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Research paper

Modification of ANFO Detonation Parameters by Addition of Ground of Ammonium Nitrate(V) and Aluminium Powder

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Abstract: The present work determined the effect of the addition of aluminium powder and ground ammonium nitrate(V) on selected detonation parameters of ANFO explosives. The detonation velocity and the characteristics of the air blast wave were determined. It has been shown that replacing part of the prilled ammonium nitrate(V) with its ground form results in an increase in the detonation velocity and the blast wave parameters. On the other hand, it was found that the addition of aluminium powder to a certain level increases the measured parameters, but after reaching maximum values, they then decrease.

Keywords: ammonium nitrate(V), aluminium powder, detonation velocity, blast wave parameters

Symbols and abbreviations

Al_a	Atomized aluminium powder
Al_f	Flaked aluminium powder
AN	Ammonium nitrate(V), NH_4NO_3
AN_g	Ground ammonium nitrate(V)
AN_p	Porous prilled ammonium nitrate(V)
ANFO	Ammonium nitrate – fuel oil
FO	Fuel oil
RDX	1,3,5-Trinitro-1,3,5-triazinane

1 Introduction

Explosive materials such as ammonium nitrate – fuel oil (ANFO), as well as emulsion explosives, are the basic blasting agents used in the mining industry. Usually, these are two-component systems of oxidizer and fuel, detonating in non-ideal regimes [1, 2]. Useful properties and detonation parameters of this type of explosive can be modified within wide limits by changing the structure of the ammonium nitrate(V) (AN) used and by the addition of various substances. The influence of the AN structure for determining the degree of porosity and of fuel oil absorption on selected detonation parameters of ANFO was investigated, among others, in [3-8]. A number of studies have concerned the impact of the addition of aluminium powder [9-16], pesticides [17] and explosives obtained from ammunition delaboration [18, 19]. The parameters determined were the detonation velocity [2-4, 7, 12, 13, 16, 17] (among other things, as a function of temperature [20], type of booster [21] and diameter of charge [20]), the ability to perform work measured with the Trauzl test [3, 4, 12, 13, 16, 20, 22-24], ballistic pendulum [9], intensity of air blast waves [14, 15] and estimated using numerical methods [25]. The toxic gases content (NH_3, NO_x, CO) in the products of the explosion of ANFO with varied oxygen balance, was also determined and the results obtained by experiment were compared with analogous data obtained for individual explosives having the ability to be initiated by a detonator [11]. The present work, in which the variables were the content and type of individual components, complements the above-mentioned articles.

2 Experimental

2.1 Characteristics of the materials

In the tested mixtures, two types of AN were used: porous prilled (AN_p) and ground (AN_g) – obtained by grinding AN_p. The prill size of AN_p was in the range 1.2-2.5 mm, and its bulk density was 0.84 g/cm^3. In order to determine the granulometric composition of AN_g, it was sieve analysed. The results of these tests are shown in Figure 1.

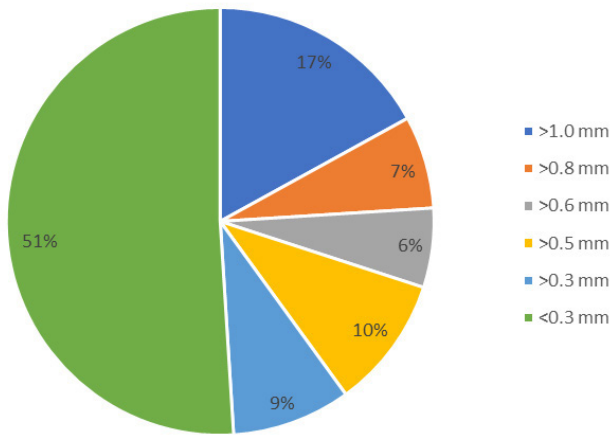
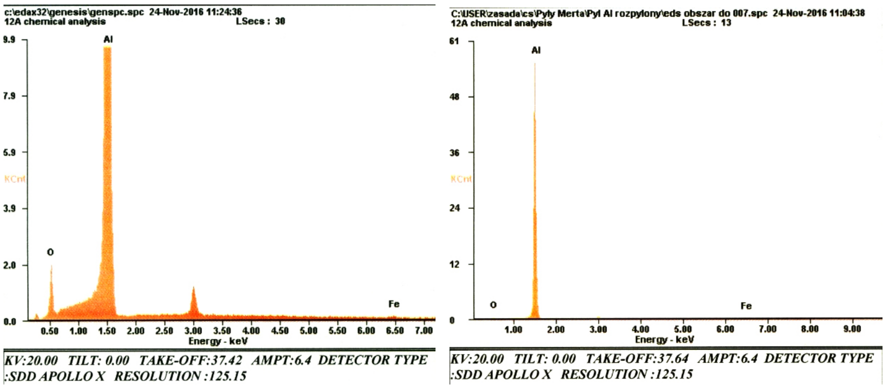


