

# Photographic study of channel effect on emulsion explosives

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## Abstract

The precursor air shock wave (PAS) in air channel, which propagates ahead of the detonation front, precompresses and desensitizes the unreacted explosive charges. On some conditions, the PAS leads to the failure of explosive detonation. This phenomenon is commonly known as the channel effect. To investigate the mechanism of the channel effect in emulsion explosives in the case of smooth blasting, some experimental work has been carried out using a high-speed framing camera. The results of photographic investigation demonstrate that the compression time by PAS caused by the difference between PAS velocity and detonation velocity is the primary factor for the occurrences of the channel effect.

**Keywords:** Emulsion explosive, Channel effect, Photographic, Precursor air shock wave (PAS)

## 1. Introduction

When an explosive detonates in a decoupled borehole, a shock wave is generated in the air channel between the explosive charge and the inner wall of the borehole. As the velocity of the precursor air shock wave (PAS) propagating in the air channel is higher than that of the detonation wave in the explosive under some conditions, the shock wave travels ahead of the detonation wave. This PAS, which propagates ahead of the detonation wave, precompresses the unreacted explosive and desensitizes the explosive charge. When the detonation wave reaches this pre-compressed point, the detonation wave ceases to propagate regularly. Thus, the decrease in detonation velocity and a detonation failure occurs. This phenomenon is well known as the channel effect. Several works on the channel effect have been conducted under various conditions, using commercial explosives<sup>1)-4)</sup>. Visual studies of the channel effect have been reported by a few researchers<sup>5)-8)</sup>.

In order to clarify the cause of the channel effect, it is necessary to elucidate detonation propagation in explosive charges and progress of the PAS in the air channel. A pho-

tographic observation using a high-speed framing camera was carried out to study the mechanism of the channel effect.

## 2. Experimental

### 2.1 Explosives

Typical water-in-oil emulsion explosives were used in these experiments. The emulsion matrix consisted of 84 % oxidizing agent, 11 % water and 5 % fuel oil and emulsifier. Microbubbles create the necessary hot spots for sensitizing the explosive. Three kinds of resin microbubbles (RMBs) were added as sensitizer to the emulsion matrix to adjust the initial explosive density to  $1000 \text{ kg} \cdot \text{m}^{-3}$ . The detonation velocity of sample explosives was controlled in the range  $3000 - 4900 \text{ m} \cdot \text{s}^{-1}$  by the choice of RMB. Three kinds of explosives were used in test series A. Table 1 shows the properties of those three kinds of explosives under unconfined conditions.

Under high pressure, glass microbubbles (GMBs) in an emulsion explosive generally crack and their structures are crushed. Then, the sensitivity of the explosive decreases.

Table 1 Properties of emulsion explosives.

Explosive	RMB average diameter ( $\mu\text{m}$ )	Density ( $\text{kg}\cdot\text{m}^{-3}$ )	Unconfined VOD ( $14\text{ mm}\phi, \text{m}\cdot\text{s}^{-1}$ )	Critical diameter (mm)
1	450	1000	3100 – 3300	7 – 8
2	90	1000	4200 – 4400	< 5
3	45	1000	4700 – 4900	< 5

The RMBs are also compressed and shrunk under high pressure. However, the shape of RMB will be restored when the pressure is released. The choice of the microbubbles is a key point whether an explosive can keep propagating under high pressure due to PAS. RMBs of higher strength were chosen in our experiments in comparison with GMBs.

## 2.2 Experimental arrangements

Figure 1 shows the experimental arrangement. An emulsion explosive was charged in a transparent tube with rectangular cross section, which was made of 4 mm thick polymethylmethacrylate (PMMA) plates. The length of this tube was 1000 mm. The inner width of the tube was maintained to be 14 mm, but the inner height was changed to modify the tube geometry. The reason for using tube with rectangular cross section is the difficulty of photographing a cylindrical tube. The decoupling index is defined in this paper as the ratio of the inner wall height of the rectangular PMMA tube to the explosive charge height. The explosive charge height in the experiment was kept to be 14 mm. The sample emulsion explosive occupied the volume of  $14 \times 14$  mm in cross section, and over 800 mm in length. Electric detonator was inserted into emulsion explosive. And explosive length from the top of detonator to the end of explosive was adjusted to be 800 mm.

