Full Paper

Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201800062

The Impact of Time on the Detonation Capacity of Bulk Emulsion Explosives based on Emulinit 8L

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Abstract: One of the elements of enhanced safety of mechanically loaded emulsion explosives is the loss of its explosive properties after a certain period of time, without reference to the particular research. The manufacturer described this time for approximately 48 hours from the time of its charging to the blasting holes with a gas sensitized product. Under regular conditions of mining works, this time is absolutely sufficient for safe mining operations. In practice, some unforeseeable situations may occur that the charged explosive is not fired within the prescribed period of time. The aim of the study was to verify the knowledge regarding the behavior of mechanically loaded emulsion explosives used in Polish underground copper mines by tracking the changes of detonation velocity over time. The subject of research was Emulinit 8L emulsion explosive manufactured by NITROERG from Bieruń, Poland. The measurements were provided using a MicroTrap™ VOD/Data Recorder, which allows for continuous measurement of the detonation velocity of explosives.

Keywords: blasting works · emulsion explosives · velocity of detonation · VOD

1 Introduction

Years of research work on more efficient and safer explosives led to the creation of emulsion explosives which offer a good alternative to ANFO and dynamites. Their advantage lies, among others, in excellent resistance to water and low gas emissions [1]. Charging of the blast holes with emulsion is almost completely automated, which increases effectiveness, comfort and security of blasting works. The very first industrial application of bulk emulsion explosives in underground Polish copper mines belonging to KGHM were conducted in 1997 in "Rudna" mine. However, the method was abandoned due to excessive explosive density and restarted again at the end of 2002. In 2004, almost 10% of explosives used in the "Rudna" mine was charged by the use of prototype of a blasting utility vehicle with an integral bulk emulsion module [2]. In the following years, an increase in the use of bulk explosives in terms of the total kilograms of explosives used, which is shown in Figure 1. In previous years, as much as 80% of all explosives used in KGHM's mines have been bulk emulsion explosives.

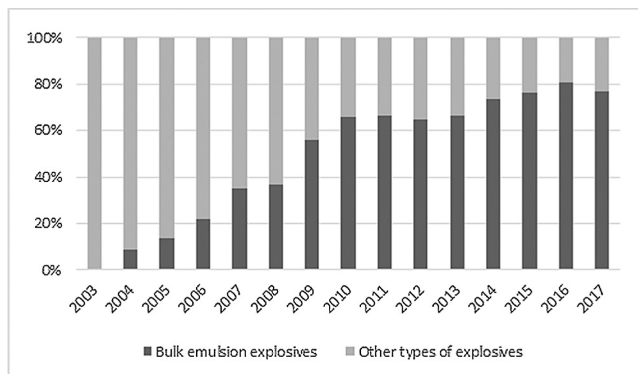

Figure 1. Percentage of the bulk emulsion explosives in relation to total explosives used in "Rudna" mine between 2004 and 2017.

One of the basic parameters describing the explosives properties in the classic Chapman-Jouguet theory is detonation velocity, which can be defined as the speed of propagation of the chemical reaction zone and the related shock wave through a detonated explosive [3,4]. During the practical use of the bulk emulsion explosives, a number of questions appeared concerning the variability of its parameters over the time from loading of the blast holes until the time of firing [5]. Bearing in mind that the addition of "hot spots" enhance the rapid explosive combustion of the emulsion. It was assumed that the bulk emulsion explosives loses detonation capacity after a period of time [6]. The sleep time for emulsion explosive is approximately 48 hours, while full detonation capacity is being reached approximately 30 minutes after being into the blast holes [7]. This means that an explosive should be initiated in a specified time period to achieve proper detonation in the blasting works. In practice, manufacturers do not specify the period in which bulk explosives should be fired, but only a range of optimal den-

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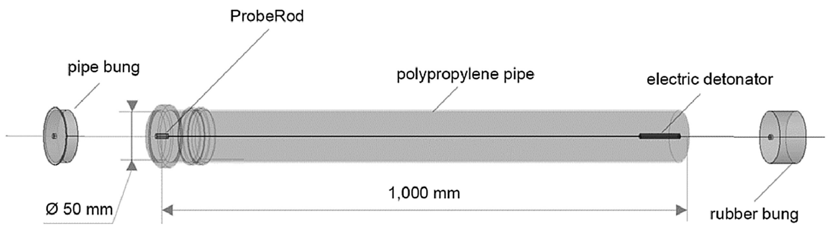

Figure 2. Scheme of installation of the ProbeRod and detonator in polypropylene pipe.

sities. To achieve a high quality of product for the blasting works when using the Emulinit 8L, its density should be between 0.80 g/cm^3 and 1.25 g/cm^3. The following paper presents the results revealing the impact of time on the detonation velocity based on Emulinit 8L bulk emulsion explosive.

