Research paper

Deflagration characteristics of thermite reaction mixtures under decoupled charges

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Received: December 31, 2019 Accepted: April 7, 2020

Abstract

Blasting to crush rocks or concrete using thermite reaction mixtures is a promising technique to reduce ground vibrations and noise. In this study, the deflagration propagation speed of a commercial thermite with different charge conditions was investigated using a modified velocity of detonation (VOD) measurement system. As a result, the continuous deflagration of thermite was intimately connected with charging and confining conditions. Therefore, it is important to consider the types of charge and confinement to utilize thermites for applications involving rock and civil engineering.

Keywords: thermite reaction, rock crushing agent, continuous deflagration, VOD measurement, decoupling charge.

1. Introduction

Fragmentation of rock masses or civil structures by blasting explosives has been widely used in various industrial applications. Since it is inevitable to induce substantial ground vibrations and noises, numerous studies have been carried out to address these challenges[1)−10)]. Recently, several approaches using thermite mixtures for rock crushing have been reported[11)−16)]. This technique employs transient loading of gas expansion to significantly reduce the induced ground vibration compared with explosives[14)]. Especially, it is advantageous in operations that demand higher precision control of noise and vibrations, such as tunnel blasting for subway construction, urban highways, and blasting near safety facilities. However, in-depth studies about deflagration characteristics of thermites subject to operating conditions (i.e., charge type, length, and confinement) are still limited in number.

Because commercial thermites (i.e. NONEX ROCK CRACKER(NRC), ROCKRACK®) for rock crushing are supplied as cartridges with limited size, it is common to apply decoupled charges for drill holes rather than the full charge in many engineering applications[12),15)−16)]. The space gap between cartridge and drill hole affects the reaction characteristics and the crushing ability, suggesting the need for intensive studies investigating deflagration characteristics of thermites under decoupled charge.

In this study, several experiments were conducted to investigate the deflagration characteristics of thermites under the charging conditions. Three types of experimental setup describing the different charging conditions are mentioned. The commercial crushing agent using thermite reactions known as NRC is used with an electric initiator. In order to estimate the deflagration characteristics, a continuous velocity of deflagration reaction (VODR) measurement technique was adopted. By analyzing the VODR, the continuous deflagration characteristic was discussed. Consequently, an empirical correlation between VODR and decoupling index (DI) is

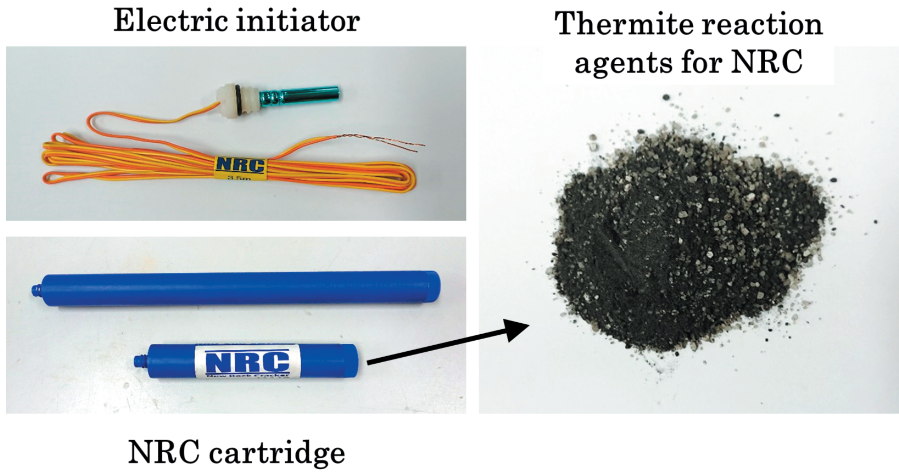


Figure 1 Photographs of NRC and electric initiator.

