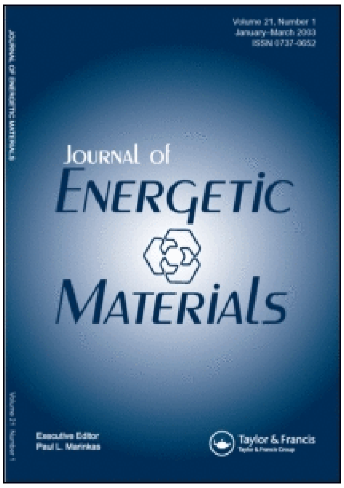

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Investigation on Detonation and Thermochemical Parameters of Aluminized ANFO

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Detonation parameters of aluminized ANFO are analyzed. Explosive compositions based on porous ammonium nitrate were investigated. Two kinds of alumnium, flakes of below 0.075 mm size and powder of dimensions below 1.5 mm were added. Diesel oil of 1.3° E viscosity was used as a moderator. The velocity of detonation of investigated explosive mixtures was measured for charges placed in PCV and steel tubes. The critical detonation diameter was estimated, and work performance capacity was appraised by lead block and ballistic mortar tests. The detonation parameters velocity, pressure, and heat liberated in the C-J point as well as pressure and heat of constant volume explosion are evaluated and analyzed.

Keywords: ANFO, Detonation velocity, Explosion energy

Introduction

Mining explosives are multi-ingredient mixtures in which oxidizers and fuels are the main components. Ammonium nitrate (AN) is the most commonly used oxidizer. But organic compounds, nonmetallic elements such as sulphur or carbon in various states, as well as some powdered metals or their alloys are employed as fuels. One of the most common metallic fuels is aluminium (Al). Its use in explosives was patented at the beginning of the twentieth century [1−3]. Then,

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H. Kast proposed the possibility of applying aluminized explosives to military purposes [4]. However, before World War I, they were only occasionally used in the mining industry. Of course, World War I generated interest in all types of explosives. For example, mixtures of ammonium nitrate and aluminium with an addition of TNT and coal were applied in Russia, Austria, and Great Britain. After the war, the price of aluminium powder fell to such a level that its application in some types of dynamites came to be economically justified. Afterwards, aluminium powders were used in nearly all subsequently developed mining explosives, as well as in mixtures containing ammonium nitrate and fuel oil.

In the course of long development of aluminized explosives over many years, various types of aluminium powders were used as an addition to the mixtures, for example, granulated powders, atomized powders, flake powders, as well as aluminium in a form of file-dust or shavings. Initially, mostly waste aluminium was used, but when demand for these explosives increased rapidly, several of the most important producers started to manufacture Al powders destined especially for the explosive industry. For example, Aluminium Co. of America started to produce Al powders characterized by special properties and intended for use in slurry explosives. The surface of aluminium grains was coated with a hydrophobic thin layer to prevent aluminium from reacting with water. For a long time, the danger of an air-dust explosion during the dosage of Al to the other ingredients was a serious problem, but it was finally resolved by the addition (in Harshaw's process) of about 0.2% of polytetrafluoroethylene to the powder. This additive considerably decreases the tendency of aluminium powder to raise dust.

In this report literature data regarding the influence of aluminium on the detonation parameters of aluminized ANFO are reviewed. In the experimental sections, results of the investigation of detonation and thermodynamical properties of explosives made in the Military University of Technology from components provided by Hydro Poland are presented. On the basis of experimental and calculated results and using physical and chemical interpretation of an aluminized mixture detonation [5], an optimization of the explosives was carried out.

Aluminium Influence Indications

In aluminized ANFO as well as in other aluminized systems, aluminium powder plays a double part. It acts as a sensitizing and energizing additive. C. G. Mason and W. C. Montgomery [6] stated that the detonation energy of mixtures of ammonium nitrate and liquid organic fuel could be significantly heightened by an addition of granulated Al. They showed that if the performance potential of ordinary ANFO was assumed to be 100, the values for aluminized ANFO containing different amounts of aluminium were as presented in Table 1. Similar results were obtained for ANFO initially containing 97% ammonium nitrate and 3% diesel oil (Table 2).

