Research paper

Effect of surface roughness on the precursor air shock wave in channel effect of emulsion explosive

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Abstract

The precursor air shock wave (PAS) in air channel, which is propagating ahead of the detonation front, precompresses and desensitizes the unreacted explosive charges. This dead-pressing 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, experimental works have been carried out in laboratory. The surface roughness of inner wall of tube or pipe was varied to simulate the actual blasting borehole. It is concluded that the surface roughness of inner wall gives some influence on the propagation of PAS. The PAS velocity is reduced as the roughness is increasing. In some experimental condition, the detonation failure can be prevented.

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

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 precompresses the unreacted explosive and desensitizes the explosive charge. When the detonation wave reaches this precompressed point, it ceases to propagate regularly. Thus, the detonation velocity decreases and the 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 some kinds of explosives [1)-9)].

In our previous work [10)], we concluded that the time lag between the PAS propagation and the detonation propagation was the primary factor in the detonation failure. The time lag means the precompression time for dead-pressing on emulsion explosives.

However, it is true that the detonation failure doesn't frequently occur in the actual blasting scene. Therefore, we have focused the surface roughness of inner wall concerning the difference of blasting condition between in actual blasting scene and in laboratory experiments.

Regarding the channel effect, it is generally known that a Mach stem moving forward in the air channel evolves into the PAS. Mach stem is produced by Mach reflection of oblique shock wave generated by explosive detonation at the upper wall. Suzuki et al. [11)] demonstrated that the structure of a reflected shock wave over a wedge with surface roughness is unsteady. Therefore, we expected that the increased surface roughness would cause the shock wave to be reflected irregularly at the upper wall, and prevent the Mach stem from producing easily. Furthermore, the evolvability into the PAS of Mach stem will be reduced. In addition, we also expected that the surface roughness will prevent the PAS as a fluid from proceeding forward smoothly in an air channel because of the friction at the wall. Thus, the PAS velocity will be decreased and the above-mentioned time lag will be shortened.

In the present work, some experiments in the laboratory were conducted to investigate the effects of surface roughness of the charge hole on the PAS propagation using an emulsion explosive. This work is comprised of two parts of investigations. One is a photographic observation using a high-speed framing camera on small-sized explosives, another is a study of detonation propagation in pipe on actual-sized explosives for smooth blasting technique.

2. Experimental

2.1 Explosives

Only one kind of typical water-in-oil emulsion explosive was applied for this work. It is just an emulsion explosive named "explosive 3" in our previous work [10]. This explosive was cap sensitive, and its critical diameter was 6-8 mm. The detonation velocity of the unconfined emulsion explosive was 3000-3300 $m \cdot s^{-1}$ in the case of a rectangular cross section of 14 × 14 mm, and 3600-3900 $m \cdot s^{-1}$ in the case of a circular cross section of 20 mm in diameter.

2.2 Experimental arrangements

Sandpaper was applied and glued on the inner wall to vary the surface roughness so as to simulate the surface roughness of an actual borehole. As previously mentioned, this work is comprised of a photographic observation and a study of detonation propagation. The former was named as "Test series A", and the latter was named as "Test series B" on the following description.

Test series A ; The experimental arrangement for this series was basically the same as our previous work [10] using a transparent tube with rectangular cross section, which was made of 4 mm thick polymethylmethacrylate (PMMA) plates. Only difference was that sandpaper was glued on the upper inner wall "ceiling" of the rectangular PMMA tube. No sandpapers were glued on the both sidewalls for photographic observation access. Surface roughness of the sandpaper was changed to investigate the effects of surface roughness on the PAS propagation. Both ends of the tube were opened not to be choked. So, initial pressure of air channel was kept under atmospheric conditions.

A photographic observation system was just the same as our previous work [10] too. In this investigation, a picture framing rate of 1.0×10^5 frames per second (FPS) was applied and the interframe time was 10 μs. The positions of the PAS and the detonation wave were determined from the sequential photographs taken.

Test series B ; Polyvinyl chloride (PVC) pipe was used to simulate the shape of an actual charge hole. Sandpaper was glued to the whole area of inner wall in the PVC pipe. Surface roughness of the sandpaper was changed to investigate the effects of surface roughness on the PAS propagation. The inner diameter and wall thickness of the PVC pipe were varied to study the effects of decoupling coefficient and pipe confinement. Table 1 presents the specification of the PVC pipe and corresponding decoupling coefficient.

