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MECHANICAL AND FRACTURE PROPERTIES OF CARBON FIBER REINFORCED SELF-COMPACTING CONCRETE COMPOSITES

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Summary: *This study covers the effect of using carbon fiber on the mechanical and fracture properties of self-compacting concrete (SCC) composites. A total of 8 SCC mixtures with and without ultra-fine silica fume were designed with a total binder content of 530 kg/m^3 and water-to-binder ratio of 0.37. Carbon fiber with 7.2 µm diameter and 12 mm length was utilized in SCC mixtures by considering four fractions of 0, 0.5, 1.0, and 1.5% by total volume. Carbon fiber used in this study had a tensile strength of 3800 MPa and modulus of elasticity of 228 GPa. Plain and carbon fiber reinforced SCC specimens were tested for determining the mechanical and fracture properties. The mechanical properties of SCCs were carried out in terms of compressive strength, modulus of elasticity, splitting tensile and net flexural strengths while the fracture characteristics were evaluated in terms of fracture energy and characteristic length. Test results indicated that incorporating carbon fiber into the matrix enhanced strength and especially fracture characteristics of SCCs, depending mainly upon carbon fiber content.*

1 INTRODUCTION

Concrete alone as a composite material is a relatively brittle material. Reinforcement of concrete with randomly distributed short fibers may enhance the toughness of cementitious matrices by preventing or controlling the initiation, propagation or coalescence of cracks [1-3]. The fibers can be made from either natural materials such as asbestos, sisal, and cellulose or manufactured products such as glass, steel, carbon, and polymer [4]. Among them, carbon fibers are very attractive to engineers due to their good thermal conductivity, lightweight, and high modulus of elasticity. Carbon fibers can also be used to eliminate or reduce drying shrinkage cracking problems in concrete. Many studies have been conducted since 1970s to investigate the effectiveness of carbon fibers on the various properties of conventional concrete. However, the studies dealing with the application of carbon fibers in self-compacting concrete (SCC) are very limited in the technical literature [5].

The SCC, which is a special type of the cement-based composites, was obtained at the end of eighties for tailored preparations by Japan [6]. The SCC is highly flowable and coherent which provide spreading and compacting under its own weight without any vibration [7-9]. The small interstices of formwork can be easily filled by using the SCC as well as complex shapes in structural members can be achieved without vibration [10-13]. The SCC can be generally produced by incorporating mineral admixtures and use of chemical admixtures such as viscosity modifying agents and new generation high range water reducers in the manufacturing and also, the amount and size of coarse aggregate in the SCC composites are limited [6]. The SCC composite is produced by using high cement content. For this reason, some problems such as high hydration heat, high autogenous shrinkage, and high cost can be introduced. In addition, serious environmental impacts can be occurred due to the natural resources consumption and carbon dioxide emissions associated with cement production [14]. Utilization of mineral admixtures such as fly ash (FA) and silica fume (SF) can be a remedy to reduce the cost of the SCC composite production and environmental impacts due to high cement content utilization [15,16]. In the literature, there are a number of studies reporting that the use of mineral admixtures improves the self-compactibility properties of the concrete [6,11,17,18]. In addition to the mineral admixtures, fibers could be used in the production of SCC composites. Even though using carbon fiber (CF) in the SCC composite manufacturing decreases its flowing ability due to restriction and preventing coarse aggregates moving uniformly, it is expected to improve hardened properties such as compressive and tensile strengths, toughness, and ductility of the such composites [19,20].

In the current study, the effect of carbon fiber (CF) on the mechanical and fracture properties of SCC composites with and without silica fume (SF) was investigated experimentally. Two different CF reinforced SCC series were produced at CF volume fractions of 0, 0.5, 1, and 1.5% by total volume. The SF was not incorporated in the first SCC series while Portland cement was replaced with 10% SF by weight in the second SCC series. In total, 8 SCC mixtures were produced and Portland cement was replaced with 30% FA by weight in all mixtures to enhance the self-compactibility of the mixtures. The mechanical properties in terms of compressive strength, modulus of elasticity, splitting tensile and net flexural strengths and fracture characteristics in terms of fracture energy and characteristic length of the SCCs were experimentally examined.

