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The effect of blasting using low-density emulsion explosives

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Keywords
blasting; low-density explosive; work capacity; seismic effect

RESEARCH ARTICLE

The effect of blasting using low-density emulsion explosives

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Abstract

Low-density emulsion explosives are essentially blends of an emulsion matrix and a certain amount of gaseous phase inclusions acting as hot spots. With the addition of expanded polystyrene for gaseous sensibilization, the resulting explosive blend was developed to reduce peak values and pressure impulse of gaseous detonation products on surrounding rock. This resulted in a decrease in rock stress and a decrease in cracking zone width outside of the minefield boundary. The use of low-density emulsion explosives correlates with the decrease in the seismic effect of blasting, more precisely, the decrease of induced rock oscillation velocities.

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Keywords: Blasting, Low-density explosive, Work capacity, Seismic effect

1. Introduction

Blasting is used in mining and civil engineering as a technological process that utilizes the energy of the explosive in rock mass fragmentation (extraction of mineral resources), excavation of underground chambers, demolition, and many other technological applications (cutting, perforating, compacting, shaping, welding). The key element of blasting to extract mineral resources is to obtain the most rock mass fragmentation possible with the lowest unit costs and adequate granulometry. On the other hand, the key element of (underground) chamber excavation is the reduction of surrounding rock mass damage to preserve the initial physical-mechanical rock properties for long-term stability.

Detonation energy released during the detonation process firstly affects the surrounding area with the compressed gaseous detonation product impact, which results in primary rock crushing. During the expansion of the detonation products, the rock mass is affected by a secondary expansion effect: the gaseous detonation products enter newly formed and pre-existing cracks, resulting in further crushing and fragmentation of the rock mass. Additionally, the rock mass is shifted from its initial position. The expansion pushing effect lasts until the gaseous detonation product pressure is equalized with atmospheric pressure.

The effect of the explosive charge on a rock mass is considered optimal when the released detonation energy is fully utilized for rock crushing. In that case, the unwanted effects of blasting, such as negative seismic effects and material scattering, are minimal. The reduction of the explosive charge impact, i.e. the reduction of the compressed detonation product pressure, is linked to the kinetic energy of the detonation product impact. That kinetic energy can be reduced by reducing explosive density or borehole loading density.

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1.1. Previous research

The explosives with an initial density lower than 0.80 g/cm^3 are called low-density explosives (LDE), while those with an initial density lower than 0.20 g/cm^3 are called ultralow-density explosives (ULDE) [1].

The primary use of LDE is in specific blasting:

- For uniform rock fragmentation, i.e. the reduction in the fine fraction (< 1 mm).
- For cost reduction.
- For minimalization of the seismic effect and the damage to the surrounding area outside of the blast field boundaries.

The basic principle of LDE is adding a low-density material to an existing explosive at a certain ratio. The materials used to lower the initial density of explosives can be divided into two groups:

- Inert materials (perlite, vermiculite, glass microspheres, plastic microspheres, etc.).
- Combustible materials, i.e. the materials that can oxidize (polystyrene, expanded polystyrene, polyurethane foam, coal, sawdust, wood flour, cellulose granules, etc.).

The first research on the development of LDE started in the 1960s with the addition of various low-density materials to commercial ANFO explosive. The main goal was to develop simple to use and cost-effective explosive with adequate detonation characteristics [1,2]. Similar research was done in Norway, where the blend of ANFO and sawdust in a 50:50 volume ratio was used in blasting [3]. The authors were among the first to use varying ratios of expanded polystyrene (EPS) in LDE development to preserve the stability of contours [1]. The first commercialized LDE was Isanol, an ANFO explosive with EPS addition [3–5]. After that, the modification of ANFO and its detonation parameters by decreasing its density was further researched by the addition of polystyrene [6], expanded polystyrene [1,7–9], sawdust [10,11], sawdust and used mineral oil [12], organic waste from sugar manufacturing [2,12], perlite [13–15], rubber [16], corn, coal and fly ash [17], wheat husk [18] and rice husks [5]. Overall, the density of these blends went down to 0.15 g/cm^3 and reported detonation velocities varied from 1.8 km/s to 3.5 km/s. Also, the research has shown that the decrease in density results in a decrease in detonation velocity, detonation pressure, surrounding rock stress, and seismic effect while still providing satisfactory rock fragmentation.