2 Materials and Methods

The research consisted of firing of previously prepared emulsion explosive samples in specified intervals of time and measuring their detonation velocity. The explosive samples were prepared by filling polypropylene sewage pipes with an external diameter of 50 mm, length of 1,000 mm with a wall thickness of 1.8 mm with the explosive (Figure 2). This is typical diameter of the blast holes used in underground Polish copper mines. Samples were equipped with MREL's VOD ProbeRod with a unit resistance of 331.7 ohm/m and fired using an instantaneous electrical detonator. Measurements were conducted using a MicroTrap™ VOD/Data Recorder allowing for the continuous measurement of the detonation velocity of explosives with a high resolution at up to 2 MHz [8].

The pipes were filled with the gas sensitized emulsion explosive and allowed to expand. The excess amount to overflow the pipe was removed. The aim was to make the explosive as homogeneous as possible by removing the voids that were created while charging of the samples. After the pipes where filled with sensitized emulsion, they were plugged and transported to the firing site in a horizontal position. The remaining samples were stored horizontally in explosives depot with a constant ambient temperature of approximately 15 degrees Celsius. The average weight of each prepared sample was approximately 2.2 kg. Prior to the detonation of each sample they were covered with a 50 cm layer of sand for noise requirements.

The research was conducted in the NITROERG company test site in Bieruń, Poland. The subject of research was Emulinit 8L bulk emulsion explosive, which was loaded from the blasting utility vehicle equipped with pumping module. Selected parameters of tested explosive are shown in Table 1.

The VOD ProbeRod is inserted axially in the sample of explosive from the opposite end of the detonator. Then the ProbeRod is connected to the coaxial cable to transmit the signal to a MicroTrap™ VOD/Data Recorder. Once the connection was checked, the instrument was placed in a safe distance away from the detonation area and left in monitoring mode.

Table 1. Selected parameters of Emulinit 8L explosive (based on manufacturer's data).

Critical diameter	34 mm
Minimal diameter of the blast holes	34 mm
Velocity of detonation	3,800 m/s
Oxygen balance	0.05 %
Sensitivity to friction	> 360 N
Sensitivity to impact	> 30 J
Heat of explosion	3,084 kJ/kg
Concentration of energy	3,456 kJ/dm^3
Specific energy	788 kJ/kg
Specific volume of gaseous products of explosion	870 dm^3/kg

3 Experimental Section

The detonation velocity of the prepared explosive charges is measured in 14 selected intervals after loading. Table 2 shows the intervals values and the results as they range from 30 minutes to 6 months. Figure 3 is a graphical representation of the data shown in Table 2. To obtain the average results, each series of the test consisted of three samples. The time interval of each test series did not exceed 5 minutes.

The VOD measurements have proven that the detonation parameters of the considered explosive changed over time. The highest detonation velocity was observed for the first explosive sample fired 30 minutes after loading into the plastic pipe. The other samples in the first series has a slight decrease in detonation velocity (2 to 5 %) in respect to the first sample was noted. The drop in detonation velocity within first series was due to operational break between individual samples that was required to prepare the next samples. This includes the inserting of the ProbeRod and detonator, placing of the samples in the firing pit and covering with sand. The consecutive measurement series show an exponential decrease in detonation velocity in relation to the first tests.

Examples of VOD graphs (distance versus time) for selected tests are shown in Figures 4 and 5. The slope of the

Table 2. Results of VOD tests of Emulinit 8L bulk emulsion explosive.

Series No.	Time	Velocity of detonation [m/s] Sample #1	Sample #2	Sample #3	Average
1	30 min.	4,345	4,210	4,135	4,230 ± 105
2	60 min.	3,958	3,975	4,055	4,005 ± 40
3	90 min.	3,910	3,905	3,895	3,903 ± 7.5
4	180 min.	3,745	3,745	3,705	3,732 ± 20
5	240 min.	3,670	3,665	3,650	3,662 ± 10
6	300 min.	3,590	3,620	3,580	3,597 ± 20
7	24 hrs.	3,510	3,565	3,555	3,543 ± 27.5
8	48 hrs.	3,450	3,385	3,425	3,420 ± 32.5
9	7 days	3,370	3,290	3,330	3,330 ± 40
10	14 days	3,180	3,130	3,150	3,153 ± 25
11	31 days	3,085	3,105	3,110	3,100 ± 12.5
12	72 days	3,060	3,045	3,055	3,053 ± 7.5
13	4 months	3,000	3,030	3,020	3,017 ± 15
14	6 months	2,905	2,905 [a]	2,955	2,930 ± 25