2 MATERIALS AND METHODS

2.1 Materials

In this study, Portland cement (PC), FA, and SF used to produce SCC had the specific gravity of 3.15, 2.25, and 2.20, respectively. The physical properties and chemical analysis of these materials are presented in Table 1. In the production of SCC mixtures, river gravel with a maximum size of 16 mm was used as coarse aggregate while the mixture of natural sand and crushed sand with a maximum size of 4 mm was used as fine aggregate. Natural sand, crushed sand, and river gravel had the specific gravity of 2.66, 2.45, and 2.72 and the fineness modulus of 2.79, 2.38, and 5.68, respectively. CF used in this study had the unit weight of 1.81 g/cm^3 and carbon percentage was 95. The length and diameter of fibers were 12 mm and 7.2 μm, respectively. The modulus of elasticity and tensile strength of CF were 228 GPa and

3800 MPa, respectively. A polycarboxylic ether type of superplasticizer (SP) with specific gravity of 1.07 was used to get the desired workability in all mixtures.

Analysis report (%)	Cement	Fly ash	Silica fume
CaO	62.58	4.24	0.45
SiO_2	20.25	56.20	90.36
Al_2O_3	5.31	20.17	0.71
Fe_2O_3	4.04	6.69	1.31
MgO	2.82	1.92	-
SO_3	2.73	0.49	0.41
K_2O	0.92	1.89	0.45
Na_2O	0.22	0.58	1.52
Loss on ignition	3.02	1.78	3.11
Specific gravity	3.15	2.25	2.20
Specific surface area (m^2/kg)	326	379	21080

Table 1: Physical properties and chemical compositions of Portland cement, fly ash and silica fume.

2.2 Mixture design

Two fiber reinforced SCC series were designed with total binder content of 530 kg/m^3 and at water-to-binder ratio of 0.37. PC was substituted with SF by weight at replacement levels of 0 and 10% in first and second SCC series respectively. CF was incorporated to SCC composite by total concrete volume at fractions of 0, 0.5, 1.0, and 1.5% in first and second series. Totally, 8 SCC mixtures were produced according to above variables. The detailed mix proportions for SCCs are presented in Table 2. In mix ID, silica fume is represented by SF while carbon fiber is denoted by CF. For example, SF10CF5 indicates that the SCC is designed with silica fume content of 10% and carbon fiber volume fraction of 0.5%.

Mix ID	w/b*	Binder			Water	Natural sand		Natural gravel	SP*	CF*
		PC*	FA*	SF*		River sand	Crushed sand			
SF0CF0	0.37	371	159	0	196.1	642.7	160.7	803.4	3.30	0
SF0CF5	0.37	371	159	0	196.1	639.1	159.8	798.9	6.89	9.05
SF0CF10	0.37	371	159	0	196.1	636.5	159.1	795.6	9.54	18.10
SF0CF15	0.37	371	159	0	196.1	633.9	158.5	792.3	12.19	27.15
SF10CF0	0.37	318	159	53	196.1	633.7	158.4	792.1	5.17	0
SF10CF5	0.37	318	159	53	196.1	631.6	157.9	789.4	7.33	9.05
SF10CF10	0.37	318	159	53	196.1	629.0	157.2	786.2	9.94	18.10
SF10CF15	0.37	318	159	53	196.1	626.4	156.6	782.9	12.56	27.15

Table 2: Mix proportions for carbon fiber reinforced SCC composites in kg/m^3, (* w/b: water-to-binder ratio, PC: Portland cement, FA: Fly ash, SF: Silica fume, SP: Superplasticizer, and CF: Carbon fiber).

2.3 Casting

To achieve the same homogeneity and uniformity in all mixtures, a special batching and mixing procedure was followed since mixing sequence and duration are very vital in SCC production. Regarding to this procedure, the fine and coarse aggregates were poured in a power-driven revolving pan mixer and allowed to mix homogeneously for one minute. After that about quarter of the mixing water was added into the mixer and it was allowed to proceed the mixing for one more min. The aggregates, then, were left to absorb the water for 1 min. Afterwards, the powder materials (cement and fly ash and/or silica fume) were added to the wetted aggregate mixture for mixing extra 2 min. For the mixtures without fiber, the remainder of the mixing water including SP was added into the mixer. After SP with remaining water was poured into the mixer, the SCC without fiber was mixed for 3 min. and then left to rest for 2 min. Finally, the concrete was mixed for additional 2 min. to complete the production. The same sequence was followed for the composite mixtures with fibers, except that the fibers were added before adding the rest of mixing water with SP. Besides, the composite mixtures containing fiber were mixed for 5 min. and then left to rest for 2 min. The composite mixtures without fiber were mixed for a total time of 9 min. while those including fiber were mixed for a total time of 11 min. excluding the resting time. At the end, fresh mixtures were poured into the moulds. After casting, all moulded specimens (150-mm cubes, Φ100x200-mm cylinders, Φ150x300-mm cylinders, and 100x100x500-mm prisms) were wrapped with plastic sheet and left in the casting room for 24 h at 20±2 °C and then they were demoulded and 90-day water curing period was applied. Afterwards, they were tested based on the testing procedures below.

