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A Review on the Prediction and Assessment of Powder Factor in Blast Fragmentation

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Abstract

Powder factor can be defined as the quantity of explosives (kg) required to break a unit volume or tonne (t) of rock. The prospect of excavating rocks by blasting is characterized by a specific consumption of explosives. In the past decades, researchers have come up with several precise approaches to predict powder factor or specific charge in blast operations other than through trial blast. Research in this area has focused on the relationship between rock mass properties, blasting material and blasting geometry to establish the powder factor. Also, the interaction between specific energy and particle size embodied in the theory of comminution that is less dependent on local conditions has been studied. In this paper, the various methods for powder factor estimation based on empirical and comminution theory modelling as well as machine learning approaches in both surface bench blasting and underground tunnel operations have been reviewed. The influence of intact rock properties on powder factor selection and the influence of powder factor selection on post-blast conditions have also been discussed. Finally, the common challenges that have been encountered in powder factor estimations have been pointed out in this regard.

Keywords: powder factor, intact rock properties, post-blast conditions and comminution theory, artificial neural networks

1. INTRODUCTION

In rock fragmentation by blasting, powder factor is considered as one of the most crucial variables in predicting efficient and optimum blasting conditions [1] in both surface and underground mining. Powder factor can be defined as the quantity of explosives (kg) required to break a unit volume or tonne (t) of rock [2]. A number of factors influence blast results, which can be grouped into controllable (which includes the powder factor) and uncontrollable factors of the in-situ rock mass conditions [3, 4]. The prospect of excavating rocks by blasting is characterized by a specific consumption of explosives [5]. Consequently, the optimum powder factor would be found at the minimum operating cost [6, 7]. The powder factor for an entire blast or each point in space can be calculated since each blasthole contributes to the explosive consumption based on the quantity of explosive and distance between blastholes [8]. In the past decades, researchers have come up with several precise approaches to predict powder factor or specific charge in blast operations other than through trial blast. Research in this area has focused on the relationship between rock mass properties, blasting material and blasting geometry to establish the powder factor. The interaction between specific energy and particle size embodied in the theory of comminution that is less dependent on local conditions has also been studied. This paper aims to review the various methods for powder factor estimation in both surface bench blasting and underground tunnel operations; to assess of the influence of intact rock properties on powder factor selection, and to analyse the influence of powder factor selection in post-blast conditions.

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2. ESTIMATED METHODS FOR POWDER FACTOR PREDICTION

Blasts are designed to fragment in-situ rock masses to their required size, taking into account, the controllable factors (bench height, hole diameter, spacing, hole length, bottom charge, powder factor) and uncontrollable factors (rock strength, spacing discontinuity and discontinuity orientation, rock density) to ensure that the desired blast output is achieved to optimize downstream processes as blast output [3, 9]. With this, several approaches have been brought forth by researchers focusing on establishing the powder factor in a way to consider the uncontrollable factors and also, an approach based on the interaction between specific energy and particle size embodied in the theory of comminution that is less dependent on local conditions.

2.1. Empirical-Based Approaches

According to Ashby [10], the powder factor needed for an efficient blast can be determined based on the density of fracturing (fracture frequency) and the effective friction angle which represents the strength of the fractured rock mass. Ashby determined the powder factor with ANFO in Bougainville Copper Mine and proposed Eq. (1) [10] and an alternate graph in Fig.1 from which powder factor can be calculated.

$$\text{Powder Factor } = 0.56 \times P \times \tan \frac{(\phi + i)}{\sqrt[3]{\frac{\text{fracture}}{\text{meter}}}} \text{ kg/(cu.m)} \tag{1}$$

Where, ϕ = Basic friction angle; P = in-situ density if rock formation; i = roughness inclination angle; (ϕ + i) = friction angle; and Fracture/meter = fracture frequency

