Influence of Stiffness Ratio and Powder Factor on Burden Rock Movement in Blasting Operations: A Case Study on Limestone Mines

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Abstract
In opencast mining, blasting is a critical operation that significantly impacts the efficiency and cost-effectiveness of material removal. This study focuses on optimizing the use of explosive energy to move the burden, thereby reducing reliance on mechanical methods. Effective blast design involves strategically utilizing energy within a blast hole, considering factors such as explosive type, quantity, detonation timing and blast hole geometry. Given the rapid nature of blasting, high-speed video cameras are employed to capture the blast progression on a millisecond scale, providing essential data for analyzing blast dynamics.

This research evaluates the influence of blast design parameters, specifically the stiffness ratio (the ratio of bench height to the burden) and powder factor (the amount of explosive per unit volume of rock), on the movement of burden rock in a limestone mine. By examining these parameters, the study aims to optimize blast designs to achieve improved fragmentation, reduced fly rock and minimized ground vibrations, ultimately enhancing the efficiency and cost-effectiveness of mining operations.

Keywords: Burden rock velocity, high-speed video camera, powder factor, stiffness ratio.

Introduction

In any open-pit mine, for controlling the size of rock fragmentation, blasting is a crucial technique followed from the years[23]. The main motto of bench blasting is to rupture and displace the rock mass, allowing for efficient loading, transportation and further processing[26]. Various factors influence rock fragmentation during bench blasting. These parameters can be categorized into two types: controllable and non-controllable[16,19] clearly shown in the flowchart in figure 1. Controllable parameters include blast geometric and explosive properties like burden, spacing, bench height, blast hole length, stemming length, firing pattern, delay sequence, hole diameter, number of holes, explosive per hole, powder factor, etc. These can be adjusted based on the rock characteristics[16].

Depending on the characteristics of the rock mass, the burden of the distance between the bench face and the first row of blast holes is fixed and usually varies between 20 to 40 times the hole diameter[22]. Spacing is the distance between two consecutive blast holes in a row, which is also influenced by the burden, the delay time between blast holes and the initiating sequence. This value primarily depends on the diameter of the drilling hole, the bench height and the desired amount of fragmentation and displacement[3]. Stemming length is often greater than 25 times the diameter of the blast hole; however, this varies depending on the rock type, explosive utilized and blasting conditions [11]. Subgrade drilling is drilling below the proposed grade to ensure effective breakage at the desired grade. Achieving optimal subgrade drilling is crucial and is generally recommended to be 8 times the diameter of the borehole[1].

Some sources suggest that sub-drilling should be 0% of the maximum burden, although, in specific scenarios, little to no sub-drilling may be required[3]. The powder factor represents the amount of explosive used per unit volume, or mass of rock blasted. It is a critical parameter in blast design, affecting both the efficiency and cost of the operation[13]. Uncontrollable parameters in blasting are external factors that significantly affect the efficiency and outcome of a blast but remain beyond the direct control of engineers[16]. These parameters primarily include geological conditions such as rock type, density, natural discontinuities, joint patterns and the presence of faults which influence the propagation of shock waves and fragmentation behavior[2,8,20]. Additionally, environmental conditions like temperature, wind speed, humidity and groundwater presence can impact explosive performance and energy distribution[20,24].

Variations in these parameters often lead to inconsistent fragmentation, vibrations and flyrock, complicating the optimization of blasting operations. A thorough understanding of these factors and their variability is critical during blast design to minimize adverse effects and to enhance the overall success of the blasting process[10]. Drilling and blasting are vital for achieving optimal fragmentation and minimizing overall mining costs. If rock breakage and the burden are not controlled, it can increase production costs and disrupt the quarrying process due to unnecessary secondary blasting or crushing[6]. Therefore, blasting design should consider rock fragment and burden movement assessments to reduce mining costs and shorten the working time since drilling and blasting in open pit mines account for 15 to 20% of total mining costs[18].

Stiffness ratio: The stiffness ratio (SF), defined as the ratio of bench height to burden, is a critical parameter influencing the dynamics of rock movement during blasting.

