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Effect of Confinement on Detonation Velocity and Plate Dent Test Results for ANFO Explosive

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Abstract: The detonation properties of nonideal explosives are highly dependent on charge diameter and existence and properties of confinement. In this study, the effect of different confinements on the detonation velocity of ANFO explosives was experimentally determined along with the results of the plate dent test. ANFO explosive was selected as one of the most commonly used nonideal explosives. Following the measurement results, we found that the detonation velocity increased with increasing wall thickness, and the velocity increase was different for different confinement materials. A strong correlation existed between the ratio of the mass of confiner and explosive (M/C) and the detonation velocity (R = 0.995), and between (M/C) and the depth of the dent (δ) (R = 0.975). The data presented in this paper represent preliminary findings in developing a confinement model required for reliable numerical modeling of nonideal explosives.

Keywords: ANFO; confinement; detonation velocity; plate dent test

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1. Introduction

Nonideal high explosives are typically highly porous, low-density materials, where the fuel and oxidizer are not mixed on a molecular level, with a low detonation velocity (3–5 km/s) and a long detonation reaction zone (approximately centimeters) [1]. Due to its safety characteristics, simple manufacturing process, low price, and satisfactory blasting and technical properties, ANFO explosive is one of the most commonly used nonideal explosives in mining, construction work, and even for explosive welding of metal. Apart from its wide use, ANFO explosive is interesting from a scientific point of view, i.e., the numerous factors that affect the degree of nonideal behavior [2].

Several authors have presented their research on the influence of various parameters on the detonation velocity of ANFO, such as:

- Grain size, density, and porosity of ammonium nitrate [3–6];
- The influence of the addition of aluminum powder of different particle sizes and in different proportions [7–9];
- Method of initiation [10,11];
- ANFO temperature [12].

The relationships between the ANFO density, radius of the charge, oil fraction, and detonation velocity are already well-known [13].

One of the research interests related to the nonideal detonation of ANFO explosives is the influence of confinement on the detonation velocity and the shape of the detonation front. This article presents research conducted on small-diameter pipes made of different metals and wall thicknesses, and the influence of confinement on the measured detonation velocity, with the results of the plate dent expressed by a linear equation.

2. Confinement

ANFO explosive is put to practical use in many situations; therefore, in actual cases, it may perform differently than in the steel tube test, which is usually used in a laboratory. For this reason, understanding the effects of confinement on the ANFO detonation is important [14]. Currently, there is no model for nonideal detonation that fully describes the interaction between the confinement and the detonation products, but many researchers have presented their work on the interaction of ANFO explosives and various confinements. The effect of confinement on detonation velocity is shown to be complex [15].

The role of confinement in the detonation process (Figure 1) can be different:

- Removing energy from the reaction zone (sink confinement);
- Neither removing nor contributing energy (perfect confinement);
- Adding energy (energetic confiner) to the subsonic region of the reaction zone.