Figure 1. Sieve analysis of AN_g

The tested explosive mixtures contained two types of aluminium powder: flaked (Al_f) and atomized (Al_a). The flaked aluminium was powder BLITZ Aluminium DEPUVAL 3083, produced by BENDA-LUTZ from aluminium with a minimum purity of 99.7% Al, and had a water coverage of 29,000 cm^2/g, a residue on a 45 µm sieve (~325 mesh) of max. 0.8%, medium sized flakes 7 µm and a bulk density of 0.4 kg/dm^3 [26]. Atomized aluminium powder had an average grain size of 100 µm. Table 1 lists the results of the elemental analysis of the individual aluminium powders, obtained by the EDX HAADT method (Figure 2). The structures of the powders used in this research are shown in Figures 3 and 4.

Table 1. Elemental composition of the aluminium powders used

Aluminium powder	Element	Content [%]	
		mass	atomic
Flaked (Al_f)	Oxygen	3.66	6.02
	Aluminium	96.08	93.85
	Iron	0.27	0.13
Atomized (Al_a)	Oxygen	1.39	2.33
	Aluminium	98.29	97.52
	Iron	0.32	0.15



(a) (b)

Figure 2. X-ray spectrum in the EDX HAADF point analysis of the aluminium powders: (a) – flaked, (b) – atomized

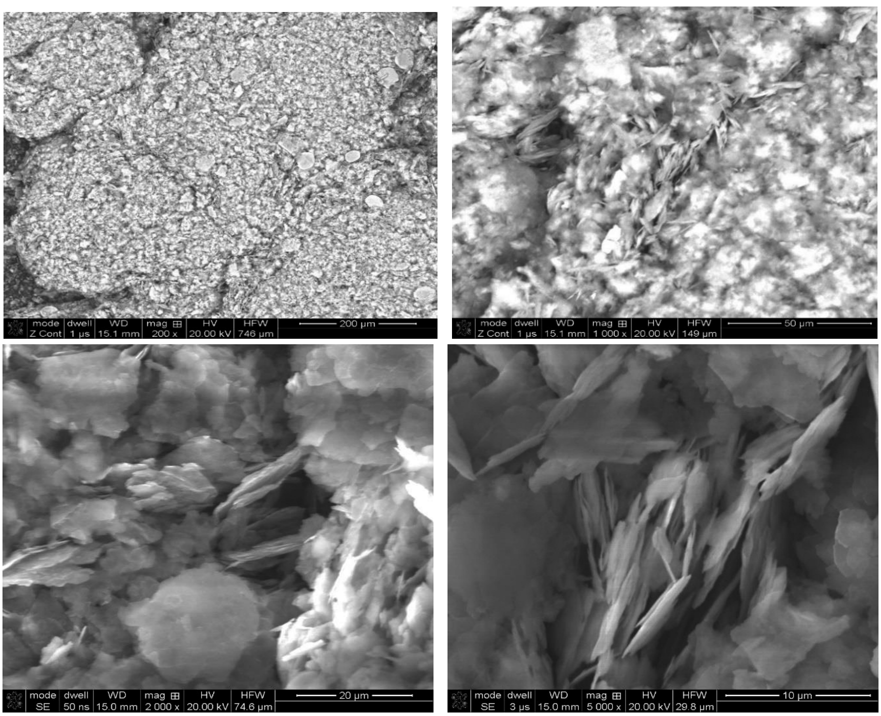


Figure 3. SEM images of flaked aluminium (Al_f)

