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## Research paper / Praca doświadczalna

# Effect of aluminium additives on selected detonation parameters of a bulk emulsion explosive Wpływ dodatku aluminium na wybrane parametry detonacyjne materiału wybuchowego emulsyjnego luzem

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**Abstract:** The article presents an assessment of the influence of aluminium granules content on selected detonation parameters of a chemically sensitised bulk emulsion explosive. The analysis covered determination of relative explosive strength using a ballistic mortar and Trauzl blocks, free field air blast tests and detonation velocity measurements. Five types of emulsion explosives with differing aluminium content were tested at loadings of 0, 1, 3, 5 and 7%.

**Streszczenie:** W artykule dokonano oceny wpływu zawartości dodatku pyłu aluminiowego na wybrane parametry detonacyjne materiału wybuchowego emulsyjnego luzem uczulanego chemicznie. Analiza zawierała oznaczenie zdolności do wykonania pracy na wahadle balistycznym i w blokach ołowianych, pomiar ciśnienia fali podmuchu oraz pomiar prędkości detonacji. Do badań zastosowano pięć typów materiału wybuchowego emulsyjnego różniących się procentową zawartością aluminium, tj. 0, 1, 3, 5 i 7%.

**Keywords:** emulsion explosives, aluminium granules, detonation parameters

**Słowa kluczowe:** materiały wybuchowe emulsyjne, aluminium granulowane, parametry detonacyjne

## 1. Introduction

The discovery of emulsion explosives dates back to 1969, when Harold Frederick Bluhm from Atlas Chemical Industries patented a water-in-oil emulsion explosive [1]. Today, over 50 years after his discovery, emulsion explosives are commonly used for rock extraction in both underground and surface mines, as well as in civil engineering, tunneling and demolition. According to a Future Market Insights research study [2], the global sales volume of emulsion explosives is projected to reach 13 million tonnes by the end of the decade. A water-in-oil emulsion matrix composition, comprising of an oxidiser and oil, is not capable of detonation. The inorganic phase consists of supersaturated oxidiser solutions such as:

- ammonium nitrate(V),
- calcium nitrate(V), or
- sodium nitrate(V),

whereas the organic phase consists of fuels, such as mineral oil with waxes added. The remaining components are:

- water,
- emulsifiers,
- sensitisers, and
- physico-chemical property modifiers.

In order to enhance the heat of explosion and increase the pressure of the gaseous products, additional solid fuels such as aluminium, are also utilised.

Aluminium is also widely used as an additive in other explosives, including high explosives, pyrotechnic products and rocket propellants [3]. This is aimed at increasing the reaction temperature, and thereby the pressure of the gaseous products. However, the addition of aluminium does not always lead to an improvement in all the thermodynamic parameters. Depending on the type of explosives, the addition of aluminium can either improve or worsen detonation parameters. In the case of ANFO, the addition of aluminium leads to a considerable improvement in detonation parameters. Increasing the aluminium content is associated with an increase in reaction temperature and detonation velocity with a simultaneous decrease in toxic detonation products. Furthermore, it leads to an increased relative explosive strength and air blast pressure. It also increases the sensitivity of ANFO to stimuli. Therefore, the addition of aluminium in this case is very beneficial [4-6].

In turn, addition of aluminium has a somewhat different effect on the detonation of high explosives of pure chemical compounds such as nitro compounds, organic nitrates or nitroamines. Chemical compounds in the form of molecules containing both fuel (primarily carbon) and oxygen, which react exothermically during detonation, are mainly characterised by a negative or close to zero oxygen balance. During detonation, aluminium consumes the oxygen required for combusting carbon originating from the decomposition of an explosive's molecule. The combustion process of aluminium is slower than elements originating from the molecular decomposition. The reaction therefore has a two-stage path which extends the detonation process over time while decreasing its rapidity. The addition of aluminium in the case of ideal explosives, leads to a decrease in detonation velocity, which depends on both the size and the form of the aluminium particles [7]. The decrease in velocity results from the chemical inertness of aluminium molecules in the chemical reaction zone behind the shock wave front [8]. Moreover, the added aluminium significantly enhances the heat of explosion of ideal explosives [9].

