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BLAST OPTIMISATION WITH *IN SITU* ROCK MASS CHARACTERIZATION BY SEISMIC PROFILING AT AN OPENCAST COAL MINE IN INDIA

More Ramulu , Anand Ganpatrao Sangode and Amalendu Sinha

ABSTRACT: Blast optimisation studies were conducted at an opencast coal mine in India for selection of a site specific explosive for different rock types. This seismic refraction survey technique was applied at sandstone benches of a coal mine for rock mass characterisation and blast optimisation by impedance matching of explosives. Field experiments were conducted on seismic profiling to characterise sandstone rock mass on the basis of P-wave velocity (Vp) measurements. The running benches were selected for the experimentation so as to cross check the results of the Vp with the exposed faces of the benches. The instrument used for seismic profiling contains 24 geophones of 14 Hz frequency. The mode of survey was the 'refraction method' which could give the Vp profile up to 50-60 m depth and about 100 m stretch. The source of vibration generation was by hammering of specific Sledge hammer. The raw seismic data collected in the field was analysed by a software called 'Seismic imager' for generating a Vp profile of the rock strata. The Vp profiles were determined for three benches of the mine, which include weak, medium and hard type of rock mass. The rock impedance was calculated based on the Vp determined by seismic profiling. This data was used for the selection of explosive with desired velocity of detonation and density, so as to match the impedance of the rock mass. The blast performance with the suitable explosives with impedance matching was obviously better than that of impedance mismatching. Trials were also conducted with heave energy-rich ANFO explosive with mismatched impedance properties and observed better results. The optimisation studies resulted in reduction of back break by 50-75% and reduction of mean fragment size by 15-47%. The paper stresses the need for conducting impedance matching exercise for all the blast sites for blast optimisation and productivity improvement.

INTRODUCTION

The mining productivity in open cast mines depends heavily on the degree of fragmentation. Various unit operations like drilling, blasting, loading and transport are influenced by fragmentation and jointly contribute to the overall productivity. It is often observed that practising engineers indiscriminately use explosive charges to improve fragmentation with scant regard to rock formations and explosive properties. This may not be in the best interest of the overall mine productivity. It calls for a study on proper selection of explosive for various rock properties. The best matching for optimum shock wave transmission to the rock occurs when the detonation impedance of explosive is equal to the impedance of the rock material (Atchison, 1964). Impedance is the product of compressional wave velocity and density of the material. Impedance calculation requires the determination of *in situ* P-wave velocity (Vp) and density of rock mass. Therefore the refraction seismic survey technique of seismic profiling was applied for rock mass characterisation of sandstone overburden in this study.

Continuous acquisition of multichannel surface wave data along linear transects has recently shown great promise in detecting shallow voids and tunnels, mapping the bedrock surface, locating remnants of underground mines and delineating fracture systems (Park, *et al*., 1999). Extending this technology from sporadic sampling to continuous imaging required the incorporation of Multichannel Analysis of Surface aves (MASW) with concepts from the Common Depth Point (CDP) method (Mayne, 1962). Integrating these two methodologies resulted in the generation of a laterally continuous 2-D cross-section of the shear wave velocity field. Cross-sections generated in this fashion contain specific information about the horizontal and vertical continuity and physical properties of shallow materials. Seismic reflection surveys are generally designed to image structural and stratigraphic features with a high degree of resolution and accuracy.

Since shear wave velocity has the greatest impact on the properties of a surface wave, the dispersion curve can be inverted in such a way as to obtain the shear wave velocity as a function of depth (Xia, *et*

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al., 1999). Barton (2007) says that the phenomena of seismic anisotropy giving lower stiffness perpendicular to layering than in parallel, has been used since the nineteenth century for investigating fractured rock at depth. The same analogy holds good for compressional wave velocity. The objective of this experimental work has been to find out the compressional wave (Vp) structure and from these dispersion curves to obtain the inferences regarding the structural quality of the strata. Ramulu *et al* (2011) extensively used the seismic refraction technique for determination of Vp of rock mass for blast optimisation by impedance matching of explosives.