[a] Detonation with booster.

graphs at any position is the detonation velocity of the explosive at that particular position. As shown in the following graphs, the measurement of detonation velocity was recorded along the entire length of the explosive charges. The considered explosive has reached the stable detonation velocity a few centimeters away from the position of detonator. Statistical dispersion of recorded VOD values within given series did not exceed 1 %, with the maximum deviation for the first series of 2 %.

The detonation capacity of bulk emulsion explosives depends primarily on the proper sensitization of the matrix [9]. As mentioned previously, formation of the "hot spots" is closely linked to the density of emulsion explosives. In fact, bulk emulsions below a certain density do not detonate. Increasing density leads to increasing detonation velocity up towards critical density at which the end product loses the detonation capacity [10]. The density of bulk emulsion explosive may be measured in mining conditions in a simple way by the operator of blasting utility vehicle. For the purposes of the presented analysis, three samples for density measurements were prepared at the same time as explosive's charges to determine the correlation between the detonation velocity of the bulk explosive and its density. The density of explosive was measured with an electronic scale with an accuracy of 1 g and with disposable 500 cm^3 cups. The cups were filled with explosive from pumping module of blasting utility vehicle. The emulsion is leveled with the top edge of the cup. The cup with explosive was then weighed. While the gassing process occurred, at specific time intervals, excess of explosives was removed by leveling and weighed (Figure 6).

The density was determined by dividing the weight of the emulsion by volume of the cup. An empty cup weighed 9 grams. The results are shown in Table 3. To determine the correlation between density and detonation velocity of bulk emulsion, researchers applied the Pearson product-moment correlation coefficient used to measure the strength of a linear association between two variables [11]. The strength of the correlation influences to what degree the records behave as it is supposed to, that is assuming that $r_{xy} > 0$, when density increases, detonation velocity is increasing too. When r_{xy} amounts to, for example 0.4, then it means, that only some of data follows the dependence (the trend is visible, however some deviations may appear). If r_{xy} is close to 1, then almost all records meet the assumptions and trend is clearly visible. Variables used for analysis of the correlation are shown in Table 4.

As the definition states, the correlation between variables X and Y is a strength measure of linear dependence between the variables. The Pearson product-moment correlation coefficient is calculated as follows:

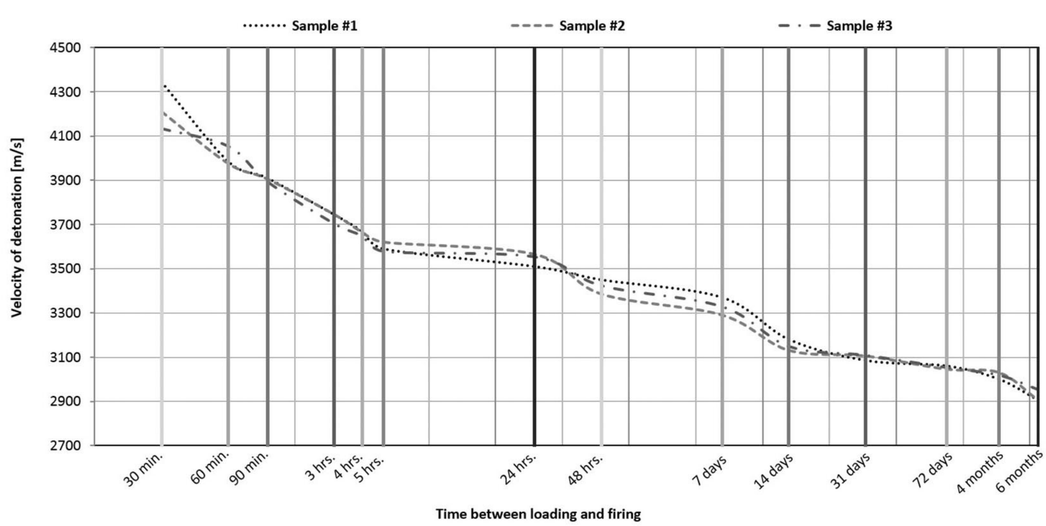

Figure 3. Graph of detonation velocity changes of Emulinit 8L samples over time.

