Article

Blast wave parameters of PETN with silicon rubber binder

Dongjoon Kim*, Yoshio Nakayama**, Tomoharu Matsumura**, Kunihiko Wakabayashi**, Atsumi Miyake*, Terushige Ogawa*, and Masatake Yoshida**

The present study focuses on the blast wave parameters of pentaerythritol tetranitrate (PETN) with silicon rubber (SR) as a binder. It is able to change the mass, the shape and density of explosives. In this study, in order to confirm the effect of the binder on the strength of blast waves, the mixing ratio was changed as PETN/SR=50/50, 70/30, 100/0 wt.%. Blast wave pressures were measured in free air and on a rigid surface. The experimental results indicate that the PETN/SR explosives can detonate even only 1g of PETN/SR=70/30 wt.%. In addition, the mixing ratio was found not to affect the blast waves parameters, which indicates that the silicon rubber had no significant effect on the blast wave. Both the experimental and numerical results indicate that the blast wave parameters can be estimated to a sufficient degree of accuracy based only on the PETN mass.

1. Introduction

In industry, the potential for an occurrence of an explosion accident is a common safety consideration. The damages from an explosion accident are a result of vibrations, fragments and blast waves. In explosion risk analysis, it is important to understand the behavior of blast wave propagation, because the blast wave could cause widely serious damage to structures as well as the loss of human life.

There are several studies on blast wave propagation[1)~5)]. Most experimental studies used TNT explosives. But, it is well known that TNT explosives are not detonated completely with a small charge. Therefore, the experiments using a large amount of explosives have been carried out on the free field. These experiments on the free field take a high cost and involve a high degree of risk. It is difficult to examine blast wave propagation in detail because of restrictions on the location and frequency of experiments. This situation requires a small-scale experiment. If the blast wave parameters from detonation of a small charge are similar to the blast wave parameters from detonation of a large charge at an identical scaled distance on the same geometry (=temperature, atmospheric pressure and humidity), blast wave propagation could be studied in greater detail because a small-scaled experiment could be carried out in the chamber of explosion.

This study used pentaerythritol tetranitrate (PETN) with silicon rubber (SR) binder as an explosion source. The explosive (PETN/SR) has several advantages. First, the mass, the shape and the density of PETN/SR can be controlled. Second, the risk involved with using PETN/SR in an experiment is low because PETN/SR is insensitive. These two factors have led to the widespread use of PETN/SR in explosion experiments[6)7)]. Although there are a few study[8)] on PETN/SR explosives, there has been no report on the strength of the blast wave of PETN/SR. The purpose of present paper is to confirm the effect of the binder of silicon rubber on blast wave parameters. This study compares results obtained by numerical calculation to experimental results as well as results reported in various sources[1)4)9)].

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*Dept. of Energy and Safety Engineering, Yokohama National University 79-5 Tokiwadai, Hodogaya-ku, Yokohama Kanagawa 240-8501, JAPAN
TEL +81-45-339-3981
FAX +81-45-339-4011
E-Mail dj-kim@aist.go.jp
**National Institute of Advanced Industrial Science and Technology (AIST) Tsukuba Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki, 305-8565, JAPAN
TEL +81-298-61-4793
FAX +81-298-61-4783
E-Mail y-nakayama@aist.go.jp

2. Experiments

2.1 Explosives

The explosives used in this experiments are shown in Table 1. The explosives of PETN (Diameter = 30 μm, Chungoku Kayaku Co. Ltd.) with silicon rubber

Table 1 Explosives used in this study.

Explosives	Weight (g)	Shape (L/D)	Density ($kg \cdot m^{-3}$)
PETN/SR=50/50 wt%	10, 20	Cylindrical (1/1)	1300
PETN/SR=70/30 wt%	1, 10, 30, 70, 130	Cylindrical (1/1)	1350
PETN/SR=100/0 wt%	10	Spherical	–

L/D: Length/Diameter of explosives

(Shin-Etsu Chemical Co. Ltd., KE10) as a binder were used. The mixing ratio was varied as PETN/SR=50/50, 70/30 and 100/0 wt.%. The explosives were initiated by electric detonators of the wire-explosion type. More than 10 g of each explosive was initiated by electric detonators (Nippon Kayaku Co. Ltd.), which include 0.8g of PETN. One gram of each explosive was initiated by a small-sized electric detonator (Showa Kinzoku Kogyo Co. Ltd.), which included 0.1 g of lead azide. The explosive charge of the detonator is less than 10% of the mass of the PETN/SR.

