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THE EFFECT OF THE BLASTHOLE DIAMETER ON THE DETONATION VELOCITY OF BULK EMULSION EXPLOSIVE IN THE CONDITIONS OF SELECTED MINING PANEL OF THE RUDNA MINE

WPŁYW ŚREDNICY OTWORU STRZAŁOWEGO NA PRĘDKOŚĆ DETONACJI MATERIAŁU WYBUCHOWEGO EMULSYJNEGO LUZEM W WARUNKACH WYBRANEGO ODDZIAŁU KOPALNI RUDNA

The blasting technique is currently the basic excavation method in Polish underground copper mines. Applied explosives are usually described by parameters determined on the basis of specific standards, in which the manner and conditions of the tests performance were defined. One of the factors that is commonly used to assess the thermodynamic parameters of the explosives is the velocity of detonation. The measurements of the detonation velocity are carried out according to European Standard EN 13631-14:2003 based on a point-to-point method, which determines the average velocity of detonation over a specified distance. The disadvantage of this method is the lack of information on the detonation process along the explosive sample. The other method which provides detailed data on the propagation of the detonation wave within an explosive charge is a continuous method. It allows to analyse the VOD traces over the entire length of the charge. The examination certificates of a given explosive usually presents the average detonation velocities, but not the characteristics of their variations depending on the density or blasthole diameter. Therefore, the average VOD value is not sufficient to assess the efficiency of explosives. Analysis of the abovementioned problem shows, that the local conditions in which explosives are used differ significantly from those in which standard tests are performed. Thus, the actual detonation velocity may be different from that specified by the manufacturer. This article presents the results of VOD measurements of a bulk emulsion explosive depending on the diameter of the blastholes carried out in a selected mining panel of the Rudna copper mine, Poland. The aim of the study was to determine the optimal diameter of the blastholes in terms of detonation velocity. The research consisted of diameters which are currently used in the considered mine.

Keywords: emulsion explosives, detonation velocity, Blasthole diameter, Fragmentation analysis

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Technika strzałowa jest obecnie podstawową metodą urabiania złóż w polskich kopalniach rud miedzi. Stosowane materiały wybuchowe charakteryzowane są najczęściej poprzez parametry wyznaczane na podstawie określonych norm, które szczegółowo opisują sposób i warunki prowadzenia badań. Jednym z parametrów, który jest powszechnie stosowany do oceny parametrów termodynamicznych materiałów wybuchowych jest prędkość detonacji. Pomiar prędkości detonacji jest wykonywany zgodnie z normą EN 13631-14:2003 i oparty jest na metodzie dwupunktowej, która określa średnią prędkość detonacji na zadanym odcinku. Wadą tej metody jest brak informacji o przebiegu procesu detonacji wzdłuż próbki materiału wybuchowego. Metodą pozwalającą uzyskać dane o propagacji fali detonacyjnej w ładunku jest metoda ciągła, która umożliwia analizę charakteru detonacji na całej długości ładunku materiału wybuchowego. W certyfikatach badań danego materiału wybuchowego podawane są najczęściej średnie wartości prędkości detonacji, jednak bez określenia charakterystyki ich zmian w zależności od gęstości czy średnicy otworu strzałowego. Dlatego też wartość ta jest niewystarczająca do oceny efektywności danego materiału wybuchowego. Analiza powyższego problemu pokazuje, że warunki lokalne, w jakich stosuje się materiały wybuchowe, znacząco odbiegają od warunków, w których prowadzi się badania normowe. Tym samym, rzeczywista prędkość detonacji może różnić się istotnie od wartości podawanej przez producenta. W niniejszym artykule przedstawiono wyniki badań prędkości detonacji materiału wybuchowego emulsyjnego luzem w zależności od średnicy otworów strzałowych, przeprowadzonych w wybranym polu eksploatacyjnym kopalni Rudna. Celem pracy było określenie optymalnej, z punktu widzenia prędkości detonacji, średnicy stosowanych otworów strzałowych. Badaniom poddano średnice, które są obecnie stosowane w analizowanej kopalni.

