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Research paper

Effect of Priming on the Detonation Development of an ANFO Explosive

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Abstract: Ammonium nitrate fuel oil (ANFO) compositions are widely used bulk industrial explosives in mining and civil engineering. Even though they are being replaced by the latest generation of emulsion explosives, some unique properties, such as a relatively simple production process, low price and very low impact sensitivity to stimuli, make them a good alternative to other explosives. However, a suitable primer should be used for the efficient initiation of ANFOs. Thus, three types of primers were studied in order to evaluate the effect of priming on the detonation development of ANFOs. Measurements were performed using the continuous resistance wire technique. The development of the detonation until it reached the stable detonation velocity has been analysed and discussed. An analysis confirmed that, depending on the type of primer used, a stable detonation velocity of an ANFO is achieved at different distances from the primer. The results have also proved that there is no significant influence of the type of primer used on the stable velocity of detonation for the tested diameter. An analysis confirmed that, depending on the type of primer used, a stable detonation velocity of ANFO is achieved at different distances from the primer.

Keywords: ANFO explosives, primer, detonation development, VOD

1 Introduction

Ammonium nitrate fuel oil (ANFO) is one of the most widely used civil explosives in the world, with the greatest consumption being in open-pit mining. Such explosives are characterised by low manufacturing cost, a simple production process and relatively good detonation parameters. ANFO explosives consist of porous prilled ammonium nitrate (AN) and fuel oil in the ratio 94:6. AN is not considered flammable and/or combustible [1]. It is an oxidizer and does not burn, but sustains burning. However, it may detonate under certain conditions. Such events may have disastrous consequences, from what was observed in a series of recent catastrophes [2, 3]. Due to their non-ideal detonation behaviour, ANFOs are treated as non-ideal explosives since the theoretically predicted values of the velocity of detonation (VOD) according to thermohydrodynamic theory cannot be reached. Even though an ANFO is characterised by a low detonation velocity and low detonation pressure, blasting effectiveness is high enough due to the large volume of gas released in the chemical reaction [4]. Zero oxygen balance may be obtained, which is associated with the high-energy value and low-volume of toxic gases. Therefore, application of ANFOs in underground mining seems to be very beneficial. However, since there is no water resistance, their application is limited to dry conditions. An ANFOs' velocity of detonation is considered stable when higher than 2,000 m/s. As pointed out by Olofsson [5], the diameter of the primer required to initiate an ANFO should be close to the diameter of the blasthole and should be sufficiently long to guarantee a stable detonation, as shown in Figure 1. In such a case, the ANFO is almost directly initiated to the full VOD.