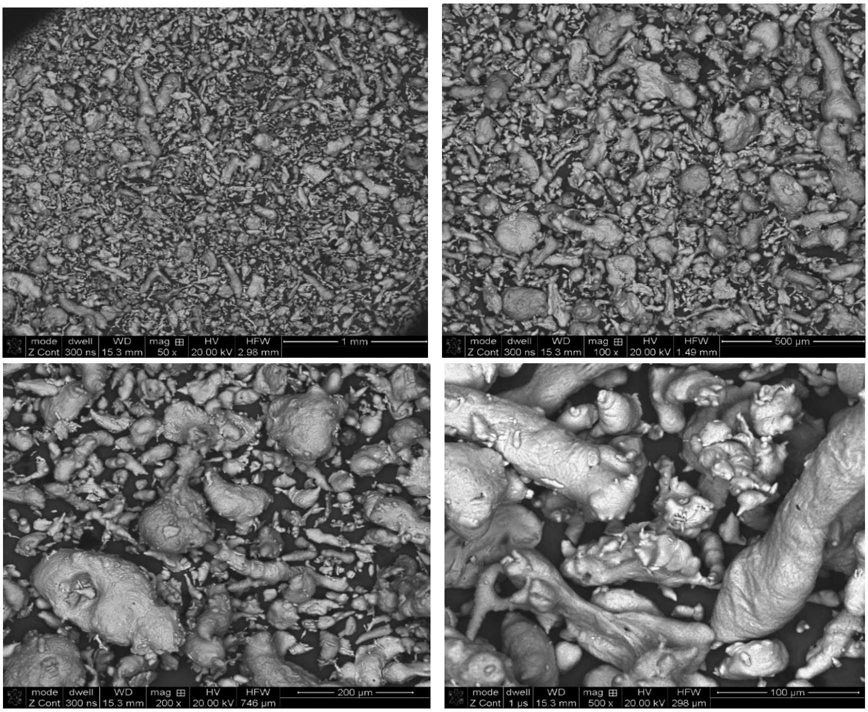


Figure 4. SEM images of atomized aluminium (Al_a)

As the fuel, engine oil Flex 5W-30 was used. The oil had a density of 0.855 g/cm^3 at 15 °C, a kinematic viscosity of 67 mm^2/s at 40 °C and a flash-point of 230 °C [27]. Samples of the tested materials were prepared by mixing the ingredients until a homogeneous composition was obtained. In the first stage, the FO was added to the AN_p, followed by a mixture of AN_g and aluminium powder.

2.2 Research methodology

The detonation velocity (*D*) was determined using the short-circuit sensor method. The explosives were placed in PVC pipes with dimensions: length 250-280 mm, internal diameter 46 mm and wall thickness 2 mm. The charges had a mass of 400 g and were initiated with a 25 g booster made of compressed phlegmatized RDX. Measurements of the overpressure of the air blast wave were made using PCB Piezotronics, Inc. series 137A22 pressure sensors. Two sensors were located at distances of 2.0 m and 2.5 m from the charge, which was hung at a height of 1.5 m above the ground and at the height of pressure pencil probes. Signals from the pressure sensors, *via* a signal conditioner 482A04, were recorded on a WAVEJET 314 oscilloscope. The total impulse was determined on the basis of the overpressure obtained *vs.* time. The measuring system is shown in Figure 5. Measurements of the detonation velocity and the overpressure of the air blast wave were carried out simultaneously.

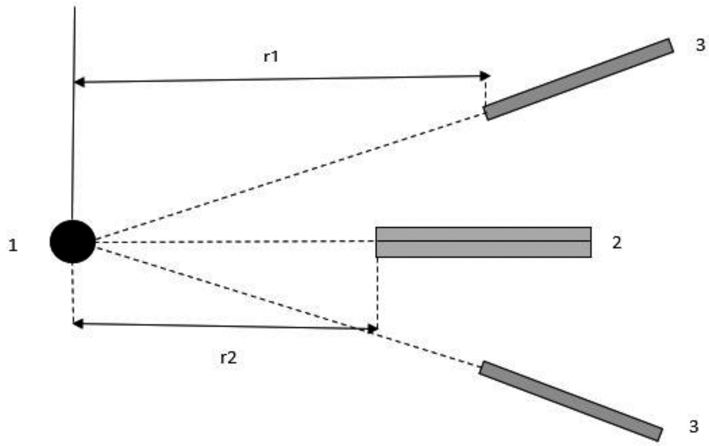


Figure 5. Diagram of the measurement system: 1 – charge of the tested explosive, 2 – two PCB pressure sensors at a distance of 2.0 m, 3 – PCB pressure sensors at a distance of 2.5 m
Note: r1, r2 – distance charge-sensors

The peak overpressure values were obtained after approximation of the first incident blast wave using the modified Friedlander equation [28] in the form:

$$\Delta P(t) = P_0 e^{-\alpha t} \left(1 - {}^{t}/_{\beta}\right) \tag{1}$$

where P_0 is the peak overpressure immediately behind the primary shock, t is the time after the arrival of the primary shock at the gauge location, α and β are constants. The specific impulses were obtained by numerical integration of the first incident blast wave during the time when the latter was positive.

