Influence of the Initiation Energy on the Velocity of Detonation of ANFO Explosive

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Velocity of Detonation of Low Density ANFO Mixture

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Abstract:

Blasting operations in built-up areas, at short distances from structures, impose new requirements on blasting techniques and properties of explosives in order to mitigate seismic effect of blasting. Explosives for civil uses are mixtures of different chemical composition of explosive and/or non-explosive substances. Chemical and physical properties, along with means of initiation, environment and the terms of application define detonation and blasting parameters of a particular type of the explosive for civil uses. Velocity of detonation is one of the most important measurable characteristics of detonation parameters which indirectly provide information about the liberated energy, and applicability for certain purposes. The level of shock effect of detonated charge on the rock, and therefore the level of seismic effect in the area, depends on the velocity of detonation. Since the velocity of detonation is proportional to the density of an explosive, the described research is carried out in order to determine the borderline density of the mixture of the low density ANFO explosive with expanded polystyrene while achieving stable detonation, and to determine the dependency between the velocity of detonation and the density of mixture.

Keywords: velocity of detonation; low density ANFO mixture

1 Introduction

There are various uses of civil explosives, i.e. explosive substances. They are used for blasting in mining and civil engineering, oil and gas exploitation, geological research, mechanical engineering and naval architecture, space technology, car industry, agriculture, medicine, landmine clearance, film industry and fireworks.

Civil (commercial, industrial) explosives are high energy materials. By explosive transformation, they convert potential (chemical) energy into kinetic energy of shock waves and into energy of expanding gases of the chemical reaction. Affected by the shock waves and expanding gases, the energy is used though the mechanical work on rock fragmentation and displacement. When the explosive charge in a borehole is detonated, a portion of energy, which was not used for useful work for rock fragmentation, affects the surrounding area as a seismic effect, i.e. earthquake, shock wave and discharge of blasted material.

Due to the expansion of urban area and building of traffic infrastructure it is necessary to apply cautious blasting, i.e. blasting which should fragment the rock mass, but on the other hand, it should also cause the least possible damage of the rock mass in order to preserve its physical and mechanical properties and result in the minimum negative impact on the environment.

Therefore, it is necessary to manufacture an explosive with detonation properties, i.e. blasting and technical characteristics, which could be used for cautious blasting.

Low density explosives possess the required properties. They function on the principle of dependence of detonation pressure on density product and detonation velocity defined in postulates of hydrodynamic, Chapman-Jouget detonation theory. On the other hand, by reducing the density of an explosive, the specific mass of a charge expressed per unit volume of a blasted rock is also reduced. Therefore the quantity of released energy which affects the unit volume of a rock also decreases and due to that induced strain is lower.

The density of an explosive is reduced by adding materials that are characterized by substantially lower density than explosives. Those materials can be divided into two groups: inert materials (perlite, vermiculite, glass microspheres, etc.) and combustible materials, i.e. the materials involved in the chemical reaction of oxidation (polystyrene, expanded polystyrene, polyurethane foam, coal dust, sawdust, sugar cane waste, peanut shells, cereals, etc.).

The quantity of the energy released by blasting depends on the mass and type of explosive. By detonating the explosive charge a portion of total energy is used for useful mechanical work. Available chemical energy of the explosive charge is used for the heat transfer to its surroundings and work carried out according to postulates of the first law of thermodynamics.

The energy released during the detonation of explosive appears in two basic forms. Shock wave energy is a consequence of high pressure on the detonation front. It primarily fragments the rock during blasting, since the pressures on the shock wave front are many times higher than dynamic hardness of the surrounding rock.

Detonation pressure, which is ideally the pressure of reaction products of detonation, can be approximately expressed according to equation 1:

$$p_d = \frac{\rho \cdot {v_d}^2}{4} \tag{1}$$

where:
p_d – detonation pressure (Pa),
ρ – explosive density (kg/m^3),
v_d – detonation velocity (m/s).

In completely filled boreholes the pressure on the borehole wall is a half of the detonation pressure, i.e. [7]:

$$p_b = \frac{\rho \cdot {v_d}^2}{8} \tag{2}$$

where:
p_b - pressure on the borehole wall (Pa).

