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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

2.1 OVERVIEW

Blasting is a critical operation in surface coal mining, influencing the entire production cycle from excavation to processing. The fragmentation of rock achieved through blasting has a direct impact on shovel productivity, cycle time, and overall equipment efficiency. The understanding of blast fragmentation and its effect on loading equipment is vital for optimizing mine operations, reducing costs, and improving safety. This chapter reviews previous studies on blast design parameters, fragmentation assessment techniques, and shovel performance indicators in surface mining environments.The review also highlights advancements in digital fragmentation analysis, empirical and numerical modeling, and integrated mine planning approaches that consider the drill-blast-load-transport chain. By examining these studies, this chapter aims to establish a knowledge foundation and identify research gaps addressed in the current dissertation.

Verma et al. (1993) advocated that performance rating of explosives has become a primary necessity due to increasing demand and rising competition in the mining industry. In their study, they emphasized that although the strength of an explosive is often used as a primary parameter in experimental assessments, there remains no universally accepted metric to comprehensively compare the performance indices of different explosives. Consequently, the only viable approach at present is to juxtapose laboratory-tested results with the performance claims made by explosive manufacturers. Ideally, the ratio of actual to claimed performance should be 1; however, due to various influencing factors such as site-specific conditions, rock properties, and detonation characteristics, the ratio typically deviates slightly from unity. Despite this, it is essential that the ratio remains close to 1 for the explosive to be considered reliable and effective. Based on this comparative approach, explosives can be systematically categorized into different classes for better operational selection and usage in surface mining activities.

Biran et al. (1994) observed that over the past two centuries, numerous empirical formulas have been developed and applied for the selection of appropriate charge sizes and blasting parameters aimed at achieving optimal fragmentation. However, they highlighted that the key to efficient blasting and uniform fragmentation lies in the uniform distribution of explosives within the blast holes. According to their study, the geometry and behavior of the blasted material heap are also crucial; specifically, greater throw is desirable when using loaders and hydraulic shovels, while more heave is preferable for rope shovels and loaders to enhance loading efficiency. The researchers emphasized that for economically viable blasting, it is essential to avoid deviation of drilled holes from the planned pattern, as such deviations can significantly reduce fragmentation quality and equipment efficiency. Achieving this requires careful planning and execution, including the use of site-mixed slurry explosives, mechanical stemming of blast holes, and pilot blasting to assess and refine critical parameters such as burden, spacing, and hole alignment.

Adhikari et. al. (1995) suggested that drilling and blasting costs can account for up to 25% of the total production cost in a mining project, highlighting the critical need to prioritize the design and implementation of blasting operations. Their study emphasized that optimizing blast design parameters can directly enhance overall profitability. To support this, they conducted a comprehensive assessment of existing blasting practices, incorporating a series of pre-blast, in-blast, and post-blast surveys. The collected data were then analyzed, and a practical model was developed to interpret the influence of different blast parameters. Through systematic comparison and iterative modifications, the researchers worked toward identifying the most effective configuration for improved outcomes. They concluded that achieving a high degree of refinement in blast design necessitates a scientific and structured approach. Moreover, the adoption of advanced instruments such as Velocity of Detonation (VOD) probes and laser profiling systems significantly enhances the accuracy, efficiency, and cost-effectiveness of blast monitoring and evaluation.

Singh et. al. (1996) emphasized that to achieve cost optimization in opencast mining operations, it is essential to fine-tune drilling and blasting parameters. In particular, they noted that the first step in optimizing explosive usage involves careful selection and reduction of booster cartridges and cast boosters, in combination with column explosives. Through field experimentation, they demonstrated that minimizing the quantity of booster required for initiating the entire explosive column can lead to substantial cost savings. Furthermore, they advocated for the adoption of a total top-initiation system in place of conventional bottom or down-the-hole initiation, as this approach significantly reduces the consumption of detonating fuse. The incorporation of air decking was also highlighted as an effective technique to lower explosive consumption without compromising fragmentation quality. Additionally, the implementation of top-initiation systems along with non-electric (NONEL) initiation methods has successfully eliminated the desensitization effect within the explosive column, thereby ensuring better control over the detonation sequence and enabling the optimal utilization of explosive energy for enhanced blasting efficiency.