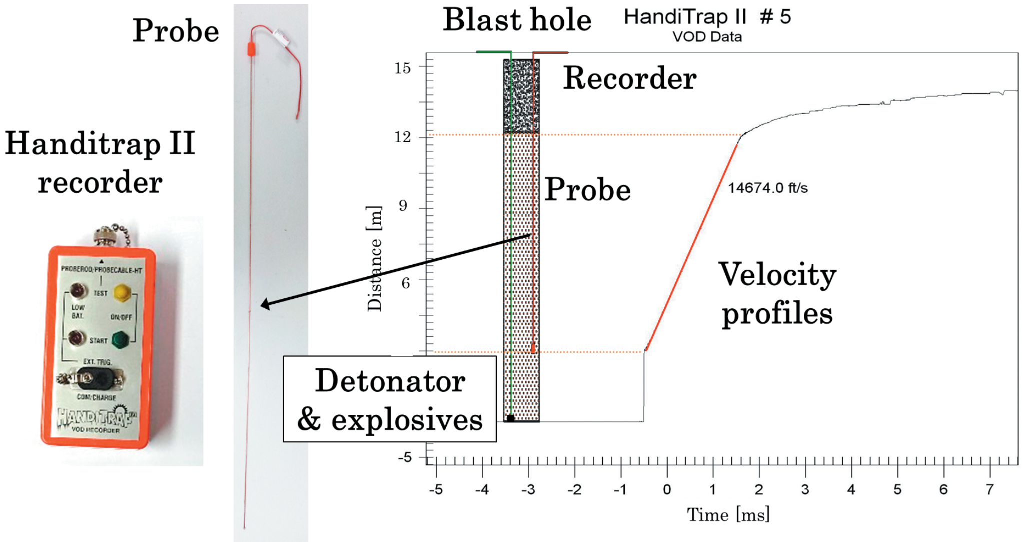


Figure 2 Schematics of typical VOD measurement system.

suggested.

2. Thermite rock crusher

A commercial crushing agent using thermite reaction known as NONEX ROCK CRACKER (NRC) was used in this study. While normal blasting uses a detonator or a primer, NRC can be ignited with an electric initiator device based on the thermite reaction as well. The mechanism of pressure generation by NRC can be classified into two steps. First, based on continuous deflagration, the copper oxide metallic compounds are rapidly heated to high temperatures, which triggers chemical substitution of metallic solid powders to vapors. Therefore, the impact pressure is generated by bulk expansion. At the same time, the crystallized waters are evaporated to steam resulting in gas expansion pressures. Figure 1 illustrates NRC cartridge, its contents, and the electric initiator. The major properties and specifications of NRC are listed in Table 1.

3. Experiments

3.1 Continuous deflagration velocity measurement

In order to investigate the deflagration characteristics of thermite crushing agents, a continuous deflagration (or detonation) velocity technique using MREL corporation's HandiTrapII apparatus was used. Figure 2 illustrates the typical configuration of continuous deflagration velocity measurement in blasting. The VODR probe connected to the recorder was inserted into the blast hole with a detonator and explosives. Detonation generating high temperature and pressure leads to fusion of the copper probe causing electrical changes in the measurement system, and the VODR can be calculated.

Table 1 Physical & chemical properties of NRC.

Parameter	Value
Specific gravity	1.25~1.35
Chemical reaction velocity [$m \cdot s^{-1}$]	200~300
Reaction temperature [K]	2502
Energy [$kcal \cdot kg^{-1}$]	409
Gas volume [$L \cdot kg^{-1}$]	351

3.2 Application of modified VOD probe

As reported previously, the sensitivity of ordinary probe can be decreased by lowering the degree of pressure and temperature of the thermites[16]. This study also compared the sensitivity of VODR probe under low-

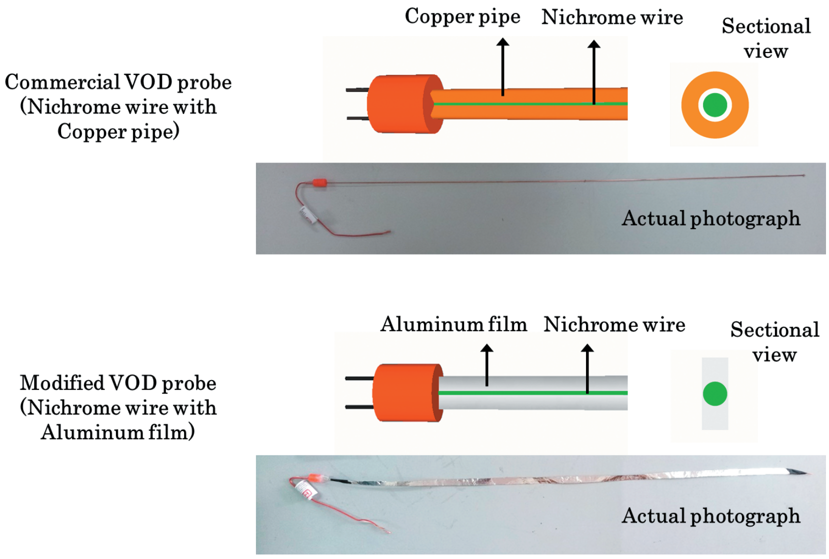


Figure 3 Schematic of different types of VODR probe.