Li et al. [11] proposed an empirical equation relating powder factor and an average fragment size (d50) based on numerical simulation and experimental data analysis as shown in Eq. (2). Also, the relational expression between the average damage factor in fragments (Da), that is, the average value of the microscopic damage factor in each broken fragment and powder factor was also established as shown in Eq. (3). The larger the average fragment size value, the more intensive the internal minute cracking which instigates the easy breakage of fragments. To reduce the simulation calculation, the study was carried out based on a horizontal section model and vertical section model of a typical bench blasting as shown in Fig. 2a and 2b, respectively. In the horizontal section model given, d represents borehole diameter, a is the borehole spacing, b is the spacing of rows and B is the burden for the first row of holes. In the vertical section model, H is the bench height, θ is the slope angle, L is the borehole depth, L2 is the loaded length, d the borehole diameter, b spacing of rows and B is the distance from the centre of the first row of holes to the bench edge.

$$d50 = a \times Q^b \times d, \text{ therefore,}$$

$$Q = \sqrt[b]{\frac{d50}{a \times d}} \tag{2}$$

where; $d50$ is the average fragment size (m),Q is the powder factor (kg/t), d is borehole diameter (m) and a, b are undetermined coefficients.

$$D_a = \alpha + \beta \ln(Q + \gamma), \text{ therefore,}$$

$$Q = 10(D_a - \alpha)/\beta - \gamma \tag{3}$$

Where; D_a is the average damage factor, Q is the powder factor (kg/t) and α, β, γ are undetermined coefficients.

Powder factor can also be determined in pounds per cubic yard as shown in Eq. (4) [12]

$$\text{Powder Factor } = \frac{PC \times 0.34 \times pe \times d^2}{B \times \times \left(\frac{H}{27}\right)} \tag{4}$$

Where; PC = powder/explosive column, ft; pe = density of explosive in g/cm3; d = charge diameter in inches; B = burden in ft; S = spacing in ft; and H = hole depth or bench height, ft.

For a single blast hole, the powder factor can be calculated by the Eq. (5):

$$PF = \frac{L(0.340d)D^2}{27BSH} \tag{5}$$

PF = Powder factor in pounds of explosive per cubic yard of rock, L is the length of explosive charge in feet, d is the density of explosive charge in grams per cubic centimetre, D is the charge diameter in inches, B is the Burden in feet, S is the Spacing in feet and H is the bench height.

Pokrovsky [13] suggested an empirical relation as shown in Eq. (6) to determine the specific charge (q) in tunnels.

$$q = q_1 \times S_t \times f \times swr \times def \left(\frac{kg}{m^3}\right) \tag{6}$$

where, q_1 = specific charge for breaking of rock against a free face in kg/m^3, S_t = factor for structure and texture of rock, f = rock confinement = 6.5 /$\sqrt{A}$, (1a), A= area of tunnel (m^2), swr = relative weight strength of explosive (ANFO = 1), and def = factor for diameter of explosive cartridge. Empirical approach in evaluating powder tend to be more prune to local geological conditions and this may cause significant variation if the effective parameters change.

2.2. Regression Models

Regression analysis is a group of statistical methods used to measure a dependent variable's relationship with one or more independent variables. It can be used to determine the strength of the relationship between variables and to model the future relationship between them. Application of regression involves several types, such as linear, multivariate linear and nonlinear [14]. The structure of the multiple linear regression model is as shown in Eq. 7 [15].

$$Y = \beta_0 X_0 + \beta_1 X_1 + \cdots + \beta_n X_n + \varepsilon \tag{7}$$

Where, Y = dependent variable, X_0, X_1, ..., X_n are independent variables, β_0, β_1, ..., β_n are regression coefficients (constants), and ε is the error term.

