P. BALAMADESWARAN
ARVIND KUMAR MISHRA
PHALGUNI SEN
and
S. RAMESH

Investigations into the influence of decking on rock fragmentation and ground vibrations by blasting in shallow benches of limestone quarries – a case study

In any quarry blasting, rock breakage is considered to be one of the significant components for carrying out the ground preparation to achieve higher production rate and also to sustain productivity. However, the performance of the blasting in terms of controlling environmental effects and the costs involved in the operation determine the profitability and sustainability of the mining company to huge extent. Thus it is necessary to study the existing conditions and accordingly implement the cost-effective technique which may enhance the blast performance with minimizing the environmental effects. Here, the decking practice in the blastholes is one of such cost-effective techniques, which is being considered to improve the blast results in the form of improvised fragmentation, effective throw, reduced vibration and less back break. Therefore, a case study involving the deep hole blasts carried out with conventional decking practice in the shallow benches of a limestone quarry located in the state of Tamil Nadu. Using the image analysis software - Fragalyst 4.0, the images of blasted muckpile were then analyzed to determine the mean fragment size and the size distribution of the fragments. It was observed that the deck blasting technique is found to be economical and also reduces the ground vibration considerably. This paper discusses the decking practices that are developed and subsequently implemented in the quarry blasting and finally outlines the recommendations to be taken for improving the performance of blasts in shallow benches of the quarry.

Keywords: *Blast design, geology,decking, fragmentation, ground vibration, back break.*

1.0 Introduction

The mining and construction industry spends heavy coins on blasting technology, explosives and their safe detonation. It is well known that about 90% of mineral production comes from surface mines in India. The drilling and blasting operations are considered to be first phase of any production operation in surface mining. Breaking of rock mass into fragments requires energy. For any specific weight of rock mass the surface area is inversely proportional to the size of the fragments formed in fragmentation. When the rock mass is fragmented and loosened by explosives, the confinement of the explosive in the blastholes generates extremely high pressure and a huge amount of heat energy. When this pressure and heat energy passes on to the surrounding rock mass, the breakage starts just behind the wall of the blasthole in the pulverized state and forming oversize materials at the greater distances. Even today, the blasting operation proves to be the most economical method of primary rock fragmentation. In spite of the best efforts to introduce mechanization fully in any surface mines even for rock breaking operation, the blasting operation continues to dominate. The major objectives are the development of an effective blast technique that minimizes the cost, maximizes face advance by producing desired fragmentation and face profile. In addition to the aforesaid objectives, the mines must consider the operational problems that occur, such as ground vibration, fly rock, etc. These operation problems lead to increased costs and decreased production in the mines, hurting the bottom line.

Hence the major thrust on the minds of mine operators has been concentrated on reduction of the cost of production which can be achieved by optimal fragmentation obtained from properly designed blasts. Therefore, optimization of blasting operation is necessary as the fragmentation obtained thereby affects the cost of the entire gamut of interrelated mining activities, such as drilling, blasting, loading, hauling, and crushing and the grinding if it is ore. Unfortunately, optimization of rock breaking by drilling and blasting is sometimes understood to indicate minimum cost in the implementation of these two individual operations only. An optimum blast is also associated with the most efficient utilization of blasting energy in the rock breaking process, reducing blasting cost through less explosive consumption

Messrs. P. Balamadeswaran, Assistant Professor, Department of Mining Engineering, CEG Campus, Anna University, Chennai, Arvind Kumar Mishra and Phalguni Sen, Professors, Department of Mining Engineering, Indian Institute of Technology (ISM), Dhanbad, Jharkhand and S. Ramesh, Assistant General Manager (Mines), India Cements Limited, Sankari Durg, Tamil Nadu, India

and less wastage of explosive energy in blasting, less throw of materials, and reduction of blast vibration resulting in greater degrees of safety and stability to the nearby structures. Therefore, the primary purpose of any blasting operation is to fracture rocks and prepare the material for excavation and subsequent transport. The end purpose of rock blasting is to produce suitable material for a crusher if it contains valuable mineral content. Hence, the following measures are to be followed to improve the fragmentation in the blasting:

- Identification of geological weak planes exists in the bench to be blasted.
- By maintaining spacing and burden as per the design.
- Charging of the holes with optimum quantity of explosives.
- Maintaining adequate stemming column in all the holes.
- Provision of decking while blasting highly fractured and varying strength of the rock.
- Proper design of blast such as initiation pattern with respect to the availability of free face.
- Adopting adequate delay interval following proper initiation sequence.
- Proper supervision during charging of blasthole.