Emulsion explosives exhibit similar behaviour. Their structure is characterised by a large contact surface between the oxidiser and the fuel. They can therefore be considered in a similar manner to chemically pure explosive compounds. Detonation velocities of emulsions decrease with increase in aluminium content. However, other detonation parameters, such as air blast pressure or energy of explosion, are improved [10-13]. The only exceptions are some low density, micro-balloon sensitised, emulsions, for which the detonation velocity increases with increase in aluminium content [14]. Unfortunately, such a high content of aluminium results in significant increases in production costs. Moreover, it causes some transport and loading problems. The addition of nitrocellulose powder extracted from expired ammunition was also analysed as an aluminium substitute in emulsion explosives [15]. It was assumed that this solution would be cost-effective and environmentally friendly as there is no toxic  $Al_2O_3$  in the post-blast gases. However, there is no practical application of this method in mining, to date.

Aluminium is highly reactive, though it is protected by a surface layer of  $Al_2O_3$ , which is rapidly formed when the metal is exposed to air. This provides excellent corrosion resistance. When adding aluminium to emulsion explosives, its surface is subjected to contact with a concentrated ammonium nitrate(V) solution. Due to the large contact surface, the addition of aluminium powder or flakes accelerates the oxidation process. In turn, aluminium granules intended for emulsion explosives are characterised by completely different behaviour. Thanks to a specific granulation process, the grain size undergoes an optimal selection for this purpose. Its surface is coated with agents, which prevent oxidation. The coated granules also ensure that the activity of the aluminium remains unchanged when the emulsion explosives are stored.

The article presents an assessment of the influence of aluminium content on the selected detonation parameters of bulk emulsion explosive commonly used in the Polish copper mining industry. The analysis covers the determination of relative explosive strength using ballistic mortar and Trauzl blocks, air blast pressure tests and detonation velocity measurements. Five types of emulsion explosives, differing in aluminium content including 0, 1, 3, 5 and 7%, were tested.

## 2. Material and methods

Studies were carried out at the Central Mining Institute's test site in Mikołów and at the NITROERG company test site in Krupski Młyn. The research was based on the Emulinit bulk emulsion explosive matrix. The matrix density was 1.42 g/cm<sup>3</sup> and consisted of:

- 55-60% ammonium nitrate(V),
- 15-20% calcium nitrate(V),
- 5-7% organic phase, and
- 12-15% water.

The sensitiser was based on sodium nitrate(III). The oxygen balance of the reference explosive (without aluminium) was 0.05%.

The aluminium granules chosen for the experimental study were from Hoesch Granules. The average aluminium content was 97% (approx) and the average particle size was 150 μm. Densities of emulsion explosives, determined 60 min after mixing of the matrix with aluminium and sensitiser at 20 °C, were as follows:

- 1.03 g/cm<sup>3</sup> (0% Al),
- 1.01 g/cm<sup>3</sup> (1% Al),
- 0.99 g/cm<sup>3</sup> (3% Al),
- 0.99 g/cm<sup>3</sup> (5% Al), and
- 0.98 g/cm<sup>3</sup> (7% Al),

indicating a slight decrease with increasing aluminium content.

A total of 45 samples were prepared for the tests, including 15 samples for the ballistic mortar test, 15 samples for the Trauzl lead block test, and 15 for the simultaneous measurement of the free field air blast wave and detonation velocity. Earlier studies of the time influence on the detonation velocity of tested explosive have shown that this parameter is highly variable [16]. Thus, in order to obtain reliable results, the samples were prepared separately and always tested after the same period of time following the beginning of the sensitisation reaction.

### 2.1. Ballistic mortar test

Determination of relative explosive strength is conducted using a standardised test facility. It consists of a ballistic mortar mounted on a ballistic pendulum at the end of which a firing chamber is located. A projectile in the form of a steel cylinder is inserted into the mortar. The sample is initiated using an 0.65 g PETN detonator. Following initiation, the projectile is fired from the mortar. As a result of forces acting in the opposite direction (recoil), the pendulum arm is propelled from the equilibrium position, and the maximum angle of swing is registered using a movable cursor on a graduated scale. The result is recorded as the angle of swing of the mortar. A view of the test facility and samples prepared for testing are presented in Figure 1.



(a)



(b)

**Figure 1.** Ballistic mortar (a) and explosive samples (b)

The angle of mortar swing is compared to that produced by the same mass of a reference charge of hexogen. The mass of the cylindrical sample (25 mm diameter) made into a cartridge in a tin foil wrapper, is 10 g. The test procedure is described in detail in Polish standard PN-C-86035:1999 [17]. Results are expressed as a percentage of that obtained for hexogen. A total of 15 emulsion explosive samples were prepared for the tests, differing in aluminium content (3 per each content) and 3 samples of the reference charge (hexogen).