Regression models that relate the geomechanical properties of rocks has been adopted by researchers in the estimation of powder factor. A case study was conducted at the island of Tenerife at Spain based on regression analysis to predict the powder factor needed to ensure the adequate performance of blasts in their quest to drill

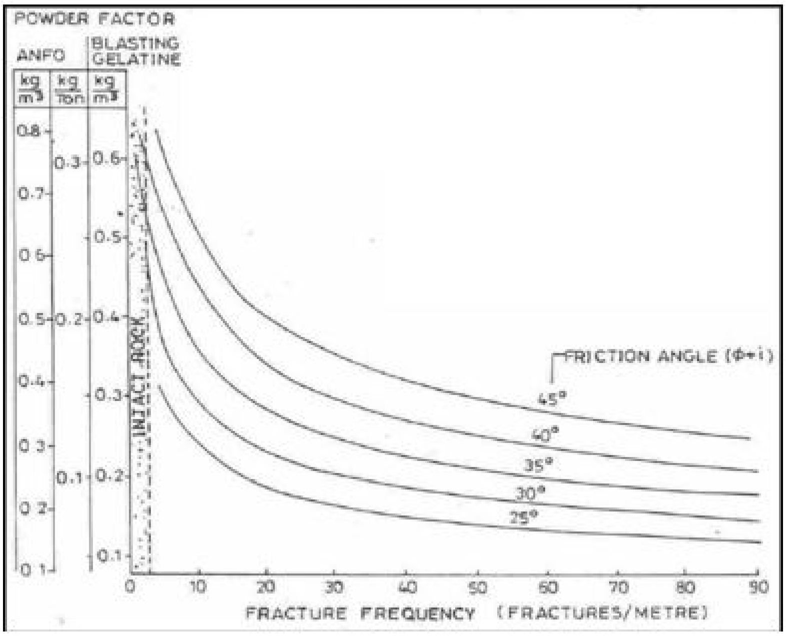
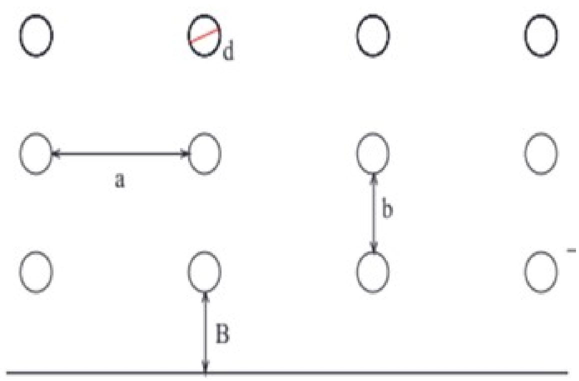
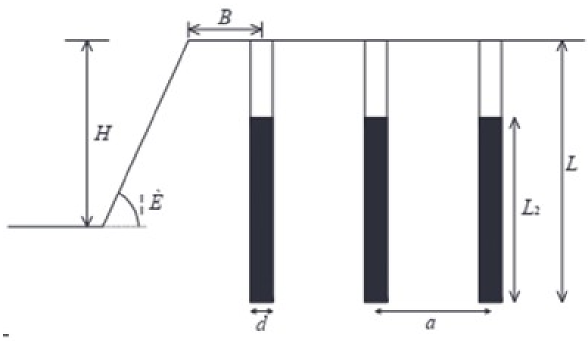


Figure 1: Empirical relation between powder factor, fracture frequency and joint shear strength [10].



(a) Horizontal section.



(b) Vertical section.

Figure 2: Horizontal and Vertical Section Model.

for underground water sources which involved the use of explosives [16].

The explosives used for the blast was gelatin-based. A method based on the regression model was constructed taking into consideration the mechanical properties of the rock which allowed the prediction of the powder factor, the number of blasts and the amount of explosive needed based on the geomechanical properties of the rocks under study. The result showed that the advance in blasting had a non-linear relationship with the geomechanical parameters with the various rock types. The non-linear regression model was recommended in the design of tunnel projects for the above-mentioned predictions.