The equation 2 shows that the pressure on the borehole wall and the induced strain in the rock mass depend both on the detonation velocity of the explosive and its density.

Dependence of detonation velocity on density can be expressed by experimentally proven relation according to equation 3 [10].

$$v_d = x + y \cdot \rho \tag{3}$$

where:
x, y – experimentally defined constants for an explosive substance.

As the shock wave moves from the centre of explosion, the pressure amplitude and energy decrease, and the shock wave turns into an elastic wave. The other form of energy is the energy of expanding detonation gases which causes strain in the rock mass fractured by shock wave.

Further expansion enables displacement and discharge of the blasted material. The expansion lasts until the pressure equals the pressure of surrounding air.

Decrease of density and detonation velocity, and ratio of shock effect is achieved by mixtures with the composition based on civil explosives with addition of polystyrene and expanded polystyrene.

ANFO explosive is selected among other civil explosives since its density can be substantially reduced.

This paper presents the procedure for reducing the density of ANFO by expanded polystyrene and it presents an overview of detonation velocity measurements and the dependence of detonation velocity on the density of low density explosives.

2 Overview of research on low density explosives and possibilities of their use

The first research on development of low density explosives started during 1970's in Russia. That early research was based on reducing density of ANFO by adding various materials of lower density. It was considered that ANFO, as the lowest density explosive, is ideal for research on low density explosives. The research was directed towards development of an explosive that could be easily prepared at the site and that would be cost-effective [2, 9].

Heltzen & Kure (1980) added expanded polystyrene to ANFO in different volume ratios. They proved that ANFO/expanded polystyrene (EPS) mixture in volume ratio of 5:95%, density of 0,18 g/cm^3 can be detonated, and the measured detonation velocity was 1600 m/s. The measurements were done in steel pipes of Ø 35 mm, and the explosive was initiated by a detonator. The result of their research was a new explosive of a trade name *Isanol*. *Isanol* is a mixture of ANFO and EPS granules in volume ratio of 10:90 with stable detonation velocity of approximately 1750 m/s. [5]

Wilson & Moxon (1989) reduced density of ANFO with polystyrene, sugar cane waste and sawdust. The aim of the research was to develop a low density explosive with ANFO that could be used for blasting rock mass of low hardness with decreased overbreak. They concluded that such an explosive could substantially reduce costs with no considerable effect on fragmentation. [9]

Hunter et al. (1993) reduced density of ANFO with polystyrene and used it for blasting with the purpose of preserving the stability of contour as a substitute for standard contour blasting. They concluded that the blasting with low density explosive results in decreased seismic effect on the rock mass behind contour in relation to standard contour blasting. [9]

Jackson (1993) mixed ammonium nitrate granules and EPS granules or microspheres with water gel (aqueous solution of nitrates with nitro derivatives) in various volume ratios thus reducing the density of explosives from initial 1,35 g/cm^3 to densities of 0,4 g/cm^3 do 0,7 g/cm^3. Detonation velocity was measured in PVC pipes of Ø 100 mm and Ø 200 mm. The measured detonation velocities ranged from 2400 m/s to 3000 m/s. He named that low density explosive *Low Strength Water Gel Explosive*. [6]

Akbari Mousavi et al. (2004.) reduced the density of ANFO by adding perlite in order to use low density explosive for explosion welding. At the lowest measured density of 0,4 g/cm^3 they achieved stable detonation velocity of 2300 m/s. [1]

Beach et al. (2004) tested ANFO mixtures with wheat husks of density of 0,56 g/cm^3 by measuring detonation velocity in boreholes in rock mass with the following results:

- 2700 m/s - 3200 m/s for a borehole of Ø 200 mm,
- 2800 m/s - 3400 m/s for a borehole of Ø 311 mm. [3]

Rock (2004) patented a low density explosive which he named SoftLOAD. He mixed *Heavy*-ANFO with rice husks in various volume ratios, which resulted in an explosive with density range from 0,45 g/cm^3 to 1,25 g/cm^3 with corresponding detonation velocities from 2000 m/s to 3000 m/s for a diameter of Ø 200 mm. The explosive is manufactured by „LD Corporation“. [8]