## 2.2. Trauzl lead block test

This test is based on determining the expansion capacity produced by the detonation of 10 g of explosive in a cylindrical lead block with a diameter of 200 mm and height of 200 mm. In the centre of a solid block, a hole with a diameter of 25 mm and depth of 125 mm is located. The sample is initiated using an 0.65 g PETN detonator. The resulting expansion is compared to that produced with 10 g of picric acid with detonator (reference charge). Detonation of this charge at 15 °C results in a cavity of 310 cm<sup>3</sup>.

A total of 15 samples were prepared for the Trauzl test, including 3 samples for each aluminium content and 3 reference samples of pure picric acid recrystallised from water, dried and pressed to a density of 0.85 g/cm<sup>3</sup>. A view of the blocks prepared for the tests and the cross-section through a block before and after firing is presented in Figure 2.



(a)



**Figure 2.** Blocks prepared for testing (a) and cross-section through a block before firing (b) and after firing (c)

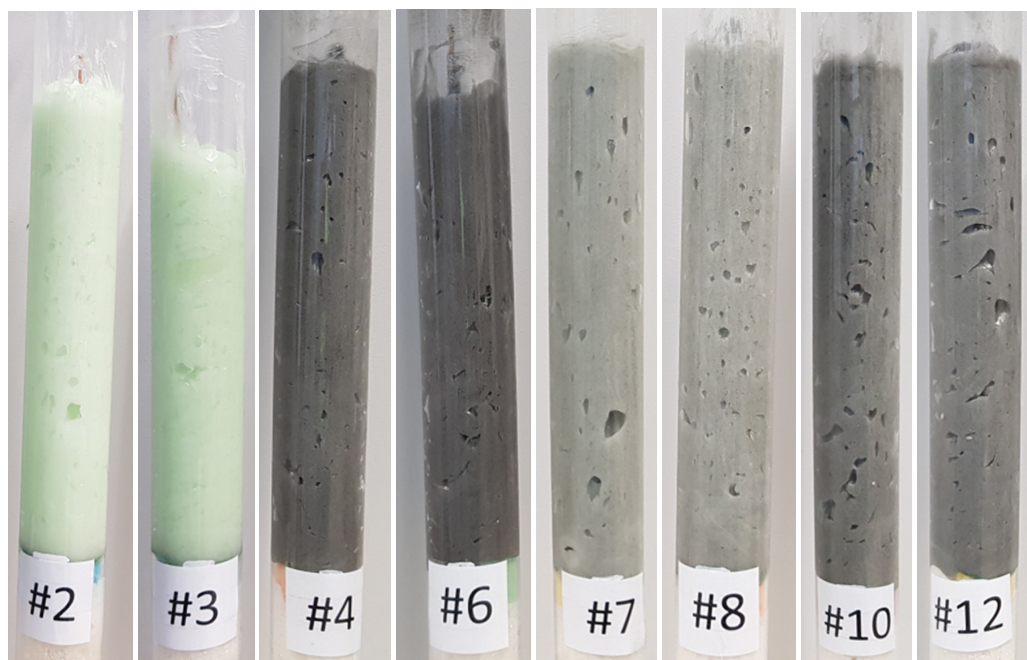
The difference between the initial volume of a lead block is then compared to the expansion produced by the explosive. Finally, the relative explosive strength is expressed as a percentage in relation to the reference charge. The test procedure is described in detail in Polish standard PN-C-86037:2000 [18].

### 2.3. Detonation velocity measurement

Detonation velocity is the velocity at which a given shock wave front propagates through an explosive charge. The technique is based on measuring the travel time of the shock front between two sensors. The procedure is described in detail in standard PN-EN 13631-14:2005 [19]. However, in this paper, the continuous method was applied using a MicroTrap VOD/Data Recorder. This method generates results complementary to those obtained using the standard method [20].

Measurements using the MicroTrap recorder utilise the widely known wire resistance technique. A precise probe of known linear resistance is placed axially along the direction of detonation inside the explosive sample. As the shock wave front propagates, the explosive consumes the probe, and the resistance of the circuit decreases in proportion to the decrease in the probe's length. A recorder registers the probe resistance change as a function of time.