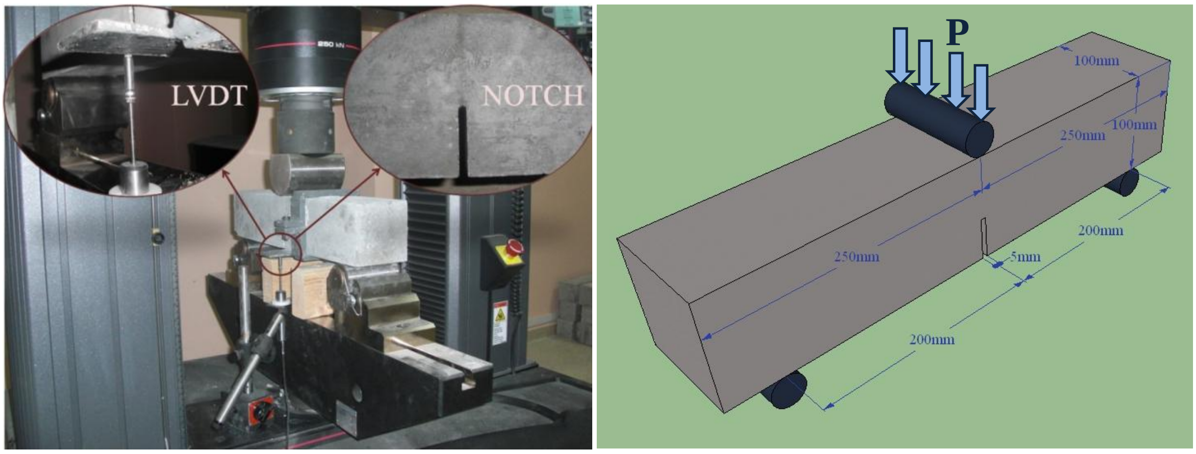
2.4 Test procedure

ASTM C39 [21] was followed to determine the compressive strength of the concretes. For this, 150-mm cube specimens were used. Static modulus of elasticity was determined as per ASTM C469 [22] on 150-mm cylinder specimens after loading and unloading three times up to 40% of the ultimate load determined from the compression test. The first set of readings from each cylinder was discarded and the elastic modulus was reported as the average of the other two sets of readings. Splitting tensile strength was tested using 100-mm cylinder specimens with respect to ASTM C496 [23] and Eq. 1 was used for its calculation:

$$f_s = \frac{2\mathrm{P}}{\pi \mathrm{h} \Phi} \tag{1}$$

where P, h, and Φ are the maximum load, length, and diameter of the cylinder specimen, respectively.

Fracture energy was determined using 100x100x500-mm prismatic specimens according to the recommendation of RILEM 50-FMC Technical Committee [24]. A closed-loop testing machine with a capacity of 250 kN was used to apply the load. The test set-up and details of the specimen are shown in Figure 1.



(a) (b)

Figure 1: Views of a) experimental setup for three point bending test and b) dimensions of the notched beam specimen.

The notch to depth ratio (a/D) of the specimens was 0.4 and the notch was opened by sawing in order to accommodate large aggregates in more abundance reduced the effective cross section to 60x100-mm. Distance between supports was 400 mm and the mid-span deflection (δ) was measured by a linear variable displacement transducer (LVDT). Load versus deflection curve was obtained for each specimen and the area under the curve (W_o) was utilized in the determination of the fracture energy using Eq. 2 given by RILEM 50-FMC Technical Committee [24].

$$G_F = \frac{W_o + mg\frac{S}{U}\delta_s}{B(W-a)} \tag{2}$$

where B, W, a, S, U, m, δ_s, and g are the width of the beam, depth of the beam, depth of the notch, span length of the beam, length of the beam, mass of the beam, specified deflection of the beam, and gravitational acceleration, respectively. The beams were loaded at a constant rate of 0.02 mm/min. Moreover, the notched beams were used to calculate the net flexural strength by Eq. (3) on the assumption that there is no notch sensitivity, where P_{max} is the ultimate load [25].