This paper deals with the blast optimisation by rock mass characterisation with seismic profiling at various benches of the mine.

REFRACTION SEISMIC SURVEY FOR ROCK MASS CHARACTERISATION

Data acquisition:

The instrument called Geode (Geometrics controllers Inc., USA) was used for acquiring the data for surface wave analysis using refraction seismic survey technique. The sensors used were of 14 Hz frequency and 24 in number. The refraction seismic survey system with various components is shown in Figure 1. The sensors were spread at 1 m spacing and the seismic source was at 5 m distance in all the experiments. A sledge hammer of 4.5 kg (10 lb) weight was used as seismic source. Each site will have specific characteristics effecting data properties. Optimising parameters and equipment is critical to maximising the accuracy, analysis format, and potential of the resultant processed sections. Data acquired for surface wave analysis using the refraction seismic survey technique are generally broadband (i.e., 4 Hz to 64 Hz), with offsets designed and based on target dimensions and depths. Standard Common Mid-point (CMP) roll-along techniques are used in conjunction with 24-channel recording systems. Shot and receiver spacing as well as near and far source offsets depend on number of recording channels and maximum and minimum depth of interest.

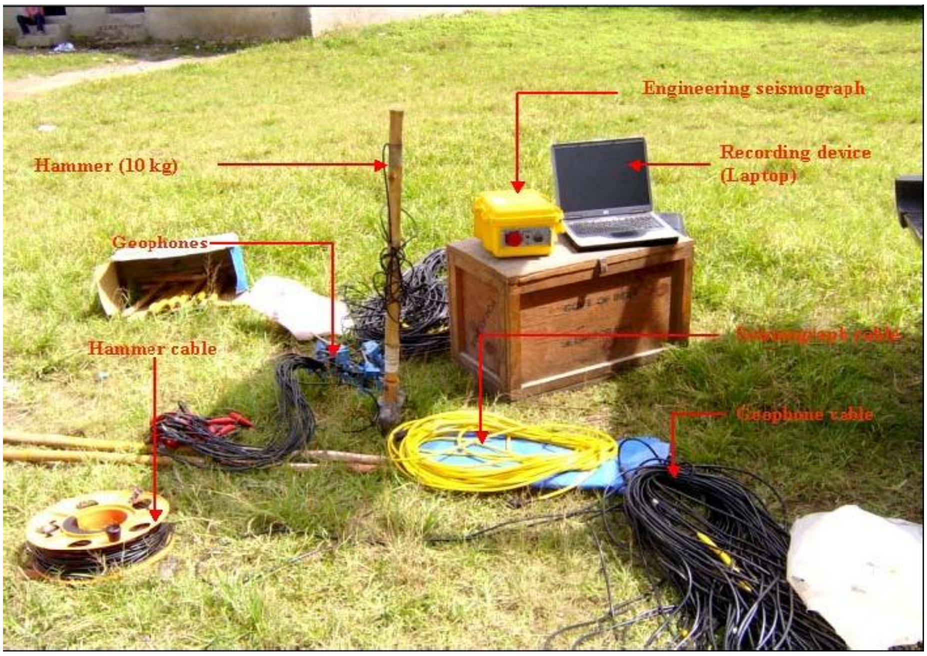

Figure 1 - Various components of the refraction seismic survey system

Ground cover (such assoil, cement, gravel and grass) has no significant influence on the accuracy of the recorded surface wave energy (Miller and Xia, 1999). Generation of surface waves is quite easily accomplished with weight drop style sources, with the particular specifications of the source only limited by the dominant frequency band of interest. For deeper penetration a large and heavy source is optimum. Receivers need to be low frequency (< 8 Hz) and broadband. With cost consideration, the optimum geophone has a natural frequency of around 4.5 Hz and can be outfitted with either flat base plates or short spikes depending on the surface to be surveyed. Recording geometries and frequency ranges of data examples presented here provided optimum data characteristics for examining earth materials in the depth range from about one to over 50 m below ground surface. Many studies have shown that receiver-ground coupling is critical for high-resolution body wave surveys (Hewitt, 1980). Maximising frequency response and recorded body waves normally requires longer spikes, well seated into competent earth. Coupling experiments at various sites have suggested receivers only require simple ground contact to record broad-spectrum surface wave energy. Little or no improvement is evident in response (frequency vs. amplitude) when geophones are "planted" using spikes, placed on the ground using plates, or held to the ground with sandbags (Miller and Xia, 1999).

