CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Advances within the world economic order, the emergence of post-industrial societies, and also the ascension of states like India and China in response to new and rising technologies, and international challenges like temperature change mitigation and adaption has created several implications for raw materials and energy demand use patterns. Besides, increasing rates of urbanization and infrastructure development in rising economies have paved some way for bigger international demand for mineral resources. Huge demand for the metals due to the fast urbanization and growth within the manufacturing sector is anticipated notably in India because the National manufacturing plan 2011 released by the govt. of India, indicates that availability of higher-grade material and production inputs are crucial for guaranteeing the expansion of manufacturing sector (Anon, 2011). These developments have resulted in an exceedingly bigger world stress on experience in services and technologies to use mineral reserves expeditiously.

The mineral industries have always been exploring the scientific and sustainable mining practices. Furthermore, the mineral industry is currently evolving itself at variant phase for benefitting from the high-end state-of-art technology, particularly within the world institutional sector. High-end technology has been dominating the surface mining by development of massive size of drill machines, shovels/excavators, dump trucks, etc as an important part of mineral production obtained from the surface mines. The giant mechanization schemes in large surface mines operations lay emphasis on higher efficiency and productivity by these equipments (Williamson et al., 1983).

To this end, a significant amount of excavated material must be made available for excavation needs regardless of rock conditions. To meet this end, the drilling and blasting operations gain significant attention. Further, the drill-blast combination is still regarded as highly versatile and cost-effective tool for rock fragmentation and excavation in mining operations (Jimeno et al.,1995). Blasting costs can account for up to 35% of overall production costs in hard rock surface mining operations and 15-20% of overall production in surface mining of coal. However, it must be borne in mind that rock breakage by blasting is not energy efficient owing to loss of explosive energy in form of fly rocks, ground vibrations, noise, air-overpressure, dust etc. (Spathis, 1999; Ouchterlony et al., 2003; Sanchidrián et al., 2007; Rai and Yang, 2010).

2.2 Rock breakage by blasting

The mining industry is mostly dependant on drilling and blasting for rock breakage and excavation. It is the first and the most important phase in the mineral production cycle. A precise application of engineering is essential in achieving the desired objectives of rock breakage by drilling and blasting (Bhandari, 1997).

In rock blasting, the main objective is to break the maximum possible quantity of rock at a minimum cost. In addition, the minimal environmental damage is also desired (Kahriman et al., 2006; Uysal et al., 2013; Karadoğan et al., 2014; Gorgulu et al., 2015). The minerals that are heavily dependent on rock breakage by blasting are limestone, dolomite, chromite, coal and their related overburden covers, aggregates for construction etc. The drilling and blasting operations must ensure quality and quantity requirements of production in such a manner that overall profits of a mining operation are maximised.

The cycle of drilling and blasting operations comprises of drilling of blast holes on a fixed pattern on the bench. The drilled blast holes are charged with explosive and stemmed with stemming materials. The blast holes are then delayed and fired using the predetermined blast patterns. The explosive action causes rock fragmentation and throw. The fragmented rock is subsequently loaded, transported crushed (wherever applicable) for downstream processing like milling, washing, beneficiations etc.

Therefore, the blast must be designed in such a manner that the resulting fragments require little need for secondary breakage. Presence of large fragments on end or excessive fines on the other end impact the PF and subsequently the downstream operations cost. In general, the acceptable levels increase the production, profitability, safety and direct as well as indirect cost of downstream mining operations.