2. 2 Measurement of blast wave pressure by free air explosion

Figure 1 shows the experimental setup, including the pressure sensors (side and upper view) in a free air explosion. The blast pressure was measured by three piezoelectric sensors (PCB piezotronics Inc., HM102A), which were located at distances of 0.5, 1.2 and 1.8 m from the explosive, respectively. Both the explosives and the sensors were located at a distance of 1 m from a net-shaped floor surface. The surface is assumed not to produce the reflected waves. Although reflected waves are produced by the surface, these waves could not reach the sensors until the primary blast wave at that location had decayed to atmospheric pressure.

Signals were transmitted through coaxial cables and were recorded on a digital waveform digitizer (Gage Applied Inc., Gage 1610, 16 Bit, 10 MS/s) at a sampling rate of 1 MS/s. Each pressure sensor was flush-mounted to a sharp-edged stainless steel disk (which had a diameter of 90 mm) and was mounted in the direction where the blast wave overpressure was to be measured.

2. 3 Measurement of blast wave pressure by the surface burst

The experiments were carried out on a rigid surface. The explosive used in this experiment was 1 g of PETN/SR=70/30 wt.%. In order to compare the reference[9] and this experiment results, the height of burst (HOB) above the ground surface was set to 16 mm. This height also helps to prevent denting of the ground surface.

Figure 2 shows the experimental setup, including pressure sensors (side and upper view). The blast pressure was measured by four piezoelectric sensors, which were located from 0.3 to 1.7 and 1.9 m from the explosive. The model of the ground surface of which the

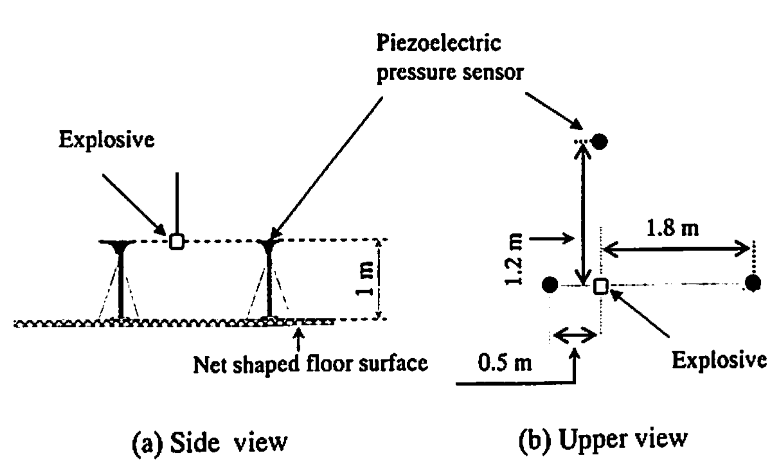

Fig.1 Experimental setup in free air.

