Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006), 5 – 6 September 2006, Kuala Lumpur, Malaysia

FLEXURAL BEHAVIOR OF CARBON FIBER CEMENT COMPOSITES

M.Z. Hossain, T. Sakai
Faculty of Bioresources, Mie University, Tsu, Mie 514-8507, Japan
E-mail: zakaria@bio.mie-u.ac.jp

ABSTRACT: It is evident that the carbon-fiber reinforced cementitious composites are, increasingly, being used day by day in the structural and construction works owing to the synergetic action from two components viz. fiber and mortar matrix. Incorporation of a very nominal percentage of carbon fibers into a mortar mixture produces a strong and durable composite that leads the product of smart material properties. Flexural behavior of cement-based matrices carrying carbon fibers reinforcement of different percentage and size is studied in this paper. Influence of fiber content, fiber length and combination is quantified using load deflection curves. Specimens containing fiber content of 0.0, 0.5, 1.0 and 1.5% with 3, 6 mm and their combination are prepared and tested. It is demonstrated that combination of 3 and 6 mm fibers enhances the bearing capacity to crack- and ultimate-stresses as well as the Young's modulus of the cement composites. The paper emphasizes the desired performances after the initiation of cracks and discusses the pre- and post-crack load-deflection characteristics of these composites.

Keywords: Carbon fiber, Cement composites, Flexural Behavior, Crack-stress, Ultimate-stress

1. INTRODUCTION

It is well known that one of the problems of a cement-based material is the intrinsically brittle type of failure owing to low tensile strength and poor fracture toughness that impose constraints in structural design and long-term durability of structures. In order to satisfy the performance of cement based matrices, incorporation of fibers is getting growing interest to increase the toughness, impact resistance, fatigue endurance, energy absorption capacity as well as tensile properties of the basic matrix. Both the development and propagation of cracks of cement based composite are resisted through stress-transfer bridges and crack tip plasticity mechanisms due to the presence of fibers. As a result of the above advantages, fiber reinforced cement based composites are steadily used in hydraulic structures, tunnel linings, highway and airfield pavements and tensile skin in concrete beams and slabs (ACI Committee 544, 1982, 1988, 1993; Najamj and Dwarakanath, 1984; Rahimi and Kesler, 1979; Dave, O'Leary and Saunders, 1974; Swamy and Ai-Taan, 1981).

Extensive literature review indicates that several types of fibers such as steel, asbestos, glass, metallic glass ribbons, polymeric, carbon, natural fibers and textile reinforcements were being used to reinforce cement matrix and considerable works has been done on the mechanical properties of these types of cement-based materials. Among the different types of fibers used in cement-based composites, carbon fibers offer distinct advantages. The non-corrodible characteristics of carbon fiber, high strength-to-weight ratio, good fatigue strength and low relaxation losses are properties that motivate structural engineers to use carbon fiber cement composites in many structures and structural components that are exposed to increased temperature and mechanical wear. Their potential use in machine foundations, earthquake resistance structures, blasts shelters, electrical and electronics industries, in thin pre-cast products like roofing elements, tiles, curtain walls, cladding panels, I- and L-shaped beams, repairing and retrofitting material are some of the examples.

Currently, very few research works are available on the use of carbon fiber in cement-based matrices even though it presents considerable versatility in the development of smart composite materials because these are inert, medically safe, as strong as steel fibers and chemically stable than glass fibers in an alkaline environment. To the knowledge of the authors, no attempt has so far been made to study the effect of fiber size and hybridization of carbon fiber on flexural properties of cement-composites except for the incomplete research works that can be found by Zheng and Chung (1989); Fan and Zhu (1989); Bayashi (1989); Akihama, Suenga and Nakagawa (1988); Ohama, Amano and Mitsuhiro (1988); Soroushian, Aouadi, Nagi (1991). Dimensional and modular hybrids using steel fiber and polystyrene fiber on crack growth resistance of hybrid fiber reinforced cement composites have been previously studied by Banthia and Nandakumar (2003); but have not been yet fully optimized and needs extensive research works towards assessing the characteristics on an optimal fiber system.

This investigation is, therefore, aimed at generating information on the overall response of flexural behavior of cement composite reinforced with differing fiber length and percentage of carbon fibers. Flexural tests on many cement composite panels of size 200×400mm containing fiber of 0.0, 0.5, 1.0 and 1.5% by weight with fiber lengths of 3 mm, 6 mm and hybridization of 3 and 6 mm were carried out. Effect of fiber content and sizes were demonstrated by the load-deflection curves. Results of crack-stress, ultimate-stress, crack-Young's modulus and ultimate-Young's modulus were also studied and depicted in tabular and graphical form for the sake of convenient design and ease of application of carbon fiber cement composites.

2. EXPERIMENTAL PROGRAM

In order to study the effects of carbon fibers on the behavior of cement composites in terms of load-deflection relationships, bearing capacity and Young's moduli; the tests were carried out on two identical specimens for each group with carbon fibers and without carbon fibers. For the case of cement composite with fiber, it was reinforced by 3 mm, 6 mm and combination of 3 and 6 mm fibers. The variable percentage of fiber content, chosen for this investigation were 0.5%, 1.0% and 1.5% whereas the thickness of the test panels was kept constant as 30 mm for all the specimens to investigate the effectiveness of both length and amount as well as hybridization of fibers in cement composites.