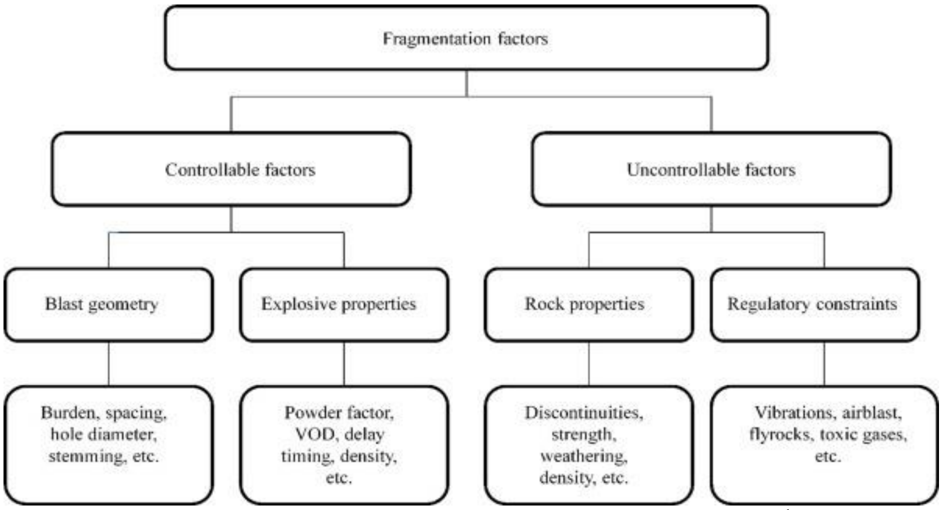

Figure 1: Factors influencing the rock fragmentation[1]

A higher stiffness ratio facilitates better energy transfer to the free face, allowing the rock burden to accelerate with greater velocity and to achieve improved fragmentation[7]. This occurs because taller benches, relative to the burden, offer enhanced confinement, enabling efficient propagation of stress waves and effective energy dissipation[4]. Conversely, a low stiffness ratio can result in limited burden movement, reduced rock velocity and suboptimal fragmentation, often leading to challenges such as increased back-break or flyrock[15].

Research has shown that the stiffness ratio also affects the distribution of explosive energy; an optimal ratio of around 2 to 4 ensures that the burden is displaced smoothly, minimizing the overuse of explosives and reducing environmental impacts, such as ground vibrations and air overpressure[10,17]. Thus, understanding and optimizing the stiffness ratio are essential for achieving uniform rock displacement, maximizing efficiency and maintaining safety in blasting operations.

Powder factor: The term powder factor (PF) is a crucial parameter in blasting operations, defined as the ratio of the mass of explosives used to the amount of rock broken or the amount of explosive needed to fragment one cubic meter of rock (1 m^3). It is typically expressed as kilograms of explosive per cubic meter (kg/m^3) or ton of rock (kg/ton). Achieving an optimal powder factor ensures effective fragmentation with minimal throw and reduced ground vibration. As noted by one of the researchers, the powder factor can act as an indicator of rock hardness, the cost of explosives, or as a guide for designing shot firing plans[4]. Mathematically, it is represented as in equation 1 as:

$$Powder\ Factor = \frac{mass\ of\ explosive\ (kg)}{volume\ of\ rock\ broken(m^3)\ or\ weight\ of\ rock\ broken(ton)} \qquad (1)$$

An optimal powder factor is critical for balancing the cost of explosives and achieving the desired fragmentation. An appropriate PF ensures efficient use of explosives, leading to effective rock breakage by attaining the required rock displacement and minimizing the need for secondary blasting or crushing. At the same time, high PF values can lead to over-blasting, increased vibrations, flyrock and environmental concerns[21]. The proper selection of the powder factor is, therefore, essential for optimizing productivity and maintaining safety standards in blasting operations. The range of the powder factor depends on several factors including the rock type, geology and blasting objectives. Recent studies have reported that for hard, dense rocks, the PF typically ranges from 0.5 to 1.5 kg/m^3, while for softer or fractured rock formations, it may vary between 0.2 and 0.6 kg/m^3 [12].

Factors such as bench height, burden and the type of explosives used also influence the appropriate PF range. Recent advancements in computational modeling have enabled more precise determination of optimal PF values tailored to specific site conditions. The powder factor directly influences burden rock velocity, as it determines the amount of energy available to displace the rock towards the free face. Higher powder factors generally result in greater burden rock velocities due to the increased energy input, leading to better fragmentation[25]. However, excessive powder factors can produce uncontrolled rock movement and adverse effects such as over-fragmentation or excessive vibrations[5].

Conversely, insufficient powder factors may result in slower rock movement, poor fragmentation and increased back-break. Optimizing the powder factor, in conjunction with other parameters like burden and stiffness ratio is essential for achieving efficient and safe blasting outcomes.

Burden rock velocity: Burden rock velocity is the speed at which the rock mass (burden) moves towards the free face during blasting and is a critical parameter in mining and construction operations. Accurately predicting this velocity is essential for optimizing blast designs to achieve desired fragmentation, to ensure safety and to enhance the overall efficiency of the blast[14].

