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Controlled Fracture Growth by Blasting While Protecting Damages to Remaining Rock

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Summary

Conventional blasting causes cracks and fractures in the rock. Controlled blasting techniques produce the macrocrack in a desired direction and eliminate microcrack in the remaining rock. Macrocrack development in desired direction is required for extraction of dimensional stone and at the same time there is need to reduce microcrack development in the block and remaining rock. To achieve the objectives, experimental work in the quarries was carried out for separating marble block from the in situ strata as practiced in some of the Indian mines by using detonating cord of 30 to 50 g/m by varying hole spacing, hole diameter, air cushioning, water and sand filled blastholes. Blasthole notching was carried out. Further, tests were carried out by using various liners inside the blasthole to determine the damages in the extracted block and remaining rock. The designed experimental work was undertaken and rock samples were collected by coring before and after blasting for quantification of microcrack in the rock. P-wave velocity and microscopic studies were conducted for quantification of damages. Experiments were also conducted at laboratory scale for the quantification of damages in single circular and notched holes with variation of stemming and liners. The P-wave velocity close to hole always reduces after blast and in case of NG-based charge and detonating cord it decreases up to $1/3^{rd}$. With PVC pipe and paper tube liners decrease is negligible. Thus, by using notched hole with paper tube, decrease in P-wave is minimum indicating least damage.

Keywords: Blast damage quantification, blasthole notching, blasthole liners, P-wave velocity.

1. Introduction

There are many rock excavation situations where blasting is used, with the objective of developing macrocracks for separating rock or for developing cracks in desired direction. However, energy released during blasting, when transmitted to the rock, causes damage in the surrounding rock in the form of unwanted micro to macro level cracks.

In dimensional stone extraction very small amount of explosive energy is used to separate rock or splitting the separated blocks especially in situations where non-blasting methods cannot be used. Drilling and blasting continued to be the main method of block production, however during the last decade, wire/chain/belt saw cutting machines were introduced in block extraction. The cost per cubic meter of block extraction by wire/chain/belt saw was higher as compared to controlled blasting technique. The wire/chain/belt saw technique is also not suitable in deeper and small deposits of Makrana and other areas of Rajasthan in India where limited space is available. In these areas, feather and wedge technique was being practiced but that had disadvantage of more time consumption, poor recovery, increased cost and slow process. Hence, controlled drilling and blasting is the only way to extract those deposits to improve recovery and increase production of marble blocks (Bhandari and Rathore, 2001). Damage due to blasting to remaining rock and block is very critical. Recovery of marketable product at the quarry site depends upon microcracks and fractures developed due to blasting in extracted block and remaining rock. The damages due to explosive energy even at micro level in dimensional stones affect the recovery of finished product at processing plant.

Damage is required to be minimized even in conventional blasting in several situations such as pit wall blasting, tunnel and underground chambers excavations, etc. For the last many years considerable efforts were made to study the effect of blasting on the rock damage and also to minimize damage resulting from blasting. Quantification of damages to remaining rock due to explosive energy was carried out in conventional blasting in the form of various models (Holmberg, 1993; Paventi et al., 1996; Yu and Vongpaisal, 1996; Zhang and Chang, 1999). However, quantification of damage resulting from blasting has remained rather incomplete.

Since a very small amount of explosive is used while blasting for dimensional stones and rock has high ''Rock Mass Rating'' (RMR), hence a study of quantification of damages with various blasting techniques is comparatively easy. As a part of this study the objective was also to develop macrocracks in dimensional stone blasting with economical techniques while protecting block/remaining rock from development of microcracks (Bhandari and Rathore, 2002).

2. Rock Breakage and Damages

The primary fracturing in the form of radial cracks is initiated near the blasthole wall during generation of strain waves and driven up to the free faces by both quasi-static stress field and pressure developed from gases. It is also proposed that strain waves are mainly responsible for radial crack development and thereafter, completion of breakage process occurring by entering the gases into these cracks.

