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ORIGINAL PAPER

Effect of aluminum content on detonation velocity and density of emulsion explosives

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Abstract
The performance of nonideal explosives, such as emulsion explosives, can be altered by metal powders like aluminum (Al) while keeping their other components the same. The high demand of emulsions coupled with various specific requirements, recommends a study on the performance of explosives. A research study on the detonation velocity of emulsion explosives variation with varying Al content in the emulsion matrix was carried out. The Al content in the emulsion matrix was varied from 0 to 20% and the corresponding density and detonation velocity (confined and unconfined) were measured. The misfire of emulsion explosives occurred at 20% Al content both in confined and unconfined conditions. The paper also focuses on the emulsion's density dependence on different Al content. The variation of density observed was in the range from 1.16 to 1.42 g/cc. The results obtained can be used by blasting engineers to design higher explosives.

Keywords Detonation velocity · Emulsion explosives · Aluminum content · Explosives performance

Introduction

Ammonium nitrate (NH_4NO_3) (AN) based explosives have been widely used as industrial explosives to form energetic compositions such as ANFO (ammonium nitrate/fuel oil) or emulsion explosives. Emulsion explosives provide low cost operation and, because of nonideal behavior, emulsions show significant effect on detonation performance owing to various parameters. Aluminum (Al) powders are used in industrial/military grade high explosives to increase reaction temperature, blast and incendiary effects. It is established that addition of powder metals to explosives is a widely used method for improving their detonating efficiency. Addition of Al enhances the energy content of the emulsion explosives, which is observed in an increase of detonation velocity (VOD) comparison with nonaluminum matrix. However, increasing the Al level beyond a certain limit leads to explosive detonation failure. Inclusion of Al powder in the emulsion results in increased energy output of the emulsion matrix and also increases sensitivity to mechanical stimuli. The effect or influence of aluminum content on the performance and sensitivity of nonideal explosives has been studied [1–4]. High energy products have been developed and used to improve the fragmentation and productivity of mines. Inclusion of a small amount of aluminum can increase the released potential energy drastically. High Al in the explosive composition is costly, especially considering that only a fraction of the added energy is utilized for the rock fragmentation and the rest of the energy gets diluted in other forms, such as kinetic energy, seismic energy, i.e., blast-induced ground vibration and air-overpressure, etc. [5]. Aluminium content in commercial blasting agents and class-A explosives are generally kept in the range of 0–5% by weight. It has been observed that the increased temperature in the vicinity of the burning Al grains appears to increase the reaction rate of the composition [6].

AN has relatively weak explosive properties and is not considered explosive in many classifications. Adding metal powders such as Al powder increases an explosive's performance. The heat of formation due to Al oxide (Al_2O_3) is very

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high per mole of the formed solid detonation product. Zygmunt [7, 8] studied the explosive properties of AN mixtures with an addition of Al.

In order to understand the detonation performance of emulsions as a function of Al content over the range of 0–20%, confined and unconfined VOD were measured and the corresponding effect of addition of metal powder was investigated in field conditions. It has been reported that the reaction kinetics are strongly influenced by shape, type of surface coating used, and the grain size of the Al powder [9, 10]. It is not unusual for post-detonation explosions to occur in the muck pile when a high content of Al is used as a fuel in explosives [11].

Effect of Al on velocity of detonation

Researchers, including Brousseau et al. [12], Hirosaki et al. [13], and Kato et al. [14], have studied the influence of Al content on detonation velocity of emulsion explosives. Ammonium nitrate is one of the significant components of the nitrate based explosive system having higher values for high density and lower values for low density. It is well known that addition of metal powder enhances the detonation performance, though certain restrictions or limitations are also associated owing to the degree of thermodynamic oxidation of aluminum to the ammonium nitrate. However, the detonation velocity can even decrease with the increase in Al content, as in the case of emulsion explosives. It was experimentally verified that the detonation velocity slightly decreases as the Al mass fraction in the emulsion explosives composition increases [15]. Some investigations have been carried out on the detonation process of aluminized explosives, but not many have focused on the aluminized emulsion explosive and the effect on density of the emulsion explosives. Warey [16] noted that owing to the difficulty of synthesis and instability of energetic material, not many experimental studies have been done on emulsion explosives. Therefore, to investigate the influence of Al powder on the performance of emulsion explosives in unconfined and confined conditions, experiments were carried out and the relation between density Al content was studied.