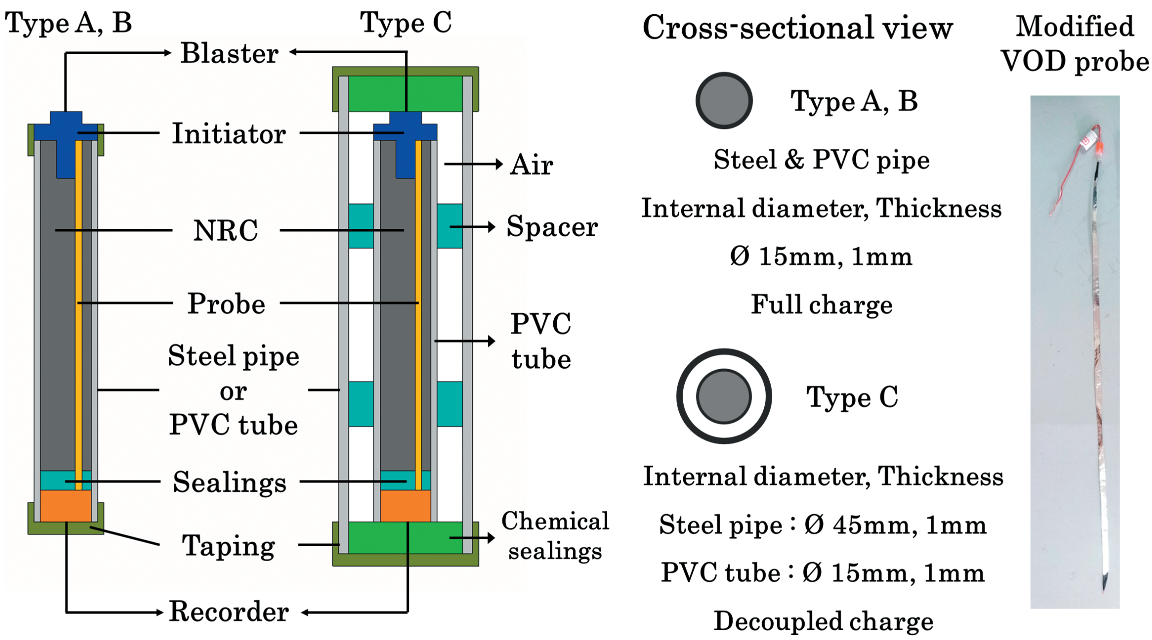


Figure 4 Schematics of VODR measurement system.

Figure 5 Photographs of experimental condition and site.

pressure conditions. Two types of VODR were prepared as shown in Figure 3: the commercial VOD probe with nichrome wire and copper pipe and the modified VODR probe consisting of nichrome wire with a thin aluminum film.

3.3 Experimental setup

Nine experiments were conducted to investigate the deflagration characteristics of NRC under different charge types as shown in Figure 4. Type A contains a full charge with 15 mm PVC tube, whereas type B involves a steel pipe. Finally, the type C is a decoupled charge in which the 15 mm fully charged PVC tube is located inside the 45 mm steel pipe. As a common setup, the length of the tube or pipe and probe was 1 m, the weight of NRC was 235 g, and the specific gravity was 1.33. All experiments were carried out in soil trenches with rubber protection mats as shown in Figure 5.

4. Results and Discussion

4.1 Comparison of VOD probe sensitivity under low-pressure deflagration

The continuous VODR profiles for different probe types are presented in Figure 6. As shown, the commercial VODR probe cannot reflect the continuous deflagration accurately under the low levels of pressure and detonation velocity conditions. However, the VODR probe modified with an aluminum film exhibits is appropriate for continuous VODR, which may relate to the melting point of the probe material. Copper applied as a commercial probe has a melting point of 1358 K, whereas aluminum used for the modified probe melts at 933 K (Table 2). Since the commercial VODR probe is originally designed for use in normal explosives, appropriate sensitivity can be ensured with copper. However, thermites such as NRC generate a very low level of pressure and a low VODR, which require materials with a low melting point (i.e. aluminum).