Apart from ANFO, the decrease in explosive density has also been applied to emulsions and water gels:

- Authors reduced the density of emulsion explosive by mixing three different emulsion matrices with 1.5 wt% of glass microspheres, non-expanded polystyrene, perlite, or sawdust. The resulting densities varied from 0.8 g/cm^3 to 1.05 g/cm^3, and measured detonation velocities were from 3.0 km/s to 5.1 km/s [19].
- Authors developed a Low Strength Water Gel Explosive by adding ammonium nitrate and expanded polystyrene prills to water gel explosives. The resulting densities varied from 0.4 g/cm^3 to 0.7 g/cm^3 and measured detonation velocities from 2.4 km/s to 3.0 km/s [20].
- Authors reduced the initial density of water gel explosive to 0.5 g/cm^3 for contour blasting in Ø270 mm boreholes [21].
- Authors used low-density emulsion explosive for explosive welding. The decrease in density was obtained by increasing the mass percentage of glass microspheres until 0.5 g/cm^3 initial density, resulting in detonation velocities from 1.8 km/s to 2.1 km/s [22].
- Authors patented a low-density emulsion explosive derived from an emulsion matrix sensitized by nitrogen bubbles with initial density ranging from 0.5 g/cm^3 to 0.9 g/cm^3 [23].
- Authors produced a novel low-density dry bulk explosive PANFO based on ammonium nitrate-coated expanded perlite and fuel oil. The initial density varied from 0.4 g/cm^3 to 0.45 g/cm^3 and measured detonation velocities from 1.8 km/s to 2.0 km/s [24].
- Authors reduced the density of emulsion explosive by mixing expanded polystyrene prills and mechanically shredded expanded polystyrene. The resulting densities varied from 0.16 g/cm^3 to 0.64 g/cm^3 and measured detonation velocities from 1.4 km/s to 2.3 km/s for emulsion explosive with expanded polystyrene prills. The resulting densities varied from 0.58 g/cm^3 to 0.92 g/cm^3 and measured detonation velocities from 2.2 km/s to 3.2 km/s for emulsion explosive with expanded polystyrene prills [25].
- Authors varied the density of emulsion explosive from 1.1 g/cm^3 to 0.65 g/cm^3 by chemical gasification [26].
- Authors measured the detonation velocity and the intensity of the air blast for different wt% of an aerating agent, i.e. plastic microballons [27].
- Authors studied nonideal detonation regimes in low-density HMX, RDX, PETN and emulsion explosives [28].

- Authors used Flexigel, a solid sensitized emulsion blend that can be pumped into a borehole, to reduce blast-induced vibrations and blasting cost. The initial density varied from 0.8 g/cm^3 to 1.1 g/cm^3 and detonation velocity from 2.0 km/s to 4.2 km/s [29].
- Authors analyzed the influence of the density of emulsion explosives on the velocity of its detonation and fragmentation of blasted muckpile. Low-density explosive was made with the inclusion of expanded polystyrene beads and expanded perlite combination with equal percentage by weight in the ratio 50:50 with densities varied from 0.6 g/cm^3 to 1.1 g/cm^3 [30].
- Authors studied the possibilities of detonation propagation in low-density explosives [31].
- Authors researched the possibility of reduction of blast-induced ground vibrations, i.e. seismic effect, using low-density emulsion explosives for environmentally sensitive areas. The use of LDE, compared to regular emulsion explosives, reduced ground oscillation velocities by 40% [32].
- Authors lowered the density of the emulsion explosive by 10% to improve blasting quality [33].

2. Description of experimental methods

The main research goal for a suitable low-density emulsion explosive was the determination of the best ratio of matrix and EPS in regard to the best detonation properties achieved and homogeneity retention during preparation and usage. In this respect, there should not come to component segregation from the time of blend preparation to the time of use. The emulsion matrix and EPS ratio varied from 50:50 to 10:90 (the ratio changes by 10%), resulting in the initial density range from 0.627 g/cm^3 to 0.085 g/cm^3. The data from the manufacturer of the used emulsion matrix are shown in Table 1 and the structure of the LDE is presented in Figure 1. The diameter of EPS prills used was 1.5–3.5 mm and acted as hot spots during a detonation process, as well as contributed to the total energy due to their composition. The performance of the low-density blends was compared to the reference explosives: pentrite

