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Influence of Explosive Charge Diameter on the Detonation Velocity Based on Emulinit 7L and 8L Bulk Emulsion Explosives

Piotr Mertuszka,[1*] Bogusław Cenian,[2]
Bartłomiej Kramarczyk,[3] Witold Pytel[1]

[1] KGHM CUPRUM Ltd. Research & Development Centre, 2-8 Sikorskieg Street, 53-659 Wrocław, Poland
[2] KGHM Polska Miedź S.A., Polkowice-Sieroszowice Mine, 100 Kaźmierzów, 59-101 Polkowice, Poland
[3] NITROERG S.A., 1 Nobla Square, 43-150 Bieruń, Poland
[*]E-mail: pmertuszka@cuprum.wroc.pl

Abstract: One of the main parameters describing the properties of explosives is the velocity of detonation, which can be defined as the propagation speed of the chemical reaction zone in the detonating explosive. The detonation velocity of an explosive depends on many parameters, such as the material's density or diameter and the shell of an explosive, plus the degree of crystal fragmentation, the initiation method and the content of particular components. The effectiveness of blasting work in underground mines depends primarily on the proper selection of the hole diameter, hole length, the distance between the holes and the delays of the detonators used. This article presents the results of studies investigating the influence of the diameter of a bulk emulsion explosive charge on the detonation velocity using a MicroTrap™ VOD/Data Recorder manufactured by MREL, Canada. The underground tests were developed in the "Polkowice-Sieroszowice" copper mine in Poland.

Keywords: blasting works, explosives, velocity of detonation

1 Introduction

Black powder, nitroglycerine and dynamite have now been practically replaced in underground mine operations by more technologically advanced types of explosives. After years of research on more efficient and safer explosives, the emulsion type of explosive has been developed. These offer a good alternative to ANFO and dynamites. Their advantage lies mainly in the reduced content of harmful gases in the explosion products [1]. Today, charging of blast holes with emulsion explosives is almost completely automated, which increases the effectiveness, comfort and security of the blasting work. Emulsion explosives are the second most commonly used explosive type worldwide [2]. Their major advantage is that the components are delivered separately to the blasting site and become explosive only after mixing and injecting into the blast hole. The time of this operation usually varies from 5 min to 20 min. Emulsion explosives are an entirely new generation of explosives in which water is one of the components [3, 4]. The emulsion is composed of two mutually insoluble liquids: non-organic (oxidizer) and organic (fuel). One of them is dispersed in the other in the form of small droplets. As such a system is relatively easily de-emulsifiable, therefore to the emulsion is added a substance (emulsifier) which reduces surface tension (interfacial) on the border of the two immiscible liquids. This covers the surface of the droplets in the emulsion with a kind of coating that has an electrical charge and mechanical resistance. The application of special manufacturing techniques provides a considerably reactive interfacial surface between the mutually reacting substances.

The first underground tests using bulk emulsion explosives in Polish copper mines took place in 1997. For this purpose, injection pumps and packaged explosives manufactured by the German company Westspreng, with the cooperation of Nitron company, were utilized. However, this activity was the only attempt using this method, implementation of which was abandoned due to the excessive explosive density and an inability for any modifications, which made the charging of explosives into the blast holes more difficult and significantly extended the process. At the end of 2002 and the beginning of 2003, further attempts at blasting work mechanization were made using bulk emulsion explosives based on the technology of the Blastexpol company. As a result of the positive results of the charging and mixing module for producing and pumping of the bulk emulsion explosives, a prototype blasting utility vehicle with an integral module was manufactured at the end of 2003. A contract was concluded with the technology supplier for the delivery of around 150-250 tonnes of bulk emulsion explosives per year and the charging of it into blasting holes using its own blasting vehicle. In 2004 almost 10% of explosives used in the "Rudna" mine was charged using this blasting vehicle. Currently, most of the explosives used in Polish copper mines are bulk emulsion explosives. Figure 1 shows the percentage of the bulk emulsion explosives in relation to the total explosives used in the "Polkowice-Sieroszowice" mine between 2004 and 2017, which in recent years is around 90% of the total explosives used.