Samples were prepared by filling clear glass tubes, length of 500 mm, internal diameter of 46.4 mm and wall thickness of 1.8 mm, with the explosive. The explosive components were blended manually in a glass beaker using a glass rod. Components were previously weighed using a laboratory balance (0.01 g resolution). In the first step, the matrix was blended with the aluminium granules and then the sensitiser was added. The net mass of a single sample was 500 g. A total of 15 samples were prepared, differing in aluminium content the range of 0-7%. The probe was inserted axially inside the explosive charge. A view of selected samples is presented in Figure 3.



**Figure 3.** View of selected samples for detonation velocity tests

The samples were taped to a dedicated stand and fired in a vertical position in an explosive bunker. The bottom of the charge was located 85 cm from the floor. An instantaneous 0.65 g PETN electric detonator was placed at the top of the charge. A view of selected samples prior to firing is presented in Figure 4.



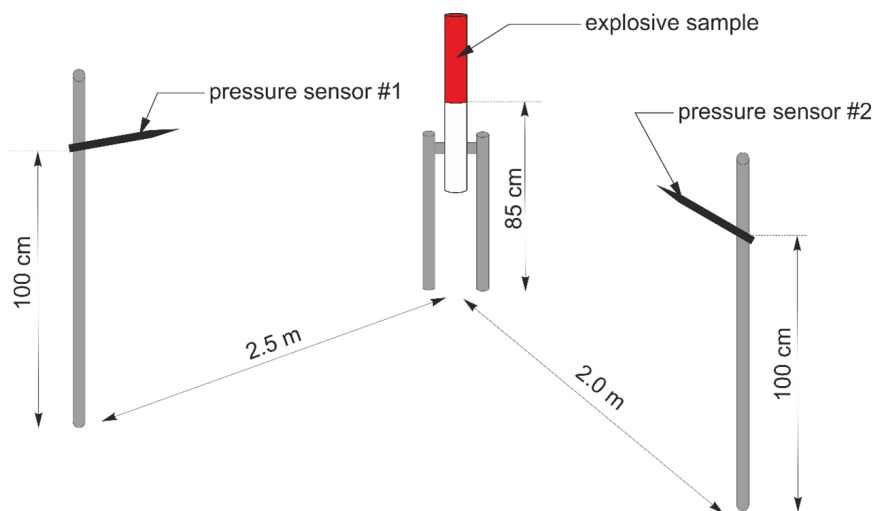
**Figure 4.** Selected samples prepared for firing

The same time of 60 min, between the blending of emulsion components and the sample being fired, was applied. As the components were blended manually, the interval between the firing of subsequent samples was approximately 15 min.

#### **2.4. Air blast testing**

Measurements of the free field air blast pressure were conducted using PCB 137B23B integral-electronics piezoelectric pressure sensors with a rise time of up to 6.5  $\mu\text{s}$  and a measuring range of 345 kPa. The tests were carried out in parallel with the detonation velocity measurements (for the same explosive samples). The sensors were placed 100 cm above the ground, at 2.0 and 2.5 m from the explosive sample. A diagram of the measuring system is presented in Figure 5.





**Figure 5.** Scheme of the air blast measurements

The data were recorded using a DEWESoft SIRIUS high-speed amplifier coupled with a computer. The sampling frequency was 1 MHz. Measurements were performed for each explosive sample. Peak overpressure, positive phase duration and positive phase impulse were determined from the data recorded on both sensors. Numerical integration, based on the trapezoidal rule (1  $\mu$ s time step size) was used to calculate the positive phase impulse.

### 3. Results

#### 3.1. Ballistic mortar

The results of explosive strength tests from the ballistic mortar, depending on aluminium content, are presented in Table 1. A relative value was determined for each aluminium content as an average based on 3 samples (same for samples of hexogen). Moreover, percentage values in relation to the samples without aluminium are presented. The relative explosive strength ( $X$ ) from the ballistic mortar was calculated using the following equation:

$$X = \frac{m_t}{m_r} \times 100 \quad [\%] \quad (1)$$

where  $m_t$  – arithmetic mean of  $(1 - \cos \alpha)$  for the tested explosive,  $m_r$  – arithmetic mean of  $(1 - \cos \beta)$  for the reference explosive.