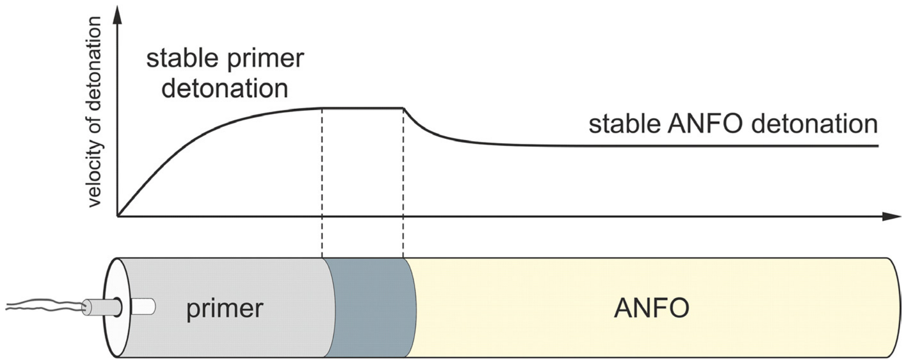

Figure 1. Optimum detonation progress of an ANFO initiated by a primer

The first studies on the detonation properties of ANFOs had already been conducted at the end of the 1960s [6]. Later, a number of research publications described the effect of different factors on the detonation parameters [7]. Dobrilović *et al.* [8] stated that the temperature of an ANFO affects the detonation velocity. The higher the charge temperature, the higher the VOD. In order to enhance the heat of explosion and increase the pressure of the gaseous products, other solid fuels such as aluminum are utilized. Replacement of a part of the oil by aluminum results in a significant improvement in the detonation parameters. Such a replacement is associated with an increase in the reaction temperature and the VOD on the one hand, and a decrease in the toxic gaseous detonation products on the other, but it also increases the sensitivity of an ANFO to stimuli [9, 10]. The detonation velocity of an ANFO is also related to the charge diameter and confinement. The VOD is increased by an increase in the charge diameter, and was confirmed by experimental tests and numerical simulations [11]. Furthermore, the detonation velocity is increased by an increase in confinement thickness [12, 13]. From the manufacturing point of view, some physical properties of prills and pores, such as porosity, particle size, pore diameter or pore volume are also being studied. An increase in prill porosity results in an increase in the detonation velocity of ANFO mixtures. Higher VODs are also observed for mixtures containing fine particles [14]. In turn, the VOD of an ANFO is increased by a decrease in pore diameter and also by a decrease in particle diameter [15]. Based on the above, one may conclude that the physical properties of AN have a significant influence on the sensitivity and propagation behaviour of the detonation of an ANFO. It is also worth emphasizing that since the implementation of AN for the production of ANFOs, emulsion explosives and water gels, the study and development of new formulations of explosives has been less active [16].

The in-hole detonation velocity of ANFOs is also highly dependent on the blasthole diameter [17]. For small diameters, the detonation may not be stable. Mesec *et al.* [18] stated that on the basis of field investigations that the detonation velocity of an ANFO increases with the detonation velocity of the primer and also therefore with the mass of the primer. Similar conclusions were obtained by Žganec *et al.* [19], who investigated the relationship between the detonation velocity of the primers used and the detonation velocity of the primed explosive for both ANFO and Heavy ANFO blends. This issue is also related to the energy of initiation, since the detonation velocity of an ANFO is increased by an increase in the shock wave energy (mass of initiator), as discussed by Bohanek *et al.* [20]. Thus, in the present paper the influence of the primer on the detonation development and detonation velocity of ANFOs has been verified and evaluated in small scale tests. Furthermore, the distance at which detonation becomes stable was determined. This problem is crucial for effective initiation of explosives in mining, and therefore the effectiveness of blasting operations.

2 Materials and Methods

The tests were conducted at the Central Mining Institute's test site in Mikołów, Poland. The object of the study was the SAL-Z mixture produced from AN porous prills (UltrAN 70 supplied by Yara) and FO (diesel oil from Orlen Refinery). The AN/FO ratio was 94:6. The declared AN bulk density of UltrAN 70 is 0.67-0.72 g/cm^3 and the diameter of the prills is in the range of 1-2 mm. The concentration of nitrogen in AN is 34.5% and the water content is below 0.3%. Selected parameters of the SAL-Z explosive are listed in Table 1.

Table 1. Selected parameters of the tested explosive based on the technical data sheet

Density [g/cm^3]	0.7 ±0.1
Minimal diameter [mm]	50
Velocity of detonation [m/s]	>2,000$^{a)}$
Oxygen balance [%]	–3.76
Heat of explosion [kJ/kg]	3,520
Concentration of energy [kJ/dm^3]	2,503
Specific energy [kJ/kg]	971
Specific volume of gaseous products of explosion [dm^3/kg]	997

$^{a)}$ measured in paper tube

Explosive samples were prepared by filling plastic sewage pipes with the explosive. The internal diameter of the pipes was 46.4 mm, length 1,000 mm and wall thickness 1.8 mm (Figure 2). Samples were equipped with MREL's VOD ProbeRods with a unit resistance of 331.7 Ω/m. The ProbeRod was inserted axially in the explosive sample from the opposite end to the detonator. The average weight of each sample was approximately 1.1 kg. The density of the samples was between 0.74 and 0.76 g/cm^3, while 0.7 ±0.1 g/cm^3 is a value declared by the producer. The detonation velocity was measured using a MicroTrap VOD/Data Recorder. A description of the measuring method may be found elsewhere [21].