Further, the importance of stress waves in the fragmentation process was felt (Bhandari, 1975; Barker and Fourney, 1978). Bhandari (1975) utilised large block models in an experimental program and reported that by reducing burden, it was possible to aid the fragmentation process because the reflected waves were made more dominant. Barker and Fourney (1978) used dynamic photoelasticity models to demonstrate the importance of both small and large flaws in increasing the role of stress waves in fragmentation process. Brinkmann (1987) used blasthole liners to remove the gas pressurization factor from the blasting process and observed that fragmentation seriously degraded. The various techniques used for development of macrocrack were circular and notched hole with M.S. pipe, PVC pipe and paper tube liners. The liners in the blastholes were used to reduce the effect of stress wave and gas pressure during blasting to control unwanted damage to extracted block and remaining rock (Bhandari and Rathore, 2002). Decoupling and simultaneous initiations were the factors that reduce unwanted crack lengths (Olsson and Bergqvist, 1996).

3. Various Techniques for Damage Quantification

Rock mass damage due to blasting is directly related to the level of stress experienced by the rock mass and its pre-blasting condition. The damage caused to the surrounding rock mass is the combined effect of stress wave and gas pressure. The extent and type of damage is a function of blast design as well as the rock mass characteristics.

Induced damage in the rock may be in the forms of increased fracture frequency, degradation in discontinuity surfaces, changes in the aperture of the discontinuities as well as damage due to stress redistribution around the excavation (Paventi et al., 1996). It is important to understand the types of damages resulting from blasting and then to link the observed damages to the blasting process and rock mass characteristics.

The mechanism of the initiation and formation of cracks along the pre-split line was studied widely (Chiappetta et al., 1987). Although the rock fails under tensile stress, the crack forms gradually by crack extension and propagation. Stress concentration plays an important role in the control of the orientation of crack initiation and propagation (Jiang, 1996).

Although the explosion load exerted in the distant region sharply attenuates and does not break rock masses, at the weak planes such as joints and bedding planes, these weak planes may produce the internal damage of rock masses and reduce their load-bearing capacity and stability (Rinehart, 1971). The blasting effects for the distant region have been a difficult problem and yet not solved (Zhang and Chang, 1999). Thus, it is important to study the microcracking mechanism for blasting in rock masses.

Blasting effect results in rock mass breaking and microcracking in a finite region, which causes the decrease of ultrasonic P-wave velocity in the region (Zhang and Chang, 1999; Bhandari and Rathore, 2001, 2002). The ultrasonic P-wave velocity for undamaged rock mass after blasting is the same as that before blasting. Thus, for determination of the boundary of microcrack zone due to blasting in rock mass ultrasonic P-wave velocity measurement of core samples collected before and after blast is the most appropriate method. The application of ultrasonic testing to rock is confined to the measurement of velocity of relatively low frequency pulses passing through the rock. In general, the higher the velocity, the higher is the quality of rock or less damages occur in the rock in the form of micro level to macro level fracturing. In general, same ultrasonic velocity in the core sample of rock is indicating no damage due to blasting.

The study of damage to remaining rock and block was carried out to get a better understanding of the damage resulting from various methods of blast loading, crack initiation and protective devices and also to get better possibilities to minimize the undesired cracks.

4. Experimental Work

Experiments were designed in marble quarries for quantification of damages due to blasting in the remaining rock. The sites selected for experimental work were Babarmal (pink) and Jaspur (white) marble areas. Geological aspects regarding formation of rocks/various deposits of dimensional stones and inherent properties to form the crack in particular direction were also studied. Quarry experiments were carried out by considering the explosive energy, blasthole stemming, blasthole diameter, blasthole spacing and blasthole liners which were selected as the variables in the present work. A brief discussion of these variables is given hereunder.

Variation of explosive energy: The different field tests were devised with explosives, as detonating cord containing 30, 40 and 50 g/m PETN and NG-based. In dimensional stone mining, low energy explosives are used. Thus, detonating cord was selected for experiments. The NG-based explosives are also used occasionally; hence, these were also selected for some experiments.

Variation of stemming: Stemming/filler material between the explosive charge and hole walls has different impact. Thus, dry and wet sand, water filling and air cushioning were selected to carry out experiments.

Blasthole diameter: Since, small diameter holes are normally used in dimensional stone mining, hence, hole diameter ranging from 32 to 42 mm were selected.