Uttarwar et. al. (1996) investigated the blast casting technique, which involves the strategic use of explosive energy not only to fragment the rock mass but also to cast a significant portion of the blasted material directly into adjacent, previously mined-out pits. This method offers dual benefits—fragmentation and material displacement—and is highly dependent on several blast design parameters. Key among them are bench height, which influences the rock trajectory, and the height-to-width ratio of the blast block, which affects the efficiency of material throw. The researchers observed that the technique is most effective when using explosives with a high ratio of heave energy to strain energy, thereby enhancing the casting potential of the blast. A higher powder factor was found to support improved casting outcomes. Additionally, optimal blast-hole diameter and inclination, appropriate stemming and decking techniques, precise burden-to-spacing ratios, well-planned delay intervals, and initiation practices were all identified as critical factors in achieving effective and economical blasting using this technique.

Karyampudi et. al. (1999) studied the persistent issue of toe formation in opencast mining operations and identified it as a significant drawback affecting blasting efficiency and excavation. Their research pointed out that several controllable factors contribute to toe formation, such as improper burden and spacing, unsuitable drill block dimensions, poor drill hole conditions, and incorrect blast hole charging and initiation practices. They emphasized that while factors like strata variation, fractured formations, and water-logged holes are often unavoidable, efforts should be made to minimize their presence within the drill block through careful planning and block design. According to their findings, effective blast planning must include accurate marking of the crest, burden, and spacing, ensuring uniform energy distribution. Furthermore, they advocated for a proper charging pattern with the correct proportion of booster, base, and column charges.

Pal et. al. (2002) conducted a comprehensive study on optimizing the blasting pattern at the Sonepur Bazari opencast project, aiming to control ground vibrations, air overpressure (noise), and fly rock, while simultaneously improving production efficiency. Their findings demonstrated that careful and systematic design of blast parameters could yield significant improvements in fragmentation quality and vibration control. However, they noted that effective supervision remained crucial for mitigating fly rock incidents. The study recommended the adoption of a non-electric (NONEL) initiation system in place of conventional detonating fuses. Although this approach increased the overall blasting cost, it resulted in enhanced safety, reduced chances of misfires and fly rock, and more consistent fragmentation—ultimately contributing to improved productivity and reduced requirements for sub-grade drilling. Additionally, they highlighted the significance of blast initiation direction in achieving controlled and effective results.

Pradhan et. al. (2002) examined the evolving trends in blasting practices across Indian opencast mines and observed that these practices have continuously adapted in response to changing operational demands. The study highlighted the introduction of advanced technologies such as electronic delay detonators, which allow for precise delay timing, and the adoption of shock tube initiation systems and air-decking techniques to enhance fragmentation control and reduce explosive consumption. Blast design has increasingly been tailored to the physico-mechanical properties of rock, resulting in improved performance and cost-efficiency. Additionally, the use of GPS technology for blast planning and alignment has added a new dimension to precision blasting. Pradhan also noted the growing emphasis on monitoring blast performance and the formulation of cost-effective explosive blends to maximize productivity. Despite these advancements, the study concluded that substantial improvements are still required in the areas of blast management and control to ensure consistent outcomes and sustainable mining operations.

Nanda et. al. (2003) emphasized the role of operations research in understanding, analyzing, and optimizing complex mining systems through the development and application of mathematical models. The study explored the use of Queuing Theory, Markov Chains, and Reliability Models to assess operational behaviors within mining systems. According to the author, operations research enables the construction of models that accurately represent real-world systems, allowing for detailed analysis and prediction of future behaviors under varying conditions. By adjusting variable values within these models, key operational parameters can be optimized to improve system efficiency. Nanda advocated that in the modern industrial landscape—where competition is high and resource utilization is critical—operations research offers a powerful decision-making framework. It not only supports the development of efficient strategies but also empowers management to take proactive, data-driven decisions that enhance system profitability, reliability, and overall competitiveness.