$$f_{flex} = \frac{3P_{max}S}{2B(W-a)^2} \tag{3}$$

Characteristic length was also calculated by Eq. (4) as an indication of the brittleness of the concretes [26].

$$l_{ch} = \frac{EG_F}{f_{st}^2} \tag{4}$$

3 RESULTS AND DISCUSSION

3.1. Compressive strength and modulus of elasticity

The compressive strength results for the SCC composites with and without SF at various CF volume fractions are presented in Figure 2. The results indicated that the utilization of CF increased the compressive strength of the test specimen till 1.0% volume fraction in both SCC series. Using more than 1.0% volume fraction of CF resulted in decreasing compressive strength. Although using 1.5% volume fraction of CF decreased the compressive strength, reduction was not so much. The compressive strength of SCC including 1.5% CF was higher than that of plain SCC (without CF) in both SCC series.

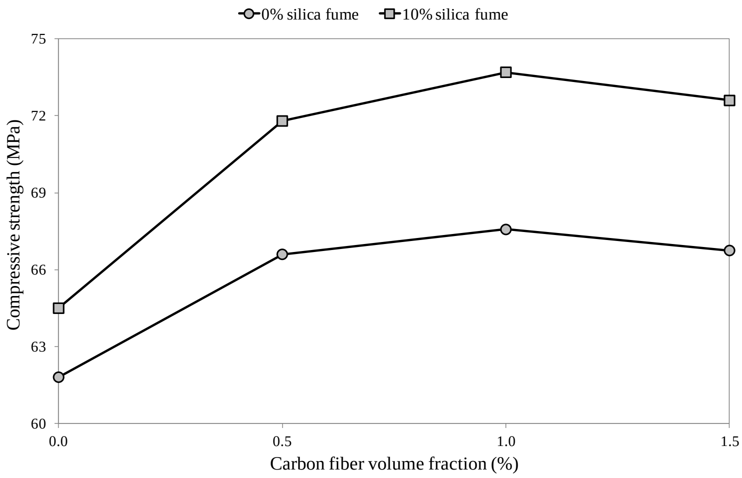


Figure 2: Compressive strength of SCC vs. CF volume fraction.

The compressive strength of SCC without SF raised 61.8 to 67.6 MPa when CF volume fraction was increased from 0 to 1.0% and the composite including 1.5% volume fraction of CF had the compressive strength of 66.8 MPa. Besides, it was clearly pointed out from Figure 2 that incorporation of SF at 10% replacement level increased the compressive strength of SCC at each CF volume fraction. The compressive strengths of SCC containing 10% SF were 64.5, 71.8, 73.7, and 72.6 MPa at 0, 0.5, 1.0, and 1.5 CF volume fractions, respectively. This situation may be explained by the pozzolanic reaction of SF and its void filling ability. In addition to SF, CF that had the length of 12 mm and diameter of 7.2 μm may also has the ability to fill the voids in the cement matrix. For this reason, the compressive strength of concrete increased when CF volume fraction increased.

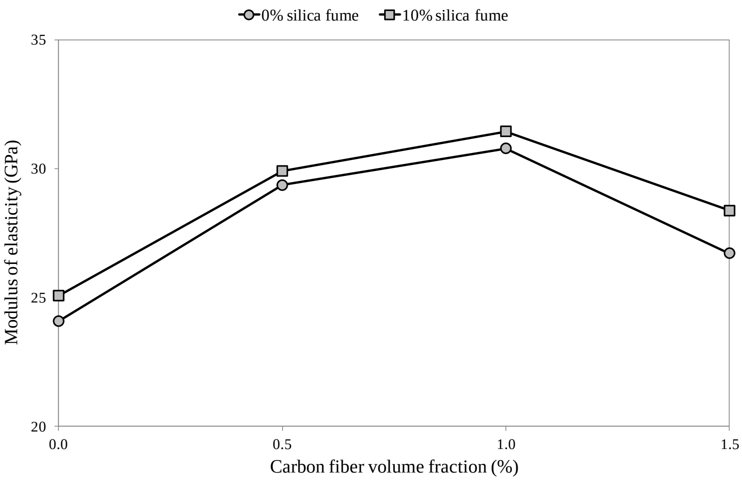


Figure 3: Modulus of elasticity of SCC vs. CF volume fraction.

