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Scientific paper

Experimental Study on Blast Resistance of SIFCON

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Abstract

Slurry infiltrated fiber concrete (SIFCON) have received considerable attention in recent years. The SIFCON is distinguished from the conventional steel fiber reinforced cementitious composite (FRCC) by its high volume ratio of fibers, far beyond that of typical steel FRCC. Although this material has already been used for important structures including power plants and military facilities, very little is known about its behavior under blast loading. We therefore have experimentally investigated the behavior of SIFCON under the contact blast loading for the first time. This paper is intended to report these blast test results, in which varying amounts of gelignite embedded in the specimens were set off. After the blast test, diameter of crater, diameter of inlet of charge hole, and bulge of top surface of SIFCON were measured from the pictures using a commercial stereophotogrammetry program ShapeMetrix3D, and compared them to that of the conventional high strength concrete. The comparison results show the much higher blast resistance of SIFCON over conventional high strength concrete. In addition, the coefficient of resistance of SIFCON is evaluated which helps us to design the SIFCON structure subject to blast loading.

1. Introduction

Fiber reinforced cementitious composite (FRCC) has been greatly improved since the 1970s. FRCC is known to increase the performance of ordinary concrete, for example its tensile strength, stiffness, and crack resistance. With these advantages, FRCC has been applied in the world of civil engineering structures. In addition to conventional FRCC, slurry infiltrated fiber concrete (SIFCON) was invented by Lankard (1984). SIFCON is made by pouring slurry containing Portland cement, water, and superplasticizer over a bed of steel fibers. SIFCON is distinguished from conventional steel FRCC by its high volume ratio of fibers (4% to 15%), which is far beyond that of typical steel FRCC (less than 2%). There have been several studies on the mechanical characteristics of SIFCON (e.g. Naaman *et al.* 1992; Wang and Maji 1994; Farnam *et al.* 2010) and its applications (e.g. Naaman *et al.* 1993; Shannag *et al.* 2001; Mohammed *et al.* 2009). The research found that SIFCON surpasses conventional FRCC in its ductility and energy absorption capacity. Because of these characteristics, SIFCON is used for important structures including military facilities, runway precast pavements, and sub-

terranean shelters.

In the last few decades, the behavior of construction materials under blast loading has been a subject of growing interest because of the huge increase in the number of nuclear power plants, terrorist threats, and military threats. With the above described features, SIFCON has considerable promise as a blast-proof material. However, very few studies have been reported on the behavior of SIFCON under blast loading due to the difficulty of blasting tests. For example, Krauthammer (1999) conducted a numerical study on the applicability of SIFCON to concrete connection subjected to explosion by finite element analysis. Meanwhile, Marchand *et al.* (1988) and Mayrhofer (1994, 2000) carried out an experimental study in which standoff blast loading by TNT was applied to SIFCON specimens. However, there has been no research on contact blast loading. We have therefore experimentally investigated the behavior of SIFCON under contact blast loading, and compared it to that of conventional high strength concrete. This paper is intended to report these blast test results, in which varying amounts of gelignite embedded in the specimens were set off. The comparison results show the higher blast resistance of SIFCON over conventional high strength concrete.

2. Description of Tests

2.1 Specimen

SIFCON and high strength concrete specimens were fabricated for the blasting test. The mix proportions of these specimens are shown in **Table 1**, and the properties of the steel fibers in SIFCON are shown in **Table 2**. This research employed loose steel fibers which were not bonded at the ends so that the fibers dispersed well during the fabrication process. The compressive and flexural

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strength of SIFCON and high strength concrete specimens had already been investigated in our previous research by following Korean Standard Specifications (KSF 2405 and KSF 2408), and the results are shown in **Table 3** (Lee and Kim 2009). While the toughness of SIFCON and high strength concrete cannot be derived from our tests because the stress-strain relation was not recorded due to the test setup, Gilani (2007), following compression tests, reported the superior toughness of slurry SIFCON specimens of similar fiber length, diameter, shape, and volume ratio to our specimens. All of these SIFCON specimens showed a high strain capacity of more than 20%. Due to the ductility, the compressive toughness of SIFCON calculated from the stress-strain curve was 17.9 times greater than that of control concrete, of which the peak compressive strength was 47.6MPa. Moreover, the performance of SIFCON in tension is impressive due to the bridging effect, which transfers the stress across the tensile crack. Homrich and Naaman (1988) reported that the highest tensile strength and

strain capacity of SIFCON observed in their study were 21MPa and 1%, respectively. Since both of these figures are one or two orders of magnitude greater than those of normal concrete, the tensile toughness of SIFCON was found to be 770 times greater than that of control concrete.