Factors affecting burden rock velocity: The velocity of burden rock caused by blasts is influenced by numerous factors, as illustrated in figure 2. These factors are interconnected, meaning a change in one will affect the others. When planning a blast, it is crucial to consider geophysical properties to achieve an optimal blast with minimal burden rock velocity, thereby lowering costs by reducing the time needed for dozers and shovels. Geological discontinuities also significantly impact the movement of burden rock[14]. Understanding and accurately predicting burden rock velocity in limestone is vital for several reasons:

Fragmentation Control: Optimal burden rock velocity ensures desired rock fragmentation, reducing the need for secondary blasting and enhancing downstream processing efficiency[9].

Safety: Controlling the velocity minimizes the risk of flyrock and excessive ground vibrations, thereby safeguarding personnel and equipment.

Environmental Impact: Proper management of burden rock velocity reduces environmental disturbances, such as noise and dust emissions.

Cost Efficiency: Effective control leads to efficient use of explosives and resources, lowering operational costs[14].

Details of the mine: The field study was carried out in the three limestone mines, referred to as mine A, mine B and mine C to achieve the study's objective, shown in figure 3 by the satellite image. These mines are located in the districts of Telangana and Andhra Pradesh States. In these mines, the study benches varied from 6m to 10m high. Limestone outcrops are in the color shades of grey and off-white, exhibiting fine-grained texture in nature. The limestone shows a typical bedded nature with varying thicknesses. Rock strata were highly fractured in structure. A general view of all three mines is given in figure 4.