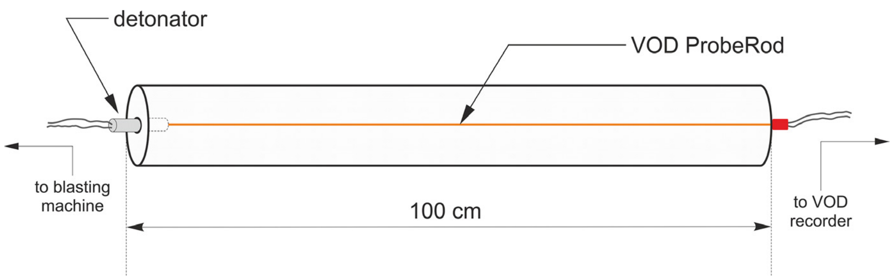

Figure 2. Scheme for the explosive sample

Three types of initiation have been tested, *i.e.* enhanced electric detonator (WZI) with a base charge of 1.3 g of crystalline hexogen, explosive booster (HC14) with 14 g of pressed phlegmatized hexogen and explosive booster (HC40) with 40 g of pressed phlegmatized hexogen, as shown in Figure 3.

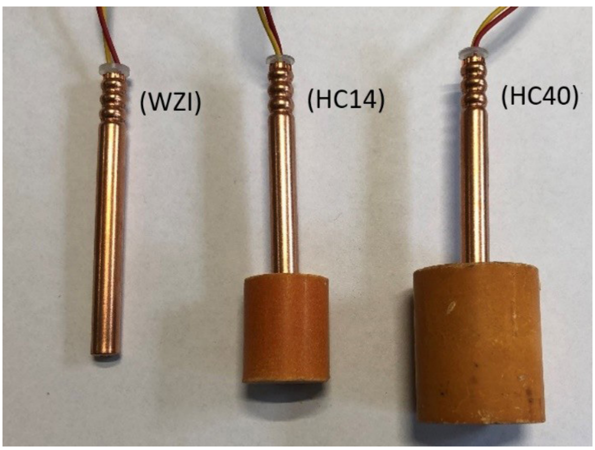

Figure 3. View of the tested primers

The samples were placed horizontally on the floor of the experimental facility and fired. Prior to firing each sample was covered with a 30 cm layer of sand to minimise noise. In the first stage, data analysis was carried out using Data Acquisition Suite software, which enables conversion of the recorded DC voltage signals over time to the velocity of detonation. Then detailed data processing and analysis was performed with the use of DIAdem software, developed by the NI company.

From the point of view of data processing, the most demanding action was conditioning the signal to so that it could be further analyzed. As can be seen in Figure 4, the raw signal showed that the change in the length of the measurement probe over time contained a number of interferences that disturb the continuity of the recorded resistance signal. Before determining the VOD waveform for the entire signal, it was necessary to eliminate any disturbances while maintaining an appropriate level of adjustment of the smoothed curve to the real measurement (blue line in Figure 4). The signal conditioning process and selected method of VOD determination is shown in Figure 5.