Silva (2007) used EPS granules coated by thin layer of ammonium nitrate in order to reduce density. He patented them under the name of LDRA (*Low Density Reactive Agent).* He mixed them with ANFO in various ratios and used it to reduce damage on the contour after detonating explosive charge in contour boreholes. The mixture was used in Chuquicamata mine for contour blasting. It was concluded, by measuring seismic wave velocity and by inspecting the slope after blasting, that less damage was induced in the foot of slope in relation to contour blasting by conventional civil explosives. He measured the velocity detonation of LDRA, of LDRA and ANFO mixture in volume ratios of 50:50% and 70:30%, and LDRA and perlite mixture in volume ratios of 50:50% and 60:40%. [10] Measurement results for the borehole of Ø 311 mm are presented in Table 1.

Table 1. Measurement results [10].

Type of explosive materials	Velocity of detonation, v (m/s)	Density, ρ (g/cm^3)
LDRA	2400	0,20
LDRA:ANFO 50:50	3500	0,49
LDRA:ANFO 70:30	3200	0,37
LDRA:perlite 50:50	1580	0,13
LDRA:perlite 40:60	1215	0,11

3 Velocity detonation measurements of low density ANFO

The standard *HRN EN 13631-14:2004: Explosives for civil uses. High explosives. Part 14: Determination of detonation velocity (EN 13631-14:2004)* is applied as the basis for detonation velocity measurement.

Measurements were carried out in the Laboratory for Testing explosives of the Faculty of Mining, Geology and Petroleum Engineering, certified according to standard *HRN EN ISO/IEC 17025:2007.*

3.1 ANFO

ANFO explosives are produced as a mixture of granulated ammonium nitrate and fuel oil. They are manufactured in two ways:

- the mixture of ammonium nitrate granules and fuel (gas oil and similar), it is used in free flowing form,
- the mixture of fragmented ammonium nitrate that can be produced in cartridges. [4]

The mixture of ANFO with a volume ratio of ammonium nitrate of 94,5 % and a volume ratio of fuel of 5,5 % is considered to be ideal. [4]

ANFO is usually packed in PVC bags (Figure 1). ANFO granules in free-flowing form are presented in Figure 2.

The density of the used ANFO is determined experimentally according to the standard *HRN EN 13631-13:2003: Explosives for civil uses. High explosives. Part 14: Determination of* *density (EN 13631-13:2003),* while detonation velocity is determined experimentally according to the standard *HRN EN 13631-14:2004: Explosives for civil uses. High explosives. Part 14: Determination of detonation velocity (EN 13631-14:2004)*. Oil phase ratio is determined by ANFO test. The results are presented in Table 2.

Table 2. Blasting and technical data for the used ANFO.

ANFO		
Density of explosive	0,834	g/cm^3
Velocity of detonation (steel tube Ø 69 mm)	3528	m/s
Oil phase ratio	5,6	%

Figure 1: ANFO

Figure 2: ANFO granules

3.2 Expanded polystyrene (EPS)

Expanded polystyrene (EPS) in granules, manufactured by the technology of suspension polymerization, was used in order to reduce density of emulsion explosives.

EPS granules measure from 1,5 mm to 3,5 mm, and the density is 0,019 g/m^3.

Expended polystyrene in free-flowing form is presented in Figure 3, and EPS granules recorded by Dino-Lite Pro microscope magnified 50 times are presented in Figure 4.

Figure 3: Expanded Polystyrene.

Figure 4: EPS granules recorded by microscope (magnified 50×).

3.3 Emulsion matrix

Emulsion matrix is a colloid mixture of nitrates dissolved in water, dispersed in oil phase and it has no explosive properties. Through sensibilizing by materials which consist of granules containing air (gas phase) in the shape of glass microspheres, granulated ammonium nitrate or clay microspheres – perlite, and that present so called hot spots which are used to support and achieve stable detonation velocity, after initial, sufficiently strong impulse, emulsion matrix turns into explosive.