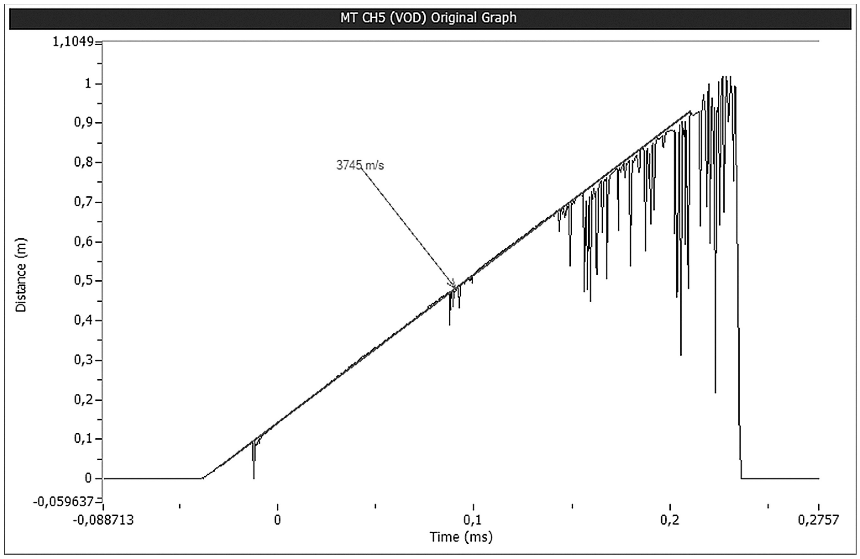

Figure 4. VOD plot of Emulinit 8L sample tested 180 minutes after loading (test #1).

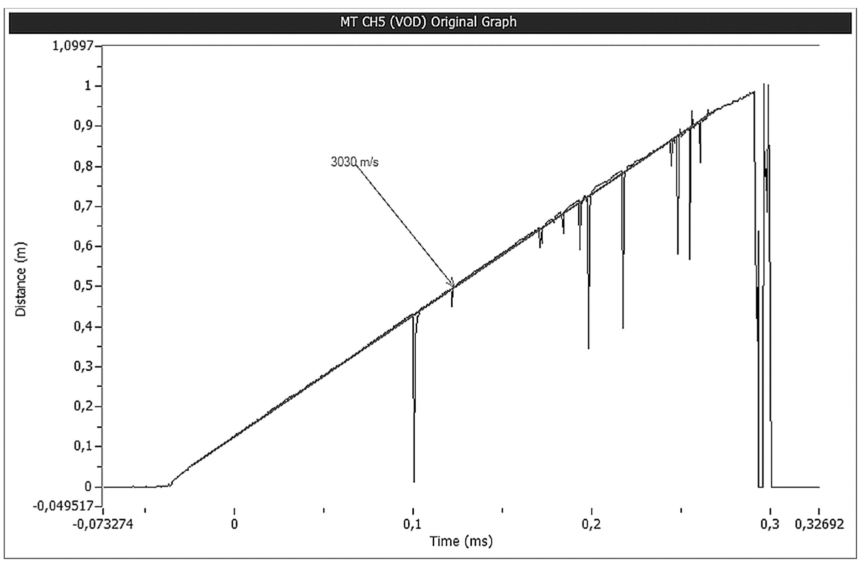

Figure 5. VOD plot of Emulinit 8L sample tested 4 months after loading (test #2).

Figure 6. View of the cup after loading (left) and while gassing process (right).

$$r_{xy}=\frac{\Sigma[(X_i-\overline{X})\cdot(Y_i-\overline{Y})]}{\sqrt{[\Sigma(X_i-\overline{X})^2]\cdot[\Sigma(Y_i-\overline{Y})^2]}}=\frac{\frac{1}{n-1}\Sigma(X_iY_i-\overline{XY})}{\sigma_x\times\sigma_y}$$

where:

r_{xy} Pearson product-moment correlation coefficient,
$X_i,\ Y_i$ i-th values observed in the X and Y datasets,
$\bar{X},\ \bar{Y}$ the mean of X and Y datasets,
$\sigma_x,\ \sigma_y$ standard deviation of datasets X and Y,
n number of observations (same for X and Y).

Using the Pearson correlation coefficient calculator, the coefficient r amounts to 0.998 (significance less than 0.001),

Table 3. Results of density measurements of Emulinit 8L.