Sample emulsion explosive was charged in polyethylene tubes made by thin film with inner diameter 20 mm and 1650 mm in length. The polyethylene tube containing sample explosive was placed inside PVC pipe of 2000 mm in length. Sample explosive was initiated by electric detonator. The ionization prove terminals were installed to detect the time of arrival of detonation in the sample explosive at the distance of 400, 800, 1200 and 1600 mm from the tip of the detonator. Also, the thin twisted wire pairs were used to detect the time of arrival of the PAS on the top of inside wall of PVC pipe at the same distance. Both ends of the pipe were opened not to be choked. So, initial pressure of air channel was kept under atmospheric conditions.

Table 2 summarizes the surface roughness of PMMA plate, PVC pipe and sandpapers. The surface roughness of the sandpaper was specified according to Japan Industrial Standard.

Table 1 PVC pipe specification.

	VP25	VP30	VE36	VP40	VU40	VP50	VU50	VP65
Inner diameter (mm) (X)	25	31	35	40	44	51	56	67
Wall thickness (mm)	3.1	3.1	3.5	3.6	1.8	4.1	1.8	4.1
Decoupling coefficient (=X/20)	1.25	1.55	1.75	2.00	2.20	2.55	2.80	3.35

These spec. are regulated by Japan Industrial Standard.

Table 2 Surface roughness of PMMA plate and sandpaper.

			Sandpaper mesh					
	PMMA	PVC	#600	#400	#220	#150	#100	#80
Rmax (μm)	3.2	6.9	60.1	78.9	135.0	166.0	286.8	395.0
Rz (μm)	1.8	3.2	47.8	62.7	114.2	126.4	188.7	233.0

Rmax: Maximum roughness Rz: Average roughness of ten point

3. Results and discussion

3.1 Test series A (PMMA tube)

Figure 1 shows high speed framing photographs taken under two different conditions. Figure 1. a) pertains to a PMMA tube without sandpaper lining, and Fig. 1. b) refers to a PMMA tube with sandpaper of mesh #80. The decoupling index of the PMMA tube was 1.79. Both photographs depict the propagation of the detonation wave and the PAS at 160 μs after initiation.

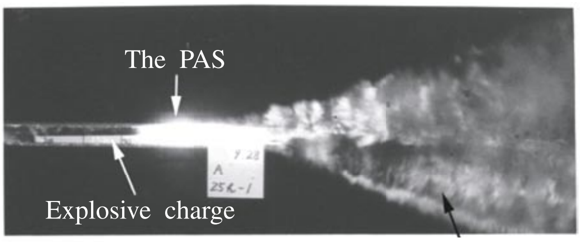
The position of detonation front is defined as the intersecting point of the lower horizontal line for explosive column with the oblique line for explosion product. It can be seen that the positions of the detonation front are identical, but in the case of the PMMA tube without sandpaper lining (Fig. 1. a)), the position of the PAS is much further ahead of the detonation front than in the case of the PMMA tube with sandpaper. Detonation failure occurred in the case of the PMMA tube without sandpaper. On the other hand, detonation failure was not observed in the case of the PMMA tube with sandpaper.

The position of the PAS was defined as the point of the middle of luminous area, and the propagation length was determined from each sequential photograph. Figure 2 presents the relationship between the propagation length and time of the PAS. It is shown that the sandpaper lining reduces the propagation velocity of the PAS and causes to prevent the occurrence of detonation failure.

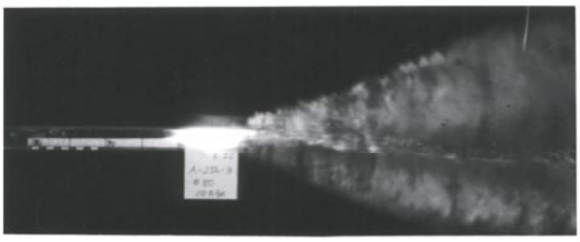
Experiments were performed for various decoupling indexes, using five kinds of sandpaper. Table 3 summarizes the experimental results obtained from this test series. The value of 800 on propagation length means that the detonation has propagated completely.

In the case of PMMA tubes without sandpaper, detonation failure was observed when the decoupling index was in the range of 1.21-2.71, as our previous work. These experimental results indicate that the propagation length of the detonation wave becomes longer as the surface roughness of tube wall is increased and the PAS velocity decreases as the surface roughness increases.

Table 3 shows that detonation failure occurs when the ratio of the PAS velocity to the detonation velocity becomes larger than 1.21. The estimation of time lag from the sequential photographs indicates that detonation failure occurs when the critical time for compression of the unreacted explosive by the PAS is 50-60 μs. These results are in good agreement with those obtained in our previous work.



a) Without sandpaper Detonation products



b) With sandpaper (#80)

Fig. 1 Photographs – 160 microseconds after initiation.