3. MATERIALS AND METHODS

3.1 Carbon Fibers

The carbon fibers used in this research work is commercially available in Japan and obtained from the Japanese company named Donac Co. Ltd. The local mane of the carbon fibers is donacarbo and grade number is S-331. It is made of petroleum or coal pitch. Diameter of the fibers varied from 10 to 18 microns. The lengths of the fibers were sized by cutting or chopping it. Therefore, it is also known as chopped carbon fiber in Japan. Common lengths of chopped carbon fiber available in Japan are 3 to 12 mm and typical tensile strengths are 2500 to 3500 MPa and elastic modulus varies from 200 GPa to 600 GPa. The physical appearance of the carbon fiber used in this investigation is shown in **Fig.1**.

Fig 1. Physical appearance of short carbon fibers

3.2 Mortar-Fiber Mixer

Ordinary Portland cement and river sand with maximum size of 2.38 mm was used. The fineness modulus of the sand was found to be 2.33. The water to cement ratio and cement to sand ratio were kept as 0.5 by weight for all the mixes. In each casting, two elements of plain mortar of size 100×200 mm with thickness 30 mm, and three cylinders of diameter 100 mm and length 120 mm, were also cast and tested to find out the compressive strength, modulus of elasticity and Poisson's ratio of the mortar. The details of the mortar properties are given in **Table 1**. The required amount of sand, cement and carbon fiber were dry mixed manually in a pan. Dry mixing was carried out in such a way that the procedure involves several passes of scoop through the dry mix to ensure an even distribution of cement and fiber in the mixture The calculated amount of water to be necessary to obtain a water-cement ratio of 0.5 was added gently to the dry mix and finally, the components were mixed thoroughly. Nearly 10 to 15 minutes were required to obtain a homogeneous mortar-fiber mixer.

Table 1. Properties of mortar specimens

Specimens	Compressive strength (N/mm^2)	Modulus of Elasticity (kN/mm^2)	Poisson's ratio
Panels	28.26	13.49	0.24
Cylinders	27.43	17.45	0.25

3.3 Casting of Panels

The test panels were cast in wooden moulds with open tops as shown in **Fig.2.** Each of the four side-walls and the base of the mould were detachable to facilitate the demoulding process after its initial setting. The specimens were air-dried for 1 day for initial setting and then immersed in water for curing. The specimens were removed from water after 28 days and were air-dried for 2 days in room temperature of about 15^{o}C and relative humidity of about 40%.

Fig 2. Wooden mould showing casting process of cement composites

3.4 Testing of Panels

Panels were tested under one-way flexure with their two edges simply supported. Loads were applied at two points each at one-third position of the span of length 360 mm (**Fig. 3**). The distance between the two loading points is 120 mm with moment arms of 120 mm at both sides of the loading points. The tests were performed with a loading speed of 1mm per minute and the readings were taken at an interval of 0.1 kN. At various stages of loading, the deflections were measured with the mechanical dial gauges having a least count of 0.01 mm at the mid-section of the element. A proving ring of 50 kN capacities was used for accurate measurement of the applied loads. Before testing, all the elements were painted white for clearly observation of the cracking patterns. In order to observe the crack phenomena, the tests were carried out with the tension side up. In general, most of the elements were produced initial cracks (visible to the naked eye) without any cracking noise. The failure patterns of some tested elements in flexure are shown in **Fig.4-6**.