3 Results

In the first series of experiments, the detonation velocity and the intensity of the air blast wave generated by the detonation of ANFO containing 5.5% of oil and the mixture of prilled and ground AN were determined. The results of the detonation velocity measurements are listed in Table 2, while Figure 6 shows the overpressure characteristic of the blast wave generated during the detonation of ANFO containing 50% of AN_g. Table 3 lists the measured maximum overpressure (Δp_{max}) and an estimation of the total impulse (I_t). ANFO without addition of AN_g does not detonate under these experimental conditions.

Table 2. Detonation velocity of ANFO containing ground and prilled AN

ANFO symbol	ANFO composition			Density [g/cm^3]	Detonation velocity [m/s]
	AN_g [%]	AN_p [%]	Oil [%]		
ANFO-10	10	84.5	5.5	0.88	1210
ANFO-15	15	79.5		0.90	2200
ANFO-20	20	74.5		0.90	2360
ANFO-30	30	64.5		0.92	2570
ANFO-40	40	54.5		0.93	2660
ANFO-50	50	44.5		0.97	2680
ANFO-60	60	34.5		0.98	2620

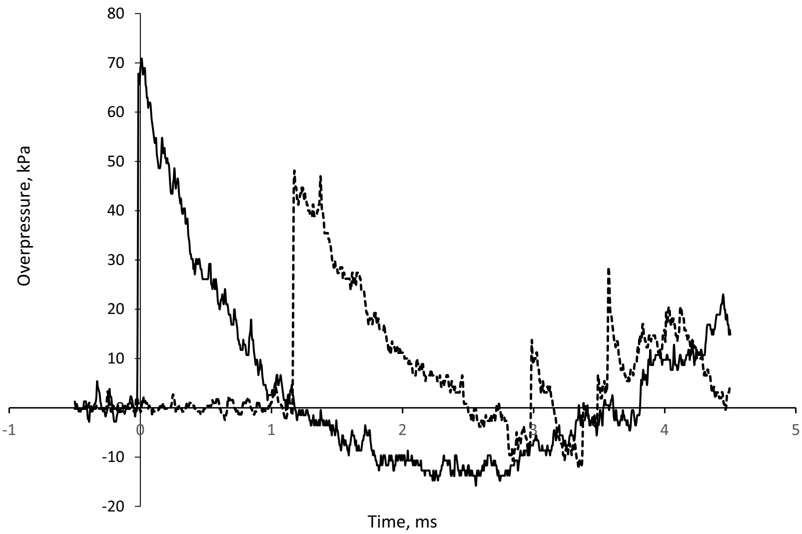


Figure 6. Overpressure generated by detonation of ANFO-50 at distances of 2.0 m (solid line) and 2.5 m (dashed line)

Table 3. Maximum overpressure of the air blast wave and total impulse for ANFO containing different amounts of ground and prilled AN

ANFO symbol	Density [g/cm^3]	Maximum overpressure [kPa] at distance [m]		Total impulse [Pa·s] at distance [m]	
		2.0	2.5	2.0	2.5
ANFO-10	0.88	42.7	30.7	20.0	14.9
ANFO-15	0.90	80.1	51.4	34.8	26.0
ANFO-20	0.90	75.8	49.9	33.5	24.9
ANFO-30	0.92	69.1	47.6	31.2	22.9
ANFO-40	0.93	74.2	51.6	33.9	26.0
ANFO-50	0.97	70.3	47.1	31.2	23.2
ANFO-60	0.98	76.7	51.1	33.3	25.9

As may be seen in Table 2, the measured values of the detonation velocity increase with increasing proportions of AN_g in the mixture. There is a slight decrease in the detonation velocity as the AN_g content increases from 50% to 60%. An increasing AN_g content in the mixture probably forces better homogenisation. A reduction in AN_p in the mixture can cause an increasing amount of oil to be available for mixing with AN_g, which enables better contact between the fuel and the AN in the entire volume of the explosive mixture.