Leu Italise [17] applied the multiple nonlinear regression method in tunnel blasting to analyse the relationship between powder factor and rock mass characteristics. Rock Quality Designation was the most important parameter of the various selected rock mechanical properties used for the analysis. The multivariate linear regression model was also applied to estimate the specific charge in various conditions of tunnel blasting [18]. The results brought forth showed that the regression models underperformed during validation as compared to the Artificial Neural Network (ANN) models.

The default which is known to be associated with the application of regression models is that many rock and explosive content requirements affect the amount of charge or powder factor needed for each application and the conventional regression models cannot easily integrate them all. One other challenge is the inability of regression models to learn hidden details from the input data [17]. In another study, however, regression models used in powder factor prediction gave better results when Principal Component Analysis was used to eliminate co-linearity effects from the input variables [19].

2.3. Artificial Neural Network Models

An artificial neural network (ANN) is a computational model that works based on the simulation of the human brain's cortical configuration. During the process of learning, memorization and reasoning, the human brain creates a complex network that is interconnected for the execution of various tasks. By interconnecting a large number of simple processing units called neurons, the human brain executes a pattern capable of performing data processing and knowledge representations. Likewise, the ANN attempts to model the functions of the human brain directly. ANN can be precisely designed to solve any specific problem, using three basic components namely, transfer function, network architecture and learning law [20]. ANNs require training to learn and, as a result, map the relationship with the data. This ability evolves from the algorithm of training. Psimpson [21] and Galushkin [22] provided various ANN methods and algorithms for training. Neurons are usually categorized into several layers in feed-forward ANNs. In the connections, a signal moves through the input layers to the output layers. During the final step of data processing, the network output is verified with the actual input values and error correction is performed. The most popular type of feed forward ANN is the Multilayer perceptron [23, 24].

The artificial neural network has been applied in the prediction of powder factor by some researchers in different rock conditions. The intact rock properties are the input parameters and therefore are established beforehand. Neural networks are classified into various types based on the kind of learning algorithm, network topology, data that they accept, etc [25]. The optimal ANN model is based on the lowest root mean square values of errors (RMSE) criteria [17, 25]. The input parameters for the ANN model are based on previously identified parameters [26, 27].

Jong and Lee [25] applied the ANN model to determine the optimal powder factor based on a series of observations and statistical experiments. There were 14 geological conditions in the input parameters as shown in Table 1. Data for the ANN application for this study were collected in a tunnel under construction in Korea. The result showed that the powder factor used in tunnel blasting was primarily affected by significant discontinuity and rock strength characteristics among the 14 geological conditions included in the analysis.

Where MD – major discontinuity set; SD – secondary discontinuity.

Leu Italise [17] used a case data of a metamorphic rock of a railway tunnel in Taiwan to forecast a model for powder factor using an artificial neural network. The ANN model had an average testing root mean square (RMS) of 0.02983. It was recorded that RQD was the most important amongst all the selected mechanical rock parameters. Also, the associated powder factor with a blast pattern with least back break and a good degree of fragmentation was successfully determined using two trained ANN models (Radial Basis Function). Further, using blast design parameter such as spacing, burden, hole diameter, hole depth, dip of joint sets and the differentiation between bench and joint set directions, the optimum powder factor trends were predicted in a case study at a cement mine.

Alipour et al. [18] estimated the specific charge of tunnel blasting based on P wave, rock quality designation (RQD), tunnel area, maximum depth of hole and coupling ratio (charge-to-hole diameter) parameters available in the existing literature. The ANN model outperformed the multivariate regression analysis model upon validation since they are able learn the hidden details patterns from the data, which results in lower errors and better coefficient of determination [18]. Comparatively, the results from the ANN applications show it has a higher level of accuracy than multiple regression analysis and therefore proves to be very efficient approach [18].

2.4. Estimation of Powder Factor from the Comminution Theory

The comminution theory emphasizes on the relationship between specific energy and particle size reduction. The relationship between specific energy and particle size is however based on the mechanisms of both blasting and comminution, which means that the powder factor could be predicted from the theory of comminution. The comminution theory and work indexes for different rock units have been applied to complement the approaches based on explosives and rock properties. There is normally a hyperbolic relationship between particle size and the energy needed to crush and grind [1]. As shown in Fig. 3, specific energy consumption decreases as the particle size increases [28, 29].