The results of tests carried out by M. A. Cook [7] showed that the degree of fineness of ammonium nitrate and aluminium has a decisive influence on detonation parameters of aluminized ANFO. He tested explosive mixtures containing 83% AN, 2% diesel oil, and 15% Al powder. The mixture containing large particles of AN (above 0.59 mm) and coarse Al had a detonation velocity of 3000 m/s (charge 152 mm in diameter, density 0.86 g/cm^3). Its critical diameter and the minimal mass of the initiating charge made from pentolite 50/50 were 102 mm and 40 g, respectively. The use of components with a higher fineness caused an increase in detonation velocity (up to 4200 m/s, charge 152 mm in diameter, with density 0.84 g/cm^3) and a decrease in critical diameter (to 19 mm). The explosive was able to detonate while being initiated by a blasting cap.

Table 1
Influence of Al addition on performance potential of ANFO containing 6% fuel oil

Amount of aluminium (%)	Density (g/cm^3)	Relative performance potential per an unit of	
		Weight	Volume
0	0.83	100	100
2.5	0.85	110	110
5.0	0.86	118	120
7.5	0.87	125	127
10.0	0.88	133	138
12.5	0.89	139	147
15.0	0.90	146	155

Table 2
Influence of Al addition on performance potential of ANFO containing 3% of diesel oil [6]

Amount of aluminium (%)	Density (g/cm^3)	Relative performance potential per an unit of	
		Weight	Volume
0	0.05	100	100
10	0.93	124	136
13	0.95	131	146
15	0.96	135	153

Source: Mason and Montgomery (1976).

Experimental

Ingredient Characteristics

Two kinds of AN manufactured by Hydro Corporation were used in the tests: porous AN 5-7-1 made in Sweden (AN-1) and porous AN made in Germany by Hydro Agri, Rostock GmbH & Co. KG (AN-2). Before the main experiments, some physical properties of the two products were determined. The bulk density, content of grain fraction below 0.5 mm, and oil absorption capability were measured. The last parameter was determined using the volumetric method described in Ref. [8]. Results of the measurements are presented in Table 3.

Table 3
Characteristics of AN types used in the experiment

Parameter	Ammonium nitrate type	
	AN-1	AN-2
Bulk density (g/cm^3)		
Cartridged with vibration	0.829–0.835	0.745–0.747
Cartridged without vibration	0.757–0.760	0.663–0.665
Amount of fraction below 0.5 mm (%)	0	0.02
Oil absorption capability (%)	8.5	9.5

To prepare the explosives, diesel oil and flake or atomized aluminium (manufactured by Benda-Lutz in Skawina) were applied. The oil density was 0.87 g/cm^3, and its viscosity value was 1.3°E. Lateral dimensions of the aluminium flakes (Al-1) were below 0.075 mm, and the grain sizes in atomized powder (Al-2) were below 0.15 mm. In order to show the differences in surface topography of the grain of porous AN and fertilizer grade AN, SEM photographs were taken. Scanning electron microscopy was also employed to examine the two kinds of aluminium powders.

Explosive Formulation and Manufacture

Two types of formulations were tested, with or without the presence of aluminium powder (Table 4). All the explosives were mixed in a motorized mixer. To an appropriate batch of AN, placed in the mixer, diesel oil was injected, and then a correct amount of aluminium powder was dosed. The mixing lasted 15 minutes.

Using this method, 10 explosives were manufactured. Their symbols and compositions are shown in Table 4.

Table 4
Composition of explosives tested

	Composition (%)				
	AN kind			Al kind	
Symbol	AN-1	AN-2	Diesel oil	Al-1	Al-2
ANFO-1	95	–	5	–	–
ANFO-2	–	95	5	–	–
ANFO-3A	–	92	5	–	3
ANFO-4A	–	90	5	–	5
ANFO-5A	92	–	5	–	3
ANFO-6A	90	–	5	–	5
ANFO-7A	–	92	5	3	–
ANFO-8A	–	90	5	5	–
ANFO-9A	92	–	5	3	–
ANFO-10A	90	–	5	5	–

Explosive Testing

In order to characterize an explosive, its detonation parameters are used. Three main detonation characteristics were measured for the explosives: velocity of detonation, critical diameter, and capacity to perform work.

