Article

Detonation behaviour of ANFO in resin tubes

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Abstract

Since the detonation properties of ANFO depend on confinement, this study investigates the detonation properties of ANFO with weak confinement tubes. In PMMA tubes, the detonation velocities of ANFO increased with an increase in wall thickness. The detonation velocity differed in four types of resins (PMMA, PVC, PC, and PP), and was related to the dynamic properties of the tube material. These confinement effects could well depend on the long reaction zone of ANFO and be influenced by the rarefaction wave from the outer and inner wall of the resin tubes. The detonation of ANFO using the PE and glass tubes failed and it was found from high-speed photography observations that the detonation behaviour was influenced by the properties of tube materials.

1. Introduction

Since ANFO (ammonium nitrate-fuel oil mixture explosive) is comparatively cheap and highly safe to handle, it is widely used as a commercial explosive. ANFO exhibits non-ideal detonation, and its properties strongly depend on the charge diameter and the confinement1)-3). There are several studies regarding diameter effects for ANFO1) 2); however, discussion regarding confinement effects is insufficient since the detonation of an ammonium nitrate(AN)-based explosive charged unconfined or in a weak confinement tends to fail easily within a small diameter.

ANFO 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 the laboratory. For this reason, understanding the effects of confinement on the ANFO detonation is important.

In this study, the influences of confinement on the detonation properties of ANFO with weak confinement were investigated through two approaches: Influences of the wall thickness and the material of the resin tubes. From these results, the relationship between the properties of confinement materials and the confinement effects was discussed.

2. Experimental

ANFO was prepared by blending 94 wt% of prilled AN with 6 wt% of No. 2 diesel fuel oil (JIS K2204). The average particle diameter of the AN was 1.1 mm, the oil absorption capacity was 11.6 wt%, the bulk density was 735 $kg \cdot m^{-3}$ and the water content was 0.07 wt%. After the blending, the ANFO was placed at room temperature for more than 24 hours before the tests.

In all the experiments, ANFO was loaded in a tube by hand with tapping. An inner diameter of all of the tube was approximately 40 mm and a length was 300 mm. In order to ascertain the influence of the wall thickness of the confining tubes on the detonation of ANFO, polymethylmethacrylate (PMMA) tubes with wall thickness between 2 mm and 10 mm were used. In order to ascertain the influence of the resin material, tubes made of five types of resins such as PMMA, polyvinylchloride (PVC), polycarbonate (PC), polypropylene (PP), and polyethylene (PE) and a borosilicate glass (Pyrex) were used for weak confinement, and a steel tube was used for strong confinement. The tube sizes used are listed in Table 1.

All shots were boosted with 50 g of emulsion explosive

Table 1 Detonation velocities of ANFO in various tubes.

Tube material	Inner diameter [mm]	Wall thickness [mm]	Charge density [kg·m^{-3}]	Detonation velocity [km·s^{-1}]
PMMA	40.0	2.0	890	1.22
	40.0	4.0	860	1.35
	40.0	5.0	860	1.48
	40.0	6.0	850	1.63
	40.0	8.0	840	1.72
	40.0	10.0	850	1.73
PVC	41.0	3.5	860	1.33
PC	41.0	3.5	870	1.13
PP	40.0	4.0	830	1.12
PE	41.0	3.5	850	failed
Glass	40.0	2.4	830	failed
Steel	41.1	4.0	880	3.11

(density = 1160 kg·m^{-3}, detonation velocity = 5.85 km·s^{-1}) and initiated with an exploding bridge-wire detonator.

The detonation velocity was measured using four ionization pin probes, each mounted in drill holes at intervals of 50 mm along the confining tube axes. The velocities were calculated by the distance of the probes and the arrival time difference of the shock wave using linear least-squares fits.

3. Results and Discussion

The results of the detonation velocities are summarised in Table 1.

3.1 Influence of the wall thickness of PMMA tube

The wall thickness effect of PMMA on ANFO is shown in Fig. 1. The detonation velocity increased from 1.22 km·s^{-1} to 1.73 km·s^{-1}. However, at wall thickness above 8 mm, the detonation velocity converged to a constant value of approximately 1.72 km·s^{-1}. This value was nevertheless far below the value of 3.11 km·s^{-1} using the steel tube.