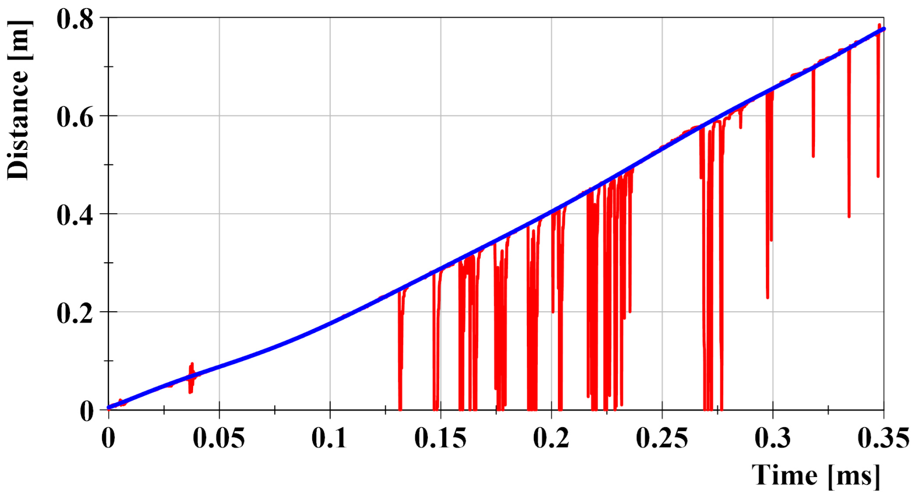

Figure 4. Example distance vs. time plot for determining the detonation velocity

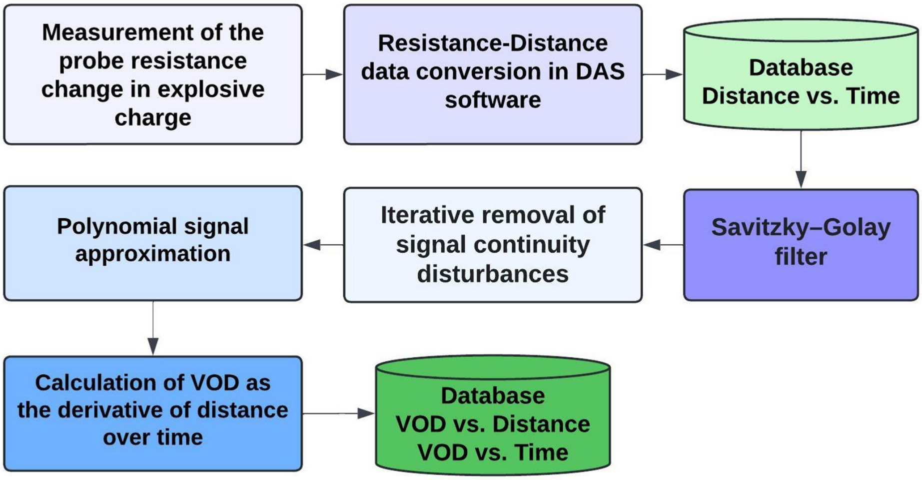

Figure 5. The flowchart for determining the VOD vs. time

After recording and converting the data, a database of signals was created, which were then subjected to filtration and conditioning processes in further stages. In the first stage, the signals were smoothed using the Savitzky-Golay filter, which is a digital filter that can be applied to increase the precision of the data without distorting the signal tendency [22]. Then, the initially smoothed signals were subjected to iterative removal of signal discontinuities. The objective function in this method was to meet the condition in which the value of the measurement point n, representing the distance, is always smaller than $n + 1$. Then, the conditioned signals were approximated with polynomial signal approximation, which eliminated any unwanted jumps or drops in resistance during the measurement. Finally, the curves obtained, representing distance *vs.* time, were subjected to the process of calculating the derived distance over time, which makes it possible to determine the full curve of the detonation velocity over time. An example of the effects of signal conditioning and computation is shown in Figure 6.