FIELD APPLICATION OF THE SEISMIC PROFILING

Mine details

The field experiments on seismic profiling and impedance matching were conducted at one of the Opencast Project (OCP) mines of Coal India Limited, which is situated about 25 km from Nagpur town. The area is characterized with flat topography having elevations ranging from 298.7 m to 304.8 m (980 ft. to 1000 ft) above mean sea level. There are five coal seams namely, I, II, III, IV, and V in the leasehold area of the colliery. There is also a problem of optimum blast fragmentation, which may be due to mismatching of rock mass properties and explosive selection.

Geology

The exposures of Lower Gondwana rocks around Tekadi – Silewara – Patansaongi – Bokhara – Khapa - Saoner belt located about 25-30 km from Nagpur. The OCP mine Coalfield is a horse-shoe shaped basin aligned in a NW-SE direction. The coalfield is blanketed by a detrital mantle. The Barakars overlie the Talchirs and underlie the Moturs conformably. They consist of fine, medium and coarse grained sandstone, intercalations of shale and sandstones, sandy shale, carbonaceous shale and coal seams and are around 300 m in thickness. Kamthis is a good aquifer and overlaps directly above Barakars. The dip of the seams is about 1 in 4.5 on the rise side and about 1 in 5 to 1 in 6 on the dip-side. It shows a tendency to further flatten beyond the existing limit of working. The rock properties of all the three benches, where tests were conducted are shown in Table 1. The intact rock P-wave velocity was tested by ultrasonic device as shown in Figure 2.

Table 1 - Intact rock properties of all the test sites

Site	Rock density (kg/m^3)
Bench-I	2550
Bench-II	2600
Bench-III	2675

Figure 2 - P-wave velocity determination of sandstone samples from Laboratory testing

Seismic profiling at OCP coal mine

A seismic profiling survey was carried out to characterise sandstone rock mass on the basis of P-wave velocity measurements. The survey was carried out at the surface of sandstone rock mass towards N.E direction of the Mine. The survey was carried out at three locations of the mine covering hard, soft and medium rock mass. The running benches were selected for the experimentation to cross check the results of the P-wave velocity profile (V_p) with the exposed faces of the benches. The experimental set up is shown in Figure 2. The seismic profiler experimental set up is shown in Figure 3. The rock samples were collected from the middle and bottom layers of bench-I for laboratory testing of P-wave velocity. The faces of exposed benches are shown in Figure 4.

(a) Hammering point **(b) Geode and geophones**

Figure 3 - Seismic profiler experimental set up

Figure 4 - Exposed face of a test site

The mode of survey was he 'refraction method' which could give the V_p profile of 50 to 60 m depth over a length of about 100 m. The source of vibration generation was by hammering by means of a 4.5 kg (10 lb) weight Sledge hammer with 5-10 numbers of blows. The seismic raw data generated in the field was stored in a lap-top computer connected to Geode while surveying. The raw data collected in the field was analysed by a software called 'Seismic imager'. The processed data generated a V_p profile of rock strata up to a depth of 25 m from the surface. The P-wave velocity profiles of the each bench were initially analysed for the composite layers and smooth layering was done afterwards for generalisation of rock mass characterisation. The V_p profiles of Bench-I, which is comparatively soft formation is shown Figure 5. The P-wave velocities of individual layers varied from 240 m/s to 2200 m/s from top to bottom. The poor V_p at the top might be because of fractures generated due to the weathering of the rock mass. The V_p profiles of Bench-II is shown in Figure 6. The P-wave velocities varied from 500m/s to 2314 m/s and the poor V_p at the top might be because of fractures generated due to the production blasting in the past. The V_p profiles of Bench-III is shown in Figure 7. The P-wave velocities in smooth layered analysis were varying from 500 m/s to 2500 m/s from top to bottom and the here also the top layer gives poor V_p, which might be because of fractures due to previous blast rounds. The *in situ* and laboratory P-wave velocities of sandstone rock for all the test sites are given in Table 2.

