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ORIGINAL PAPER

Influence of Gassing Agent and Density on Detonation Velocity of Bulk Emulsion Explosives

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Abstract The demand for coal from surface mining projects are on the higher side like never before for which blasting is the basic unit operation. The explosive plays an important role in blasting and also influence the explosive-rock interaction. The most common explosive type used in surface mines is emulsion explosives. This paper presents the study on the detonation velocity of bulk emulsion explosives due to variation in gassing agent and density. In this study Sodium Nitrite ($NaNO_2$) has been used as the gas generating additive and the performance of emulsion explosives with different concentrations of gassing agents at different temperatures has been observed. This study was undertaken to also understand the cyclic variation of temperature on gassing kinetics and performance of explosive. The effect of cooling on detonic-behaviour of bulk emulsion explosives has also been studied and presented in this paper.

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1 Introduction

Emulsion explosives (EMX) were developed more than 40 years ago (Egly and Neckar 1964) and their detonation behavior and performance under various conditions has been studied extensively by different researchers (Hattori et al. 1982; Cooper and Leiper 1989; Lee et al. 1989; Lee and Persson 1990; Chaudhri et al. 1993; Holcomb 1997; Hirosaki et al. 2002; Sosnin and Kolganov 2003; Sil'vestrov 2006; Yunoshev et al. 2012). Bulk products initially became very popular in large open-pit mining operations and this further accelerated with the advent of bulk emulsion products and their blends with ANFO. The commercial use of bulk delivered explosives, including ANFO and other composite explosives, has been increasing while the use of packaged explosives is falling on a percentage basis (Kent 2012). Modern commercial explosives range from pure ANFO to pure emulsions and also include various blends of these. Emulsion explosives became so popular because their

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Table 1 Composition of emulsion explosives used in experiment

Oxidizer fraction	Composition (%)	Kg	Fuel fraction	Composition (%)	Kg
AN	78.53	19.64	LSHS	0.88	0.22
Water	14.95	3.74	Process oil	4.00	1.00
			SMO	1.64	0.41

performance is dependent on detonic-behavior and possess advantages which include high detonation velocity, low toxicity of explosion products, high water resistance, the low value of critical diameter, and the possibility of mechanical loading. A suitable explosive not only produces desired blasting result but also takes care of the associated geo technical environment (Esen 2008). Emulsions being one such explosive has shown excellent result and is also considered cost effective.

EMX is prepared or obtained by adding sensitizer to an emulsion matrix in a fixed composition. An emulsion matrix contains substantial amounts of oxidizer dissolved in water as droplets surrounded by an immiscible fuel (Bhandari 1997), and is not capable of detonation by its own. To achieve explosive nature and to show detonic behavior it requires sensitizer in fixed amount (Medvedev et al. 2008). Due to the non-explosive behavior of emulsion matrix and low sensitivity to a mechanical stimulus which allows mechanical loading, emulsion explosives are still the most modern mining explosives (Maranda et al. 2014). One of the prime and significant parameter to judge an explosives performance is the velocity with which it detonates in the explosive column. The velocity of detonation (VOD) of any explosives is the supersonic speed with which the reaction mixture self-propagates in the explosive column (Carcedo et al. 1995), and hence it is of great significance. It is observed that there are many parameters which affect the velocity of detonation like confinement, formulation characteristics, density, sensitizing agents, temperature and temperature cycling, primer size and type, sleep time in blast hole, borehole loading techniques, blast design, explosive column length, blast environment, storage-shelf life and mixing in bulk loading system (Tete et al. 2013). In order to formulate emulsion matrix and imparting explosives properties, a sensitizer is added which is generally $NaNO_2$. The chemical reaction between gassing agent (GA) and Ammonium Nitrate (NH_4NO_3) leads to the release of nitrogen gas (N_2) which gets entrapped in the matrix as air bubbles, creating porosity in the matrix, decreasing density and making the explosives oxygen balance. The gassing agent reacts with Ammonium Nitrate (NH_4NO_3) present in the emulsion matrix as per the following reaction.

$$NaNO_2 + NH_4NO_3 \rightarrow NaNO_3 + N_2(\uparrow) + 2H_2O.$$
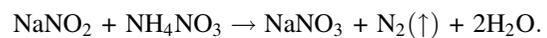
2 Emulsion Preparation

The weight percentage of the emulsion has been as follows: Ammonium Nitrate (AN) 78.53%, low sulphur heavy stock heavy petroleum fraction (LSHS) 0.88%, process oil 4.0%, Sorbitan Monooleate (SMO) 1.64%. The composition with quantity wise is shown in Table 1. A batch of emulsion was prepared in Patterson ribbon and blade mixer. While preparing the oxidizer fraction had a crystallization point of 72 °C and was maintained at 85 °C liquor temperature. The viscosity measured at 50 rpm with the number-1 spindle on the viscous meter was 20 cP (centipoise).