Presently it is considered that the provision of decking of particularly in the highly fractured and varying strength of rock may yield better results through effective fragmentation. As far as measurement of fragmentation is concerned, there has been no accepted means available globally. It has been measured and expressed in numerous ways, some of the techniques indicated are listed as below:

- Screen sieving method
- Crusher monitoring
- Boulder count and secondary breakage
- Loading equipment diggability study
- Photographic analysis
- Image analysis method
- High speed photography

Even today, in several cases, the effect of blasting on the fragment size of the broken material is determined by eye only during the post-blast observations in spite of more knowledge available on rock fragmentation by blasting along with great advances of computer technologies (Kryukov et al, 2009). However, it may bring an error of 150-200% while estimating the effectiveness of fragmentation through naked eye observation (Singh and Abdul, 2012). Of the image processing softwares developed for the assessment of fragmentation over the period, WipFrag (Maerz et al, 1996; Marez, 1999), SPLIT (Kemeny, 1994) and Fragalyst (Raina et al, 2002) are commercially available. In this case study, Fragalyst 4.0, a windows based digital image analysis technique software is used for blast fragmentation estimation and analysis (Fig. 1).

Fig.1 Fragmentation analysis using image analysis software

2.0 Decking practices in quarry blasting – background

Deck charge is an explosive charge which is separated from other charges in the blasthole by stemming or by air cushions (Atlas Powder, 1987). Generally, the stemming between decks in dry holes should have a minimum length of 6 times to maximum length of 10 times the diameter of the blasthole and in wet holes it should have a minimum length of 12 times to maximum of 20 times the diameter of the blasthole. However, the stemming material that works best should have a particle size between 1/10 and 1/20 of the diameter of the blasthole (Konya, 1996). Deck charging is the procedure to charge or load the decks with explosives.

When the blastholes are short, continuous explosive charges are used. But, if they are long (ratio of length of the explosive charge to diameter of the drill hole is more than 20), deck charging will result in best cost-effectiveness relationship (Hustrulid, 1999). Deck charging is also resorted to when there is considerable variation in the strength of the rock along the length of the drill hole. Deck loading or charging (or decking of explosive charges) is a method of distributing the explosive charge in a single deep drill hole into more number of columns, each separated by certain length of stemming or air cushion as shown in Fig. 2.

When blasting is carried out with concentrated explosive charges at the back of a long blasthole and with long stemming lengths, big boulders are generated from the rock near the collar of the hole, as no explosive is in direct contact with this portion of the rock. Therefore decking of the charges in such holes ensures better distribution of the explosive energy along the length of the hole producing better fragmentation (Singh et al, 1999). Decking also helps reducing maximum explosive charge per delay, when each or group of the decks are blasted separately by adopting delay within a single hole. This results in reduced ground vibrations. Decking also reduces fly rock and reduces displacement of the blasted rock from the face (Mishra and Balamadeswaran,

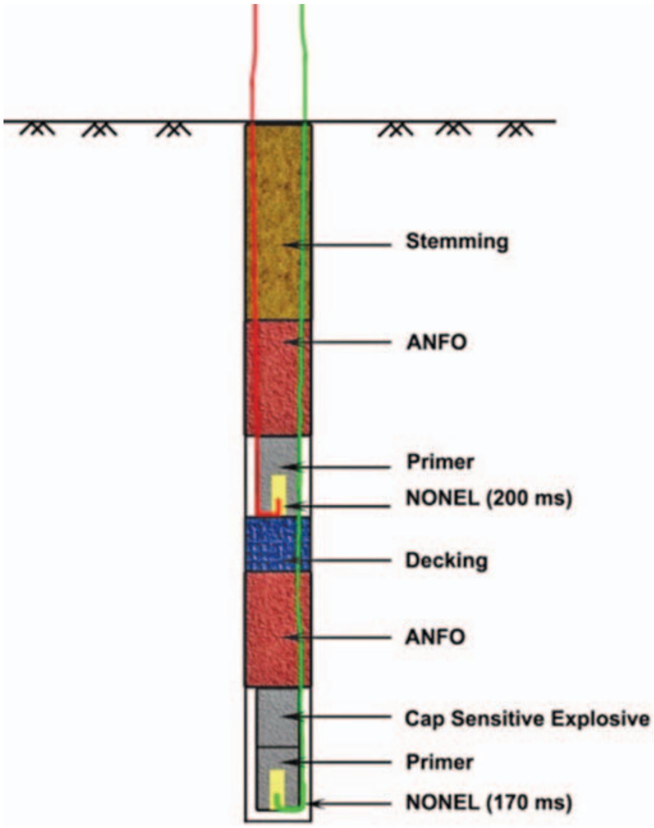

Fig.2 Typical decking practices in the quarry blasting

2004). However it also possesses the following demerits:

- Due to reduced displacement, swelling of the blasted rock would be less, necessitating harder digging by the loading machine.
- Cost will increase due to increase in blasting accessories (Suttithep et al, 2013).
- Increased complexity of charging, stemming and hooking up, calls for expertise and increases the time of the operations.
- Where a thick layer of highly deformable material lies between beds of stronger and massive rocks, lowest overall mining costs are usually achieved by charging only those parts of the blasthole and stemming deck for the weak rock (Hagan, 1973).
- The decking by filler material near the open joints in the blasthole have influence on the fragmentation. The fine fragmentation increased in case of strong material compared to weaker material (Bhandari, 1997).

