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Research paper

Measurements of the VOD of Selected Mining Explosives and Novel "Green Explosives" Using the Continuous Method

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Abstract: Explosive velocity, also known as detonation velocity or velocity of detonation (VOD), is one of the most important and basic parameters describing the properties of explosives. This work presents the VOD results of three different explosives. Two of the explosives were ammonium nitrate-based (straight emulsion and Heavy ANFO). The third explosive was based on hydrogen peroxide (HP). The aim of the experiments was to compare the VOD of the HP-based against the VOD of the ammonium nitrate-based explosives. The final conclusions and results of this preliminary work and the analysis of available literature show that HP-based explosives, so called "green explosives", have the potential to successfully replace ammonium nitrate-based explosives in some applications. The results of this work will be used to develop production technology for new HP-based explosives and to find their possible applications, considering their environmentally friendly character (this novel formulation of explosive eliminates post-blast nitrogen oxide fumes (NOx), as a direct product of the detonation process). During the burning reaction, nitrogen oxides (NO, NO_2) are produced as a result of the use of bulk ammonium nitrate-based commercial explosives. Exposure to these toxic gases can have negative effects on the health and safety of personnel and the surrounding environment. The results obtained

for the new emulsion explosives allow them to be used extensively in the industry as a competitive product on the market.

Keywords: detonation velocity, emulsion explosives, hydrogen peroxide, MicroTrap™ System

Nomenclature:

AN	Ammonium nitrate(V), NH_4NO_3
ANFO	Ammonium nitrate(V) – Fuel Oil explosive
HP	Hydrogen peroxide, H_2O_2
VOD	Velocity of detonation [m/s]

1 Introduction

One of the basic parameters of explosives is velocity of detonation (VOD). The value of this parameter indicates the amount of heat produced within the chemical reaction zone of a detonation wave. Once this parameter is known, it is possible to use explosives to perform specified types of blasting works. Methods of measuring detonation velocity can be divided into two groups: electrical and optical [1]. The optical methods employ various kinds of high speed cameras (electronic with a rotating mirror or drum). The electrical methods employ sensors (ionisation and electrocontact) connected with an electric counter or an oscilloscope. Ionization and electrocontact sensors can also be used for the continuous recording of detonation velocity. They are employed in MicroTrap™ VOD/Data Recorder, which was applied to measure the detonation velocity of the explosives considered here. The aim of the research was to determine the VOD of selected mining explosives using the continuous method for different diameters and cartridge casings.

2 Description of the Measurement System

The MicroTrap™ VOD/Data Recorder (Figure 1) [2-4] is an instrument for continuous explosive VOD measurement. It is a single channel capable of a recording rate of two million data points per second. To measure VOD, it uses the proven continuous resistance wire technique. A precise measuring probe of known linear resistance (*i.e.* Ω/m or Ω/ft) is placed axially in the explosive sample or column. As the detonation front of the explosive consumes the probe,

the resistance of the circuit drops in proportion to the reduction in the length of the probe. As this is happening, a decrease in probe voltage *versus* time is recorded. When the recorder is operating it outputs a low voltage (less than 5 V DC) and an extremely low current (less than 50 mA), which ensures that the recorder will not prematurely initiate the explosive. This makes the instrument quite safe for VOD measurement.

Figure 1. MicroTrap™ VOD/Data Recorder

Two types of VOD resistance probes may be used: a probecable (ProbeCable™) or a proberod (ProbeRod™). They have the classic configuration of a standard RG-type coaxial cable, where the high-resistance cable is the central conductor and the braided shield functions as the return conductor. Probecables are used for measuring the VOD of explosives in blastholes while proberods are specifically designed to measure the VOD of explosive cartridges and short sample tubes of explosives. The uncertainty of the measurements declared by the manufacturer is ±2%. The procedure for preparing a VOD test is shown in Figure 2.