Table 1. *Data of the emulsion matrix [34].*

Quality mark	Unit	Value
Nitrogen	%	24,8–26,5
pH (oxidizer solution)	–	4,3
Density	g/cm^3	1,40
Viscosity at 25°C (spindle n° 7, 20 rpm)	poise	270

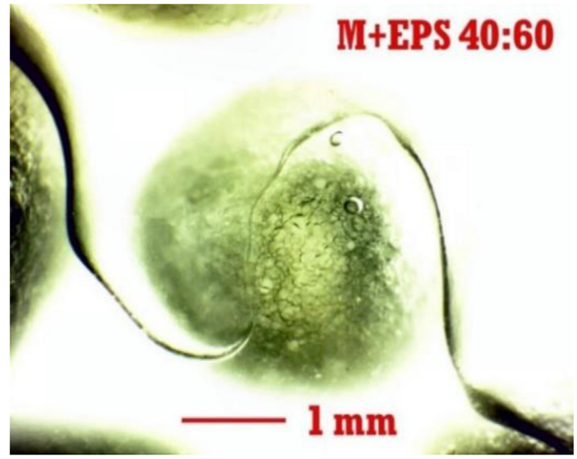

Fig. 1. Emulsion matrix and EPS blend in 40:60 volume ratio (40 × magnification, microscope BIM 313T).

(ρ = 1.126 g/cm^3), glass microballons sensitized emulsion explosive (ρ = 1.175 g/cm^3), and classical ANFO explosive (ρ = 0.838 g/cm^3; ammonium nitrate: fuel oil 94.5:5.5).

To determine the work capacity of low-density explosives, based on matrix and EPS, on rock mass, the following methods have been used:

- Detonation velocity measurement in boreholes and charges confined in steel tube.
- Modified crater test – determination of the breakage volume.
- Granulometry analysis of the blasted material.
- Determination of the oscillation velocities.

The work capacity of the explosive is determined as a measure of the detonation effect in a medium and the conditions of energy transfer into a medium, in this case, rock material. It is not unambiguously defined, but its expression depends on the experimental method used. To start, the work capacity depends on theoretical detonation energy, energy losses, and energy transfer dynamics. In the end, the mechanical work during the expansion of the detonation products in a rock mass is used for fracturing, fragmenting, and general moving of the blasted rock mass. From the hydrodynamic detonation theory, it follows that the available energy of an explosive can be, in ideal conditions, consumed for mechanical work (E_e) on the surrounding material reduced for compression energy (E_c), and, to a lesser extent, heat losses during the expansion. The graphical representation of the detonation energy available for mechanical work is represented by the surface area under the detonation product adiabat (Fig. 2).

The detonation energy available for mechanical work (E_e) can also be given as:

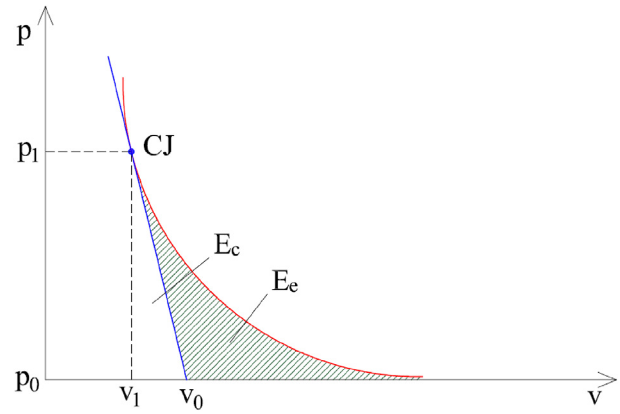

Fig. 2. The detonation energy available for the mechanical work.

$$E_e = -\int_{v_0}^{v_{cj}} p_{cj} dv - \frac{u^2}{2} \tag{1}$$

where E_e is the detonation energy available for mechanical work (kJ/kg), p_{cj} is the detonation pressure in the CJ state (Pa), v is the specific volume (m^3/kg), u is the particle flow velocity (m/s) and $u^2/2$ (or E_c) is the compression work (kJ/kg).