3.0 Case study

The case study involving the experimental blasts were carried out in two limestone quarries belonging to a premier cement manufacturing company situated in the central part of Tamil Nadu and a total of 15 blasts were carried out using with decking and without decking concepts. In these 15 blasts, 8 blasts were carried out without decking and the remaining 7 blasts were carried out with decking. For each blast, vibration level, fragmentation (rock pile) photos for future analysis, actual quantity of rock broken, loading and rock breaker machine fuel consumption were measured to study the effect of decking on rock fragmentation and environment.

Location of the quarry

The two quarries are located in the central part of Tamil Nadu state at a distance of 5 km from the nearest town in the north-north east direction. The quarry is located at a distance of about 20 km from another town in the west north-west direction. The aerial map of the quarry and its working position is shown in Fig.3.

Fig.3 (a) Aerial view of limestone quarry (b) Limestone quarry in operation

Geology

The relief of the area is 253 m above mean sea level. The limestone deposit is basically made up of metamorphic formation. The deposit is dipping towards north east. The country rocks of the deposit are gneiss, biotite gneiss and pegmatite. There is no top soil since the terrain is of rocky formation. Even through the deposit is proved below ultimate pit limit, the mining of limestone below the ultimate pit depth is economically not viable. The waste from this mine is side burden and interstitial waste. The most common are gneiss, pegmatite and biotite gneiss and they are non-toxic.

The limestone deposit is spread out in two mines and one limestone mine belongs to Archean age. This limestone is intruded by younger pegmatite and the contact rock is calc gneiss. The length of the limestone deposit is 670 m and the width varies from 60 m to 270 m. The general strike is NE - SW and a small band strikes NE-SW for a length of 80 m. the limestone contains 79-80 % $CaCO_3$ and 16-18% SiO_2.

The limestone deposit in another limestone mines belongs to Archean age. It strikes north east-south west for about 1000 m with a plunge towards west and takes a turn and strikes at north south for about 500 m in the area where it strikes north east south west the limestone band dips towards north west. The dip is about 60º. The band where it strikes north south is having a dip of 70º towards eat. The width of the main band varies from 60 to 250 m.

Mining methodology

Both the limestone mines are being worked as open pit mechanized mine. The rock breakers in combination with controlled blasting are used for breaking the in situ rock for ensuring controlled throw and also to limit the environmental impacts such as vibration, flyrock, etc. Therefore, the smaller diameters of 32-45 mm holes are drilled by hydraulic drilling machines. Similarly, the controlled blasting with very low specific charge is being practiced which develops necessary fractures and cracks leads to controlled throw. Here, it was observed that there is little or no displacement of muckpile. Thereafter, the primary breaking is carried out by Atlas Copco Breaker HB 5800 mounted on Tata Hitachi excavator 600 and L&T excavator 300 are used to break fracture induced oversized blocks due to blasting in such way that limestone, mixed stones and rejects are broken and loaded separately. A wheel loader is used for dozing, heaping and loading purpose. One backhoe is exclusively engaged for sorting rejects stone from limestone ROM at the site.

Blasting operation

The experimental blasts were carried out in the limestone having a density of 2.9 g/cc. Here the drilling and blasting method was followed in the mine to remove the overburden and the ore. The diameter of the hole drilled was 32 mm. The type of explosive used in the mine is slurry only primer cartridge of 25 mm of slurry type is used and no column charge was used {Fig.4(c)}. Here the shock tube detonators, electrical delay detonators and detonating fuse are used to have a better and safe blast. The shock tube provides a true bottom initiation and the length of the tube depends on the depth of the blasthole. The maximum charge per delay (MCD) for all the experimental blasts was maintained in the range of 2 kg to 2.5 kg as each hole was initiated with individual delay. At any circumstances, it was ensured that no two holes are blasted at the same time period by maintaining a time interval of atleast 5 ms between successive shots using noiseless trunk delays (NTD) of 17 ms and 25 ms at the surface. Here, the detonating fuse is used to connect the cap sensitive charges which are separated by decking as shown in Fig..4(b).

