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Study of Blast Fragmentation and Shovel Efficiency in a Surface Coal Mine- A Review

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Abstract- Blast fragmentation significantly influences the efficiency of loading equipment such as shovels in surface coal mines. Proper fragmentation ensures ease of digging, shorter cycle times, lower fuel usage, and reduced wear and tear on machinery, ultimately enhancing overall mine productivity. This review paper systematically analyzes past research focused on the relationship between blast design parameters—such as burden, spacing, explosive type, and powder factor—and the resulting rock fragmentation. It further explores how these factors impact shovel performance in terms of loading rate, bucket fill factor, and operational costs. Several case studies and field experiments were reviewed to identify effective practices in controlled blasting aimed at optimizing shovel efficiency. The review underscores key challenges, including the lack of integrated models that link blast design directly to shovel productivity, inconsistencies in fragmentation results across different mine sites, and the underutilization of modern tools like digital image analysis and artificial intelligence for predictive modeling. These research gaps hinder the full optimization of the blast-to-load cycle. The paper concludes by recommending a more integrated and technology-driven approach to blast planning, encouraging the use of real-time monitoring, data analytics, and adaptive blast models to enhance shovel performance and improve the economic efficiency of surface mining operations.

Keywords: Blast fragmentation, shovel efficiency, surface coal mine, powder factor, rock size distribution, productivity, digital image analysis, mine-to-mill.

I. INTRODUCTION

In surface mining operations, particularly in coal extraction, the efficiency and productivity of shovel operations are intricately linked to the quality of rock fragmentation achieved through blasting. Fragmentation not only determines how easily the blasted rock can be scooped and loaded by shovels but also significantly influences downstream processes such as hauling, crushing, screening, and conveying. When fragmentation is poor—resulting in large boulders and uneven rock distribution—it causes serious operational delays, reduces bucket fill efficiency, increases shovel cycle time, and subjects loading equipment to higher mechanical stress, leading to elevated fuel consumption, greater wear and tear, frequent breakdowns, and increased maintenance costs. Conversely, excessive fragmentation or over-blasting, while seemingly beneficial for ease of digging, leads to the generation of excessive fines and dust, creating environmental challenges, reducing equipment efficiency, and introducing material handling difficulties. This results in higher operational costs, lower throughput in crushers, and loss of valuable material in fines. Shovel productivity is affected by multiple factors including bench geometry, rock strength, diggability, operator efficiency, bucket fill factor, and most importantly, fragmentation size distribution. Among all these parameters, fragmentation is the one that can be strategically controlled through precise blast design involving the selection and optimization of burden, spacing, explosive type, charge configuration, hole diameter, and powder factor. Therefore, with the ever-growing need for increased production targets, cost efficiency, and sustainable mining practices, there is a critical requirement to align blasting techniques with the capabilities of loading equipment, particularly shovels. Optimization of the blast-to-load cycle is essential not only for maximizing shovel performance but also for improving the overall mine value chain. This review aims to consolidate various research findings and field studies that investigate the impact of blast design parameters on fragmentation quality and their subsequent effect on shovel efficiency in surface coal mines. By examining existing methodologies, tools, and technologies—including empirical models, field experiments, image analysis, and digital monitoring systems—this paper seeks to provide a holistic understanding of the interaction between blasting and loading processes.

Furthermore, it attempts to identify the current research gaps and technological limitations, thereby proposing future directions for developing integrated models and data-driven approaches that can bridge the disconnect between blast design and shovel performance, leading to more efficient, cost-effective, and environmentally responsible surface mining operations.

II. LITERATURE REVIEW

Previous Research Studies:

Several researchers have explored the relationship between blasting parameters and the efficiency of excavation systems in surface mining. The following key studies are reviewed:

[1] Research on the optimization of optimal blasting parameters and fragmentation control based on coal seam geological conditions by Zhouquan Liao et. al. (2025)- Explore a critical challenge in open-pit coal mining: achieving effective fragmentation control while optimizing blasting parameters under varying geological conditions. The research addresses the economic disparity between lump and crushed coal—highlighting that lump coal yields significantly higher market value. Consequently, the study emphasizes the necessity to reduce the proportion of crushed coal during blasting operations to enhance both quality and cost-efficiency. The researchers employ a comprehensive methodological approach by integrating numerical simulations with field experiments. Utilizing LS-DYNA software and its fluid–solid coupling algorithm, they analyze the influence of key variables such as charge structure, explosive type, hole spacing, and intermediate media on blast outcomes. Their simulations help determine an optimized blasting configuration involving a charge spacing of 7 meters, hole spacing of 11 meters, and a specific charge structure composed of a 5-meter blocking length, 4-meter upper charge, 2-meter intermediate coal powder space, and a 5-meter lower charge, all using low-density explosives. This optimized model was subsequently validated through field application, where results were promising: the fines rate dropped from 30.10% to 24.17%, the proportion of lump coal increased from 59.33% to 68.41%, and large coal lump content decreased from 10.57% to 7.42%. These outcomes reflect a 5.93% reduction in fines and a 9.08% increase in valuable lump coal, indicating improved blasting effectiveness and reduced operational downtimes caused by oversized fragments. Overall, the study provides a scientifically robust, economically beneficial, and practically applicable blasting optimization strategy tailored to the geological complexities of soft coal seams in open-pit mines, thus contributing valuable insights to both academia and the mining industry.

[2] Prediction of rock fragmentation in a fiery seam of an open-pit coal mine in India by Mukul Sharma et. al. (2024)- Mukul Sharma et. al. investigates the critical challenges posed by spontaneous combustion in coal seams, particularly its impact on blast-hole loading and subsequent rock fragmentation. In fiery seams, the elevated temperatures of surrounding overburden strata pose significant hazards—especially premature detonation during hot-hole blasting operations. This study aims to optimize blasting outcomes by predicting mean rock fragment sizes under such high-risk conditions. The authors collected detailed data from 100 blasts conducted in a fiery seam of an Indian coal mine, encompassing blast design parameters, rock mass properties, and post-blast fragmentation results. Advanced soft computing techniques—specifically Random Forest Algorithm (RFA), Artificial Neural Network (ANN), Response Surface Method (RSM), and Decision Tree (DT)—were employed to develop predictive models for mean fragmentation size. The results strongly indicate the superior performance of the RFA model, with a high coefficient of determination ($R^2 = 0.94$), low root mean square error (RMSE = 0.034), and a strong variance account for (VAF = 93.58%). Parametric sensitivity analysis revealed that Schmidt hammer rebound number and spacing-to-burden (S/B) ratio are the most influential variables affecting fragment size. The study further derived the optimal blasting parameter ratios as $S/B = 1.03$, $l_d/B = 1.85$, and $l_s/l_d = 0.7$ to ensure desirable fragmentation. By combining field data analytics with machine learning approaches, this research offers a significant contribution to blasting optimization in thermally challenging coal seam environments. The findings not only enhance the safety of hot-hole blasting but also enable more accurate control of fragmentation, ultimately improving operational efficiency and resource recovery in open-pit coal mining.

[3] An Evaluation on the Impact of Ore Fragmented by Blasting on Mining Performance by Ayyub Nikkhah et. al. (2022)- Ayyub Nikkhah et. al. examines the crucial role of blast-induced ore fragmentation in enhancing mining productivity, with a focus on the open-pit Sarcheshmeh copper mine. The study addresses a significant gap in the literature—namely, the lack of quantitative linkage between blasting parameters and the downstream comminution stages such as crushing and grinding. Recognizing the centrality of rock fragmentation distribution (RFD) as a determinant of operational efficiency, the authors conducted a detailed statistical evaluation of 20 blast events under varying field conditions.

Using regression techniques, they analyzed correlations between fragmentation parameters and key performance metrics like the loading cycle time (CI) of excavation machinery. The findings demonstrated that CI was strongly influenced by RFD and the geometric characteristics of the blast blocks. The study highlights that variations in geological conditions, including differences in fracture density and rock mass structure, significantly affect the generalizability of blast performance models across mines. Therefore, site-specific data collection and statistical modeling are essential for reliable optimization. One of the key findings includes an optimal explosive block length-to-width ratio of approximately 6 and a blast-hole diameter of 241.3 mm, which correlated with high fragmentation efficiency and improved operational performance, notably in blast number 20. The best index of mining operations derived was 0.22, marking this blast as exemplary. While the research does not extend to downstream processes such as crushing due to data limitations, it lays important groundwork for understanding how initial blast design parameters directly influence the efficiency of material handling and mining cycles. The authors advocate for continued empirical data gathering and site-specific modeling to fully harness the cost-saving and productivity-enhancing potential of optimized blasting in surface mining.