The P-wave velocities indicate that there is 19-25% increase in laboratory Vp values in comparison to field V_p values at all the test sites. This indicates that the field V_p profiles are realistic measurements by the seismic profiling surveys as reported by Barton (2007).

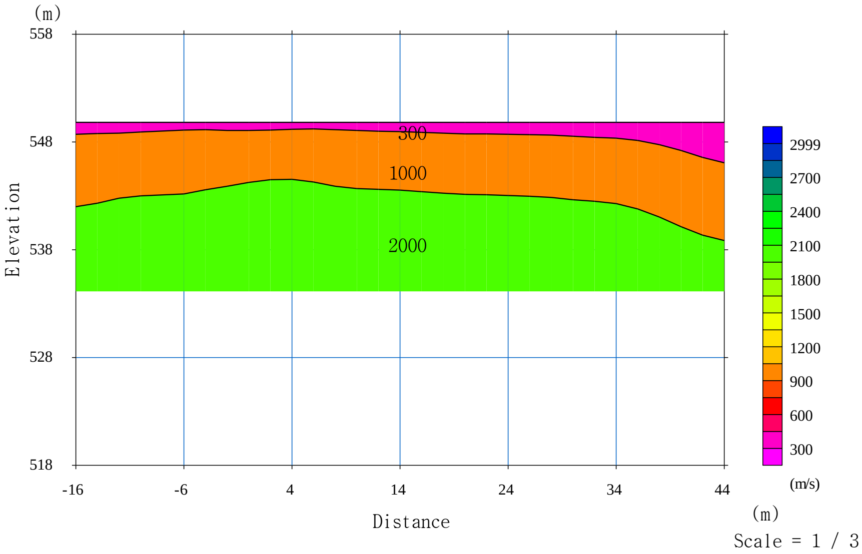

Figure 5 - Vp profile of major cluster of layers of sand stone strata at bench-I

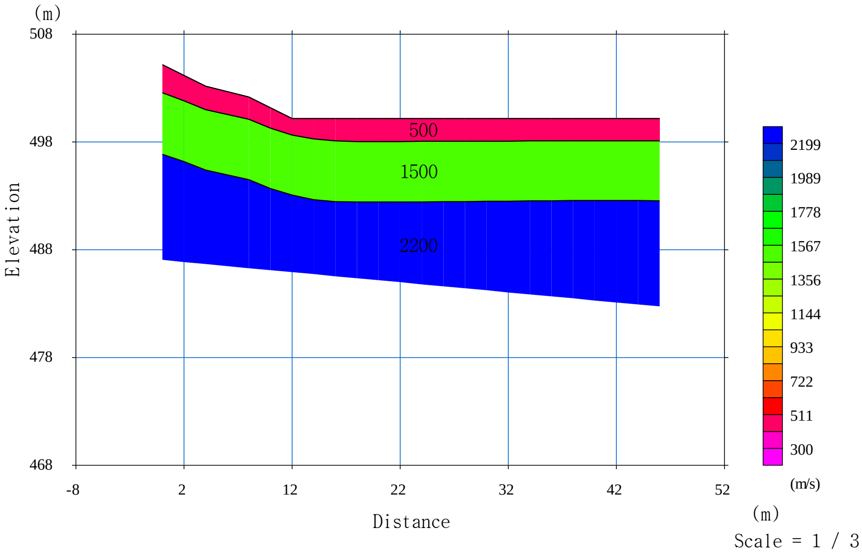

Figure 6 - Vp profile of major cluster of layers of sand stone strata at bench-II