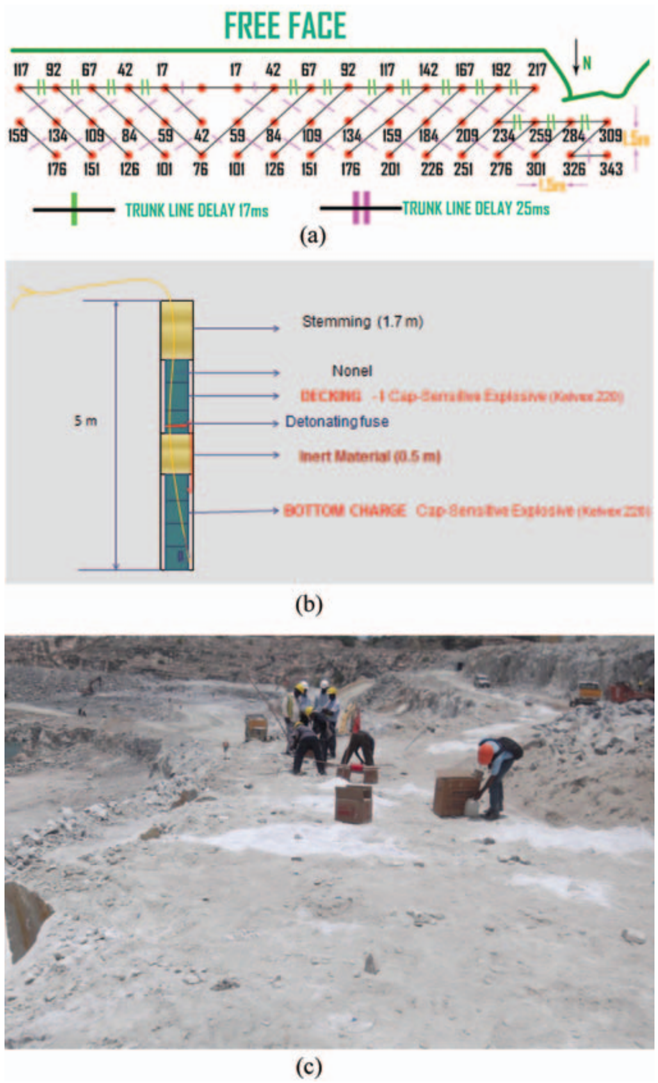

Fig.4 (a) Initiation pattern (b) Modified charging geometry with 'decking' (c) Charging of holes in the site

4.0 Data collection and analysis

A total number of 15 blasts as shown in Table 1 for the depth of 4 m to 5 m in the limestone and overburden benches were carried out. Here, four vibrating monitoring instruments of INSTENTEL make (seismographs) were placed at various locations behind the last row of the blast and at side of the blasts covering different distances for the blasts shown in the Table 3. The photographs of blasted muckpiles were captured at different positions immediately after the blast and also during the excavation for carrying out fragmentation analysis using FRAGALYST 4.0 software in the laboratory. Prior to the blasting, the following conditions were observed:

- Actual front row burden was existing from 0.8 m to 1 m in the site.
- There was no loose material present at the free face but however, the presence of toe was found in two cases.
- The spacing to burden ratio was maintained at 1 and

however, the Burden Stiffness Ratio (BSR) was ranging from a minimum value of 2.8 to the maximum value of 3.8.

- All the blasts were carried out in totally dry condition as the holes were containing no water.
- The stemming was carried out with drill cuttings which were available locally.

ANALYSIS OF DATA

Digital image analysis technique was used in the present study by the capturing of scaled digital images of the blasted muck pile to quantify the fragment size and its distribution. The complete fragment size distribution revealing the K25, K50, K80, K90 and K98 for all the blasts were measured using the image analysis software - FRAGALYST 4.0. A sample of fragmentation distribution curve produced for the blast no.1 is given in Fig.5. The mean fragment size (K50) found for the blasted muck was ranging from 0.16 to 0.52 m as shown in the Table 2. The maximum fragment size (K98) found for the blasted muck was found to be 1.3 m. Besides, the following results were observed.

1. The mean fragment size was found to be increasing with the length of deck splitting the charges in the hole, as shown in Fig.6. Here, it was observed from the blast no.3 that the quantity of explosives charged in upper deck portion higher than the charges placed in lower deck portion has produced the mean fragment size of 0.33 m with decking length of 0.70 m maintained to split the charges. However, the mean fragment size of 0.19 m was resulted in the blast no.14 when the quantity of explosives was charged equally in the both deck portions with maintaining the same decking length of 0.70 m. When the decking length was increased to 0.80 m in the blast no:15, it has produced the mean fragment size of 0.24 m.
2. The large quantity of bouldery formations were found to exist in the blasts (nos. 2 and 8) which were carried out with and without decking in the mineralized zone where the ore body is plunging and taken a turn in the gneiss host rock. Here, the intensity of shock waves produced from the blast was insignificant in producing the fractures due to change of geological and geomechanical characteristics over a shorter distance.

