Influence of density of emulsion explosives on its velocity of detonation and fragmentation of blasted muckpile

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Opencast mining accounts for about 86% of the produced coal in India. Most of the opencast mines in the country use bulk emulsion explosives. The total consumption of explosives in India is around 550,000 tonnes annually. It has been shown that detonation velocities vary with the density of the emulsion explosive. Here we describe experiments that have been conducted to understand the influence of velocity of detonation of emulsion explosives on fragmentation of blasted muckpile over a range of densities. The density of explosives was varied from 0.6 to 1.1 g/cc which resulted in the variation of detonation velocity from 3262 to 4624 m/s.

Keywords: Blasted muckpile, detonation velocity, emulsion explosives density, opencast mines.

THE primary objective of blasting in a mine is to properly fragment the rock mass so that the muckpile can be efficiently and economically excavated, loaded and transported with minimum damage to the environment[1]. Many researchers have indicated the extensive use and advantages of emulsion explosives for better and cost-effective fragmentation of rocks in mining activities. Although the continual process of development and trials of emulsion explosives started several decades ago, emulsions attract the attention of researchers even now and are considered the most modern and widely used explosives[2–9]. One of the main features, apart from low sensitivity to mechanical stimulus which makes it so popular, is the ability to vary density over a wide range resulting in different detonation velocities. Variation in density of the emulsion explosive causes an equivalent change in energy density, that is energy per unit volume[10–12].

At present, there are several low-density products available in the global market. They are sought after for improving production and cost economics. More emphasis has been given on their development due to the extensive scope of application. With increasing environmental concerns and difficulties in blasting at certain areas, such as places near habitation, emulsions with some variation in their properties are considered as a highly potential and viable option for specific and specialized blast operations. It is a common prenotion that it is difficult for low-density explosives to break rocks effectively, but with continuous emphasis being given to environmental and social commitments, a shift in trend is observed from current use of site mixed bulk emulsion products to low-density emulsion explosives in medium to hard grounds. Heltzen and Kure[13] showed that low-density explosives with minimum sequestration could be a good alternative for applications like contour blasting. This may in turn not only provide better specialization and blast performance, but also provide economic benefits to the mining industry with extra safety. Krzelowski and Szulik[6] showed that emulsion explosives may be used as low-density explosives with some ingredients having low density, like bagasse (sugar cane waste), sawdust, polystyrene beads and perlite, etc. The low density formulated with the help of expanded polystyrene beads and perlite has an advantage that it does not require any chemical gassing, as the air voids available inside the polystyrene beads and perlite act as hot spots for steady-state velocity of detonation (VOD) in explosive column.

Du Pont[14] referred to a Du Pont product named 'Nilite ND' (ND means 'no-deck') whose density can be varied in the range of 0.45 to 0.55 g/cc. This product was successful in vertical holes. Another variation to this product was developed later and was an ANFO and polystyrene mixture. Wilson and Moxon[15] diluted ANFO with various low-density bulking agents, including polystyrene, bagasse (sugarcane waste) and sawdust, and observed the ease in mixing to form homogenous blends. They achieved controlled detonation pressure with an aim to develop a low-shock energy ammonium nitrate-based product to easily fragment weak overburden materials. Hunter *et al.*[16] conducted a study over a density range 0.36–0.45 g/cm^3 with a view of minimizing ore dilution and wall damage. They concluded that a low-density product could be loaded consistently, which showed reliable performance and resulted in lower levels of blast-induced damage and vibration. Jackson[17], and Grouhel and Hunsaker[18] obtained an emulsion-based LDE combining chemical gassing agents, glass micro balloons and polystyrene beads. They performed field trials and found that a significant reduction (about 30%) in the powder factor did not significantly affect the fragmentation, as it produced similar results in terms of fragmentation, breakage, better wall stability and reduced fines even with different VODs. Rock *et al.*[19] also observed that 'low-density explosives can lead to significant cost savings without compromising fragmentation or production'. Lownds[20] and Rock[21] performed field trials and obtained good field results using lower density products having lower detonation velocities in some areas where ANFO was used to blast.