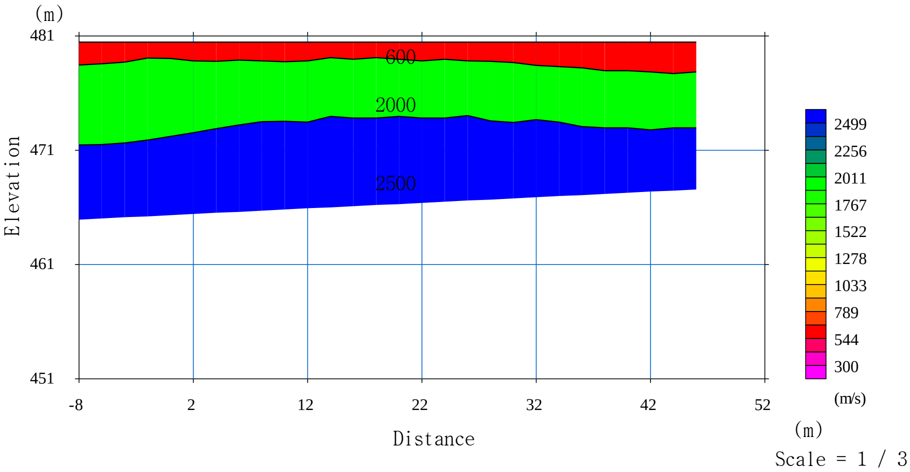

Figure 7 - V_p profile of major cluster of layers of sand stone strata at bench-III

Table 2 – *In situ* and laboratory P-wave velocities of sandstone rock

Site	Field P-wave velocity, m/s	Laboratory P-wave velocity, m/s
Bench-I	2000	2380
Bench-II	2200	2640
Bench-III	2500	3125

OPTIMISATION OF BLAST FRAGMENTATION BY IMPEDANCE MATCHING AT OC MINE

Blasting practice at OCP mine

The prevailing blasting practice at OCP mine is carried out with cartridge explosives of fixed velocity of detonation (VOD) for all the benches, irrespective of various rock properties. The blast results like fragmentation, throw and peak particle velocity of vibration were monitored using high resolution video camera and seismographs. Fragmentation size distribution analysis was carried out by image analysis software called Wipfrag. The blast design parameters and the blast results are given in Table 3 and Table 4 respectively.

Table 3 - Existing blast design parameter at OCP mine

Blast No.	1	2	3	4	5	6	7	8	9
Location	OB bench-I	OB bench-I	OB bench-I	OB bench-II	OB bench-II	OB bench-II	OB bench-III	OB bench-III	OB bench-III
Drilling pattern	Staggered	Staggered	Staggered	Staggerd	Staggerd	Staggere	Staggered	Staggered	Rectangular
No. of rows	4	4	4	4	4	4	4	4	2
Hole diameter, mm	150	150	150	150	150	150	150	150	150
Bench height, m	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	4.5
Hole depth, m	7	7	7	7	7	7	7	7	7
Burden, m	4	4	4	4	4	4	4	4	4
Spacing, m	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Stemming, m	3	3	3	3	3	3	3	3	3
Delay used, ms	25	25	25	25	25	25	25	25	25
Charge/hole, kg	50	50	50	50	50	50	50	50	50
VOD of explosive, m/s	3000	3000	3000	3000	3000	3000	3000	3000	3000
Density of explosive, kg/m^3	1100	1100	1100	1100	1100	1100	1100	1100	1100
Specific charge, kg/m^3	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Table 4 - Blast results with existing impedance values

Blast No.	Location	Throw, m	Back break, m	Mean Fragment size, m	PPV at 55m distance, mm/s
1	Bench-I	10	1.0	0.46	15.8
2	Bench-I	8	2.0	0.38	17.2
3	Bench-I	9	1.0	0.52	16.6
4	Bench-II	8	3.0	0.41	17.2
5	Bench-II	10	3.0	0.36	15.9
6	Bench-II	9	2.0	0.42	16.3
7	Bench-III	8	2.5	0.45	15.5
8	Bench-III	10	1.0	0.53	17.3
9	Bench-III	10	2.0	0.51	16.0

Blast optimisation by impedance matching of shock energy

The best matching for optimum shock wave transmission to the rock occurs when the detonation impedance of the explosive is equal to the impedance of the rock material. According to the theory of impedance matching, the explosive impedance should be as nearer to the rock impedance as possible to couple the explosive induced stress waves through the rock mass. The impedance matching expression is given below (Persson, *et al.,*1994).

$$\rho_e C_d = Zr\ \rho_r C_p$$

Where:

ρ_e = explosive density;
C_d = VOD of explosive;
ρ_r = rock density;
C_p= P-wave velocity; and
Z_r = impedance ratio.