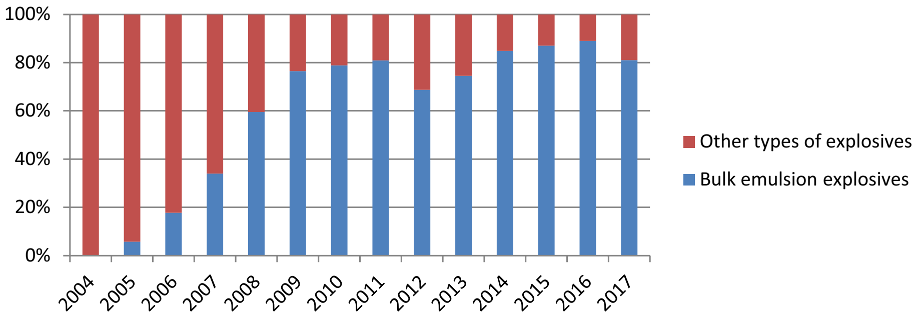

Figure 1. Percentage of bulk emulsion explosives in relation to total explosives used in the "Polkowice-Sieroszowice" mine between 2004 and 2017

One of the basic parameters for describing an explosive's properties, of both theoretical and practical importance, is the detonation velocity of the explosive charge. This parameter describes the velocity at which the shock wave front travels through a detonated explosive. For the typical explosives used in the mining industry this velocity varies from 1600 m/s even up to 7600 m/s for the explosives used in boosters and detonating cords.

Since the detonation velocity strongly depends on the explosive's diameter [5], the present paper gives test results revealing the influence of the explosive charge diameter on the velocity of detonation. The focus of the research was the Emulinit bulk emulsion explosive manufactured by NITROERG.

2 Detonation velocity of explosives (VOD)

2.1 Theoretical background

According to mining practice and the available literature, one may assume that the amount and growth speed of post-blast gas pressure in blast holes depends on the type of explosive used. The maximum gas pressure in the blast hole [6] is equal to:

$$p_g = \rho_{ex} \cdot D \cdot u_m \tag{1}$$

where: ρ_{ex} – explosive density, D – velocity of detonation, u_m – mass velocity of post-blast gases ($u_m = \frac{D}{(k+1)}$, where: k – coefficient of polytropic transformation, for most explosives the usual value is 3).

Considering that the average value of the detonation pressure is approximately half the size than the maximum value, it may be calculated from the following formula:

$$p_{av} = \rho_{ex} \cdot \frac{D^2}{8} \tag{2}$$

A comparison of the acoustic density of an explosive with the density of the excavated rock mass may be applied for an assessment of the suitability of a given type of explosive for blasting work.

The acoustic density of an explosive may be expressed by the following equation:

$$A_{ex} = \rho_{ex} \cdot D \tag{3}$$

and for a rock mass:

$$A_r = \rho_r \cdot u_l \tag{4}$$

where: u_l – velocity of the longitudinal acoustic wave, ρ_r – rock mass density.

It was found empirically that the quotient A_r/A_{ex} should remain within the range 0.8 to 1.2 [6], which means that less energetic explosives should be used in rock masses of lower acoustic density, and more energetic explosives in rock masses of higher acoustic density. This is a relatively simple method of checking whether the appropriate explosive was applied. It may be assessed by measurement of an explosive's detonation velocity directly in the blasting hole, taking into consideration most of the factors influencing the velocity of detonation, *i.e.* blast hole diameter, density and heterogeneity of the explosive, contamination of the explosive (*e.g.* by drill cuttings), moisture content and the primary rock mass temperature. It is assumed that each explosive has a certain minimum charge diameter, a so-called critical diameter (d_{cr}), at which an explosive detonates every time. As the charge diameter increases above the critical value, the velocity of detonation increases, reaching a maximum velocity at a certain limiting diameter (d_{max}), which is typical for a specific explosive and particular testing conditions.

The knowledge of the maximum explosive detonation velocity is extremely important when designing the optimal conditions for a particular explosive. Determination of this parameter may be associated with VOD measurements of massive samples. This is due to the fact that some explosives do not reach their maximum velocity of detonation even when the charge diameter is several times larger than the critical diameter [6].

2.2 MicroTrap™ VOD / Data Recorder

Due to the rapid development of measuring systems for the purpose of VOD determination (see [7]), two of the following groups of methods are currently used:

- optical methods, that use different types of a high-speed cameras,
- electrical methods, which use various types of sensors connected to an electronic counter or oscilloscope, and
- electro-optical methods, that use fibre-optic measurements connected to an electronic counter.