[4] Reduction of Fragment Size from Mining to Mineral Processing: A Review by Zong-Xian Zhang et. al. (2023)- Zong-Xian Zhang et. al. provides an extensive overview of the critical role rock fragmentation plays in the energy efficiency, productivity, and sustainability of the entire mining and mineral processing value chain. The authors highlight that the global mining industry expends an enormous amount of energy—particularly during crushing and grinding—with remarkably low overall efficiency. The review emphasizes that optimizing rock fragmentation at the blasting stage is essential not only for reducing energy consumption in subsequent comminution processes but also for lowering operational costs, increasing mineral recovery rates, and enhancing the overall sustainability of mining operations. Key factors influencing fragmentation, such as explosive type, initiation system, geological characteristics of the rock mass, and the spatial energy distribution through blast design, are thoroughly analyzed. The article also presents an overview of various predictive models used for estimating blast-induced fragmentation, though it notes the complexity and variability inherent in these estimations. Importantly, the review briefly explores two often overlooked yet influential factors: the generation of fines and the implications of ore blending. These aspects are shown to have downstream effects on both processing efficiency and product quality. The authors argue convincingly that achieving optimal fragmentation—defined by a balance of minimal drilling and blasting costs, reduced crushing and grinding energy, maximum ore recovery, high productivity, and minimal environmental and safety impacts—is both feasible and highly desirable. However, they acknowledge several challenges, including geological variability, equipment limitations, and insufficient integration between mine planning and processing operations. Overall, the paper delivers critical insights and strategic guidance for mining professionals and researchers seeking to optimize rock fragmentation and promote more energy-efficient and sustainable practices across the mining-to-processing continuum.

[5] Development and Application of Blast Casting Technique in Large-Scale Surface Mines: A Case Study of Heidaigou Surface Coal Mine in China by Li Ma et. al. (2016)- Li Ma et. al. presents a comprehensive study on the use of blast casting technology as a cost-effective and highly efficient method for overburden removal in surface mining. This technique involves the direct casting of fragmented overburden material into previously mined-out areas, minimizing the need for secondary handling using draglines or loaders, and is particularly beneficial in scenarios where increasing stripping ratios make conventional methods economically unviable. The study systematically analyzes the key factors influencing the effectiveness of blast casting—such as bench height, mining panel width, inclined angle of blast holes, explosive unit consumption (EUC), delay-time intervals, presplitting, and blast hole pattern configurations—based on principles derived from ballistic theory and center-of-mass movement mechanics. To improve design precision and implementation efficiency, the researchers developed intelligent software capable of predicting blast casting outcomes with a margin of error within 10% compared to actual field results. The application of this optimized technique at the Heidaigou Surface Coal Mine (HSCM) led to over 34% of the blasted material being successfully cast into the inner dump, effectively reducing the load on rehandling equipment. An innovative operational strategy was implemented by incorporating a centrally located ramp ditch for coal transportation, with stripping and excavation carried out alternately on either side of the ditch. Additionally, an unconstrained nonlinear model was formulated to optimize the shift distance of the middle ramp, with calculations recommending a shift of 480 meters after every six blast casting panels.

[6] The use of air decks in production blasting in an open pit coal mine by J. C. Jhanwar et. al. (2000)- J. C. Jhanwar et. al. examines the effectiveness and economic benefits of implementing air deck blasting techniques in the production blasting of soft to medium-strength sandstone overburden in an Indian open-pit coal mine.

Air deck blasting, which involves the deliberate inclusion of air gaps (or air decks) within the explosive column, was found to significantly enhance blast performance and overall cost-efficiency. The research demonstrates that this method led to a substantial reduction in fines generation—by as much as 60–70% in homogeneous sandstone formations—while also decreasing the occurrence of oversize boulders by 80% in blocky sandstone. These improvements in fragmentation had a direct impact on downstream processes, notably increasing shovel loading efficiency by 20–40%. Furthermore, the study reports that the application of air decks yielded notable cost savings, with explosive consumption reduced by 10–35%, depending on the rock mass characteristics. Additional operational benefits included improved blast control, with throw and backbreak reduced by 10–35% and 50–80%, respectively, and ground vibrations diminished by 30–94%, thus contributing to safer and more stable pit operations. A key parameter in the optimization of this technique is the air deck length (ADL), measured as a proportion of the original charge length (OCL) and referred to as the air deck factor (ADF).