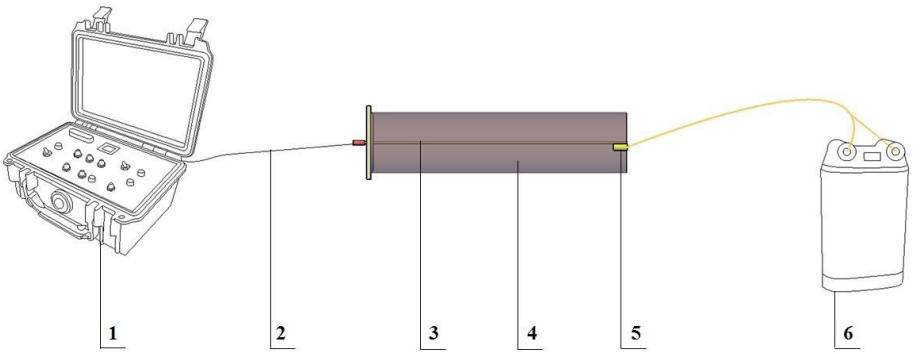


Figure 2. The procedure for measuring VOD of explosive sample: 1 – MicroTrap VOD/Data Recorder; 2 – coaxial cable; 3 – VOD proberod; 4 – explosive sample; 5 – detonator; 6 – blasting machine

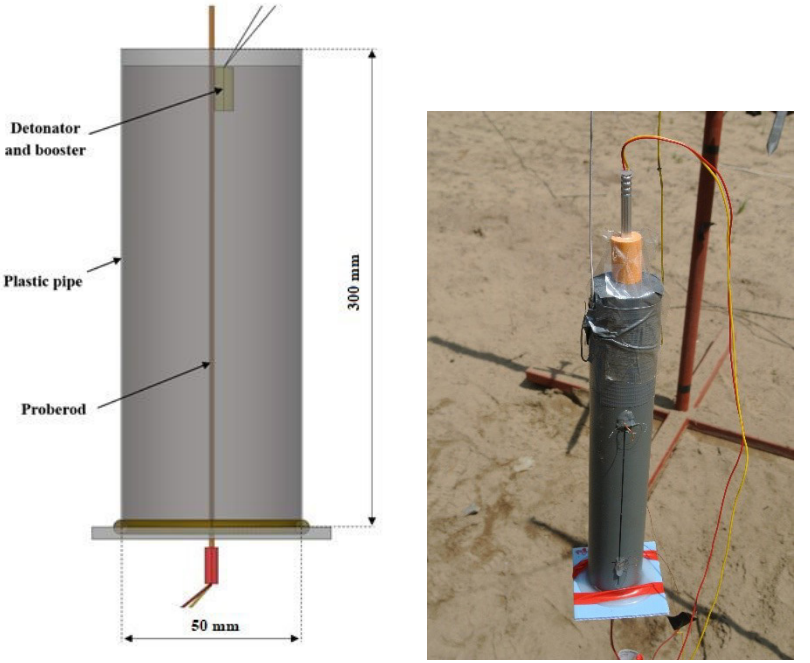
The DAS™ Data Acquisition Suite Software automatically converts the recorded data into a graph as a function of distance *versus* time. The graph slope at any position is the VOD of the tested explosive at that particular position. The DAS™ Software can automatically calculate and display the VOD of an explosive at any selected location in the graph.

3 Materials and Methods

The tests were conducted at the explosive testing site of the Institute of Industrial Organic Chemistry in Krupski Młyn. The aim of the tests was to determine the VOD of selected explosives and analyse any changes in VOD along the entire length of the explosive samples. At the explosive testing site, the samples were placed vertically and separated from the firing point with an earth berm. The recorder was placed in a protective shelter approximately 100 m from the blast area.

The charges were initiated using an instantaneous electric detonator and a booster. The booster was made up of hexogen/ceresin 90/10 and had a total mass of 16 g. The explosive samples were prepared by filling plastic tubes with inner diameters of 46.4, 71.4 and 75 mm and steel tubes with an inner diameter of 55 mm and lengths of 300 and 600 mm. A 1 m long proberod with a unit resistance of 331.7 Ω/m was used in the tests. A diagram of the proberod installation in an explosive charge is presented in Figure 3(a). A photograph of an HP-charge with MicroTrap™ installation proberod, booster,

detonator and two copper measuring probes (short circuit VOD method) is presented in Figure 3(b).