Experimentation

Initially, the emulsion matrix was prepared in a Patterson ribbon and blade mixer, and the weight percentage of the emulsion has been kept as follows: ammonium nitrate (AN) 78.14%, fuel oil 4.3%, SMO 2.69%, and water 14.85%. Paint-grade fine Al powder was used for experiments, which had purity of 99%, was spherical in shape, and had average size of 75 μm. Initially, density of the emulsion matrix was adjusted at 1.15 g/cc after mixing of Al powder.

Several trial blasts were conducted at the R&D facility of IDL Explosives Limited for unconfined conditions. For confined conditions, the trial blasts were conducted at a coal mine, and in field (coal mines) for rock confined conditions, to understand the detonic behavior of the obtained emulsion matrix over a wide range of Al content, which varied from 0, 5, 10, and 20%.

Two different diameters of emulsion explosive cartridges, 83 and 110 mm, were prepared for unconfined conditions at the R&D facility. The Al content was varied over a range of 0, 5, 10, 15, and 20%. Detonation velocity was measured by the D'Autriche method. For the rock confined situation in field conditions, the diameter of prepared cartridges were 83 and 125 mm and trial blasts were conducted with a single sample blast hole charged by varying the percentage of Al as 0, 5, 10, 15, and 20%. The in-hole VOD measurements were carried out by using VODMate™ (continuous in-hole VOD measuring instrument).

Dependence of detonation velocity on Al content

The unconfined VOD data was recorded for sets of experiments, and the temperature of explosives, percentage of Al content, density, and detonation velocity were measured and recorded. A trial blast was conducted for each set, wherein the percentage of Al was varied from 0 to 20% with an equal increment of 5% and velocity of detonation was determined by the D'Autriche method. Several sets of trials were conducted at an opencast coal mine to observe and understand the influence of Al percentage on the confined VOD of explosives. Figures 1 and 2 show the relation between percentage variation of Al content and unconfined VOD and confined VOD of emulsion explosives, respectively. Figure 3 shows the variation in detonation velocity in confined space to unconfined space for an 83 mm cartridge diameter at the same Al content.

From Figs. 1 and 2, it is evident that the values of VOD obtained were in the range of 3200–4700 m/s for unconfined space and 3700–5400 m/s for rock confined space with variation of Al content from 0 to 15%. As the Al percentage was increased, the detonation velocity of the aluminized emulsion explosive reduced, and the graphs indicate a linear downward trend between them. Owing to the higher percentage of Al powder, the emulsion has become oxygen negative (amount of oxygen available from oxidizer) because Al oxidizes at lower temperature than the fuel. Another possibility is that the number of voids or air bubbles would have reduced per unit cross-sectional area of the aluminized emulsion

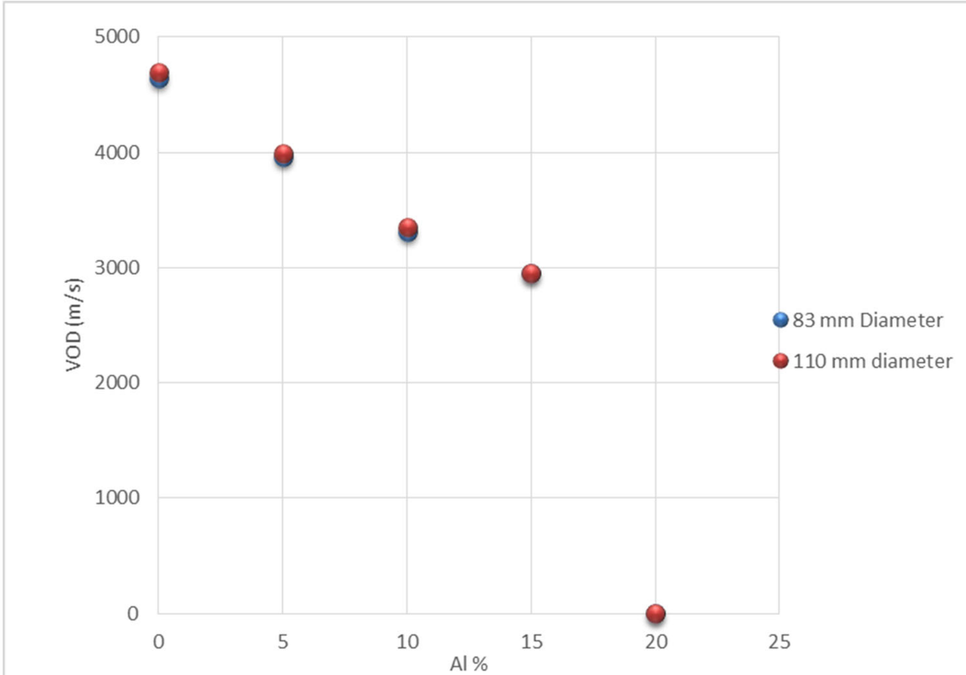

Fig. 1 Detonation velocity as a function of Al content in unconfined space

explosives resulting in fewer hot spots as Al usually forms Al oxide at the detonation wave front and the reaction is an endothermic one. In Fig. 3, higher values of detonation velocity in rock-confined space were observed than in the unconfined conditions at the same percentage of Al, which may be due to the effect of confinement.