Figure 1 shows the plywood mold of SIFCON. This was carefully sealed to prevent leaks because the flowability of slurry is much higher than that of ordinary concrete. As also seen from **Fig. 1**, slurry was carefully poured from a corner in a gradual manner, and this allowed the air inside to escape from the other corner. The age of specimens at testing was more than 28 days so as to alleviate the effect of initial hydration development. During the curing period, the specimens were covered by insulation to keep the temperature constant.

The dimensions of the SIFCON and the high strength concrete specimens are shown in **Fig. 2**. The specimen was 500mm in length and width, 300mm in depth with a charge hole of 20mm diameter and 130mm depth. The charge hole was used to embed the gelignite into the specimen. The length of resistance burden was 116mm,

Table 1 Mix proportion of SIFCON and high strength concrete specimen in unit volume (1m³).

	SIFCON	High strength concrete
Water	466kg	168kg
Cement	1332kg	318kg
Super plasticizer	13.32kg	4.09kg
Fly ash		45kg
GGBFS		91kg
Fine aggregate		757kg
Course aggregate		932kg
Fiber volume fraction	9%	

Table 2 Properties of fiber.

Diameter	0.5mm
Length	30mm
Material	Steel

Table 3 Compressive and flexural strength of SIFCON and high strength concrete specimen.

	Compressive Strength		Flexural Strength	
	SIFCON	High strength concrete	SIFCON	High strength concrete
Test 1	102.9MPa	36.2MPa	28.1MPa	5.6MPa
Test 2	104.3MPa	35.7MPa	28.9MPa	5.9MPa
Test 3	103.9MPa	38.1MPa	28.3MPa	6.1MPa
Average	103.7MPa	36.7MPa	28.4MPa	5.9MPa

Table 4 Properties of gelignite.

Product Name	MegaMITE
Type of Explosive	gelignite
Diameter	19mm
Heat of Explosion	1152kcal/kg
Detonating Velocity	6100m/sec

Fig. 1 Fabrication process of the SIFCON specimens.

Fig. 2 Dimensions of blasting test specimen.

which was the distance between the top surface and the center of the gelignite. Details of the gelignite are shown in **Table 4**.

2.2 Test Setup

Before testing, the specimens were painted white and grid lines were drawn with a grid spacing of 100mm so that the craters formed after the blast could be easily observed and measured. Next, the gelignite and electric blasting cap were embedded in the charge hole. The heat of explosion of the gelignite is 1152kcal/kg, which is similar to TNT (1150kcal/kg). The emulsion explosive was fully charged and the charge hole was filled with clay and sand; therefore the decoupling effect can be neglected in this blasting test. The quantity of gelignite used was determined by referring to the basic quantity of explosives derived from Hauser's blasting equation (Altun *et al.* 2007).

$$L = CW^3 \quad (1)$$

where

L (kg): the basic quantity of explosive in the charge to blow up

W (m): the length of least resistance burden, which was 0.116m in this research as shown in **Fig. 2**

C (kg/m³): the blasting coefficient which can be described as in the following Eq. (2).

$$C = ged \quad (2)$$

where

g : coefficient of resistance

e : coefficient of explosive

d : coefficient of tamping.

The coefficient e is 1 when gelignite is used, and the coefficient d is also 1 when the charge hole is completely filled. The coefficient g is assumed to be 9.5kg/m³ for SIFCON and 1.2kg/m³ for high strength concrete. The assumed coefficient g for SIFCON (9.5kg/m³) is taken from the coefficient of resistance of liparite which has a similar strength to SIFCON. By substituting these coefficients into Eqs. (1) and (2), the required quantity of gelignite to blast was roughly derived as 14.8g for the SIFCON and 1.9g for the high strength concrete. Taking these values into account, the quantity of gelignite was determined as 3g to 27g for the SIFCON and 0.5g to 9g for the high strength concrete as in **Table 5**. The SIFCON and high strength concrete specimens are referred to as SC1 to SC9 and HC1 to HC6, respectively. Then, the gelignite was detonated by an electrical blasting cap. After the explosion, the diameter of the crater and the inlet of the charge hole along line A to D shown in **Fig. 3** were measured by using a commercial stereophotogrammetry program ShapeMetrix3D, and the results were averaged. The software allows reproduction of the surface in the photos from two different angles so that the length between two arbitrary points can be measured. In addition, the bulge of the surface after the explosion was

also measured and a contour plot was produced by the software.

Note that the number of specimens is not necessarily enough because the test is very dangerous; nevertheless the test results shown in the next section evaluate the higher blast resistance of SIFCON over conventional high strength concrete well in a quantitative manner.