It is very clear from the rock mass properties of the sandstone that the compressional wave velocity is varying from 2000-2500 m/s from Bench-I to Bench-III, however there is no change in the explosive properties, especially VOD. Substituting the values of rock and explosive parameters given in Tables 3 and Table 4, in the Equation (1), the impedance ratio (Z_r) values were calculated as 0.65, 0.58 and 0.49 for Bench-I, Bench-II and Bench-III, respectively. These Z_r values are considered as poor from the impedance matching point of view (Persson, *et al.,* 1994). This indicates that the explosive which was used for blast fragmentation is relatively suitable for Bench-I, but not for Bench-II and Bench-III.

Based on the impedance values of various rock masses at all the three benches, the best possible explosive impedance was calculated and shown in Table 5. As there was some technical limitations on the increase of density of explosive beyond 1100 kg/m^3, only VOD values were adjusted as 3400 m/s, 3700 m/s and 4100 m/s for Bench-I, Bench-II and Bench-III, respectively. This combination of explosives resulted in the Z_r value of above 0.7 for all the benches. The modified VOD values were applied in all the three test sites and the blast results with modified explosive parameters i.e. impedance matching are given in Table 5.

Table 5 - Blast results with modified VOD values

Blast No.	Location	Throw, m	Back break, m	Mean Fragment size, m	PPV at 55m distance, mm/s
1	Bench-I	6	0.50	0.39	11.3
2	Bench-I	7	1.00	0.31	12.4
3	Bench-I	9	1.00	0.41	14.3
4	Bench-II	9	0.75	0.30	12.5
5	Bench-II	6	1.25	0.32	12.2
6	Bench-II	9	1.00	0.31	14.5
7	Bench-III	9	0.50	0.28	11.5
8	Bench-III	7	0.75	0.31	9.6
9	Bench-III	6	0.50	0.27	10.7

The improvements in blast performance due to impedance matching are given in Table 6. The results clearly indicate that the selection of proper explosives with impedance matching to the rock impedance result in improving the blast fragmentation, reducing the throw and reducing blast vibrations. The overall throw in the modified blast rounds was reduced by about 25%. The back break was reduced by about 50% at Bench-I and upto 75% at both Bench-II and Bench-III. The mean fragment size of blast fragmentation was reduced by 15-21% at Bench-I, 11-26% at Bench-II and it was 37-47% reduction at Bench-III. Earlier works on the relation between VOD and damage by Singh and Xavier (2005) also indicate that the high VOD explosives produce less damage for the reason that generally the high VOD explosives yield higher shock energy and less gas energy.

Blast optimisation by considering heave energy

As the rock mass to be blasted is sandstone which is not so hard, a low brisance explosive such as ANFO was proposed for blasting. Considering the density of ANFO as 800 kg/m^3 and VOD as 4100 m/s, the impedance ratio (Z_r) values were calculated as 0.66, 0.6 and 0.52 for Bench-I, Bench-II and Bench-III, respectively. These Z_r values are considered as poor from the point of view of shock energy impedance matching. In spite of the poor Zr values, ANFO was proposed to be used for sandstone benches and the blast performance was monitored. The representative blast fragmentation images captured for both the explosives are shown in Figure 8. The fragmentation analysis was done by the digital image analysis technique by using Wipfrag software. The sieve analysis of the fragmentation was performed to both ANFO and emulsion explosives. The mean fragment size, which is the representative size of the average fragmentation size was 0.23 m with Emulsion explosive and 0.16 with ANFO explosive, which is about 30% improvement. Use of ANFO explosive also reduced the vibration intensity by 15-20% in comparison to the vibration induced by Emulsion explosive. The comparative results are shown in Figures 9 and 10. From the sieve analysis results it is very clear that the ANFO with poor impedance matching resulted in better fragmentation than the emulsion explosives with very good impedance matching. This indicates that the heave energy component of an explosive plays a vital role in fragmentation than the shock energy for the rock formations like sand stone. This might be because of the reason that a meager amount of shock energy is sufficient for forming crack network in soft to medium hard rocks. But there should be enough heave energy to extend the cracks for fragmentation.

