An Experimental Study on Blast Resistance of Polyethylene Fiber Reinforced Concrete

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When designing blast resistant structures, reducing spall damage due to reflected tensile stress waves is the most significant problem. To investigate the application of polyethylene fiber reinforced concrete (PEFRC) with high toughness for use in blast resistant structures, experimental investigations were conducted to evaluate the damage to the PEFRC slabs subjected to contact detonation. As a result, it was shown that PEFRC was effective in reducing the spall due to contact detonation as compared with normal concrete. Moreover, a formula for estimating damage depth to the PEFRC slab subjected to contact detonation was derived based on the test results.

Key words: Polyethylene fiber reinforced concrete, Blast resistance, Contact detonation, Crater, Spall, Flexural toughness

1. INTRODUCTION

When designing important structures such as industrial plants and public facilities, it is necessary to ensure their safety against accidental explosions and terrorist bomb attacks.

The fracture modes of reinforced concrete (RC) slabs subjected to blast loadings are characterized by spalling due to the tensile stress wave being reflected from the back side of the slab. To protect humans inside a structure under such conditions, it is necessary to prevent the launch of concrete fragments that accompany spalling. Therefore, reducing spall damage is the most important problem in designing blast resistant RC structures.

In this study, in order to apply polyethylene fiber reinforced concrete (PEFRC) with high toughness to blast resistant structures, experimental investigations were conducted regarding the evaluation of the damage to PEFRC slabs subjected to contact detonation. Furthermore, the test results were compared with the formulae for estimating the size of the external damage to normal RC slabs [1], and then a formula for estimating total damage depth (the sum of crater and spall depths) in PEFRC slabs was proposed.

2. EXPERIMENTAL METHOD

2.1 Materials

Table 1 and 2 show materials and mix proportions used for the PEFRC, respectively. The mix proportion of the PEFRC was determined based on the mix proportion of which flexural toughness was at its peak [2]. As a normal concrete for comparison, ready-mixed concrete with 30 MPa in nominal strength and 18 cm in specified slump was employed.

Table 1. Materials used for PEFRC

Cement	High-early strength Portland cement Density: 3.13 g/cm^3
Fine aggregate	River sand Surface-dried density: 2.63 g/cm^3 Water absorption: 2.69% Maximum size: 2.5 mm Fineness modulus: 2.58
Coarse aggregate	Crushed stone Surface-dried density: 2.95 g/cm^3 Water absorption: 1.27% Maximum size: 15 mm Percentage of absolute volume: 56.3%
Admixture	Blast furnace slag Density: 2.89 g/cm^3 Specific surface area: 6140 cm^2/g Superplasticizer
Short fiber	Polyethylene fiber (Strand type) Density: 0.97 g/cm^3 Size: 68 μm (diameter) × 30 mm (length) Tensile strength: 1870 MPa Tensile elastic modulus: 43 GPa Elongation: 5%

Table 2. Mix proportions of PEFRC

V_f (%)	W/B (%)	Sg/B (%)	s/a (%)	W (kg/m^3)	Sp/B (%)	*Slump* (cm)
2.0	33	50	65	325	0.25	20.1
4.0	33	50	65	325	0.50	13.1

Notes; V_f: Fiber volume fraction, W/B: Water-binder ratio,
Sg: Blast furnace slag, s/a: Sand percentage, W: Water,
Sp: Superplasticizer

Table 3 shows material test results. Flexural toughness T_b is an important mechanical characteristic representing energy absorption capacity of fiber reinforced concrete and also an important characteristic against detonation loadings. The values of the flexural toughness of the PEFRC were 26.5 kN･mm (in V_f=2.0%) and 36.1 kN･mm (in V_f=4.0%).

2.2 Contact Detonation Test Method

Fig. 1 shows the configuration and bar arrangement of slab specimen. Each specimen was of the same size, 600 mm long, 600 mm wide and 100 mm thick. Specimens were cured in wet conditions for 14 days (for PEFRC) and 28 days (for normal concrete).

Fig. 2 shows the test set-up of the contact detonation. The specimen was supported by two wooden jigs with an inside span of 510 mm, in accordance with the previous study [1]. Explosive (density: 1.30 g/cm^3, penthrite : paraffin = 65 : 35, detonation velocity: 6900 ms^{-1}) was installed in the center of the upper surface of the specimen and blasted using an electric detonator. The explosive had a cylindrical shape of which the diameter was equal to the height, and the amount of explosive was either 100 or 200 g in weight.