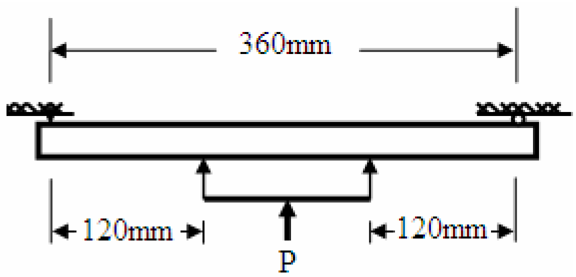

Fig 3. Specification for the test

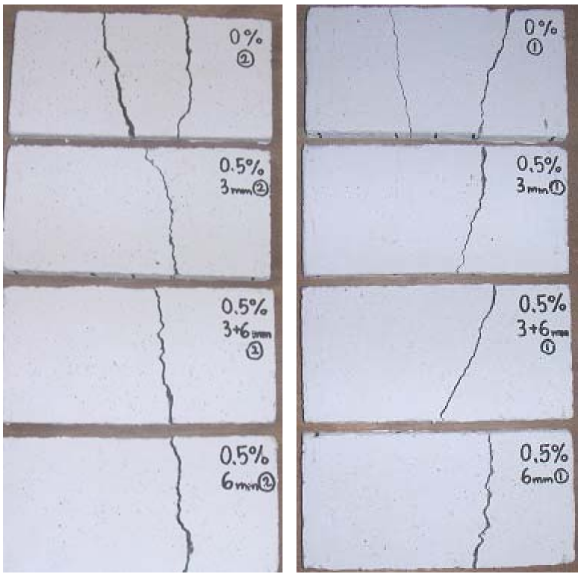

Fig .4 Failure patterns of cement composites containing 0.0% and 0.5% fiber

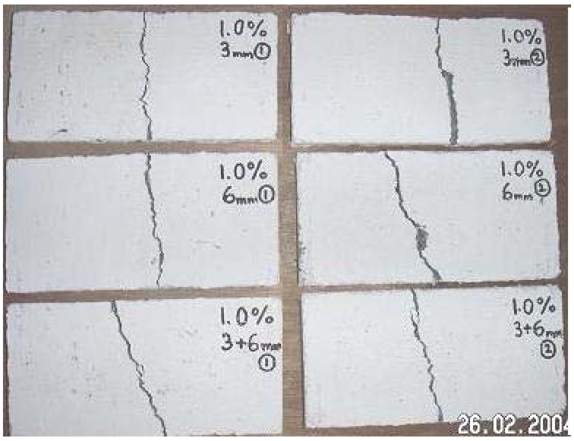

Fig .5 Failure patterns of cement composites containing 1.0% fiber

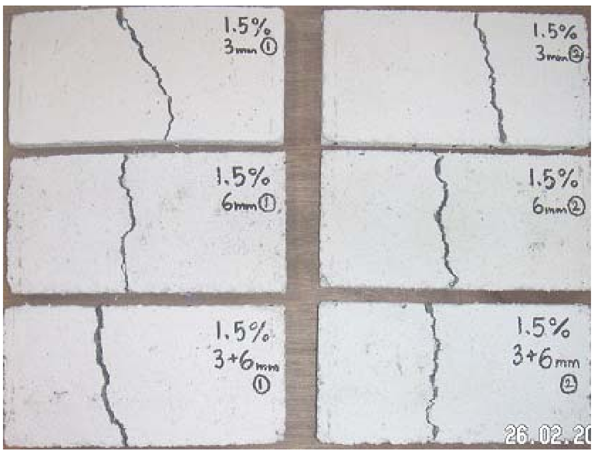

Fig 6. Failure pattern of cement composites containing 1.5% fibers

3.5 Crack-Stress of Cement Composites

Considering the homogeneous nature of the ferrocement composite, the crack-stress in flexure can be obtained in the elastic range as

$$\sigma_{cr} = \frac{LtP_{cr}}{12I} \qquad (2)$$

where L is the span length between the supports, t is the thickness of the specimens, I is the moment of inertia and P_{cr} is the crack-load assumed very nearly equal to the maximum load.

4. RESULTS AND DISCUSSION

The control cement mortar panels were tested and the load-deflection curves are given in **Fig.7** for two samples with same mortar composition, from where it is clear that the cement mortar exhibits its pure brittle nature without showing any softening or ductility. Both sample fail more or less at the same ultimate load of 6.7 kN in flexure due to the same homogeneous composition of cement and sand. The load-deflection curves of the cement based composite panels subjected to two-point loadings with same matrix/mortar with different fiber contents and fiber length as well as fiber combination are given in the **Figs. 8-16** and for their clear comparison another **Fig.17** is depicted consequently. In the experimental program, a set of two samples per fiber composition was used to examine the variation in the load-deflection curve for the presence of fiber in the matrix and average values were used to find out the value of the bearing capacity and Young's modulus. For fiber contents: 0.5,1.0, and 1.5% with fiber length 3mm, there is slight increase in the load carrying capacity as can be seen in **Figs.8-10** and also the central deflection corresponding to ultimate load varies vaguely depending on the specimen. The ultimate load for the cement composite containing 3mm carbon fiber can be taken as 7.0, 7.5 and 7.9 kN, respectively for fiber contents 0.5, 1.0, and 1.5% corresponding to central deflection ranging from 0.5 to 0.7mm. It is observed that the softening or ductility nature of the composite is increased with the increase of fiber contents due to the bridging effect of the fibers, stress transfer and crack tip plasticity mechanism.

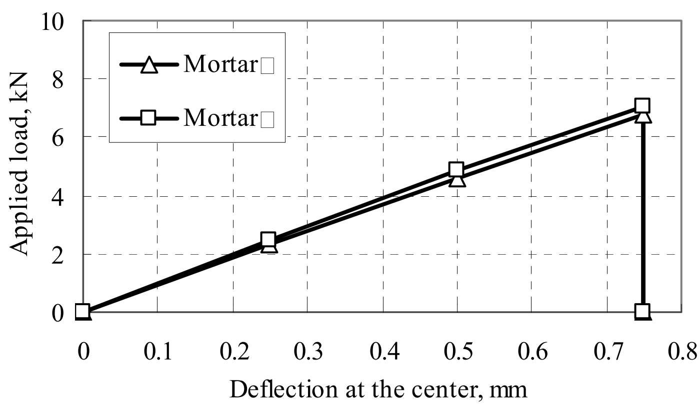

Fig 7. Load-deflection relationships of cement composites (Control specimens, fiber content 0.0%)