Konari et al. (2004) highlighted blast casting as a significant innovation in blasting techniques, particularly suited for overburden removal in opencast coal mines. The method has gained importance in response to the increasing demand for coal, driven by the expanding needs of the power sector. Their study outlined that blast casting not only enhances production levels but also contributes to reducing capital investment, improving equipment productivity, and optimizing mine planning through more efficient overburden handling. Key parameters influencing the success of blast casting include the physical and mechanical properties of the overburden rock, blast geometry, spacing-to-burden ratio, delay intervals, stemming and decking techniques, bench height-to-width ratio, and the type of explosive used. The authors emphasized that systematic optimization of these parameters can significantly enhance the effectiveness of blast casting. They concluded that this technique holds strong potential for future applications in Indian opencast mines, especially in the context of increasing mine depths. Furthermore, the method offers notable advantages in terms of safety, equipment utilization, and overall operational economics.

Kumar et al. (2004) conducted a study to evaluate the performance potential of bulk explosives in response to rising rock excavation targets in large opencast coal mines. Their research focused on the performance assessment of explosives in the Nigahi and Jayant mines, where they observed a direct correlation between rock properties and blasting efficiency. Specifically, they found that as the tensile strength of the rock increased, the powder factor decreased, indicating a higher energy requirement for effective fragmentation. Additionally, they reported that an increase in the blastability index was associated with higher rock density and P-wave velocity, which adversely affected fragmentation quality. The study emphasized the need for careful management of explosive consumption to achieve the desired fragmentation size efficiently. Furthermore, the authors stressed the importance of monitoring the Velocity of Detonation (VOD) of the explosive, as higher VOD values are directly linked to increased shock energy and improved fragmentation performance. They concluded that further research is needed to validate their findings and optimize explosive performance under varying geological and operational conditions.

Bhandari (2004) introduced the concept of a Blast Information Management System (BIMS), designed to store, analyze, audit, document, and manage data related to blasting operations in mining projects. The development of BIMS was aimed at optimizing the entire drilling and blasting process through digital integration and real-time data accessibility. The study highlighted that incorporating such software into blasting operations significantly simplifies the overall workflow. BIMS was noted for its user-friendly interface, ease of data entry, reliable data storage, efficient analysis capabilities, and customizable features that cater to site-specific requirements. By streamlining data handling and providing insights into blast design performance, BIMS not only reduces operational time and cost but also enhances the decision-making process. Furthermore, the tool serves as a valuable resource for training personnel and evaluating the effectiveness of various drilling and blasting strategies, thereby supporting both technical and managerial improvements in surface mining operations.

Sethi et. al. (2004) conducted a detailed study on blast design practices in Indian surface mines and revealed that most existing designs were heavily reliant on trial-and-error methods, often lacking a scientific basis. They emphasized the potential benefits of adopting computerized blast design systems to overcome the limitations associated with traditional approaches. Through a systematic evaluation of various blasting parameters, the researchers analyzed the relative significance of each factor influencing blasting efficiency. Their findings indicated that fragmentation size and hole diameter had a more substantial impact on the powder factor, while parameters such as charge per hole had a negligible effect on overall performance. Additionally, they observed that hole length and bench height, as well as spacing and burden, carried nearly equal importance in determining blast outcomes. Based on these observations, Sethi and Dey suggested that quantifying the weightage of each parameter could facilitate the development of specialized software tools, capable of generating optimized and site-specific blast designs. Such advancements, they noted, would enhance both the precision and cost-effectiveness of blasting operations in Indian mines.

2.2 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, ld/B = 1.85, and ls/ld = 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 (Cl) of excavation machinery. The findings demonstrated that Cl 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. The study concludes that while blast casting offers substantial economic and operational advantages, its effectiveness is heavily dependent on site-specific geological and engineering conditions. As such, this work contributes valuable insights and tools for the broader application and optimization of blast casting in large-scale surface mining projects worldwide.

[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). The research identifies that an ADF in the range of 0.10 to 0.35 yields optimal fragmentation and burden movement, while exceeding this range results in diminished performance and inadequate rock displacement. Overall, this pioneering work underscores the technical and economic viability of air decking in production blasting for overburden removal, offering a practical and efficient alternative to conventional blasting methods in appropriate geological conditions. It provides both theoretical insights and empirical validation for the application of controlled energy distribution in surface mining operations.