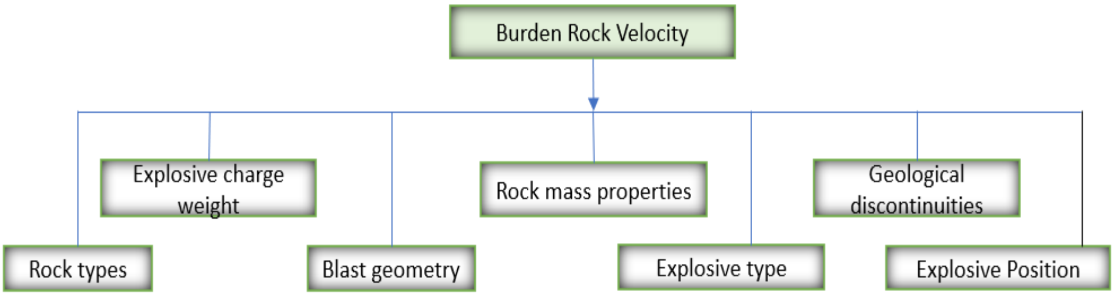

Figure 2: Factors affecting burden rock velocity

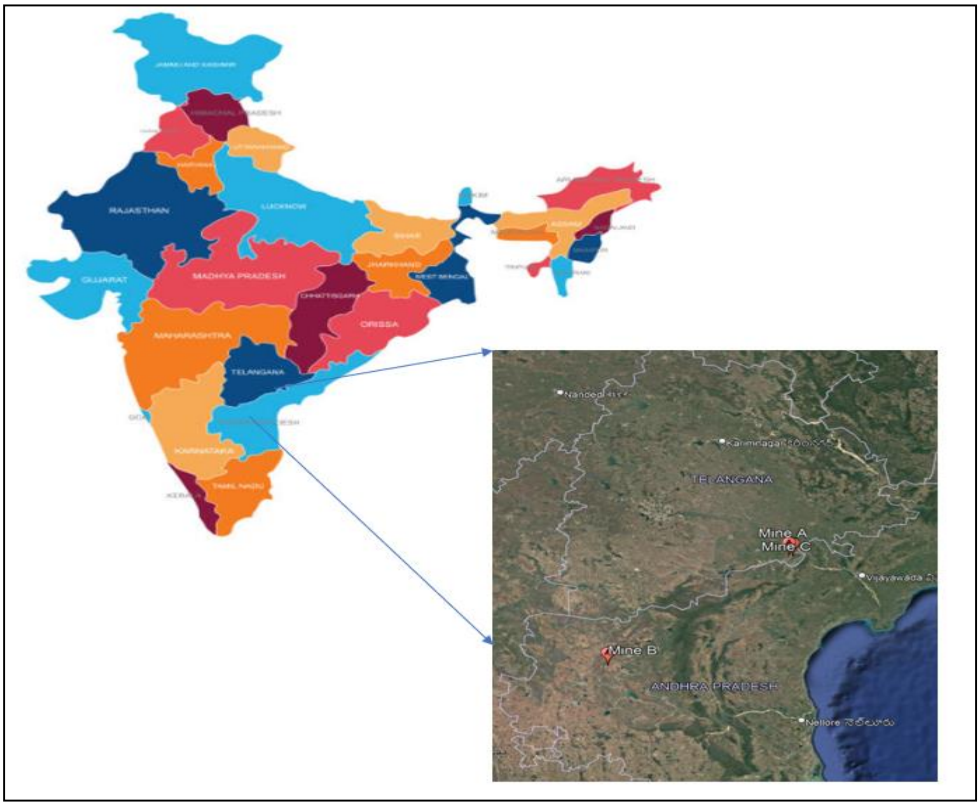

Figure 3: Satellite image of all the three mines

(a)

(b)

(c)

Figure 4: (a) A general view of Mine A (b) A general view of Mine B (c) A general view of Mine C

(a)

(b)

Figure 5: (a) and (b) showing the drilling operation and diameter of the blasthole

Material and Methods

Methodology: The limestone formation is excavated using the benching method, with bench heights generally ranging from 6 to 10 meters. The surface profile of the benches varies across different locations. Drilling and blasting techniques are employed to fragment the fractured limestone formation. The production cycle begins with drilling 115 mm diameter blast holes using wagon drills, as shown in figure 5 (a) and (b).

In general, the depth of blast holes varies from 6.5m to 10m, as per the profile of the bench height. Angular drilling with about 15^0 (from vertical) is being adopted in all three mines. Subsequently, the blastholes are charged with ANFO mixed with husk for building up the explosive column. This technique reduces the charge concentration. An ideal boost is a class-II type explosive used as a primer. Excel Du Eldet shock tube detonators are used to achieve in-hole initiation (for initiating explosive charges in the blast holes) and surface delay in blast rounds. Figures 6 (a), (b), (c) and (d) show the explosive cartridges, ANFO bags and also the priming of the explosive cartridges with Nonels and the loading of explosives into blast holes.

After placing a required quantity of explosive cartridges into blastholes for building up the explosive column, the remaining 2m-2.75m top portion of blastholes is stemmed using inert drill cuttings (Figure 7). After the stemming operation is over, all blast holes are connected and the blast round is established.

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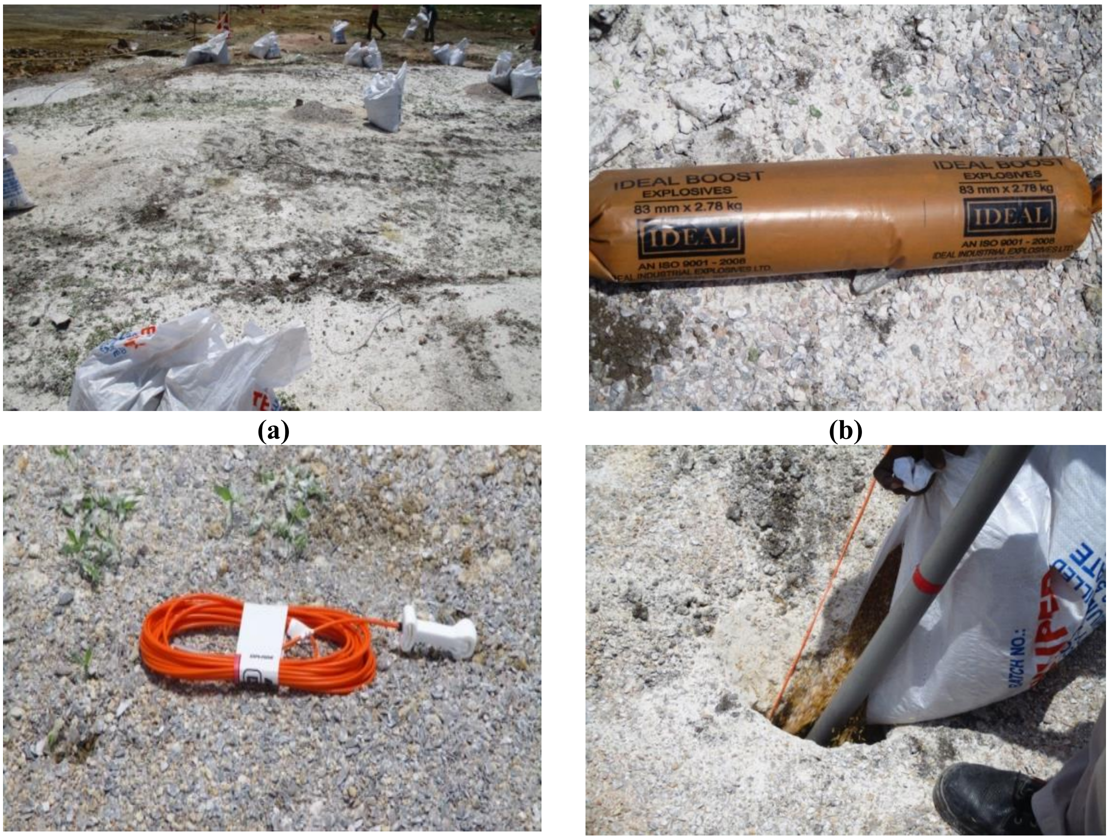