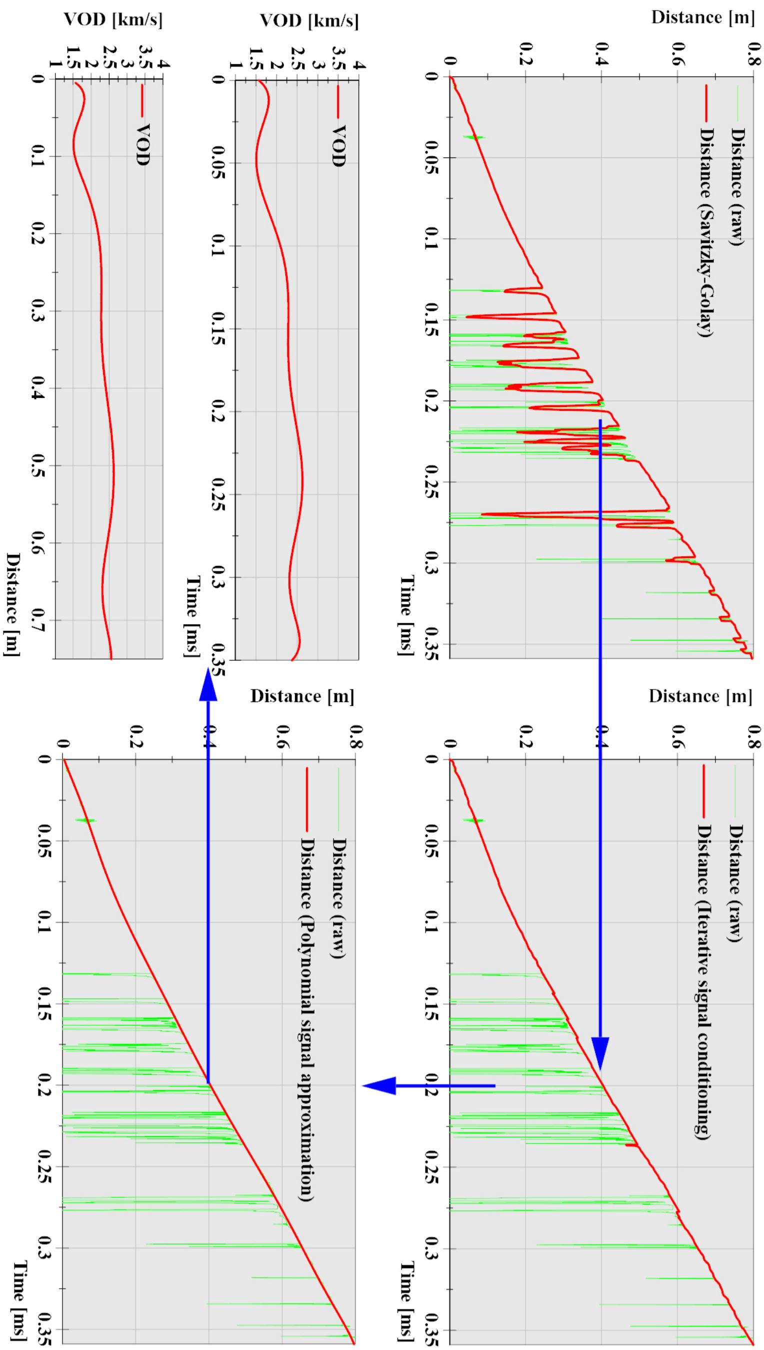

Figure 6. Graphical presentation of the signal conditioning process and VOD *vs.* time determination

In order to determine the VOD based on the time and distance recorded during the measurements, a method based on the calculation over the Second Order Central Difference Quotient was used. The calculations were made using the following equation:

$$y'_n = \frac{y_{n-2} - 8y_{n-1} + 8y_{n+1} - y_{n+2}}{12(x_{n+1} - x_n)}, 2 < n < N \quad (1)$$

where y is the distance in a given time (in m), x is the time (in ms) and N is the number of values in the analysed signal.

This procedure requires equidistant and strictly monotonically increasing x-values. It should be noted that in the calculation method used, the necessary number of interpolation points for the calculation of the central difference quotient is not available at the edges. Therefore, the second order forward difference quotient for the first two points of the signal were calculated according to the following formulas:

$$y'_1 = \frac{3y_1 + 4y_2 - y_3}{2(x_{n+1} - x_n)} \quad (2)$$

$$y'_2 = \frac{-3y_2 + 4y_3 - y_4}{2(x_{n+1} - x_n)} \quad (3)$$

The second order backward difference quotient for the last two points of the signal were calculated according to the following formulas:

$$y'_{N-1} = \frac{y_{N-3} - 4y_{N-2} + 3y_{N-1}}{2(x_{n+1} - x_n)} \quad (4)$$

$$y'_N = \frac{y_{N-2} - 4y_{N-1} + 3y_N}{2(x_{n+1} - x_n)} \quad (5)$$

3 Results and Discussion

The results of the detonation velocity measurements along with the corresponding curves, after the signal conditioning process, are shown in Figure 7.