[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. Additionally, the study emphasizes the role of precise fragmentation in reducing vibration and environmental impacts, contributing to a broader framework of sustainable mining. This research represents a significant step toward integrating digital tools and data analytics into traditional mine operations, demonstrating the potential of image-based blast analysis as a cost-effective and environmentally conscious solution in large-scale mining projects.

[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. The integration of 3D point cloud technology with machine learning algorithms not only enhances the precision of fragmentation analysis but also contributes to cost savings, reduced environmental impact, and improved operational decision-making in large-scale surface mining environments.

[9] Environmental Impacts of Blasting in Surface Mining by Sarang Prabhakarrao Akkewar et. al. (2022)- Sarang Prabhakarrao 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. Advancements over the last decade in explosive materials, blasting accessories, monitoring instrumentation, and data processing tools have enhanced the ability of engineers to predict, measure, and control the environmental footprint of blasting activities. Modern techniques now allow for better prediction models and safer blasting practices that aim to reduce fly rock, minimize vibration, and achieve effective fragmentation. Overall, this study provides a vital perspective on the dual challenge faced by surface mining operations: maintaining productivity while adhering to environmental and safety standards. It calls for integrated blasting strategies that combine technological innovation with environmental sensitivity to ensure sustainable mining 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.

[11] Analysis and Optimization of Blasting Practices at the Sangaredi Mine by Fode Idrissa Conde et. al. (2022)- Fode Idrissa Conde and Ousmane Sanoh provide a detailed evaluation of the blasting methodologies employed at the Sangaredi open-pit bauxite mine in Guinea, West Africa. With the Mohs hardness of bauxite ranging between 2.5 and 3.5, and local geological conditions exhibiting a rock hardness coefficient between 3 and 6, along with clay-rich zones, pre-blasting is a critical prerequisite to facilitate efficient ore extraction in this deposit. The study emphasizes the dual objective of improving blasting efficiency while minimizing environmental nuisances, particularly ground vibrations. Through a comprehensive analysis of existing blasting practices—including explosive types, charging patterns, equipment selection, and the longitudinal blasting technique—the authors identify inefficiencies and opportunities for refinement. They conduct a targeted optimization of key parameters such as hole diameter, burden, spacing, stemming length, and explosive column distribution to suit the mixed lithology of the deposit. Special attention is paid to the vibration data collected from earlier blasting events, with the goal of proposing techniques to mitigate vibration levels and minimize the impact on nearby infrastructure and ecosystems. One of the significant contributions of the study is the reconfiguration of the drilling and blasting sequence to better align with the stratigraphic layering and mechanical properties of the bauxite ore and overburden. The proposed optimization scheme demonstrated measurable improvements in fragmentation quality, reduced overbreak, and enhanced overall blast efficiency. Moreover, this optimized approach led to an increase in production output, while also promoting safer and more environmentally responsible mining practices. By integrating geological analysis with practical blasting operations, the study offers a strategic framework for enhancing production while controlling environmental impacts in open-pit mining. The findings are particularly valuable for similar bauxite operations in tropical and clay-dominated terrains, where balancing efficiency with environmental stewardship is imperative.

[12] The Influence of Blasting Energy Factor on the Loading Performance by Paulo Couceiro et. al. (2019)- The influence of blasting parameters, particularly the Blasting Energy Factor (BEF), plays a crucial role in optimizing the performance of downstream mining operations such as excavation and loading. Couceiro and Santos (2019) emphasized that effective rock fragmentation, resulting from high-energy blasting techniques, leads to better muckpile characteristics—such as reduced boulder size, improved swell, and more uniform fragmentation—which significantly enhances loading efficiency and equipment performance in open pit mining. Their case study, conducted at a prominent gold mine in South America, revealed that adjusting the energy levels during the blasting phase resulted in notable improvements in loader productivity and reduced excavation resistance. The study concludes that a well-designed blasting strategy not only contributes to improved digging rates but also minimizes equipment wear, fuel consumption, and operational delays. This integrative approach demonstrates that blasting is not an isolated event but a determinant of overall mine productivity, reinforcing the need for strategic blasting designs that align with the performance requirements of downstream unit operations.