Measurements were made of the diameter and depth of the crater, spall, and breach, as shown in Fig. 3. The diameters of the crater, spall, and breach were defined as the average value of four measurements along straight lines 1-4 shown in Fig. 3. The depth of the crater and spall in non-breached specimens was measured at the deepest point, while that of breached specimens was measured on a minimum level in the breach area.

Table 3. Material test results

	σ_B* (MPa)	E* (GPa)	σ_t* (MPa)	σ_f** (MPa)	T_b** (kN･mm)
Normal concrete	41.6	31.9	3.48		
2%-PEFRC	59.9	26.2	6.36	6.34	26.5
4%-PEFRC	54.6	22.6	7.65	8.79	36.1

Notes; σ_B: Compressive strength, E: Young's modulus,
σ_t: Splitting tensile strength, σ_f: Flexural strength,
T_b: Flexural toughness (area under load-displacement curves)
Specimen: * ϕ100×200 mm cylinder
** 100×100×400 mm (span length: 300 mm) prism

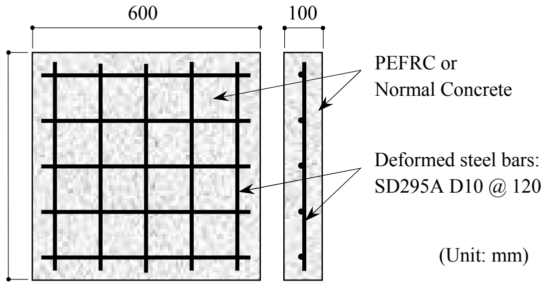


Fig. 1. Configuration and bar arrangement of specimen

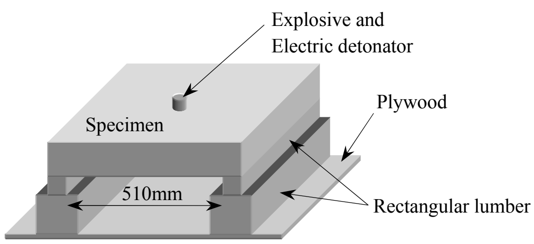
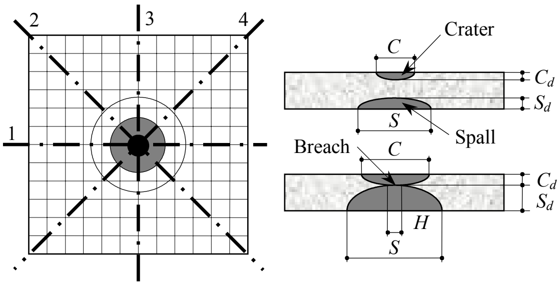


Fig. 2. Test set-up of contact detonation



Notes; C: Crater diameter, S: Spall diameter, H: Breach diameter,
C_d: Crater depth, S_d: Spall depth

Fig. 3. Measurement of size of external damage

3. RESULTS AND DISCUSSION

3.1 Fracture Behaviors of Specimens

Table 4 and 5 show fracture behaviors of the specimens and sizes of external damage measured, respectively.

(1) Using 100 g of Explosive

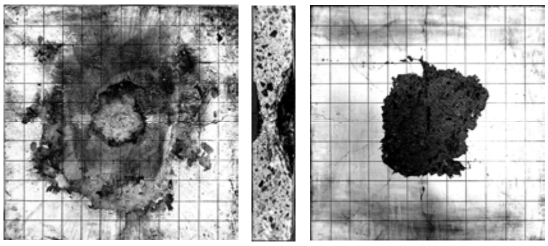
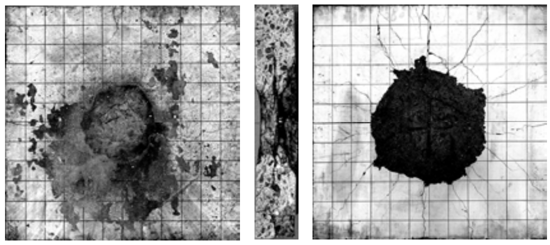
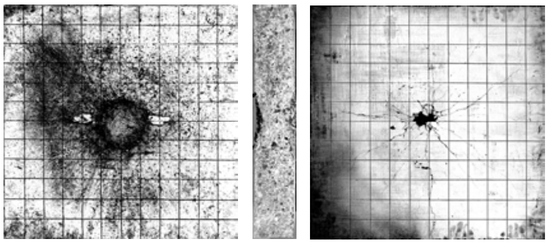
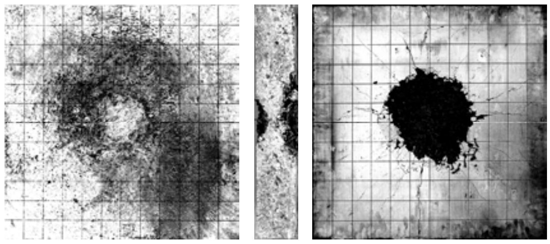
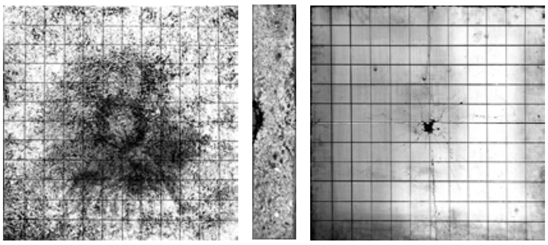
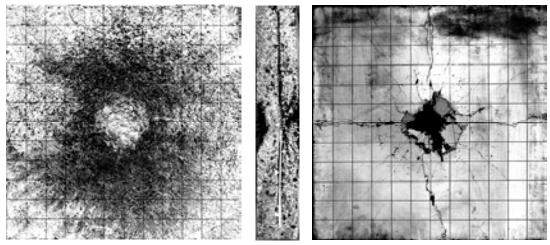
Both the normal concrete and PEFRC around the detonation point were broken into pieces, and nearly circular craters were created in all of the specimens. The sizes of the crater in the PEFRC slabs were almost as large as those in the normal RC slabs. Both the normal concrete and the PEFRC inside the crater were slightly whitened because of dehydration due to elevated temperature [1].