In the mining industry, the impact of bench blasting is represented by the term ‘rock (or blast) fragmentation’. In the past over three decades, a commendable advancement has been witnessed in the study of fragmentation mechanisms, which is critical for developing equations involving rapid excavation of rock (Rai and Baghel, 2004). Blasting involves the interaction of explosives and rock. The rock damage in blasting is a result of the co-action of the blast wave and the action of gaseous explosion products. A number of researchers have been reported in this regard (Mosinets, 1966; Kutler and Fairhurst, 1971; Dally et al.,1975; McHugh, 1983; Brinkmann, 1990; Olsson et al., 2002; Lanari and Fakhimi, 2015; Changyou et al., 2017). Rock fragmentation depends mainly on the stress wave and gas pressurization. The significance of shock waves and gas in rock fracturing has been in debate for the last six decades. Studies by Fourney et al., 1993, stated that the stress waves developed after the explosive detonation are responsible for the damage zone developed around the rock mass, and for the subsequent size of fragment distribution (Figure 2.1). While the explosion gases are involved in separating the crack pattern that is created after the propagation of the stress waves and displacing the broken rock mass.

When an explosive charge is confined in a blast hole at various depth and detonated, it produces high temperature and pressure. The explosives release energy that gets divided into seismic acoustic or seismic waves (primary waves and secondary waves) and heat energy and remaining energy which is left is involved in rock breakage.

Whenever an explosive charge detonates with in blast hole, extreme dynamic pressures are set up around it by detonating gas pressure on the hole wall due to a sudden acceleration of the rock mass. The stress waves transmitted on the rock set a wave motion in the ground (Amiri et al., 2020). When the intensity of the stress wave decreases to the extent that there is no permanent rock deformation, the stress waves propagate as elastic waves throughout the medium, oscillating the particles they pass through (Khandelwal and Singh, 2007). Both elastic and inelastic procedures are initiated at a distance from the source of detonation. Generally speaking, only a fraction of the explosive energy produced is rendered into elastic energy (Amiri et al., 2020; Verma and Singh, 2013). These elastic energies that spread away from the source of the explosion are identified as Body and Surface waves in the form of seismic waves. The movement of these seismic waves in the ground generates the blast induced ground vibration (as shown in Figure 2.2).

Therefore, only, 15–30% of energy (Cutler and Fairhurst, 1971; Hagan, 1979; Jimeno et al., 1995) is utilized for rock breakage and leads to desirable fragmentation results. The remaining energy is responsible for undesirable consequences such as blast-induced ground vibrations (BIGV), air overpressure (AOP), back breaks and fly rocks (as shown in Figure 2.3).