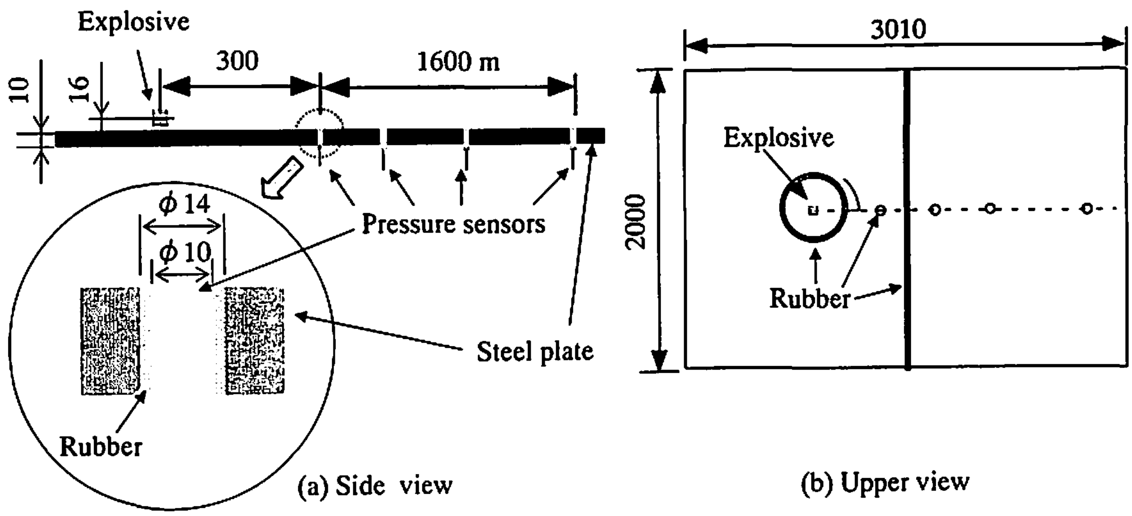

Fig.2 Experimental setup on surface burst.

thickness is 10 mm is made of steel. Special care was taken to minimize the effects of vibrations (ground shock) in the steel plate on the sensors[10]. Figure 2 also shows three places where the rubber elements (Chloroprene) were used. All sensors do not directly contact the steel plate by damping rubber elements in order to minimize the ground shock.

3. Numerical calculations

A numerical calculation was carried out in order to investigate the strength of the blast wave of PETN.

The simulation code employed in the present study was the AUTODYN-2D Euler code, which was confirmed the method of calculation of blast waves parameters by previous study[11)12)].

Figure 3 shows schematic illustrations of the 1 dimension and 2 dimension experimental setups. Figure 3a) illustrates the 1D spherically symmetric calculation for a free air burst. In the simulation, the X and Y direction were the symmetry axes. The mass of the PETN charge was 10 g. The ignition point was assumed to be the center of the explosive charge. The 1D simulation was performed in three stages with different grid resolutions in order to reduce calculation time. The cell width in the Y direction was fixed at 1 mm (ΔY=1 mm). Within the initial calculation time of 1.2 ms, the calculation range in the X direction was 1 m with a grid spacing of ΔX=1 mm. From the time of 1.2 ms to 3.5 ms, the calculation range was extended to 2 m. The grid spacing (ΔX) within the range from 1 m to 2 m was changed to 2 mm. After 3.5 ms, the calculation range was further extended to 4 m. The grid spacing (ΔX) within the range from 2 m to 4 m was changed to 4 mm. The simulation was completed at 15 ms.

Figure 3b) is the symmetric calculation of 2D for the surface burst. The Y direction in the simulation was the symmetry axis. The mass of the PETN charge was 1 g. The height of burst (HOB) was set to 16 mm. The ignition point was assumed as the center of the explosive charge, the position at which a hole for the detonator. The 2D simulation was also performed in three stages. At the beginning, the calculation domain was 500 mm × 400 mm with X and Y. Both of the grid spacing ΔX and ΔY were set to 1 mm within the initial calculation time of 0.5 ms. From the time of 0.5 ms to 1.4 ms, the calculation

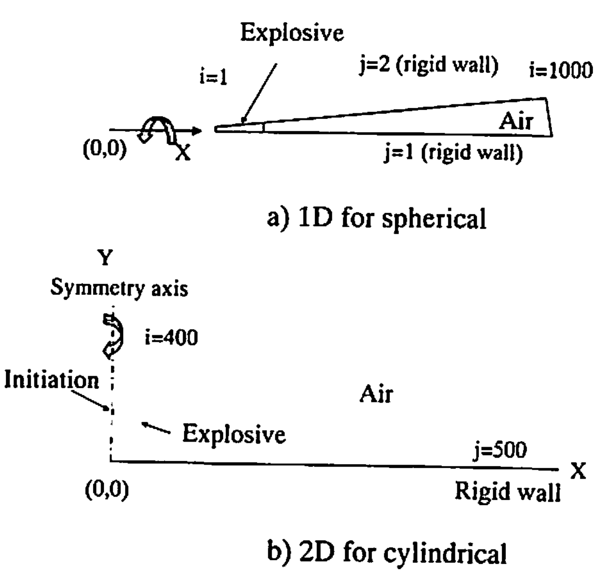

Fig.3 Schematic illustrations for 1D and 2D analysis.