Blasthole shape and spacing: The circular and notched blastholes were selected to carry out the devised experiments. Circular holes are the traditional practice and easy to drill, therefore, these types of holes were selected for experimental work. Further, notched holes control the damages in extracted block and remaining rock and increase blasthole spacing also. Therefore, notched holes were also selected for experiments. Blasthole spacing for experimental work in conventional circular holes in marble was from 200 to 300 mm and with notched holes it was from 300 to 500 mm.

Blasthole liners: Three types of slitted liners were used for the experimental work. These devices were M.S. pipe, poly-vinyl-chloride (PVC) pipe, and cardboard (paper tube).

Core samples were collected before blasting at a distance of 0.14 m to 0.45 m and after blast 0.01 m to 0.45 m from blasthole line as given in Tables 1 and 2. After carrying out the blasting, one core sample was collected just adjoining the blasthole and another was collected nearby the sample collected before blasting. After carrying out experiments in the quarry, core samples were transported to laboratory site to carry out various tests such as ultrasonic P-wave velocity and damage detection at grain level.

Ultrasonic P-wave velocity: The ultrasonic P-wave velocity equipment was used in the laboratory to determine P-wave velocity. The application of ultrasonic testing to rock is confined to the measurement of velocity of relatively low frequency pulses

Table 1. P-wave velocity determination of Babarmal (pink) marble

Blast no.	No. of holes (shape)	Explosive used	Stemming/ hole liner	Distance from blast (m)	P-wave velocity (km/sec)	
					Before blast	After blast
BM-6	03 (circular)	30 g/m d-cord	sand filled	0.03	–	5.71
				0.20	9.63	6.13
BM-9	02 (circular)	30 g/m d-cord + 50 g NG based	wet sand filled	0.02	–	6.54
				0.35	–	7.50
				0.45	7.67	–
BM-11	02 (circular)	30 g/m d-cord	sand filled + PVC liner	0.05	–	5.77
				0.45	5.95	5.94
BM-14	04 (circular)	40 g/m d-cord	wet sand filled + paper tube liner	0.05	–	3.92
				0.30	3.96	3.95
BM-21	05 (circular)	40 g/m d-cord	sand filled + paper tube liner	0.04	–	3.05
				0.28	–	4.10
				0.35	4.32	–

Table 2. P-wave velocity determination of Jaspur (white) marble

Blast no.	No. of holes (shape)	Explosive used	Stemming/ hole liner	Distance from blast (m)	P-wave velocity (km/sec)	
					Before blast	After blast
JM-01	05 (circular)	40 g/m d-cord	sand filled	0.03	–	4.23
				0.12	–	4.80
				0.30	6.72	–
JM-04	07 (circular)	40–50 g/m d-cord	sand filled + paper tube liner	0.02	–	5.20
				0.10	–	5.20
				0.30	5.33	–
JM-09	04 (circular)	40 g/m d-cord	sand filled	0.01	–	4.00
				0.05	–	4.43
				0.14	5.20	–
JM-14	08 (circular)	40–50 g/m d-cord	sand filled + paper tube liner	0.01	–	5.30
				0.08	–	5.31
				0.20	5.31	–
JM-15	06 (notched)	30–40 g/m d-cord	sand filled + paper tube liner	0.03	–	5.00
				0.10	–	5.06
				0.30	5.11	–
JM-17	05 (notched)	40 g/m d-cord	sand filled + paper tube liner	0.02	–	4.10
				0.12	–	4.12
				0.35	4.14	–

passing through the rock. In general higher is the velocity, higher is the quality of rock or less damage in the rock occurs in the form of micro level to macro level fracturing. It can be theoretically proved that the velocity of a pulse of longitudinal ultrasonic vibrations in an elastic solid can be given by the following equation:

$$V = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{1}$$

where,

V = P-wave velocity (km/sec)
E = modulus of elasticity (MPa)
ρ = density kg/m^3
ν = Poisson's ratio.

Before each blast P-wave velocity was measured with ultrasonic equipment for assessing the quality of rock. In that apparatus, pulses were generated and accurately measured was the time of their transmission through the rock. The distance, which the pulses travel in the rock, was also measured to calculate the pulse velocity. The P-wave velocity determined of various types of core samples is given in Tables 1 and 2.