Velocity of detonation (VOD) is one of the main parameters characterizing an explosive, and for this reason knowledge of its accurate value has both theoretical and practical importance. To measure VOD, a probe of four short-circuit sensors located in a charge was applied. The sensor was a charged electrical probe consisting of two insulated thin cooper wires plaited together. During passage of the detonation wave through the charge, the sensors were short-circuited, and it generated steering pulses for a digital timer of resolution 10 ns. Dividing the measurement course length by the time of the detonation wave passage through the course, the mean detonation velocity on each course was calculated. In any one charge, there were three measurement courses, so the values of detonation velocity (Table 5) are an average of three experimental results. The average error for any one datum was ± 100 m/s. The explosive mixtures were

Table 5
Velocity of detonation (VOD) and critical diameter (CD) of explosives tested

	Parameter				
Explosive	Density (g/cm^3)	VOD (m/s) PCV tube	Density (g/cm^3)	VOD (m/s) steel tube	CD [mm]
ANFO-1	0.87	1500	0.90	2970	–
ANFO-2	0.83	2700	0.85	3500	–
ANFO-3A	0.80	3330	0.8	3520	30
ANFO-4A	0.80	3300	0.83	3550	30
ANFO-5A	0.83	2340	0.85	3060	45
ANFO-6A	0.84	2700	0.85	3190	45
ANFO-7A	0.80	3340	0.80	3580	30
ANFO-8A	0.80	3480	0.81	3600	30
ANFO-9A	0.85	2820	0.85	3200	45
ANFO-10A	0.80	2770	0.85	3200	45

cartridged in PCV tubes (71.4 mm in diameter, 1.8 mm wall thickness) or in steel tubes (34.2 mm in diameter, 5 mm wall thickness). The steel envelope reduces propagation of the lateral unloading wave into the chemical reaction zone, and this favors more complete chemical reaction in the detonation wave. Therefore the conditions in thick-walled steel tubes are close to conditions in which the detonation wave propagates in a bore hole.

Critical diameter (CD) is one of the parameters determining an explosive capability to detonation. It is the minimum diameter of an explosive charge at which detonation can still take place. For rough appraisal of CD, the conical charges method was used while accurate values were obtained by the method of telescopic charges. Critical diameter values are shown in Table 5.

Work performance capacity. Gaseous products released during an explosion process are compressed to a pressure of the order of some scores GPa and heated to a temperature of several thousands K. Then, during an expansion process, they perform work and its value is one of the most important characteristics of an explosive. There are two commonly used measuring methods to determine the parameter: the lead block test and the ballistic mortar test.

These methods enable us only to determine comparative values of performance of different explosives. In both cases a relatively small amount of the explosive (on the order 10 g) is initiated. For this reason accurate comparative data can be obtained only with more sensitive explosives. For less sensitive materials with a longer detonation development distance, other methods should be used in which much larger samples are employed (up to 500 g). The results of the measurements are shown in Tables 5 and 6.

Detonation Parameters Analysis

Legitimacy of Calculation Method Selection

To calculate detonation and explosion parameters, an original method was applied. This method has been developed at the Military University of Technology, and it was especially designed to determine detonation properties of explosives having low density. It had been verified by comparison of calculated and experimental values of detonation velocity (VOD) and pressure (p_H). Selected data are shown in Table 7.

Table 6
Work performance of tested explosives

Explosive	Capability to perform work: Lead block test (cm^3)	Capability to perform work: Ballistic mortar test (%)
ANFO-1	202	67
ANFO-2	260	71
ANFO-3A	283	76
ANFO-4A	241	72
ANFO-5A	251	82
ANFO-6A	262	84
ANFO-7A	295	73
ANFO-8A	238	75
ANFO-9A	255	73
ANFO-10A	299	81

Satisfactory conformity of the experimental and theoretical values, not only for molecular explosives but also for nonideal explosives, confirms the usefulness of the chosen method.