On the back side of the normal RC slab, a large spall was created and reinforcing steel bars could be seen in the center of the slab. On the other hand, the PEFRC slabs showed radial cracks and a small bulge occurred but no fragmentation was observed on the back side of the slab. Therefore, it was shown that PEFRC was effective in improving the blast resistance of the RC slab. Multiple fine cracks propagated from the center of the back side of the slab in the PEFRC specimens, while radial macro-cracks occurred in the normal RC specimen. This means that the bridging effects of the polyethylene fibers contributed to the excellent blast resistance of the PEFRC slab.

(2) Using 200 g of Explosive

On the back side of the normal RC slab, a very large spall was created and macro-cracks propagated in a radial pattern from the spall. In the PEFRC slab with V_f=2.0%, a spall was created but was smaller than that in the normal RC slab. Moreover, the size of the spall created in the PEFRC slab with V_f=4.0% became still smaller than that in the PEFRC slab with

Table 4. Fracture behaviors of specimens

	Explosive: 100 g	Explosive: 200 g
	- Detonation side - - Section - - Back side -	- Detonation side - - Section - - Back side -
Normal RC		
2%-PEFRC		
4%-PEFRC		

V_f=2.0%. Therefore, the blast resistance of the PEFRC slab may be raised with increasing in fiber volume fraction of the PEFRC.

3.2 Evaluation of the Damage Depth

When designing blast resistant RC structures, it is important to estimate the damage depth. Morishita et al. proposed useful formulae for estimating the damage depth in normal RC slabs subjected to contact detonation [1]. The formulae for estimating the crater and total damage depths in the normal RC slab are as follows:

a) Crater depth;

$$\frac{C_d}{T} = -0.046 \frac{T}{W_m^{1/3}} + 0.42 \qquad (1)$$

b) Total damage depth;

$$\frac{C_d + S_d}{T} = \frac{C_d}{T} \quad \left(3.6 < \frac{T}{W_m^{1/3}} \right) \qquad (2)$$

$$\frac{C_d + S_d}{T} = -0.49 \frac{T}{W_m^{1/3}} + 2.0 \quad \left(2.0 \le \frac{T}{W_m^{1/3}} \le 3.6 \right) \qquad (3)$$

$$\frac{C_d + S_d}{T} = 1.0 \quad \left(\frac{T}{W_m^{1/3}} < 2.0 \right) \qquad (4)$$

where, the modified-scaled concrete thickness $T/W_m^{1/3}$ is defined as follows:

Table 5. Size of external damage measured

	W (g)	C (cm)	S (cm)	C_d (cm)	S_d (cm)
Normal RC	100	16.1	3.4	27.7	4.8
	200	19.4	3.9	30.4	6.1
2%-PEFRC	100	13.3	2.9	6.1	1.1
	200	14.1	3.5	22.1	4.9
4%-PEFRC	100	11.6	3.2	2.8	0.7
	200	15.0	3.6	13.5	4.3

Notes; W: Amount of explosive, C: Crater diameter, S: Spall diameter, C_d: Crater depth, S_d: Spall depth

$$\frac{T}{W_m^{1/3}} = \frac{T}{W^{1/3}} \cdot \left(\frac{K_{TNT}}{K} \right)^{1/3} \quad \text{(Unit: cm/g}^{1/3}\text{)} \qquad (5)$$

where, T: slab thickness (cm), K_{TNT}: Chapman-Jouguet (C-J) detonation energy of tri-nitro-toluene (MJ/kg), and K: the C-J detonation energy of explosive used (MJ/kg).