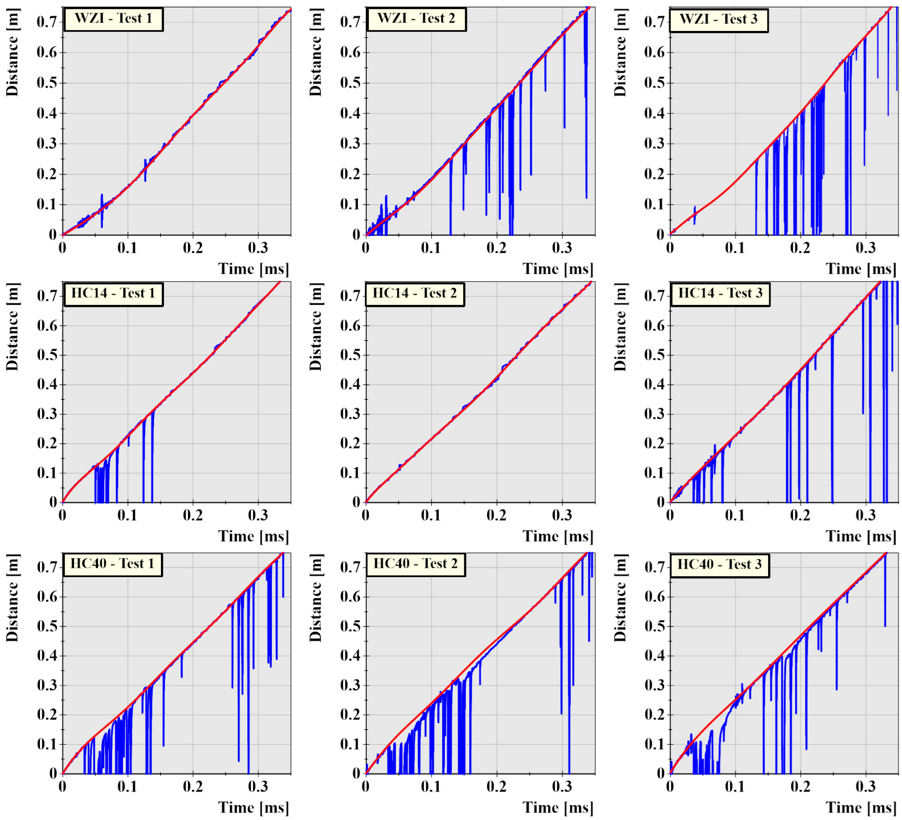

Figure 7. Graphical presentation of the signal conditioning process and VOD *vs.* time determination

3.1 Determining the peak VOD value

Based on the calculations performed in accordance with the procedure described in section 2, VOD curves were calculated, which can be compared with time or distance along the measurement probe (Figure 8).

By analyzing the calculated curves, it is possible to qualitatively determine the stability of detonation in specific samples and to define the peak VOD value for each sample. It should be noted, however, that when analyzing the peak VOD value of an ANFO explosive, the section of the curve related to the initiation process should be omitted because the high velocity values recorded in the initial phase of detonation are related to the VOD of the boosters. Therefore, the sections in the range from 0 to 0.1 ms and from 0 to 0.2 m were omitted in this part of the analysis. The peak VOD values along with the average values for different types of initiation are listed in Table 2.

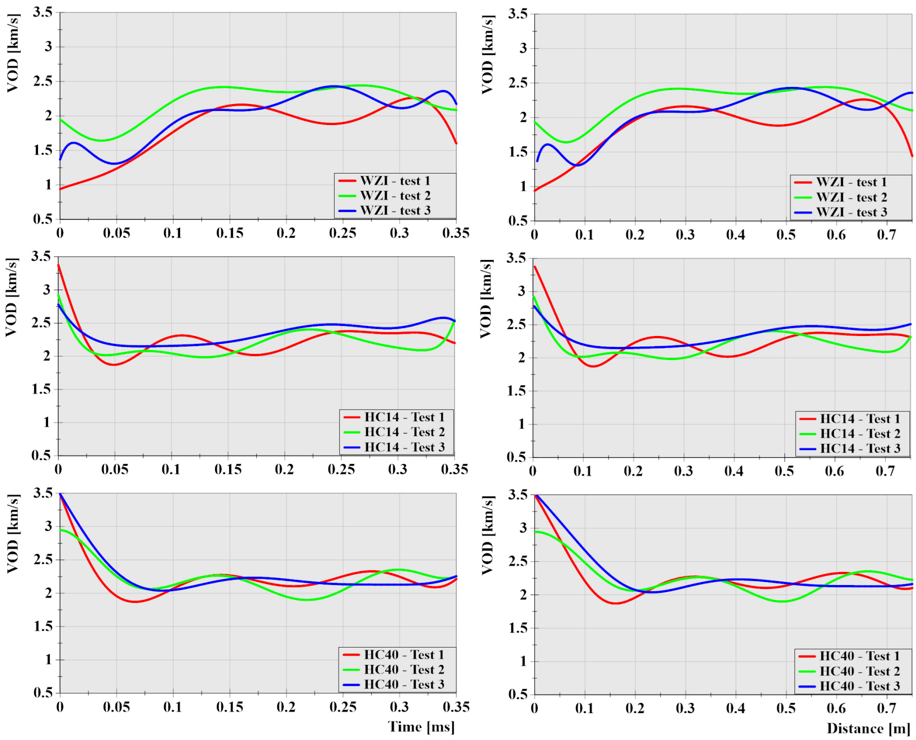

Figure 8. VOD vs. time (left) and VOD vs. distance plots (right)

