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Experimental study of torsional strength of RC beams constructed with HPFRC composite mortar

Jinsup Kim [a], Minho Kwon [b,*], Hyunsu Seo [b], Jeonghee Lim [b]

[a] Dept. of Civil Engineering, University of Texas at Arlington, Arlington, TX 76019, USA
[b] Dept. of Civil Engineering, ERI, Gyeongsang National University, Jinju 660-701, South Korea

HIGHLIGHTS

- Torsional performance of RC beam with HPFRC composite mortar was evaluated.
- HPFRC composite mortar has high compressive and split tensile strength than plain concrete.
- Torsional performances of RC beam specimens were compared experimentally.
- HPFRC composite mortar enhanced the torsional performance of RC beam.

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ABSTRACT

The torsional performance of reinforced concrete (RC) beam members covered with high-performance fiber-reinforced cementitious (HPFRC) composite mortar was evaluated through pure torsion tests. The HPFRC composite mortar has higher compressive strength and higher split tensile strength than plain concrete. Four beam specimens were constructed for the pure torsion test. Two types of section, and different materials, were used to produce the RC beam specimens. Various types of torsional performance (i.e., first-cracking torque, ultimate torque, and twist angles) were compared experimentally to evaluate the performance of the RC beam specimens. The torque and twist angle at first visible cracking, of the HPFRC composite mortar specimens were greater than those of the others. Therefore, the use of HPFRC composite mortar appears a useful method to enhance the torsional performance of RC-beam members. Moreover, a simple design equation to determine ultimate torque was proposed and tested, for predicting the torsional strength of RC beams with covers of HPFRC composite mortar. The proposed equation performed well.

1. Introduction

Due to recent destructive earthquakes (e.g., 2008-Wenchuan, 2009-Honduras), numerous reinforced concrete (RC)-frame buildings collapsed or were damaged. In general, the performance of RC-frame structures mainly depends mainly upon the strength of the beams and columns, specifically, upon their flexural, shear, and torsional strength.

During the last decades, experimental studies have been performed to investigate the behavior of RC members subjected to pure torsion [1–7]. Among these, Fang and Shiau [8] published test results of the torsional response of steel-fiber-reinforced concrete beams. It was reported that the improved tensile performance of the concrete could increase torsional strength. This makes sense because the torsional failure of concrete members is initiated by the tensile stress developed by pure-shear due to torsion. Thus, inclusion of fibers in concrete may increase moderately the tensile strength of the matrix.

A number of studies have reported the use of high-performance fiber-reinforced cementitious (HPFRC) composite mortar. It is one of the fiber-reinforced cementitious composites, and has exhibited pseudo strain-hardening characteristics under uniaxial tensile stress [9–12]. The material characteristics of HPFRC composite mortar allow it to retain the capacity for high ductile deformation, with about 2% tensile strain being due to multiple fine cracks, in comparison to plain concrete. The development of HPFRC composite mortar was primarily motivated by the need to improve the brittle tensile behavior of plain concrete and mortar. Unlike for plain concrete, HPFRC composite mortar generally shows multiple

* Corresponding author at: Dept. of Civil Engineering, Gyeongsang National University, Jinsu-daero 501, Jinju 660-701, South Korea. Tel.: +82 55 772 1796; fax: +82 55 772 1799.

E-mail address: kwonm@gnu.ac.kr (M. Kwon).

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fine cracks of reduced width, without strain localization, and can sustain tensile stresses corresponding to high strains [13–15].

In recent years, HPFRC composite mortar has been applied to reinforced concrete members [16–18]. In those studies, it improved cyclic-lateral-load and deformation capacities, and minimized flexural and shear cracks in critical regions of the flexural members, or of reinforced concrete columns. These are among the particular advantages provided by HPFRC composite mortar, if used to strengthen RC members under flexural or shear loading. However, there have been no studies of the torsional performance of RC beams with covers of HPFRC composite mortar.

In this paper, HPFRC composite mortars was used to improve the torsional performance of RC beam member. HPFRC composite mortars, which has both high tensile strength and high tensile ductility, was used to cover part of a RC beam. Four beam specimens were fabricated and tested using a pure torsion test. The experimental results were used to compare and discuss the torsional performance of the different RC beam specimens.

2. Experiment setup

2.1. Material properties

Four beam specimens were used in the experiments. Two types of plain concrete were used to make the RC-beam specimens in this study (N21 and N40). These had 21 MPa and 40 MPa of target compressive strength, respectively. Two types of HPFRC composite mortar were used to cover parts of two other RC-beam specimens (F1.5 and F2.0). The HPFRC composite mortar used for these had 1.5% and 2.0% fiber-volume fractions, respectively. In this study, PVA (Polyvinylalchol) fibers with a length of 12 mm and diameter of 0.015 mm were mixed into the HPFRC composite mortar as a reinforcing material to reduce the brittleness of the concrete or mortar. An oiling agent was used to treat the surface of PVA fiber to control fiber lumping. The material properties of the PVA fibers are shown in Table 1.