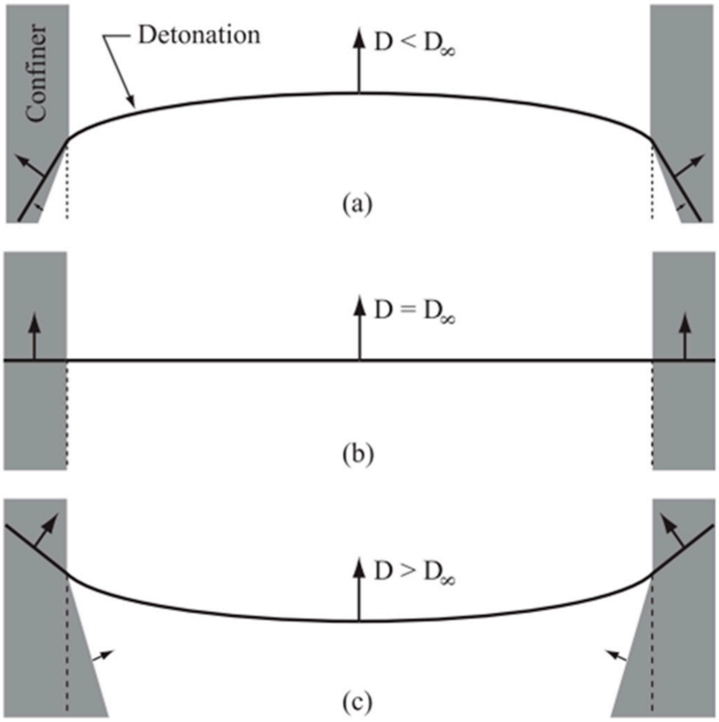

Figure 1. Different types of confinement: (**a**) sink, (**b**) perfect, and (**c**) energetic [1]. D, detonation velocity; D∞, ideal detonation velocity.

For sink confiners, the detonation velocity is higher than the sonic velocity of the confiner; for perfect confiners, the velocities are equal; and for energetic confiners, the sonic velocity of the confiner is higher than the detonation velocity of the explosive. For perfect confiners, the detonation front shape is perfectly flat as it would be in a charge of infinite radius and ideal detonation velocity [1].

The previous research on confinement has been conducted with different materials and with different wall thicknesses. Roughly, the confinement materials can be divided into three groups:

- Weak confinement, which includes paper and various types of PMMA, PVC, PC, and PP pipes;
- Strong confinement, which includes metal pipes (mainly steel, aluminum, or copper);
- Rock confinement, which includes various types of rock blasted in mining operations.

The wall thickness of strong and weak confinements used in research is quite small compared with rock confinements during blasting. For weak confinement, the detonation velocities of ANFO increase with an increase in wall thickness. The detonation velocity differs in four types of polymeric confiners (PMMA, PVC, PC, and PP), and is related to the dynamic properties of the tube material, such as the dynamic Young's modulus, dynamic bulk modulus, and dynamic Poisson's ratio [14]. For strong confinement, increasing confinement results in increased detonation velocity relative to identical unconfined charge diameters [16]. For rock confinement, the increase in velocity of detonation (VoD) due to confinement is higher at small blasthole diameters and lower at large blasthole diameters. An increase in confinement and/or blasthole diameter at very large diameters or infinite diameters does not exceed the ideal VoD [17,18].

3. Materials and Methods

The velocity of detonation measurement and plate dent test were simultaneously conducted. Detonation velocity is one of the most important parameters of an explosive, which nowadays can be measured very accurately [19]. A plate dent test is an adequate tool for obtaining the brisance by demonstrating the capability of a detonating explosive to impart a dent or a depression on a steel plate or any other suitable metal; thus, the deeper the dent depth tests, the more brisant the explosive. One important advantage of the plate dent test is the calculation of detonation pressure using an empirical correlation [20]. Cold-rolled steel plate of given hardness is usually used; however, sometimes plate dent tests are also conducted using aluminum alloy plates [21]. In the reported tests, ANFO explosive with an ammonium nitrate/fuel oil ratio of 94.4/5.6 was used for the measurement, with bulk density ranging from 0.85 to 0.88 g/cm^3. Commercial ANFO was produced from prilled/granulated AN with a minimum 6.0% oil absorption, maximum of 0.3% moisture, and minimum 90.0% prills, with dimension between 1.0 and 2.83 mm. Oxygen balance was calculated by EXPLO 5 thermochemical code as 0.99%. Tubes made of steel, aluminum, or copper with different wall thicknesses were used for the test samples. Although in Figure 1 the sound velocity in confinement is considered the most important factor influencing the detonation velocity, confinements with similar sound velocities were used in this study. The main difference between confinement materials was the density of the different metals and the total mass of the tube. The length of the samples was 800 mm, the inner diameter was 37–42 mm, and the wall thickness was 2.0 to 10.25 mm. The weight of the tubes was measured before and after filling the pipe with explosives to determine the metal/explosive ratio.