TABLE 1: CHARGE DETAILS OF TRIAL BLASTS CARRIED OUT IN THE LIMESTONE QUARRY

Blast no.	Burden (m)	Spacing (m)	Average depth (m)	Deck length (m)	No. of holes	Total charge (kg)
1.	1.5	1.5	5	-	43	76
2.	1.5	1.5	5	-	51	80.750
3.	1.5	1.5	5	0.70	40	70
4.	1.3	1.3	4	-	27	50.675
5.	1.3	1.3	4	-	48	63
6.	1.3	1.3	5	0.30	48	108
7.	1.3	1.3	5	0.50	24	45
8.	1.5	1.5	5	-	34	59
9.	1.5	1.5	5	1.0	52	82
10.	1.5	1.5	5	-	41	72.50
11.	1.3	1.3	4	-	28	52
12.	1.5	1.5	4		44	60
13.	1.5	1.5	5	0.40	49	107
14.	1.5	1.5	5	0.70	26	46
15.	1.5	1.5	5	0.80	20	34

TABLE 2: FRAGMENTATION ANALYSIS OF THE BLASTS WITH DECKING AND PERFORMANCE OF ROCK BREAKERS

Blast no.	Explosive without decking (kg)	Explosive with decking (kg)	Deck length (m)	Reduction of explosive (%)	Average fragment size (m)	Fuel consumption of rock breaker (lit/hr)	Rock breaker output (t/hr)
1.	76	-		-	0.46	29	159
2.	80.750	-		-	0.52	42	148
3.	85	70	0.70	17.64	0.33	36	171
4.	50.675	-		-	0.23	28	177
5.	63	-		-	0.16	31	180
6.	120	108	0.30	10	0.19	28	215
7.	54	45	0.50	16.67	0.20	30	205
8.	59	-		-	0.51	45	152
9.	82	69	1.0	15.85	0.48	34	169
10.	72.50	-		-	0.36	39	185
11.	52	-		-	0.21	36	190
12.	60	-		-	0.19	32	175
13.	107	98	0.40	8.41	0.20	27	204
14.	46	38	0.70	17.39	0.19	26	192
15.	34	29	0.80	14.70	0.24	28	189

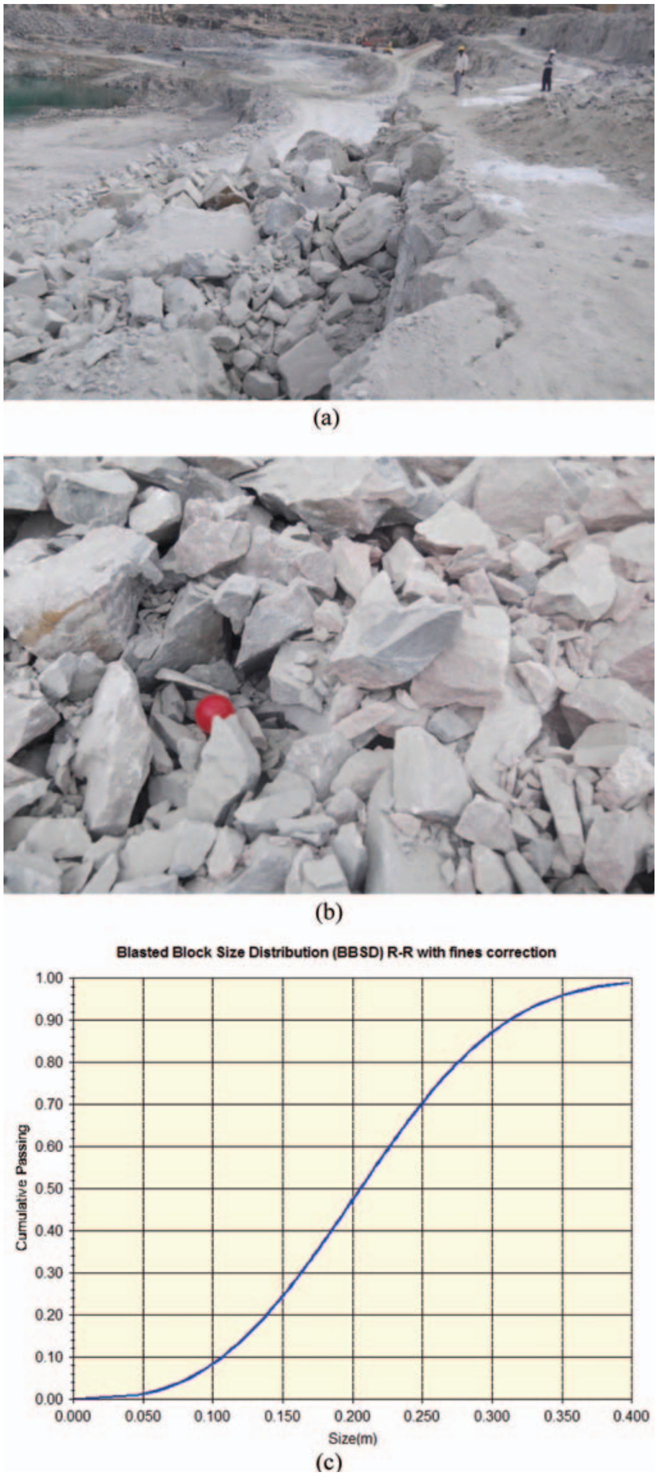

Fig.5.0 (a) Presence of 'drop' and coarser fragmentation after the blast (b) Muck pile produced by blasting (c) Fragmentation analysis curve