Table 2 JWL parameters of PETN and TNT explosive used in this study.

Explosives	A (kPa)	B (kPa)	R_1	R_2	ω	D (m/s)	P_{cj} (kPa)	E_0 (kJ/m^3)	ρ_0 (kg·m^{-3})
TNT	3.738E+8	3.747E+6	4.15	0.90	0.35	6930	2.10E+7	6.00E+6	1630
PETN	6.171E+8	1.693E+7	4.40	1.20	0.25	8300	3.37E+7	1.010E+7	1770

domain was enlarged to 1000 mm × 800 mm. With the increased domain, the grid spacing of ΔX and ΔY were set to 2 mm. Finally, after 1.4 ms, the domain was further enlarged to 2000 mm × 1600 mm, and the grid spacing of ΔX and ΔY was set to 4 mm. The simulation was completed at 10 ms.

In this study the Jones-Wilkins-Lee (JWL) equation of state (EOS) was used for the product gas of the explosive[13]. Table 2 shows the JWL parameter and the detonation properties for PETN and TNT[14] employed in this calculation. The EOS for the detonation products was converted into the EOS for an ideal gas after the detonation products expanded to one hundred times the initial volume. Air was treated as ideal gas with a specific heat ratio of 1.4.

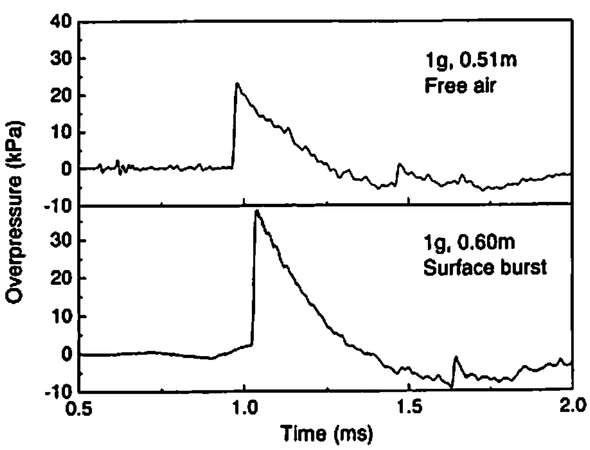

Fig.4 Typical blast wave histories of explosives. k (PETN/SR=70/30 wt.%)

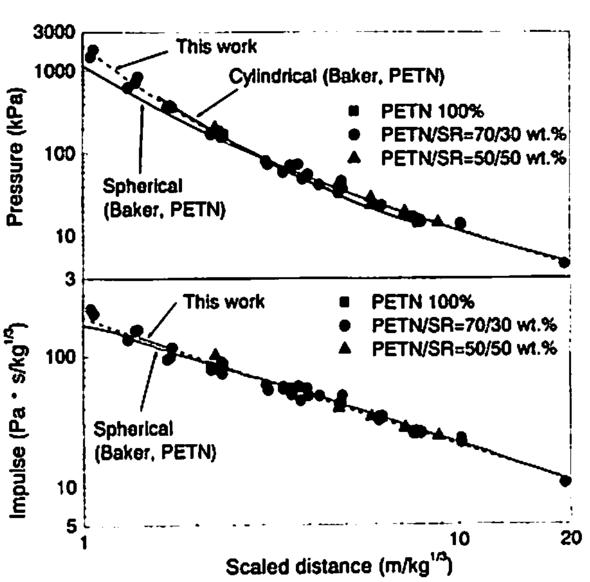

Fig.5 Peak overpressure and scaled impulse in free air.

4. Results and discussions

4.1 Blast wave parameters in free air

Figure 4 shows a blast wave history for example. Even though the mass of the explosive was only 1 g, the waveforms were similar to the typical wave form obtained experimentally for a large charge. The experimental result of the surface burst revealed that the damping rubber elements greatly minimized the effects of vibrations in the steel plate. In this study, the time-history of pressure wave was interpolated by smooth cubic natural spline functions to obtain peak static overpressure and impulse (the time-integral of the overpressure during the positive pressure phase).