Since the matrix contains no substance which is explosive itself and due to desensibilization effect of extremely high water content it possesses high security level. [4].

The results achieved by chemical analysis of the used emulsion matrix are presented in Table 3.

Table 3. Chemical anlysis of emulsion matrix

Quality mark	**Unit**	**Value**
Water	%	14,2
Oil phase and emulsifier	%	5,73
Solution of inorganic salts	%	80,07

Density of the used emulsion matrix is determined experimentally according to the standard *HRN EN 13631-13:2003: Explosives for civil uses. High explosives. Part 14: Determination of detonation velocity (EN 13631-13:2003)* and it equals 1,376 g/cm^3.

Figure 5: Emulsion matrix.

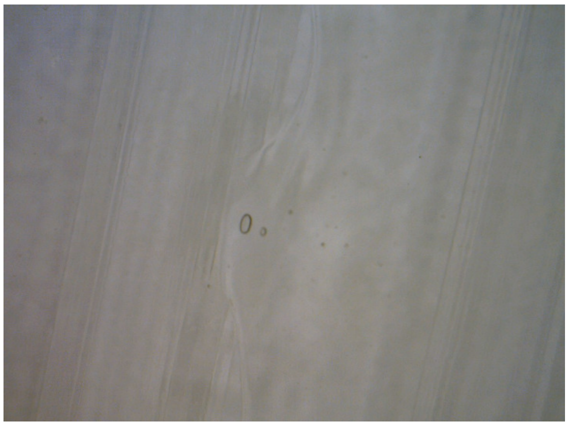

Figure 6: Emulsion matrix recored by a microscope (magnified 500×).

3.4 Measurement scheme

Detonation velocity of the explosive charge of the prepared mixtures is measured by electro-optical optical method by the electronic timer Explomet-Fo-2000 presented in Figure 7. The device can measure detonation velocity on five segments. The method measures time necessary for detonation wave front to pass the distance between two points. On the basis of measured time and defined distance the velocity is calculated. The accuracy of time measurement equals ± 0,1 μs on the total duration up to 10 000 ms.

Figure 7: Electronic timer Explomet-Fo-2000.

Explosive charge was placed in steel pipes of inside diameter of Ø 20 mm (3/4"). The length of steel pipes equalled 150 mm. Detonation velocity was measured on 2 segments with 3 sensors which were placed on equal distances of 20mm. The first probe was placed on the distance that equalled five times length of diameter from the initiation point. By cumulating distances between sensors and measured time on both segments it is possible to calculate the detonation velocity between the first and third sensor according to the equation:

$$v_{1-2} = \frac{l_1 + l_2}{t_1 + t_2} \cdot 1000 \qquad (4)$$

where:
v_{1-2} – detonation velocity between the first and third sensor (m/s),
l_1 – distance between the first and second sensor (mm),
l_2 – distance between the second and third sensor (mm),
t_1 – measured time between the first and second sensor (μs),
t_2 – measured time between the second and third sensor (μs).

Schematic representation of measurement scheme is presented in Figure 8, and the photography of measurement scheme in Figure 9.

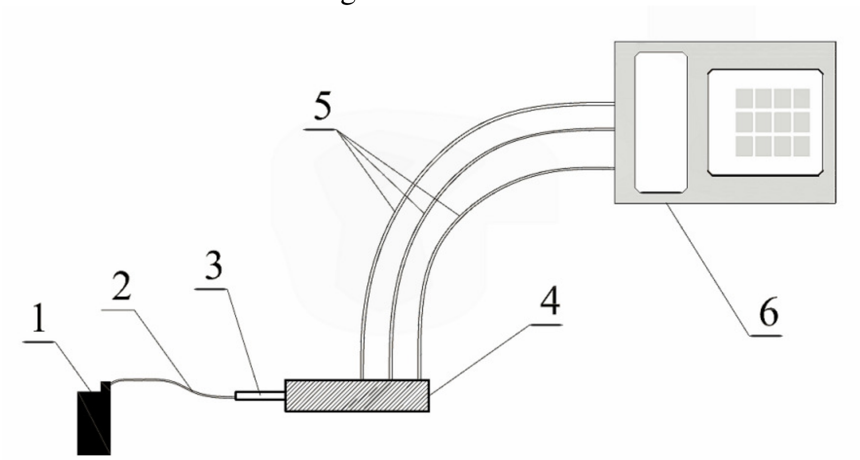

Figure 8: Schematic representation of measurement scheme.