Słowa kluczowe: materiały wybuchowe, prędkość detonacji, analiza rozdrobnienia

1. Introduction

The copper ore deposit located in the Lower Silesia region in Poland lies at a depth from several hundred to even a fifteen hundred meters below the surface. The copper-bearing rocks situated between the sandstone and dolomite layers are characterised by high strength parameters, which make exploitation difficult. Room-and-pillar mining system based on drilling and blasting technology has been developed (Butra et al., 2015). Depending on the expected effect and the local geomechanical conditions, different types of explosives are used. In the following years, as much as 70% of all explosives used in KGHM's mines have been bulk emulsion explosives with the total annual consumption between 12,000 and 14,000 Mg. The selection of type of explosive is based on the analysis of a number of parameters including: density, critical diameter, volume of the post-blast fumes, detonation pressure, velocity of detonation (VOD), as well as sensitivity to external energy source. Selection of explosive should be also related to the geomechanical conditions of rock mass in the blasting area. These parameters have a greater or lesser impact on the blasting performance. They are determined theoretically based on a number of calculations or empirically by standardised tests. In most cases the actual conditions under which explosives are used differ significantly from those defined in the standards. Such conditions cover, among others, the temperature of the rock mass and surroundings, humidity, rock strength parameters and the diameter of the blastholes. As a result, the parameters of the explosives given by the manufacturers may not correlate with those specified in situ, which has been confirmed in a number of control tests (Dobrilović et al., 2014; Mertuszka & Kramarczyk, 2018).

Within the framework of presented paper, the impact of the blasthole diameter on the detonation velocity of bulk emulsion explosive has been evaluated. The velocity of detonation was measured in the blastholes with diameters varying from 38 to 76 mm, corresponding to the diameters of the drilling bits currently used in the Rudna mine. The difference between the individual diameters may have a significant impact on the detonation process within the blasthole and thus on the effectiveness of the mining works. This problem becomes particularly important in the conditions of high rock pressures, where compression of the blastholes may lead to the reduction of their diameter. In order to evaluate the effectiveness of blasting works the research was supplemented with an analysis of the rock fragmentation of the fired faces in which selected diameters were applied.

2. Evaluation of the blasting works effectiveness

The blasting performance can be evaluated from different points of view depending on the desired result. One of them should involve the type of explosive and its suitability to the local geological and mining conditions. Another may be the actual effect of explosive's detonation in the blastholes. The basic parameter defining the quality of explosives that is frequently used to describe them is the velocity of detonation. In turn, the assessment of the effectiveness of result of blasting may involve the analysis of the rock fragmentation, which provides information on the particles size distribution in the muck pile.

2.1. Detonation velocity

The velocity of detonation is a commonly used parameter in determination of the detonation pressure and thus the energy of the explosive (Kabwe, 2018; Cooper, 1996). The use of explosives with a relatively low detonation velocity is usually associated with a lower blasting efficiency than those which detonates with a high velocity (Chiapetta, 1998; Heit, 2011). Based on the formula (Trzciński et al., 2008):

$$P_d = \frac{\rho_{ex} \cdot D^2}{\gamma + 1} \tag{1}$$

where:

P_d — detonation pressure, GPa,
ρ_{ex} — initial density of the explosive, g/cm^3,
D — detonation velocity, m/s,
γ — isentropic exponent of the detonation products, -,

the decrease of the detonation velocity leads to the drop of detonation pressure and thus reduces the impulse of generated energy. Moreover, the detonation velocity is closely related to the acoustic impedance of the explosive, which is defined by t following formula:

$$A_{ex} = \rho_{ex} \cdot D \tag{2}$$

where:

A_{ex} — acoustic impedance of the explosive, kg/(m^2·s),
ρ_{ex} — density of the explosive, kg/m^3.

The A_{ex} value should be close to the acoustic impedance of the surrounding rocks described by the following relation:

$$A_r = \rho_r \cdot c_l \tag{3}$$

where:

A_r — acoustic impedance of the rock, kg/(m^2·s),
ρ_r — density of the rock, kg/m^3,
c_l — velocity of the longitudinal wave, m/s.

To achieve the highest efficiency, the A_r/A_{ex} ratio should be equal to 1.0. However, the range from 0.8 to 1.2 is also acceptable. Considering the above dependencies one may conclude that the detonation velocity is of great importance in the efficient use of the detonation energy (Batko, 2004). Having in mind that the VOD value is influenced by many factors resulting from the adopted mining technology, including the diameter of the blasthole, explosives initiation method (boosters usage) and their sleeping time, the in situ testing is justified. Particular attention should be paid to the diameters of explosive charges and the diameters of the blastholes since many research works have shown that they have a significant impact on the value of the detonation velocity (Mertuszka et al., 2018; Arvanitidis et al., 2004). The generalized relation between the detonation velocity and the charge diameter is shown in Figure 1.