4.2 Effect of confinement on deflagration ability

Figure 7 shows sample images before and after the test. As shown in Figure 7 (a), the PVC tube near the electric initiator is damaged, which may cause a leak of gas pressure and inhibit further reactions. The whole deflagration was performed in other cases, and no NRC remnants were found as shown in Figures 7 (b) and (c). One of the deflagration profiles for type A experiment is depicted in Figure 8, suggesting less than 2 cm of

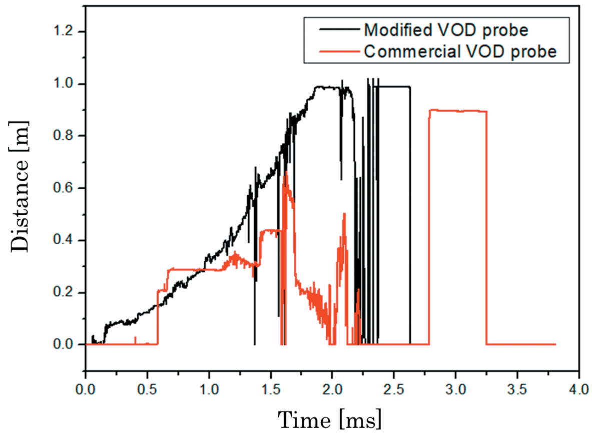
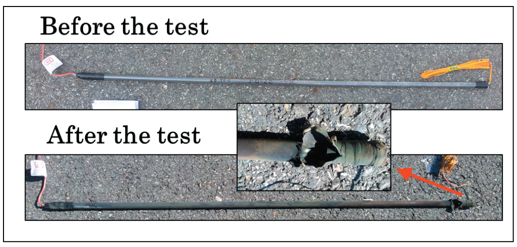


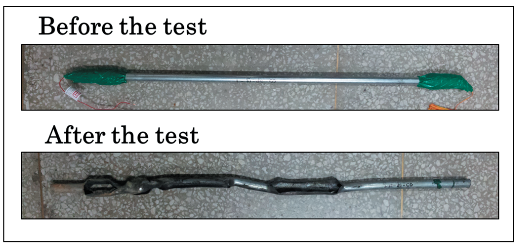
Figure 6 Comparison of VODR profiles with different probe types.

Table 2 Specifications for types of VOD probe.

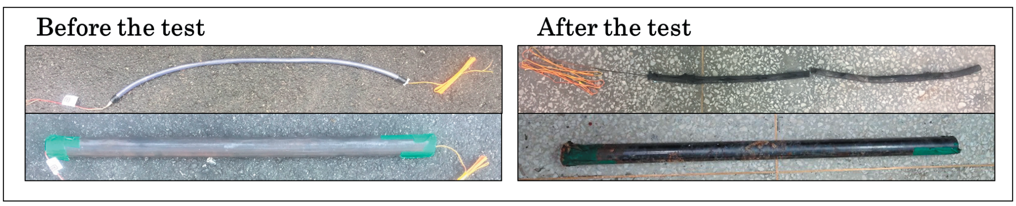
Parameter	Value	
	Commercial VOD probe	Modified VOD probe
Reaction material	Copper	Aluminum
Melting point [K]	1358	933
Electric resistance [Ω]	331.7	332



(a) Type A



(b) Type B



(c) Type C

Figure 7 Photographs of charging pipes and tubes; before and after the test.

deflagration as well as uncertain behaviors with a number of oscillations. The weak confinement for deflagration of thermites may induce leakage of gas pressure, and prevent continuous deflagrations. Accordingly, proper confinement of the operation using thermites is recommended.

4.3 Interpretation of deflagration velocity profiles

Figure 9 shows typical VODR profiles in continuous deflagration of thermites with different charges. As reported previously, they exhibit nonlinear behavior under adequate duration for sustained continuous reactions[16]. The experimental results show that the VODR profiles exhibit common behaviors irrespective of charge types, which can be classified into three major stages. First, during the initial stage of reaction, the VODR increases linearly to about 200 m·s^{-1} of VODR, which is similar to that of chemical reaction velocity (CRV). In the next stage, VOD appears relatively large with a nonlinear increase, and finally a proportional increase in the terminal stage. A comparison of Figures 9 (a) and (b) indicates similar behaviors compared with the values of VODR. Furthermore, the different stages are related to the reaction length regardless of the VODR: 0 m to about 0.3 m for the initial stage, about 0.3 m to 0.7 m for the intermediate state, and higher than 0.7 m for the terminal stage.