Figure 3 indicates the variation of the modulus of elasticity of SCC with carbon fiber volume fraction. The static modulus of elasticity of SCC showed same trend with compressive strength. The static modulus of elasticity changing between 24.1 and 31.5 GPa was obtained in this study. The SCC produced with 10% SF had higher modulus of elasticity than those produced with 0% SF. The SCC with higher compressive strength had greater modulus of elasticity. Modulus of elasticity of SCC was increased with increasing CF volume fraction from 0 to 1.0%.

3.2 Splitting tensile strength

The variation in splitting tensile strength of SCC versus CF volume fraction is illustrated in Figure 4. It was clearly observed from the figure that increasing CF volume fraction resulted in systematical increasing of the splitting tensile strength of both SCC series. The splitting tensile strength of SCC with 0 and 10% SF contents were 4.57 and 4.82 MPa at CF volume fraction of 0%, respectively. CF utilization significantly increased the splitting tensile strength of SCC. Increasing CF volume fraction from 0 to 1.5% resulted in 24.4 and 26.2% increment of splitting tensile strength in SCC incorporating 0 and 10% SF, respectively. Even though SF incorporation increased the splitting tensile strength of SCC, the increment ratio due to SF utilization was not high as much as CF addition. Substituting Portland cement with 10% SF increased the splitting tensile strength as much as 5.4 and 6.9% for SCC with 0 and 1.5% CF volume fraction, respectively.

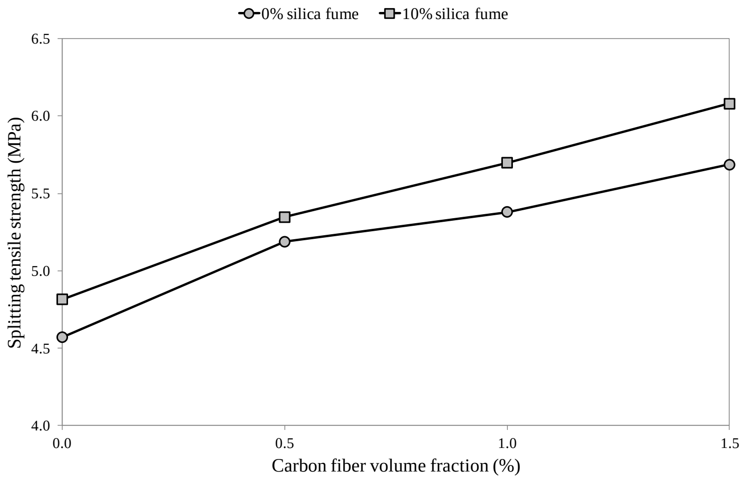


Figure 4: Splitting tensile strength of SCC vs. CF volume fraction.

3.3 Net flexural strength

Net flexural strengths obtained from three-point bending test on the notched specimen versus CF volume fraction are presented in Figure 5. The results indicated that CF had remarkable influence on the tensile strength of SCC. The similar trend in splitting tensile strength was observed for the net flexural strength of SCC. The net flexural strengths of SCC without fiber were 6.17 and 6.19 MPa at 0 and 10% SF contents, respectively. Systematical increasing in the net flexural strength was obtained when the volume fraction of CF increased from 0 to 1.5% and the increment ratio in the net flexural strength was 12.9 and 22.6% for SCC at 0 and 10% SF contents, respectively. The highest net flexural strengths were observed in SCC including SF. Incorporating SF resulted in higher net flexural strength as in the splitting tensile strength.

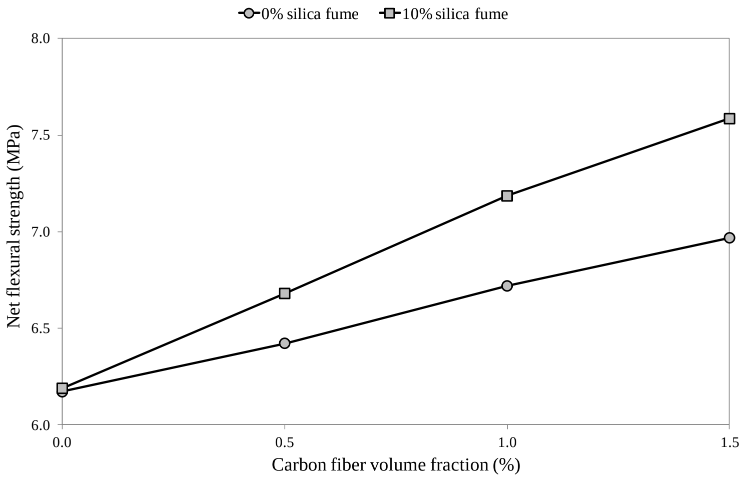


Figure 5: Net flexural strength of SCC vs. CF volume fraction.