(a) (b)

(c) (d)

Figure 6: (a), (b), (c) and (d) show explosive cartridges, ANFO bags and also the priming of the explosive cartridges with Nonels and the loading of explosives into blast holes.

Figure 7: Stemming of blasthole

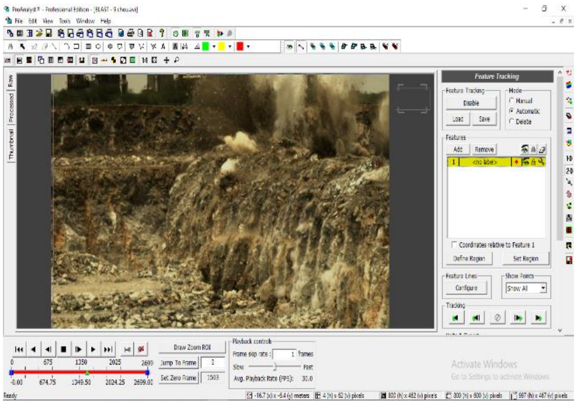
Results and Discussion

During a blast, rock breakage and movement occur so rapidly that the naked eye cannot detect the details of the fragmentation process. To overcome this obstacle, high-speed videography technique (Figure 9) is introduced as a blast assessing tool. The data on the importance of blast casting can be quantified in the form of films. Later, these films are fed into Proanalyst, a motion analyzing software in AVI video format to measure the burden of rock movement. Then the calibration of the video using known distance, generally burden distance or bench height, is taken as shown in figure 8.

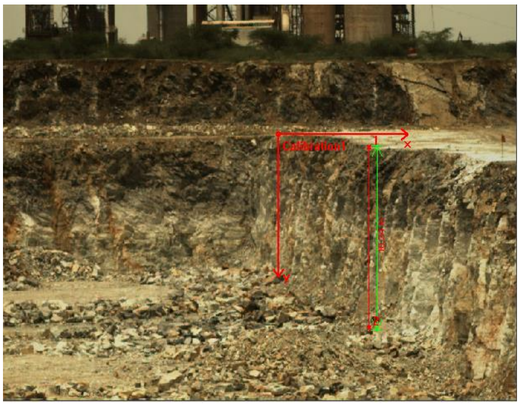
Figure 8 also shows a blast analyzed through Proanalyst software. The blast was also tracked using Proanalyst software to find the velocity of rock movement while blasting, as shown in fig. 8(c). From the analysis made by Proanalyst software, using the time taken by a rock particle to reach a certain distance traveled, the velocity of burden rock movement is calculated. Hence, from the analysis made by Proanalyst software, for a certain time (the time taken by a rock particle to reach a particular distance), the velocity of rock movement is calculated. The velocity at the top, center and toe portion is determined as shown in the figure. However, the velocity at the center was higher than the top and toe portion and hence, it is considered the most representative measure for evaluating the overall effectiveness of the blast.

Table 1 provides the summary of various parameters of the blasts in three different mines. It presents specifications for 17 distinct blasting scenarios in all three mines: A, B and C. In the context of mining or similar operations, several key parameters are detailed in the methodology of each blast. The bench height, representing the vertical distance between levels, varies between 6 and 10 meters across the different blasts. The burden, or the horizontal distance between blast holes, is consistently set at 3 meters and 6 meters spacing between blast holes. The number of blastholes per blast ranges from 22 to 68.

Explosive parameters are also specified, with the explosive amount per hole varying between 33 and 69 kilograms. The total explosive charge for each blast is calculated based on the number of blastholes, with values ranging from 770 to 3800 kilograms. A uniform stemming of around 2.5 meters is kept. Finally, the burden rock velocity calculated from the blast is specified, varying from 6.197 to 10.1 meters per second. These comprehensive specifications provide a detailed overview of the blasting conditions for each scenario, offering valuable insights for optimizing and analyzing blasting operations in the given context.