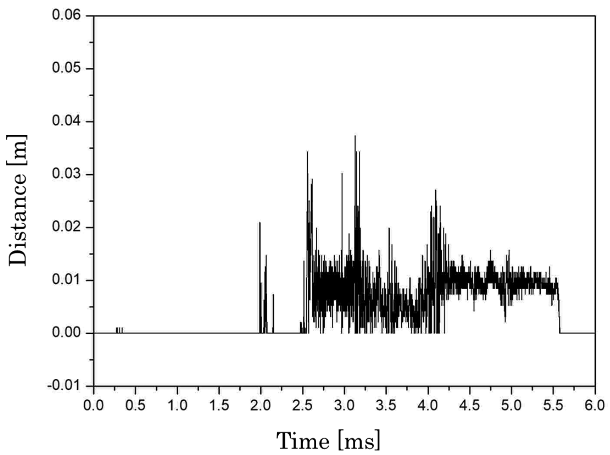


Figure 8 VODR profile of Type A; CF-PVC-01.

4.4 Deflagration characteristics under different charges

All experimental results of VODR measurement are tabulated in Table 3. The VODR was determined by the calculation of averaged slope degree for each stage. As

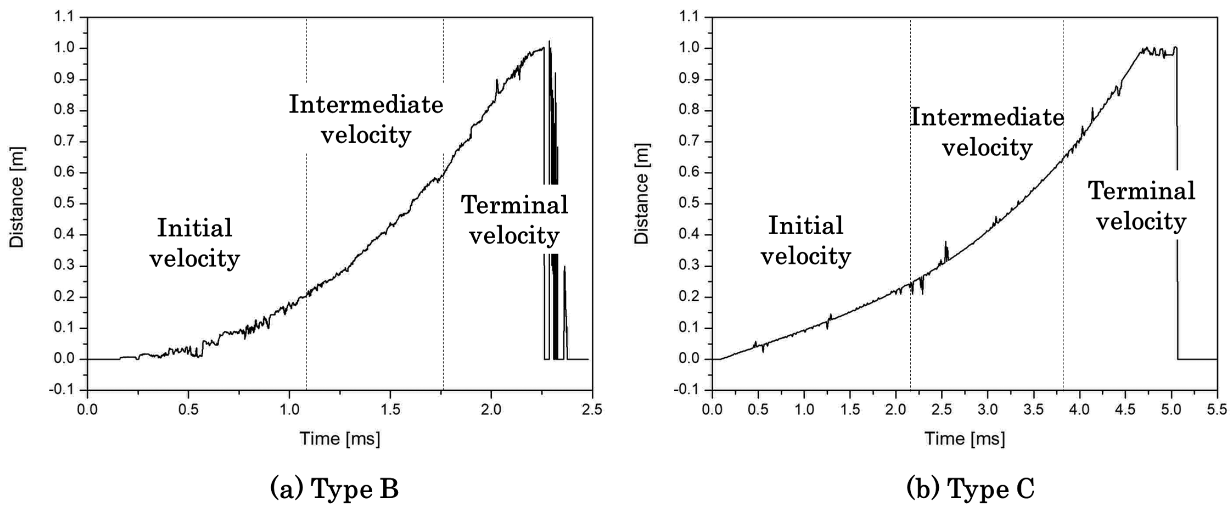


Figure 9 VODR profiles of Type B and C; CF-ST-01 and DE-ST-01.

Table 3 Experimental results for VOD measurement.

Type	Test ID	Initial velocity [m·s^{-1}]	Intermediate velocity [m·s^{-1}]	Terminal velocity [m·s^{-1}]	Averaged
Type A PVC tube	CF-PVC-01	Failed	Failed	Failed	–
	CF-PVC-02	Failed	Failed	Failed	–
	CF-PVC-03	Failed	Failed	Failed	–
Type B Steel pipe	CF-ST-01	183.72	535.19	928.07	**548.99**
	CF-ST-02	240.29	600.46	902.5	**581.08**
	CF-ST-03	283.11	543.31	781.63	**536.02**
	Averaged	**235.71**	**559.65**	**870.73**	**555.36**
Type C PVC tube & Steel pipe	DE-ST-01	159.54	270.17	396.59	**275.43**
	DE-ST-02	179.37	306.31	445.91	**310.53**
	DE-ST-03	172.84	281.69	433.96	**296.16**
	Averaged	**170.58**	**286.05**	**425.49**	**294.04**