3.2 Test series B (PVC pipe)

The PAS propagation was detected by the thin twisted wire pairs with intervals of 400 mm. Figure 3 presents the relation between propagation length and time of the PAS for various surface roughness of the PVC pipe in the case of decoupling coefficient ; 2.0.

These results indicate that the PAS velocity is decreased when surface roughness of the PVC pipe is increased because the slope of line presents the PAS velocity.

To investigate the PAS velocity prior to the detonation failure, the thin twisted wire pairs were installed to detect the time of arrival of the PAS on the top of inside wall of PVC pipe at the distance of 800 and 900 mm from the tip of the detonator. Table 4 summarizes the PAS velocity obtained in various decoupling coefficient and surface roughness.

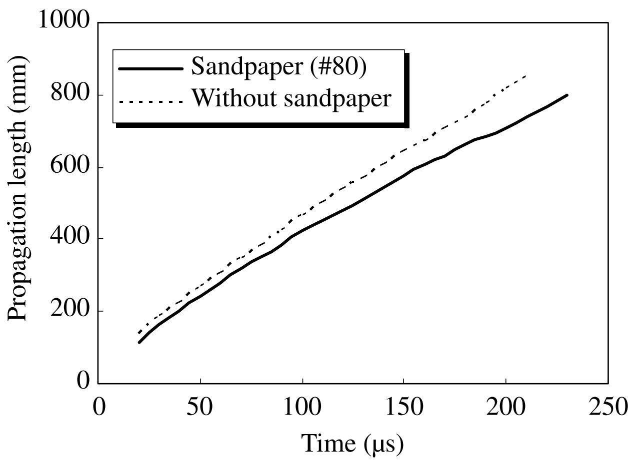


Fig. 2 Relationship between the propagation length and time of the PAS.

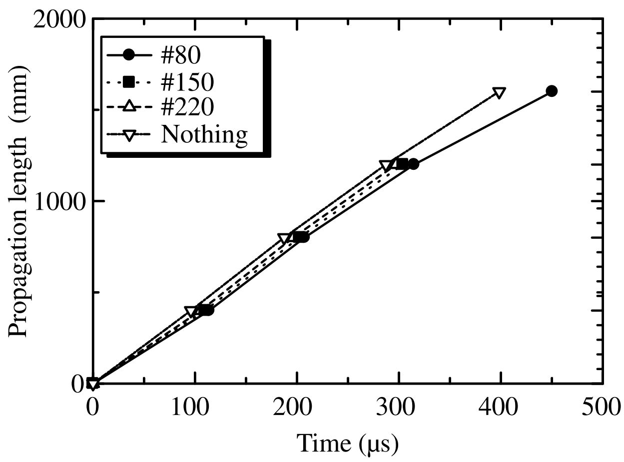


Fig. 3 Relationship between the propagation length and time of the PAS.

Table 3 Experimental results in test series A.

Decoupling coefficient	Sandpaper mesh	Propagation length (mm)	Detonation velocity (m·s^{-1})(X)	PAS velocity (m·s^{-1})(Y)	Velocity ratio (Y/X)
1.21	Nothing	**410**	3080	3860	**1.28**
↑	#600	**430**	3010	3730	**1.24**
↑	#400	**430**	3060	3760	**1.23**
↑	#220	**800**	3120	3740	**1.20**
↑	#150	**800**	3030	3200	**1.06**
↑	#80	**800**	3190	3250	**1.02**
1.50	Nothing	**400**	3130	4060	**1.30**
↑	#600	**490**	3180	4010	**1.26**
↑	#400	**470**	3150	3910	**1.24**
↑	#220	**530**	3120	3810	**1.22**
↑	#150	**800**	3120	3300	**1.06**
↑	#80	**800**	3170	3230	**1.02**
1.79	Nothing	**500**	3170	4020	**1.27**
↑	#600	**600**	3180	3940	**1.24**
↑	#400	**590**	3080	3830	**1.24**
↑	#220	**630**	3070	3750	**1.22**
↑	#150	**800**	3260	3360	**1.03**
↑	#80	**800**	3200	3300	**1.03**
2.29	Nothing	**580**	3130	3800	**1.21**
↑	#600	**610**	3080	3730	**1.21**
↑	#400	**630**	3050	3720	**1.22**
↑	#220	**690**	3010	3650	**1.21**
↑	#150	**800**	3130	3350	**1.07**
↑	#80	**800**	3230	3290	**1.02**

Nothing; without sandpaper

Table 4 PAS velocity under the various conditions.