Rock fragmentation by explosives in mines and quarries aspires produces *in situ* rocks of the desired size and separates them from the earth's crust using the least energy

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Table 1. Emulsion matrix composition

Oxidizer fraction	Composition (%)	Weight (kg)	Fuel fraction	Composition (%)	Weight (kg)
Ammonium nitrate	84.03	351.66	Sorbitan Monooleate	38.46	12.1
Water	15.97	66.84	Process oil	61.54	19.4
Total	100.00	418.5	Total	100.00	31.5

Table 2. Summary of trial blasts with LDEX

Quantity of emulsion matrix used	450 kg
Blast hole diameter	150 mm
Variation of expanded polystyrene bead and perlite concentration (50 : 50)	1.5–1.9%
Oxidizer to fuel ratio	93 : 7
Length of blast hole	5–7 m
Stemming	1.5–3.0 m
Initiation system	Nonelectric shock tube

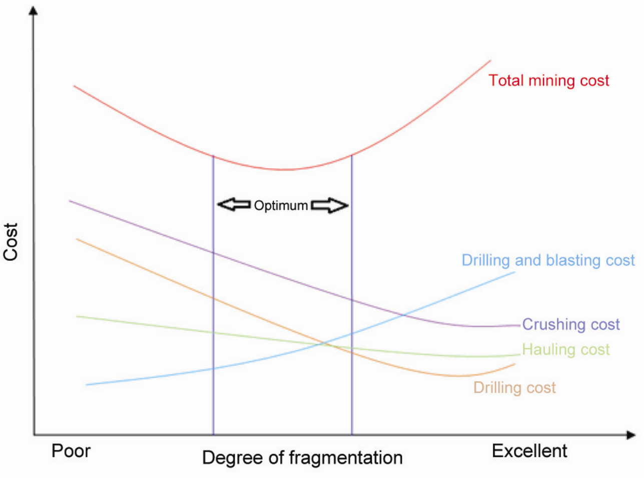

Figure 1. Blast fragment optimization.

or expenditure possible. The efficiency of any mining operation depends on the fragmentation of the muckpile produced. Rock fragmentation has been the subject of many studies as it is the most important aspect of production blasting, since it affects the cost of drilling and blasting, and the efficiency of all the subsystems such as loading, hauling and crushing in mining operations[22–25]. Prediction of rock fragmentation size is the first step towards optimization of blast design parameters to produce the required fragment size[26]. The explosives significantly upgrade the efficiency during the extraction stages of the mining cycle[27].

Fragmentation is generally used as a comparative word, e.g. like ‘good fragmentation’ or ‘poor fragmentation’. Good fragmentation can be defined as the desired size of fragmented rock compatible with the loading machine bucket size, dumper and opening of the primary crusher. Optimum or good fragmentation not only improves the loading rate, but also reduces overall maintenance costs and those associated with other operations such as hauling, crushing, grinding, etc. Rock fragmentation is an important phase in the blasting process, which directly affects the economics of the mining operation (Figure 1)[28]. Fragmentation is the liberation and breakage of *in situ* blocks that make up the mass[29,30]. Fragmentation basically depends on the natural geological discontinuities and their spacing, frequency, true burden and spacing of free faces, and the location of explosive energy at strategic points in the rock mass with precisely matched release of energy for proper interaction of blasted mass and energy. In open-pit mining where a mineral or several minerals are being extracted from a matrix formation, it is usually desirable to achieve good fragmentation. Fragment size in a blast depends on two principles, namely proper explosive energy input at strategic locations within the rock mass and its proper time of release for optimum interaction[31].