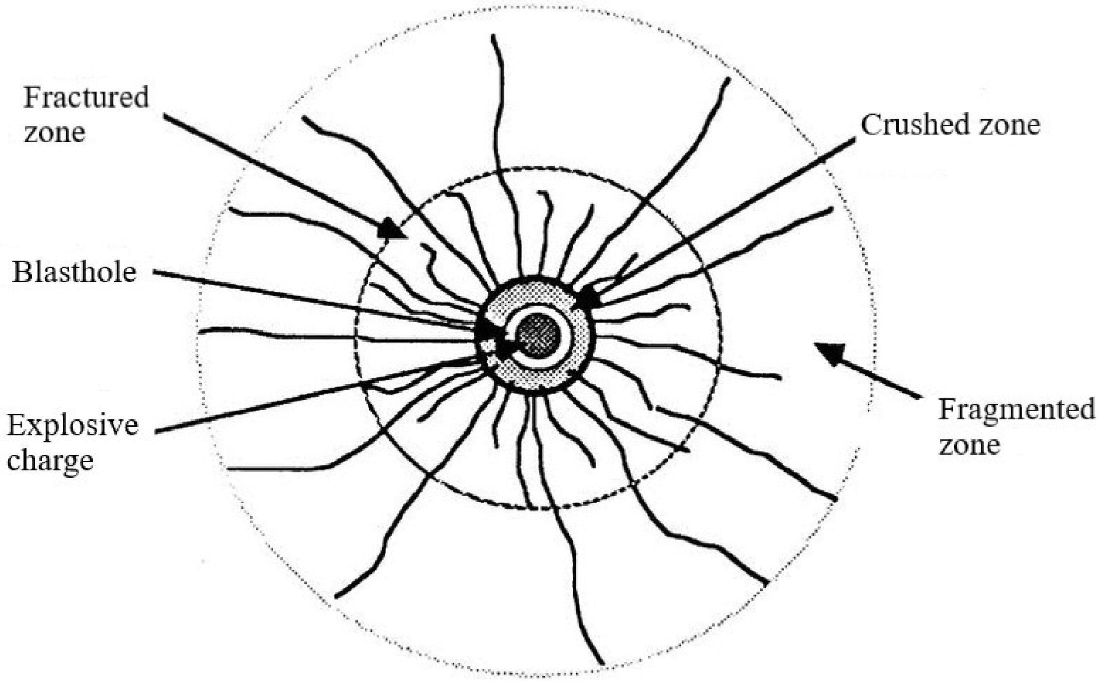

Figure 2.1: Schematic illustration of processes occurring in the rock around a blast hole, showing formation of crushed zones, fractured zones and fragmented zones (After Whittaker et al., 1992)

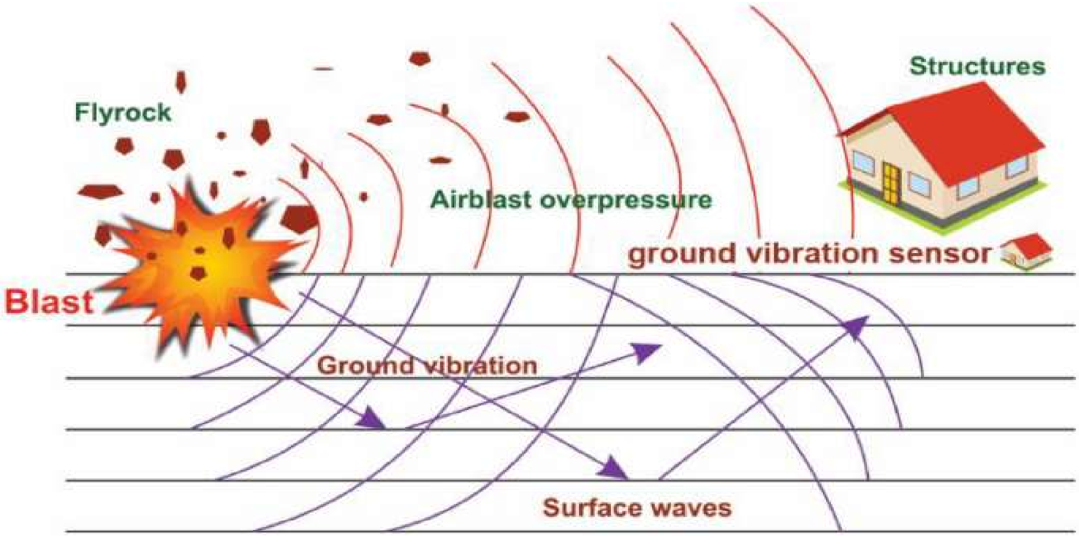

Figure 2.2: Blast induced nuisances (After Chen et al., 2019)