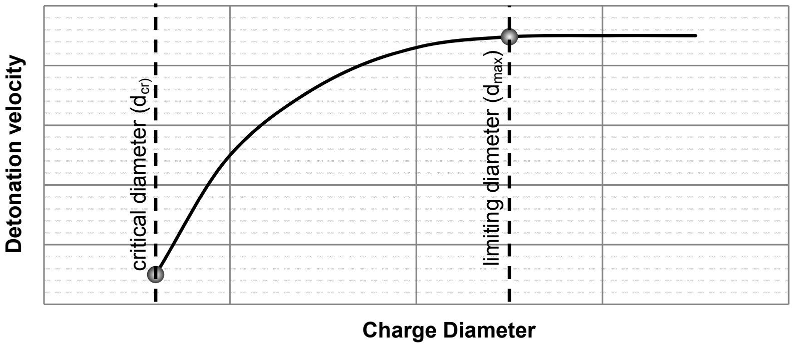


Fig. 1. Generalized characteristics of the relation between detonation velocity and the explosive charge diameter (according to Batko & Pyra, 2010)

It is assumed that each explosive has a certain minimum diameter (d_{cr}) above which the charge should always be able to detonate. As the diameter increases, the velocity of detonation increases as well until the threshold diameter is reached ($d_{\max}$). This value should be considered individually depending on the type of explosive and the local test conditions. As shown in Figure 1, the optimum diameter of the blasthole should be close to the threshold diameter of the given explosive.

The VOD measurement systems can be divided into two groups, depending on the sampling frequency, i.e. continuous and sectional (point-to-point) measurement systems. As pointed out by Kabwe, (2018), the latter method, although covered by the European standard *EN 13631-14:2003 – Explosives for civil uses – High explosives – Part 14: Determination of velocity of detonation* (Kabwe, 2018), has a number of limitations affecting their usability in the in situ (mining) conditions. Significantly higher recording resolution may be achieved with the continuous method, which is much better adapted to in situ applications. A detailed description of the abovementioned measurement methods can be found elsewhere (Mertuszka et al., 2017; Harsh et al., 2005; Mishra & Sinha, 2003).

2.2. Fragmentation analysis

The effect of blasting performance can be considered in relation to the fragmentation of rocks resulting from the detonation of explosive. Depending on further elements of the ore enrichment process, one can determine the optimum grain distribution for the given conditions. The first step of fragmentation analysis should be the determination of the actual grain size curve, which represents the content of specific particle size. Conventional methods of particle-size distribution curve determination based on sieve analysis, are basically not feasible for large scale blasting. As fragmentation analysis is of key importance in the appropriate assessment of the effect of blasting performance, a number of algorithms have been developed to analyse the fragmentation of blasted rock based on photogrammetric techniques. In most cases, the determination of the grain curve is based on the analysis of digital photographs of the muck pile. The knowledge of the rock fragmentation distribution may also be the basis to modify the parameters of the blasting pattern (Biessikirski et al., 2016). As a result of empirical tests, the distribution histogram and the actual curve can be determined. In practice, some functions that approximate the actual grain curve are also used. The most popular functions used for description of the grain distribution are (Ouchterlony, 2005):

- The Rosin-Rammler function

$$y = 1 - e^{\left[-\left(\frac{x}{x_c}\right)^n\right]} \tag{4}$$

where:

y — the cumulative percent passing, %,
x — the particle size, mm,
x_c — the characteristic particle size, which is the size at 63.2% passing, mm,
n — a parameter describing the spread of the distribution, -.

- The Swebrec function

$$y = \left[\ln\left(\frac{x_{\max}}{x}\right) / \ln\left(\frac{x_{\max}}{x_{50}}\right)\right]^b \tag{5}$$

where:

y — the cumulative percent passing, %,
$x_{\max}$ — the largest particle size in the set, mm,
x_{50} — the characteristic particle size, which is the size at 50.0% passing, mm,
b — a curve undulation, -.

In principle, both functions aim to determine, with the greatest possible accuracy, the distribution of fines in the analysed samples. In case of fragmentation analysis of the output, accurate fines projection is not required. Therefore, the determination of histograms and actual curves is sufficient to evaluate the effects of blasting works in terms of the particle size fragmentation and the percentage of individual fractions. It should be borne in mind, that the photogrammetric method significantly lowers the contribution of fines. This is due both to technical limitations (camera resolution) and to the fact, that a significant part of fines is covered by boulders and thus not visible on the photographs (WipFrag Manual, 2018).

3. Materials and methods

Currently, depending on technical and organisational conditions, different blasthole diameters are used in the underground mines belonging to KGHM, usually ranging from 45 to 64 mm. Therefore, the following diameters were considered: 45, 48, 51, 56, 64 and additionally 38 and 76 mm, to estimate the VOD of tested explosive to a greater extent.