3. Test results and discussion

3.1. Blasting test results of the high strength concrete

The blasting test results of the high strength concrete specimens are presented in this section. Six specimens were blasted with varying quantities of gelignite from 0.5g to 9g as in **Table 5**. **Fig. 4** shows the top surface of the high strength concrete specimens after the blast. In specimens HC1 and HC2, of which the quantity of gelignite is smaller than the basic quantity of explosive derived in Section 2 (1.9g), no damage was observed on

Table 5 Quantity of explosives for the SIFCON and high strength concrete specimens.

Name of specimen	Quantity of gelignite (g)	TNT conversion (g)
SC1	3.00	3.01
SC2	6.00	6.01
SC3	9.00	9.02
SC4	12.00	12.02
SC5	15.00	15.03
SC6	18.00	18.03
SC7	21.00	21.04
SC8	24.00	24.04
SC9	27.00	27.05
HC1	0.50	0.50
HC2	1.00	1.00
HC3	2.00	2.00
HC4	3.00	3.01
HC5	6.00	6.01
HC6	9.00	9.01

Fig. 3 Diameters of crater and inlet of charge hole.

Fig. 4 High strength concrete specimens after the blasting test.

Table 6 Average diameter of crater and the charge hole inlet of SIFCON specimens.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9
Crater (cm)	8.82	10.21	13.21	14.44	13.66	20.17	24.90	21.22	21.38
Charge hole (mm)	20	22	23	26	28	32	34	32	43

the surface. In specimen HC3, of which the amount of gelignite was similar to the basic quantity of explosive, tensile cracks were observed on the top surface. Meanwhile, significant failure occurred when the amount of gelignite was much larger than the basic quantity. For example, on the surface of specimen HC4, a crater was seen in the photo and its average diameter was 22.2cm. In addition, large cracks radiated outward. At the same time, the diameter of the inlet of the charge hole was also measured; however, the size had not changed after the blast. As for specimens HC5 and HC6, which were blasted with more than three times the basic quantity of explosives, they were totally obliterated as shown in Fig. 4(e) and (f).

3.2 Blast test results of the SIFCON

Nine SIFCON specimens were blasted using 3g to 27g quantities of gelignite in 3g increments. Fig. 5(a) shows the SIFCON specimen blasted with 3g gelignite. Surface delamination is seen in this specimen, which is due to tensile stress near the surface caused by the shock wave from the explosion and the reflected wave from the free surface. A small crater is observed at the center, and the diameter is 8.82cm, which is 1/2.5 of the diameter of the crater of the HC4 specimen blasted by the same quantity of gelignite described in the previous section. This indicates that the SIFCON has higher blast resistance than the high strength concrete. Fig. 5(b) shows the specimen

blasted with 6g gelignite. A crater and surface delamination are also observed in this case. The SIFCON specimen blasted with 9g gelignite is seen in Fig. 5(c). Not only the crater, but also tensile cracks in radial directions can be seen in the picture. These cracks are considered to be caused by the stress wave moving in a tangential direction, which also played a role in developing the crater. From Fig. 5(d) to (i), the quantity of explosive was increased from 12g to 27g in 3g increments. It is observed that the size of the crater and inlet of the charge hole increase as the quantity of gelignite increases, and these changes are shown in Table 6. In addition, the length of the tensile cracks increases and they reach the end of the specimen when the amount of gelignite is 18g, as shown in Fig. 5(f). On the other hand, it is observed that the entire specimen is expanded by the shock wave especially when the quantity of gelignite is more than 21g. This shows the superior ductility and energy absorption capacity of SIFCON over conventional concrete.

3.3 Discussion

3.3.1 Diameter of crater and inlet of charge hole

The variation of the crater diameter with the weight of explosives is shown in Fig. 6. It is observed that the crater diameter varies linearly with the quantity of explosives, so that the following regression formula can be developed.

Fig. 5 SIFCON specimens after the blasting test.

$$d_c = 0.62L_e + 7.08 \quad (3)$$

where

d_c (cm): the crater diameter

L_e (g): the weight of explosives.

We can make use of the above Eq. (3) when a similarly sized SIFCON object is designed to resist the blast loading caused by an arbitrary quantity of explosives. The blast test result of high strength concrete (HC4) is also included in Fig. 6, where $L_e = 3$ g and $d_c = 22.2$ cm. According to Eq. (3), 24.4g of explosives are required to develop the same size of crater on the SIFCON specimen, which is 8.13 times more than the quantity used to blast the HC4 specimen. This indicates the excellent blast resistance of SIFCON.

Meanwhile, Fig. 7 shows the dependence of the amount of explosives on the inlet diameter of the charge hole of high strength concrete and SIFCON. As in the case of the crater diameter, the diameter of the charge hole inlet of SIFCON has a linear relationship to the amount of explosives, and the regression formula is

Fig. 6 Dependence of the crater diameter on the quantity of explosives.

developed as follows:

$$d_i = 0.83L_e + 16.39 \quad (4)$$

where

Fig. 7 Dependence of the diameter of the charge hole inlet on the quantity of explosives.

d_i (mm): the diameter of the charge hole inlet.