2.1. The determination of detonation velocity in boreholes and of charges confined in steel tube

The detonation velocity is a measure of the work capacity of an explosive, but its value also directly impacts the detonation pressure and the pressure impulse in the borehole. The pressure dependence is usually given as:

$$p_d = \frac{\rho v_d^2}{(1+\gamma_{CJ})} \tag{2}$$

where p_d is the detonation pressure (GPa), ρ is the explosive density (kg/m^3), v_d is the detonation velocity (m/s), and γ_{CJ} is the adiabatic expansion coefficient of the gaseous detonation products in the CJ state. That γ_{CJ} depends on the explosive and the detonation conditions. For most solid-state explosives having initial densities between 1.0 and 1.8 g/cm^3, γ_{CJ} equals approximately 3, resulting in:

$$p_d = \frac{\rho v_d^2}{4} \tag{3}$$

The detonation velocity in charges confined in a steel tube was compared between the low-density explosive and referent explosive (pentrite), ANFO, and emulsion explosive. The measurements were made using a discontinuous electrooptical method, and the distribution of the detonation velocity was obtained for nine segments along the charges confined in a steel tube of 1000 mm length and initial diameter of 25 mm (Fig. 3). Optical fibres were placed along the charge axis at even distances (50 mm), with the first sensor at a minimum of 100 mm from the initiation point. The detonation velocity was determined by measuring the time of arrival at nine different positions (segments) along the charge axis, and the mean value from 1st to 9th segment of detonation velocity was taken. The same comparison was made for detonation velocity in the boreholes, diameter of 32 mm with explosive in PVC charges (diameter of 25 mm) and depth of 1000 mm (Fig. 4), but only two optic fibres were used, resulting in steady-state detonation velocity near the end of the explosive charge. For both measurements, the initiation was performed using electric detonators of the same type and equal properties; the strength of a blasting cap no. 8 and blastholes are fired one by one. The results of the detonation velocity measurement are given later (3. Results and discussion).

Fig. 3. The steel-charge detonation velocity measurement setup.

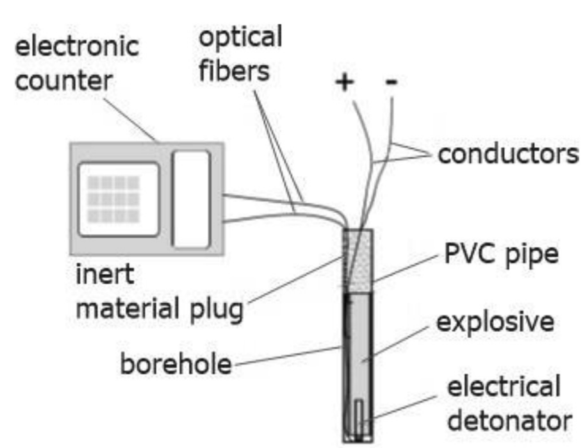

Fig. 4. The borehole detonation velocity measurement setup.

2.2. The modified crater test — the determination of the breakage volume

The methodology of the crater test was developed in the 50s by C.W. Livingston, who concluded that the degree of the transferred energy through a material depends both on the explosive properties and material properties. Also, the energy transfer through the solid materials remains the same either if the mass of the explosive increases at a constant depth of the borehole or the depth of the borehole decreases with a constant mass of the explosive [35].

In the case of this study, the mass of the explosive was varied, while the depth of the borehole was kept constant to determine the performance of the LDE on the rock mass. Table 2 gives details of the blasted rock mass; diabase, which is characterized by high compression strength and high impact and wear resistance.

A total of 25 boreholes were drilled, i.e. five boreholes each for emulsion explosive and for each mixture of emulsion matrix with granulated EPS. Borehole characteristics were kept the same: 32 mm diameter and 240 mm depth. The same was applied to the charges themselves: light PVC confinement with an outer diameter of 25 mm and constant length to ensure the same volume of explosive, while the mass of the explosive varied. The charges were placed up to 2/3 of the borehole depth. The boreholes were covered with a geotextile on which larger chunks of stone were placed to prevent the material from scattering in the borehole after the explosive charge was detonated. The explosive charges were detonated from the bottom of the borehole using electric detonators of the same type and characteristics and with the same energy as the energy of reference detonator No. 4. Each explosive charge in the borehole was detonated separately. The detonation velocity and oscillation velocity were measured for each blast. After each blast, the material was manually removed from the formed hopper and taken to the laboratory, where the volume of the blasted material and its grain size were determined. The depth and radius of the crater created by the blast were also determined on site. The volume of the blasted material and its grain size were determined in the laboratory. The depth and diameter of the hooper were measured.