Both ends of the tube were opened not to be choked. So, initial pressure of air channel was kept at atmospheric conditions.

## 2.3 Photographic observation system

The propagation of the detonation wave and the PAS was observed using a high-speed framing camera (Cordin model 124). This camera can take 26 pictures at a framing rate of  $1.0 \times 10^5 - 2.5 \times 10^6$  frames per second (FPS). In our experiments, a framing rate of  $1.0 \times 10^5 - 5.0 \times 10^5$  FPS was used and the interframe time was 2 – 10  $\mu\text{s}$ . A Xenon flash was served as a light source. The electric detonator was controlled within 1  $\mu\text{s}$  precision for initiation and synchronized with the framing camera and the Xenon flasher. Photographic observations were conducted from the side face of the PMMA tube. Using the sequential photographs taken, the position of the PAS was defined as the point of the middle of luminous area. And the position of detonation front was determined as the intersecting point of the lower horizontal line for explosive column with the lower oblique line for explosion product.

## 3. Results and discussion

In test series A, a study on the influence of the detonation velocity on detonation propagation was conducted. And in the test series B, a study on the influence of the geometric conditions was conducted.

The PAS, propagating faster than the detonation wave, was observed in the experiments using a rectangular PMMA tube. The PAS emitted high intensity visible light over 100 – 200 mm in length. Because the PAS was self-luminous, the PAS front could not be identified. However, no PAS was observed in experiments using a PMMA tube without the confining roof.

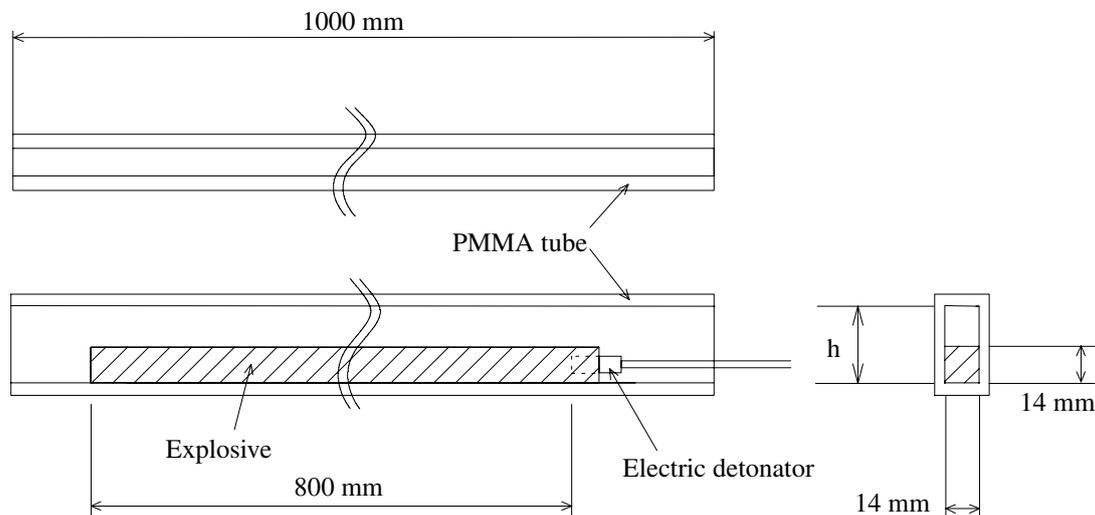


Fig. 1 Sample explosive in PMMA tube.

Table 2 Experimental results of test series A.

Experiment no.	Explosive type	Decoupling index (= h / 14)	Propagation length (mm)	Detonation velocity (m·s <sup>-1</sup> ) (X)	PAS velocity (m·s <sup>-1</sup> ) (Y)	Velocity ratio (Y/X)	Angle β in Fig. 2 (degree)
A-1	1	2.00	490	3120	3900	1.25	]60-65
A-2	1	3.00	800	3110	3550	1.14	
A-3	2	2.00	800	4350	4840	1.11	
A-4	2	3.00	800	4390	4730	1.08	]45-55
A-5	3	2.00	800	4850	5190	1.07	
A-6	3	3.00	800	4800	5040	1.05	]40-50

Decoupling index ; inner height of PMMA tube / explosive height = h / 14

The detonation velocity was very much reproducible within ±100 m · s<sup>-1</sup> along the whole length of the rectangular PMMA tube, except in the case of detonation failure.