Kahryman Italise [30] predicted the powder factors of fourteen different rock units in different surface bench blasting mines using the comminution theory and work index to support previous works which considered different rock and explosive properties. This resulted in optimum blasting conditions for each unit of rock under study.

2.5. Prediction Based on Bond's Work Index

The Bond work index approach for estimating powder factor is based on the relationship between the specific energy and the particle size embodied in the theory of comminution [32]. The common approach to powder factor prediction has been to use the relationship between rock mass properties, blasting materials, and geometry, while the work index is generally calculated using standard methods in a Bond grinding mill, the parameters of which are reliable and constant. Bond stated that the energy required for size reduction is a function of the ' work index ' and particle size distribution of the feed and the crushed products as found in Eq. (8).

Table 1: Description of the input and output parameters of the neural network.

Parameter	Description	Data Type	Range (Unit)
Input	A Tunnel Orientation	A	0-360
	B1 Dip direction of MD	A	0-360
	B2 Dip of MD	A	0-90
	B3 Spacing of MD	B	1-5
	B4 Separation of MD	B	1-5
	B5 Persistence of MD	B	1-5
	C1 Dip direction of SD	A	0-360
	C2 Dip of SD	A	
	C3 Spacing of SD	B	1-5
	C4 Separation of SD	B	1-5
	C5 Persistence of SD	B	1-5
	D Rock strength	B	1-5
	E RQD	B	1-5
	F RMR	A	1-100
Output	Powder Factor	A	Kg/m^3

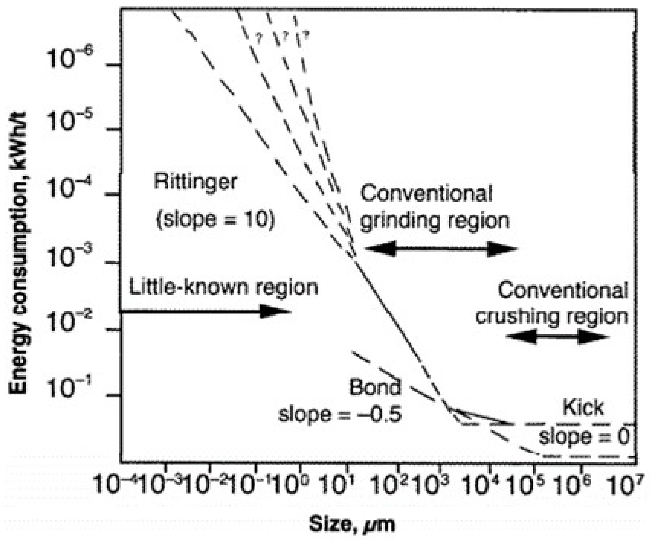


Figure 3: Relationship between energy and particle size [31].

$$W = 10 \times W_i \left(\frac{1}{P^{0.5}} - \frac{1}{F^{0.5}} \right) \quad (8)$$

where W is the required energy for a certain weight of the material, kWh/t, W_i is a work index value, kWh/t, and F and P are particle sizes of the feed and product, respectively (80% passing a certain screen size), in micrometres.

Kahriman Italise [1] predicted the powder factor using this concept and concluded that if the work index, block size and particle size values can be calculated with reasonable precision for a certain type of rock unit, the bond equation could be used to estimate the powder factor. In the study, the block size was treated as a function of the burden given as $F = 2.27$ b. Researchers and blasters have accepted the concept of a burden being a function of the hole diameter. Practical applications of such approaches show that hole diameter in inches equals burden in metres. Therefore, the block size was formulated as a function of blast-hole diameter given as F = 2.27 d. The result was known to be valid for rock units which are homogeneous and isotropic of which their block sizes have not been determined by detailed geotechnical work during blasting. This approach to the estimation of initial block size was followed in further evaluations in the study of which data was drawn from 14 rock units. It was stated that, during the blasting of a rock mass with rigid, homogenous and isotropic properties, the block size can be accepted theoretically as infinite. In this scenario, Bond's equation could be modified as $W = 10 \times W_i(1/P^{0.5})$. Statistical and mathematical methods were used to establish a relationship between the Bond work index and the powder factor, taking into account the initial block sizes and product fragment sizes which brought up the relationship in Eq. (9) from which the powder factor was calculated.

