in Table 1, necessitated site-specific optimization approaches rather than universal parameter prescriptions. Higher density iron ore deposits required increased powder factors to achieve fragmentation comparable to lower density copper-gold ores, reflecting the greater work required to fracture denser materials. The positive correlation between rock quality designation values and fragmentation uniformity suggests that naturally fractured rock masses facilitate more efficient explosive energy utilization through exploitation of pre-existing discontinuities. This observation supports the concept of blastability indices that incorporate structural features as key parameters in blast design optimization. Loading time reductions of 35-40% observed with optimized fragmentation represent substantial productivity improvements with cascading benefits throughout the mining value chain. Reduced loading times translate directly to increased truck cycles, improved equipment utilization, and enhanced overall production capacity. The concurrent reduction in specific crushing energy, declining by up to 23% as fragment size decreased from 395 to 225 mm, demonstrates the mine-to-mill optimization potential of superior blast fragmentation. These findings quantify the economic justification for investment in blast optimization initiatives, potentially generating returns significantly exceeding incremental explosive costs.

The dramatic reduction in boulder frequency from 12.5 to 3.8 instances per 100 cubic meters with powder factor optimization from 0.65 to 0.85 kg/m³ addresses one of the most disruptive challenges in hard rock mining operations. Boulder management through secondary breaking causes production delays, equipment damage risks, and safety hazards. The near-elimination of oversized material through proper explosive energy distribution, as documented in Table 4, represents a critical operational improvement. However, the marginal increase in fines generation at higher powder factors requires careful balance to avoid excessive dust and material handling complications. Comparative analysis of explosive types reveals the complexity of cost-effectiveness assessments in blasting operations. While emulsion explosives commanded 50% price premium over bulk ANFO, their superior energy density and detonation characteristics generated 18%

better fragmentation, resulting in favorable overall economics when downstream benefits are considered. The efficiency index developed in this research provides a useful framework for economic evaluation, though site-specific conditions including haul distances, crusher capacities, and production targets influence optimal explosive selection. The intermediate performance of heavy ANFO blends suggests their potential as compromise solutions balancing cost and performance objectives.

The observed reduction in ground vibration with optimal burden values, though modest at 12-18% compared to suboptimal configurations, contributes to environmental compliance and enables blasting operations in proximity to sensitive structures. Electronic detonation systems employed in later experimental phases demonstrated potential for further vibration reduction through precise delay timing optimization, though this aspect requires additional investigation beyond the scope of current research. The relationship between vibration levels and burden-spacing combinations suggests opportunities for simultaneous optimization of fragmentation quality and vibration control through integrated blast design approaches. Backbreak occurrence patterns identified in Table 5 highlight the importance of proper burden-spacing relationships in controlling damage to remaining rock mass. Excessive spacing relative to burden created zones of inadequate confinement between blast holes, allowing premature energy release toward previously blasted areas rather than toward intact burden. This mechanism explains the elevated backbreak indices observed at S/B ratios exceeding 1.35. Conversely, optimal geometric configurations concentrated explosive energy toward the burden, minimizing undesired fracturing behind the blast. These findings have implications for highwall stability in open pit operations and pillar integrity in underground applications.

The research findings complement and extend recent numerical simulation studies that have investigated blast-induced rock damage mechanisms under variable stress conditions (Yi et al., 2018; Rong et al., 2024). While numerical approaches provide valuable insights into stress wave propagation and fracture development, field validation through systematic parameter variation and performance measurement remains essential for practical application. The convergence between empirical findings from this research and theoretical predictions from computational studies strengthens confidence in both approaches and suggests pathways for integrated blast design methodologies. Limitations of this research include the focus on specific rock types within metal deposits, potentially limiting generalizability to other geological settings. Additionally, the study emphasized conventional drilling and blasting approaches without extensive investigation of emerging technologies including pre-conditioning methods, chemical rock breaking agents, or advanced explosive formulations. Future research directions include investigation of electronic detonation system optimization, rock mass characterization refinements using advanced geophysical techniques, and integration of real-time blast monitoring technologies for adaptive blast design implementation.

7. CONCLUSION

This research has successfully demonstrated that systematic optimization of blast design parameters substantially enhances rock breakage efficiency in hard rock metal deposits, generating measurable improvements in fragmentation quality, operational productivity, and downstream processing performance. The comprehensive field investigation across multiple mining operations, supported by rigorous data analysis and statistical evaluation, has established quantitative relationships between controllable blast parameters and fragmentation outcomes applicable to operational decision-making. Optimal burden values ranging from 3.5 to 4.2 meters combined with spacing-to-burden ratios of 1.20 to 1.25 consistently produced superior fragmentation characterized by mean fragment sizes between 245 and 295 mm, significantly enhancing loading efficiency and reducing crusher energy requirements. The strong correlation between powder factor and multiple performance metrics validates the critical importance of explosive energy density optimization, with powder factors of 0.75 to 0.80 kg/m³ emerging as optimal for typical hard rock metal deposit conditions. However, the necessity for site-specific calibration based on rock properties, operational requirements, and economic considerations cannot be overstated. The research has quantified substantial productivity benefits including loading time reductions of 35-40%, specific crushing energy decreases of up to 23%, and near-elimination of problematic oversize material through proper parameter selection.

Comparative evaluation of explosive types revealed that while emulsion explosives command price premiums over conventional bulk ANFO, their superior fragmentation performance generates favorable overall economics when downstream benefits are considered. The development of efficiency indices incorporating both cost and performance metrics provides a useful framework for explosive selection decisions. The investigation of burden-spacing relationships has clarified optimal geometric configurations while identifying mechanisms responsible for common blast performance problems including toe formation and backbreak occurrence. The findings contribute to the broader understanding of blast optimization in challenging hard rock environments and provide practical guidelines immediately applicable to mining operations. The research demonstrates that investment in systematic blast design optimization generates returns substantially exceeding incremental costs through multiple value chain improvements. Future research should focus on integration of emerging technologies including electronic detonation systems, real-time monitoring capabilities, and advanced numerical modeling to further refine blast design methodologies and enhance operational efficiency in hard rock metal mining.

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