### 3.1 Influence of the detonation velocity on the detonation propagation

The experimental results for the test series A are shown in Table 2.

Detonation failure was observed in the experiment No. A-1. As can be realized in Table 2, the detonation velocities of the three explosives charged into the PMMA tube were within the same range as previously shown in Table 1 for unconfined charges. Therefore, it is concluded that the confinement of the PMMA tube doesn't extremely influence the detonation velocity.

The PAS velocity of the explosives with high detonation velocity was higher than that of the explosives with the lower detonation velocity. However, the ratio of the PAS velocity to the detonation velocity increases with decreasing detonation velocity.

Figure 2 shows the schematics of Mach reflection of the air shock in the channel based on the theory. When an explosive detonated in a PMMA tube, it was observed that the angle ("β" in Fig. 2) between the products/air interface caused by the detonation and the axis of the explosive charge depended on the type of the explosive. The degree of angle β observed in our experiments is shown in Table 2. The angle β for explosive type 1 was larger than that

for explosive type 3. This angle is smaller than an angle ("α" in Fig. 2) between the invisible shock wave caused by detonation and the axis of the explosive charge. It is assumed that in the case with explosive type 1, the shock wave in the air channel reaches the upper wall in a shorter time than in the other experiments. Therefore, an explosive with lower detonation velocity will give a PAS with higher relative velocity than an explosive with higher detonation velocity.

It is assumed that precompression caused by the PAS gives various effects on its detonation propagation depending on the type of emulsion explosives. No detonation failure was observed in our experiments using the explosive types 2 and 3. However, as long as there is a difference between the detonation velocity and the PAS velocity, time necessary for the PAS to desensitize the explosive will be available later during detonation propagation. A detonation failure may occur in such a situation. However, it is concluded that the enhancement of explosive performance, especially by means of the detonation velocity, is one of the effective methods to prevent a detonation failure.

In actual blasting scene, an explosive with higher detonation velocity releases a higher shock pressure to the rock in a borehole. If such an explosive is placed at the limit of excavation contour, the fractures and breakages extend beyond this limit and into the rock mass. This is the reason why explosives with higher detonation velocity cannot be used for smooth blasting techniques.

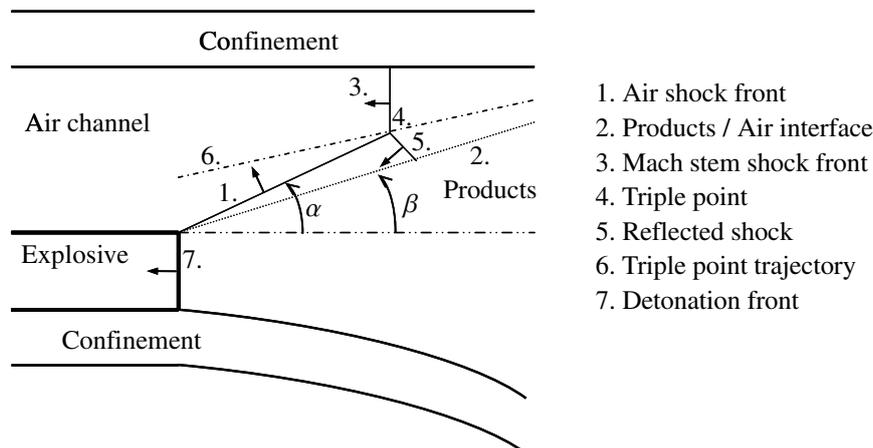


Fig. 2 Theoretical schematics of Mach reflection.