The batch prepared was divided into three samples, two of 10 kg each and one of 5 kg. The two batches of 10 kg were kept at 50 °C, using hot cell. For inserting GA into the matrix a syringe was used as shown in Fig. 1 and simultaneously stirred intensely using glass rod. After the addition of sensitizer, the mixture gradually acquired the properties of an EMX. The density of the formulated emulsion was monitored at different time lapse of 5, 10, 15, 20, 25 and 30 min. The variation of the density for different concentration of gassing agent at pre-determined temperature with the effect of time lapse is shown in Figs. 2, 3, and 4. The emulsion matrix was formulated with a different concentration of gassing additive ($NaNO_2$), at different predetermined temperatures. The samples were kept at a pre-determined temperature of 31, 47, and 70 °C respectively. After a time lapse of 30 min, the

Fig. 1 Injection of gassing agent to emulsion explosive

unconfined VOD was measured using D'Autriche method for different densities obtained due to varying concentration of gassing agent at a maintained prefixed temperature. On the evaluation of Figs. 2, 3, and 4 we find that the reaction between the density of emulsion explosive, after mixing of GA to emulsion matrix and time, has been found to be an upward parabolic curve with an optimum value between 20 and 25 min.

3 Dependence of Detonation Velocity on Gassing Additive

The VOD of emulsion explosive matrix was tested at different temperatures 31, 47 and 70 °C as it was allowed to cool, while the quantity of GA added was
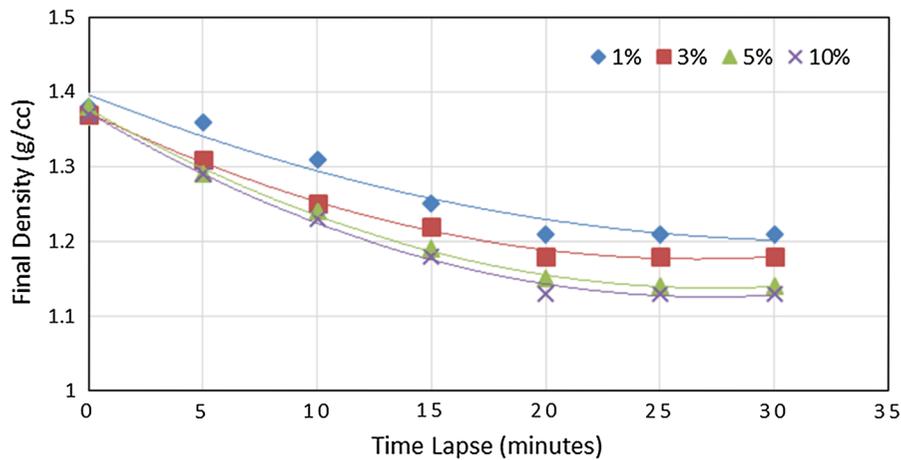
Fig. 2 Density variation of emulsion explosive with time lapse at 31 °C
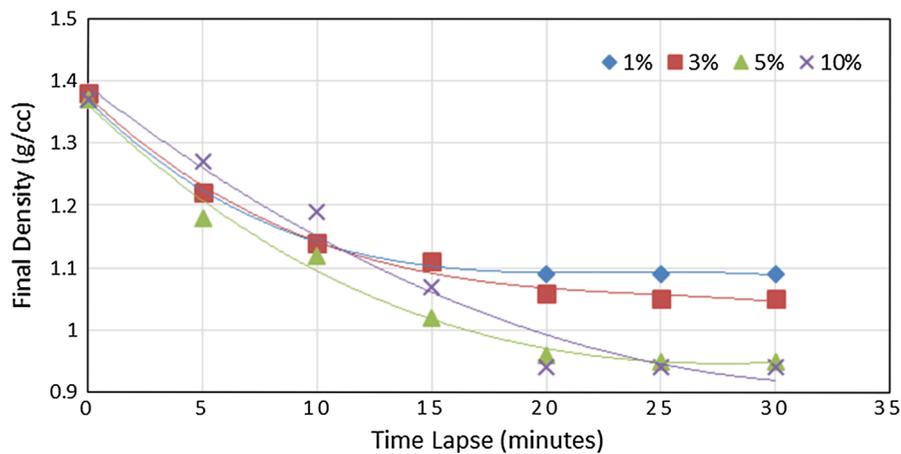
Fig. 3 Density variation of emulsion explosive with time lapse at 47 °C
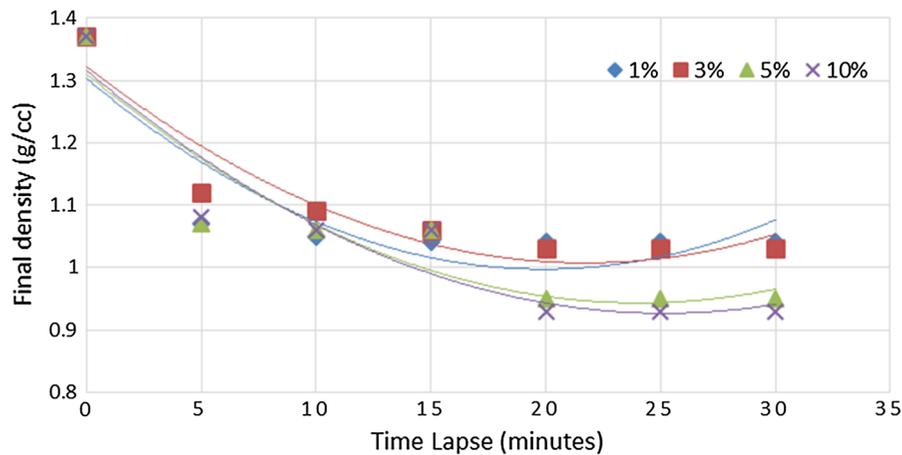
Fig. 4 Density variation of emulsion explosive with time lapse at 70 °C