ANFO containing 50% of AN_g (ANFO-50) was selected for the second series of experiments because of its superior detonation velocity result. The study was conducted for ANFO-50 mixtures with the addition of two types of aluminium powder: Al_f and Al_a. The results of the detonation velocity measurements are summarized in Tables 4 and 5. Figure 7 illustrates an example of the overpressure of the air blast wave generated by the detonation of ANFO with 20% addition of Al_f (ANFO-Al_f-20) and with 20% addition of Al_a (ANFO-Al_a-20). The maximum overpressure of the air blast wave and estimates of its total impulse are summarized in Tables 6 and 7.

Table 4. Detonation velocity of ANFO with the addition of flaked aluminium

ANFO symbol	ANFO composition [%]				Density [g/cm^3]	Detonation velocity [m/s]
	AN_p	AN_g	Al_f	FO		
ANFO-50	44.5	50	–	5,5	0.97	2680
ANFO-Al_f-5	42.3	47.5	5	5.2	0.97	2710
ANFO-Al_f-10	40.1	45.0	10	4.9	0.96	2840
ANFO-Al_f-20	35.6	40.0	20	4.4	0.88	2300
ANFO-Al_f-30	31.2	35.0	30	3.8	0.83	1490

Table 5. Detonation velocity of ANFO with the addition of atomized aluminium

ANFO symbol	ANFO composition [%]				Density [g/cm^3]	Detonation velocity [m/s]
	AN_p	AN_g	Al_a	FO		
ANFO-50	44.5	50	–	5.5	0.97	2680
ANFO-Al_a-5	42.3	47.5	5	5.2	0.97	2680
ANFO-Al_a-10	40.1	45.0	10	4.9	0.98	2990
ANFO-Al_a-20	35.6	40.0	20	4.4	1.01	2400
ANFO-Al_a-30	31.2	35.0	30	3.8	1.03	ND

ND – Composition did not detonate

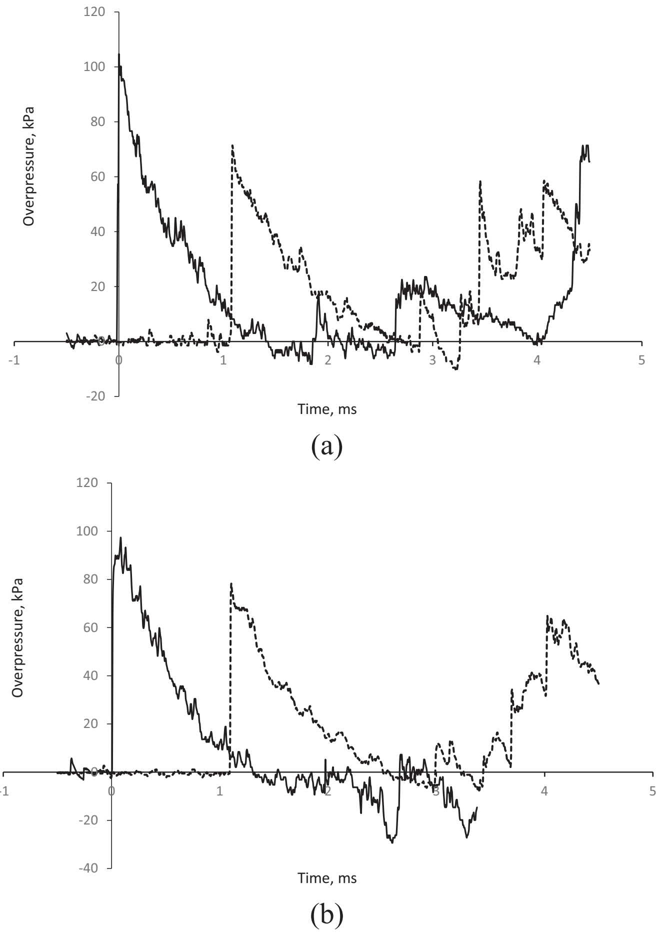


Figure 7. Overpressure generated at distance 2.0 m (solid line) and 2.5 m (dashed line) by detonation of ANFO-Al_f-20 (a) and ANFO-Al_a-20 (b)

Table 6. Maximum overpressure and total impulse of the air blast wave of ANFO containing flaked aluminium