PVC pipe	Dco	Nothing	Sandpaper mesh				
			#400	#220	#150	#100	#80
VP 30	1.55	4180	4100	4000	*3960	*3970	*3920
VE 36	1.75	4170	4150	4130	4130	4110	*3970
VP 40	2.00	4270	4240	4170	4150	4100	*3960
VU 40	2.20	4170	4150	4110	4100	*4000	*3910
VP 50	2.55	4390	4320	4260	4220	4150	*4080

*; detonation wave is propagated completely without detonation failure (m·s^{-1})

In the Table 4, " * " marks indicate the cases where detonation wave is propagated completely without detonation failure.

In these experiments, the PAS velocity is 3920-4080 m·s^{-1}, which is 1.0-1.1 times the detonation velocity in the sample explosive. These results show that detonation failure is observed when the PAS velocity exceeds 1.1 times the detonation velocity in the PVC pipe. These results differ from the results obtained in test series A using rectangular PMMA tube. In rectangular PMMA tube, detonation failure is observed when the PAS velocity exceeds 1.21 times the detonation velocity.

It is assumed that the difference between the results obtained in a rectangular PMMA tube and a circular PVC pipe is due to the difference of the precompression mode in two geometries. In rectangular PMMA tube, unreacted explosive receives planner compression by the PAS. However, in circular PVC pipe, unreacted explosive receives axial compression by the PAS. It is considered that precompression of unreacted explosive by the PAS is more severe in the PVC pipe.

Regarding the occurrence of detonation failure, it is considered that the factor for reduction of occurrence rate exists in actual blasting scene. It has been found by Tanguay et al. [9] in laboratory-scaled experiments that increasing pressure inside an air channel decreases the time lag or make it more difficult for the PAS to run ahead of detonation. Both ends of the PVC pipe were opened not to be choked in our test condition. However, both ends of actual borehole must be choked by the bottom of borehole and the stemming material. Pressure inside a borehole will be increased by the PAS pushing upstream like a piston. Therefore, it is guessed that the PAS propagation will be reined.

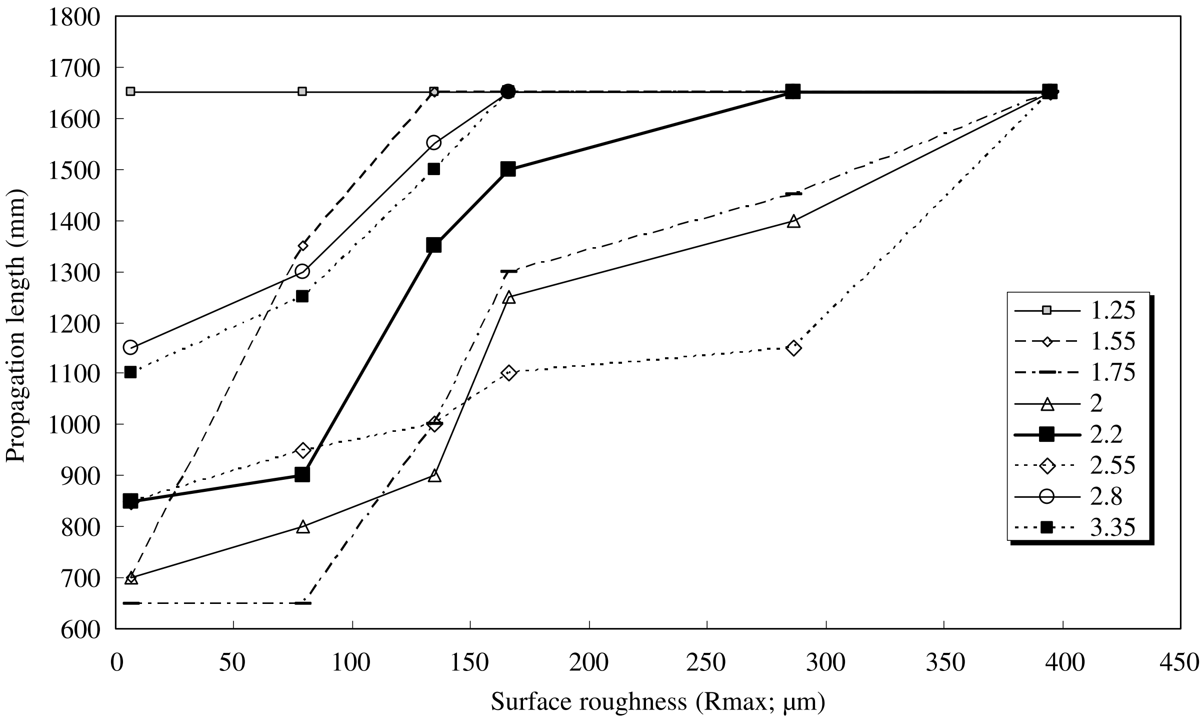


Fig. 4 Relationship between the detonation propagation length and surface roughness.