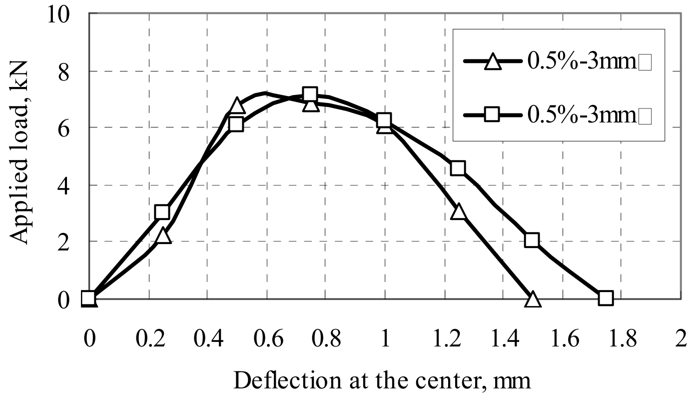

Fig 8. Load-deflection relationships of cement composites (Fiber content 0.5%, fiber length 3 mm)

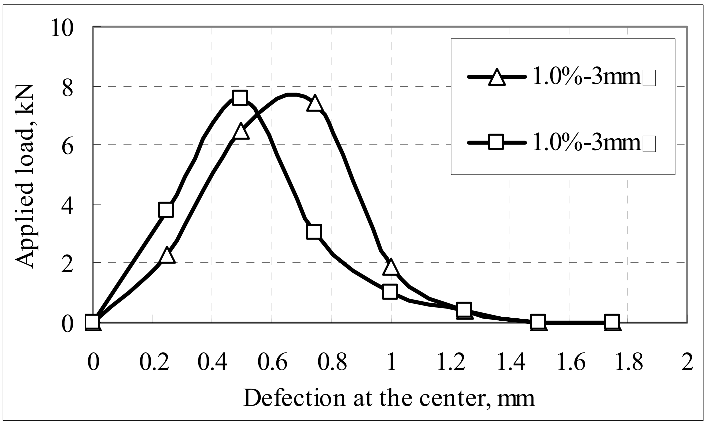

Fig 9. Load-deflection relationships of cement composites (Fiber content 1.0%, fiber length 3mm)

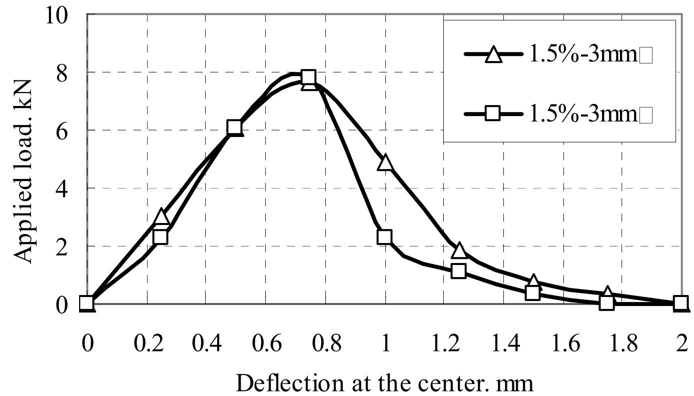

Fig 10. Load-deflection relationships of cement composites (Fiber content 1.5%, fiber length 3 mm)

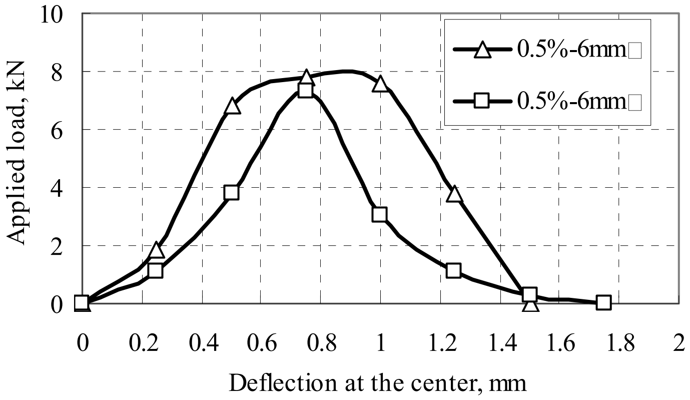

Fig 11. Load-deflection relationships of cement composites
(Fiber content 0.5%, fiber length 6 mm)

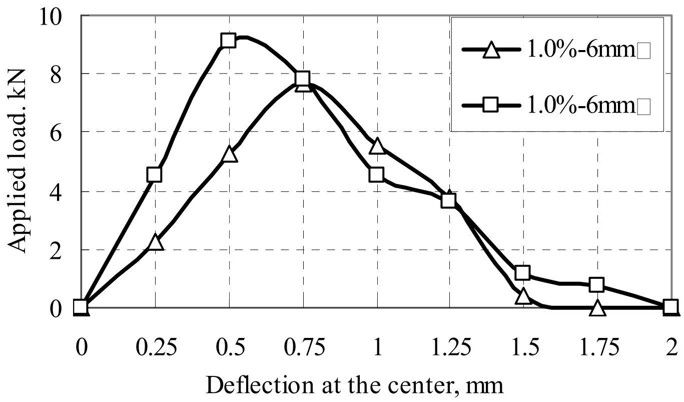

Fig 12. Load-deflection relationships of cement composites
(Fiber content 1.0%, fiber length 6 mm)