In the previous studies, the detonation velocities of AN[4-6] and AN-based explosives[7] using steel tubes increased with wall thickness. In this study, similar behaviour was observed for PMMA tubes, and the wall thickness of weak confinement such as the resin tube also has an influence on the detonation velocities of ANFO.

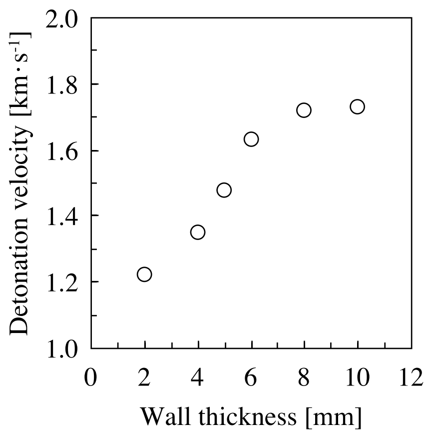

Fig. 1 Influence of the wall thickness of the PMMA tube on the detonation velocity of ANFO. (Inner diameter: 40 mm)

This phenomenon depends on the reaction zone; the reaction zone of AN-based explosives is thicker than that of other common high explosives[7-9]. Furthermore, since the detonation velocities of ANFO in PMMA tubes were lower than the sound velocity of PMMA, the wall thickness effect on ANFO appeared significantly in not only the steel tube but also the resin tube. In the condition of this study, a rarefaction wave from the outer wall influenced the reaction zone that caused a decrease in the detonation velocity at a wall thickness of less than 8 mm[10]. At a wall thickness of more than 8 mm, the reaction was finished when the rarefaction wave reached the area and consequently the detonation velocity converged to a constant value.

3.2 Influence of the tube materials

The detonation velocities were different in the different resin tubes as shown in Table 1.

Since the conditions of the shots were nearly identical except for the tube material, and the deformation behaviour of each resin tube due to the detonation of ANFO was observed to be different from the high-speed photographs[11], the different velocities measured must depend on the mechanical properties of the tube materials. In this study, the velocities were compared with the dynamic properties, such as dynamic Young's modulus, dynamic shear modulus, dynamic bulk modulus and dynamic Poisson's ratio.

These moduli were calculated from the longitudinal and transverse wave velocities using Eqs. (1) to (4) [12,13].

$$\mathrm{E} = \rho \frac{V_S{}^2(3V_P{}^2 - 4V_S{}^2)}{V_P{}^2 - V_S{}^2} \tag{1}$$

$$G = \rho V_S{}^2 \tag{2}$$

$$\kappa = \rho \frac{3V_P{}^2 - 4V_S{}^2}{3} \tag{3}$$

$$\nu = \frac{V_P{}^2 - 2V_S{}^2}{2(V_P{}^2 - V_S{}^2)} \tag{4}$$

Table 2 Wave velocities and dynamic moduli of tube materials.

Tube material	Density [kg·m^{-3}]	Longitudinal wave velocity [km·s^{-1}]	Transverse wave velocity [km·s^{-1}]	Dynamic Young's modulus [GPa]	Dynamic shear modulus [GPa]	Dynamic bulk modulus [GPa]	Dynamic Poisson's ratio
PMMA	1190	2.35	1.32	5.25	2.06	3.81	0.271
PVC	1420	2.02	1.05	4.13	1.58	3.65	0.311
PC	1190	1.92	0.893	2.60	0.95	3.13	0.362
PP	902	2.16	1.14	3.08	1.18	2.64	0.306
PE	949	2.01	0.953	2.33	0.86	2.69	0.355
Steel	7820	5.12	3.14	184	77.0	102	0.199

where E is the dynamic Young's modulus, G is the dynamic shear modulus, κ is the dynamic bulk modulus, ν is the dynamic Poisson's ratio, ρ is the density, V_P is the velocity of the longitudinal wave and V_S is the velocity of the transverse wave of the tube material. The wave velocities were measured by an ultrasonic wave velocity measurement system (OYO Corp. SonicViewer-SX) with the tubes. The values measured and calculated are shown in Table 2.

In Fig. 2, the detonation velocities in each tube with the wall thickness of 3.5 or 4.0 mm were plotted as a function of the dynamic moduli of the tube material. The detonation velocity increased with an increase in Young's modulus, shear modulus, and bulk modulus, and there was a tendency that the Poisson's ratio increased with the decrease in the detonation velocity.