Table 5 Effects of pipe confinement on detonation propagation length.

Pipe name	Wall thickness (mm)	Sandpaper mesh #400	#220	#150	#100	#80
VU40	**1.8**	900	1350	1500	1650	1650
VU40+VP50	**1.8 + 4.1**	850	900	1000	1050	1150

(mm)

Figure 4 presents the relation between detonation propagation length and surface roughness for various decoupling coefficients.

These results show that detonation propagation length is increased when surface roughness is increased. However the improvement of detonation propagation by the increase of surface roughness is different depending on the decoupling coefficient. In Fig. 4, in case of decoupling coefficients in the range 1.75-2.55, the detonation does not propagate well. However, the experimental results obtained for decoupling coefficient ; 2.2 present some particular results. The wall thickness of VU40 PVC pipe used in the experiments for this decoupling coefficient is considerably smaller than the wall thickness of other types of the PVC pipes. Therefore, it is assumed that the wall thickness of the PVC pipe, in other words, pipe confinement, influences on the phenomena of detonation failure.

To study the effect of pipe confinement on the detonation propagation, some additional experiments were performed. A VU40 PVC pipe was inserted into a VP50 PVC pipe to increase pipe wall thickness from 1.8 mm to 5.9 mm. Table 5 shows the effects of pipe confinement on the detonation propagation length.

It is shown that detonation failure occurs at shorter propagation length when pipe confinement is increased. It is clearly concluded that pipe confinement has some influence on detonation propagation.

4. Conclusion

The purpose of this study was to investigate the effects of surface roughness of the charge hole on the PAS propagation. The following conclusions could be drawn from this research.

The increase of surface roughness reduces the PAS velocity and improves detonation propagation in the charge hole.

Detonation failure is observed when the ratio of the PAS velocity to the detonation velocity becomes greater than 1.21 and 1.1 respectively in rectangular PMMA tube and in circular PVC pipe.

It is assumed that the difference observed between the experiments with rectangular PMMA tube and those with circular PVC pipe is due to the difference of precompression mode of unreacted explosive by the PAS.

The strength of confinement has some influence on detonation propagation.

References

1) C. H. Johansson, H. L. Selberg, A. Persson, and T. Sjolin, Preprint from XXXI International Congress of Industrial Chemistry, (1958), Belgium.
2) M. Nakano and N. Mori, Kogyo Kayaku (Sci. Tech. Energetic Materials), 40, 245 (1979).
3) K. Hanasaki, Y. Muneta, H. Sakai, and N. Mori, Kogyo Kayaku (Sci. Tech. Energetic Materials), 45, 149 (1984).
4) Q. Liu, A. Bauer, and R. Heater, Fourth Mini-symposium on Explosives and Blasting Research, pp. 33-48 (1988), Anaheim.
5) G. Bjarnholt, and U. Smedberg, Eighth Symposium (International) on Detonation, pp. 1069-1079 (1985), Albuquerque.
6) U. Smedberg, and M. Edvardson, Swedish Detonic Research Foundation(SveDeFo) Report, DS-1987-10 (1987).
7) V. Tanguay, and A. J. Higgins, J. App. Phys., 95, 6159 (2004).
8) V. Tanguay, and A. J. Higgins, J. App. Phys., 96, 4894 (2004).
9) V. Tanguay, P. Vu, P. J. Oliver, E. Timofeev, and A. J. Higgins, AIAA, 278, 1 (2005).
10) F. Sumiya, Y. Hirosaki, Y. Kato, Y. Wada, Y. Ogata, and K. Katsuyama, Sci. Tech. Energetic Materials, 67, 147 (2006).
11) T. Suzuki, T. Adachi, and S. Kobayashi, 1989 National Symposium on Shock Wave Phenomena, pp. 21-29 (1989), Saitama.

エマルション爆薬のチャンネル効果における，先行衝撃波に対する管内壁面粗さの影響

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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い，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。この衝撃波による死圧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スブ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解明することを目的とし，実際の発破装薬孔を模擬するため，管内壁面の粗さを調整して各種検討を行った。

管内壁の表面粗さの変動により，先行衝撃波の進行が影響を受け，表面が粗くなった場合，先行衝撃波の速度が低下することが判明した。そしてある表面粗さの試験条件では爆轟中断現象はみられなくなった。

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