Evaluation of Theoretical Parameters of Aluminized ANFO

Density of the explosives examined was within a range from 0.73 to 0.85 g/cm^3. In order to gain the possibility of comparing calculated and experimental values, the calculations were carried out at three

Table 7
Comparison of experimental and calculated parameters

Explosive	Density (g/cm^3)	Exp. VOD (m/s)	Exp. p_H (GPa)	Cal. VOD (m/s)	Calc. p_H (GPa)	Ref.
RDX	1.00	5981		6098	10.90	[9]
RDX	0.97	5950 ± 50		6020	10.35	[10]
NH_4NO_3	0.85	3950		4089	3.63	[11]
ANFO 94/6	0.782	5080	5.5	5047	5.497	[12]
ANFO 94/6	0.88	5500		5407	6.89	[9]

densities: $\rho = 0.75\,g/cm^3$, $\rho = 0.80\,g/cm^3$, and $\rho = 0.85\,g/cm^3$. Another problem concerns the behavior of aluminium in the detonation wave in condensed explosives. The degree of aluminium oxidation in the zone of chemical reactions is still the subject of debate. Therefore the calculations were performed with the following assumptions:

- Aluminium is chemically active and fully reacts in a detonation wave
- Aluminium partly reacts in a detonation wave
- Aluminium is an inert additive.

However, one should take into consideration that even when aluminium does not fully react in the chemical zone, it is still able to influence the work performed by the detonation products. Behind the Chapman-Jouget plane, both aluminium grains and fragments of AN grains can react further, releasing some energy that next converts to the expansion work. In such a nonideal detonation process, only a part of potential energy of an explosive is released in a detonation wave. Keeping this in mind, closed-vessel calculations were also performed. The explosion energy in a closed system corresponds to the total potential energy of an explosive that can be converted to the work. The computations were executed for two explosive mixtures (A and B) containing:

A: 92% AN, 5% diesel oil, and 3% aluminium
B: 90% AN, 5% diesel oil, and 5% aluminium.

The parameters obtained in the calculations are presented in Tables 8−13. From the analysis of the calculation results it follows (as one can expect) that for any amount of aluminium an optimal set of detonation parameters is gained when the oxygen balance of the explosive mixture is close to zero.

General Discussion and Conclusions

Performance parameters of an explosive mixture are determined by chemical and physical structure of the mixture. The structure depends on ingredient contents, their chemical and physical properties, their fineness, and the degree of mixture homogeneity. Aluminized ANFO explosives are three-ingredient mixtures in which each component influences detonation and thermochemical parameters. Porous ammonium nitrate is an oxidizer that has slightly marked explosive

Table 8
Calculated parameters of explosive A, fully active aluminium

AN 92% Diesel oil 5% $Al._{active}$ 3%	Detonation parameters [p] = GPA Closed-vessel parameters [Q] = MJ/kg		
$\rho = 0.850\,g/cm^3$	D = 5283 m/s	$p_{C\text{-}J} = 6.465$ $p_V = 3.022$	$Q_{C\text{-}J} = 4.332$ $Q_V = 4.336$
$\rho = 0.800\,g/cm^3$	D = 5096 m/s	$p_{C\text{-}J} = 5.752$ $p_V = 2.692$	$Q_{C\text{-}J} = 4.328$ $Q_V = 4.334$
$\rho = 0.750\,g/cm^3$	D = 4911 m/s	$p_{C\text{-}J} = 5.090$ $p_V = 2.387$	$Q_{C\text{-}J} = 4.324$ $Q_V = 4.332$

properties. It can be initiated to detonation by a shock wave generated by a large enough booster made from a high explosive.