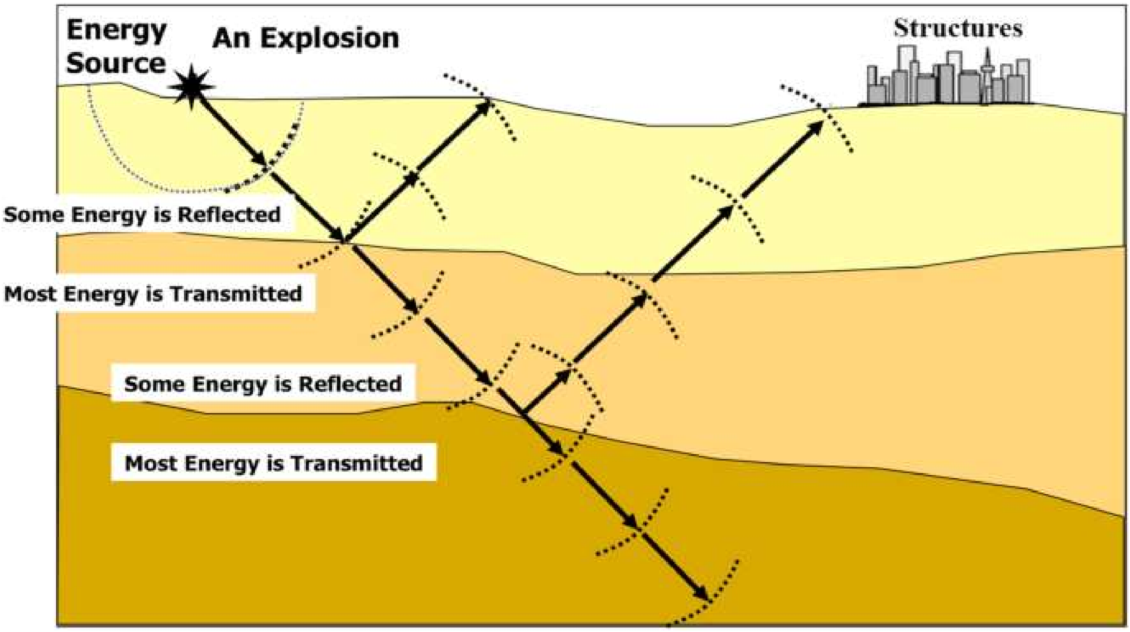

Figure 2.3: Energy release and distribution of Seismic waves (After Fattahi et al., 2020)

2.3 Assessment of blast performance

The blast results are subjective and depend on the nature of the operation. It is therefore difficult to provide a definitive measure to quantify blasting results and only generalized assessments are made. The subsequent usage of blasting material, equipment used for excavation and size of the crusher decide the efficacy of any blasting program. The parameters that are generally assessed for quantifying blast performance are classified into two categories, one is direct parameters and other is indirect parameters. Direct parameters include fragment size, ground vibration, air overpressure, fly rock, noise, dust, damage to remaining rock, powder factor etc. and indirect parameters include excavator loading, unloading times, dumper loading, secondary breakage costs, boulder count in the blasted muck piles etc. The fragmentation and powder factor give an idea about the efficacy of blast, whereas, the ground vibrations, air overpressure, fly rocks etc. indicate the quantum of energy wasted due to blasting. The direct and indirect parameters for assessment of blast performance are thus describe below.

2.3.1 Fragmentation

Rock fragmentation using explosives has been extensively investigated by conducting various experiments. Optimum fragmentation plays a vital role in the overall economics of mines. An essential criterion to judge optimum fragmentation is to achieve a fragment size where the rocks need least post-blast treatment. The energy spent in fragmentation and throw accounts for 7–25% of the explosive energy (Sanchidrian et al., 2007). Rest of the energy is wasted and dissipated in the form of fly rock, ground vibration, air blasts, noise, back break, etc. Consequently, the blasting performance can be significantly improved by minimizing the amount of waste energy. Several factors affect the degree of rock fragmentation in surface mines (Cunningham, 1983; Olofsson, 1990; Jimeno et al., 1995; Thornton et al., 2002, Kose et al., 2005; Elevli and Arpaz, 2010; Afum and Temeng, 2015). Fragmentation can be optimized by judiciously engineering controllable blasting design parameters.

The energy content and blast hole pressure generated by the detonation of explosive also affects the rock fragmentation. Extensive research has been carried out on size distribution and generation of fines (Hagan, 1979, Djordjevic, 1999, Moser, 2005, Mitchel et al., 2008). Research on the effect of explosive properties on rock fragmentation has considerably improved the blast performance. In addition, there are many other experimental studies and numerical simulations that help in better understanding the rock fragmentation process (Ouchterlony et al., 2004, Hu et al., 2015, Xiao et al., 2017, Li et al., 2017, Chen et al., 2017, Yang et al., 2018, Xia et al., 2018, Kabwe, 2018).