3. From Fig.6, it was seen that the decking length of 0.30 m, 0.40 m and 0.50 m maintained in the blast nos: 6, 7 and 13 has produced the mean fragment size of 0.19 m, 0.20 m and 0.20 m respectively. Based on a commonly used rule of thumb for dry holes, the stemming length should be 20 to 30 times the hole diameter (Liu and Katasbanis, 1996) and

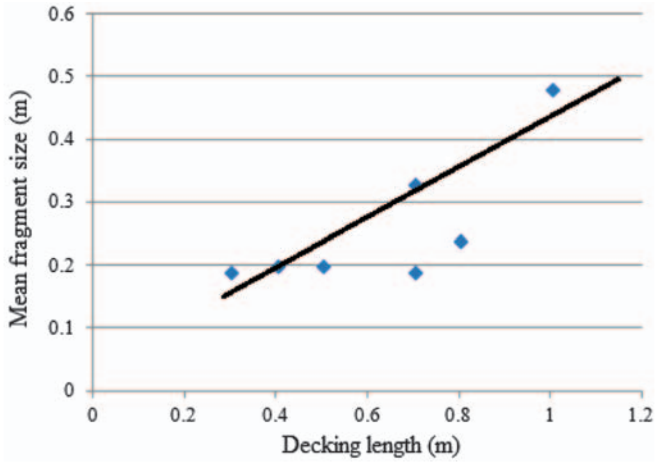

Fig 6 Influence of deck length on fragmentation

hence it should have atleast 0.60 m length for decking with drill cuttings which will not create any sympathetic detonation. Hence, by maintaining the decking length of 0.60-0.80 m in the blast nos: 3, 14, 14 have produced effective breakage and also eliminated the possibility of sympathetic detonation.

4. In order to find solution for eliminating the sympathetic detonation when the conventional drill cuttings are used for decking, plastic lay-flat tubing with outer diameter within 5 mm of the hole diameter was filled with crushed aggregate (passing size 10-12% of hole dia.) to manufacture "stemming plugs" in the form of cartridge (as shown in Fig.7) was experimentally used for decking in the blasts nos. 6 and 7. It was expected to withstand immense heat and pressure with locking characteristics besides completely eliminating the sympathetic detonation during the initiation. Besides, it has also produced mean fragment size of 0.19 m and 0.20 m and reduced ground vibration levels (ppv) of 1.52 mm/s and 1.71 mm/s.

5. It was observed from the blasts which were carried out with BSR of less than 3 has resulted in producing tight muckpiles and hard toe even though the breakage was fair enough, compared to the blasts possessing the BSR value of more than 3.5.

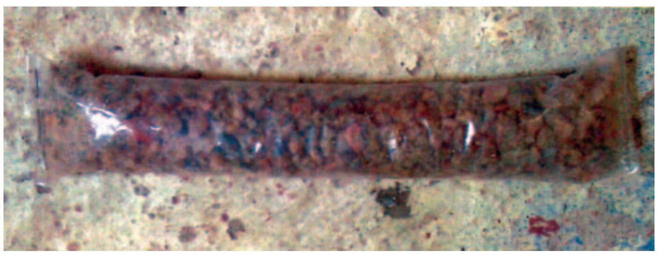

Fig.7 Cartridged packing of crushed angular stones used for 'decking'

6. In certain blasts (nos. 2 and 8), the back break of even up to 3.5 m was found. Here, the direction of rows dictates or causes the formation of back break, particularly, when it was formed in parallel to face direction or oblique to face

TABLE 3: GROUND VIBRATION MONITORING AT VARIOUS DISTANCES FROM THE BLAST SITES

Blast no.	Explosive without decking (kg)	Explosive with decking (kg)	Deck length (m)	Max. charge per delay (MCD), kg	Reduction of explosive (%)	Observed ground vibration, ppv (mm/s)					
						30m	50m	70m	100m	250m	300m
1.	76	-		2.0	-	-	-	-	4.54	1.29	0.35
2.	80.750	-		2.0	-	-	-	-	3.43	1.14	0.69
3.	85	70	0.70	1.70	17.64	9.76	7.86	3.32	1.22	-	-
4.	50.675	-		1.875	-	-	-	-	-	2.08	-
5.	63	-		1.5	-	9.05	-	4.64	4.62	1.40	-
6.	120	108	0.30	2.5	10	-	-	13.1	1.52	-	-
7.	54	45	0.50	2.0	16.67		--	-	1.71	0.746 (150m)	-

direction in the mineralized zone where the ore body is intruding in unconventional manner. Besides the above situation, non-availability of sufficient time or poor stemming quality, the back holes are simply pushing the front burden which produces the back break effects considerably without creating significant ‘drop’ in the blast.

7. The rock breaker was used (Fig.8) very extensively even up to 8 hour duration for creating necessary breakage in the muckpiles of the blasts conducted without decking and however it has got reduced to minimum value of 5.6 hours with increased output when the blasts were carried out with decking in the limestone benches. Hence, it has proved to be more economical as the fuel consumption was considerably (Table 2).