To obtain a low-density explosive (LDEX) product, emulsion matrix was prepared from the site mixed emulsion explosive system at the mine site. Table 1 shows the emulsion matrix and the composition (by weight). LDEX was made with the inclusion of expanded polystyrene beads and expanded perlite combination with equal percentage by weight in the ratio 50 : 50. The average density of expanded polystyrene bead and perlite was 24–30 and 48 kg/m^3 respectively.

Trial blasts were conducted at the site using emulsion explosive whose density varied from 0.6 to 1.1 g/cc. The density was varied by mixing different combinations of expanded polystyrene beads and perlite with the emulsion matrix. Figure 2 shows the cup densities measured at the site. Table 2 presents a summary of the obtained LDEX used for conducting trials at the site. Figure 3 shows manual charging of the obtained LDEX into the blast holes.

Experimentation of the prepared LDEX with different densities was carried out in the field. Table 2 also describes the blast parameters used during trials.

D'Autriche method having cartridge diameter of 125 mm and individual length of 50 cm was used to measure unconfined VOD of LDEX at different densities. Similarly, VODMate^{TM} was also used to record the in-hole continuous VOD measurements (Figure 4). The readings on unconfined VOD and in-hole VOD measurements were recorded. Univariate regression analysis (UVRA) of the recorded measurements at different densities shows the effect of density variation on VOD (Figures 5 and 6).

Figure 2. Density measurement of low-density explosive (LDEX) on site.

Figure 3. Charging of LDEX into blast holes.

Table 3 shows the performance indices of UVRA for both unconfined and confined VOD with respect to density of LDEX. With an increase in density, the number of polystyrene beads and perlite reduces per unit cross-sectional area of explosives column, and fuel and oxidizer droplets at the detonation front increases significantly indicating a high VOD of emulsion explosives with variation of density in the range 0.6–1.1 g/cm^3.

Properties of rock mass, degree of fragmentation and desired displacement are the parameters that govern the selection of suitable explosives. The most important properties of explosives are density, velocity of detonation and critical diameter. Among these, VOD influences

Table 3. Performance indices of UVRA for VOD

VOD	R^2 (adjusted)	RMSE	Standard error of the estimate
Unconfined	0.99	33.86	33.89
Confined	0.99	49.21	49.22

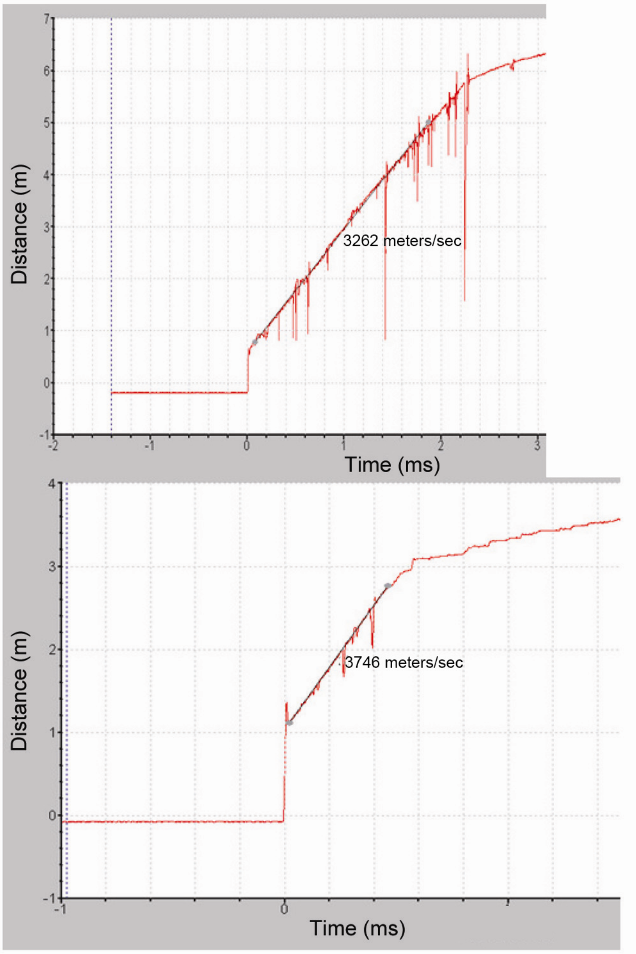

Figure 4. In-hole velocity of detonation (VOD) analysis of LDEX by VODMateTM.