2.3.2 Air overpressure

Apart from ground vibration, blasting is accompanied by a local noise called air blast or air overpressure. Air overpressure (AOP) is an undesirable phenomenon in blasting operations, and it is also a dangerous adverse effect of blasting (Dehghani and Alimohammadnia, 2021). Air overpressure, however, is not simply the sound that is heard, it is an atmospheric pressure wave consisting of high frequency sound that is audible (20-20000Hz) and low frequency sound or concussion that is sub-audible (<20Hz) and cannot be heard (Jimeno et al., 1995). Either or both of the sound waves can cause damage if the sound pressure is high enough. Overpressure is generally an annoyance problem which may not cause damage but may result in confrontation between the operator and those effected. Air overpressure is measured in decibels(dB). The recommended values of AOP limitation in decibels (dB) is 134 dB (Siskind et al., 1980). At first the AOP travels at supersonic speed, but depending on the magnitude of the energy released by the explosion, it will decay in time to an ordinary sound wave. AOP has a direct correlation with a number of factors, including the design of blast, weather, and terrain settings etc. AOP is created by a huge shock wave from the detonation spot into free surface (Harandizadeh and Armaghani, 2021).

The AOP effects can be observed on nearby constructions; it can lead to severe damage to quarrying, which might cause some situations, including a conflict between the quarry managers and the people affected (Persson et al., 2018).

Blasting noise, a major construction pollution factor along with vibration, can be caused by air pressure waves generated from blasting of of rocks in quarries, but it is mainly caused by air pressure waves. Air blast or Noise produced by blasting in surface mines and quarries areas is considered a major detrimental blasting effect and can be a menace to nearby residents and workers in the mine (Siskind et al., 1976). Although a major portion of the emitted energy from mine blast is sub-audible (lower frequency), there exist a component that is audible (high frequencies from 20 Hz to 20 KHz) and as such within the range of human hearing as noise (Temeng et al., 2021).

2.3.3 Fly rock

When blasting operations are carried out, the rock gets fragmented and the fragmented material heaves to make mucking of the fragmented mass easier and less costly. In addition to this desirable displacement of broken fragments in case of surface mine blasting or excavation blasts, some blast fragments get torn and travel to very large distances. Usually this unexpected projection of blasted fragments is termed as fly rock.

Fly rock is the most hazardous effect of rock blasting resulting into fatalities and serious injury to people, cattle and damage to dwelling property, mine equipment etc. (Manoj and Monjezi, 2013; Bajpayee et al., 2004; Hasanipanah et al., 2017). Fly rock occurs when explosive energy in the form of gas energy is vented into atmosphere and propels the rock in front of it. Two types of rock movements are caused during opencast bench blasting, namely, the forward movement which is called throw (first movement) and second movement is the fly rock which is undesirable movement of rock that throws the broken rock fragments to large distance due to excessive pressure caused by an unexpected blast of explosives (Zhou et al., 2019). Blast area, with an ostensibly greater radius than productive throw of fly rock has been demarcated as danger zone. The Director General of Mine Safety (DGMS) has now recommended 500 m radius as zone for safety in open pit blasting and radial distances beyond 500m are put under danger zone.

Some controllable and uncontrollable factors have been identified as the most influential parameters in creating flyrock phenomenon. The controllable factors for flyrock consist of blasting pattern design and its condition, like improper delay timing, burden, spacing etc. Moreover, the main effective uncontrollable parameters on flyrock are related to geotechnical and geological conditions, such as joints, rock quality and other rock parameters (Ye et al., 2020).

2.3.4 Powder factor

The powder factor (Kg/t) is the amount of explosive required to break the per unit vol. of rock. It is an important parameter affecting the blasting economy. Experimental studies have been conducted to study the effect of powder factor on overall economy of mining operations (Mertz et al., 1988; Kojovic et al., 1995; Fuerstenau et al., 1995; Nielsen and Kristiansen, 1995; Kanchibotla et al., 1998).