Fig. 4 shows the experimental data of the crater depth and the total damage depth created in the PEFRC and normal RC slabs. In this figure, experimental data on PEFRC (T_b = 37.6-47.6 kN･mm) and normal RC slabs investigated in the previous study [3] were also given.

The measurements of the normalized crater depth C_d/T showed a fairy good correspondence with calculations using Eq. (1), in spite of the variety of specimens and amounts of explosive. This means that the crater damage in the PEFRC slab is almost as large as that in the normal RC slab.

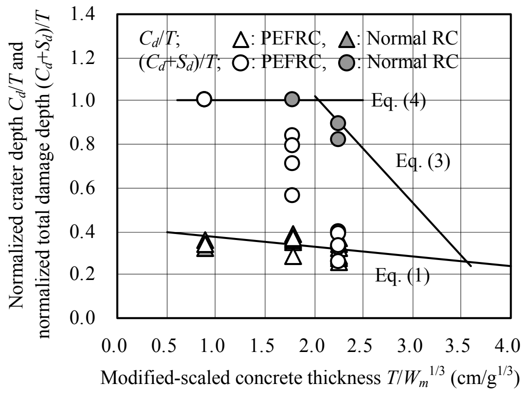


Fig. 4. Relationship between modified-scaled concrete thickness and normalized crater and total damage depths

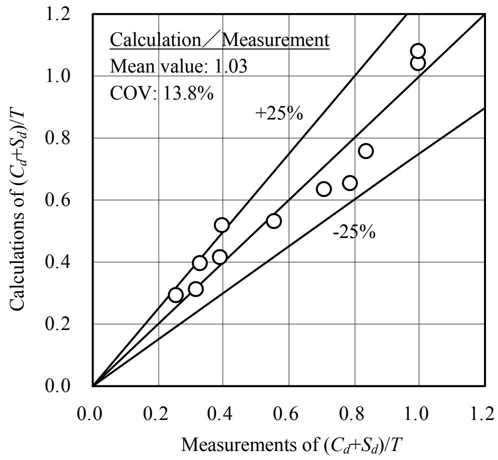


Fig. 5. Relationship between measurements and calculations of normalized total damage depth in PEFRC slabs

On the other hand, the measurements of the normalized total damage depth $(C_d+S_d)/T$ in the PEFRC slabs were considerably lower than those in the normal RC slabs. This suggests that PEFRC is more effective in reducing spall damage due to contact detonation as compared with normal concrete.

3.3 A Method for Estimating Total Damage Depth in PEFRC Slabs

For accurate estimation of the total damage depth in the PEFRC slab, the modified-scaled concrete thickness $T/W_m^{1/3}$ and the flexural toughness T_b might be important parameters. Therefore, the following equation was assumed:

$$\frac{C_d + S_d}{T} = \alpha + \beta \cdot \frac{T}{W_m^{1/3}} + \gamma \cdot T_b \quad (6)$$

where, α, β and γ: regression coefficients.

The experimental data on the PEFRC slabs were substituted for Eq. (6), and multiple regression analysis was carried out. As a result, the following formula was derived:

$$\frac{C_d + S_d}{T} = 1.946 - 0.5075 \cdot \frac{T}{W_m^{1/3}} - 0.01068 \cdot T_b \quad (7)$$

Eq. (7) suggests that Eq. (3) shown in Fig. 4 shifts to the left side with an increase in the flexural toughness of the PEFRC. Fig. 5 shows the relationship between the measurements and the calculations of the normalized total damage depth $(C_d+S_d)/T$ in PEFRC slabs. The calculations by Eq. (7) are in good agreement with the measurements, but more investigations are needed for more accurate estimation of the sizes of the crater and spall in PEFRC slabs subjected to contact detonation.

4. CONCLUSIONS

(1) PEFRC was more effective in reducing the spall damage and the launching of concrete fragments due to contact detonation as compared with normal concrete;

(2) since the size of the crater in the PEFRC slab was almost as large as that in the normal RC slab, the formula for estimating the size of the crater in the normal RC slab could be adapted to the PEFRC slab;

(3) the total damage depth in the PEFRC slab subjected to contact detonation could be estimated based on the flexural toughness of the PEFRC and the modified-scaled concrete thickness of the PEFRC slab.

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