Two kinds of fuel are used in aluminized ANFO: organic liquid oil and aluminium powder. The presence of the fuels enhances the capability of AN to detonation and causes an increase in detonation heat due to a better oxygen consumption. For that reason, the minimal critical diameter and the maximal detonation velocity are gained when the oxygen balance is close to zero. An improvement in detonation performance also can be obtained by using mixtures with a possibly large surface of potential chemical reactions.

Table 9
Calculated parameters of explosive A, partly active aluminium

AN 92% Diesel oil 5% Al_{active} 2% Al_{inert} 1%	Detonation parameters [p] = GPA Closed-vessel parameters [Q] = MJ/kg		
$\rho = 0.850\,g/cm^3$	D = 5232 m/s	$p_{C\text{-}J} = 6.327$ $p_V = 2.956$	$Q_{C\text{-}J} = 4.148$ $Q_V = 4.161$
$\rho = 0.800\,g/cm^3$	D = 5046 m/s	$p_{C\text{-}J} = 5.629$ $p_V = 2.634$	$Q_{C\text{-}J} = 4.144$ $Q_V = 4.158$
$\rho = 0.750\,g/cm^3$	D = 4862 m/s	$p_{C\text{-}J} = 4.980$ $p_V = 2.334$	$Q_{C\text{-}J} = 4.140$ $Q_V = 4.155$

Table 10
Calculated parameters of explosive A, inert aluminium

AN 92% Diesel oil 5% Al_{inert} 3%	Detonation parameters [p] = GPA Closed-vessel parameters [Q] = MJ/kg		
$\rho = 0.850\,g/cm^3$	$D = 5073\,m/s$	$p_{C\text{-}J} = 5.889$ $p_V = 2.752$	$Q_{C\text{-}J} = 3.608$ $Q_V = 3.616$
$\rho = 0.800\,g/cm^3$	$D = 4892\,m/s$	$p_{C\text{-}J} = 5.239$ $p_V = 2.457$	$Q_{C\text{-}J} = 3.606$ $Q_V = 3.615$
$\rho = 0.750\,g/cm^3$	$D = 4713\,m/s$	$p_{C\text{-}J} = 4.635$ $p_V = 2.171$	$Q_{C\text{-}J} = 3.604$ $Q_V = 3.614$

On the basis of the published data and the results of experiments and calculations carried out at Military University of Technology, the following conclusions can be made:

- Detonation parameters of aluminzed ANFO are better than those for ordinary ANFO
- A better improvement in performance was observed in the case of ANFO containing porous AN of 5-7-1 made in Sweden
- An addition of aluminium powder to ANFO containing Hydro Agri porous AN reveals a little influence only on the detonation parameters
- There are very small differences in registered performance of aluminized ANFO containing 3% or 5% aluminium

Table 11
Calculated parameters of explosive B, fully active aluminium

AN 90% Diesel oil 5% Al_{active} 5%	Detonation parameters [p] = GPA Closed-vessel parameters [Q] = MJ/kg		
$\rho = 0.850\,g/cm^3$	$D = 5311\,m/s$	$p_{C\text{-}J} = 6.574$ $p_V = 3.069$	$Q_{C\text{-}J} = 4.708$ $Q_V = 4.702$
$\rho = 0.800\,g/cm^3$	$D = 5124\,m/s$	$p_{C\text{-}J} = 5.849$ $p_V = 2.737$	$Q_{C\text{-}J} = 4.702$ $Q_V = 4.698$
$\rho = 0.750\,g/cm^3$	$D = 4938\,m/s$	$p_{C\text{-}J} = 5.177$ $p_V = 2.427$	$Q_{C\text{-}J} = 4.696$ $Q_V = 4.695$