Similar to the load-deflection curves of cement composites containing 3mm carbon fiber, cement composites reinforced by 6mm carbon fiber also showed its crack resistance properties at the ultimate load and at the post crack stages (**Figs.11-13**). Both the bearing capacity and ductility increased with the increase in fiber length and amount of fibers. An amazing improvement of the bearing capacity can be observed from **Figs 14-16** where the fibers are hybridized in size/length. Dimensional hybridization of fibers by mixing of 3 and 6 mm lengths fibers enhances a significant bearing capacity due to the combined effect of lengths and synergetic action of varying dimension. Even for 0.5% fiber content the ultimate loading capacity is increased to about 8.5 kN which is equivalent or more than that of previous 1.5% fiber content with fiber length 3 mm or 6 mm. This is obvious because the small fibers reinforce the mortar phase at the micro-crack stages and enhance the response during crack-initiation whereas the large fibers provide the toughness at the stages of larger crack opening. This idea can also be reinforced from the synergetic action of different sizes of aggregate in concrete where particle of different sizes are combined to achieve a dense packing and dimensional stability. Therefore, by using the hybridization system of fibers, one can save fiber by on an average 50% for the same desired ultimate load. Also, the dimensionally-hybrid fiber composite can sustain more deflection at the post-crack stages i.e. it is more ductile in nature. This phenomenon is further clarified through a clear comparison of the load deflection curves depicted in **Fig.17** in which the curves are plotted from the average values of two specimens.

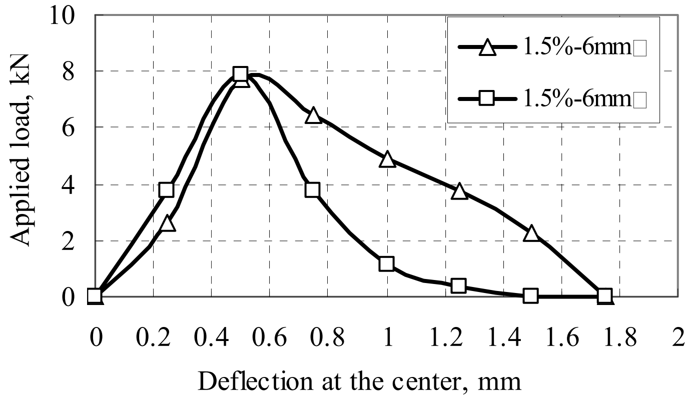

Fig 13. Load-deflection relationships of cement composites (Fiber content 1.5%, fiber length 6 mm)

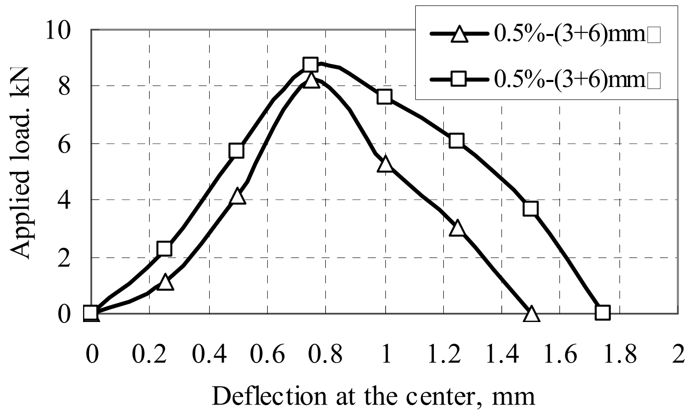

Fig 14. Load-deflection relationships of cement composites (Fiber content 0.5%, fiber length 3 and 6 mm)

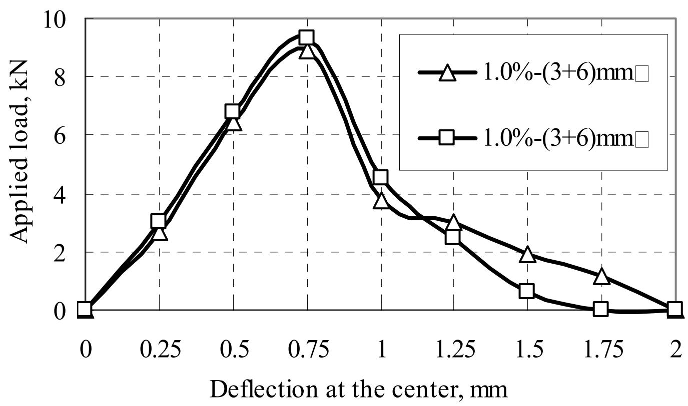

Fig 15. Load-deflection relationships of cement composites (Fiber content 1.0%, fiber length 3 and 6 mm)