(a) (b)

Figure 3. (a) Diagram of installation of the proberod and detonator with a booster in a plastic tube and (b) photograph of a HP-charge with MicroTrap™ proberod, booster, detonator and two copper measuring probes (short circuit VOD method)

The method of explosive acceleration to the optimal VOD is crucial, from the point of view of effective blasting works, which results from the need to deliver sufficient energy to the bottom of a blasthole. Moreover, if stable VOD is reached swiftly, it minimizes the possibility both of misfires and of unexploded charges remaining in the bottom of a blasthole, which directly translates into safer blasting activities. In the graphs of the VOD of the analysed explosives, points are marked where an explosive reaches the so-called stable velocity, assuming linear character. For more detailed analysis, the threshold condition was assumed which states that the coefficient of determination, defining the dependence between a generated trend line and the actual VOD in a given section, ought to be $R^2 \geq 0.99$ [5]. To generate a straight

line, classical linear regression using the least squares method was applied. It may be described with the following Equation 1:

$$Y = b \cdot x + a \tag{1}$$

where coefficients b and a are calculated with Equations 2 and 3, respectively:

$$b = (\Sigma(X \cdot Y) - N \cdot X \cdot Y)/(\Sigma X^2 - N \cdot X^2) \tag{2}$$

$$a = \overline{Y} - b \cdot \overline{X} \tag{3}$$

where Y – dependent variable, X – predictor, $\overline{Y}$ – average for dependent variable, $\overline{X}$ – average for predictor, N – number of observations.

The linear regression method is quite sensitive to outliers. It means that if there is a slight change in the inclination angle of the graph representing VOD, the value of the coefficient of determination drops below the assumed adjustment threshold. Thus it is possible to determine the border point between accelerating an explosive and the velocity of a stable detonation. Therefore, the method can be applied in further analysis.

4 Preparing Explosive Charges for Tests

Three types of explosives were tested: emulsion (Hydromite 100), heavy ANFO (HEET 50) and HP-based explosives. The emulsion explosives and heavy ANFO are current commercial products for mining blasting [6]. These products are insensitive to external stimuli until sensitisation is incorporated, just prior to being loaded. They are also waterproof and it is possible to shape them directly in a blasthole [7]. HP-based explosives, with no or low nitrogen oxide emission, may, in the future, be applied as “green explosives” for blasting activities in special conditions [8-12].

HP-based explosives were prepared on the day of the tests with a DRAIS type planetary mixer. Ammonium nitrate(V) (AN) was mixed with a 52% solution of H_2O_2 until it dissolved, then glycerine, a viscosity modifier and glass microspheres K-015 type (producer 3M) were added. The compositions and the density of the explosive mixtures obtained are presented in Table 1. The HP-based explosives were handloaded into 300 mm long, 50 mm outer diameter polypropylene tubes (1.8 mm wall thickness).

Table 1. Composition and density of HP-based explosive mixtures

Sample symbol	Composition [%]				
	HP	AN	Glycerine	Guar flour	Glass microspheres
HP-1	77.15	4.95	13.9	3.0	1.0
HP-2	72.05	9.90	13.9	3.0	1.0
HP-3	67.10	14.95	13.9	3.0	1.0

Hydrox S emulsion-based explosives were prepared at the location of the blast tests by AUSTIN POWDER POLSKA Sp. z o. o. using Mobile Explosive Manufacturing Unit MAN UGPL-1. The general composition of Hydrox S matrix was as follows:

– oxidising agents: 76.0%,
– organic phase: 6.7%,
– water: 17.3%.

Hydromite 100 explosive contained 100% of Hydrox S matrix, while HEET 50 contained 50% of Hydrox S matrix, oil (4%) and AN (46%). By adding different amounts of the gassing agent, explosive mixtures of different densities were obtained. The density was determined in handloaded cartridges. Table 2 presents the cartridges dimensions and materials used in the tests.