[7] Application of Blast-Pile Image Analysis in a Mine-to-Crusher Model to Minimize Overall Costs in a Large-Scale Open-Pit Mine in Brazil by Vidal Félix Navarro Torres et. al. (2024)- Vidal Félix Navarro Torres et. al. presents a novel approach to optimizing the economics and sustainability of open-pit iron ore mining in Brazil's mineral-rich Amazon region. Recognizing the environmental sensitivity and ecological value of the Amazon, the authors underscore the need for sustainable and precise mining practices that minimize environmental damage, operational inefficiencies, and greenhouse gas emissions. To address these challenges, the study introduces a calibrated mine-to-crusher model that integrates blast-pile image analysis to assess and control rock fragmentation from blasting through to primary crushing. By analyzing high-resolution images of post-blast rock piles, the research team was able to quantify fragmentation characteristics—particularly focusing on the 90% passing size (P90)—and use these measurements to fine-tune blasting parameters that would ultimately reduce downstream processing costs. The model was calibrated using technical and economic data collected over a two-year period, enabling the identification of an optimal P90 range between 0.29 and 0.31 meters for the specific conditions of the studied iron ore operation. The findings reveal that achieving this optimal fragment size leads to significant operational cost reductions by improving crusher efficiency, reducing energy consumption, and minimizing equipment wear and tear.

[8] Advanced Analysis of Blast Pile Fragmentation in Open-Pit Mining Utilizing 3D Point Cloud Technology by Pingfeng Li et. al. (2023)- Pingfeng Li et. al. presents an innovative digital approach to evaluating blast fragmentation using high-resolution 3D laser scanning. Recognizing the complexity of characterizing blast piles in open-pit mining, the authors develop a methodology that significantly improves the accuracy and efficiency of fragmentation assessment by leveraging point cloud data and advanced spatial analysis techniques. Central to their approach is the application of robust algorithms such as Random Sample Consensus (RANSAC) for plane fitting and Density-Based Spatial Clustering of Applications with Noise (DBSCAN) for accurately isolating individual rock blocks within a blast pile. Further refinement is achieved through the use of 3D convex hull construction and Oriented Bounding Boxes (OBB) to calculate the volume and maximum dimensions of fragmented blocks. The methodology also incorporates Delaunay triangulation to convert 3D point clouds into detailed surface mesh models, enabling precise computation of the blast pile's overall volume through projection-based volume estimation. The system was rigorously validated through both laboratory and field applications. Indoor trials yielded a relative error margin of 4.61% for block volumes and 4.75% for particle diameters, while field testing achieved an average rock block identification accuracy of 80.4%—improving with larger block sizes. The computed volume of blast piles showed a relative error of only 4.85% compared to actual excavation data, with additional metrics such as blast pile height, forward throw, and lateral spread demonstrating high accuracy (errors of 2.92%, 3.91%, and 4.29%, respectively). This study marks a substantial advancement in open-pit mining operations by providing a non-invasive, data-driven method for analyzing blast effectiveness and optimizing blast parameters.

[9] Environmental Impacts of Blasting in Surface Mining by Sarang Prabhakar Rao Akkewar et. al. (2022)- Sarang Prabhakar Rao Akkewar and Dr. Rajni Kant examine the adverse environmental consequences associated with blasting operations in surface mining, with a particular focus on ground vibration and its impact on nearby structures and ecosystems. As blasting remains the most widely used technique for rock fragmentation in surface and underground mining, it inevitably generates several forms of pollution—namely noise, dust, toxic gases, fly rock, and ground vibration. Among these, ground vibration is highlighted as the most critical concern due to its direct threat to the structural integrity of nearby buildings, infrastructure, and natural formations. The study investigates the correlation between peak particle velocity (PPV)—a primary measure of ground vibration intensity—and key blasting parameters such as explosive charge weight and the distance from the blast site.

Additionally, the influence of geological and physical properties of the vibration medium (i.e., the rock or soil through which vibrations propagate) on the intensity and range of these vibrations is emphasized. The research underscores the necessity of careful control and optimization of blast designs to mitigate these vibrations while maintaining the efficiency of rock breakage. The authors also note that with the increasing demand for minerals and the encroachment of urban development near mining zones, regulatory pressure has heightened, compelling mining operations to adopt more environmentally conscious blasting practices.