$$q^B = 10 \times W_i \left\{ \left(\frac{1}{P^{0.5}} \right) - \left(\frac{1}{F^{0.5}} \right) \right\} \times K \quad (9)$$

where K is a conversion constant. $K = (860/912) \times$ sp.gr. (1 kWh = 860 kcal; 1 kg ANFO = 912 kcal).

The powder factor was also calculated locally regarding similar applications of bench blasting on the same minerals and rocks, and the results were also correlated with that derived from the modified bond formula which gave a meaningful relationship as shown in Eq. (10).

$$q = 0.941 q_B + 0.052 \quad (10)$$

where q is the powder factor deduced in the fieldwork, kg/m^3, and q_B is the powder factor calculated from the modified Bond approach. The relationship was obtained with a correlation coefficient of 0.92.

3. ASSESSING THE RELATIONSHIP BETWEEN POWDER FACTOR AND IN-SITU ROCK PROPERTIES

The aim of assessing the relationship between the geomechanical properties of rocks and powder factor is to investigate the effect of rock mass strength on explosive requirements during blasting.

3.1. Powder Factor vs. Uniaxial Compressive Strength of Rocks (UCS)

The uniaxial compressive strength of rock has been determined by several researchers through the use of the Schmidt hammer rebound test. The rebound number which is an indicator of the hardness of a rock can be used subsequently to determine the strength of the rock. When the strength of a rock is high, it means that it would be difficult to break and therefore would require more explosive energy. Table 2 shows typical powder factors for surface blasting. A study of the effect of Schmidt hammer rebound number or transformed compressive strength of rocks on the powder factor was conducted in opencast coal mines [33, 34].

3.1.1. Powder factor vs. rebound number

Rebound extent is a measure of the hardness of a material. Increase in rebound number means that the rock mass is compact and as a result, more explosives would be required to charge the holes to achieve the required blast results in terms of improved fragmentation. Soft rock requires less explosive than hard or compact rocks. According to Fig. 4, powder factor is directly proportional to rebound number. In this case rebound number increases with an increase in powder factor.

3.1.2. Powder factor vs. UCS

When UCS increases, it means that the rock mass is strong which would require more explosive energy to break and vice versa. Fig. 5 depicts an increase in powder factor which corresponds to an increase in the uniaxial compressive strength of the rock. This means that more explosives need to be pumped into drilled holes to get the required blast fragmentation results.

3.2. Powder Factor vs. Rock Types and their Related Densities

The rock density is a key determinant of how much explosive is needed to displace a given rock volume (powder factor). The burden-to-charge diameter proportion varies with the rock density, thereby altering the powder factor. The probability of extracting rocks by blasting is characterized by a specific explosive consumption and can be calculated roughly by Protodyakonov rock classification [35]. Low-density rocks require a less explosive charge to break a unit volume of the rock whereas very dense rocks require a higher amount of specific explosive charge to detonate [35].

$$q = 0.27\sqrt[3]{f}\ kg/m^3 \qquad (11)$$

Where f is rock sturdiness index.