(a)



(b)

(c)

Figure 8: (a), (b) and (c) Analysis of blast using Proanalyst software

Figure 9: High-speed video camera

Table 1
Summary of Various parameters of the blast from all three mines.

Specifications	Blast Number									
	Mine A					Mine B				
	1	2	3	4	5	1	2	3	4	5
Measured Bench height by software (m)	7.237	7.561	6.414	8.201	8.81	8.822	8.955	9.919	8.74	10.23
Burden (m)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Spacing (m)	6.0	6.0	6.0	6.0	6.25	6.0	6.0	6.0	6.0	6.25
No. of blastholes	40	38	46	53	55	60	62	61	53	68
Subdrilling (m)	1	1	1	1	1	1	1	1	1	1
Explosive/ Hole (kg)	46	53	39	59	69	42	43	50	40	55
Total Explosive Charge (kg)	1940	2050	1830	3130	3800	2520	2710	3050	2120	3740
Stemming (m)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Burden Rock velocity (m/s)	8.39	8.63	8.024	9.01	9.77	8.6	9.58	10.1	8.36	10.89
Stiffness Ratio	2.41	2.52	2.138	2.733	2.93	2.97	2.98	3.30	2.91	3.41
Powder Factor (kg/m^3)	0.36	0.39	0.34	0.4	0.42	0.27	0.27	0.28	0.25	0.29

Specifications	Blast Number						
		Mine C					
	6	1	2	3	4	5	6
Measured Bench height by software (m)	7.689	5.849	7.629	6.388	6.301	6.197	7.5
Burden (m)	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Spacing (m)	6.0	6.0	6.0	6.0	6.0	6.0	6.0
No. of blastholes	22	27	38	34	26	30	32
Subdrilling (m)	1	1	1	1	1	1	1
Explosive/ Hole (kg)	35	33	48	38	40	37	44
Total Explosive Charge (kg)	770	920	1824	1300	1040	1120	1430
Stemming (m)	2.75	2.5	2.5	2.5	2.5	2.5	2.75
Burden Rock velocity (m/s)	8.13	9.6	8.84	8.48	8.9	9.41	8.13
Stiffness Ratio	1.94	2.54	2.12	2.10	2.06	2.5	1.94
Powder Factor (kg/m^3)	0.24	0.31	0.39	0.36	0.35	0.36	0.37

Influence of stiffness ratio on burden rock velocity: Burden rock velocity was determined and compared with the stiffness ratio for all the three mines. A statistical analysis was also carried out to find the correlations between them.

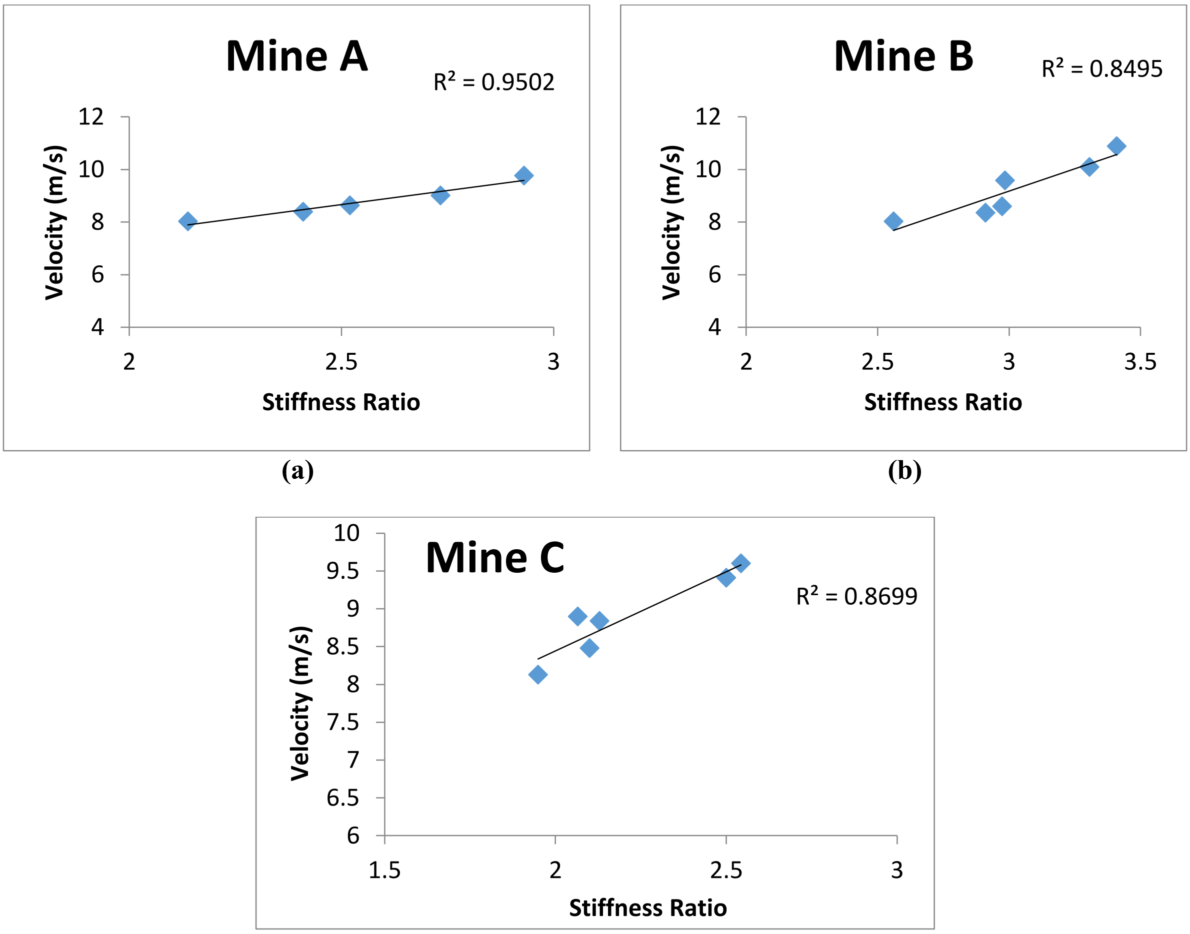
From the analysis, it is clearly shown that as the burden rock velocity increases, the stiffness ratio also increases. A higher stiffness ratio, as proposed in the beam analogy indicates greater flexural behavior of the bench. In Mine-A, high-speed videography analysis revealed that blast-5, with 55 blast holes and the highest stiffness ratio of 2.93, exhibited the maximum rock movement velocity of 9.77 m/s, with an R^2 value of 0.950, as shown in figure 10(a).