Figure 5 shows the experimental results of peak overpressures and the scaled impulse with respect to the scaled distance in free air. In obtaining the scaled distance, we considered only the mass of the PETN, ignoring the mass of the silicon rubber. For the sake of comparison with the reference data, the detonation energy of PETN (See table 2) was used because the data of Baker4) is dimensionless. The spherical PETN data of Baker is shown as a straight line in Fig. 5.

Although the peak overpressure was slightly greater than Baker's data for the scaled distances of less than 3 m·kg$^{-1/3}$, the experimental results of the present study generally agreed with the data reported by Baker. This means that the mixing ratio has no effect on the blast wave parameters. Due to these results, when analyzing the blast wave parameters, the effect of the silicon rubber is considered to be insignificant.

Based on the above results, in order to obtain blast wave parameters with respect to the scaled distance, we used a smooth quadratic curve to interpolate the data as shown in Fig. 5. This is commonly used with a smooth quadratic curve in previous study[15].

The curve equations are as follows:

Peak overpressure

$$log(P_f) = -0.68947\{log(Z)\}^2 - 3.03643\,log(Z) + 6.31939 \qquad (R=0.9964) \quad (1)$$

Scaled impulse

$$log(I_f) = -0.06029\{log(Z)\}^2 - 1.04178\,log(Z) + 2.30064 \qquad (R=0.9892) \quad (2)$$

where, P_f is the peak static overpressure [Pa], Z is the scaled distance [m·kg$^{-1/3}$] and I_f is the scaled impulse [Pa·s·kg$^{-1/3}$]. The coverage of this curve is from 1 m · kg$^{-1/3}$ to 20 m·kg$^{-1/3}$. The curves are not suitable for extrapolation.

4. 2 Effect of shape of explosive

It is already mentioned that the peak overpressure is slightly greater than Baker's data for scaled distances of less than 3 m·kg$^{-1/3}$ in Fig. 5. The data of Baker were for a spherical explosion, but this work used cylindrical explosives. There is the study of effect of explosive shape on blast wave overpressure[5]. It is necessary to convert blast wave pressure from the spherical explosives of Baker into blast wave pressure from the cylindrical explosives in order to compare the experimental result to the data of Baker. In Fig. 5, the line of cylindrical is converted from the data of Baker by the NSWC data[5]. It is found that the line of cylindrical agreed greatly with this experimental results.

It is considered that near explosives, the peak overpressures obtained in the present experiment are slightly greater than those of Baker because of the effect of the explosive shape.

4. 3 Blast wave parameter by surface burst

There are a few studies[1)9)] about the surface burst. In this study, the MITI87[9] is used in order to compare with the experimental results. Figure 6 shows that the experimental results of the peak overpressures and the scaled impulse with respect to the scaled distance. The mass of the explosives is considered to be the mass of only the PETN.

In Fig. 6 this experiment results are generally greater than MITI87. But, MITI87 was used TNT explosives. It is necessary to consider the energy of explosive. We confirmed that when the blast wave parameters convert in dimensionless form, these experimental results agree with the MITI87.

Using these results, in order to obtain the relationship between the scaled distance and the blast wave parameters, we used a smooth quadratic curve to interpolate the data as shown in Fig. 6 as the dotted line.

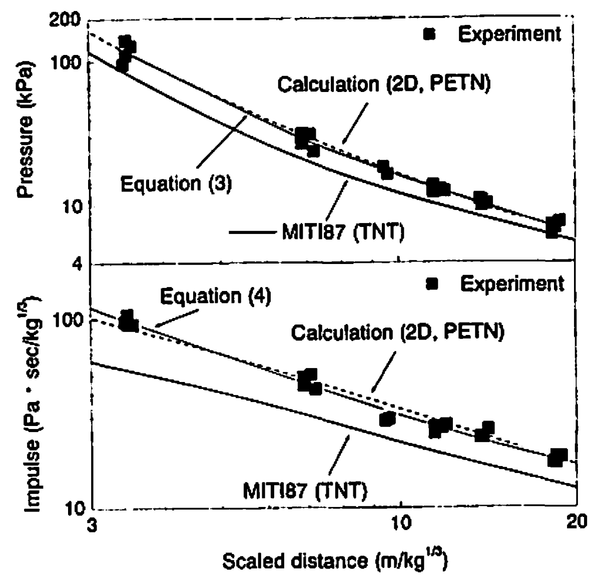

Fig.6 Peak overpressure and scaled impulse on surface burst.