It is not clear whether these properties of the tube material relate directly to the confinement effect on the detonation. However dynamic properties measures of deformation due

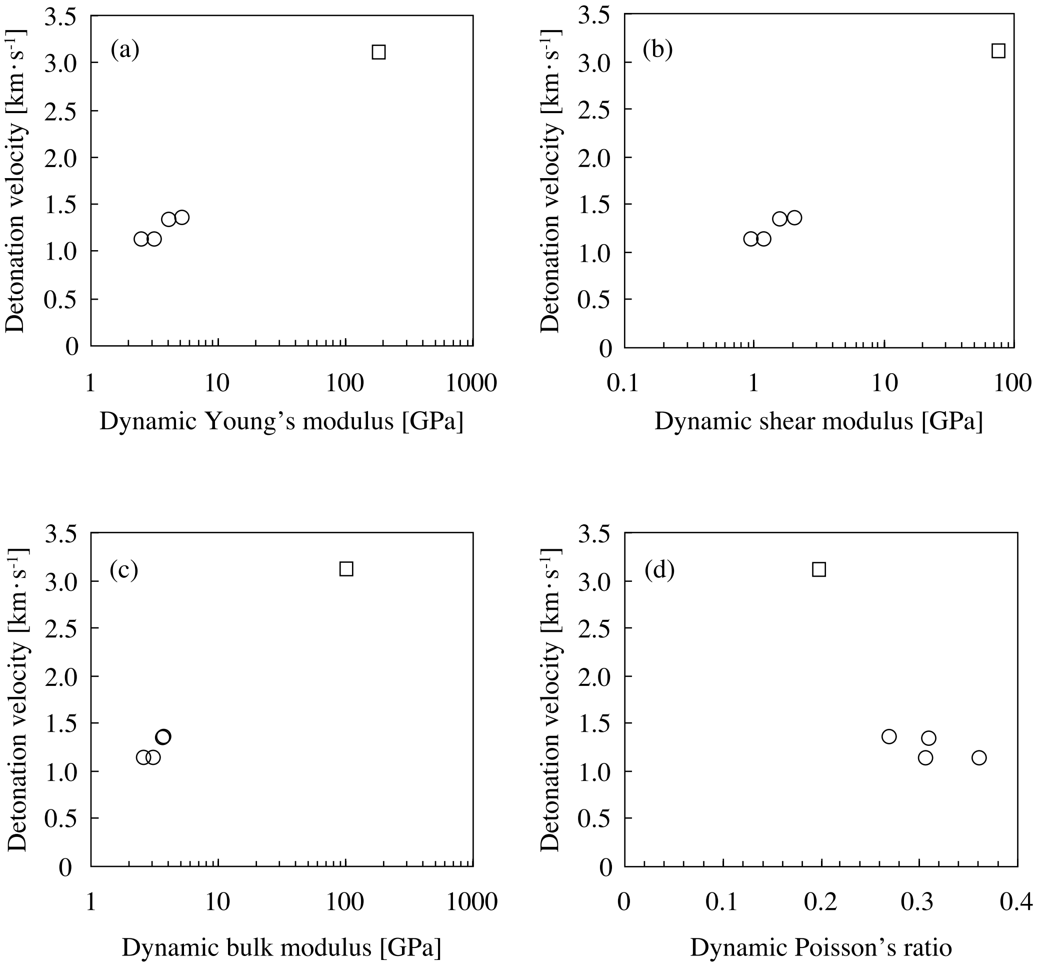

Fig. 2 Detonation velocity of ANFO as a function of the dynamic moduli of tube materials.
(Inner diameter: ca. 40 mm, wall thickness: 3.5 or 4.0 mm, ○ : resin, □ : steel)
(a) dynamic Young's modulus (b) dynamic shear modulus
(c) dynamic bulk modulus (d) dynamic Poisson's ratio