The MicroTrap™ VOD/Data Recorder is a portable, single channel, high resolution, explosive VOD recorder. It allows the continuous measurement of detonation velocity in any hole diameter and explosive sample. The VOD probe was specifically designed to measure VODs of explosive cartridges or short sample tubes of explosives. The ProbeRod is a rigid probe consisting of a high resistance insulated wire placed within a small diameter metal tube, which acts as the return lead of the circuit. One VOD channel is capable of recording at up to 2 MHz (2 million data points/s). This speed provides a time resolution of one data point for every 0.5 μs. When testing explosive samples out of the blast hole, the ProbeRod should be used. The ProbeRod should be inserted axially in the explosive sample starting at the opposite end from where the detonator will be placed. Immediately when the MicroTrap is set to monitoring mode, the recorder will start recording in the circular memory. When the trigger criteria has been met, the recorder will record the final loop of data, including the pre-set pre-trigger amount.

As the detonation front of the explosive consumes the probe, the resistance of the circuit will decrease in proportion to the reduction in length of the probe. The MicroTrap records the resulting decrease in voltage across the probe *versus* time.

3 Underground Measurements of Velocity of Detonation

Underground tests on the influence of the explosive charge diameter on the detonation velocity were carried out in the "Polkowice-Sieroszowice" mine. The tests were conducted in one of the retention fore-shafts, which was excluded from operation. It provided for good test site ventilation and removal of post-blast gases after firing of each sample. Samples of the bulk emulsion explosives were prepared by filling plastic sewage pipes with internal diameters of 32 mm, 40 mm and 50 mm, length 1000 mm and wall thickness 1.8 mm (Figure 2).

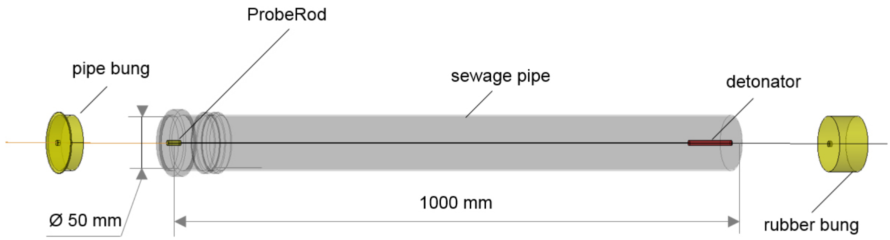

Figure 2. Diagram of the installation of the ProbeRod and detonator in a sewage pipe

Pipe filling was performed using the blasting utility vehicle equipped with a pumping module. After filling the pipes with the emulsion explosives and waiting until the explosive matrix mixed with the sensitizer began to increase in volume as a result of a chemical reaction, the excess of emulsion was removed. The aim was to make the explosive as homogeneous as possible by removing the air bubbles that were created while charging the samples. After completion of the gassing process of the samples, they were plugged at the other end and transported to the firing site. The average weight of the prepared samples varied from 0.9 kg to 2.2 kg. They were then placed on the floor of the fore-shaft (Figure 3) and fired using an electric detonator.

Figure 3. The test sample of bulk emulsion explosive in a sewage pipe

The MicroTrap recorder and blasting machine were placed in a secure location, ca. 200 m from the test site at the end of a parallel mining drift. Each series of tests consisted of three samples, which were fired at short time intervals, not more than 5 min between each test.

Two types of the bulk emulsion explosives used in the "Polkowice-Sieroszowice" mine were tested, *i.e.* Emulinit 7L and Emulinit 8L. Selected parameters of tested explosives are listed in Table 1.

Table 1. Selected parameters of the explosives (based on manufacturer's data)

Parameter	Emulinit 7L	Emulinit 8L
Critical diameter [mm]	34	34
Minimal diameter of the blast holes [mm]	35	34
Velocity of detonation [m/s]	3900	3800
Specific energy [kJ/kg]	787	788
Energy concentration [kJ/dm^3]	3529	3546