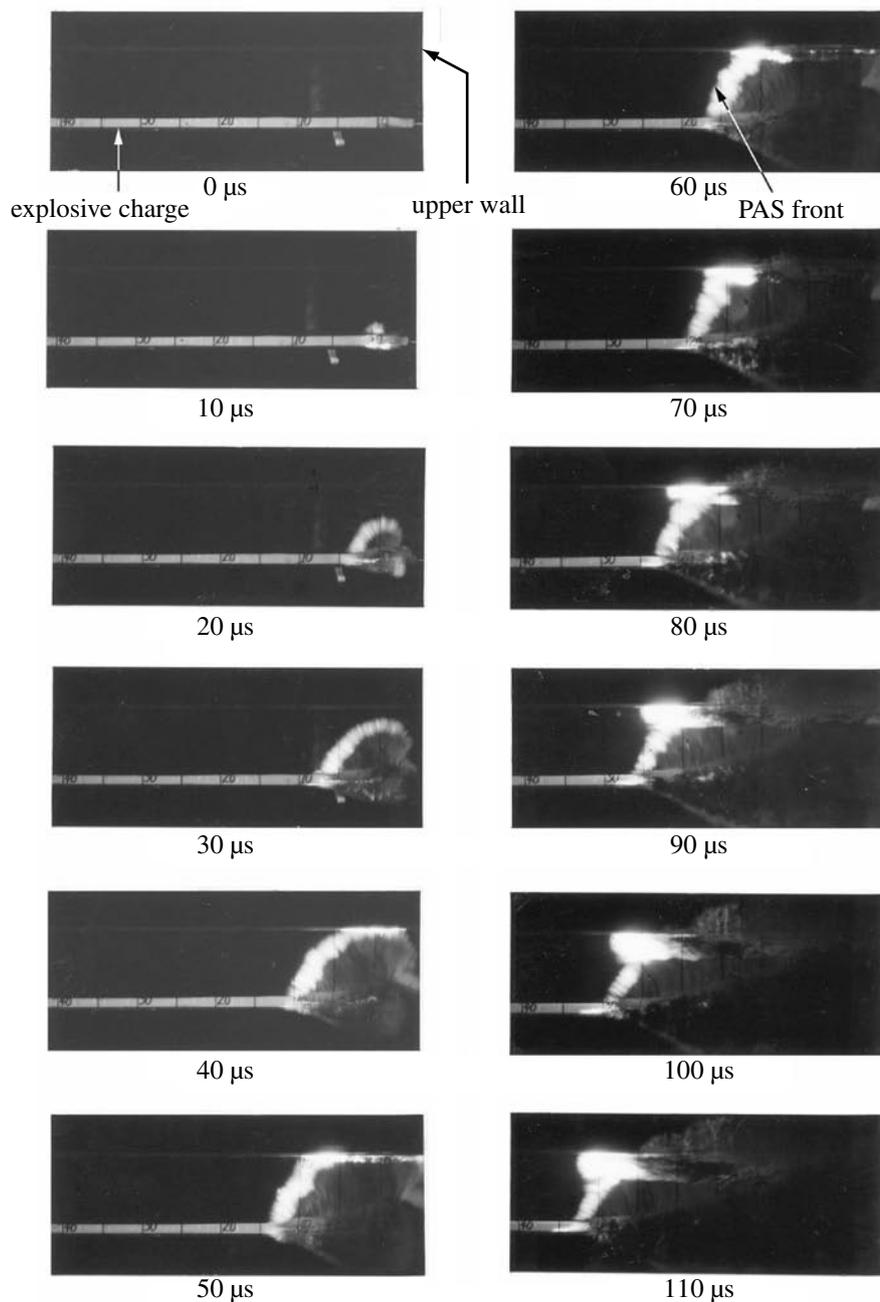


Fig. 3 Sequence of high-speed framing photographs.

It was considered that self-luminous point was very high temperature. Based on the PAS velocity evaluated from the photographs, the temperature  $T_1$  and the pressure  $P_1$  were calculated by using the following equation.

$$\begin{aligned} T_1 / T_0 &= [2 + (\gamma - 1)M^2] [2\gamma M^2 - (\gamma - 1)] / (\gamma + 1)^2 M^2 \\ P_1 / P_0 &= 1 + (M^2 - 1)2\gamma / (\gamma + 1) \end{aligned}$$

where the initial temperature  $T_0$  was 298 K, the initial pressure  $P_0$  was 0.1 MPa.  $M$  was Mach coefficient, which meant the PAS velocity / the speed of sound. The  $\gamma$  was the ratio of specific heat whose value was 1.4.