Index:
1 – initiating device,
2 – shock tube,
3 – non-electrical detonator,
4 – steel pipe with explosive substance,
5 – sensors (optical cables),
6 – electronic timer.

Figure 9: Photography of a measurement scheme.

The density of explosive was reduced by adding EPS in granules to the explosive in various volume ratios. Volume ratios were 90:10, 80:20, 70:30, 60:40, 50:50, 40:60, 30:70, 20:80 and 10:90, where the first figure represents the percentage of explosive volume, and the second figure the percentage of EPS volume. Taking into account the large difference in density and size of ANFO and EPS granules there was a possibility of segregation of ANFO and ESP granules. Therefore, to each mixture of various volume ratios, 10 % of volume emulsion matrix was added to the ANFO explosive with the purpose of solder. Figures 10 and 11 present microscopic view of samples of ANFO + emulsion matrix and EPS in volume ration 30:70 with the addition of emulsion matrix where it is visible that emulsion matrix functions as a solder.

Every mixture of ANFO + emulsion matrix and EPS was tested on 4 samples for each ratio of explosive + emulsion matrix and EPS.

Each mixture was prepared manually in glass bowls with glass stick for stirring.

Figure 10: (ANFO + emulsion matrix) and EPS 30:70 (50×).

Figure 11: (ANFO + emulsion matrix) and EPS 30:70 (200×).

3.5 Measurement results

Average values for detonation velocity measurement for the explosive mixture for each volume ratio mixture of explosive and EPS are presented in Table 4. The appearance of particular mixtures is presented in Figure 12.

The dependence of detonation velocity on the density of the explosive charge for each measurement is presented by a diagram in Figure 13, 14 and 15.