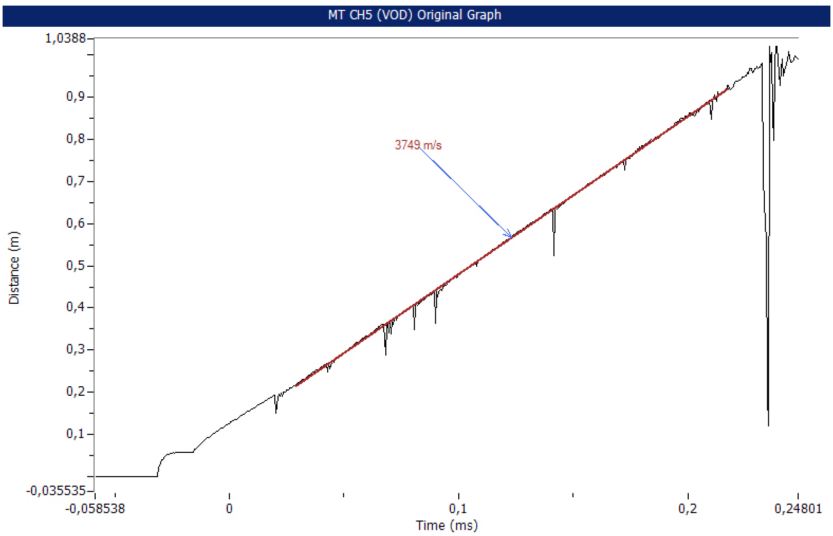

Figure 4. VOD plot of an Emulinit 7L sample tested in a sewage pipe (40 mm, 1400 g), test #3

The DAS™ Data Acquisition Suite Software was used for analysis of the recorded VODs. This automatically converts the recorded data into a graph of distance *versus* time. The slope of this graph at any position is the detonation velocity of the explosive at that particular position. The VOD may be calculated using a 2-point function, which is used when the data is “noisy” and the points in the middle need to be ignored, or using linear regression to produce a line of best fit of the points between the two end points. Examples of VOD graphs for selected tests are presented in Figures 4 and 5.

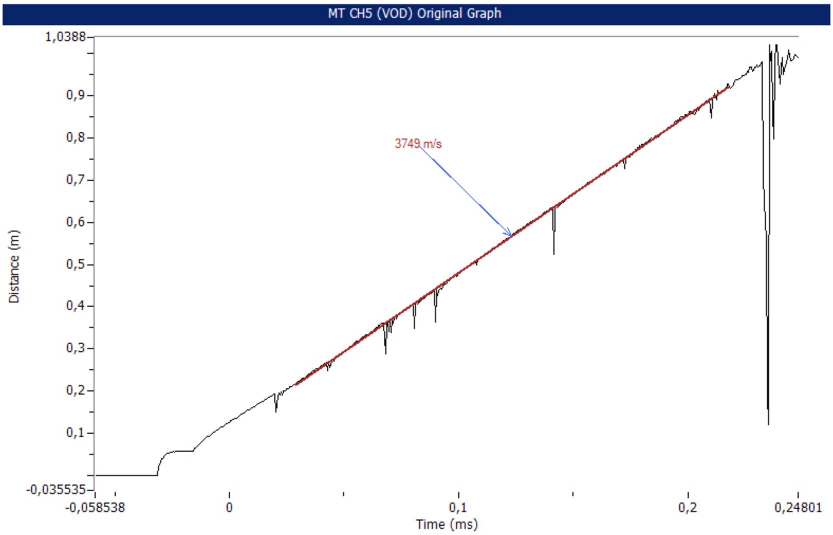

Figure 5. VOD plot of an Emulinit 8L sample tested in a sewage pipe (50 mm, 2200 g), test #3

Additional research comprised the VOD testing of three additional samples of varying diameters. Each sample was divided into three sections with a total length of approximately 1000 mm and a variable diameter reaching 50 mm on the detonator side, 40 mm in the central part and 32 mm at the end of the sample (Figure 6). As previously, they were filled with bulk emulsion explosives (Emulinit 8L) and after gasification transported to the firing site. The charge was fired at the point of its greatest diameter to reduce the risk of a failed detonation of the explosive, if the critical diameter of the tested emulsion had not been reached.

An example plot of the VOD changes on individual sample sections is shown in Figure 7. This shows that the detonation velocity decreases nearly linear along the sample with the decrease in charge diameter. However, it remains relatively stable in lengths of the same diameter. A reduction in the charge diameter by 20% resulted in a decrease in detonation velocity of ~5% for each test (*e.g.* from 4671 m/s to 4420 m/s for test #1). The VOD in the final section decreased to 3808 m/s (test #1), *i.e.* almost 20% of the initial velocity, while the diameter of this section was reduced by 40% (from 50 mm to 32 mm). The same trend was also observed in tests #2 and #3. The following VOD values were recorded for subsequent samples: Test #2 – 4625 m/s (50 mm), 4380 m/s (40 mm), 3808 m/s (32 mm) and Test #3 – 4620 m/s (50 mm), 4402 m/s (40 mm) and 3779 m/s (32 mm).