Table 2. Peak VOD values in relation to priming method

Primer	Peak VOD [m/s]			
	Test #1	Test #2	Test #3	Average peak VOD
WZI	2,260	2,440	2,430	2,380
HC14	2,380	2,400	2,580	2,450
HC40	2,350	2,470	2,370	2,400

From Table 2, one may conclude that the difference between the average VOD values for the explosive initiated using the WZI detonator, HC14 and HC40 boosters is less than 3% in extreme cases. Based on this, it can be stated that the method of initiation did not affect the peak value of the tested explosive. However, on the other hand, it can be observed that the method of initiation affects the process of achieving stable detonation of individual explosive charges. Therefore, in further research, attempts were made to determine the point of achieving stable VOD for each of the tested samples.

3.2 Determining the stable detonation point

Stable detonation, according to the definition by the Center for Chemical Process Safety Glossary [23], is a detonation that progresses through a confined system without significant variation of velocity and pressure characteristics. Thus, in order to determine the range of acceptable VOD variability for each sample within the limits of stable detonation, the change in the value for each sample in the window between 0.125 and 0.330 ms was analysed. This was the range of the smallest fluctuations in the VOD. The results of the analysis are listed in Table 3.

Table 3. Stable VOD ranges and stable detonation limits for further calculations

Primer	VOD_{min} [m/s]	VOD_{max} [m/s]	VOD_{av} [m/s]	Upper boundary of stable detonation [%]	Lower boundary of stable detonation [%]
WZI-1	1,880	2,260	2,070	9	9
WZI-2	2,180	2,440	2,370	8	6
WZI-3	2,070	2,430	2,220	7	10
HC14-1	2,020	2,380	2,240	10	6
HC14-2	1,980	2,400	2,210	10	9
HC14-3	2,170	2,580	2,360	8	5
HC40-1	2,100	2,330	2,210	5	5
HC40-2	1,900	2,350	2,080	9	13
HC40-3	2,130	2,230	2,170	2	3
Average	2,050	2,370	2,210	7	7

Finally, it was found that the point of reaching stable detonation is the distance at which VOD reaches a value in the range of ±7% of the average VOD of a given sample. The results of the analysis are presented in Figure 9 and Table 4.

Table 4. The point of achieving stable detonation and the percentage of points with VOD greater than the lower limit of stable VOD

Primer	Point of reaching stable detonation [m]	Average [m]	VOD above the lower boundary of stable detonation [%]	Average [%]
WZI-1	0.177	0.180	67.1	68.1
WZI-2	0.164		71.9	
WZI-3	0.200		65.2	
HC14-1	0.159	0.071	88.3	94.8
HC14-2	0.031		96.2	
HC14-3	0.022		100.0	
HC40-1	0.207	0.157	86.3	95.4
HC40-2	0.129		100.0	
HC40-3	0.136		100.0	

A detailed analysis of the detonation process made it possible to determine the moment of achieving stable detonation for each of the tested samples. Based on this analysis, explosive charges of the ANFO initiated by the WZI detonator on average reached a stable detonation after 0.18 m from the point of initiation. In the case of initiation with a booster, these values were 0.071 m for HC14 and 0.157 m for HC40, respectively. However, by analyzing the waveforms presented in Figure 9, it can be observed that an assessment of the detonation process based solely on the moment of achieving stable detonation may not reliably reflect the studied problem, since the nature of the initiation is also important. In the case of priming using the WZI detonator, the VOD curves indicate a clear trend of "accelerating" the ANFO explosive until stable detonation is reached. When using boosters (both HC14 and HC40), this trend is completely the opposite. In these cases, the detonation velocity in the initial phase is significantly higher than the stable detonation velocity of the ANFO explosive. As a result, the use of a booster, even if it does not affect the detonation velocity of the explosive, is the basis for increasing the efficiency of mining at the bottom of the blast hole. Additionally, by analyzing the distribution of VOD above the lower limit of stable detonation, it can be observed that the use of boosters ensured achievement of VODs with values within the stable detonation range or higher in the case of 94.8% of the points for the HC14 booster and 95.4% of the points for the HC40 booster, respectively. In turn, when priming using the WZI detonator, the stable detonation range was achieved for 68.1% of the points, which means that 31.9% of the charges, on average, detonated at a velocity lower than the stable VOD.