[13] Environmental Consequences of a Burning Coal Mine: A Case Study on Jharia Mines by Mayank Chhabra et. al. (2016)- Coal mining, especially when associated with underground fires, has long been recognized for its severe and multi-dimensional environmental impacts. In their case study on the Jharia coalfields, Chhabra and Mukherji (2016) provide a comprehensive overview of the geo-environmental consequences of coal mining, with a specific focus on the persistent coal fires plaguing the Jharia region. These subsurface fires, some of which have been burning for decades, pose significant risks not only to the sustainability of coal extraction but also to environmental safety and human health. The study identifies critical environmental parameters such as air quality, water resources, soil integrity, agricultural productivity, vegetation cover, and overall landform stability as being highly vulnerable to the disturbances caused by ongoing mining operations and combustion events. The authors further analyze data collected from Environmental Impact Assessment (EIA) reports and highlight that the degradation in air and water quality in particular is alarming, often exceeding permissible limits, thereby affecting nearby ecosystems and human settlements. The paper emphasizes that the burning of coal in situ leads to the release of hazardous gases including methane, sulfur dioxide, and carbon monoxide, all of which contribute to atmospheric pollution and global warming. Additionally, land subsidence resulting from these fires leads to displacement of communities and loss of arable land. The findings strongly advocate for a more rigorous application of environmental monitoring and remediation techniques, supported by robust decision-making tools like the Analytic Hierarchy Process (AHP), to mitigate the long-term consequences of unregulated coal mining. This study underscores the urgent need for integrated environmental planning and policy interventions to address the persistent and growing challenges associated with coal mine fires in regions like Jharia.

[14] Blasting Fragmentation Study Using 3D Image Analysis of a Hard Rock Mine by Janine Figueiredo et. al. (2023)- Blasting is a critical preliminary stage in the rock fragmentation process and plays a decisive role in the overall performance and productivity of the mining chain. Figueiredo et al. (2023) investigated the effectiveness of blasting in hard rock environments, specifically focusing on the fragmentation outcomes of very compact itabirite formations through the application of 3D image analysis. The study underscores that achieving optimal fragmentation hinges on multiple parameters—chiefly the efficient use of explosive energy, its precise distribution within the rock mass, and the controlled release of that energy during detonation. Through four experimental blasting trials conducted using an alternative design approach, the researchers utilized the PortaMetrics™ tool to assess fragmentation performance. This modern image-based analysis method was benchmarked against traditional particle size distribution models, namely the Kuznetsov and Rosin–Rammler equations, in order to validate its accuracy. The study found that PortaMetrics™ offered practical, real-time insights into blast outcomes, supporting its usefulness for preliminary blast evaluation. Moreover, the post-blasting productivity estimates—derived from particle size distribution data—highlight the substantial impact of well-optimized blasting strategies on downstream mining efficiency. The research concludes that while theoretical models provide a foundational framework, advanced digital tools like PortaMetrics™ enhance reliability and precision in evaluating fragmentation results. This integration of modern imaging technologies into conventional blasting analysis signals a significant shift toward data-driven decision-making in mine planning and performance optimization.

[15] Parametric study to develop guidelines for blast fragmentation improvement in jointed and massive formations by A.K Chakraborty et. al. (2004)- Fragmentation efficiency in opencast blasting operations plays a pivotal role in determining the productivity and cost-effectiveness of downstream mining activities. In their study, Chakraborty et al. (2004) conducted a comprehensive parametric investigation aimed at developing practical guidelines for improving blast-induced rock fragmentation in both jointed and massive rock formations. While digital image analysis tools have enhanced the ability to quickly assess fragmentation outcomes, there has been a notable gap in formulating structured, formation-specific guidelines. Addressing this, the authors analyzed data from 35 blasting events carried out in the overburden benches of three major opencast coal mines. Through Step-wise Multiple Linear Regression Analysis, the study identified key parameters—such as burden, spacing, stemming length, charge per delay, and geological conditions—that significantly influence fragmentation quality. The findings helped establish the relative impact of these variables in differing rock conditions, allowing for the formulation of practical, step-by-step corrective measures tailored to jointed versus massive rock structures. The proposed guidelines serve as a foundation for site-specific blast design optimization, enhancing fragmentation, reducing the generation of oversized boulders, and improving the overall efficiency of the mining process. This work is particularly valuable for field engineers and mine planners aiming to move beyond general blast practices toward more data-driven, customized blasting strategies in varied geological contexts.