In order to determine the actual values of the detonation velocity for different blasthole diameters, a series of underground tests were carried out. Measurements were performed in selected workings of the G-3 mining district of the Rudna mine. The subject of the study was a bulk emulsion explosive Emulgit RP-T2 manufactured by Maxam, described by parameters presented in Table 1. The density of tested explosive measured prior to firing was ~1.1 g/cm^3.

TABLE 1

Selected parameters of Emulgit RP-T2 (according to manufacturer's data)

Parameter	
Critical diameter	30 mm
Minimum diameter of blastholes	35 mm
Detonation velocity	>3.200 m/s
Oxygen balance	–0.55%
Friction sensitivity	317.8 N
Impact sensitivity	34.3 J
Specific energy	797 kJ/kg
Energy concentration	3562 kJ/dm^3
Explosion heat	3392 kJ/kg
Volume of post-blast fumes	876 dm^3/kg

In order to ensure similar filling ratio in each blasthole, different amounts of explosives were loaded into the blastholes depending on tested diameter. The parameters of the blastholes and the amount of explosives loaded are shown in Table 2.

Based on the Authors' own experiences obtained during the long-term in situ VOD measurements, a stable and maximum detonation velocity is usually reached at a distance of ca. 15-20 cm from the position of detonator/booster and it does not depend on the initiation method (Mertuszka et al., 2017). Thus, the assumed length of the blastholes was sufficient to measure stable VOD.

The blastholes were drilled in a sandstone stratum in selected workings of G-3 mining panel with the average uniaxial compressive strength of about 98 MPa. Six blastholes were drilled within each of the three mining faces, as shown in Figure 2. The distance between the adjacent holes was at least 1.5 m in order to reduce the negative impact of the detonation on the other blastholes within the same face.

TABLE 2

Selected parameters of blastholes

Parameter	**Blasthole diameter, mm**					
	38	**45**	**51**	**56**	**64**	**76**
Volume of the blasthole*⁾, m^3	0.0034	0.0048	0.0061	0.0074	0.0097	0.0136
Explosive's mass, kg	2	3	3	5	5	5
Volume of explosive**⁾, m^3	0.0018	0.0027	0.0027	0.0045	0.0045	0.0045
Blasthole fill rate, %	53.44	57.16	44.50	61.52	47.10	33.40
Length of explosives charge, m	1.60	1.71	1.34	1.85	1.41	1.00

*⁾ blasthole length = 3 m; **⁾ explosives density = 1.1 g/cm^3

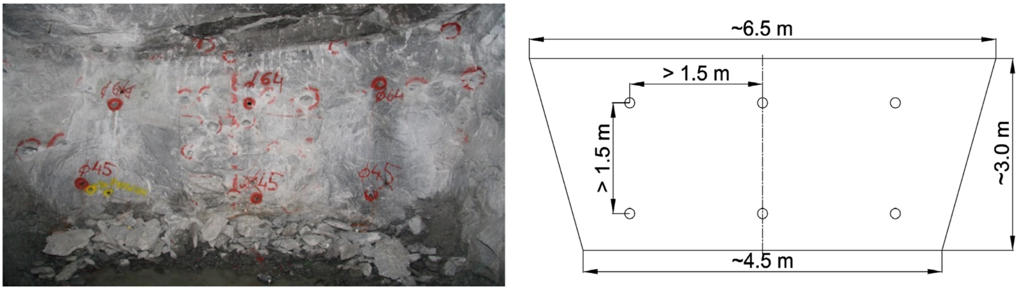


Fig. 2. Location of the blastholes in selected mining face

In order to obtain detailed information on the VOD traces within the blastholes, velocity measurements were carried out by the use of the MicroTrap recorder (continuous method) with the sampling rate of 2 MHz. The VOD measurements in this system are based on the resistance wire technique. The trigger signal is received from the probe located inside the explosive charge. During detonation the resistance of the circuit decreases in proportion to the reduction in length of the probe placed in the explosive column. Then device records a voltage decrease in time, which is converted into a graph of detonation velocity. The variability in unit resistance of the probes results in a ±2% error in VOD. Blastholes were equipped with MREL's VOD Probe Cables with a unit resistance of 10.8 Ω/m and fired using a 0.65 PETN non-electric detonator.

The analysis of the recorded data was done using the Data Acquisition Suite software, which automatically converts the recorded measuring probe resistance data over time into a diagram presenting the change in the length of the measuring probe over time. The detonation velocity can be determined by the two-point or by the linear regression methods. An example VOD plot is shown in Figure 3.