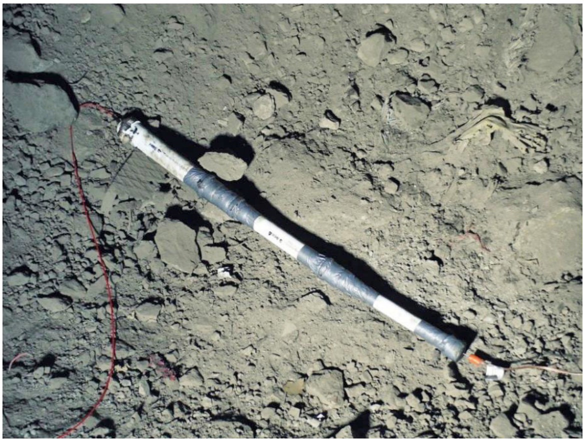

Figure 6. Sample of bulk emulsion explosive in a sewage pipe of varying diameter

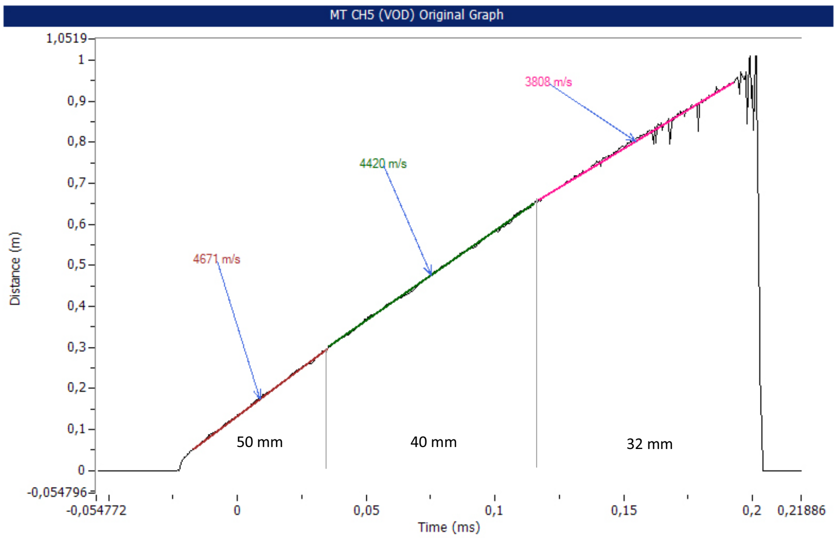

Figure 7. VOD plot of an Emulinit 8L sample tested in a sewage pipe of varying diameter

4 Results and Discussion

Based on the recorded VOD graphs of Emulinit 7L and Emulinit 8L emulsion explosives, a significant number of conclusions on the detonation process can be drawn, such as the correctness of the assessment of the detonation process, whether the detonation velocity changes over the charge length or whether the velocity significantly decreases, which could suggest that there are some gaps within the explosive charge or that the emulsion is contaminated by drill cuttings or fragments of rocks from the blast hole. The distance at which the detonation velocity changes from zero (position of detonation or booster) until the stable maximum velocity is achieved has practical relevance. The shorter this distance is, the shorter are the remains of the blast holes, so-called sockets. The detonation velocities of the explosive charges according to charge diameter are listed in Table 2.

Table 2. Results of VOD tests on selected bulk emulsion explosives

Type of explosive	Diameter of charge [mm]	Velocity of detonation [m/s]			
		Test #1	Test #2	Test #3	Average
Emulinit 7L	32	$< d_{cr}$	$< d_{cr}$	$< d_{cr}$	-
	40	3660	3700	3740	3700 ± 40
	50	3940	3910	3880	3910 ± 30
Emulinit 8L	32	3310	3480	3140	3310 ± 170
	40	3610	3670	3610	3630 ± 30
	50	4050	3940	3980	3990 ± 55

The VOD graphs obtained for the tested explosives and the selected diameters revealed a stable velocity value along the entire length of the explosive charge. In the range of the analyzed charge diameters, an approximately monotonic increase in detonation velocity was observed, when the sample diameters were enlarged (see Figure 8).