As a result of calculation, we found out that the temperature  $T_1$  was the range of 6250 – 14600 K, the pressure  $P_1$  was the range of 12 – 29 MPa. Tanguay et al.<sup>7)</sup> described the shock temperature and pressure obtained with com-

puter code regarding the shock wave with a velocity of 5 km · s<sup>-1</sup>. These values give 7866 K and 32.8 MPa. Both his result and our calculation results are in similar range of temperature and pressure. Anyway, emulsion explosives were exposed under the drastic conditions.

### 3.2 Influence of the geometric conditions on the propagation of the detonation wave and the PAS

These experiments were conducted using the explosive type 1. Figure 3 shows a sequence of high-speed framing photographs obtained in the experiment No. B-11. These photographs clearly illustrate Mach reflection of the PAS driven by detonation products and the formation of Mach stem at the ceiling of PMMA tube as previously shown in Fig. 2.

Table 3 Experimental results of test series B.

Experiment no.	Decoupling index (= $h/14$ )	Propagation length (mm)	Detonation velocity ( $\text{m}\cdot\text{s}^{-1}$ ) (X)	PAS velocity ( $\text{m}\cdot\text{s}^{-1}$ ) (Y)	Velocity ratio (Y/X)	Critical length (mm)	Critical time ( $\mu\text{s}$ )
B-1	1.00	800	3200	3200	1.00	—	—
B-2	1.21	410	3080	3860	1.28	180	60
B-3	1.50	400	3130	4060	1.30	210	60
B-4	1.79	500	3170	4020	1.27	170	50
B-5	2.00	490	3120	3900	1.25	180	50
B-6	2.29	580	3130	3800	1.21	180	50
B-7	2.71	610	3180	3840	1.21	180	50
B-8	3.00	800	3110	3550	1.14	—	—
B-9	4.00	800	3100	3450	1.11	—	—
B-10	5.00	800	3130	3430	1.10	—	—
B-11	7.00	800	3100	3290	1.06	—	—

Critical length ; [travel length of the PAS at detonation failure] – [length of propagation of detonation up to the point of detonation failure]

Critical time ; [time from initiation to detonation failure] – [time elapsed when the PAS reaches the point of detonation failure]

Experimental results in test series B are shown in Table 3. The detonation wave propagated with almost the same velocity in all experiments. In the experiment with the smaller decoupling index, the PAS gave a higher relative velocity than that for larger decoupling index. In these experiments, the detonation propagation distance increases with increasing decoupling index but decreases with increasing PAS velocity.

The detonation failure was observed in experiments Nos. B-2 – B-7, for which the decoupling index varied within the range 1.21 – 2.71. Johansson et al.<sup>1)</sup> concluded that detonation failure in dynamite of diameter 25 mm occurs in the range of decoupling index 1.12 – 3.82. Liu et al.<sup>4)</sup> described that for an emulsion explosive of charge diameter 25 mm, the detonation failure occurs in the range of decoupling index 1.28 – 3.56.

It is considered that the detonation failure is dependent on both the decoupling index and the diameter of the explosive charge. When the decoupling index is sufficiently large, the PAS precompressing the explosive scarcely travels ahead of the detonation wave. In addition, the channel effect is a characteristic of an explosive charge whose diameter is as small as its critical diameter. When the explosive diameter is large enough, the PAS will not be able to compress the explosive to cause a detonation failure. Our experimental scale was relatively small and the explosive diameter was close to the critical diameter. Consequently, the range of the decoupling index in which the detonation failure occurred was different from that obtained by previous researchers.

There were differences with respect to test conditions, too. They used a tube with circular cross section, and we used a tube with rectangular cross section. Considering the different decoupling index range for the channel effect in the two geometries, it is concluded that the condition with circular cross section is more difficult for detonation propagation when compared with that of a rectangular cross section. Our earlier experiments confirmed that in a circular cross section tube, detonation failure occurred

at a decoupling index of 3.00 in a charge of 15 mm in diameter<sup>9)</sup>.