The detonation velocities were measured approximately 12 hours after the charging of explosive into the blastholes. This allowed to minimize the influence of time on the value of VOD. Three series of measurements were made for each of the analysed diameters.

Based on previous research one may conclude, that bulk emulsion explosives used in the Polish underground copper mines are extremely time sensitive during first few hours after loading (Mertuszka & Kramarczyk, 2018; Mertuszka et al., 2019). In order to obtain reliable results,

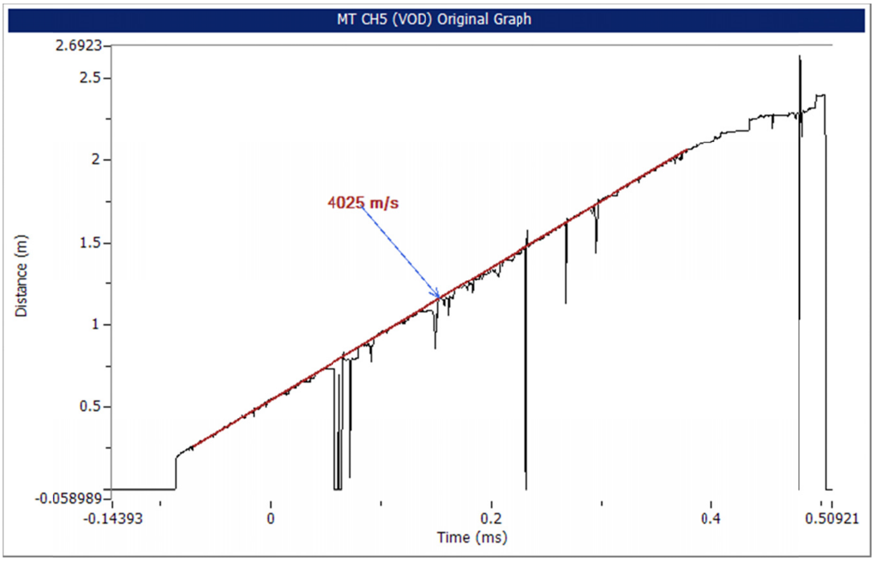


Fig. 3. VOD plot of Emulgit RP-T2 tested in a 51 mm diameter blasthole

the Authors decided to reduce the influence of time on the thermodynamic parameters of tested explosive. It was assumed, that after this period of time, the VOD will be relatively stable. It should also be noted, that according to the EU-type examination certificates, the tested explosive is stable for 48 hours after loading.

4. Results and discussion

Recorded detonation velocities for all 18 tests are shown in Table 3. The maximum dispersion of results around the mean value was 40.88 m/s for blastholes with a diameter of 56 mm. The smallest differences were observed for diameters 45 and 76 mm, for which the average deviation was at 7.50 m/s and 6.75 m/s, respectively. In consequence, the total dispersion of results remained within the measurement error range, which is ±2% for the MicroTrap device.

TABLE 3

Results of the VOD measurements in relation to blasthole diameters

Blasthole diameter, mm	Detonation velocity, m/s				
	Test #1	Test #2	Test #3	Average	Average absolute deviation
38	3,695	3,550	3,605	3,617	39.25
45	3,890	3,905	3,920	3,905	7.50
51	4,025	4,070	4,035	4,043	13.38
56	3,995	3,855	3,960	3,937	40.88
64	3,805	3,850	3,810	3,822	14.25
76	3,865	3,890	3,875	3,877	6.75

The measured velocities are also shown as a scatter plot in Figure 4. The greatest differences reach even 520 m/s, which means that the diameter of the blasthole has a clear impact on the value of detonation velocity.

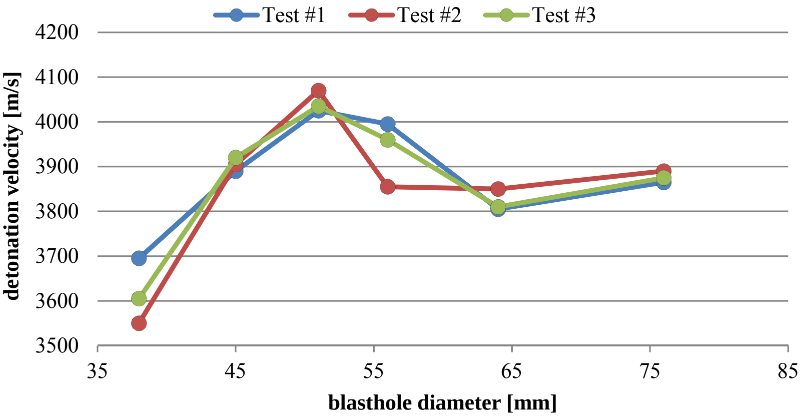


Fig. 4. Relationship between the diameter of the blasthole and velocity of detonation