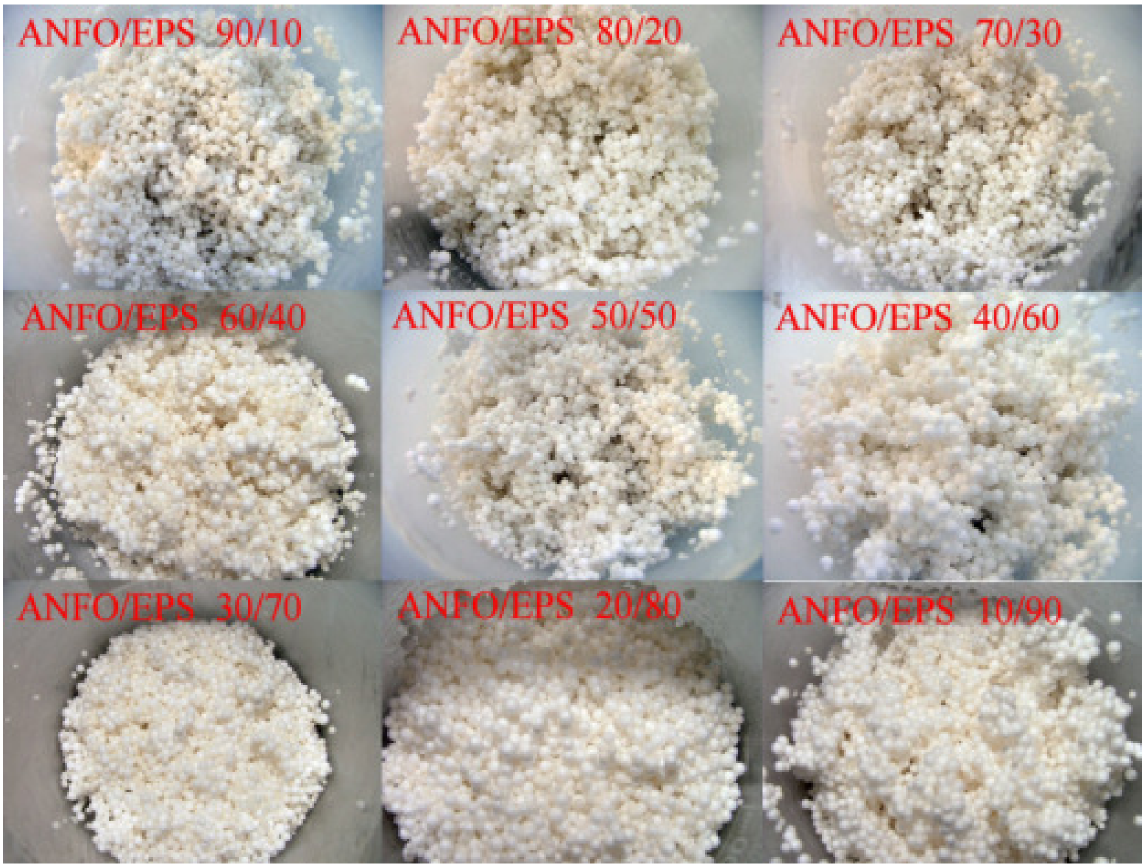

Figure 12: Appearance of particular mixtures.

Table 4. Average measurement values of detonation velocity in the pipe of Ø 20 mm (3/4").

Type of explosive materials	Volume ratio (%)	Density, ρ (g/cm^3)	Velocity of detonation on the 1st segment, v_1 (m/s)	Velocity of detonation on the 2nd segment, v_2 (m/s)	Velocity of detonation on both segments, $v_{1\text{-}2}$ (m/s)
(ANFO+Matrix)/EPS	90/10	0,801	1968	2031	1999
(ANFO+Matrix)/EPS	80/20	0,714	1740	1819	1777
(ANFO+Matrix)/EPS	70/30	0,628	1577	1629	1602
(ANFO+Matrix)/EPS	60/40	0,541	1550	1584	1562
(ANFO+Matrix)/EPS	50/50	0,454	1586	1474	1520
(ANFO+Matrix)/EPS	40/60	0,367	1195	1340	1260
(ANFO+Matrix)/EPS	30/70	0,280	818	814	804
(ANFO+Matrix)/EPS	20/80	0,193	523	527	524
(ANFO+Matrix)/EPS	90/10	0,106	503	-	-