fragmentation and varies with composition of the explosive. The dependence of detonation velocity on the density of the explosive is non-monotonic as the reaction width varies with variation in the density of the emulsion explosive[2,9]. An LDEX is preferable in soft or medium hard rock or highly jointed rock structures, as it permits a controllable energy for rock fragmentation. The low VOD provides sufficient shattering action needed for the required fragmentation[7,32]. Detonation impedance measures the relative ability of different explosives to transmit their pressure to stress waves in a given rock and is a product of density and VOD of the explosives. Hence, explosives with high VOD are more favourable in hard rocks, whereas in softer materials explosives with lower VOD give better results. Generally, lower VOD explosives tend to release a larger proportion of the explosive energy as heave or gas pressure over a longer period of time, than explosives with higher VOD. As a result, an explosive with a low detonation velocity will form a heave structure after blasting[33].

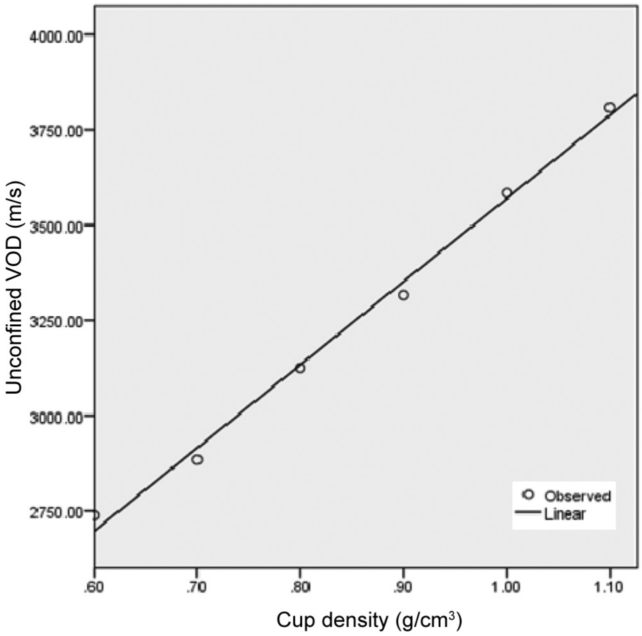

Figure 5. VOD variation with density of LDEX in unconfined condition.

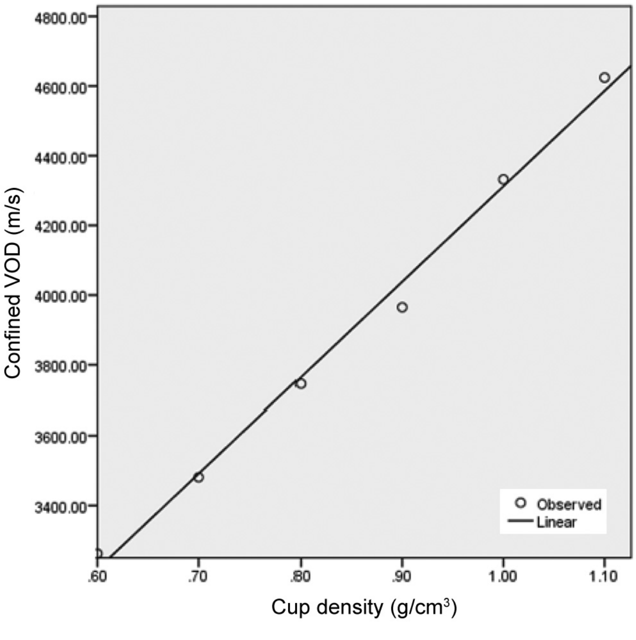

Figure 6. In-hole VOD variation with density of LDEX in rock confined space.

