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FLEXURAL AND TENSILE STRENGTH DEVELOPMENTS OF VARIOUS SHAPE CARBON FIBER-REINFORCED LIGHTWEIGHT CEMENTITIOUS COMPOSITES

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ABSTRACT

Effects of three types of carbon fiber shapes (C, round, and hollow shape) on tensile and flexural strength developments of randomly oriented carbon-fiber-reinforced lightweight cement composites (CFRLC) were investigated. C-shape CFRLC (C-CFRLC) showed higher tensile and flexural strength development than any other shape. C-CFRLC loading $V_f = 3\%$ in particular increased about 40% in tensile and flexural strength, compared to round shape CFRLC (R-CFRLC). Hollow-shape CFRLC (H-CFRLC) showed slightly higher tensile and flexural strength than R-CFRLC. C-CFRLC presented stronger fiber-matrix interfacial adhesive force, due to mechanical anchorage into the matrix, than any other fibers. Silica fume significantly influences the increase of tensile and flexural strength for the CFRLC. *© 1998 Elsevier Science Ltd*

Introduction

Fiber reinforcement is generally used to enhance the mechanical properties of a brittle matrix, especially cement paste. Carbon fiber is one of the most common for reinforcing cementitious materials because of superior mechanical properties. When carbon fiber was incorporated into the cementitious matrix, various properties of carbon-fiber-reinforced cement composites (CFRC) were improved, such as tensile strength, flexural strength, toughness, drying shrinkage, earthquake resistance etc. (1–2). The properties of CFRC are influenced by fiber loading and length because interfaces between fibers and matrix play important roles (3–4). In the CFRCs, the interfacial bonds between fibers and cementitious matrix are mainly composed of three types of bonds (chemical, electrical, and mechanical) and these are greatly dependent on the character of fibers (5).

In this study, various shapes of carbon fibers, C, hollow, and round, were used to reinforce a cementitious matrix containing lightweight aggregates with/without silica fume in order to enhance mechanical bond. C-shape and hollow-shape carbon fibers have higher specific surface area than conventional round-shape carbon fiber. Flexural and tensile strength

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TABLE 1
Mixing ratios of cement matrix for CFRC (unit : wt.%).

Ordinary portland cement	Fine aggregates			Admixtures (C × wt.%)			Carbon fibers	W/C
	Sirsu balloon	Micro cell	Silica Fume	BMC	A-803	M-150		
100	15	5	16	0.25	0.5	3.0	1 ~ 3 V_f%	0.465
	31	5	–				3 ~ 25 mm *C, H, R	

*C, C shape carbon fiber; H, Hollow shape carbon fiber; R, Round shape carbon fiber.

development properties of various lightweight cement composites reinforced with randomly-oriented carbon fibers were investigated. Effects of the shape of fibers, fiber loadings and aspect ratios on strength development and microstructures were also studied.

Experimental

The lightweight cementitious composites were prepared with ordinary Portland cement (OPC, Ssangyong cement), lightweight fine aggregate (Sirasu Balloon, MSB301 Japan, and micro cell, SL150 Austria, bulk density 0.35–0.4, fineness max. 180 μm), and silica fume (Blaine specific surface area 200,000 cm^2/g). Other materials as admixtures, such as super-plasticizer (Mighty-150, Japan), methyl cellulose (BMC-324, Germany), and anti-foaming agent (Agitan-803, Germany), were used to produce a homogeneous matrix. The typical formulation of cementitious matrix of CFRC is shown in Table 1. Carbon fibers were incorporated into the above lightweight cementitious composites. Table 2 shows the properties of the carbon fibers used.

Specimens were prepared according to the following process: firstly, carbon fiber and dry materials were mixed for 5 min., water was added to the dry mixtures, and they were mixed for 5 min. in an Omni mixer. Secondly, the wet mixtures were cast for a flexural specimen, 40 × 40 × 160 mm, and a tensile specimen, 12 × 30 × 330 mm. Finally, the cast samples were cured at 20°C with 80% RH for 2 days, autoclave-cured at 180°C with 10 atm for 4 h, and then dried at room temperature for 14 days (6). The flexural and tensile load were applied

TABLE 2
Properties of carbon fibers used in the study.