Fig.8 Rock breaker working with blasted muckpile

8. Due to in-flight collision between the rows, the 'V' initiation sequence pattern {Fig.4(a)} adopted in the blast nos: 4, 5, 10, 11 and 12 has produced excellent results in breakage by obtaining the mean fragment size in the range of 0.19 m to 0.36 m, even without adopting decking practices in the blasting and it also controlled the production of flying fragments. However, it was observed that the blast no:9 was carried out with decking, has produced the mean fragment size of 0.48 m by adopting ‘row-by-row’ initiation sequence as no collision has occurred and it became choked condition due to non-availability of adequate free face.

9. Similarly, the performance of rock breaker has reduced with increase in length of decking in the blastholes as shown in Fig.9. It was also observed that the rock breaker has produced an effective output in the range of 171 t/hr to 192 t/hr when the optimum decking length of 0.60 m to 0.80 m was maintained as per the requirements. Further, it was observed that when the decking length was increased beyond 0.80 m has produced coarser fragment size that has significantly reduced the output of the rock breaker (t/hr).

10. The production of flyrock was controlled very effectively as it was falling within blast-secured area ranging from 15 m to 20 m when the blast were carried out with decking. Similarly, the throw was limited to be within 10-12 m distance from the blast face.

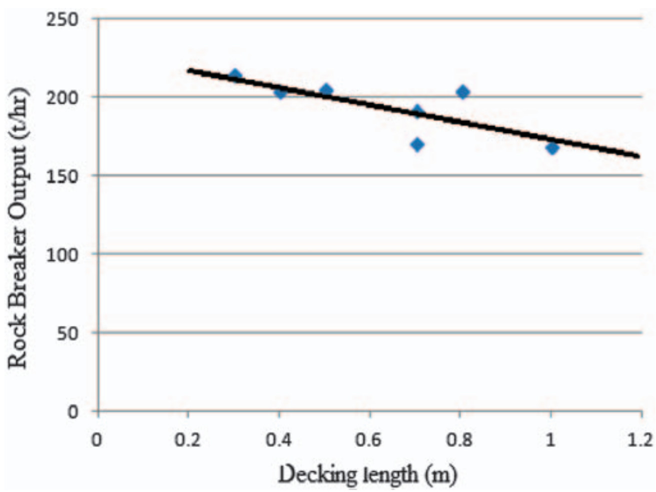

Fig.9 Graph representing the relation between deck lengths and rock breaker performance

Ground vibration – analysis of data

The ground vibration levels were considerably reduced in the blasts carried out with decking compared to the blasts carried out without decking as shown in the Table 3. The ground vibrations level monitored by the mine management was well within permissible level at the distance of 150 m from blast location. However, the following observations demonstrate the development of an effective vibration control programme through carrying out the blasting activities with decking practices:

1. From Table 3, it was observed that the blasts carried out without decking has produced the vibration level of 4.54 mm/s, 3.43 mm/s and 4.62 mm/s from the blast nos: 1, 2 and 5 where as the blasts carried out with decking has produced reduced ground vibration level of 1.22 mm/s, 1.52 mm/s and 1.71 mm/s at a distance of 100 m from the same limestone bench maintaining the same free face.
2. It was also observed that increasing the MCD to 2.5 kg with deck charging, the ground vibration (ppv) level of 1.52 mm/s was obtained whereas even the blasts were carried out with a reduced MCD of less than 2 kg in the same benches without decking has produced the higher ground vibration levels of 4.54 mm/s, 3.43 mm/s and 4.62 mm/s.
3. It was also evident that the blasts carried out with decking has produced reduced ground vibration level of 1.22 mm/s from the blast no.3, when the explosives consumption was reduced by 17.64% thereby lessening the Maximum Charge per Delay (MCD). Therefore, the charge per delay influences the ground vibration to the large extent even the blasts are carried out with decking practices.
4. It was observed from Table 3 that the ground vibration level (ppv) of 9.76 mm/s was obtained with decking at a distance of 30 m from the back row against the ppv of 9.05 mm/s at the same distance when the blast was carried out without decking. The higher vibration (ppv) level in the blast carried out with decking may be due to the shock energy produced from the upper deck of blast as 57% of total explosives were placed in it as it was seen that lowest frequency range of 21 Hz was obtained from the deck blasting against the frequency range of 28 Hz in the blast carried out without decking.