Table 2. Parameters of emulsion explosive and heavy ANFO explosive cartridges

Sample symbol	Parameters of casing			Explosive
	Material of casing	Inner Diameter [mm]	Length [mm]	
HT-50-1	Polypropylene	46	600	HEET 50
HT-50-2				
HT-50-3				
HT-50-4				
HT-50-5			300	
HT-50-6				
HT-50-7		72	300	
HT-50-8				
HT-50-9	Steel	55	600	
HT-50-10				
HT-50-11				

Sample symbol	Parameters of casing			Explosive
	Material of casing	Inner Diameter [mm]	Length [mm]	
HM-100-1	Polypropylene	75	600	Hydromite 100
HM-100-2				
HM-100-3				
HM-100-4				
HM-100-5				

The explosive samples were detonated in polypropylene or steel tubes. To avoid scattering debris, cartridges of HEET 50 in steel tubes were placed in holes in the ground.

5 Results of the Measurements of VOD

Figure 4 presents the VOD plot for the HP-1 sample (test no. 2). Figures 5 and 6 display the VOD plot, which allows VOD analysis to be conducted in a different section of the VOD trace. Results of the VOD obtained for the given tested explosives are presented in Tables 3 and 4.

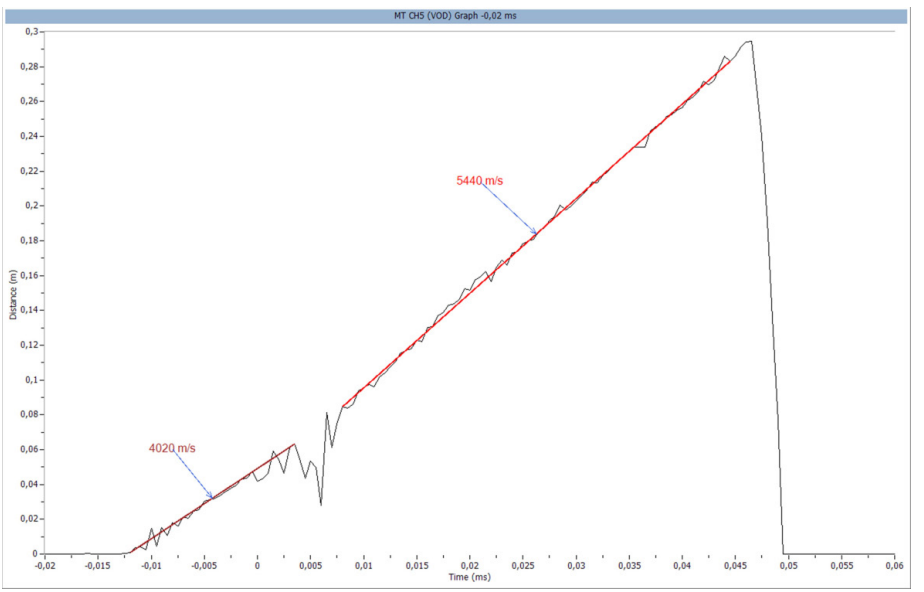
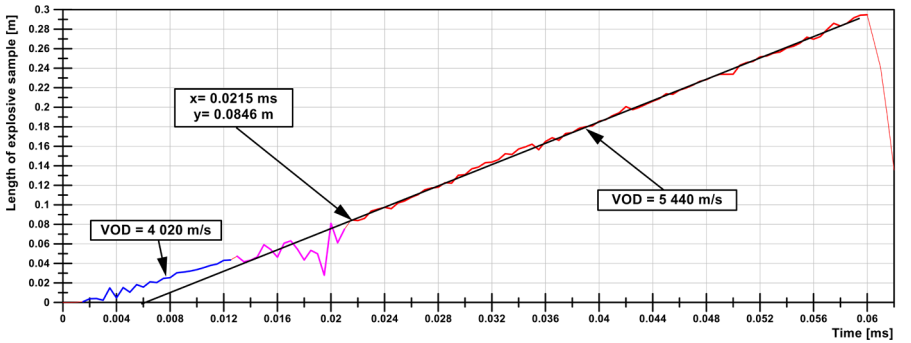
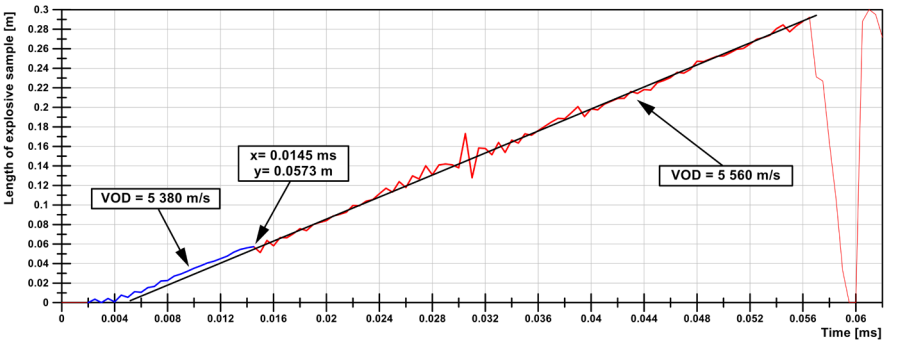