The charges were initiated by an electric detonator, with an explosive charge mass of 720 mg of PETN, and an APG20 Mini Booster (20 × 90 mm, containing 20 g PETN charge) produced by Austin Powder GMBH.

The velocity of detonation was measured by an electrical method with an electronic timer Explomet2 and fiber optic probes. Optical fibers can detect and transmit a light signal accompanying a detonation wavefront. The optical fibers also serve as a convenient means of transporting the signal from the experimental assembly in the firing area to the recording shed [22]. The method measures the time necessary for the detonation wavefront to pass the distance between two probes. Based on the measured time and predefined distance between probes, the velocity is calculated. The distance between the two probes P1 and P2 was 160 mm.

The steel tubes were placed vertically on a 40 mm thick aluminum plate. AlMgSi 0.5 aluminum was used as the witness plate, and the aluminum plate was placed on a 1018 steel plate, which served as a buffer plate. For the same explosive load, the dent in the aluminum plate was much larger than in the steel plate, which enabled a more reliable measurement of the dent. The test setup is shown in Figure 2.

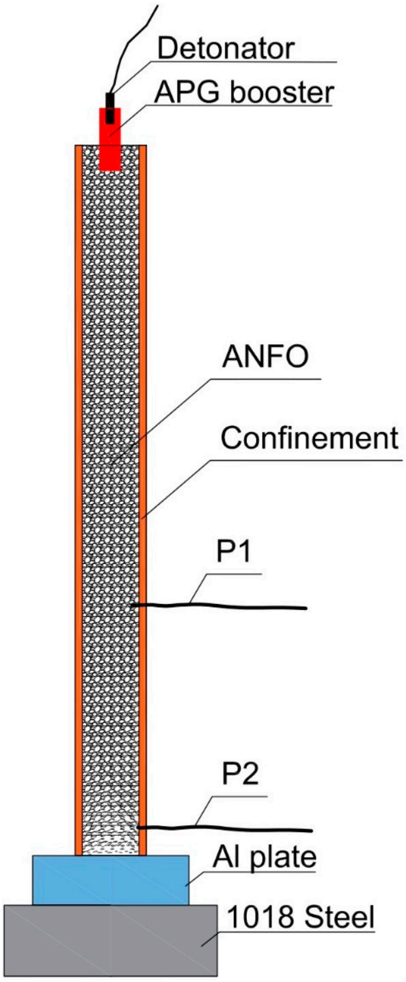

Figure 2. Measurement setup.

4. Results and Discussion

During the measurement, the detonation velocities were recorded, and after the measurement, the aluminum plates were cut in half and the depths of the resulting dents were measured. Three experiments were carried out for each tube, and the mean value of measurement is presented. One half of the aluminum plate after detonation is shown in Figure 3, and the results of measurement are in Table 1.

Figure 3. Aluminum plate cross-section after testing.

Table 1. Measurement results.

No.	**Confinement Material**	***ID***	***W***	***M/C***	***VoD***	***δ***
		(mm)	**(mm)**		**(km/s)**	**(mm)**
1	Steel	39	2,8	3.00	2.19	7.6
2	Steel	37	7.1	8.44	3.22	13,9
3	Steel	40	10.3	11.31	3.46	20.0
4	Al	40	2.5	0.82	*	*
5	Al	42	4.0	1.45	1.75	5.3
6	Al	40	10.0	4.03	2.54	9.1
7	Cu	40	1.0	0.99	1.66	3.4
8	Cu	40	5.0	6.15	2.90	13.4

Legend: *ID*—internal diameter; *W*—wall thickness; *M*/*C*—metal/explosive ratio; *VoD*—velocity of detonation; *δ*—plate dent depth; * detonation interrupted.