5.0 Conclusion

On the basis of the experimental blasts conducted in the limestone mines we may conclude the following:

1. By maintaining the decking length of 0.60 - 0.80 m in the blasts, it has produced effective breakage and also eliminated the possibility of sympathetic detonation.
2. The mean fragment size was found to be increasing with the increase in deck length in the hole.
3. In order to find alternative solution for eliminating the sympathetic detonation which arises due to usage of regular drill cuttings for splitting the charges within the hole, the plastic or polythene lay-flat tubing with outer diameter within 5 mm of the hole diameter filled with crushed aggregate (passing size 10-12% of hole dia.) was experimented successfully for decking. It produced an effective fragmentation of 0.19 m and 0.20 m, in the blasts nos.6 and 7 respectively.
4. The performance of rock breaker used for breaking the blasted muckpile has decreased with increase in length of decking. Further, it was also seen that the rock breaker has produced an effective output in the range of 170 t/hr to 190 t/hr when an optimum decking length of 0.60 m to 0.80 m was maintained as per the blast design requirements. However, it was evident that when the decking length was increased beyond 0.80 m, it produced coarser fragment size significantly reducing the output of the rock breaker (t/hr).
5. It was observed that the decking length maintained at an optimum length of 0.70 m produced lower ground vibration level (ppv) of 1.22 mm/s against the ppv of 4.62 mm/s obtained without decking at a distance of 100 m from the back row of the blast, even though the maximum charge per delay was kept less in the later case.

Acknowledgments

Authors gratefully acknowledge the excellent support received from the field personnel of the limestone mine where the experimental blasts were carried out in the state of Tamil Nadu. The authors also wish to thank the Indian Institute of Technology (ISM), Dhanbad and Anna University, Chennai for granting permission to publish the article in the journal.

References

1. Kemeny, J. M. (1994): "Practical techniques for determining the size distribution of blasted benches, waste dumps and heap leach site," *Mining Engineering*, pp. 1281-1284, 1994.
2. Maerz, N. H., Palangio, T. C. and Franklin, J. A. (1996): WipFrag images based granulometry system, In: Franklin, J.A & Katsabanis, P.D (eds), Measurement of blast fragmentation, Rotterdam: Balkeme, pp.91-98, 1996.
3. Maerz, N. H. (1999): Online Fragmentation Analysis: Achievements in the Mining Industry, Center For Aggregates Research (ICAR) Seventh Proceedings of Annual Symposium Proceedings, Austin Texas, April 19-21, pp. C1- 1-1 to B1-1-10, 1999.
4. Raina, A. K., Choudhury, P. B., Ramulu, M., Chakraborty, A. K.. and Dudhankar, A. S. (2002): "Fragalyst – an indigenous digital image analysis system for grain size measurement in mines," *Journal of Geological Society of India*, Vol.59, pp.561-569, 2002.

5. Konya, C. J. and Walter, E. J. (1996): Surface Blast Design, Prentice Hall Inc, New Jersey, 297p, 1996.
6. Bhandari, S. (1997): Rock Blasting Operations, A. A. Balkema, Rotterdam, 390p., 1997.
7. Mishra, A. K. and Balamadeswaran, P. (2004): Blast Design Approach for Better Fragmentation in Surface Mines, Proceedings of National Seminar on Rock Fragmentation (NSRF-2004), Institute of Technology, Banaras Hindu University, January 23~24, Varanasi, pp.35-48., 2004.
8. Hagan, T. N. (1973): "Rock Breakage by Explosives," *US Bureau of Mines*, R.I. 5336, 52p, 1973.
9. Hustrulid, W. (1999): Blasting Principles for Open Pit Mining, Vol. 1, General Design Concepts, A.A. Balkema, Rotterdam, 344p, 1999.
10. Singh, M. M., Singh, R. B. and Gupta, R. N. (1991): "Blast design to improve fragmentation in a mismatched combination of drill diameter and depth in bedded rock," *Mining Science and Technology*, Vol.12, *Elsevier Science*, pp.179-186, 1991.
11. Singh, S. P. and Abdul, H. (2012): Investigation of blast design parameters to optimize fragmentation, Proceedings of International Symposium on Rock Fragmentation by Blasting (FRAGBLAST-10), Singh & Sinha (Eds), New Delhi, pp.181-186, 2012.
12. Atlas Powder, Explosives and Rock Blasting. Atlas Powder Company, Dallas, Texas. Maple Press, 662p, 1987.
13. Kryukov, G. M., Belin, V. A., Stadnik,V. V., Vaver, P. A. and Zhavoronko, S. N. (2009): Laws governing the formation of particle-size distribution in case of some solid material blocks fragmentation by blast: Selected papers of the *Mining Information and Analytical Bulletin*. No 8. M.: Gornaya Kniga Publishers, 2009. 75 p. (in Russian), 2009.
14. Suttithep, R., Chewchan, L. and Pirat, J. (2013): "Influence Of Air-deck Length On Fragmentation in Quarry Blasting," *European Scientific Journal*, Vol.3, Thailand, pp.200-207, 2013.
15. Liu, L. and Katsabanis, P. D. (1996): Numerical modeling of the effects of air decking/decoupling in production and controlled blasting. In: Mohanty (ed) Proceeding 5th International conference on rock fragmentation by blasting, A. A. Balkema, Rotterdam, pp. 319-330, 1996.