It is considered that time interval during which the unreacted explosive charge is precompressed by the PAS is very important factor in the channel effect. If the distance between the PAS front and the detonation front becomes long enough, the PAS will compress a layer of explosive thick enough to prevent further propagation of the detonation at this compressed point of the explosive charge. We define the critical length and critical time as follows.

Critical length;

[travel length of the PAS at detonation failure]  
- [length of propagation of detonation up to the point of detonation failure]

Critical time;

[time from initiation to detonation failure]  
- [time elapsed when the PAS reaches the point of the detonation failure]

From experimental results shown in Table 3, it is estimated that the critical time is 50 – 60  $\mu\text{s}$  and the critical length is about 200 mm. Bjarnholt et al.<sup>5)</sup> concluded that a critical time for compression was about 90  $\mu\text{s}$  in their experiments using Gurit explosive, which is a powder explosive sensitized by NG/EGDN and  $\text{SiO}_2$  is added as inert material.

### 3.3 Compression speed of emulsion explosive by the PAS

Compression speed of unreacted emulsion explosive by the PAS was estimated by means of using several sheets of close-up photographs at the point of detonation failure. That speed could be estimated to be approximately 120 – 170  $\text{m}\cdot\text{s}^{-1}$ . Independent of the hardness of the explosive charge, the compression speed is considered to be almost the same for all kinds of explosives. Smedberg et al.<sup>6)</sup> reported that the compression speed was estimated to 350  $\text{m}\cdot\text{s}^{-1}$  on their experiments using emulsion explosive.

As mentioned in previous paragraph, the critical time for compression is approximately 50  $\mu\text{s}$ . From these photographs, the thickness of the unreacted explosive is reduced

from 14 mm to 6 – 8 mm at the detonation failure. It is concluded that the density of the explosive became considerably higher.

In these experiments, the explosives were compressed from top to bottom. But in actual blasting scene, both the borehole and the explosive charge have a circular cross section. The explosive is then compressed axially. In other words, the mode of compression is different in our experiments. As mentioned previously from the viewpoint of geometric condition, the explosive in an actual borehole should be exposed to more severe conditions.

Our earlier experiments empirically confirmed that air shock in a circular cross section tube propagated with rotation. Spiral traces of soot were observed on the inner wall of transparency tube.

#### 4. Conclusion

The purpose of this study was to clarify the mechanism of occurrence of the channel effect. In this study, a photographic observation was applied to elucidate detonation propagation in explosive charges and progress of the precursor air shock wave (PAS) in the air channel. And these experiments were conducted by using emulsion explosives with a small diameter and a small tube with rectangular cross section for explosive charge. The following conclusions could be drawn from this study under the above-mentioned conditions.

The use of emulsion explosives with higher detonation velocity, which is over  $4000 \text{ m} \cdot \text{s}^{-1}$ , is advantageous to preventing the channel effect.

The geometry of the tube in which the explosive is placed has the influence on the range of the decoupling indexes

that affects the channel effect. The channel effect was observed within the range of 1.21 – 2.71.

The channel effect occurs when the precompression time, i.e. the time lag between the PAS and the detonation front, reaches a threshold value. The threshold value in this study is estimated to be 50 – 60  $\mu\text{s}$ .

The compression speed of emulsion explosives is estimated to be 120 – 170  $\text{m} \cdot \text{s}^{-1}$  with respect to the experimental configuration selected.

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## エマルション爆薬におけるチャンネル効果の光学的検討

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穿孔内に装薬された爆薬が爆轟したときに、爆薬薬包と穿孔内壁との間に空間が存在すると、その空間の中を爆轟波に先行して伝播する衝撃波が生じる。これを先行衝撃波と言ひ、この衝撃波が反応を起こしていない爆薬を加圧し、不感度化する。さらにある条件において爆轟伝播が中断する。この現象はチャンネル効果としてよく知られている。

制御発破工法の一手法であるスムーズプラスティング工法において、エマルション爆薬におけるチャンネル効果の発生機構を調査するため、高速度カメラを用いて種々の実験を行った。

この光学的検討によりチャンネル効果の発生要因として、先行衝撃波速度と爆轟波速度との違いに起因する、先行衝撃波による爆薬の加圧時間が重要な要因であることが判明した。

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