In marble formation, variation in rocks was observed frequently due to foliation planes. Local joints were also observed throughout the marble formations. The micaceous minerals of low-grade metamorphism have produced localized foliation planes, which were irregular in nature. Due to these foliation planes, marble splits into pieces. Hence, at time of experiment, it was difficult to differentiate between naturally occurring weak planes and that developed due to blasting. Thus, the measured P-wave velocity and observations at microscopic level were not uniform in all the test blasts. Due to these difficulties some tests in uniform limestone blocks were also carried out for damage quantification.

In all the tests of Babarmal and Jaspur marbles, there was a decrease in P-wave velocity in the cores taken from close vicinity of holes in which blasting was carried out. In case of NG-based charge and detonating cord there was almost 1/3rd decrease in P-wave velocity, whereas with PVC and paper tube liner decrease was much less as given in Tables 1 and 2. In notched hole with paper tube decrease in P-wave velocity was negligible, thus indicating that the damage was minimum. In blast BM-11 and BM-14, P-wave velocity observed at a distance of 0.45 m and 0.30 m was the same before and after blast, thus, negligible damages were observed (Table 1). In Blast JM-15 and JM-17, damages observed were negligible beyond a distance of 10 cm to 15 cm as given in Table 2. Thus, core samples were not taken before and after blast from the same place in notched hole blast with liner beyond a distance of 15 cm.

4.1 Laboratory Blasting in Limestone Blocks

Test blasts in limestone blocks (550 mm × 300 mm × 250 mm) at laboratory scale were conducted. These blocks were extracted by drilling the holes at close interval in vertical direction to a depth of about 25 cm. Thereafter, using feather and wedge carried out separation, these extracted blocks were brought to the laboratory to carry out test blasts. The tests were carried out in circular and notched holes with varying stemming material and/or hole liners. In all the single blasthole tests, holes were drilled of 8 mm diameter to a depth of 65 mm. An explosive used was 8.5 g/m detonating cord. After the blasts each block was cut at the depth of 40 mm. As a result, typical patterns of cracks were formed with circular hole, without protective device as shown in Fig. 1. In this test, the length of crack was extended up to 0.15 m.