Figure 4. VOD plot of explosive HP-1 recorded with MicroTrap™ (test no. 2)



(a)



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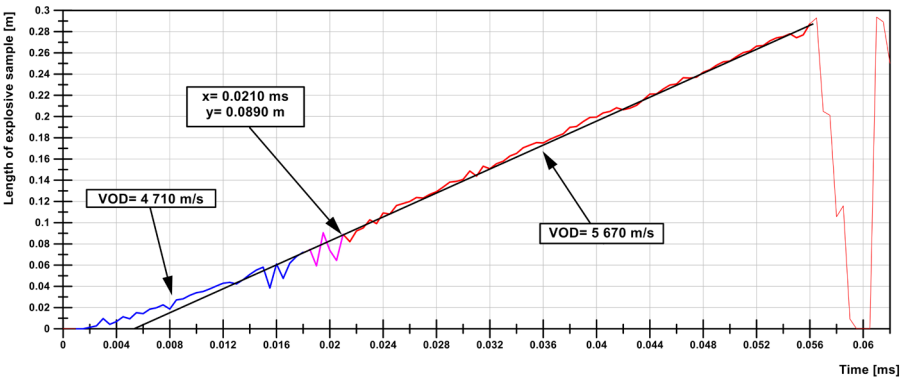
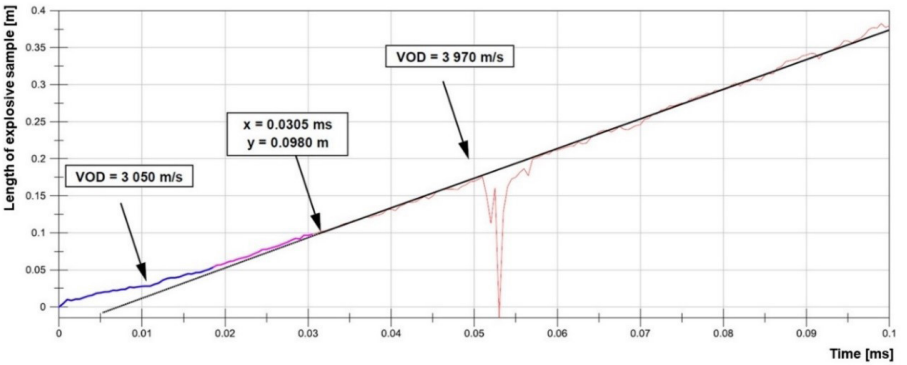
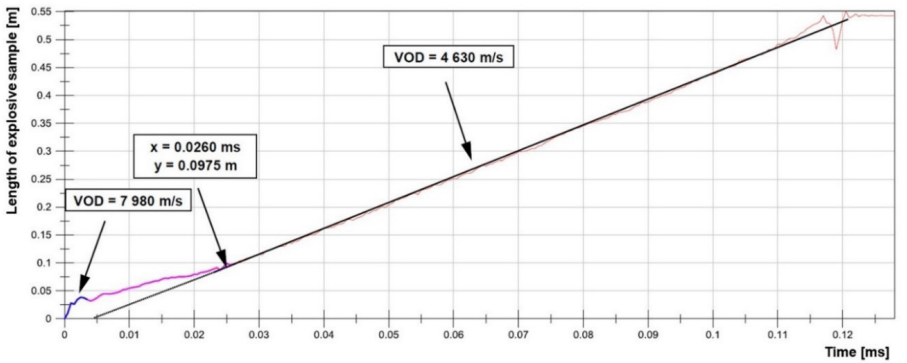