As shown in Table 1, a stable detonation velocity was measured in seven of eight samples, and in one sample, the detonation process stopped a few centimeters after the initiation point. Although the charge diameter was similar, only in this case was the detonation stopped for aluminum with a wall thickness of 2.5 mm, which clearly showed the influence of confinement on the critical diameter of ANFO explosive. For all metals, the detonation velocity increased with the thickness of the tube wall, which indicated that confinement had a similar effect on the ANFO detonation velocity as the diameter of the charge. In both cases, the increase in detonation velocity was associated with the reduction in the radial expansion of detonation products, i.e., energy loss. The effect of wall thickness on *VoD* for different metals is shown graphically in Figure 4. To show the difference in *VoD* between metals and PMMA, data on the measurement of *VoD* of ANFO in PMMA tubes with a diameter of 40 mm and different wall thicknesses were taken from the literature [14].

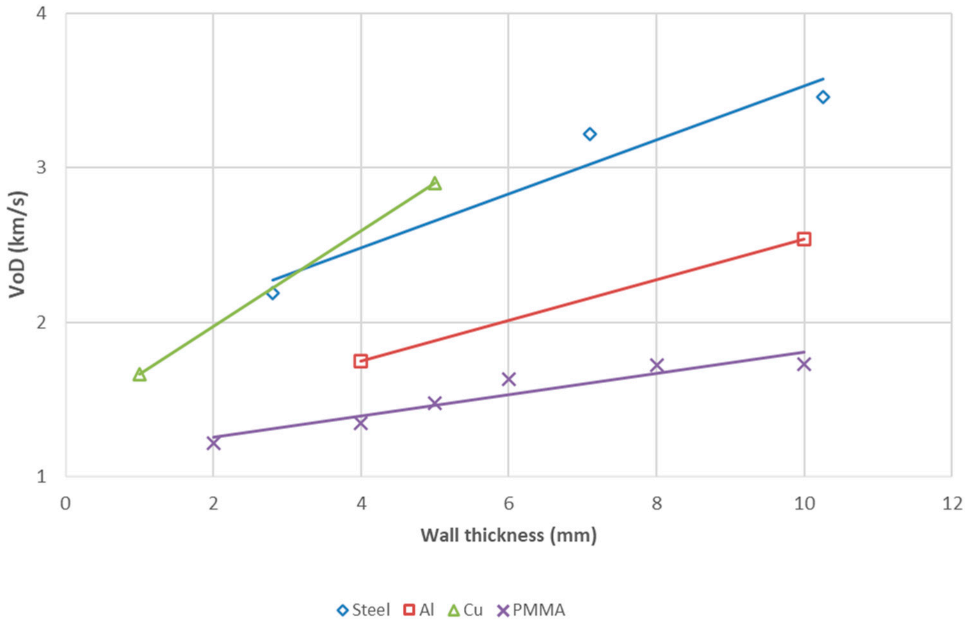

Figure 4. Influence of wall thickness on *VoD*.

The measured *VoD* increased as the wall thickness of the tubes increased for each material, and the measured *VoD* for the same wall thickness was different for each material. For example, the *VoD* for pipes with a wall thickness of 10 mm for PMA, Al, and steel was 1.72, 2.54, and 3.46 km/s, respectively. Although mechanical properties of metals can influence the *VoD* of ANFO in confinement, in this case, only the weight of the confinement relative to the weight of the explosive (M/C) was considered. R.W. Gurney formulated simple and reliable mathematical equations that predict the terminal velocity of metal fragments accelerated by the detonation of an explosive charge. Gurney proposed a semiempirical model that relates linear velocity (v_m) and the ratio of the mass of metal to the mass of explosive (M/C) and Gurney energy (E_G) [23]. Gurney's method can be directly and easily applied in many cases of interactions between explosives and metals; for an expanding circular geometry, this relationship can be expressed by the equation:

$$\frac{v_m}{\sqrt{2E_g}} = \left(\frac{M}{C} + \frac{1}{2}\right)^{1/2} \tag{1}$$