Table 12
Calculated parameters of explosive B, partly active aluminium

AN 90% Diesel oil 5% Al_{active} 3% Al_{inert} 2%	Detonation parameters [p] = GPA Closed-vessel parameters [Q] = MJ/kg		
$\rho = 0.850\ g/cm^3$	$D = 5222\ m/s$	$p_{C\text{-}J} = 6.317$ $p_V = 2.952$	$Q_{C\text{-}J} = 4.358$ $Q_V = 4.359$
$\rho = 0.800\ g/cm^3$	$D = 5037\ m/s$	$p_{C\text{-}J} = 5.619$ $p_V = 2.631$	$Q_{C\text{-}J} = 4.354$ $Q_V = 4.357$
$\rho = 0.750\ g/cm^3$	$D = 4853\ m/s$	$p_{C\text{-}J} = 4.971$ $p_V = 2.332$	$Q_{C\text{-}J} = 4.350$ $Q_V = 4.354$

- Measuring methods used to determine the capability to perform work (lead block test, ballistic mortar test) do not make it possible to obtain accurate data for the explosives tested
- The most reliable method to determine the performance of aluminized ANFO seems to be the measurement of detonation velocity in charges placed in steel tubes, while measuring conditions are closer to those in a bore hole
- The results of the calculations show that theromochemical parameters increase while the amount of aluminium increases. However, the maximum performance is obtained when the oxygen balance is close to zero.

Table 13
Calculated parameters of explosive B, inert aluminium

AN 90% Diesel oil 5% Al_{inert} 5%	Detonation parameters [p] = GPA Closed-vessel parameters [Q] = MJ/kg		
$\rho = 0.850\ g/cm^3$	$D = 5032\ m/s$	$p_{C\text{-}J} = 5.803$ $p_V = 2.712$	$Q_{C\text{-}J} = 3.689$ $Q_V = 3.700$
$\rho = 0.800\ g/cm^3$	$D = 4852\ m/s$	$p_{C\text{-}J} = 5.160$ $p_V = 2.416$	$Q_{C\text{-}J} = 3.687$ $Q_V = 3.698$
$\rho = 0.750\ g/cm^3$	$D = 4672\ m/s$	$p_{C\text{-}J} = 4.564$ $p_V = 2.138$	$Q_{C\text{-}J} = 3.685$ $Q_V = 3.696$

On the basis of the obtained results the following final conclusions concerning the optimal composition of the aluminized ANFO can be made:

- Oxygen balance of aluminized ANFO should be sustained close to zero, while in this case the explosives are characterized by an optimal set of detonation properties
- Porous AN can be used as an oxidizer, but its oil absorption shouldn't be too high because aluminium powder acts as an additional sensitizing agent
- Atomized aluminium powder should be used as a solid fuel because it usually contains a smaller amount of aluminium oxide and does not raise dust. It is cheaper than flake powder as well.

References

[1] Escales, R. 1899a. British Patent 24,377.
[2] Escales, R. 1899b. Belgian Patent 145,599.
[3] Roth, G. 1900. German Patent 172,327.
[4] Urbańsk, T. 1955. *Chemistry and Technology of Explosives*. Warsaw: Wyd. MON (in Polish).
[5] Maranda, A. 1990. Research on the process of detonation of explosive mixtures of the oxidizer fuel type containing aluminium powder. *Propellants, Explosives, and Pyrotechnics*, 15: 4.
[6] Mason, C. N., and W. C. Montgomery. 1976. Aluminum additives impart energy and sensitivity to many explosives. *Engineering Mining Journal*, 7: 83–85.
[7] Cook, M. A. 1974. *The science of industrial explosives*. IRECO Chemicals: Salt Lake City.
[8] Maranda, A., D. Gałęzowski, and M. Swietlik. 1998. Investigations on the influence of ammonium nitrate oil absorption on detonation parameters of mining explosives (in Polish). *Przegląd Górniczy*, 54: 11.
[9] Mader, C. 1979. *Numerical modelling of detonations*. Berkeley: University of California Press.
[10] Cudziło, S. 1997. Private communication.
[11] Miyake, A., A. C. Van der Steen and H.H. Kodde. 1989. Detonation velocity and pressure of the non-ideal explosive ammonium nitrate. In *9th Symposium (International) on Detonation*, Portland, p. 560.
[12] Hornberg, H. 1986. Determination of fume state parameters from expansion measurements of metal tubes. *Propellants, Explosives, and Pyrotechnics*, 11:1, pp. 23–31.