(c)

Figure 5. Changes in VOD of HP-type of explosive: (a) HP-1 (test no. 2), (b) HP-2 (test no. 3), (c) HP-3 (test no. 6) along the first section of sample



(a)



(b)

Figure 6. Changes in VOD of Hydromite: (a) HM-100-1, (b) HM-100-4 along the first section of sample

Table 3. Results of density and VOD measurements of HP-based explosives

Type of explosive	HP-1 (short circuit method)	HP-1 (MicroTrap™)	HP-2 (short circuit method)	HP-2 (MicroTrap™)	HP-3 (short circuit method)	HP-3 (MicroTrap™)
Density [g/cm^3]	0.78	0.78	0.80	0.80	0.81	0.81
VOD [m/s] (average value)	4970	5440	5270	5560	5390	5670

Table 4. Results of density and VOD measurements of HEET 50 and Hydromite 100

Type of explosive	HT-50-1	HT-50-2	HT-50-3	HT-50-4	HT-50-5	HT-50-6	HT-50-7	HT-50-8
Density [g/cm^3]	1.02	1.03	1.04	1.06	1.01	1.04	1.01	1.02
VOD [m/s]	3530	3530	3440	3610	3440	3560	3270	3530
Type of explosive	HT-50-9	HT-50-10	HT-50-11	HM-100-1	HM-100-2	HM-100-3	HM-100-4	HM-100-5
Density [g/cm^3]	0.95	1.01	1.02	0.96	1.05	1.09	1.11	1.12
VOD [m/s]	4040	4170	4120	3970	4310	4380	4670	4190

During the tests, VOD was measured for 19 explosive samples (3 types of HP-based explosive samples and 16 types of HT- and HM-based explosive samples).

6 Discussion

The tests were conducted for cartridges of different diameters and different materials. For HP-based explosives, VOD was measured by using two different methods: short circuit method (traditional) and with continuous method (MicroTrap™) (see Table 3). The structure of the tested explosive mixtures also changed. The matrix of HP-based explosive mixtures, thickened with guar flour, contained AN and glycerine dissolved in HP 52%, sensitised with glass microspheres. All the ingredients, apart from the sensitizer, were in the form of a solution. The mixtures were prepared according to the available literature. Hydrox S matrix, which is the base for both Hydromite 100 and HEET 50, is a water-in-oil (W/O) type emulsion, which was chemically sensitised to render the product explosive [13, 14]. Hydromite 100, like the HP-based explosives, does not contain any solid ingredients. Instead, HEET 50 contains ANFO. The aforementioned variables were found to influence the value of the measured VOD. From the data presented in Table 3 one may conclude that an increase in AN content, at the cost of HP solution, increases the value of the VOD. This results from the fact that in compositions with a higher AN content there is a higher content of the ingredient with explosive properties

(namely the AN) and less water, which in the tested compositions, both stabilises the texture and serves as energy ballast. The value of the VOD was 5,397 m/s (measured using the traditional method) and 5,670 m/s (measured using MicroTrap™) for HP-3 which contained the highest percentage (15%) of AN. These values are the highest for all the VODs obtained during the tests presented in this article. For mixtures, the VOD was found to depend on the degree of homogenisation of the explosive mixture, which is at the highest molecular level (all the ingredients in solution) in the HP-type of explosives.