The HPFRC composite mortars were mixtures including different fiber volume fractions of PVA fibers, ordinary Portland cement (C), silica sand (S, maximum grain size 0.25 mm), water (W), fly-ash (FA), blast-furnace-slag (BFS), a high-range water-reducing admixture, and admixtures to enhance the fresh properties of the mortar. The fluidity of the matrix and dispersibility of the fiber were increased by the use of a polycarboxylate superplasticizer (PCSP). Hydroxypropyl methylcellulose was applied to prevent separation of the materials. In addition, an antifoaming agent was employed to control the air content. The HPFRC composite mortar had a water/binder ratio (W/B) of 0.45, and a silica sand/binder ratio (S/B) of 0.83; the mix proportions of the HPFRC composite mortar are summarized in Table 2.

Cylindrical samples molds (100 × 200 mm) were used to evaluate the compressive strength of the plain concrete types (N21 and N40). Cubic samples (5 × 5 × 5 mm) were used to evaluate the compressive strength of the two HPFRC composite mortar types (F1.5 and F2.0). Cubic samples were used because the predicted compressive strength of HPFRC composite mortar cylinders was greater than the capacity of the compression-testing machine. Cylindrical samples were also used for a split tensile test of plain concrete and HPFRC composite mortar.

From these tests, it was determined that the compressive strength of the N21 concrete was 21.6 MPa, and that of the N40 concrete was 41.2 MPa. The compressive strength of the HPFRC composite mortar with 1.5% PVA fiber volume (F1.5) was 38.2 MPa, and the compressive strength of the HPFRC composite mortar with 2.0% PVA fiber volume (F2.0) was 39.4 MPa. The split tensile test results for N21, N40, F1.5 and F2.0; were 2.2 MPa, 3.3 MPa, 4.6 MPa, and 4.4 MPa, respectively. The results of the compression and split tensile tests of normal concrete and of HPFRC composite mortar are summarized in Table 3.

Table 3
Material properties of plain concrete and HPFRC composite mortar.

Designation of material	Compressive strength (f_{ck}, MPa)	Split tensile strength (f_{spt}, MPa)
N21	21.6	2.2
N40	41.2	3.3
F1.5	38.2	4.6
F2.0	39.4	4.4

Comparisons of the results showed that the compressive strength of the N40 concrete was two times that of the N21 concrete, and that the split tensile strength of the N40 concrete was 1.56 times that of the N21 concrete. The compressive strength of both HPFRC composite mortar specimens was similar to the compressive strength of the N40 concrete. However, the split tensile strength of both HPFRC composite mortar specimens was higher than that of the N40 concrete. The compressive strength and split tensile strength of the HPFRC composite mortar specimens was greater than that of N21 concrete. Both D16 (16 mm diameter) and D10 (10 mm diameter) rebar was used in the test specimens and the material properties of each kind of rebar are summarized in Table 4.

2.2. Details of specimens

The torsional behavior of RC beams of plain concrete and HPFRC composite mortar were explored. Therefore, four RC-beam specimens were created for the experiment, based on the strength of their cores, and on the covering over the concrete. American Concrete Institute-Committee 318 [19] design code was used to calculate the torsional strength of each RC beam. Two of the specimens had cylindrical cross sections; the other two had square cross-sections (Fig. 1). Specimens BN21 and BN40 had cross-section Type-I, as shown in Fig. 1(a), and specimens BF1.5 and BF2.0 had cross-section Type-II, as show in Fig. 1(b). The BN21 specimen consisted of N21 concrete, which had a 28-day compressive strength of 21 MPa, in the whole section. The BN40 specimen consisted of N40 concrete, which had a 28-day compressive strength of 40 MPa, in the whole section. The BF1.5 and BF2.0 specimens consisted of an N21 concrete core with a cover of HPFRC composite mortar (F1.5 or F2.0), shown in Fig. 1(b). The core of the BF1.5 specimen was covered using HPFRC composite mortar F1.5, and the core of the BF2.0 specimen was covered with HPFRC composite mortar F2.0. Details of the specimens are summarized in Table 5.

Fig. 2 shows the dimensions of the experimental beam specimens. The length of the RC beam specimens was 3000 mm (pure span: 2700 mm), and the cross-sectional dimensions were 300 × 300 mm. The thickness of the cover was 50 mm, and the core was 200 × 200 mm. Four deformed D16 (16 mm dia.) rebars were used as longitudinal reinforcement in each beam. D10 (10 mm dia.) rebars were used for transverse reinforcement in each specimen, and those were placed with 150 mm intervals.

2.3. Test setup

The pure torsion test setup was designed based on previous research [2,3,20–23]. Details of the test setup are shown in Fig. 3. One end-boundary was configured to resist torque while allowing longitudinal movement using the upper

Table 1
Properties of PVA fiber.

Type	Density ρ_f (g/cm^3)	Normal length L_f (mm)	Normal diameter d_f (mm)	Aspect ratio S_f	Tensile strength E_f (MPa)	Elastic modulus E_f (MPa)	Elongation (%)
PVA (Polyvinyl alcohol)	1.3	12	0.015	800	1269	27,640	3–113

Table 2
Mix proportions of HPFRC composite mortar.

Designation of the material	W/B[a] (wt.%)	S/B (wt.%)	FA/B (wt.%)	BFS/B (wt.%)	Unit: kg/m^3									
					W	B[a]	C	FA	BFS	Silica sand	PCSP	HPMC	Defoamer	PVA (vol.%)
F1.5	45	83	20	20	375	834	500	167	167	692	0.37	0.18	0.45	19.5 (1.5)
F2.0	45	83	20	20	375	834	500	167	167	692	0.37	0.18	0.45	26.0 (2.0)

[a] B = C + FA + BFS.