3.3. Powder Factor vs. Blastability Index

Blastability is a term used to denote a rock mass's susceptibility to blast and is closely linked to the powder factor. A correlation between powder factor and blastability index is shown in Table 3

3.4. Powder Factor vs. Seismic Wave Velocity in Rock Mass

When a rock mass is subjected to stress, the effect of the force is not distributed throughout the rock instantly. This stress wave propagates through the rock with a finite velocity known as the propagation velocity of the rock [36]. The propagation velocity of the compressional rock wave is known to be one of the most important rock properties that can be useful in selecting appropriate explosives, excavation methods, designing a blast and efficiently using explosive energy. Rocks with higher propagation velocities are expected to break with the use of high-velocity explosives whereas rocks with lower propagating velocities require lower detonation explosives to be blasted. [37] Applied seismic survey in blast design, resulting in a relationship between the powder factor and the velocity of seismic propagation. It was observed that a significant amount of energy was required to obtain sufficient fragmentation when the velocity increased.

4. INFLUENCE OF POWDER FACTOR SELECTION ON POST-BLAST CONDITIONS

The purpose of rock blasting is to achieve optimum fragmentation without any other blast-induced nuisances. Nuisances can be controlled with the proper use of explosive quantity and powder factor and thus the energy generated. In fragmentation by blasting, the amount of explosive used to break a unit volume of rock can have an impact on post-blast conditions if the right quantity of explosive is not decided. A good production blast fractures only the rock which needs to be removed, leaving the host rock with minor damage [38]. The inability to adequately fracture the needed rock can cause what is called underbreak.

Likewise, when the required volume to be broken breaks into its surrounding host rock, it can be termed as overbreak or back break. Ideally, underbreak and overbreak can be eliminated but in reality, reducing underbreak might in all result in a greater likelihood of increasing overbreak [39]. In effect, higher and lower powder factor than required would result in overbreak and underbreak respectively. Blast movement can as well be influenced by the specific energy of the blast.

Zhang [40] studied the blast-induced rock movement in Rain mine and Coeur Rochester mine and its effect on grade control. Six blasts in the Rain mine and twelve blasts in the Coeur mine were monitored. The study reported that the powder factor and the magnitude of the blast pattern movement were directly related.

In order words, as the powder factor increases, the magnitude or extent of the blast pattern movement will increase and vice versa. Blast-induced

Table 2: Typical powder factors for surface blasting.

Rock breakage difficulty	Powder Factor in Ib/yd^3	Powder Factor in Kg/m^3
Low	0.25–0.40	0.10–0.18
Medium	0.40–0.75	0.18–0.34
High	0.75–1.25	0.34–0.57
Very High	1.25–2.50	0.57–1.14

displacement of rock mass may have a major impact on grade control. The mischaracterisation of grade limits without a proper understanding of blast movement can lead to significant financial losses in terms of ore losses and dilution. Ore dilution occurs when the waste material is miscategorised as ore and sent for processing [41]. The addition of waste rock to the ore reduces the grade of the ore and increases the tonnage of the estimated ore. This would reduce the mill head grade of the estimated material which would, in turn, affect production [42].

Inappropriate prediction of powder factor can also cause post-blast effects such as inducing flyrocks. Flyrocks are debris that is ejected from the blast site that travels through the air or along the ground. Flyrocks is the most dangerous adverse effect that can result in property damage and personal injury or death. The distance a flyrock travels will depend on the amount of the specific charge. A high specific charge throws flyrock at a longer distance than a low specific charge [22, 43]. For instance, a flyrock accident as a result of high powder factor reported that the distance travelled by the flyrock from the blasting site to their plant was estimated to be 350m [43].

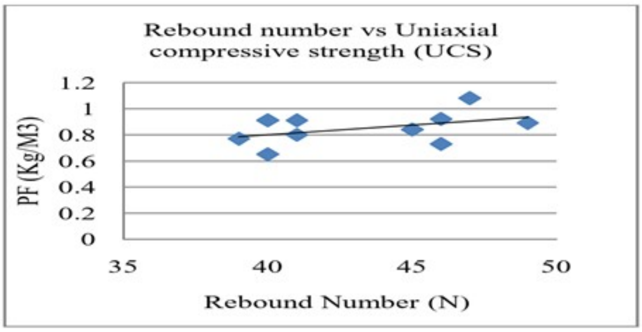


Figure 4: Rebound number vs. Powder factor [31].