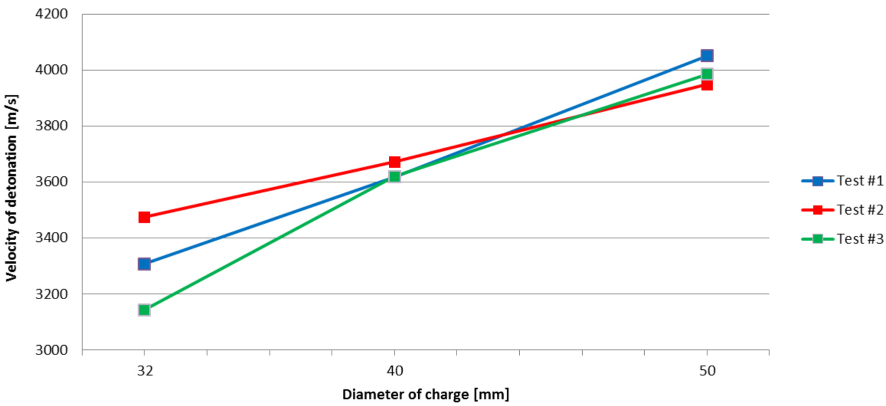

Figure 8. Graph of VOD as a function of charge diameter for Emulinit 8L

The explosive samples with a diameter of 50 mm are the most representative for the blasting technique used in Polish copper mines. Charges of that diameter reached a detonation velocity of 3900 m/s; the declared value on the EC examination certificate was 3800 m/s. The VOD values determined within the framework of the present analysis are lower than those measured directly in the blast hole. This proved that the type and resistance of the surroundings (*e.g.* explosive charge shell or type of rock) significantly affects the detonation velocity of a given explosive.

All of the three tested samples of Emulinit 7L with a diameter of 32 mm failed to detonate. This implies that the minimum diameter, which guarantees detonation of an explosive charge, *i.e.* the critical diameter, has not been reached. As shown in Figure 9, only the part of the pipe where the blasting cap was placed was destroyed, but the explosive charge was not detonated. The documentation of the Emulinit 7L explosive states that its critical diameter is 35 mm. Thus, it may be assumed that the diameter of the tested charge was smaller than required to ensure the proper propagation of a shock wave. However, when testing the explosive samples of varying diameter, detonation succeeded for their whole length, even at the section of 32 mm diameter. This proves that the critical diameter of the tested emulsion explosive under given conditions (composition of explosive, temperature *etc.*) was lower than declared by the manufacturer. It also confirms how the parameters of a bulk emulsion explosive produced directly at the firing site are variable and how many factors may affect its effectiveness.

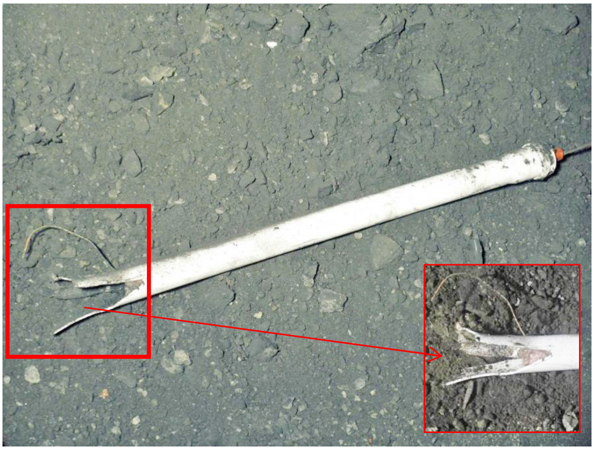

Figure 9. View of the 32 mm Emulinit 7L sample after firing

5 Conclusions

The analysis of the influence of charge diameter on detonation velocity, based on the selected bulk emulsion explosives used in Polish copper mines, developed within the framework of this paper, has proved a nearly linear increase in VOD depending on the explosive charge diameter. A monotonic increase in detonation velocity in the range of the considered charge diameters was observed. Detailed knowledge of the impact of blast hole diameters, and therefore the explosive charge diameter, on the detonation velocity directly affects the effectiveness of the blasting work. Presumably, not all of the blast holes have diameters properly optimized for a particular type of explosive. Bearing in mind the variability of the mechanical properties of the rock mass in Polish underground copper mines, the impact of the explosive charge's diameter on the detonation velocity with regard to the stress/deformation parameters of the rock mass should be analyzed. Such a comprehensive parametric analysis of the blasting process should include, for example, the geometry and type of the cut holes, the type of excavated rock mass, described by relevant strain and strength parameters, as well as the applied delays between sequentially fired blast holes.

It should also be noted that it is not just the charge diameter that influences the behaviour of a bulk emulsion explosive under particular conditions in a given blast hole. One may expect that other factors, such as the temperature inside the blast hole, the amount of sensitizer used and the time that has elapsed from the moment of loading to firing, may influence the firing process too. Comprehensive knowledge of the impact of other factors on the detonation velocity of bulk emulsion explosives may allow for the optimal application development of a given explosive under mining conditions. This may prove that modification of the gasification process would be required, which can be achieved by changing the sensitizer composition.

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