The arithmetic means for the reference charge ( $m_r$ ) and tested explosives ( $m_t$ ) were calculated according to the following equations:

$$m_t = \frac{(1 - \cos \alpha_1) + (1 - \cos \alpha_2) + (1 - \cos \alpha_n)}{n} \quad (2)$$

$$m_r = \frac{(1 - \cos \beta_1) + (1 - \cos \beta_2) + (1 - \cos \beta_n)}{n} \quad (3)$$

where  $\alpha_1, \alpha_2, \alpha_n$  – angles of the pendulum swing for the tested explosive,  $\beta_1, \beta_2, \beta_n$  – angles of the pendulum swing for the reference explosive,  $n$  – number of tests.

**Table 1.** Results of ballistic mortar tests

|  | Aluminium content [%] |       |       |       |       |
|--|-----------------------|-------|-------|-------|-------|
|  | 0                     | 1     | 3     | 5     | 7     |
| Relative explosive strength ( $X$ ) [%]  | 80.4                  | 81.3  | 82.5  | 83.1  | 84.4  |
| Dependence of relative explosive strength in relation to explosive without aluminium [%] | 100.0                 | 101.1 | 102.6 | 103.3 | 105.0 |

Results indicate a linear increase in relative explosive strength on a ballistic mortar with increase in aluminium content. The linear correlation coefficient ( $r$ ) of this relationship is 0.67 with a coefficient of determination ( $R^2$ ) of 0.981. The maximum aluminium content of 7% resulted in a 5% increase in relative explosive strength.

### 3.2. Trauzl lead block

Results of the Trauzl tests in relation to the aluminium content are presented in Table 2. The net expansion volume was determined for each sample, and the average value was then calculated for a given aluminium content. As above, the table also presents the percentage increase of lead block volume in relation to samples without aluminium.

**Table 2.** Results of Trauzl tests

| Parameter  | Sample No. | Aluminium content [%] |       |       |       |       |
|--|------------|-----------------------|-------|-------|-------|-------|
|  |            | 0                     | 1     | 3     | 5     | 7     |
| Net expansion in a lead block [cm <sup>3</sup> ]   | 1          | 304.0                 | 323.5 | 325.5 | 358.5 | 359.0 |
|  | 2          | 304.0                 | 314.5 | 330.5 | 347.5 | 348.5 |
|  | 3          | 299.5                 | 320.5 | 322.0 | 340.0 | 352.5 |
|  | Average    | 302.5                 | 319.5 | 326.0 | 348.5 | 353.5 |
| Dependence of net expansion in a lead block in relation to explosive without aluminium [%] |            | 100.0                 | 105.6 | 107.8 | 115.2 | 116.9 |

The results showed that the volume in lead blocks produced by the detonation of explosive samples increases with increases in aluminium content. Within the considered ranges of added aluminium, the net expansion values ranged from 5.0 to 22.5 cm<sup>3</sup> per 2% added. The linear correlation coefficient of this relationship is 2.4 at a coefficient of determination of 0.944. The maximum volume was nearly 360 cm<sup>3</sup>, which corresponds to an increase of about 20%, compared to explosive samples without aluminium.

### 3.3. Detonation velocity

Detonation velocity was determined from the slope of the plotted curve based on any 2 points selected on the graph. The results are presented in Table 3. The recorded velocity values were rounded to 10 m/s. The table also shows the percentage change in detonation velocity compared to samples without aluminium.

**Table 3.** Results of detonation velocity tests

| Parameter  | Sample No. | Aluminium content [%] |      |      |      |      |
|--|------------|-----------------------|------|------|------|------|
|  |            | 0                     | 1    | 3    | 5    | 7    |
| Velocity of detonation [m/s]   | 1          | 4410                  | 4300 | 4350 | 4360 | 4270 |
|  | 2          | 4390                  | 4320 | 4360 | 4370 | 4270 |
|  | 3          | 4400                  | 4280 | 4340 | 4320 | 4300 |
|  | average    | 4400                  | 4300 | 4350 | 4350 | 4280 |
| Dependence of detonation velocity in relation to explosive without aluminium [%] |            | 100.0                 | 97.7 | 98.9 | 98.9 | 97.3 |

The obtained results do not indicate any significant influence of the added aluminium on the detonation velocity value. A slight decrease in velocity with increase in aluminium content can be observed. However, when considering average values, they do not exceed 120 m/s for 7% of aluminium. Bearing in mind that the uncertainty in the MicroTrap system is  $\pm 2\%$  of the measured value, then at an average velocity of 4400 m/s (without aluminium), the system generates an error close to 90 m/s.