In another study at a limestone quarry in India, flyrock distances were measured using a laser profiling survey system [44]. The flyrock distance varied from 40 m to 250 m, while the specific charge varied from 0.10 kg/t to 0.14 kg/t. As the specific charge was lower than the optimum, its role in abetting flyrock was not reflected. In essence, high powder factor in blasting greatly influence the distance of flyrock [45].

According to Abhishek et al. [46], powder factor has an effect on mean fragment size after blasting. The relation between mean fragment size and powder factor can be explained as the actual explosives energy requirement to create efficient fragmentation and cause displacement of the rock mass. It was found that the relation kept increasing until a powder factor of 1.02 kg/cu. m was achieved. Also, the increase in powder factor beyond the optimum caused untoward post-blast effects like early ejection of stemming column, over-breaks, air blasts, etc. which resulted in less explosion energy to cause actual fracturing and movement of the rock mass, resulting in coarser mean fragment size. Similar trends were observed in another research [47].

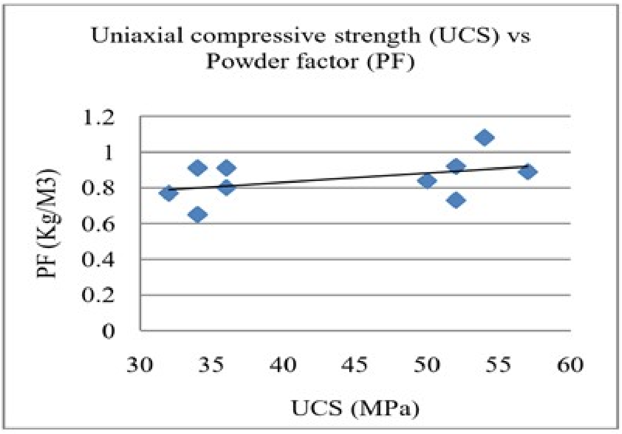


Figure 5: . UCS vs. Powder factor [31].

Table 3: Relationship between powder factor and blastability index.

Blastability Index	Powder Factor (kg/m3)
30–40	0.7–0.8
40–50	0.6–0.7
50–60	0.5–0.6
60–70	0.3–0.5
70–	0.2–0.3

Powder factor vs. Blasthole Productivity: Blasthole productivity is a quantity index of the effectiveness of blasting which characterizes the volume of rock blasted per unit of blasthole length. According to Massawe and Baruti [48], as powder factor increases, blasthole productivity decreases and vice versa. This is because, as powder factor increases, stemming height alternately decreases and the energy wasted on blown-out holes also increases. Therefore, there is an increase in blasting cost due to the increase in powder factor. It was proposed that this cost is not significant since the powder factors assessed were closely matched with the rock mass and other blast design parameters of the mines.

5. CONCLUSION

Assessment and prediction of powder factor in both surface bench blasting and underground tunnel operations have been reviewed. The various methods for powder factor estimation from the review have focused on the relationship between rock mass properties, blasting material, blast geometry; and also, the interaction between specific energy and particle size embodied in the theory of comminution.

It can be concluded from the review that, intact rock properties such as the rebound hardness number and its subsequent uniaxial compressive strength, the type of rocks and their related densities; and the seismic wave velocities in rock masses influence the specific energy or the amount of explosive required to blast a unit volume of rock.

Lastly, powder factor was reviewed for its influence on post-blast conditions. Increase in powder factor beyond its optimum can cause effects such as early ejection of stemming column, overbreak, and increase in the extent of blast pattern movement, flyrocks, and finer fragment size. Alternately, low powder factor selection than expected can cause underbreaks or toes, coarser fragment size or boulders which would consequently increase marginal cost production since extra energy would be required for secondary blasting.

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