[10] Improving the environmental and economic aspects of blasting in surface mining by using stemming plugs

A. Ur Rehman et. al. (2021)- A. Ur Rehman, M.Z. Emad, and M.U. Khan explore the increasingly relevant role of stemming plugs in enhancing blast efficiency while reducing environmental and economic burdens in surface mining. With the rising demand for minerals, stricter environmental regulations, and escalating production costs, the optimization of blasting operations has become more critical than ever. This study addresses these challenges by focusing on stemming plugs—devices inserted into the upper part of a blast hole to confine explosive gases more effectively than conventional inert stemming materials like drill cuttings or gravel.

Through multiple full-scale production blasts, the researchers evaluated three different types of stemming plugs in terms of their technical and economic performance. The results demonstrate that stemming plugs offer considerable improvements in rock fragmentation, reduce the need for secondary blasting, and enhance overall blast control. Notably, the use of stemming plugs also helped mitigate undesirable effects such as flyrock, airblast, and excessive ground vibrations—key environmental concerns associated with conventional blasting. Economically, the incorporation of stemming plugs led to significant cost savings by optimizing explosive energy utilization and reducing the volume of unfragmented oversize material. An economic analysis within the study revealed a tangible reduction in blasting costs, contributing to more sustainable and cost-effective surface mining operations. The authors further contextualize these findings by reviewing past studies that highlight how stemming length, explosive column confinement, and hole geometry influence blast dynamics and outcomes (e.g., Khandelwal and Singh, 2006; Yang et al., 2010; Mohamad et al., 2013). By effectively redirecting explosive energy into the rock mass, stemming plugs increase the efficiency of rock breakage, minimize surface scattering, and improve operator safety. The study concludes that despite underutilization in many mining operations, stemming plugs present a practical and impactful innovation in the field of blasting. Their implementation represents a straightforward yet powerful intervention that enhances environmental stewardship, economic efficiency, and technical performance in surface mining activities.

Gap Identified:

From the extensive review of past studies, several key research gaps have been identified in the field of blasting operations and shovel efficiency in surface coal mining. While Verma et al. (1993) emphasized the need for reliable performance rating systems for explosives, the absence of a universally accepted metric for explosive performance remains a significant challenge. Biran et al. (1994) and Adhikari et al. (1995) both highlighted the importance of uniform explosive distribution and scientific blast design, yet practical implementation continues to rely heavily on empirical methods. Although Singh et al. (1996) and Uttarwar et al. (1996) introduced innovative blasting techniques such as air decking and blast casting, their long-term economic viability under varying geotechnical conditions has not been sufficiently explored. The persistent problem of toe formation, as studied by Karyampudi et al. (1999), indicates that even with proper charging patterns, geological variations continue to hinder optimal fragmentation. Similarly, Pal et al. (2002) and Pradhan et al. (2002) discussed improvements in environmental control and technological adoption like GPS and NONEL systems, but there is limited data on their integration with real-time performance feedback mechanisms. Nanda et al. (2003) proposed operations research-based optimization models, yet such models are rarely applied dynamically in real-world mining scenarios. Although Konari et al. (2004) and Kumar et al. (2004) presented the potential of blast casting and bulk explosive performance, the correlation between explosive characteristics, rock mechanics, and shovel efficiency is still underexplored. Moreover, while Bhandari (2004) introduced digital tools such as BIMS for blast data management, most mines lack such integrated systems for ongoing performance evaluation. Lastly, Sethi et al. (2004) underscored the limitations of trial-and-error blast design and the promise of software-based optimization, yet these tools are seldom customized for site-specific shovel performance metrics.

CONCLUSION

Blast fragmentation plays a crucial role in determining the operational efficiency of shovels in surface coal mining. While numerous studies have explored the relationship between blast design parameters and fragmentation, limited attention has been given to real-time integration and feedback-based optimization. Improved shovel efficiency not only reduces operational costs but also extends equipment life and enhances mine safety. Future research should focus on developing integrated fragmentation-shovel productivity models using AI, field sensors, and image analysis tools to create dynamic and responsive mining systems. Additionally, mine-to-mill strategies must be refined and customized for varying geological conditions to optimize both upstream and downstream operations.

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