The lowest detonation velocity was observed for blastholes with a diameter of 38 mm. This was expected result as the minimum diameter of the blasthole for the Emulgit RP-T2 emulsion should not be lower than 35 mm. An increase in the diameter of the blastholes was accompanied by an increase in the velocity of detonation up to a diameter of 51 mm, where the peak values were recorded. Further increase in the diameter led to a decrease in detonation velocity. This may mean that the diameter close to 50 mm can be treated as the limiting diameter ($d_{\max}$) of considered explosive under the test conditions. It can therefore be concluded that, from the VOD point of view the diameter of 51 mm was the most optimal diameter of the blastholes in G-3 mining panel conditions.

As a part of supplementary research, an analysis of the fragmentation of the muck pile from the blasting of two faces was performed. The same drilling and firing pattern for both considered faces were applied. They differ in blasthole diameters only, i.e. 45 mm and 56 mm, since the detonation velocities for these cases were similar. The average recorded VOD values were as follows: 3.905 m/s for 45 mm, and 3.937 m/s for 56 mm. Similar VOD values allowed the determination of the effect of the applied blasthole diameter on the rock fragmentation. The test blasting of two faces were carried out in same faces as tests in single blastholes. The applied blasting pattern with the amount of explosive and the sequence of delays is shown in Figure 5.

First mining face marked as “A” was drilled entirely using a 45 mm drill bit while 56 mm bit was used for the second face marked as “B”. Both faces were loaded with Emulgit RP-T2 bulk emulsion explosive with a density of ~1.1 g/cm^3 and a total weight of 166 kg per each face. The fragmentation analysis was performed using the WipFrag software. The standard procedure for this type of analysis was applied and consisted the following steps: taking a representative set of photos, reviewing and selecting photos for further analysis, analysing of individual photos in WipFrag software and determining the collective grain curve for the considered case.

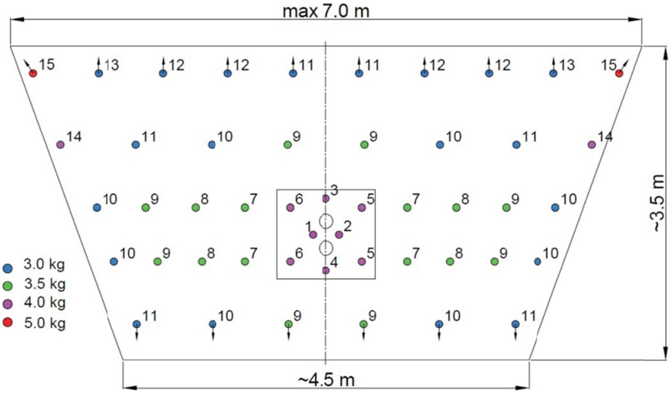


Fig. 5. Blasting pattern used to the fragmentation analysis

The assessment of fragmentation was based on the photogrammetric analysis of a series of photographs taken after the blasting works (Fig. 6). Photos were taken during the different phases of the mucking to determine the grain distribution for the entire output.