The values of the VOD measured using both methods (traditional and continuous) are similar, but a maximum difference was found of about 10%. This may result, for example, from the accuracy of the sensor installation in the short circuit method. A small shift between the start and stop points can generate an error of a few percent, especially on such a small measuring section (according to the European Standard, mentioned in [2], the first sensor should be placed at least 5 diameters from the end of the igniter). In the case of a 100-mm measurement section, an inaccuracy of 2 mm in determining the distance between two measurement bases, generates an error in the VOD of 110 m/s at a velocity of approximately 5,500 m/s. The results of continuous measurements are slightly higher than those determined by the short circuit method. However, the trend in velocity changes is almost identical.

Concerning the degree of homogenisation of the explosives, Hydromite 100 is less homogenized than HP-based explosives but more homogenized than HEET 50. VOD measurements for Hydromite 100 were conducted in plastic cartridges of 75 mm diameter and 600 mm length. The density of the mixtures was the parameter that was varied. The results show that in the tested density range the maximum VOD was obtained for a density of 1.11 g/cm^3 (4,670 m/s, HM-100-4), then there was a decrease in the value of the measured parameter. The character of the obtained dependence of VOD on density is typical for non-ideal explosives, including AN-based explosives. However, the decrease seems to be too sudden, especially in cartridges of such a large diameter. Taking into consideration the VOD value of tested explosives in the density range of over 1.00 g/cm^3, the VOD of Hydromite 100 is lower than the VOD of HP-based explosives.

The next explosive tested was HEET 50, which had the lowest degree of homogenisation of components, due to the occurrence of solid granules of porous AN in its structure. At the testing stage the variables were: density, type of casing, diameter and length of charges. The HEET 50 cartridges placed in 46 mm diameter polypropylene tubes (mixtures HT-50-1 to HT-50-6) were detonated within a narrow velocity range 3,440-3,610 m/s. The HEET 50 and HT-50-4 with a density of 1.06 g/cm^3, displayed the highest

VOD were only slightly different than the average VOD. The fact that there were no significant differences between results obtained with 300 mm and 600 mm long tubes (Table 4) shows that for the diameter of 46 mm, the stabilization of detonation processes occurs in a 300 mm-long cartridge. VOD measurements for mixtures HT-50-7 and HT-50-8 obtained for cartridges with a larger diameter (72 mm) should be higher than the VOD measured in 46 mm cartridges. Therefore, it can be assumed that the detonation process is not fully stabilised at a length of 300 mm. Hence, to obtain a proper VOD in 72 mm cartridges, the VOD measurement needs to be conducted in longer tubes. Placing HT-50 in a steel tube enabled much higher results of VOD to be obtained than in a polypropylene tube. The cause of the drop in VOD in Figure 5(a) is connected with the momentary opening of the measuring probe during the test (not observed in any other test).

7 Conclusions

Results obtained during tests showed that one of the essential factors which influences the VOD of AN-based mining explosives is the phase composition of the mixture (liquid-liquid or liquid-solid). The liquid-liquid explosive compositions (HP-based explosives and Hydromite 100) have a higher reaction speed (hence higher VOD) than liquid-solid compositions (HEET 50). This is due to the fact that AN-based explosives are mixtures of an oxidising agent and a combustible component and the degree of mixing of the basic components determines the velocity of the reaction between them, which in turn, determines the VOD. Currently, HP-based explosives, whose VOD results are also presented within this paper, can belong to this group.

Measurements made for Hydromite 100 and HEET 50, have mainly a practical significance, as they were conducted within the frames of monitoring and certifying tests. Results of the experiments show that the tested explosives detonate due to following parameters (VOD, cartridge diameter, type of booster) specified by the manufacturer. They also confirm a well-known thesis that by changing the content of ANFO in emulsion explosives it is possible to modify the detonation parameters of explosive mixtures and adjust them to the mechanical properties of the rock mass.

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