The effect of M/C on the VoD ratio is shown in Figure 5. VoD increases with the M/C ratio, approaching the ideal detonation velocity of 4.78 km/s (calculated by EXPLO5 thermochemical code). Using Autodyne hydrocode, we estimated that the calculated detonation velocity of ANFO approaches the ideal detonation velocity at $M/C \approx 115$ (which corresponds to steel pipe wall thickness of 50 mm). Autodyne calculations showed that for M/C = 112, VoD equals 4.7 km/s (i.e., 98% of the ideal velocity). Autodyne calculations were performed using the Lee-Tarver Ignition and Growth reaction rate model for ANFO decomposition. The constants in the reaction rate model were taken from [24] with the constant G_1 modified to 5.4 ($1/(\mu s \cdot Mbar^{0.9})$).

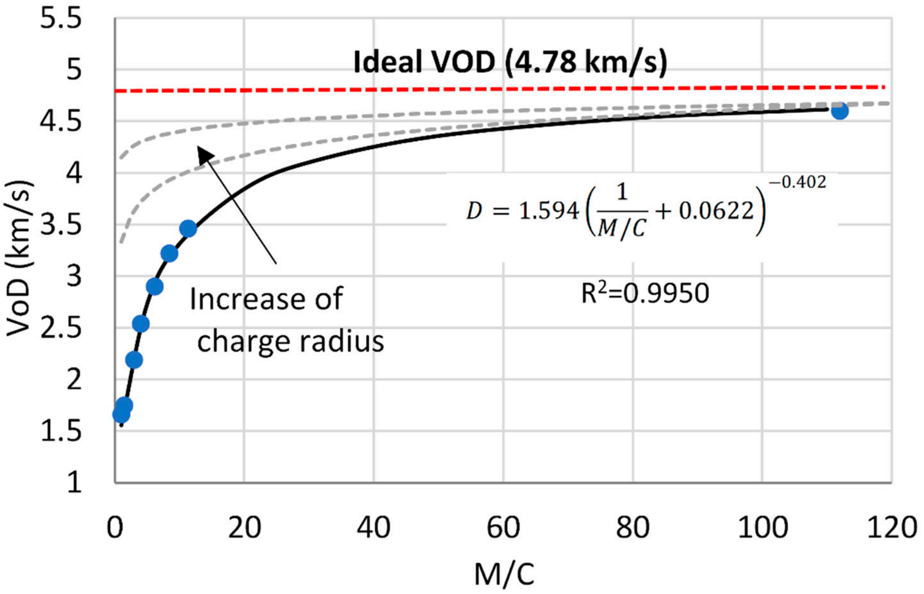

Figure 5. Influence of M/C on VoD. Note: Dashed lines represent the anticipated trend in VoD–M/C curves for larger charge diameters [1].

We found that the experimental M/C on VoD could be described very well with an equation similar to Gurney's equation for the cylinder wall velocity calculation of (Equation (1)). Because the effect of M/C on wall velocity and detonation velocity is inverse (an increase in M/C decreases wall velocity but increases detonation velocity), we took the inverse M/C ratio, i.e., C/M, which resulted in the following equation:

$$VoD = a\left(\frac{C}{M} + b\right)^{c} \tag{2}$$

where a, b, and c are constants that were determined by nonlinear regression analysis of experimental VoD–M/C dependence (a = 1.594, b = 0.0622, and c = −0.402).

The constants in Equation (2) were derived for a 40 mm charge diameter. Because the VoD of ANFO explosives at $M/C \to 0$ increases with the charge diameter, the shapes of VoD–M/C curves for various charge diameters are different (Figure 5). This means that the constants a and c change with the charge diameter.

In previous work, the depth of dent (δ) was used to predict detonation pressure P and the plate dent test was used to predict other performance parameters such as the acceleration ability of an explosive, with the results showing that a correlation exists between the Gurney velocity and δ/ρ_0 ratio [20]. In this case, where the density of the explosive is constant, the relation between the M/C ratio and the depth of dent is also established, as shown in Figure 6.