In blasting of highly jointed rocks requiring few new cracks, the most desirable fragmentation is achieved when explosion gases jet into and wedge open the structural discontinuities already present in the rock mass. For this type of application and structure, low-density and correspondingly low-detonation velocity explosives such as ANFO are more efficient than high strain energy explosives, as the extension of radial cracks is terminated at the joints.

Detonation velocity is one of the important performance characteristics of explosives determining their functioning and performance. It generally varies between 2000 and 7500 m/s for most commercial high explosives when confined, but when tested under unconfined conditions the value would only be approximately 75% of the confined value[33]. Liedig *et al.*[34] found that the highest ground vibration induced by blasting was as a result of high VOD. More than 50% of VOD generated in a blast is wasted in generating fragmentation of the rock in the crushed zone. For an explosive to effectively fragment rock mass its detonation velocity must exceed the seismic

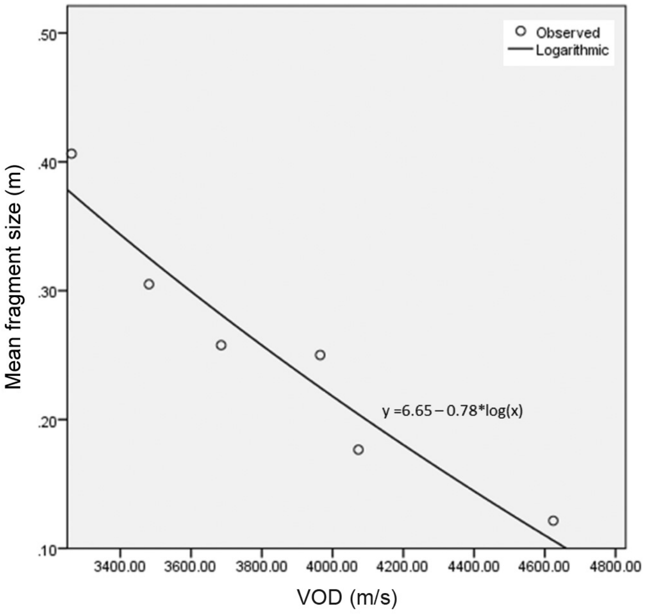

Figure 7. Influence of VOD on mean fragment size (k_{50}).