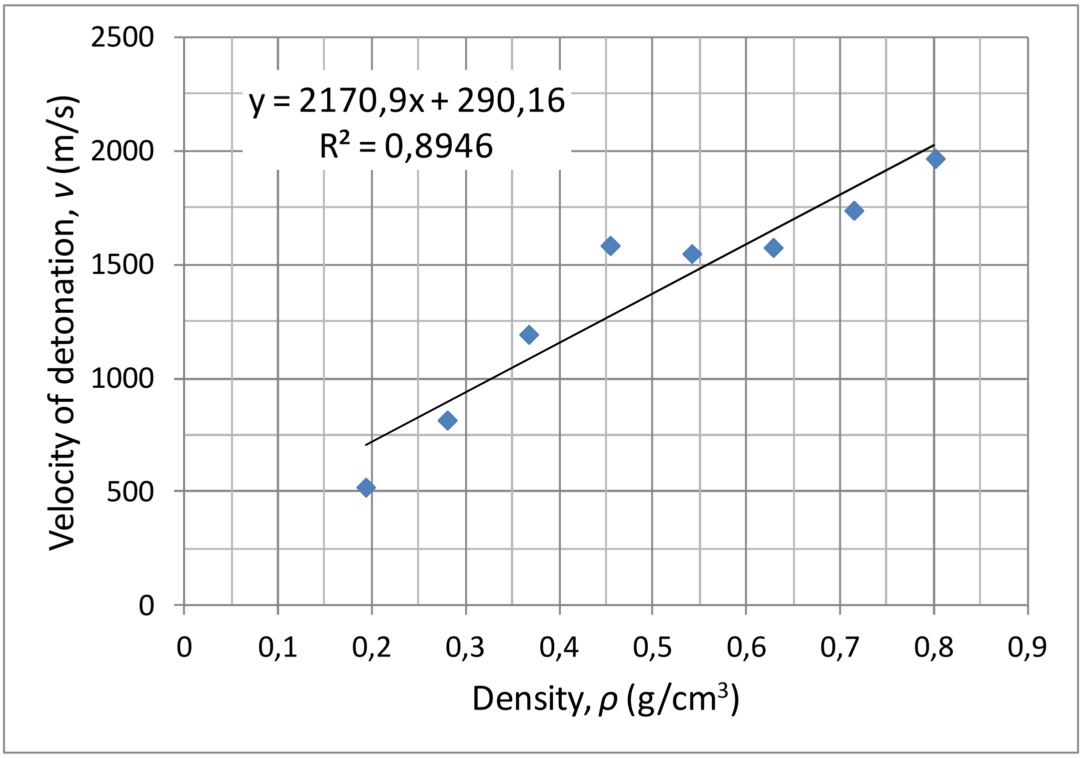

Figure 13: Dependence of detonation velocity on density of explosive charge on the 1st segment, v_1.

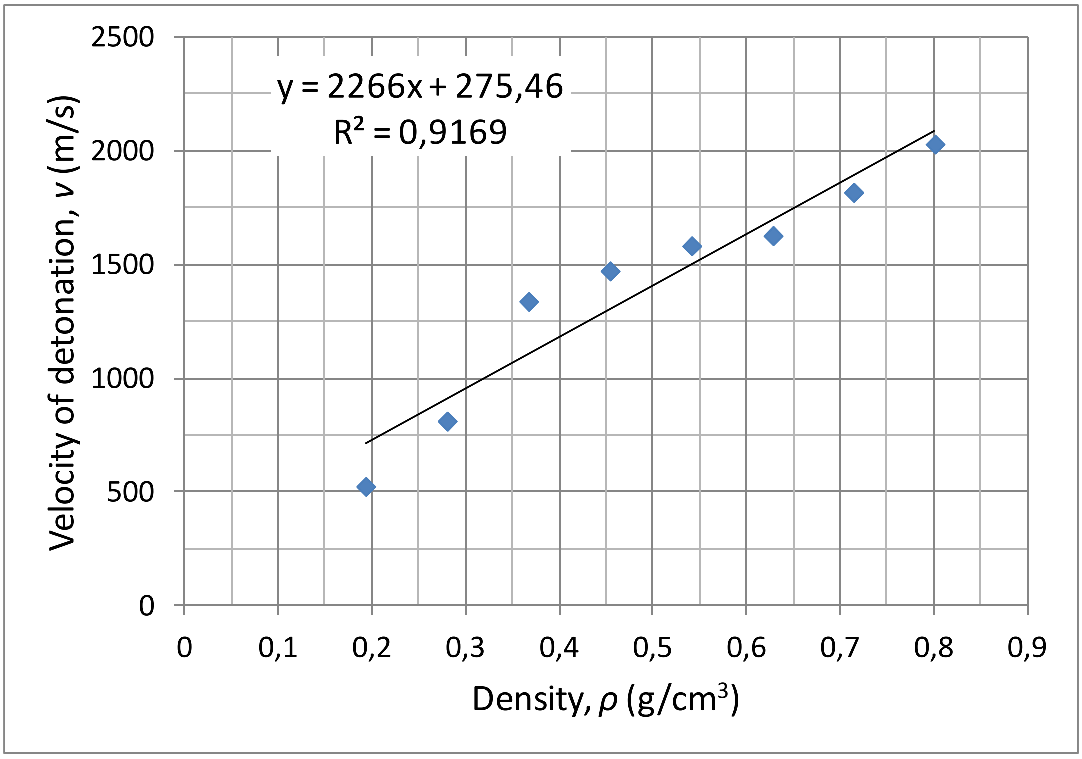

Figure 14: Dependence of detonation velocity on density of explosive charge on the 2nd segment, v_2.