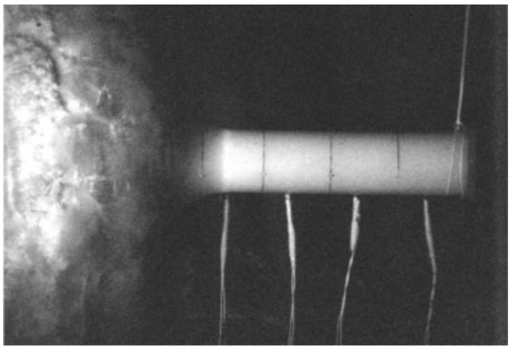

Fig. 3 High-speed photograph of detonation behaviour of ANFO using a PE tube. (Inner diameter: 41 mm)

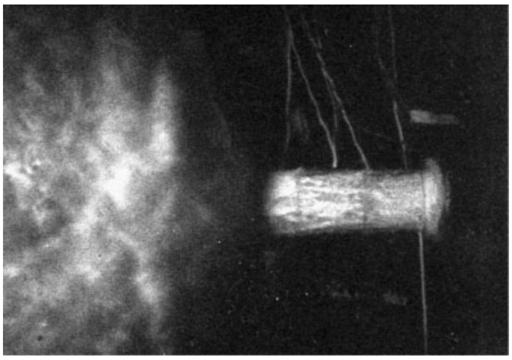

Fig. 4 High-speed photograph of detonation behaviour of ANFO using a glass tube. (Inner diameter: 40 mm)

to high-speed stress, and they may measure the influence of the rarefaction wave generated due to the deformation at the inner wall of the tubes. For example, since a small dynamic modulus implies that a large deformation occurs due to small forces, materials like PP whose moduli are small can easily be deformed by the detonation. The rarefaction wave due to the deformation of PP influences the reaction zone more than that due to PMMA. Due to the long reaction zone of the ANFO detonation, a small difference in tube deformation has large effects on the detonation.

The detonation of ANFO using the PE tube failed. Figure 3 shows the detonation behaviour using the PE tube, taken by a framing hi-speed camera (Cordin model-124). In this photograph and recovered tube, it was broken but did not fragment by the detonation. Since the dynamic moduli of PE are smaller than those of the other resins, the PE tube became more deformed by the detonation, and the rarefaction wave reduced the energy release from reaction zone. Furthermore, a value of tensile elongation of PE at failure is much higher than that of the other resins: The value of the static tensile elongation of PE is approximately 1000 and those of the other resins are from 3 to 600 in literature[14]. These properties of PE might cause the non-fragmentation and the failed detonation.

Further, the detonation in the glass tube failed. It was found from the photograph of the detonation behaviour shown in Fig. 4, that the glass tube was already broken prior to the arrival of shock front. Since the sound velocity of the glass is much higher than the detonation velocity; the stress wave passes through the glass tube ahead of the detonation wave, and when the reaction zone of ANFO arrived, the tube was already damaged and the detonation failed.

4. Conclusions

In order to investigate the influence of resin confinement on the detonation behaviour of ANFO, the detonation velocities in resin tubes were measured.

The detonation velocity of ANFO in the PMMA tubes increased with an increase in the wall thickness between 2 mm and 8 mm. Weak confinement as in PMMA has an influence on the detonation of ANFO. The detonation velocity of ANFO differed in the four types of resins (PMMA, PVC, PC and PP) and was related to the dynamic properties (dynamic Young's modulus, dynamic shear modulus, dynamic bulk modulus and dynamic Poisson's ratio) of the tube material. These phenomena could well depend on the long reaction zone of ANFO and be influenced by the rarefaction wave from the outer and inner walls of the resin tubes.

The detonation of ANFO using the PE and glass tubes failed and from the high-speed photographs it was found to be dependent on the properties of tube materials.

Acknowledgments

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樹脂容器中でのANFO爆薬の爆ごう特性

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ANFO爆薬は密閉強度効果が大きいことが知られており, 本研究では樹脂容器中でのANFO爆薬の爆ごう特性について検討した。PMMA管では肉厚の増加に伴いANFO爆薬の爆速が増加した。4種類の同径同肉厚の樹脂容器(PMMA, PVC, PC, PP)でも爆速に違いが見られ, 容器材質の動的弾性率との関連性がみられた。これらの現象はANFO爆薬の持つ長い反応帯長に依るもので, 容器の外側および内側からの希薄波によってもたらされたと考えられる。PEおよびガラス管を用いた場合はANFO爆薬の爆ごうは中断し, 高速度カメラの写真からそれぞれの容器の物性によるものであることが判った。

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