[16] Study on Blasting Effect Optimization to Promote Sustainable Mining under Frozen Conditions by Ping Cheng et. al. (2022)- In the pursuit of environmentally responsible and efficient mining practices, especially in harsh alpine environments, optimizing blasting strategies under frozen conditions has become an area of significant research interest. Cheng et al. (2022) undertook an in-depth study aimed at enhancing blasting outcomes in underground frozen rock formations, with a specific focus on improving sustainability and reducing environmental degradation. The research was conducted in the context of mining operations in the Heilongjiang Province of China, where severe cold conditions complicate conventional blasting methods. By constructing three different joint blasting geometric models and simulating rock mass responses using LS-DYNA software, the study analyzed how various joint patterns affect blast-induced rock fragmentation. Laboratory experiments, including blasting crater tests and triaxial compression tests on frozen rocks at varying temperatures, further supported the simulations. The study employed established fragmentation characterization functions—Rosin–Rammler (R-R) and Grady–Grady–Schmidt (G-G-S)—to evaluate and quantify the effects of temperature and joint distribution on fragment size, rock strength, and stiffness. From these investigations, optimal blasting parameters were proposed, including a hole spacing of 4.0 m, row spacing of 2.5 m, and hole depth of 11.5 m, implemented with a V-type initiation network. These optimized parameters significantly improved blasting performance, reducing the large block generation rate to 3.1% and boosting mining efficiency. This study makes an important contribution to sustainable mining practices by tailoring blast design to frozen geological conditions, thereby minimizing environmental impact and promoting resource-efficient extraction in alpine and permafrost regions.

[17] Analysis of Blast Fragmentation Results of the Top Air Decking Method in Coal Mines by Adnan Allama (2023)- Blasting efficiency, particularly in coal mining operations, has a profound influence on productivity, cost, and equipment performance. One specialized technique gaining traction for improving fragmentation results is the Top Air Decking (TAD) method, which introduces an air column between the explosive charge and stemming material. In his study, Allama (2023) investigates the factors influencing fragmentation outcomes and excavation efficiency when applying the TAD method in coal mines. Using a quantitative approach supported by field data and literature, the study focuses on key parameters such as powder factor (PF), air deck length (ADL), air deck factor (ADF), stemming depth, and geological conditions like wet holes. The findings reveal a clear inverse relationship between PF and fragment size—higher PF values yield finer fragmentation. However, a larger ADL can reduce stemming depth, increasing the risk of stemming ejection and undesired boulder formation. The research further identifies an optimal ADF value of 0.3, with ADL ranging from 0.4 to 1.47 meters, which significantly enhances fragmentation quality. This configuration reduced the boulder percentage from 18% to 7% and improved digging time from 11.87 seconds to 10.57 seconds. These outcomes suggest that careful adjustment of blast geometry and air decking design can lead to notable improvements in operational efficiency and explosive utilization. The study supports the growing body of evidence that top air decking is a viable strategy to promote controlled energy release, better fragmentation, and reduced mechanical loading on excavation equipment, all of which are crucial for sustainable coal mining operations.

[18] Fragment Size Distribution of Blasted Rock Mass by Jasmin Jug et. al. (2017)- Blasting-induced fragmentation plays a pivotal role in the cost-effectiveness and efficiency of subsequent mining operations, including loading, hauling, crushing, and grinding. Jug et al. (2017), in their study presented at the World Multidisciplinary Earth Sciences Symposium (WMESS), emphasize the importance of accurately predicting and optimizing fragment size distribution in blasted rock masses to improve operational outcomes in open-pit mines. The authors underline the inherent heterogeneity of rock masses and its influence on the variability in fragmentation results. Critical factors affecting blast fragmentation include the geometry of blast holes, the type and quantity of explosives, timing sequences, and a wide range of rock properties such as uniaxial compressive strength, Young's modulus, rock density, and discontinuity characteristics. The study employs the widely accepted Kuz-Ram model for predicting rock fragmentation, integrated into a proprietary software tool ("SB") developed by the authors. This program allows simulation and optimization of blast design parameters, offering predictive insights into the expected fragmentation outcomes. The effectiveness of the Kuz-Ram model was verified through calibration using image analysis data of actual post-blast rock fragments collected from a limestone quarry in Dalmatia, Croatia. The calibrated model successfully reflected realistic fragmentation distributions, demonstrating its potential for guiding future blast designs in similar geological contexts. Ultimately, the integration of such predictive models aids in refining blasting techniques, minimizing oversize fragments, and optimizing resource use, thereby contributing to more sustainable and economically efficient mining practices.