Table 6 - Improvements in blast performance due to impedance matching

Blast No.	Location	Percentage reduction in throw, m	Percentage reduction in back break, m	Percentage reduction in Mean Fragment size, m	Percentage reduction in PPV at 55m distance, mm/s
1	Bench-I	40	50	15.22	28.48
2	Bench-I	12.5	50	18.42	27.91
3	Bench-I	0	0	21.15	13.86
4	Bench-II	-12.5	75	26.83	27.33
5	Bench-II	40	58	11.11	23.27
6	Bench-II	0	50	26.19	11.04
7	Bench-III	-12.5	80	37.78	25.81
8	Bench-III	30	25	41.51	44.51
9	Bench-III	40	75	47.06	33.13

(a) Fragmentation with Emulsion **(b) Fragmentation with ANFO**

Figure 8 - Representative images of blast fragmentation with Emulsion and ANFO explosive

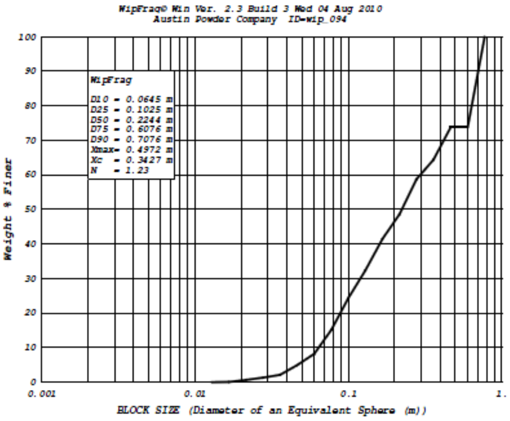

Figure 9 - Fragment size distribution of muckpiles of test blasts with Emulsion explosive

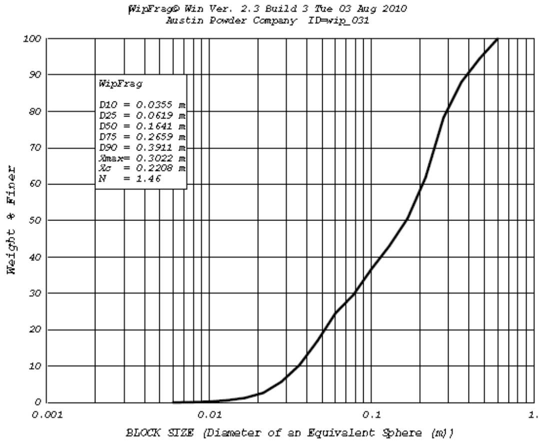

Figure 10 - Fragment size distribution of muckpiles of test blasts with ANFO explosive

CONCLUSIONS

The improvements in blast performance due to impedance matching were substantial in terms of blast fragmentation and vibration as well as damage control. The overall throw in the modified blast rounds was reduced by about 25%. The back break was reduced by about 50% at Bench-I and upto 75% at both Bench-II and Bench-III. The mean fragment size of blast fragmentation was reduced by 15-21% and Bench-I, 11-26% at Bench-II and it was 37-47% at Bench-III. The vibration intensity was also reduced by 14 to 45% with increase of impedance matching of explosives. The blast results shown in this study, clearly indicate that the selection of proper explosives with impedance matching to the rock impedance result in improving the blast fragmentation, reducing the throw and reducing of blast vibrations. The study also reveals that the heave energy factor plays a mare vital role than the impedance matching of the shock energy for fragmentation of rock formation like sandstone. Test blasts with ANFO explosive with mismatched impedance properties resulted in 30% improvement of fragmentation and reduced the vibration intensity by 15 to 20% in comparison to the Emulsion explosive. Therefore, impedance matching as well as heave energy utilisation should be given adequate importance while selecting of explosives for improving blasting productivity and safety.

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