In the laboratory, the granulometry analysis was performed on the blasted rock mass to determine the percentage of each particle size sieved (4 mm, 8 mm, 16 mm, 32 mm, 50 mm, and 70 mm). The results of the granulometry analysis are given later (3. Results and discussion).

Table 2. Physical and mechanical characteristics of diabase [36].

DIABASE		
Density	2.85–3.15	g/cm^3
Spatial mass	2.8–3.1	g/cm^3
Porosity	0.1–1	% volume
Water absorption	0.2–1	% mass
Compression strength	200–400	MPa

2.3. The determination of oscillation velocities

As mentioned, not all energy released during the detonation process is used for rock fracturing and fragmenting. Some of the released energy is distributed radially from the place of initiation in the form of elastic waves of different velocities and intensities [37]. With the increase of the distance from the point of initiation, the energy is dissipated, and the oscillation amplitude exponentially decreases. The stress in the rock mass or building caused by blasting can be expressed as:

$$\sigma = \frac{v\,E}{c} \tag{4}$$

where σ is the stress (Pa), v is the oscillation velocity (m/s), E is the modulus of elasticity (N/m^2), and c is the wave propagation velocity (m/s). Considering that the modulus of elasticity is characteristic of the surrounding material, and, in the case of this study, unchanged for all boreholes, the stress is directly dependent on the oscillation velocity. On the other hand, the oscillation velocity depends on the explosive characteristics, the mass of the explosive, and the distance from the blast site. By reducing the oscillation velocity while achieving satisfactory rock fragmentation, the risk of a potentially negative effect of blasting on the environment is drastically reduced.

In this study, the ground oscillation velocities were measured for 27 boreholes: 5 per each matrix/EPS blend, 5 for pure emulsion, 1 for pentrite, and 1 for ANFO, and the measurement setup is shown in Figure 5. In total 6 seismographs were used, 3 per line spread apart 2 m. The lines were perpendicular to each other. This setup allowed for the calculation of the amplitude attenuation and the analysis of data in different directions.

3. Results and discussion

The mean value of measured detonation velocities on 5 samples for low-density emulsion explosive blends (LDE), pure emulsion explosive, ANFO, and pentrite both in boreholes and in charges confined in steel tube are given in Table 3, while the

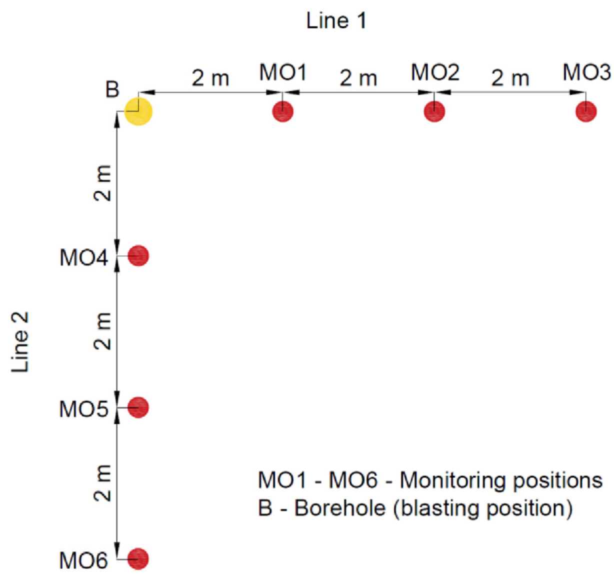

Fig. 5. Oscillation velocity measurement setup.

dependence of detonation velocity of LDE on the initial density both in the borehole and in charges confined in steel tube (different matrix/EPS blends) is shown in Figure 6.

The dependence of the detonation velocity of LDE on the initial density both in the borehole and in charges confined in a steel tube (different matrix/EPS blends) is shown in Figure 7. Except for the already mentioned slight differences in the detonation velocities in the borehole and in charges confined in a steel tube, the trend of decreasing detonation velocity with the decrease in the initial density is the same. The lowest value of a steady-state detonation velocity was obtained for an initial density of 0.218 g/cm^3 (M : EPS 20:80). The addition of 50 vol% of EPS reduced the density by 60% compared to pure emulsion explosive, and the detonation velocity 62% in boreholes and 57% in charges confined in steel tube.