stated in section 4.1, no reliable VODR profiles for type A were obtained due to leakage of gas pressure. Compared with the average VODRs of type B and C, several remarkable differences were found. Figure 10 presents a histogram of VODR compared with the charge types. The initial VODR in both types did not differ substantially, and indicated values similar to CRV of NRC. However, in the intermediate and terminal stages, the VODR of type B increased significantly while the VODR of type C showed a gradual increase, which may be attributed to the impact pressure and its propagations. The deflagration mechanism of the thermite agents such as NRC is based on the transition of continuous chemical reactions, and the effect of impact pressure and gas expansion on the system should be considered. In normal operations involving open systems, it is not a significant factor. However, it may have a significant role in the general crushing operation of rocks or structures in a closed (confined) system. Figure 11 shows the schematic of probable reaction mechanisms for different charge types. The shock waves generated by bulk expansion with substitution of metallic compounds exhibit a propagation velocity of several hundreds to thousands of meters-per-second compared with the CRV of NRC, which show a propagation velocity of 200 to 300 m·s^{-1}. The high temperature and pressure underlying the deflagration of thermite reaction mixture may explain the differences of VODR in the experiments.

In a previous study, Kim et al.[16] reported the presence of VODR transition zone along the stages. Based on further investigations, the presence of VODR transition zone and its degree of increment are closely related to the charge type and confinement.

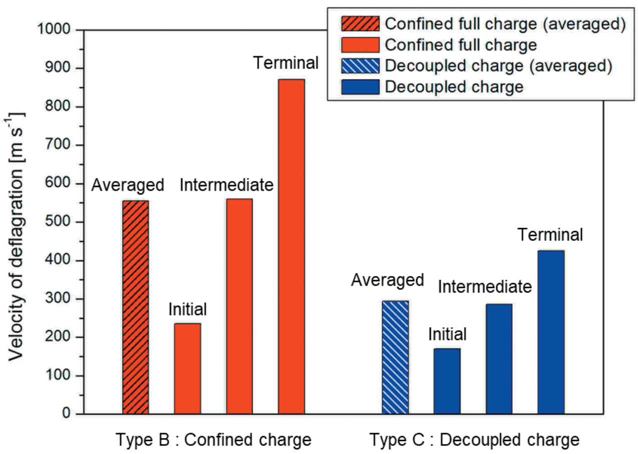


Figure10 Histogram of VODR comparison between type B and C.

4.5 Relationship between decoupling index and continuous VODR

In the blasting operations for rocks and concrete structures, decoupled charge using explosives with a smaller diameter than the drill hole is frequently applied. This method can reduce blast-induced vibrations and noise, and may be utilized depending on the field conditions. Because of the limited size (diameter) of commercial cartridge for thermite agents, many engineering applications using thermites have been conducted using decoupled charge method[12),14),15)]. In this study, the influence of decoupling effect on the VODR of thermites is discussed.

The decoupling index *DI* is commonly used in the blast design for mining and civil engineering. It can be defined by the ratio of hole diameter d_b to that of the explosive d_e (Equation (1)).

$$DI = \frac{d_b}{d_e} \tag{1}$$

In our experiments, the *DI* values of types B and C were 1 and 3, respectively. The relationship between *DI* and VODR based on the experimental results is shown in Figure 12. The VODR is decreased with increasing *DI*, and the VODR of type C is 40 % less than that of type B. According to the experimental results, a linear regression slope of correlation between VODR and *DI* is suggested