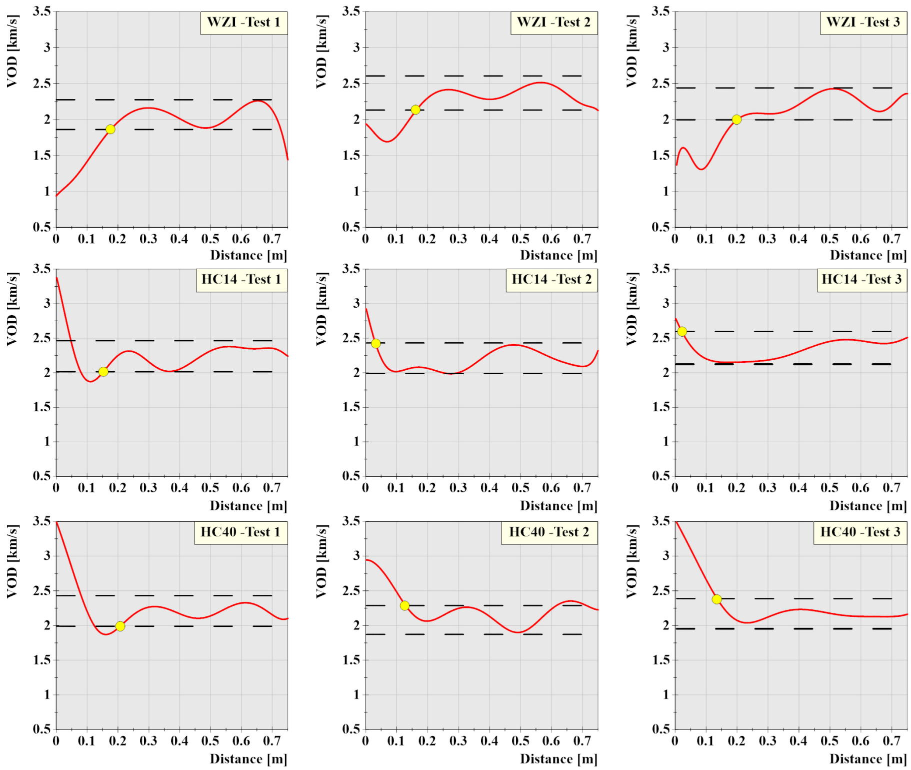

Figure 9. VOD curves with stable detonation points (yellow dots) and limits (black dashed lines)

4 Conclusions

- The analytical evaluation of the effect of priming on the detonation development of an ANFO explosive presented in this paper, has shown that the type of priming does not affect the value of the peak VOD for the tested ANFO explosive. Using a strong primer causes the explosive to start detonating with a VOD higher than its stable VOD and then achieves a stable detonation. In turn, using a less energetic primer causes the explosive to start detonating with a VOD lower than its stable VOD and then achieves stable detonation. Using a less energetic primer causes the initial part of the charge to detonate in an "understable" way and does not utilize the full energy of the explosive. Full utilization of energy of the explosive is achieved when a relatively strong booster is used.

- Based on the data analysis, the use of boosters, in both cases, ensured the appropriate level of VOD for over 95% of the length of the explosive charge. When using a detonator only, the explosion "accelerates" to a stable value over a longer distance, which may affect the blasting effect, especially in high-strength rocks.
- The analysis confirmed that there was no significant impact of the type of applied primer used on the steady VOD for the tested conditions. Even though the diameter of the charges was smaller than the minimal diameter specified in the technical data sheet, all measured VOD's fulfilled the requirements of the EU-type examination certificates, according to which it should be greater than 2,000 m/s.
- Based on the conducted research, it was also observed that the issue of a stable VOD requires further analysis, because, due to the large fluctuation of VOD during detonation, determining the range of stable VODs is not an unambiguous process.

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Authorship contribution statement

Piotr Mertuszka:	conception, foundations, methods, performing the experimental part
Krzysztof Fuławka:	performing the statistical analysis
Daniel Buczkowski:	conception, foundations, performing the experimental part
Mateusz Pytlik:	conception, methods, performing the experimental part

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