Fiber shapes	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Diameter (μm)	Cross sectional area (μm^2)	Specific gravity
C	922	102.4	0.9	Do 40.2 Di 22.8	574.0 open θ = 120°	1.76
Hollow	830	118.5	0.7	Do 36.1 Di 23.8	589.8	1.78
Round	859	71.6	1.2	26.8	564.1	1.74

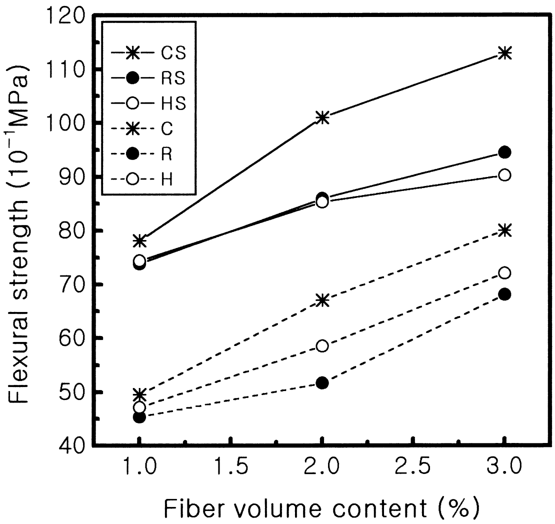

FIG. 1.
Flexural strengths of various shapes of carbon-fiber-reinforced lightweight cementitious composites (CFRLC) as a function of fiber loading. Solid Lines represent CFRLC containing silica fume. Dotted lines represent CFRLC without silica fume. Shapes of carbon fibers: C, C-shape; H, hollow shape; R, round shape; S, silica fume addition.

at a constant displacement rate of 0.5 mm/min. cross head speed by the center point load method. The fracture surface of CFRLC was observed by SEM.

Results and Discussion

Flexural Strength

As shown in Figure 1 the flexural strength of CFRLC was dramatically increased with increasing a fiber loading. The CFRLCs containing silica fume show higher flexural strength than the CFRLCs without silica fume because of increased interface area between fiber and matrix due to the densification of microstructure. The C-CFRLC presents higher flexural strength than R- and H-CFRLC, regardless of the addition of silica fume. The C-CFRLC containing silica fume shows the highest flexural strength, about 40% higher than R and H-CFRLCs at a fiber loading volume of 3%. The inside space of C- shape carbon fiber was compacted by the matrix, and the fiber acted as a mechanical anchor. The C-shape carbon fiber also showed a large interface between fiber and matrix as shown in Figure 3. The H-CFRLC without silica fume shows higher flexural strength than R-CFRLC. But H- and R-CFRLC containing silica fume show almost the same flexural strength.

Figure 2 shows the flexural strength as a function of aspect ratio for the CFRLC fiber loading volume of 2%. The C-CFRLC presents high flexural strength and an optimum aspect ratio, 250 and 150 for without silica fume and with silica fume, respectively. When the fiber is too long the fibers are easily agglomerated together during the mixing process, resulting in decreasing dispersability and flowability, and increasing the air entrapped in the matrix. The