The specific breakage volume was calculated, and the results are given in Table 4, while Figure 8

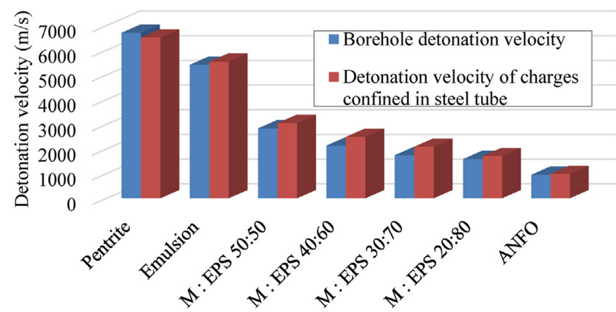

Fig. 6. The confinement effect on the detonation velocity of different explosives.

shows the crater formed with the largest specific breakage with M + EPS 40:60.

Figure 9 presents the grouping of the specific breakage vs. crater depth data in a diabase rock mass for each explosive blend used in this paper. The highest value of the specific breakage in relation to the crater depth was obtained for matrix/EPS blend 40:60 (ρ = 0.437 g/cm^3), with satisfactory results also obtained for matrix/EPS blend 50:50 (ρ = 0.627 g/cm^3), pentrite and ANFO. The optimization of the crater depth-specific breakage relation (the highest value of the crater depth with the highest value of the specific breakage) has been shown to affect the drill depth during blasting.

Regarding blasting as a way of rock exploitation, a uniform distribution of larger fractions, with as little as possible fine fraction, is considered the most satisfactory. The excess amount of the fine fraction is related to a too strong explosive impact on the rock mass and not enough pushing effect responsible for fragmenting. Another negative impact of too high impact is higher values of the oscillation velocities, covered in the following section.

The results of the granulometry analysis are given in Figure 10 and Table 5. As expected, the highest amount of fine particles (< 4 mm and 8–4 mm) is obtained for pentrite, which has the highest impact

Table 3. Measured detonation velocities in boreholes and charges confined in steel tube.

Explosive	Density ρ (g/cm^3)	Borehole detonation velocity (m/s)	Detonation velocity of charges confined in steel tube (m/s)	% difference in detonation velocity
Pentrite	1.148	6706	6517	2.85
Emulsion	1.175	5408	5534	2.30
Matrix: EPS 50: 50	0.627	2836	3051	7.30
Matrix: EPS 40: 60	0.437	2136	2491	15.34
Matrix: EPS 30: 70	0.302	1746	2089	17.89
Matrix: EPS 20: 80	0.218	1590	1710	7.27
ANFO	0.838	952	985	3.41

Note: measurement uncertainty $U = v \pm 75$ (m/s).
EPS = expanded polystyrene Ø1.5–3.5 mm.

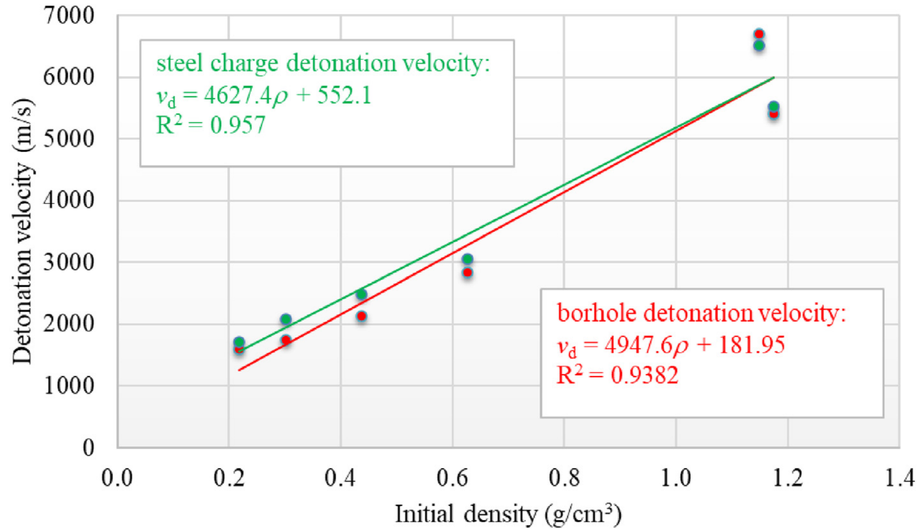

Fig. 7. The dependence of detonation velocity of LDE on the initial density.