kept same (Figs. 2, 3, and 4). The temperature of emulsion explosive matrix was measured by laboratory thermometer. Figure 5 shows the dependence of VOD on gassing agent concentration at a different temperature. These temperatures were selected as the usual temperature of manufacturing of emulsion matrix in India is 70 °C, while average summer temperature is around 47 °C and temperature after cooling of the matrix has been considered to be at 31 °C.

It has been observed that the completion of the reaction between emulsion matrix and gassing agent took place within 25–30 min which was evident by no further change in the density of the matrix. Hence, we
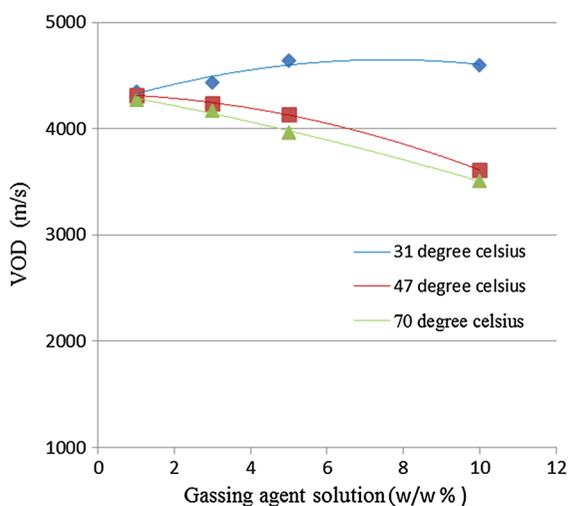
Fig. 5 Graph showing trend of VOD with different gassing agent percentage

may conclude that the optimum time required for gassing may be considered as 30 min. Therefore, we took the density of explosive being tested for VOD measurement as the density obtained after 30 min of the injecting of the gassing agent and mixing of the same to the matrix. Form Fig. 3 it is evident that at 31 °C the lowest density which could be achieved was more than 1.1 g/cc, while at 47 °C after 13 min of mixing GA density achieved was lower than 1.1 g/cc (Fig. 3) and after 25 min it was 0.92 g/cc at 70 °C of temperature (Fig. 4). When the temperature of the premix was at 70 °C the density of emulsion matrix could be achieved below 1.1 g/cc after 7 min and the lowest value of density (0.94 g/cc) could be achieved after 25 min. The graph between percentage of gassing agent ($NaNO_2$) mixed with emulsion matrix and unconfined VOD of emulsion explosive at 31, 47 and 70 °C indicates that at room temperature peak value of unconfined VOD 4381 m/s could be obtained with 4–6% (w/w) solution of sodium nitrite ($NaNO_2$). With the increase in temperature of emulsion matrix, the unconfined VOD is reduced. Beyond 5% (w/w) addition of gassing agent $NaNO_2$ into the emulsion explosive matrix, no appreciable change in VOD of EMX was observed for all samples at 31, 47, and 70 °C.