Similarly, in mine-B, blast-5, comprising of 68 blast holes and a maximum stiffness ratio of 3.41, recorded a peak rock movement velocity of 10.89 m/s, with an R^2 value of 0.849, as shown in figure 10(b). In mine-C, blast-2, with 68 blastholes and a stiffness ratio of 2.543, resulted in the highest rock movement velocity of 9.6 m/s, with an R^2 value of 0.869, as shown in figure 10(c). These observations conclusively demonstrate that an increase in the stiffness ratio directly correlates with increased velocity of burden rock movement.

Influence of powder factor on burden rock velocity: Burden rock velocity was determined and compared with the powder factor for all three mines and statistical analysis was conducted to identify correlations between them.

From the analysis made, it was observed that in Mine - A. blast - 3 with a lesser powder factor of 0.34kg/m^{3}is having a lesser velocity of 8.024m/s as compared to blast - 5 with higher powder factor of 0.42kg/m^3, which resulted in velocity of rock mass of about 9.77m/s and R square value for all the blasts after comparison resulted as 0.902 as in the figure 11(a). Similarly, in mine - B, blast - 6 with a lesser powder factor of 0.24kg/m^3 resulted in a lesser velocity of 7.689m/s compared to blast - 5 with a higher powder factor of about 0.29 kg/m^3 having a velocity of rock mass about 10.89m/s.

R square value for all the blasts after comparison resulted as 0.990 as in the figure 11(b). Also, in mine – C, blast – 1 with a minimum powder factor of 0.31 kg/m^3 resulted in a lesser velocity of 8.13m/s compared to blast - 2, whose charge factor is 0.39 kg/m^3, which is the highest amongst all blasts, resulting in a maximum velocity of rock mass about 9.6m/s and R square value for all the blasts after comparison resulted as 0.876 as in the figure 11(c). It could be concluded that with the increase in powder factor, there is an increase in burden rock movement. With the above discussion, it can be said that as the powder factor increases, burden rock movement also increases.