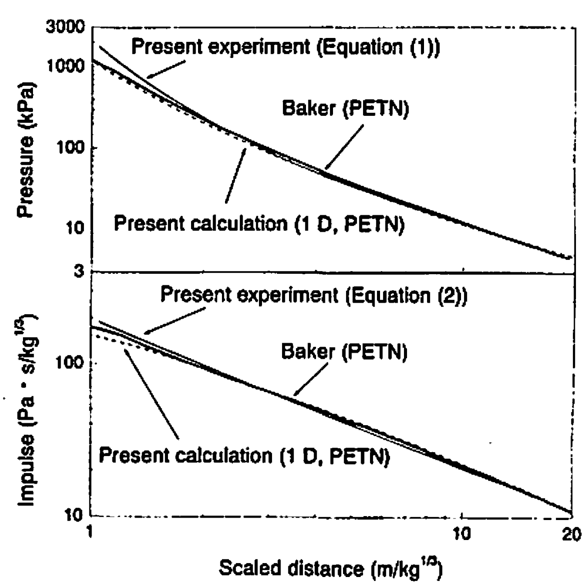

Fig.7 Comparing the calculation values and the experimental data in free air.

The curve equations are as follows:

$$log(P_s) = 0.74886\{log(Z)\}^2 - 3.03643\,log(Z) + 6.49411 \quad (R=0.9954) \quad (3)$$

Scaled impulse

$$log(I_s) = 0.26229\{log(Z)\}^2 - 1.50011\,log(Z) + 2.72640 \quad (R=0.9935) \quad (4)$$

where, P_s is the peak static overpressure [Pa], Z is the scaled distance [$m \cdot kg^{-1/3}$] and I_s is the scaled static impulse [$Pa \cdot s \cdot kg^{-1/3}$]. The Coverage of this curve is from 1 $m \cdot kg^{-1/3}$ to 20 $m \cdot kg^{-1/3}$. The curves are not suitable for extrapolation.

4. 4 Numerical calculation results and comparisons

Figure 7 shows the 1 D calculation results of peak overpressures and the scaled impulse with respect to the scaled distance for free air explosion. First, in order to confirm the calculation, we compare the calculation results using TNT to available TNT data[4]. The calculation results agreed well with the TNT data of Baker, confirming validity of the calculation model. Next, we compared the calculation results using PETN to experimental results. The calculation results for PETN also agreed well with the PETN data of Baker[1] and experimental results of the present study. In order to make the figure simple, the results of PETN are only shown.

Figure 6 also shows that the calculation results of peak overpressures and the scaled impulse versus the scaled distance on the surface burst. It is found that the calculation is greatly agreed with this experimental result. With all these results, it is considered that the estimation of the blast wave parameters with the JWL parameters of PETN which density is 1770 $kg \cdot m^{-3}$ is sufficient, even though JWL parameters have been reported to depend on the density of PETN[16].

5. Conclusions

This paper describes the blast wave parameters of PETN with silicon rubber as a binder.

From the experimental results obtained by measuring the blast wave pressures, the PETN/SR explosives are confirmed to have completely detonated using the small charge (only 1 g of PETN/SR=70/30 wt.%). The mixing ratio did not affect blast wave parameters. The present results indicate that it is possible to analyze the strength of PETN/SR blast wave based only on the mass of the PETN, taking no account to the mass of the silicon rubber.

The numerical calculation was carried out to determine the strength of the blast wave of PETN. By comparing the calculation results with the experimental results, the calculation results were found to closely agree with the experimental results. As such, blast wave pressure of PETN/SR can be calculated using the JWL parameters of PETN.

The mass, density and shape of PETN/SR explosives can be controlled and it is safe when we use it. It is expected that PETN/SR explosives will be important in the small-scale explosion experiments.

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