Table 4. The average of crater test measurements for different explosives in diabase (ρ = 2.9 g/cm³).

Explosive	Mass of mined material (g)	Crater depth (mm)	Mass of explosive (g)	The volume of the blasted material (cm³)	Specific breakage = volume of the mined material/mass of explosive (cm³/g)
Pentrite	38,825	205	72.03	13,388	185.86
ANFO	26,110	105	66.03	9003	136.35
Emulsion	18,065	150	72.81	6229	85.55
M: EPS 50: 50	16,796	142	42.20	5792	137.30
M: EPS 40: 60	15,741	135	33.67	5428	161.20
M: EPS 30: 70	10,441	104	23.60	3600	152.52
M: EPS 20: 80	2943	79	15.63	1015	64.80

Fig. 8. The crater formed with the largest specific breakage (M + EPS 40:60).

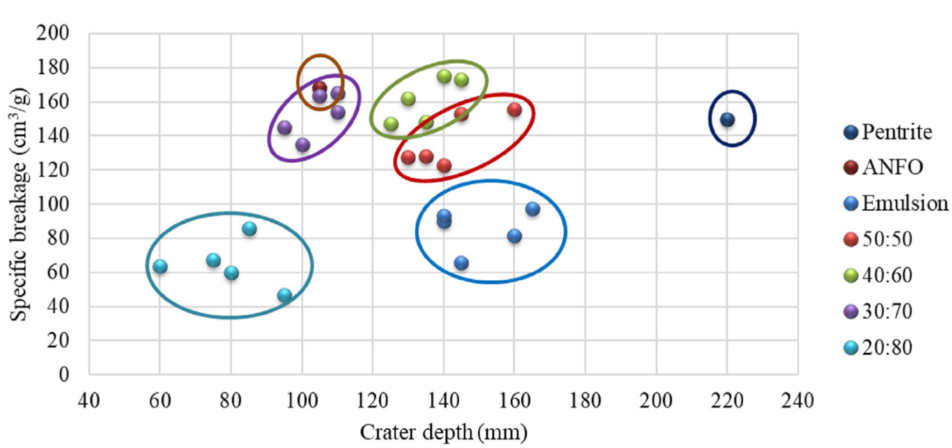

Fig. 9. The grouping of the specific breakage (V/Q) — crater depth (h_L) data.

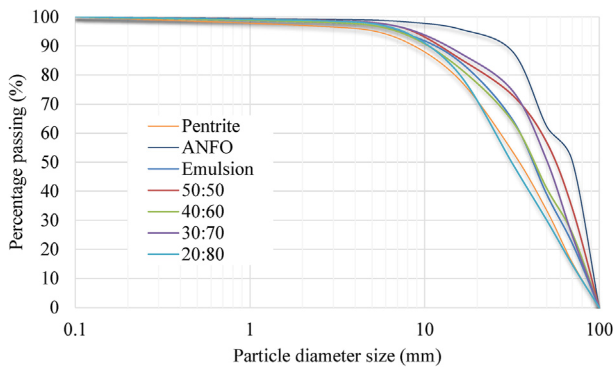

Fig. 10. The granulometry curve of the blasted material.

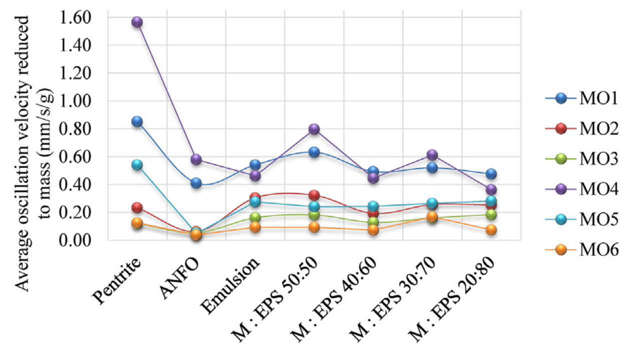

Fig. 11. The average PVS value reduced to mass on line 1 and on line 2 for different explosives.

effect. Based on the experimental data, the matrix/EPS blend 40:60 (ρ = 0.437 g/cm^3) results in the optimum relation of the needed larger fraction in the blasted material and the decrease of the negative impact of blasting on the environment. This goes to show that the reduction of the impact effect of the explosives, and consequently reduction of the negative seismic effect on the environment, can be achieved with the low-density emulsion explosives based on an emulsion matrix and EPS blend.