2.3.5 Ground vibration

The BIGV can cause damage to the structures surrounding the mining locality. In recent times the ground vibration and air overpressure are drawing more and more attention due to increased human settlements near the mine. Study of the characteristics of ground motion and air overpressure involves various complexities. Various studies have been performed to predict, control and understand the factors affecting blast-induced ground vibration and air overpressure.

Frequency of the blast wave, peak particle velocity (PPV), displacement and acceleration of the particles is important parameters associated with ground vibration. Among these parameters, PPV is considered as the most important criterion to study the structural damage (IS 6922, 1973; Kumar et al., 2016). PPV is more predictable and consistent as it is less sensitive to change in geological conditions than acceleration or displacement (Nateghi, 2011). Blast induced vibrations are not perfectly harmonic and they can spread their energy (or in other words amplitude) to a wide bandwidth of frequencies. The spread however is often negligible and most of the energy could be concentrated on a certain narrow frequency band with only little spread. In such case the frequency is concentrated and an individual blast induced vibration occurrence can be characterized by one (main) frequency level that is dominant frequency and corresponding amplitude (Lonardi, 2021).

Ground vibration not only reduces the safety and stability of the excavated area, but also leads to problems in adjacent buildings. (Fomel and Landa, 2014; Lu and Hustmild, 2001; Lu et al., 2012; Singh and Roy, 2010). Three factors of ground vibration used to assess the associated damage on adjacent rock mass and structures are amplitude (peak particle velocity), dominant frequency and vibration duration (Aldas, 2010; Aldas and Ecevitoglu, 2008; Singh and Roy, 2010). Dowding (1985), underlined the importance of frequency because the structural response depended on the frequency of ground vibration.

2.4 Concept of scaled distance in ground vibrations

Scaling correlates ground motion levels at various distances from blasts. A scaling factor based on a dimensionless parameter for distance is used. The scaled distance is derived from effects of geometrical spreading on the outbound ground motion wave from an explosion (Bhandari, 1997).

Scaled Distance is a commonly used technique for estimating the vibration and air overpressure from blasts. The most acceptable concept of vibration prediction is of scaled distance given by the United States Bureau of Mines (USBM) (Duvall and Fogelson, 1962). It uses the amount of explosive energy in shock and seismic waves, while considering the effects of distance (Siskind et al., 1980, Siskind et al., 1994). The scaled distance is derived by combining the distance between the source and measurement points, and the maximum charge per delay. This scaled distance is defined as follows (Eq.2.1),

$$SD = \frac{D}{\sqrt{Q}} \tag{2.1}$$

Where, SD=Scaled distance (m/Kg0.5), D= Distance between shot and measuring point (m), and Q=Maximum explosive charge per delay (Kg)

The peak level of ground motion at any given point is inversely proportional to the square of the distance from the shot point (Siskind et al., 1980).

The PPV is given by the following equation (Eq.2.2):

$$\text{PPV}= \alpha(\text{SD})^{-\beta} \tag{2.2}$$

where α and β are the site and geological constant factors, respectively. The site factors are determined by a logarithmic plot of PPV versus scaled distance.

Various researchers have been used to predict the ground vibration in terms of PPV using the concept of scaled distance (Agrawal and Mishra, 2019; Tosun, 2020). They used the modified scaled distance with the help of regression analysis in prediction of PPV.

2.5 Powder Factor

The powder factor is an absolutely important performance indicator of any production blasting episode in surface mine. Rock blasting in open pit mining requires good fragmentation control through effective blast design and optimum acceptable PF for higher productivity. Excessively high PF may cause damage to remaining rock and also may become detrimental by generating large, blocky fragments.

Several studies have been conducted to estimate the normative value of powder factor which included a host of rock mass parameters and explosive properties. Some empirical relationships like Rock Quality Index (RQI), blastability index, drilling index, and relations between rock mass properties are also used for estimation of powder factor. Some other models used for estimation of powder factor include Kuz-Ram model, modified Kuz-Ram model, Swedish Lundborg model, Larson model, Kuznetsov model, Persson-Holmberg-lee model Svedefo model and Rustan model (Kuznetsov, 1973; Cunningham, 1983; Cunningham, 1987; Rustan,1998; Dey and Sen, 2003; Roy, 2005). The powder factor estimated using these models can be used in designing of the blast.