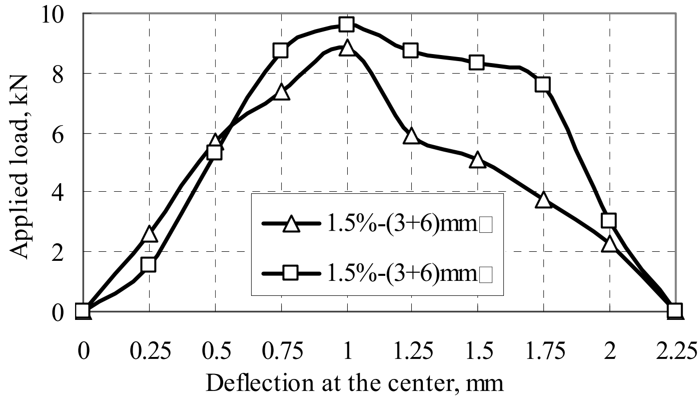

Fig 16. Load-deflection relationships of cement composites (Fiber content 1.5%, fiber length 3 and 6 mm)

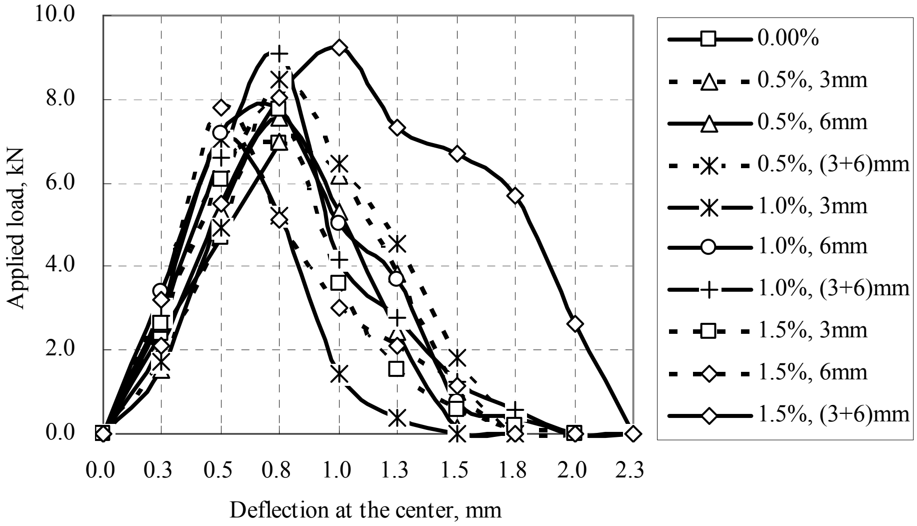

Fig 17. Comparison of load-deflection relationships of cement composites

Figs.7-17 were reanalyzed and quantified for the sake of clear perception of the bearing capacity and basic flexural properties of cement composites containing carbon fibers; and the crack-stress, ultimate-stress, crack-Young's modulus and ultimate-Young's modulus are summarized in tabular form (**Table 2)**. Noticing in **Table 2**, it is clear that the mortar and the carbon fibers have significant effect on the bearing capacity and Young's modulus of the cement composite in flexure. Specifically, just upon cracking initiation, the bearing capacities and Young's moduli change with the change of fiber length and amount of fibers as well as within the cement composite containing same amount and dimension of fibers.

Table 2 Comparison of stresses and Young's modulus of cement composites

Specimen	Crack-stress, σ˺ꟳ	Ultimate-stress, σ_{ult}	E_{cr}	E_{ult}	Average σ_{cr}	Average σ_{ult}	Average E_{cr}	Average E_{ult}
Control‡ a	10.2	25.6	14.1	15.9	10.4	26.1	14.4	16.2
Control‡ A	10.6	26.6	14.6	16.5				
0.5% 3mm□▦ a	10.3	25.7	14.2	16.0	10.87	27.29	14.48	16.32
0.5% 3mm□▦ A	11.5	28.9	14.8	16.7				
0.5% 6mm□▦ a	11.7	29.3	16.2	18.2	11.32	28.42	15.65	17.64
0.5% 6mm□▦ A	11.0	27.5	15.1	17.1				
0.5% 3mm+6mm□▦ a	12.3	31.0	17.1	19.2	12.70	31.86	17.55	19.78
0.5% 3mm+6mm□▦ A	13.0	32.7	18.0	20.3				
1.0% 3mm□▦ a	11.1	27.9	15.4	17.3	11.22	28.17	15.51	17.49
1.0% 3mm□▦ A	11.3	28.5	15.7	17.7				
1.0% 6mm□▦ a	11.5	28.9	15.9	17.9	12.55	31.51	16.36	19.56
1.0% 6mm□▦ A	13.6	34.2	16.8	21.2				
1.0% 3mm+6mm□▦ a	13.4	33.6	18.5	20.8	13.65	34.25	18.86	21.26
1.0% 3mm+6mm□▦ A	13.9	34.9	19.2	21.7				
1.5% 3mm□▦ a	12.5	28.9	15.9	17.9	12.58	29.07	16.01	18.05
1.5% 3mm□▦ A	12.7	29.3	16.1	18.2				
1.5% 6mm□▦ a	11.5	33.0	16.0	21.0	11.69	32.84	17.16	20.72
1.5% 6mm□▦ A	11.8	32.7	18.4	20.5				
1.5% 3mm+6mm□▦ a	13.3	33.3	18.3	20.7	13.81	34.65	19.09	21.51
1.5% 3mm+6mm□▦ A	14.4	36.0	19.8	22.4				