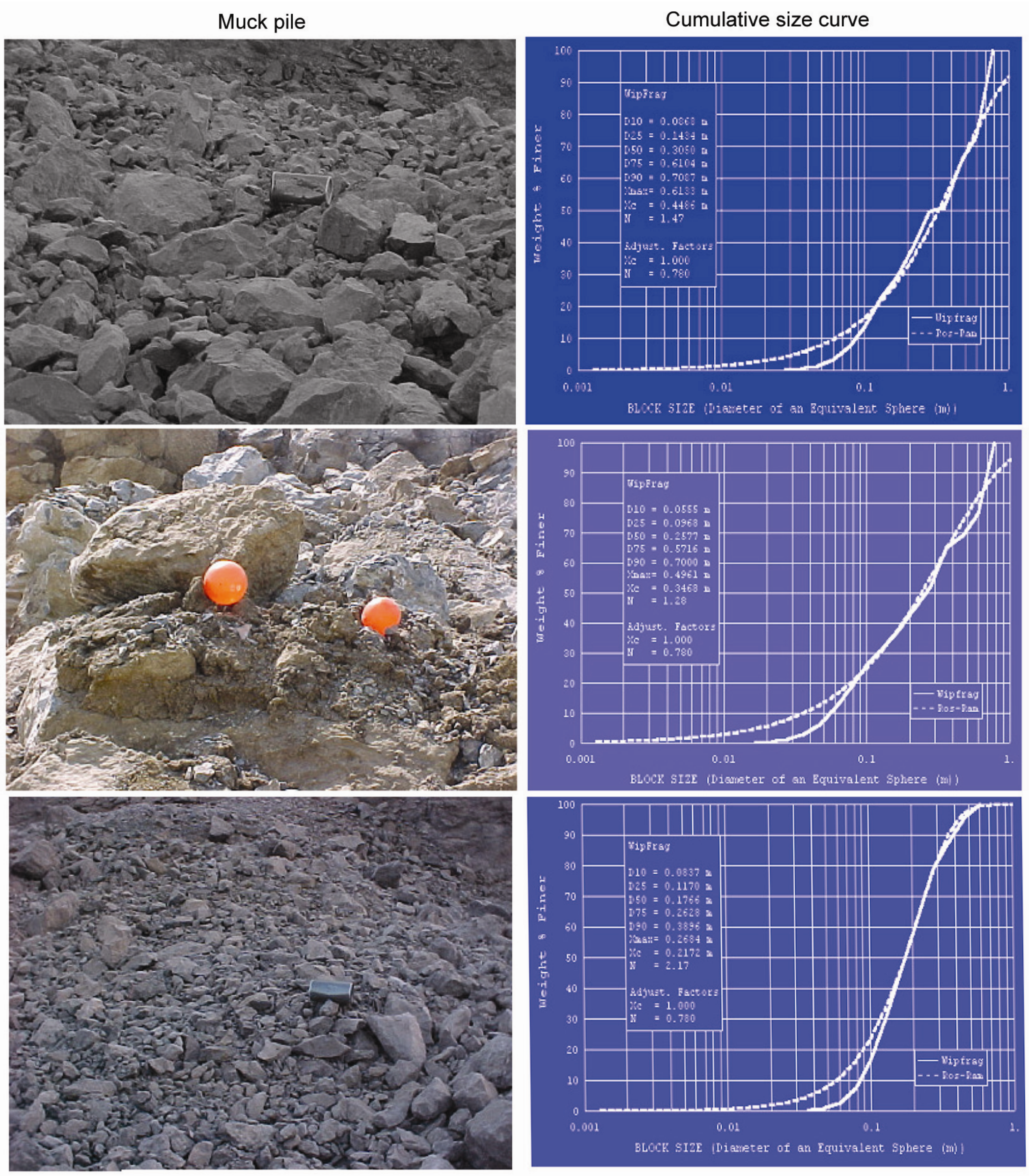

Figure 8. Digital photographs of blast fragmentation using WipFrag software.

Table 4. VOD measurement and blast fragmentation analysis

VOD (m/s)	Fragment size k_{50} (m)	Maximum fragment size (m)
3481	0.3050	0.774
3685	0.2577	0.774
3262	0.4063	1.292
3965	0.2501	0.599
4624	0.1215	0.278
4073	0.1766	0.599

velocity of the rock being blasted, whereby the explosive shock waves create adequate tensile stresses responsible for the fragmentation[35].

In order to study the impact of VOD of emulsion explosives on fragmentation of blasted material, a series of experimental blasts was conducted at Block-II Opencast Project (OCP) of M/s Bharat Coking Coal Limited (BCCL), a subsidiary of Coal India Limited (CIL). The blasts monitored at Block-II OCP have been named B1–B6. Table 4 represents a summary of VOD measurements and blast fragmentation analysis. All the trial blasts were conducted for understanding and studying the influence of VOD on fragmentation keeping in mind that all the geological parameters are maintained almost the same. Figure 7 shows the univariate analysis of fragmentation of rock mass obtained by blasting with different

Table 5. Performance indices of UVRA fragmentation

Fragmentation	R^2 (adjusted)	RMSE	Standard error of the estimate
Fragmentation k_{50}	0.912	0.031	0.030

detonating velocities. Table 5 presents the performance indices of the analysis.