The term powder factor is defined as the quantity of explosive required for the fragmentation of a unit cubic metre of rock (Rai et al., 2016). Acceptable powder factor results in good fragmentation, having adequate throw and drop with less blasting nuisances. The powder factor varies between 0.1 Kg/t and 0.53 Kg/t for bench blasting in open surface quarries (Bhandari, 1997). According to Mohamed et al., 2015, powder factor can serve as an indicator for rock hardness, cost of explosives used or as a guide to shot firing plan. Higher energy explosives, such as those containing large amounts of aluminium powder, higher density can break more rock per unit weight than lower energy explosives. Most of the commonly used explosive products have similar energy value and thus, have similar rock breaking capacities. Hence, soft and low density rock requires less explosive energy than hard and dense rocks.

For any given rock mass, the explosive required for acceptable fragmentation gets affected by the geology of the rock, blasting geometry, and explosive properties. These factors are neglected in the theoretically calculated value of powder factor. The theoretically calculated values of powder factor may not reflect the actual conditions in the field. The weight of the fragmented rock should be used for determination of the actual powder factor at field scale.

2.5.1 Factors influencing PF

Powder factor in any blast round is one of the most effective parameter to evaluate the blast performance. A host of parameters affect the powder factor. These parameters can be classified into two categories, namely, the controllable parameters and the uncontrollable parameters. Controllable parameters are primarily associated with the blast design and explosive attributes; these are the burden, spacing, height of the bench, stemming length, blast hole length, delay sequence, firing pattern, the diameter of a hole, number of holes, charge per hole, etc. (Adamson et al., 1999). Uncontrollable parameters are related to rock formation and rock properties. PF is so significant that any deviation from its accepted value manifests in the form of back-break, fragmentation, fly rock, and ground vibration (Ahangaran et al., 2012).

2.5.2 Approaches for Prediction of Powder factor

Although it can be expressed through several possible combinations (Prasad et al., 2017), powder factor for a single hole is given by this relation which considers powder column, density of explosive, drilled holes diameter, burden, spacing and bench height, which is given in Eq. 3.

$$PF = PC \times 0.34P \times D2/B \times S \times (H/27) \tag{2.3}$$

Where, PC= Powder column (m) (portion of borehole filled with explosives), P= Density (g/cm3), D= Diameter (mm), B= Burden (m), S= Spacing (m) and, H= Height of bench (m)

Large holes pattern requires less explosive per volume of rock because a large portion of stemming is used. The PF in Kg/m^3 has been calculated using the given Eq. 2.4.

Hence, PF = Quantity of explosive/ Amount of rock blasted (2.4)

For a specified blast condition to minimize the overall mining cost, optimum powder factor must be selected. Presently, the optimum powder factor is established through trial blasting. However, powder factor may be approximated using rock blast design and explosive parameters. Cardu et al., 2015, used a specific method to establish the powder factor to achieve a fragmentation with the desired fragment size. This method was developed by study conducted by Clerici (1974), was based on the analysis of the results of over 250 blasts in Italian limestone quarries for different applications. For Italian limestone such as the one encountered in the Alps, therefore, the minimum acceptable magnitude of powder factor ranges between 0.15 and 0.2 kg/t.

According to Singh et al., 2016, higher powder factor causes oversize, while lower powder factor results in crushed rock. Thus, a reasonable balance has to be maintained between extremely high and low powder factors in rock blasting. Although the study by Singh et al., 2016, showed that the general trend reveals increase in powder factor and decrease in the mean fragment size, this phenomenon remains an important parameter in blast design and has a vital influence on the resultant fragmentation.