[19] Optimization of powder factor, fragmentation and oversized boulders through subsystem studies in an opencast coal mine by Pijush Pal Roy et. al. (2023)- Efficient blast design is integral to improving fragmentation, reducing oversized boulder generation, and optimizing the powder factor in opencast mining operations. Roy, Sawmliana, and Singh conducted an in-depth study at the Chotia Opencast Coal Mine to address critical challenges in blasting performance, particularly within a 20-meter thick overburden of medium-grained sandstone situated above the coal seam. The existing blasting practices were yielding sub-optimal fragmentation results, characterized by a lower powder factor and high occurrence of oversized boulders, especially in the stemming zones. To resolve these issues, the researchers implemented a series of subsystem studies incorporating techniques such as pilot holes, pocket charges, decked and air-decked charges, and static energy distribution analyses. Additionally, the use of rebound hardness testing, explosive quality assessment, and detailed examination of blasting patterns—including optimized surface delay connections—provided a framework for refining the overall blast design. Their approach involved conducting multiple test blasts and analyzing fragmentation outcomes in relation to different design variables. The findings revealed that tailored blasting solutions—considering site-specific geological conditions and equipment capabilities—can lead to significant improvements in fragmentation efficiency and minimize the production of oversized boulders. This research offers valuable, generalizable insights for similar opencast coal mines facing challenges related to energy distribution, rock hardness, and suboptimal blasting performance. The adoption of systematic, data-driven adjustments in blast parameters, as demonstrated in this study, highlights the practical benefits of combining empirical field observations with engineering analysis for sustainable and cost-effective rock excavation practices.

[20] Estimation of Optimum Burden for Blasting of Different Rock Strata in an Indian Iron Ore Mine by Vivek K. Himanshu et. al. (2021)- In surface mining, the accurate estimation of burden—the distance between the blast hole and the free face—is a critical factor influencing the effective utilization of explosive energy, fragmentation quality, and overall blast performance. Himanshu et al. (2021) conducted an extensive study to estimate the optimum burden for blasting across various rock strata in an Indian iron ore mine, where heterogeneous rock conditions present a significant challenge to uniform blast design. Recognizing that the ideal burden value is influenced by the mechanical properties of rock and the characteristics of explosives, the authors employed two distinct but complementary approaches for its determination. The first method utilizes rock mass and explosive parameters in conjunction with the widely applied Kuz-Ram fragmentation model, where optimal burden is derived through back-calculation from the desired fragment size. The second method is grounded in vibration control, where optimum burden is estimated by predicting the distance up to which critical particle velocity limits—based on site-specific rock mass properties—are maintained. A comparative analysis of both methodologies demonstrated a strong correlation (correlation coefficient of 0.78), indicating the reliability of these estimation techniques. Field-scale experimental blasts conducted using the computed burden values showed significant improvements in fragmentation quality and blast performance. This study highlights the importance of incorporating both empirical and vibration-based approaches for site-specific optimization, particularly in complex stratified rock formations. The research provides valuable insights for mine planners and blasting engineers seeking to enhance the precision of burden design, reduce boulder formation, and ensure safer and more productive blasting operations.

2.3 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. Collectively, these studies underscore the necessity for an integrated, data-driven approach that links blast fragmentation characteristics with shovel productivity in a quantifiable and predictive manner. A significant gap exists in establishing a robust relationship between blast design variables, fragmentation indices, and their direct impact on loading equipment efficiency, especially under Indian mining conditions. This gap presents an opportunity to develop comprehensive models that integrate blasting parameters, rock behavior, explosive performance, and shovel cycle times into a unified analytical framework.

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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