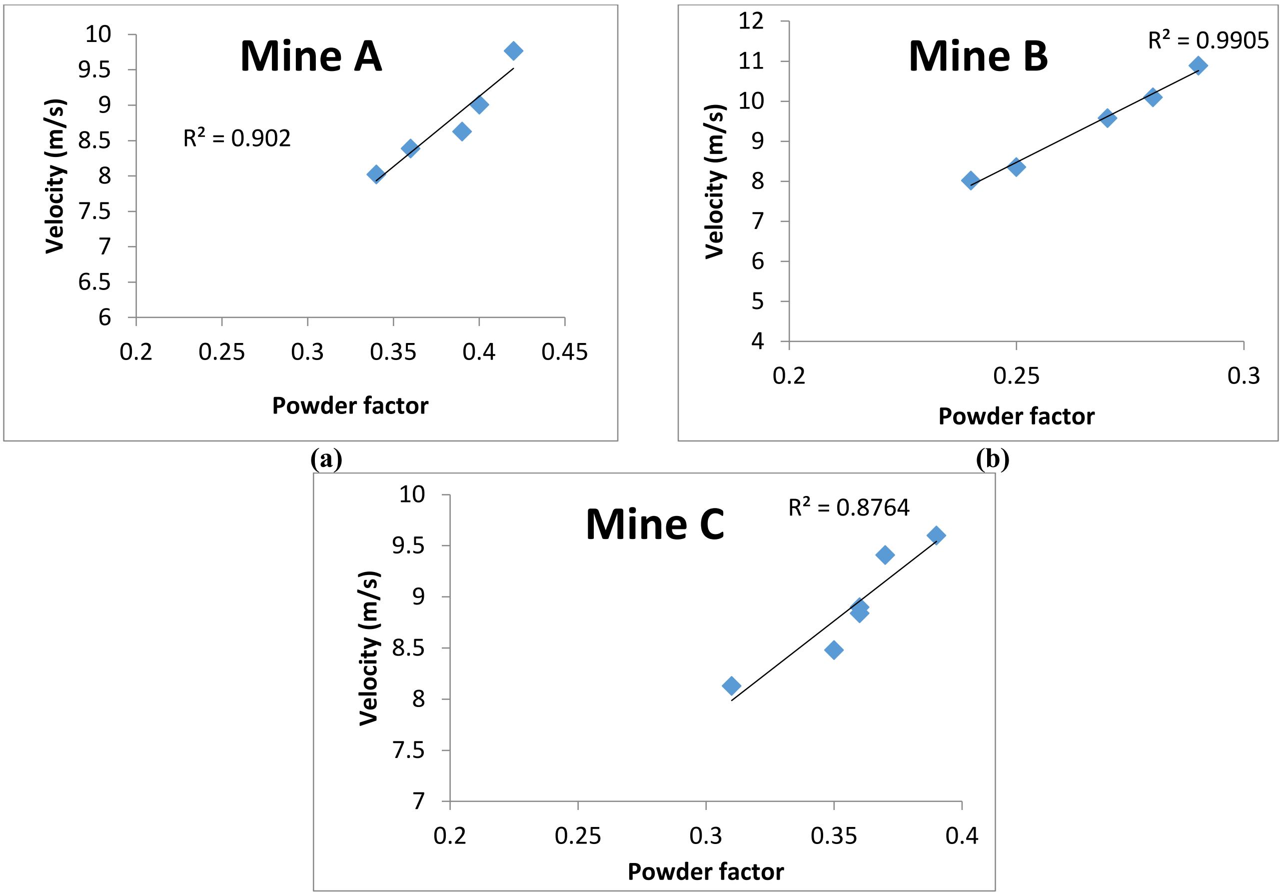


(a) (b) (c)

Figure 10: (a) (b) and (c) variation of burden rock velocity with stiffness ratio.

Conclusion

1. The velocity of burden rock movement increases with an increase in the bench height-to-burden ratio. This relationship is attributed to the higher stiffness ratio which reflects the greater flexural behavior of the bench as described in the beam analogy.
2. High-speed videography analysis indicates that in mine-A, mine-B and mine-C, blasts with the highest stiffness ratios resulted in the maximum rock movement velocities, with R² values of 0.950, 0.849 and 0.869 respectively. These findings confirm a direct correlation between the stiffness ratio and the velocity of burden rock movement.
3. A higher charge factor consistently leads to increased velocity of burden rock movement. This trend was observed across all three mines, with blasts having higher charge factors producing greater rock movement velocities.



(c)

Fig. 11: (a) (b) and (c) variation of burden rock velocity with powder factor.

4. Statistical analysis demonstrates strong correlations between charge factor and burden rock velocity, as indicated by high R^2 values for mine-A (0.902), mine-B (0.990) and mine-C (0.876). This confirms that the charge factor is a critical parameter influencing rock mass displacement.

The combined analysis of stiffness ratio and charge factor highlights their significant roles in determining the extent of burden rock movement. Increasing either parameter results in more significant displacement, underscoring their importance in blast design optimization. These findings provide valuable insights into the factors governing rock mass movement during blasting operations, which can guide more efficiently with controlled blast designs.

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