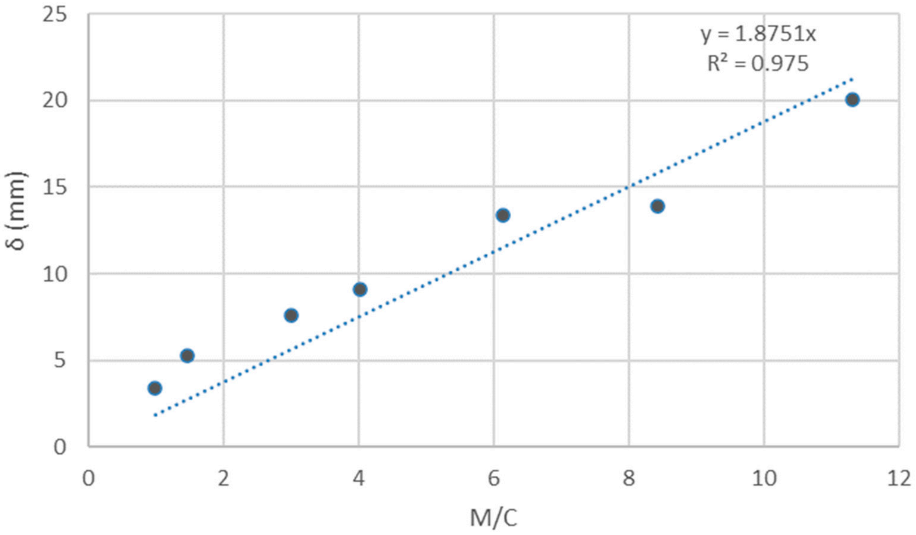

Figure 6. Influence of M/C on the depth of dent.

Our preliminary simulations using Autodyne hydrocode showed that the plate dent depends not only on the detonation pressure but also on the cylinder wall thickness and the charge diameter and length. Thus, a simple correlation between the pressure and the dent is not possible due to the above-mentioned effects that should be considered.

In both cases, shown in Figures 5 and 6, a strong correlation exists between the M/C ratio and the VoD, and between the M/C ratio and the depth of dent (δ). The correlation coefficient R^2 between VoD and M/C is 0.995, and that between M/C and depth of dent (δ) is 0.975.

5. Conclusions

The results obtained in this study demonstrated that confinement has a similar effect on the detonation velocity as the diameter of the ANFO explosive charge and can be associated with the radial losses of energy of detonation products. For the same charge diameter and confining material, the detonation velocity increases with wall thickness because confinement reduces the radial losses of energy of detonation products. Similarly, at larger charge diameters, radial energy losses are lower, resulting in a higher detonation velocity. Moreover, the critical diameter for ANFO explosive depends on the confining material and pipe wall thickness.

To show the effects of different confining materials and different wall thicknesses on the detonation velocity at one point, it is best to use the M/C ratio. The same applies to the dent depth in a plate dent test. The influence of the M/C ratio on detonation velocity and the depth of the dent in aluminum material in metal pipes with a diameter of 40 mm can be expressed by the following equations:

$$VoD = 1.594\left(\frac{1}{M/C} + 0.0622\right)^{-0.402},\ R^2 = 0.995 \tag{3}$$

$$\delta = 1.875\ (M/C),\ R^2 = 0.975 \tag{4}$$

where VoD is expressed in kilometers per second and δ in millimeters.

These equations can be used to calculate the *VoD* and plate dent test depth for various metals, hence, in the future, reducing the need for work-intensive parametric studies with various setups. For larger charge diameters, it is necessary to conduct additional measurements and adopt the equations. The data presented in the paper represent preliminary findings to develop a confinement model required for reliable numerical modeling of non-ideal explosives.

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