The average values of the measured oscillation velocities reduced to a mass of explosive are given in Table 6. The reduction to mass was needed to be able to compare the measured data since the initial density and mass of the explosive changed, while the volume of the explosive was kept constant:

$$v_m = \frac{v_{average}}{m_E} \tag{5}$$

where v_m is the oscillation velocity reduced to mass ((mm/s)/g), $v_{average}$ is the average value of the measured oscillation velocity ((mm/s)/g), and m_E is the mass of the explosive per borehole (g).

Figure 11 shows the average value of measured oscillation velocity reduced to mass for each explosive measured on the observation sites on line 1 and line 2, respectively. The lowest oscillation velocities in both directions are obtained for ANFO explosive, which is not surprising since ANFO also resulted in the lowest measured detonation velocity. Also, ANFO was initiated only using a detonator, not a booster, which contributes to the lower values of the detonation and oscillation velocity. Besides ANFO, low oscillation

Table 5. The granulometry analysis of the blasted material.

Explosive	Granulometric fractions of the blasted rock material (%)						
	> 70 mm	70–50 mm	50–32 mm	32–16 mm	16–8 mm	8–4 mm	< 4 mm
Pentrite	14.72	17.83	20.26	24.94	12.79	4.95	4.51
Emulsion	22.12	16.85	25.46	20.03	9.55	3.60	2.39
M : EPS 50:50	34.18	22.64	16.12	12.60	10.18	2.71	1.57
M : EPS 40:60	25.56	15.47	22.85	18.31	11.44	4.02	2.35
M : EPS 30:70	24.83	25.82	23.79	13.06	8.34	2.55	1.61
M : EPS 20:80	14.79	15.26	19.26	30.58	14.4	3.93	1.78
ANFO	49.57	11.92	25.85	7.81	2.65	0.99	1.21

Table 6. The measured oscillation velocities.

Explosive	The average value of measured oscillation velocity reduced to mass ((mm/s)/g)						Mass of explosive (g)
	Line 1			Line 2			
	MO1	MO2	MO3	MO4	MO5	MO6	
ANFO	0.410	0.062	0.054	0.579	0.048	0.038	66.03
Emulsion	0.541	0.304	0.161	0.462	0.275	0.094	72.81
M : EPS 50:50	0.632	0.322	0.181	0.796	0.239	0.093	42.29
M : EPS 40:60	0.493	0.192	0.128	0.446	0.242	0.073	33.67
M : EPS 30:70	0.520	0.256	0.160	0.612	0.264	0.168	23.60
M : EPS 20:80	0.476	0.253	0.183	0.362	0.281	0.074	15.63
Pentrite	0.852	0.233	0.120	1.566	0.541	0.124	71.98

velocity was also obtained for the matrix/EPS blend 40:60 ($\rho = 0.437$ g/cm^3) in both directions.

4. Conclusions

The crater test was performed to determine the work capacity of low-density emulsion explosive on rock mass and to determine the optimal emulsion matrix-to-EPS blend for blasting in the tested rock mass. The highest value of specific breakage compared to achieved crater depth was obtained for blend 40:60 (40% emulsion matrix and 60% expanded polystyrene, $\rho = 0.437$ g/cm^3). Good results were also obtained for blend 50 : 50 and ANFO explosive, while pentrite resulted in the highest value of crater depth and specific breakage.

The results of the granulometry analysis showed the uniform distribution of larger fractions for blend 40:60 and pure emulsion explosive, while, once again, pentrite caused the highest percentage of fine fraction, due to the highest amount of energy released.

The measurement of oscillation velocities showed the highest values of measured oscillation velocity reduced to a mass of explosive for pentrite and pure emulsion explosive. This is expected as these explosives have a stronger impact on the surrounding materials than other explosive blends used in this study. On the other hand, ANFO resulted in the lowest values of measured oscillation velocity reduced to mass, while the low-density blend 40:60 follows closely after.

Based on all the performed experiments, it can be concluded that the low-density emulsion matrix-expanded polystyrene blend 40:60 ($\rho = 0.437$ g/cm^3) is optimal for reducing the negative impact effect while retaining the work capacity needed in blasting. This results in optimal fragmentation and reduction of oscillation velocities, e.g. the potentially negative effect of blasting on the surrounding environment.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflicts of interest

The authors declare no conflict of interest.

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