In view of the convenient design of structures, the average values of the bearing capacity and Young's modulus given in **Table 2** are further analyzed and plotted in **Figs.18-21**. It is noted that both crack- and ultimate-stresses are increased with the increase in the amount of fiber. The rate of increase of the crack- and ultimate stresses is more for cement composites containing 6 mm fiber than that for 3 mm fibers especially up to 1.0% fiber content. This is expected because the longer the length of the fibers, the more is the embedded length inside the mortar resulting more stress-transfer ability of the composites. It is also noticed that the hybrid fiber cement composites warrantee the maximum enhancement in both the loading stages. This is apparent owing to the synergy between the two fibers in the hybrids. The bearing capacity at crack-stress and ultimate-stress increases nonlinearly with the increase in fiber content for 6 mm and hybrid fiber cement composites whereas it is almost linear for 3 mm fiber cement composites.

Effect of carbon fiber on the trends of improvement in properties that was observed in the case of crack- and ultimate stress noticed some common features in the case of Young's moduli with the increase in fiber content and variation of fiber types. On one hand, the curves in **Fig.20-21** clearly indicates that incorporation of hybrid fibers in the matrix can derive significant advantages and effectiveness towards improvement of both crack- and ultimate Young's modulus of the cement composite in flexure. On the other hand, a closer inspection of the plotted results revealed that the increment trend of the Young's moduli containing 3mm fiber are somewhat different from the bearing capacities that were observed in **Figs. 18-19** while remaining the same pattern in the case of hybrid fiber cement composites and thereby, further optimization attempts using hybrid carbon fiber are obviously warranted.