The linear increase of the diameter of the charge hole inlet proves the high ductility of SIFCON, while no increase was observed for the high strength concrete specimen, which is a brittle material. The difference is considered to be caused by fibers in the SIFCON. When the crack occurs, several fibers bridge across the crack and transfer the stress. This bridging effect prevents failure due to brittleness and improves the ductility of the material.

3.3.2 Estimation of the coefficient of resistance g

The coefficient of resistance g in Eq. (2) is estimated from the test results. The value of g is very important to design the SIFCON structure if it will be subject to blast loading, but the value has not been evaluated in the literature. Since both the coefficient of explosive e and the coefficient of tamping d are 1, Eq. (1) and (2) are developed as follows Eq. (5).

$$g = L / W^3 \quad (5)$$

The observation of the blast test results of high strength concrete revealed that a huge crater and crack

reaching the end of the specimen appeared when the quantity of explosive was 3g (HC4 specimen). Meanwhile, 18g of explosive were required for SIFCON to develop a similar failure (SC6 specimen). By substituting these gelignite amounts into Eq. (5), the coefficient of resistance g of SIFCON and high strength concrete is roughly derived as 11.4kg/m^3 and 1.9kg/m^3 , respectively. The coefficient of resistance of SIFCON is six times greater than that of high strength concrete.

At the same time, Eq. (5) can also be used to derive the burden W if the coefficient of resistance of g is already obtained. The difference in g makes a difference in W when the same quantity of explosive is used. By substituting $g = 11.4$ for SIFCON and $g = 1.9$ for high strength concrete in Eq. (5), it is found that the layer of SIFCON required to resist a given weight of explosive is only 1/1.8 of the thickness of the high strength concrete. The result helps the designer to design the structure with SIFCON.

3.3.3 Observation of the surface after the blast

Figure 8 shows a contour plot of the HC4 and SC6 specimens obtained by ShapeMetrix3D after the blast. As described, HC4 and SC6 have similar failure modes in which tensile cracks reached the end of the specimen. Different colors indicate the variations in surface height, and the legend is also shown above the figures. It is observed that the surface of the SIFCON heaved less than that of the high strength concrete. The reasons include the fact that the void ratio in the SIFCON specimen as a result of crash was less than that in the high strength concrete specimen. This also indicates the remarkable ductility and blast resistance of SIFCON.

4. Conclusion

In this research, the blast behavior of SIFCON was experimentally investigated and compared to that of high strength concrete. A series of contact blasting tests were conducted with varying quantities of gelignite. It was found that SIFCON has much higher blast resistance than

Fig. 8 Contour plot of the top surface of the HC4 and SC6 specimens after the blast.

high strength concrete. SIFCON did not break even when 27g of gelignite was used, though the high strength concrete was totally smashed with only 6g of gelignite. In the test, it was observed that the SIFCON specimens expanded, especially when the quantity of gelignite was more than 21g, and this proves the superb ductility and energy absorption of SIFCON. It is considered that these characteristics are due to the bridging effect of steel fibers in SIFCON, which transfers the stress across cracks.

In addition, the diameter of the crater and the charge hole inlet were measured from the pictures using a commercial stereophotogrammetry program Shape-Metrix3D. It was found that these diameters had a linear relation to the quantity of gelignite, and the crater size of SIFCON was much smaller than that of high strength concrete. In addition, the coefficient of resistance g in Hauser's blasting equation was estimated for SIFCON and high strength concrete from the blasting test results. It was found that the coefficient of resistance g of SIFCON is six times greater than that of high strength concrete, which means that the layer of SIFCON required to resist a given weight of explosive is only 1/1.8 the thickness of the high strength concrete layer that would be needed.

Furthermore, the observation results of the top surface also indicate the excellent blast resistance of SIFCON. Hence it is reasonable to say that SIFCON is suitable for structures which may be subject to blast loading. These achievements will help us to design and provide safer structures by SIFCON.

For further work, it is suggested to develop a numerical method to analyze the blasting effect, though it is difficult to model SIFCON and blast loading. This is important because it is not very easy to conduct a huge number of blast tests due to their dangerousness. The experimental results shown in this paper are expected to contribute significantly to developing such a numerical method. In addition, we will attempt to conduct a series of experiments with a sufficient number of specimens with various fiber volume fractions. This would serve to improve understanding of the effect of fibers in SIFCON on blast behavior. For example, it would be useful for the design purpose if the relation between the coefficient of resistance g and the fiber volume fraction were obtained.

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