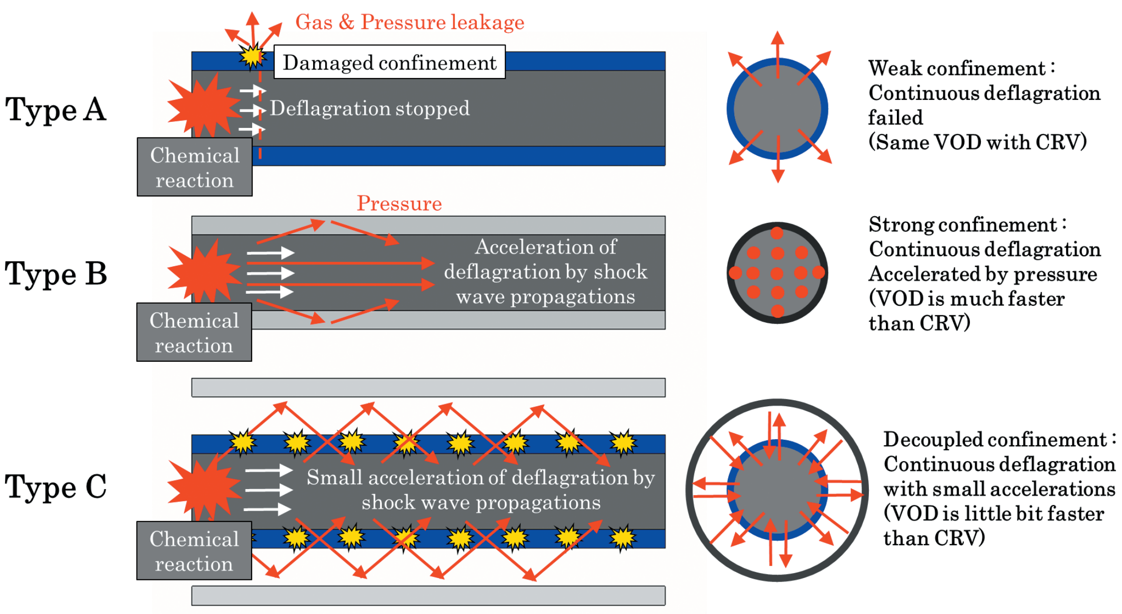


Figure11 Schematics of continuous deflagration mechanism of thermite reaction agents with different charging states.

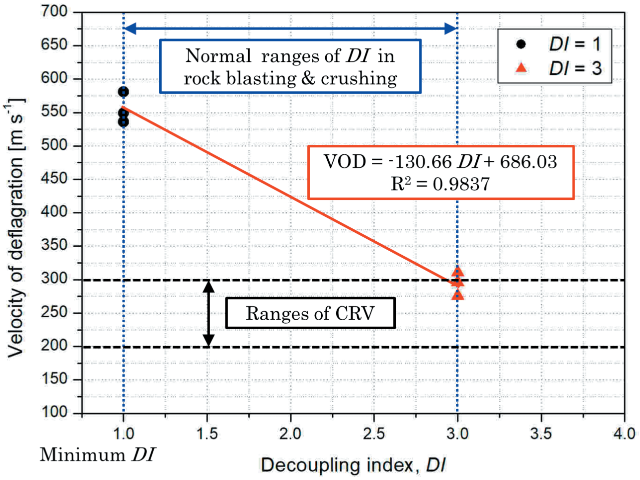


Figure12 Relationship between VODR and *DI*.

by Equation (2) as follows:

$$\text{VODR} = -130.66\, DI + 686.03 \qquad (2)$$

Over the ranges of *DI* 3, the VODR is almost similar to the CRV of NRC. Since the CRV indicates the reaction velocity in the open system, the VOD of NRC may merge with the CRV depending on the three values of *DI*. According to the ranges of *DI* in general blasting operations, the *DI* cannot exhibit a value lower than 1. Note that the Equation (2) is expressed as a linear correlation because it was consisted of two types of experimental data.

5. Conclusions

This study investigated the effect of charge types on continuous deflagration characteristics of thermites. Several types of charging methods including full charge with PVC tube (type A), full charge with steel pipe (type B), and decoupled charge with PVC tube and steel pipe (type C) were used in the experiment. A commercial rock crushing agent using thermites such as NRC was used. A continuous VODR measurement technique was adopted to estimate the deflagration characteristics of NRC.

Based on the experimental results, continuous deflagration of NRC may fail under insufficient confinement such as in PVC tube. In case of types B and C, continuous deflagrations were conducted successfully; however, the VODR of type B was 40 % larger than that of type C. The findings suggest that the impact pressure generated by chemical reaction contributes to continuous deflagration depending on the confinement condition. In addition, an empirical equation for correlation between VODR and *DI* has been suggested. Therefore, a careful analysis of continuous deflagration characteristics is required for application of thermite mixtures in rock and civil engineering operations.

Acknowledgement

This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 20TSRD-B151228-02).

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