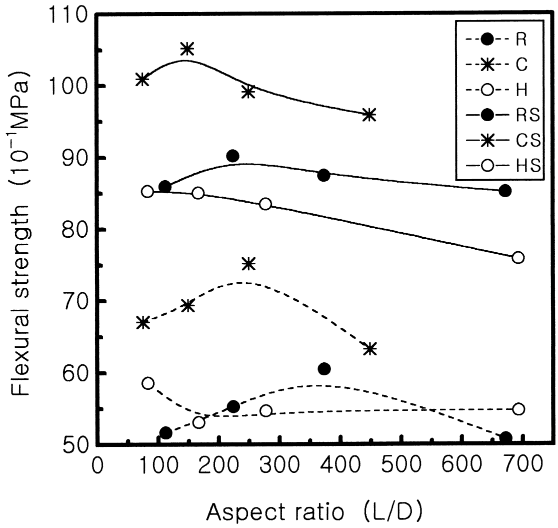

FIG. 2.
Flexural strengths of various shapes of carbon-fiber-reinforced lightweight cementitious composites (CFRLC) as a function of aspect ratio at fiber loading volume of 2%. Solid lines represent CFRLC containing silica fume. Dotted lines represent CFRLC without silica fume. Shapes of carbon fibers: C, C-shape; H, hollow shape; R, round shape; S, silica fume addition.

aspect ratio for the R-CFRLC is less significant for the flexural strength than in C-CFRLC. H-CFRC decreased flexural strength with increasing aspect ratio because it is difficult for the matrix to penetrate the hole of fiber when the fiber is long. Silica fume greatly influences the developing flexural strength, as do fiber loadings in Figure 1.

Figure 3 shows SEM micrographs of fracture surfaces for the various carbon fiber shapes incorporated into CFRLCs containing silica fume. The shape of fiber significantly influences interface area between fiber and matrix. The C- shape carbon fiber mechanically anchors in the matrix and increases interfacial contact area. These characteristics improve mechanical properties of C-CFRLC. The H-shape of carbon fiber shows compaction of the hole of fiber by the matrix. The compaction also acts as a mechanical anchor when the fiber is short

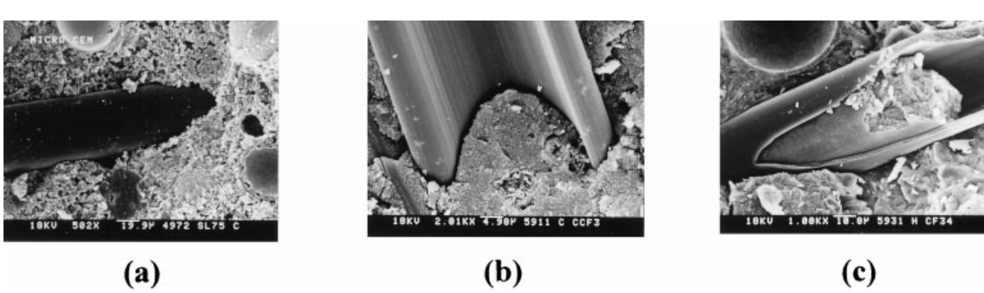

FIG. 3.
SEM micrographs of fracture surfaces for the various shapes of CFRLC s containing silica fume. (*a*) Round-shape carbon fiber, (*b*) C-shape carbon fiber, (*c*) Hollow-shape carbon fiber

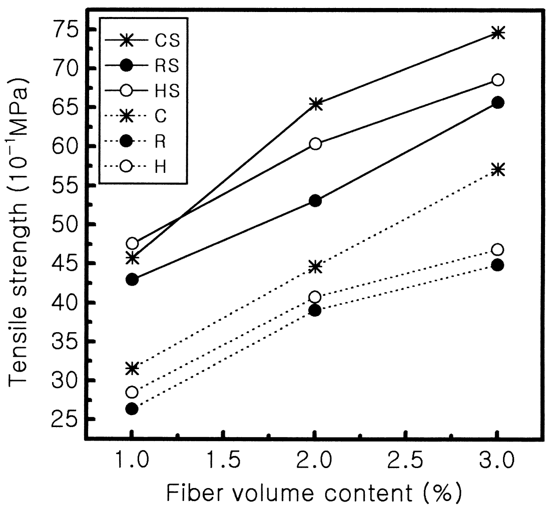

FIG. 4.
Tensile strengths of various shapes of carbon-fiber-reinforced lightweight cementitious composites (CFRLC) as a function of fiber loadings. Solid lines represent CFRLC containing silica fume. Dotted lines represent CFRLC without silica fume. Shapes of carbon fiber: C, C-shape; H, hollow shape; R, round shape; S, silica fume addition.

enough for the matrix to penetrate. When the fiber is too long, it is difficult for the matrix to penetrate the carbon fiber holes by capillary force.