In order to assess the fragment size, a series of photographs was taken using a digital camera with proper scaling. Scaled photographs were taken from a location normal to the slope of the muckpile. VOD of the explosives was varied by varying the polystyrene and perlite dopants in the emulsion explosives. The blast fragmentation was studied from the digital photographs with the help of the software WipFrag (Figure 8)[36].

It has been observed that even at a low density (0.6 g/cm^3) of emulsion explosives, the detonating velocity of 3262 m/s in rock under confined conditions could obtain sufficient fragmentation of the rock mass with a mean fragment size (k_{50}) of 0.41 m. LDEX formulated with the help of polystyrene beads and perlite did not require any chemical gassing due to availability of air voids inside the polystyrene beads acting as hot spots. With the reduction in VOD from 4624 to 3262 m/s, the fragment size (k_{50}) was observed in the range 0.12–0.41 m, giving a logarithmic trend. This might have occurred since with a higher rate of release of energy, more shattering energy would have been imparted to the rock mass. Lower density of explosives reduces the energy content per unit volume and so the total energy will also be reduced.

On the basis of the conducted experiments it may be concluded that with the significant reduction in the density of emulsion explosives (up to 45%), detonation velocity also reduces up to 28% both in unconfined and confined situation; fragmentation confirmed a reduction in the shattering effect. Mean fragment size (k_{50}) analysis with velocity of detonation for the coal measure rock strata, indicates that the mean fragment size exhibits a logarithmic trend with good correlation to VOD of low-density emulsion explosives within the experimental data range. On the basis of the obtained results it can be concluded that low-density emulsion explosives with a detonation velocity capable of fragmenting rocks can be used in areas where explosives of higher detonation velocities are not allowed or restricted. LDEX coupled with low VOD confirm that the blast-induced ground vibration level will also be reduced significantly, as it is a function of maximum instantaneous charge which will be reduced with reduction in density.

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Record of post-collisional A-type magmatism in the Alwar complex, northern Aravalli orogen, NW India

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The Alwar complex is situated in the northern part of the Aravalli orogen, NW India and contains A-type granites of late Palaeoproterozoic age. The current study focusses on the Harsora and Dadikar plutons to characterize and constrain the tectonic setting of Palaeoproterozoic felsic A-type magmatism in this crustal segment using whole-rock geochemical data. The rocks studied are metaluminous to slightly peraluminous A-type ferroan granites. The granites are generally characterized by strongly fractionated LREE patterns with nearly flat HREE profiles and show moderate to strong negative Eu anomalies, in addition to prominent negative anomalies in Ba, Nb, Sr, P and Ti. The results show the post-collisional setting of A-type granites in the northern Aravalli orogen and signify that A-type granites may not only form in anorogenic setting. This study provides a new dimension to the understanding of palaeoproterozoic geodynamic evolution in the Aravalli orogen.

Keywords: A-type granites, post-collision, Aravalli orogen, Alwar complex, whole-rock geochemistry.

GRANITOIDS form one of the most common components of the continental crust[1,2], especially in Precambrian terrains. Knowledge of nature and genesis of granitoids is, therefore, crucial for understanding the evolution of any crustal block. Based on chemistry and petrography, granitoids are usually classified into I-S-M and A-types[3–5]. The term A-type granite was introduced by Loiselle and Wones[4] for a specific suite of granitoids, which are anhydrous, alkaline and anorogenic[6,7]. A-type granites occur in a number of regionally extension-related environments, such as continental rift zones, post-collisional setting, and even in subduction-related settings[4,7–11]. Therefore, they provide significant information on the extensional magmatic processes that contribute to the chemical evolution of upper continental crust[10,12].

In the northern Aravalli orogen, a number of A-type intrusions occur in two igneous-metamorphic complexes, designated as the Alwar complex[13–15] and the Khetri complex[16–20], also known as the Alwar basin or the Khetri basin. These rocks are late Palaeoproterozoic spanning an age range of 1.72–1.70 Ga (refs 14, 18, 19, 21). However,

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