4 Temperature Cycle Effect on Density of EMX

The experiments were conducted on three sets of cartridges to know the effect of heating and cooling
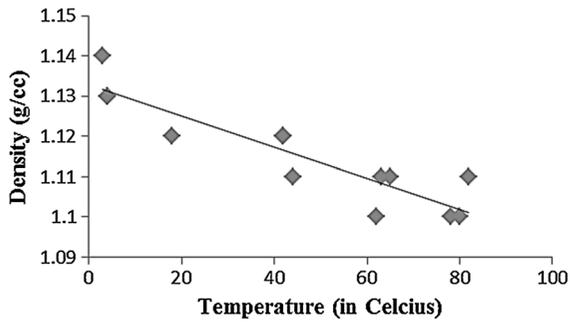
Fig. 6 Effect of temperature on density of emulsion

cycle due to storage of EMX on its performance. In each set sample cartridges were maintained at different temperatures. To increase the temperature of the explosive, sample cartridges were wrapped in a paper and heated in an oven at a constant temperature of 100 °C. To bring down the temperature of the explosive, the cartridges were cooled in a refrigerator. The temperatures of the samples were monitored regularly and the densities of the explosive were also measured. The VOD was determined at various measured densities to understand the detonic behaviour of EMX. The temperature of the sample cartridges was recorded just before firing. The graph has been plotted between temperature and observed densities of EMX which is presented in Fig. 6. From the graph, it is evident that at a higher temperature, the rate of reaction will be higher, and it would have resulted in higher rate of release of air bubbles. This

would have resulted in more number of air bubbles per unit volume, which ultimately reduced the density. At 3 °C, partial crystallisation on the surface of the cartridge was visible.

4.1 Effect of Density on VOD

As the density increased from 0.95 to 1.15 g/cc, the VOD increased almost linearly, while beyond 1.15 g/cc a drop in VOD of emulsion explosives was observed and at a density of 1.27 g/cc the detonation failed and misfire occurred. Figure 7 clearly depicts that density influences VOD of EMX and indicates that at higher density the number of air bubbles would have drastically reduced causing a reduction in hot spots which severely affected the sensitivity of emulsion explosives, and 1.27 g/cc can be considered as dead press density for the tested emulsion explosives. The reduction in detonation velocity at lower density might be due to float up and escape of air bubble from the EMX which was evident from the observation of low density emulsion product.

5 Conclusions

From the parametric study between time lapse after mixing of sensitizer and density of emulsion matrix with varying dose of gassing additive it is evident that there has been drastic change after 15 min of time
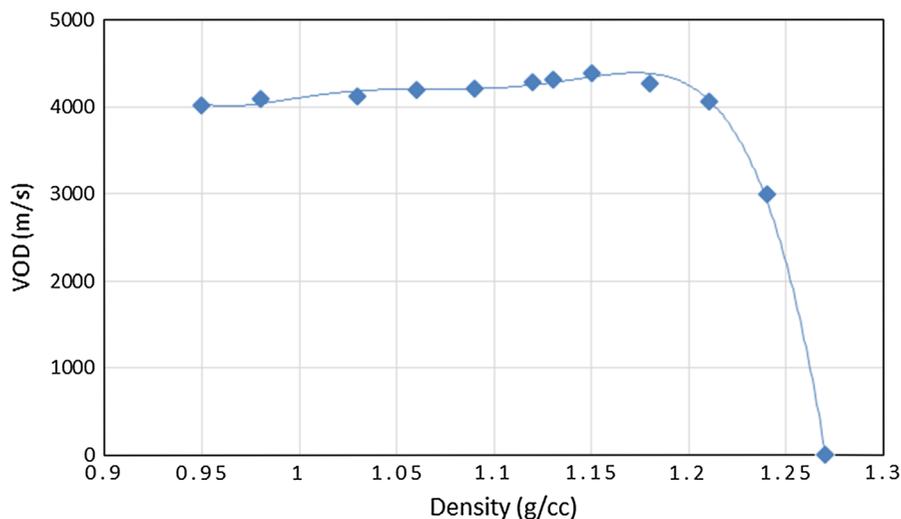
Fig. 7 VOD as a function of density

lapse at 47 and 70 °C respectively for 5 and 10% NaNO$_2$ solution. Therefore, for all practical purposes, the gassing agent doses may be maintained at 3% or less in the field.

It has been found that relation between density and detonation velocity of EMX exhibits a non-monotonic dependence. Detonation velocity of EMX increased linearly with increase in density from 0.95 to 1.15 g/cc, and beyond 1.15 g/cc, VOD reduced and misfire occurred at 1.27 g/cc. Lower densities have occurred due to a higher rate of reaction between gassing additive and emulsion matrix causing an excessive amount of air bubbles trapped in the matrix which should have reduced the number of fuel and oxidizer droplets participating in the reaction at CJ plane. Beyond 1.18 g/cc density of EMX, the numbers of air bubbles required for the detonation of EMX have been reduced causing a low level of hot spots resulting in reduced sensitivity and lower detonation velocity. The cartridges of EMX misfired at 1.27 g/cc.

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