Tensile Strength

As shown in Figure 4 the tensile strength of CFRLC was proportionally increased with increasing fiber loadings. Tensile strength of CFRLC shows a similar trend to that of the flexural strength. Silica fume is a significant factor for increasing tensile strength of CFRLC.

The silica fume added to cement matrix probably penetrates well into a hole or surface groove of fibers and densifies the matrix, resulting in improvement of fiber-matrix interfacial bonding zone (7–9). The C-CFRLC shows the high tensile strength regardless of silica fume and presents the highest tensile strength at fiber loading volume of 3% with silica fume.

The H-shape carbon fiber shows an increased tensile strength at high fiber loadings. The H-shape fiber is more strongly anchored in the matrix when tensile stress is applied than flexural stress. Therefore, tensile strength increases more than flexural strength as the fiber loading increases (10). The R-CFRLC shows the lowest tensile strength.

Figure 5 shows the tensile strengths as a function of aspect ratio for the various CFRLCs at fiber loading volume of 2%. The C-CFRLC containing silica fume shows the highest tensile strength at aspect ratio 250. The C-CFRLC without silica fume also presents very high tensile strength at this aspect ratio. All CFRLC have an optimum aspect ratio. Tensile strength of CFRLC decreases at a high aspect ratio greater than an optimum value because of formation of balls of fibers and increased porosity in the matrix (11). The R-CFRLC presents higher tensile strength than H-CFRLC at high aspect ratio because of difficult penetration of matrix into a hole of fiber when the fiber is too long.

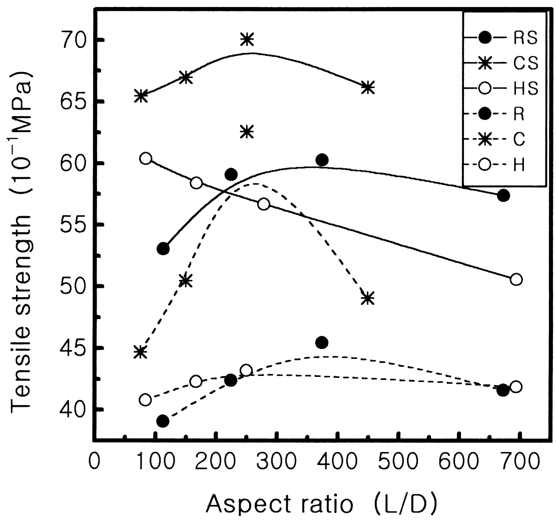

FIG. 5.

Tensile strengths of various shapes of carbon fiber-reinforced lightweight cementitious composites (CFRLC) as a function of aspect ratio at fiber loading volume of 2%. Solid lines represent CFRLC containing silica fume. Dotted lines represent CFRLC without silica fume. Shapes of carbon fibers: C, C-shape; H, hollow shape; R, round shape; S, silica fume addition.

Conclusions

Shapes of carbon fiber influence development of flexural and tensile strength. The C-shape carbon fiber acts as an anchor in the matrix and increases interfacial area between fiber and matrix. The C-CFRLC shows the highest flexural and tensile strength than any other CFRLCs. The C-CFRLC containing silica fume at fiber loading volume of 3% presents about a 40% increase in flexural and tensile strength of the H- and R-CFRLC. Mechanical anchorage of hollow shape carbon fiber is less than with C-shape carbon fiber. The H-CFRLC decreases flexural and tensile strength with increasing fiber length (aspect ratio). Flexural and tensile strength developments show almost the same trend for the CFRLC. Silica fume is a greatly significant factor for developing strength for CFRLC.

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