No. of test	Time [min.]	Density [g/cm^3] Sample #1	Sample #2	Sample #3	Average
1	0	1.34	1.35	1.33	1.34
2	10	1.30	1.29	1.29	1.29
3	20	1.26	1.27	1.26	1.26
4	30	1.23	1.24	1.22	1.23
5	50	1.19	1.19	1.19	1.19
6	60	1.19	1.17	1.17	1.18
7	70	1.17	1.17	1.15	1.17
8	90	1.17	1.15	1.14	1.15
9	140	1.13	1.13	1.12	1.12
10	180	1.12	1.12	1.12	1.12
11	240	1.11	1.10	1.09	1.10
12	300	1.09	1.09	1.07	1.08

Table 4. Variables used in correlation analysis.

No. of test	Time [min.]	Average density (variable X) [g/cm^3]	Average VOD (variable Y) [m/s]
1	30	1.23	4,230
2	60	1.18	4,005
3	90	1.15	3,903
4	180	1.12	3,732
5	240	1.10	3,662
6	300	1.08	3,597

which can be interpreted as a very strong and almost perfect correlation between density and detonation velocity of explosive in a period from 30 minutes to 5 hours. The correlation here is a positive one, i.e. when the density of bulk emulsion explosive decreases, so does its detonation velocity.

4 Results and Discussion

Years of work on more efficient, safer and cheaper explosives led to the creation of so-called third generation explosives, i.e. bulk emulsion explosives, which are mechanically loaded into the blast holes. In previous years, as much as 80% of all explosives used in Polish copper mines belonging to KGHM (the biggest national consumer of explosives and blasting agents) were represented by bulk emulsion explosives. They achieve full detonation capacity approximately 30 minutes after being loaded into the blast holes. For technological and organizational reasons, the time elapsed between loading and firing of the mining faces in KGHM's mines conditions varies between 30 minutes and 10 hours. In specific cases, however, this time may be extended up to 48 hours. This situation might happen when the blasting works are focused on destressing blasting that may release the seismic energy accumulated in the rock-mass. This research has shown that the detonation velocity of Emulinit 8L reduces over a period of 24 hours after loading. This reflects that the brisance has fallen every hour. To maximize the effectiveness of the used explosives, mining faces should be fired as fast after loading as possible. Table 2 shows that the detonation velocity of the samples detonated 5 hours after loading (series 6) decreased by 15% in comparison with the first sample (series 1). This issue should be further studied in detail as detonation velocity is one of the main factors affecting the efficient advance and progress of mining works. To maintain the stability of the manufactured in situ bulk emulsion explosive, sensitizing parameters need to be selected so that the obtained material reaches stable detonation velocity within the specified time period. This would necessitate taking into consideration other factors influencing the changes of density and detonation velocity such as the composition of the emulsion matrix, the amount of added sensitizer or temperature.

5 Conclusions

Research findings on the impact of time on detonation velocity as a parameter describing the detonation process of an explosive, developed within the framework of this paper have proved that this parameter is highly variable over time, especially within the first few hours after loading. It affects directly the effectiveness of blasting works. Presumably, not all of the mining faces are fired in an interval that is optimal for this type of explosive, which may result in smaller face advance. The issue is of major importance in the case of destressing blasting of group of mining faces, which are loaded by several consecutive crews and fired a day or even two days after loading of the first mining face was done. The detonation velocity of considered Emulinit 8L bulk emulsion explosive is stabilizing after about 48 hours and its detonation capacity is maintained for at least 6 months.

It should be also noted that not only time influences the behavior of the bulk emulsions in given mining conditions. One may expect that other factors include the temperature of the rock-mass, diameter of the blast hole, and the amount of sensitizer used may influence the firing process as well. Comprehensive knowledge on the influence of other factors on the detonation velocity of bulk emulsion explosives may allow to define the rules of optimal use of selected explosive in given mining conditions. This may prove that modification of gassing process of considered emulsion would be required. It can be reached by changing the sensitizer composition or dosing of this component. Additionally, the results of research performed allow to reject the thesis, that the considered bulk emulsion explosive loses its detonation capacity after approximately 48 hours after loading. Almost the same behavior has been observed for RP-T2 bulk emulsion manufactured by Maxam, which is also widely used in Polish underground copper mines conditions.

Acknowledgements

This research was supported by Polish Ministry of Science and Higher Education of Republic of Poland. The authors would like to thank the management of NITROERG S.A. for providing necessary facilities and assistance during the field investigations. Special thanks to Bogusław Cenian whom helped intensively in the field work. Unfortunately he passed shortly after completion of presented research.

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Received: February 22, 2018
Published online: July 4, 2018