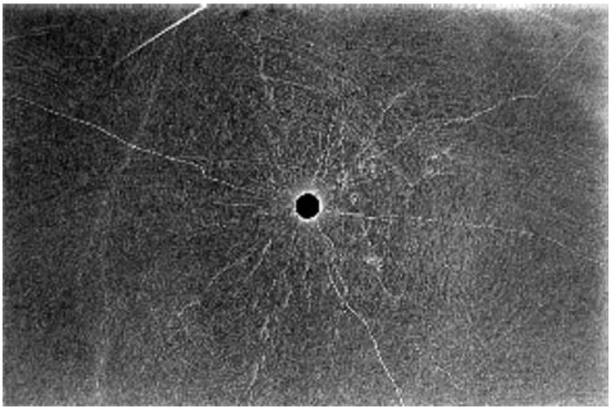

Fig. 1. Crack pattern in limestone block with circular hole without using liners

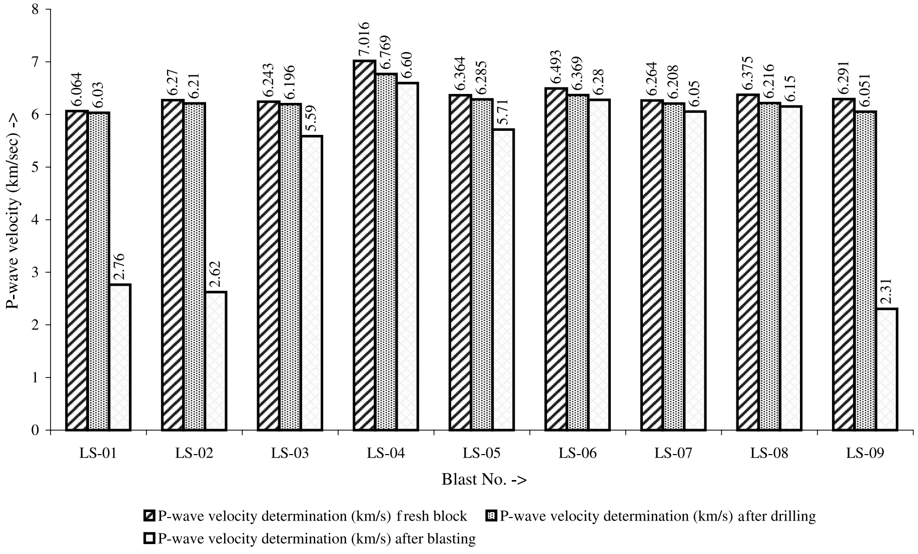

Fig. 2. Comparative study of P-wave velocities in limestone block

Before blasts, P-wave velocity was measured for each of the block at two stages i.e. before and after drilling of hole. As a result, P-wave velocity was slightly reduced after drilling a hole, as shown in Fig. 2. After blasting P-wave velocity was again measured in each block. As a result, the reduction in P-wave velocity was observed in circular hole without liner. But, with notched hole and by providing the liners, macrocrack developed in desired direction and very little difference was also observed in P-wave velocity after blast and before blast, indicating damages were negligible or minimum in notched hole with liner. Figure 2 provides a comparison of P-wave velocities obtained at various stages.

5. Results and Discussion

Several test blasts in pink and white marble quarries were carried out for quantification of damages. The P-wave velocity before and after blast of core samples was measured to find out the damages in various blasts. As given in Table 1, in blast BM-06 and BM-09, damages due to blasting occurred and P-wave velocity reduced nearby. The P-wave velocity observed at distance 0.35 m in blast BM-09 after blast is nearly same as before blast by using even NG-based explosive indicating there was no damage. In blast BM-06, the P-wave velocity reduced 40.70% adjoining the hole and 38.34% at a distance of 0.20 m. In blast BM-11 and BM-14, PVC pipe and paper tube liners were used and those have controlled damages and reduction in P-wave velocity was only 1.01% to 3.02% nearby the blasthole. In blast BM-21, the P-wave velocity was reduced 29.40% nearby the hole and that may be due to local variations in the rock.

As given in Table 2, in blast JM-01 and JM-09, circular hole with sand filled, P-wave velocity was reduced 36% to 37.35% close to the hole indicating damages due to blasting. In blast JM-04 and JM-14, circular hole with paper tube liners were used and was observed 2.44% and 18.83% reduction in P-wave velocity close to the blast as compared to before blast observed far from the blasthole. In those blasts, crack was initiated and developed in irregular shape. In blast JM-15 and JM-17 notched holes with liner were used and 0.97% and 2.15% reduction in P-wave velocity was observed close to the hole after blast as compared to before blast observed far from the hole and crack was also initiated at the notch location.

The blasting was also carried out in limestone blocks at laboratory scale and comparative results of nine single blastholes are given in Fig. 2. From Fig. 2, it is clear that reduction in P-wave velocity was observed in circular hole without liner. But with notched hole and by providing the liners, macrocrack was developed in desired direction and other damages were minimum. Thus, damages were controlled in notched hole with liners.

6. Conclusions

On the basis of the study carried out, the following conclusions are drawn:

i) NG-based explosives damage the extracted block and remaining rock. But, no damages beyond a distance of 0.30 m from blasthole were observed in the study carried out by using the NG-based explosives.

ii) Detonating cord extraction technique without lining may create damages and hence, without liner, use of detonating cord is not preferred.

iii) Several test blasts in dimensional stones using detonating cord were carried out on the pattern of conventional drill and blast technique. With this technique, crack in the desired direction was achieved but unwanted micro level cracks were also developed in the extracted block and remaining rock.

iv) Spacing between holes in Jaspur (white) marble ranges from 0.20 m to 0.30 m with detonating cord splitting technique whereas results of experimental trial using notched hole technique showed that hole spacing could be extended from 0.30 m to 0.50 m. In Babarmal (pink) marble, the spacing varies from 0.20 m to 0.30 m without notching and with notching that was increased from 0.30 m to 0.50 m.

v) While using notched hole damage was controlled by using cardboard (paper tube) liner. No unwanted cracks appear when cardboard (paper pipe) liner was used in notched holes in marble blasting.

vi) From these studies in two types of marble, it was observed that more cracks, due to blasting, were generated near foliation or joint planes, and reason for that was the reflected stress waves generated during blasting.

vii) Test blasts at laboratory scale were also carried out and it was concluded that by using notched hole with liner, crack was developed in desired direction and damages were controlled in extracted block and remaining rock.

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