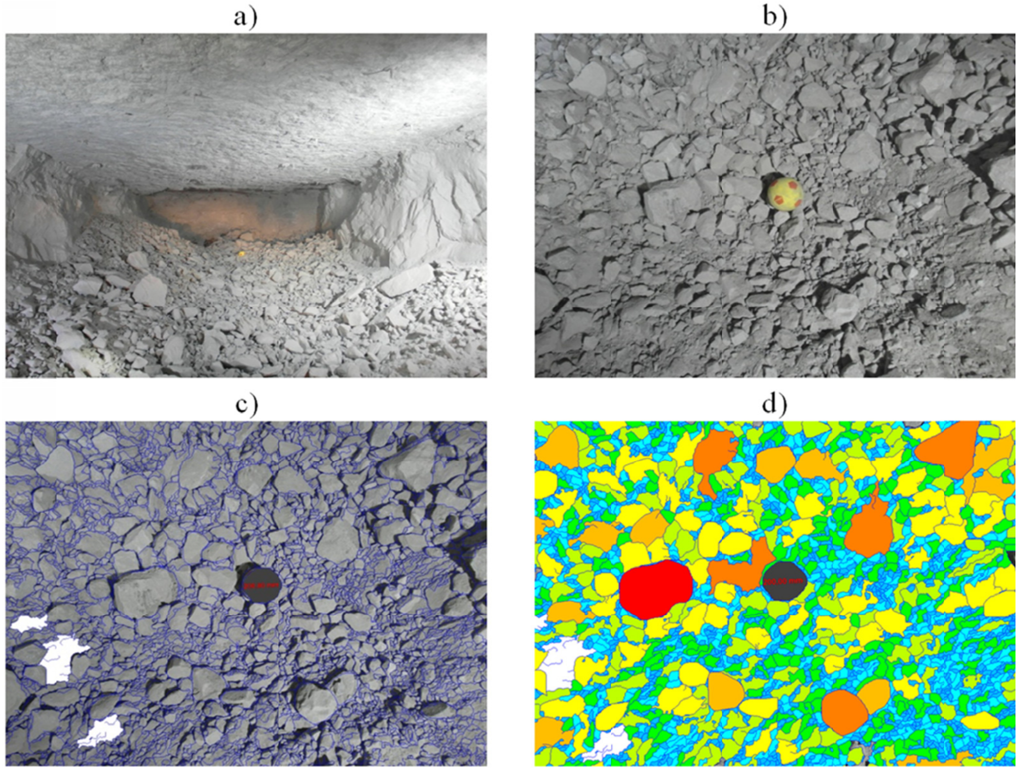
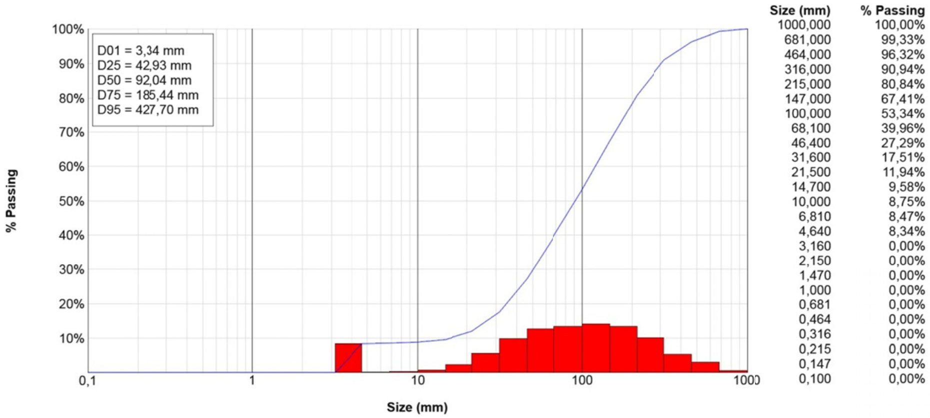


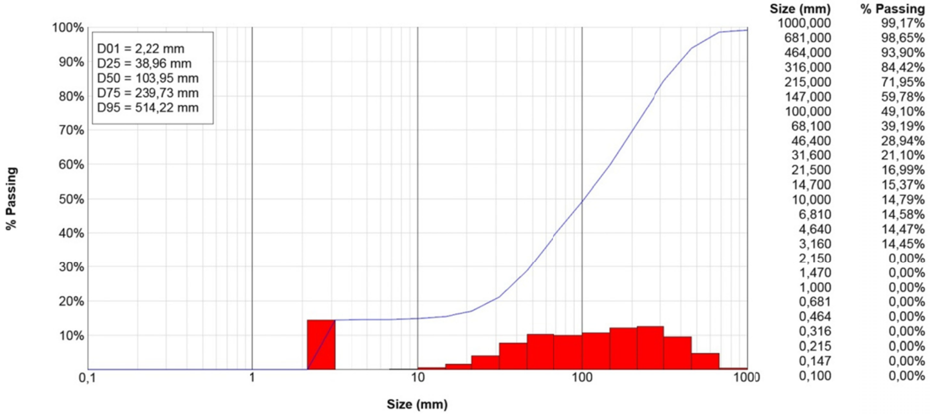
Fig. 6. View of the entire output (a), selected cross-section (b) and different stages of analysis (c) and (d)

The analysis was based on 59 photographs for face A and 41 for face B. Only high-quality photographs were selected which represented properly a given cross-section of the output. As a result of the analysis, a distribution of fragmentation for face A (Fig. 7) and B (Fig. 8) were obtained.