3.4 Fracture energy and characteristic length

Figure 6 illustrates the variation in fracture energy of SCC composites with and without SF at various CF volume fractions. CF addition also increased the fracture energy of SCC in both series. The figure clearly showed that CF had remarkable effect on the fracture energy.

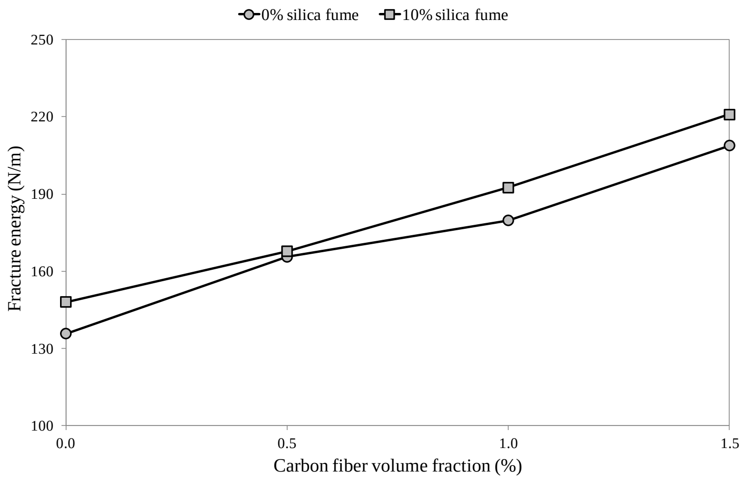
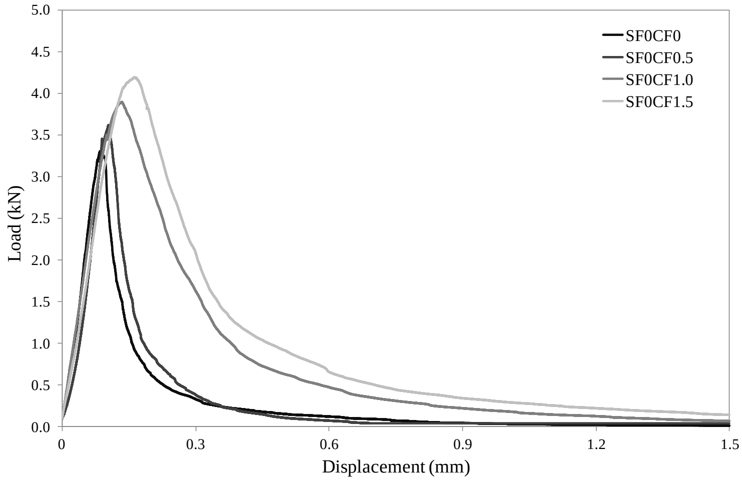


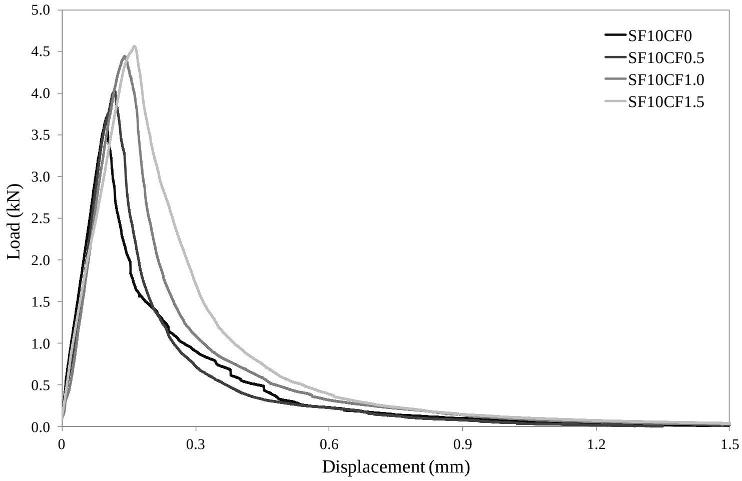
Figure 6: Fracture energy of SCC vs. CF volume fraction.