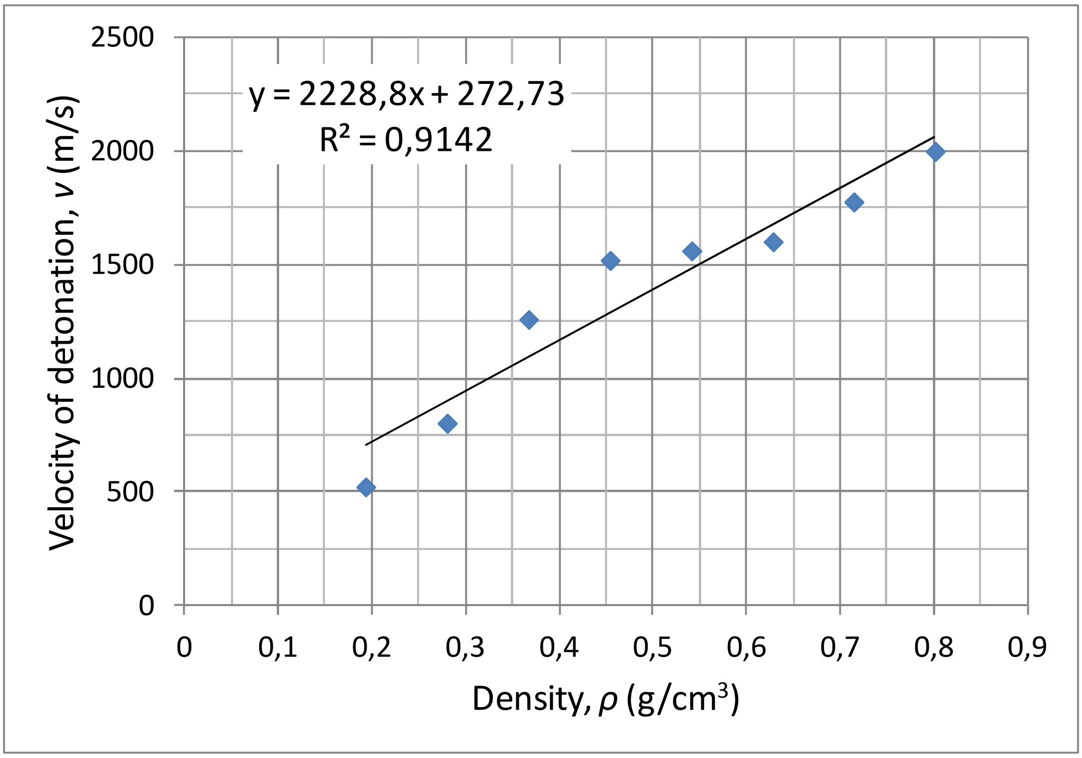

Figure 15: Dependence of detonation velocity on density of explosive charge on both segments, $v_{1\text{-}2}$.

4 Analysis of results and conclusion

The preparation of low density ANFO mixture with EPS has been described. The explosive properties of these low density mixtures showed a significant reduction of the velocity of detonation with decreasing density.

The results in Table 4 show that the mixture of (ANFO+Matrix) and EPS with the volume ratio of 20:80 has the lowest density with the stable detonation velocity for these charge and diameter. Mixture with the volume ratio of 10:90 ((ANFO+Matrix):EPS) at the lowest density had no stable detonation velocity.

For most ratios of (ANFO+Matrix)/EPS measured detonation velocity on various segments is lower or higher with more or less difference but between the first and the third sensor is aligned. That can be explained with measurement uncertainty which equals ± 150 m/s.

Dependence of detonation velocity on density for the explosive mixture of (ANFO+Matrix)/EPS is linear and can be expressed by experimentally proven relation according to equation 3 with strong coefficient of determination of 91,42 %:

$$v_d = 272{,}73 + 2228{,}8 \cdot \rho \tag{5}$$

Differences from linearity according to equation 5, shown on diagrams in figures 13, 14 and 15, also can be explained with measurement uncertainty.

Performed tests in laboratory conditions have proved possibility of ANFO-based low density mixtures with great ratio of EPS to achieve stable velocity of detonation.

Further research should be directed for testing samples with larger length and diameter and with the mechanical preparation of mixtures.

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