Dependence of density on Al content

While preparing the emulsion explosives, Al content variation in the emulsion matrix induces a change in the final density of the obtained emulsion explosives. The obtained density of emulsions over a range of 0, 5, 10, 15, and 20% Al content

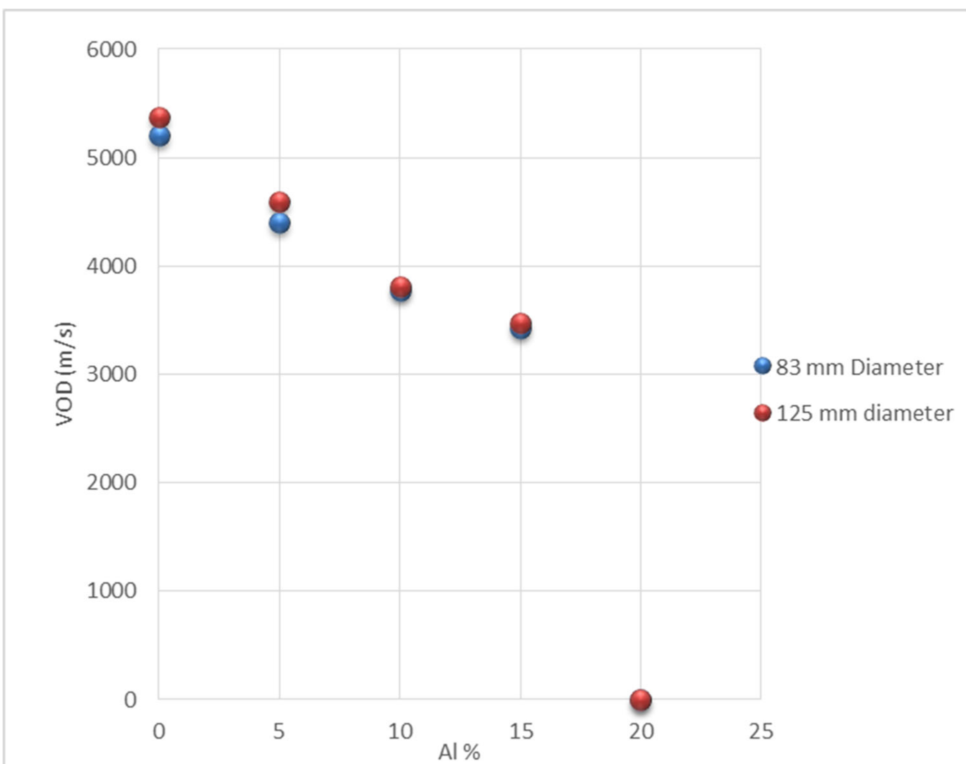

Fig. 2 Detonation velocity as a function of Al content in rock confined space

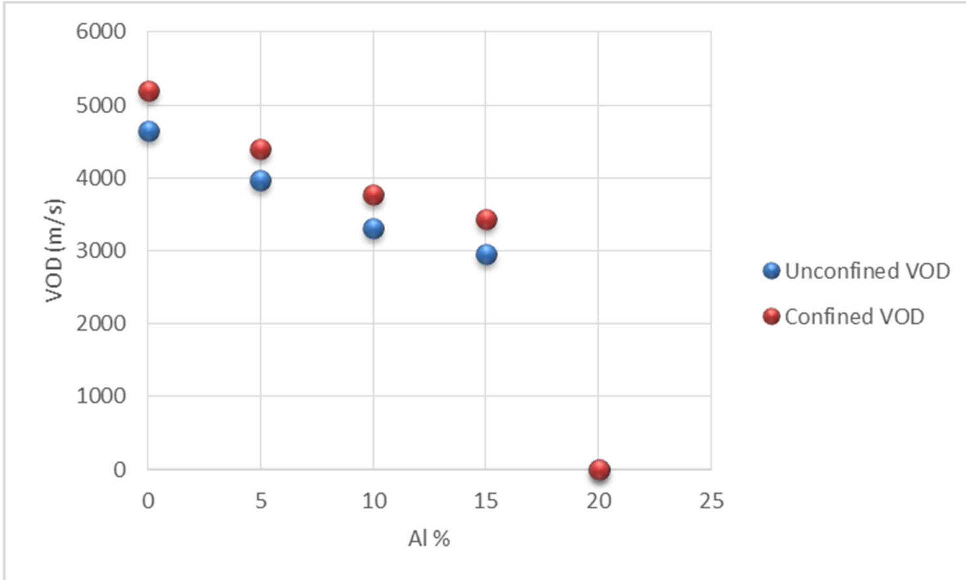

Fig. 3 Unconfined and confine VOD at the same Al content

were measured at a fixed temperature (40 °C), and the density dependence of emulsions on varying Al content was analyzed as well. The temperature was maintained at 40 °C, as in Indian conditions the average temperature in summers is around the same level in most of the mining areas. Figure 4 shows the relation of density as a function of Al content.

The density of the emulsion explosives varies from 1.16 to 1.42 g/cc for a corresponding variation of Al content from 0 to 20%. Figures 2 and 3 show the failure of blast, i.e., misfire at 20% of Al content, which is clearly evident here also, as the density at 20% Al content is 1.42 g/cc. At this density, the emulsion explosive fails and misfire occurs [17]. Figure 3 clearly shows a linearly progressive trend of density for increasing Al content with a high correlation. The increase in density might have occurred owing to increased Al content, as Al was