### 3.4. Air blast

Results of the air blast tests recorded using the SIRIUS amplifier are presented in graphical form. Based on the obtained waveforms of pressure as a function of time  $p = f(t)$ , the positive phase impulse ( $I_s$ ) was calculated using the trapezoidal rule of numerical integration according to the following formula [21, 22]:

$$I_s = \int_{t_1}^{t_2} p(t) dt \quad [\text{Pa}\cdot\text{s}] \quad (4)$$

where  $t_1$  – positive phase start and  $t_2$  – positive phase end.

Given the amount of data, peak overpressure values as well as the positive phase impulses and positive phase durations were presented as average values determined on the basis of 3 test samples of explosive. Results, in the form of average values and degree of uncertainty, are presented in Table 4.

**Table 4.** Results of air blast tests (average values)

| Parameter                                  | Aluminium content [%] |                   |                   |                   |                   |
|--|-----------------------|-------------------|-------------------|-------------------|-------------------|
|  | 0                     | 1                 | 3                 | 5                 | 7                 |
| Peak overpressure $P_{s,2m}$ [kPa]         | 101.1 $\pm$ 1.3       | 105.3 $\pm$ 2.3   | 113.3 $\pm$ 3.4   | 110.1 $\pm$ 1.0   | 114.1 $\pm$ 2.2   |
| Peak overpressure $P_{s,2.5m}$ [kPa]       | 58.3 $\pm$ 1.8        | 58.9 $\pm$ 1.9    | 63.5 $\pm$ 1.7    | 62.9 $\pm$ 1.4    | 63.5 $\pm$ 0.7    |
| Positive phase duration $t_{s,2m}$ [ms]    | 1.126 $\pm$ 0.068     | 1.206 $\pm$ 0.014 | 1.231 $\pm$ 0.039 | 1.233 $\pm$ 0.034 | 1.244 $\pm$ 0.013 |
| Positive phase duration $t_{s,2.5m}$ [ms]  | 1.443 $\pm$ 0.004     | 1.492 $\pm$ 0.009 | 1.506 $\pm$ 0.002 | 1.537 $\pm$ 0.024 | 1.532 $\pm$ 0.002 |
| Positive phase impulse $I_{s,2m}$ [Pa·s]   | 45.4 $\pm$ 0.7        | 46.7 $\pm$ 0.2    | 48.2 $\pm$ 0.2    | 49.0 $\pm$ 0.2    | 50.3 $\pm$ 0.1    |
| Positive phase impulse $I_{s,2.5m}$ [Pa·s] | 36.0 $\pm$ 0.4        | 36.5 $\pm$ 0.1    | 37.5 $\pm$ 0.1    | 38.6 $\pm$ 0.1    | 39.8 $\pm$ 0.1    |

The results indicate that peak overpressure, positive phase duration and positive phase impulse, increase with increases in aluminium content. A comparison of the blast overpressure waveforms measured during detonation of an explosive sample with 7% aluminium and without aluminium is presented in Figure 6 (values averaged from 3 samples). The peak overpressure for the explosive without aluminium, at a distance of 2.0 m from the detonated sample, was approximately 101 kPa, and 58 kPa at a distance of 2.5 m. In turn, the peak overpressure measured for the sample with 7% of aluminium were 114 and 63 kPa, respectively. This indicates an increase of nearly 13% in air blast pressure at a distance of 2.0 m and nearly 9% at a distance of 2.5 m from the detonation. Furthermore, an increase in blast wave impulse duration was observed with increases in aluminium content. This was 0.118 ms at the sensor located 2.0 m from the sample and 0.089 ms at 2.5 m, which indicates an increase of 10.5 and 6.1% respectively compared to explosive samples without aluminium. In order to determine the influence of added aluminium on these parameters, percentage increases of air blast parameters were calculated with reference to an explosive without aluminium. Then, percentage increases recorded by the sensors located 2.0 m and 2.5 m from the detonated sample were averaged. Results are presented in Figure 7.