Size (mm)	% Passing
1000,000	100,00%
681,000	99,33%
464,000	96,32%
316,000	90,94%
215,000	80,84%
147,000	67,41%
100,000	53,34%
68,100	39,96%
46,400	27,29%
31,600	17,51%
21,500	11,94%
14,700	9,58%
10,000	8,75%
6,810	8,47%
4,640	8,34%
3,160	0,00%
2,150	0,00%
1,470	0,00%
1,000	0,00%
0,681	0,00%
0,464	0,00%
0,316	0,00%
0,215	0,00%
0,147	0,00%
0,100	0,00%

Fig. 7. Cumulative distribution of fragmentation and histogram – face A (Ø 45 mm holes)

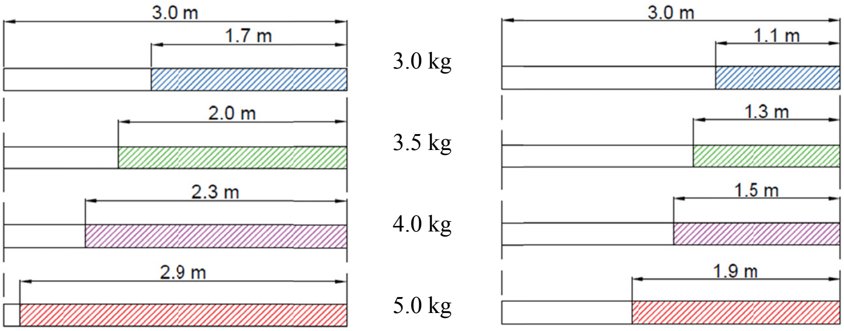


Size (mm)	% Passing
1000,000	99,17%
681,000	98,65%
464,000	93,90%
316,000	84,42%
215,000	71,95%
147,000	59,78%
100,000	49,10%
68,100	39,19%
46,400	28,94%
31,600	21,10%
21,500	16,99%
14,700	15,37%
10,000	14,79%
6,810	14,58%
4,640	14,47%
3,160	14,45%
2,150	0,00%
1,470	0,00%
1,000	0,00%
0,681	0,00%
0,464	0,00%
0,316	0,00%
0,215	0,00%
0,147	0,00%
0,100	0,00%

Fig. 8. Cumulative distribution of fragmentation and histogram – face B (Ø 56 mm holes)

Analysing the above curves and histograms one may notice a significant differences in the fragmentation depending on the blastholes diameter. For the face B (Ø 56 mm) considerably higher content of fines can be observed compared to the content of the same fraction in face A. Moreover, the output included almost 15% of particles smaller than 10 mm, which was approximately 40% more than the same fraction in face A (approx. 9%). In parallel, a higher content of oversized particles (>400 mm) was found in face B. This is mainly due to the shorter length of the explosive column in the blasthole, as shown in Figure 10.

The analysis indicates a significant differences in the fragmentation of the muck pile depending on the diameter of the blastholes. The efficiency of mining from the fragmentation



*) explosive density = 1.1 g/cm^3

Fig. 10. Theoretical length of explosive column in blastholes of 45 mm (left) and 56 mm (right)

point of view should be related to further stages of the exploitation and enrichment process. This aspect should be applied to both technological and economic issues related to the entire mining process. Control of the fragmentation may be also used for selective ore exploitation as efficient supporting tool in the ore enrichment process. Since the fragmentation analysis was carried out for the mine faces located in similar mining and geologic conditions and using the same amount of explosives, the powder factor for all cases was similar. There were some differences in local powder factor, e.g. at the bottom of blastholes, but the global factor was similar.

5. Conclusions

The underground tests carried out as part of presented research confirmed a significant correlation between the diameter of blastholes and the velocity of detonation of a bulk emulsion explosive. Therefore, there is a reasonable presumption that not all currently used blastholes' diameters are optimal for applied explosive. Hence, the selection of the appropriate diameter of boreholes for local mining and geological conditions should be whenever considered at the stage of blasting works designing. The performed measurements allowed to determine the optimal diameter of the blastholes in terms of detonation velocity under the test conditions. In this case, the measured VOD has the highest value, which means the efficient use of energy of tested explosive. The optimum diameter of the blasthole for the given explosive was 51 mm. It should be emphasised that this diameter is one of currently applied diameters in the Rudna mine. It has a practical application in the process of optimizing blasting works.

The fragmentation analysis of the output indicates a significant influence of the diameter of the blastholes on the actual grain size curve. This provides reasonable base to conclude that the selection of optimal parameters of blasting performance in relation to the diameters of blastholes and explosives used, based on in situ testing, has a significant impact on the effectiveness of the blasting performance.

Therefore, underground measurements of the detonation velocity in connection with the fragmentation analysis of the output should be carried out periodically and in case of significant changes in the thermodynamic parameters of explosives and/or changing of the geotechnical conditions.

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