Increasing CF volume fraction from 0 to 1.5% increased the fracture energy from 135.8 to 208.9 N/m for SCC without SF and from 148.1 to 220.9 N/m for SCC with SF. Despite incorporating of SF increased the fracture energy, the increasing amount was not so much. The increments due to SF incorporation were 9.1 and 5.7% at CF volume fraction of 0 and 1.5%, respectively. However, the increments owing to CF addition at 1.5% fraction were 53.8 and 49.2% for SCC including 0 and 10% SF, respectively.

Typical load versus displacement curves for SCC at 0 and 10% SF contents are given in Figure 7a and 7b, respectively. All SCC composites had the maximum displacement value of 1.5 mm. The figure exhibited that addition of CF to SCC increased both the ultimate load and area under the load-displacement curve. Moreover, it was observed that the displacement at the ultimate load was increased with increasing CF volume fraction. This implied that the utilization of CF in SCC production made the composites more ductile. Besides, it was noticed that incorporating SF increased the ultimate load of SCC under three-point bending test but decreased the displacement at the ultimate load. This might be explained as substituting Portland cement with SF increased load carrying capacity of SCC, however, it made the composite more brittle.



(a)



(b)

Figure 7: Typical load vs. displacement curves for plain and carbon fiber reinforced SCC at (a) 0% SF and (b) 10% SF.

The characteristic length of SCC, which is the indication of brittleness of concrete, versus CF volume fraction is presented in Figure 8. The results indicated that CF addition increased the characteristic length of the SCC till 1.0% volume fraction of CF. This indicated that CF addition made SCC more ductile. Although using CF at 1.5% decreased the characteristic length of SCC, it was still higher than the composite including no fiber. The results also revealed that SF incorporating yielded the lower characteristic length values that meant SCC composites containing SF were more brittle than the composite did not include SF.

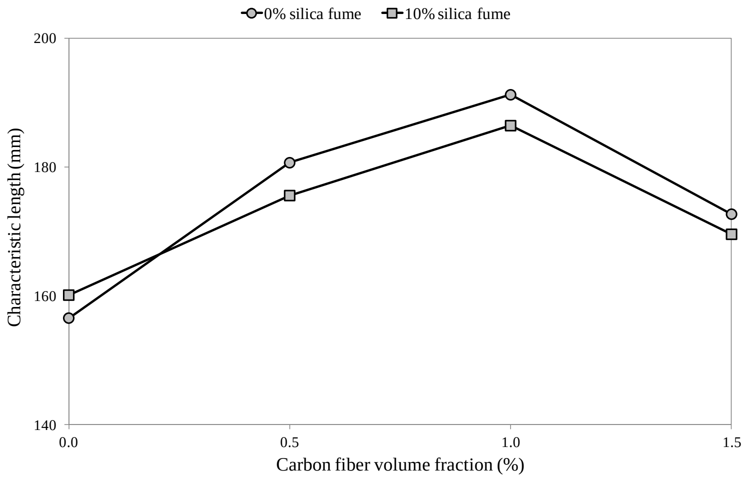


Figure 8: Characteristic length of SCC vs. CF volume fraction.

4 CONCLUSIONS

Based on the experimental results aforementioned, the following conclusions can be drawn:

- The compressive strength of SCC was significantly affected by both SF content and CF volume fraction. SF incorporation increased the compressive strength. Increasing the volume fraction of CF increased the compressive strength of SCC till 1.0% volume fraction and then resulted in small amount decreasing of the compressive strength of the composites.
- The modulus of elasticity of SCC indicated same trend with the compressive strength. Substituting cement with SF resulted in higher modulus of elasticity and increasing CF volume fraction increased the modulus of elasticity up to 1.0% volume fraction.
- There was a systematical increasing in both splitting tensile and net flexural strengths of SCC as CF volume fraction increased. The results of splitting tensile and net flexural strengths indicated that CF had superior influence on the tensile characteristic of SCC composite. Moreover, SF blended SCC series had higher tensile strength than SCC without SF.
- The fracture energy of SCC was systematically increased by increasing CF volume fraction. Moreover, SCC including CF had higher ultimate load under three-point bending test. Additionally, SF incorporation increased both fracture energy and ultimate load of SCC.
- The characteristic length of SCC indicated that the utilization of CF in SCC production enhanced the ductility of the composite. However, replacing cement with SF decreased the characteristic length of SCC.

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