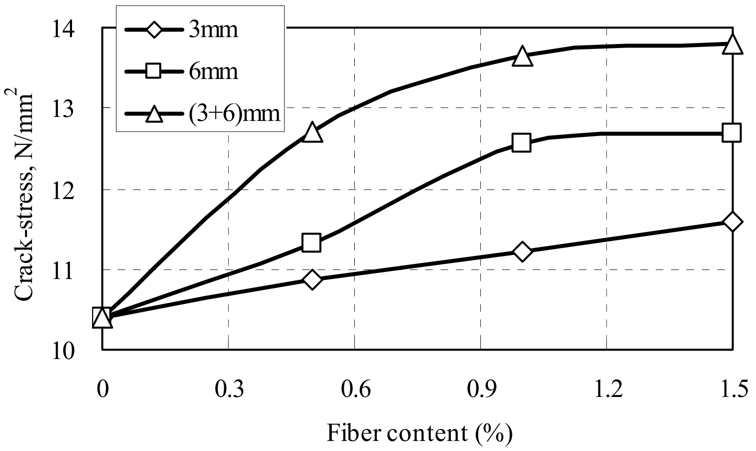

Fig 18. Variation of crack-stress with the variation of fiber content

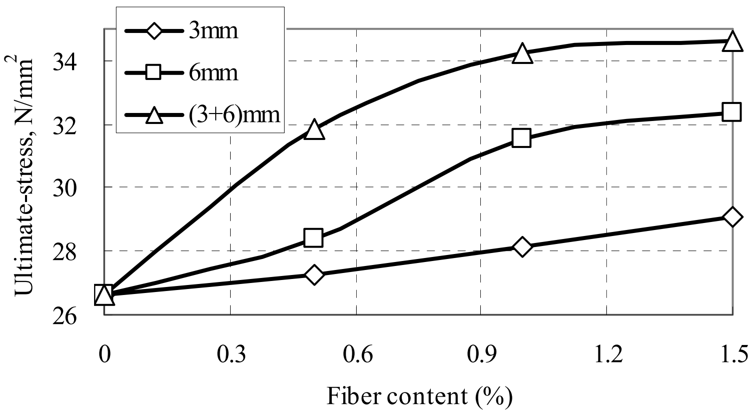

Fig 19. Variation of ultimate-stress with the variation of fiber content

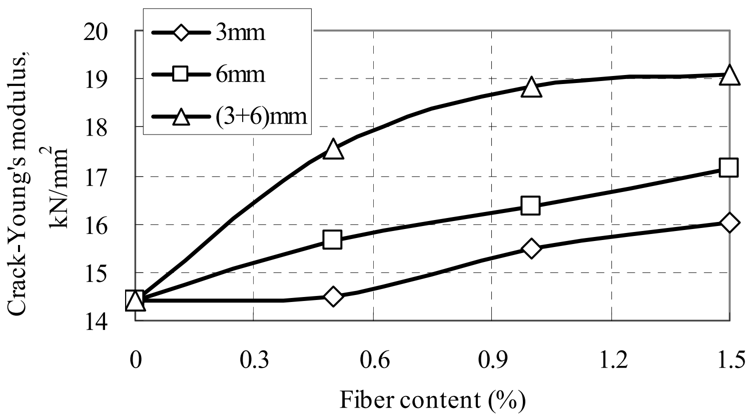

Fig 20. Variation of crack-Young's modulus with the variation of fiber content

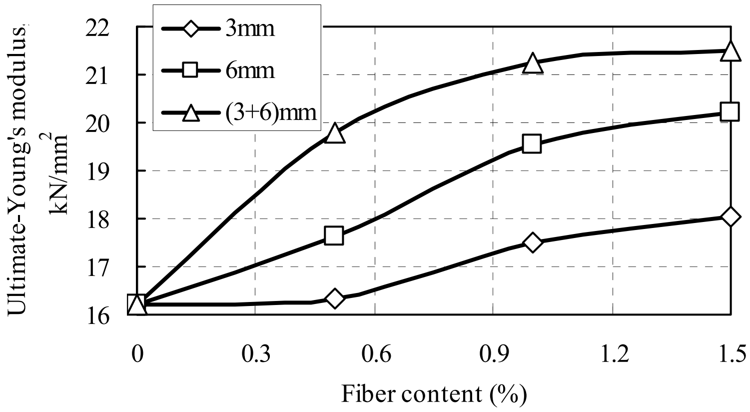

*Fig 21. Variation of ultimate Young's modulus with the varia*tion of fiber content

5. CONCLUSIONS

A very nominal dosage of carbon fiber such as 0.5%, 1.0% and 1.5% in cement composites appeared to be highly effective for improving the flexural behavior of thin cement composites. Test results revealed that the addition of small amount of carbon fiber not only increased the bearing capacity of cement composites significantly but also improved the ductility and Young's moduli of mortar matrix. In the present study, it is also revealed that the maximum load occurred at the deflection of nearly 0.5-0.7 mm for most of the cases. It is also observed that the post-crack load deflection performances of cement composites are enhanced by mixing the varying lengths of fiber. Simple flexural tests can also be effectively used in characterization of load-deflection behavior of the fiber reinforced cement composites. Among the three categories of fibers (3mm, 6mm and hybrid) tested in this study, the dimensional hybrids of carbon fibers appeared to be more effective than the individual ones.

6. REFERENCES

ACI Committee 544, State of the art report on fiber reinforced concrete, ACI 544, 1R-82, Concrete International, 1982:5:9-30.

ACI committee 544, Guide for specifying, mixing, placing and finishing steel-fiber reinforced concrete, ACI Material Journal, 1993; 90(1):94-101.

ACI Committee 544, Measurement of the properties of fiber reinforced concrete, ACI Material Journal, 1988; 85(6):583-589.

Najamj, T. and Dwarakanath, H., Structural response of partially fibrous concrete beams, ASCE Journal of Structural Engineering, V.111, No.11, Nov. 1984, 2798-2812.

Rahimi, M., and Kesler, C, Partially steel-fiber reinforced mortar, ASCE Journal of Structural Engineering, ASCE Journal of Structural Engineering.105, No.1, Jan, 1979, 101-109.

Dave, N.; O'Leary, D:; and Saunders,J., Structural use of fibrous cement in composite concrete construction, ACI special publication, 44, Fiber reinforced concrete, 1974, 511-532.,

Swamy, R, and Ai-Taan, S., Deformation and ultimate strength in flexure of reinforced concrete beams made with steel fiber concrete, ACI journal, 78, (5), sept,-oct., 1981, 395-405.

Zheng, Q. and Chung, D.D.L., Carbon fiber reinforced cement composites improved by using chemical agents, cement and concrete research, Jan, 1989, vol.19, no.1, 25-41.

Fan, C. and Zhu, L."Study of mix proportion of the no slump concrete [with] melt-extracted carbon steel fiber, Transportation Research Record, 1989, No. 1226, pp 98-104,

Banthia, N. and Nandakumar, N, 2003, Crack growth resistance of hybrid fiber reinforced cement composites, cement and concrete composites, 25, 3-9.

Bayasi, Z, Properties and applications of carbon fiber reinforced cement composites, Proc., Symp. On advancements in concrete materials, Bradley University, Mar, 1989,4.1-4.35.

Akihama, S; Suenga, T. and Nakagawa,H. Carbon fiber reinforced concrete, concrete international,v10,n1, Jan, 1988, 40-47.

Ohama, Y., Amano, M. and Mitsuhiro, E. Properties of carbon fiber reinforced cement with silica fume, concrete international, v7, n3, March, 1985, 59-62.

Soroushian, P., Aouadi, F. and Nagi, N. Latex-Modified carbon fiber mortar, ACI materials Journal, v88,n1, jan-Feb, 1991, 11-18.