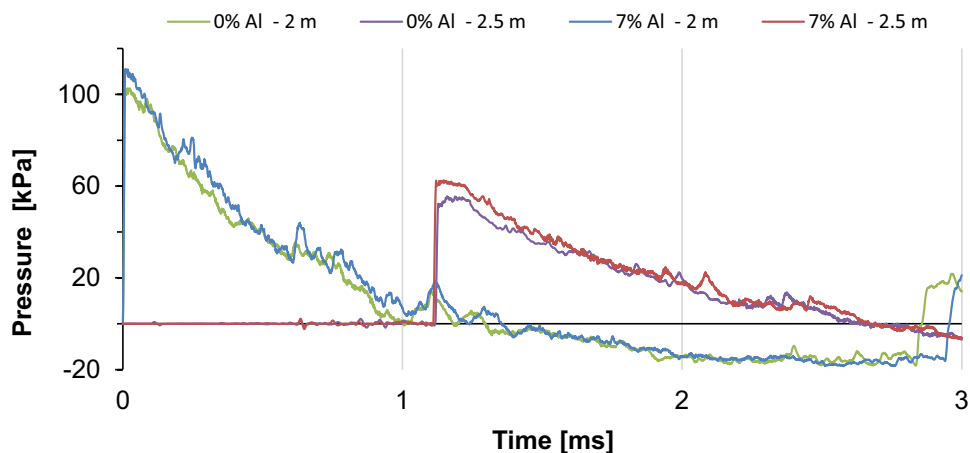


Figure 6. Blast pressure waveforms for 0 and 7% aluminium

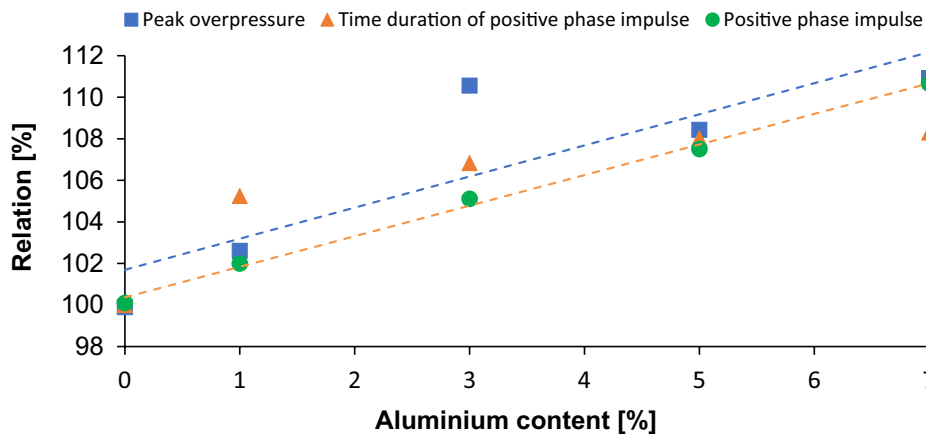


Figure 7. Percentage increases of the air blast parameters depending on aluminium content

The results show that the relationship between aluminium content and peak overpressure and positive phase impulse, is linear within the studied aluminium content range. The linear correlation coefficient of the peak overpressure is 1.49 at a coefficient of determination of 0.748. The linear character of this relationship is disrupted by the result obtained for the 3% content, for which the greatest dispersion of results around the average value was observed. Therefore, positive phase impulse seems to be the more suitable parameter for comparison of air blast characteristics. This allows any disturbances in the results to be filtered out. Thus, results are significantly improved and a smaller dispersion around the average value is observed. The linear coefficient of the positive phase impulse is 1.48, but at a much greater  $R^2$  coefficient of 0.996. In turn, the relationship of positive phase duration and aluminium content is not linear. For 1% of aluminium additive, the observed phase duration increase was 5.2%, whereas a 7% addition resulted in an increase of 8.3%, compared to an emulsion explosive without aluminium.

## 4. Discussion

Based on the presented analysis, one may conclude that no significant improvement was found by adding aluminium at an economically justified level and the detonation parameters of bulk emulsion explosives. Admittedly, the free field air blast parameters may be enhanced, but this is more important in military technology than mining. This is related to the influence of the blast pressure on a remote environment, which is not directly associated with rock fragmentation.