ANFO symbol	Density [g/cm^3]	Overpressure [kPa] at distance [m]		Total impulse [Pa·s] at distance [m]	
		2.0	2.5	2.0	2.5
ANFO-50	0.97	70.3	47.1	31.2	23.2
ANFO-Al_f-5	0.97	73.4	49.5	33.0	26.4
ANFO-Al_f-10	0.96	101.6	60.4	50.1	32.5
ANFO-Al_f-20	0.88	97.7	60.5	49.5	34.0
ANFO-Al_f-30	0.83	88.6	55.6	52.7	35.7

Table 7. Maximum overpressure and total impulse of the air blast wave of ANFO containing atomized aluminium

ANFO symbol	Density [g/cm^3]	Overpressure [kPa] at distance [m]		Total impulse [Pa·s] at distance [m]	
		2.0	2.5	2.0	2.5
ANFO-50	0.97	70.3	47.1	31.2	23.2
ANFO-Al_a-5	0.97	73.7	50.6	32.6	27.4
ANFO-Al_a-10	0.98	82.8	62.1	39.3	34.2
ANFO-Al_a-20	1.01	87.7	73.3	45.3	42.1
ANFO-Al_a-30	1.03	53.1	40.6	30.6	22.3

4 Analysis of the Test Results

The results of the experiments conducted showed that addition of ground ammonium nitrate to porous ammonium nitrate significantly influences the value of the detonation velocity of ANFO explosives. Under the measurement conditions, the rapid increase in this parameter (by almost 1000 m/s) occurred when the AN_g content was changed from 10% to 15% (ANFO-10 and ANFO-15 in Table 2). A further increase in AN_g content had a small influence on the detonation velocity, and for additions between 30% and 60% of AN_g the detonation velocity had an essentially constant value (Table 2).

When measuring the intensity of the air blast wave, very low values of the maximum overpressure and total impulse were obtained with an AN_g content of 10% (Table 3), which probably results from the incomplete detonation of the explosive. For ANFO with AN_g contents between 15% and 60%, small changes in Δp_{max} and I_t were observed at both sensor distances from the charge (Table 3).

The addition of aluminium powder influenced the value of the measured parameters to different degrees. The detonation velocity increased to within 10% for both kinds of Al (Tables 4 and 5). The maximum increase in the detonation velocity between ANFO-50 and ANFO containing Al was 310 m/s for ANFO-50 on addition of 10% Al_a. For higher contents of added Al there was a decrease in the detonation velocity, and in the case of Al_a, at 30% content, no complete detonation of the tested charges was achieved (Table 5).

The highest value of the maximum overpressure of the air blast wave was obtained with an aluminium content of (10-20)% for both kinds of aluminium (Tables 6 and 7). For all aluminium levels the characteristics of the blast waves for the studied materials had higher values than for ANFO-50 without additives, except for the ANFO-Al_a-30 mixture (Tables 3 and 6). Furthermore, the total positive phase impulse for the mixtures containing 20% of Al_a and 10% or 20% of Al_f, was much higher than that of ANFO-50 without a metallic additive (with the exception of the ANFO-Al_a-30 mixture, which did not detonate under the conditions of the experiment).

5 Summary

The research conducted showed that changes in the degree of ammonium nitrate atomisation influences the detonation velocity of ANFO to varying degrees. It should be emphasized that a small amount (15%) of ground ammonium nitrate significantly increases the detonation velocity of the tested ANFOs. An increasing AN_g content significantly improved the detonation characteristic of the detonation velocity. An increase in the AN_g content above 10% (by 5% or more) results in a significant increase in the blast wave parameters. However, there is no clear trend in the changes in these parameters dependant on the AN_g content.

For ANFO with the addition of 50% AN_g (ANFO-50), the addition of 5-15% of Al causes an increase in the detonation velocity and blast wave characteristics. For the addition of 20% and 30%, the detonation velocity is reduced or the detonation process is interrupted, as observed for the mixture with 30% Al_a.

The tested ANFOs can be used in the high-energy method of metal welding. Considering their ability to detonate in low-strength PVC shells with an inner diameter of 46 mm, they should detonate in layers with a minimum thickness of 25 mm. So they could be used to propel 2.5 mm thick metal plates. Especially interesting are the observations on ANFO with a content of 10% AN_g. Its low detonation velocity (1210 m/s) predisposes it to be used when plating with lead sheets.

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