increased but the reaction has been slowed down causing fewer voids per unit cross sectional area. An empirical relation can be established for calculating the density of emulsion explosives for different percentages of Al in the emulsion matrix. The empirical relation was found to be $d = 0.01a + 1.16$ where, 'd' is density in g/cc and 'a' is aluminum content, for the test conditions.

Conclusions

On the basis of conducted experiments, the density of emulsion explosives were found to increase linearly from 1.16 to 1.42 g/cc, while detonation velocity decreased linearly with the increase in Al content in emulsion explosives from 5 to

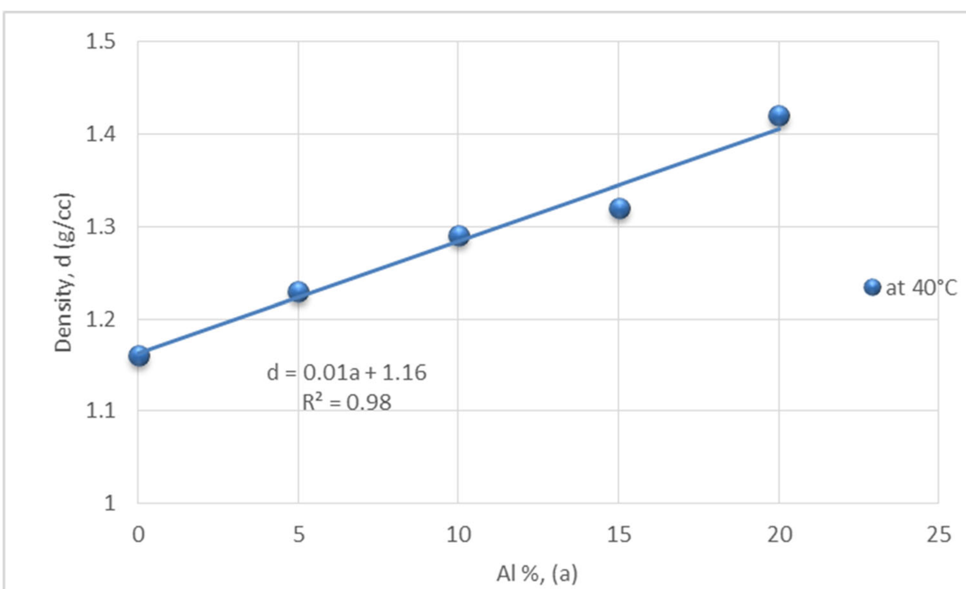

Fig. 4 Density dependence on Al content at 40 °C

20%. The detonation was stable up to 5% Al addition, while it reduced with further addition of Al and detonation failed, which was evident with misfire at 20% of Al content. This is due to the increase in density, where the number of voids per unit cross-sectional area of explosives column reduced causing a drop in enough hot spots leading to a sustainable reaction at the detonation front. With an increase in Al content, the emulsion matrix became oxygen deficient and failed at 20% Al content. Therefore, it is imperative to maintain a balance between density and sensitivity of emulsion-based high-energy explosives formulation.

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