Determination of explosive strength using both methods, revealed divergent results. However, a linear increase in energetic parameters with an increase in aluminium in the range 0-7%, was observed. The least effect of aluminium addition was noticed in the ballistic mortar test, in which the linear correlation coefficient was 0.67. It can therefore be concluded that aluminium added to the tested emulsion explosive has a minor influence on brisance. In turn, the linear coefficient of the explosive strength in the Trauzl test was 2.40, which is over 3.5 times greater than that obtained with the ballistic mortar. This may indicate that addition of aluminium affects an improvement in the energetic properties of the analysed emulsion explosive, but that only a part of that energy is directly related to brisance, which is significant from a rock excavation point of view.

It should be noted that samples used for determining relative explosive strength with the ballistic mortar and Trauzl test are relatively small. When testing bulk emulsion explosives, some deviations and errors may occur. This is because the detonation process in such small samples is not fully developed and the detonation parameters do not achieve their optimal values. Furthermore, chemically sensitised emulsion explosives exhibit limited stability compared to those sensitised by a physical method. The placing of a detonator in a charge or handling such a small charge, can result in damage to the sensitised structure and migration of gas bubbles, which are the key factors influencing the initiation and detonation parameters. Preparation of small samples of sensitised explosive may also affect the accurate reproducibility of results.

The air blast test of a detonation of 500 g of bulk emulsion explosive, seems to be a more relevant approach. Results indicate a linear relationship between the positive phase impulse and aluminium content. In turn, the relationship between the aluminium content and positive phase duration demonstrates a significant increase for 1% of aluminium additive. Further increases in aluminium content do not correspond to the increase in positive phase duration. This is probably related to the fact that the addition of aluminium greater than 1% in the analysed case, does not react with the oxygen originating from the oxidiser phase of the matrix.

Another major issue is the addition of aluminium at the matrix production stage, which is associated with the use of additional dosing systems. The matrix of emulsion explosives is thermodynamically unstable, and any additions or inclusions have a negative influence on their stability. Moreover, they may accelerate the crystallisation process. The mixing-charging units used in Polish copper mining are equipped with static mixing devices in the form of a cross-stream static mixer. The pumping of a crystalline matrix, apart from the obvious influence on detonation parameters, results in the clogging of mixing devices. This in turn leads to increases of pressure above permissible values, which will stop the loading.

It should also be noted that an explosive matrix is delivered from the production plant to mines in tanker trucks or IBC tanks of 5.1 transport class (oxidising agents). An aluminium addition of 3% or greater may result in sensitisation of the matrix, thus changing its transport class to a higher, more restrictive, classification. It may also create an additional risks at the production stage. In most cases, infrastructure elements such as pipelines or storage tanks are not banded, and therefore they do not need to fulfil the strict requirements concerning transport and storage of explosives, since a pure emulsion matrix is not capable of detonation.

The last issue which needs to be raised is the presence of toxic aluminium oxides in the post-blast gases. This is particularly significant in underground mining. Explosives with added aluminium generate quantities of aluminium oxide nanoparticles during detonation, which has a negative impact on a mine's atmosphere, but may also increase the exposure risk of mine workers to potentially pathogenic agents [23].

## 5. Conclusions

The presented analysis concerning the influence of aluminium additives to selected detonation parameters of bulk emulsion explosives, has confirmed certain relationships between these factors. With an increase in aluminium content, the density of the analysed explosive initially decreases, and subsequently stabilises. With increases in aluminium content, the amount of oxygen in the oxidiser phase of the matrix is insufficient to burn the excess metal, which should result in a reduction of detonation velocity. However, within the considered range of aluminium addition, no significant influence on the detonation velocity was found, though a minor decrease with an increase in aluminium content was noted.

While the tests of relative explosive strength using ballistic mortar and Trauzl blocks may not reflect real detonation parameters due to the size of the sample, comparison of results obtained for the same explosive and under the same conditions, represents their character. The detonation velocity measurements and air blast tests were performed using much bigger samples. Diameters of charges were much greater than the critical diameter of the analysed explosive. This means that simulation of practical conditions was more realistic. Thus, correlation of the results from all test types is not an appropriate approach. However, certain conclusions can be drawn regarding the relationships between aluminium content and the strength and energy properties of explosive under given conditions.

From the results obtained, it can be concluded that addition of aluminium in the case of the analysed explosive affects the improvement of the detonation parameters (proportionally to the content), except the detonation velocity, which slightly decreases with an increase in aluminium content. This means that the general thermodynamic characteristic does not change significantly. The obtained results have proven that further research on alternative solutions aimed at enhancing the detonation parameters of chemically sensitised bulk emulsion explosives is justified.

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