Adebayo and Umeh (2007) studied the blast casting technique that utilizes explosive energy to fragment the rock mass and cast a portion of it directly into previously worked out pits. The technique depends on bench height thereby helping in efficient trajectory of thrown rocks and height- to -width ratio. It is most effective with explosives that maximize ratio of heat energy, strain energy and higher powder factor. Blasting in-situ rock to its desired fragment size requires both controllable (bench height, hole diameter, spacing, burden, hole length, bottom charge, specific charge) and uncontrollable (rock strength, discontinuity spacing and orientation, rock density) parameters for mining cycle optimization (Ninepence, et al., 2016).

According to Prasad et al., 2017, the uncontrollable parameters are geological properties such as joint, dips, strike and strength which cannot be controlled by a mining engineer. Nenuwa and Jimoh (2014) also studied the cost implication of explosives consumption in some selected quarries in Ondo and Ekiti States in South-Western Nigeria with the observation that the quarries are consuming more explosives than required. This translates to higher cost of production which could be minimized by adopting ideal blasting parameter and design. The excess explosive consumed, however, represents wasted energy which would make the blasting operation to be associated with environmental problems like high ground vibration, excess fly rocks, dust and undesirable air blast. Consequently, poor blasting has an effective cost that is several times the cost of the entire blast itself (Afum and Temeng, 2015).

According to Choudhary and Sonu (2013), the aim of rock blasting is to achieve optimum fragmentation without generating any other nuisances. Nuisances may be controlled by the use of proper quality of explosives, its generated energy and finally optimum powder factor. Hence, such fragmentation optimization ensures quality control, consistent, safe and efficient blasting. Yet, Jethro et al., 2016, agree that such production blasting is mainly targeted at optimum fragmentation. However, the entire optimization could be jeopardized unless selection of powder factor is matched with well-planned drilling and blasting parameters as well as study of rock

2.5.3 Approaches for prediction of ground vibrations due to blasting

In generally, the ground vibrations due to blasting are monitored purely based on two parameters, PPV and frequency of the wave produced from the blast. Among these two, various researchers (Kahriman 2002; Singh and Verma 2010; Arora and Dey, 2010) have reported that PPV is an index valid for recording the ground vibrations and hence it will be considered as a significant indicator for controlling the structural damage criteria.

Many researchers have investigated the PPV prediction and in the last few decades there have been a lot of empirical model for prognosis of PPV (Hasanipanah et al., 2017; Ambraseys and Hendron 1968; Dowding 1992). Most of the studies have propounded that the PPV of blast induced ground vibration can be expressed in terms of the quantitative relation between the distance and the charge per delay. The most commonly used equation to characterize the PPV was established by USBM (Duvall and Fogelson 1962; Nicholls et al,. 1971) and is given in Eqs.2.5 & 2.6:

$$PPV = \alpha \times SD^{-\beta} \tag{2.5}$$

$$\text{where, } SD = \frac{D}{Q^{a}} \tag{2.6}$$

where, SD = scaled distance $(\frac{m}{kg^{0.5}})$, D = radial distance of measuring station from blasting site (m), Q = amount of explosive (kg) , PPV= peak particle velocity (mm/s), a = constant , α and β are site constants, dependent on site characteristics.

However, several researchers (Langefors and Kihlstrom 1978; Singh et al., 1997; Giraudi et al., 2009; Cardu et al., 2019) have developed as many as more that 27 vibration predictors empirically which determine the PPV commonly from the two primary factors, i.e., maximum charge weight per delay; distance between the blasting site and monitoring pinit. As a result, these predictions by empirical methodology are not adequately providing high degree of precision for quantifying the safe zone of blasting due to only two available influencing parameters on PPV but ignoring the other design parameters such as drill hole diameter, burden, spacing, stemming, etc. Globally, damage criteria presently in use are largely based on correlation of damage in the structures in conjunction with PPV (Siskind et al., 1980; Dowding, 1985 and Wiss and Linehan, 1978; Spathis, 2009).

An elaborate and chorological summary of the BIGV studies is tabulated in Table 2.1.