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Flexural response of hybrid carbon fiber thin cement composites

Md. Zakaria Hossain *, A.S.M. Abdul Awal

Graduate School of Bioresources, Mie University, 1577 Kurimamachiya, Tsu, Mie 514-8507, Japan
Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor, Malaysia

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ABSTRACT

It is evident that the carbon-fiber-reinforced cementitious composites are being used 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 and length of the fiber is quantified using load–deflection curves. Specimens containing fiber of 0.0, 0.5, 1.0 and 1.5% with 3 mm (0.12 in.), 6 mm (0.36 in.), and their combination are prepared and tested. It is demonstrated that combination of 3 mm (0.12 in.) and 6 mm (0.36 in.) fibers enhances the bearing capacity to crack- and ultimate-stresses as well as the Young's modulus of the fiber reinforced cement composites. The paper emphasizes the desired performances after the initiation of cracks and discusses the pre- and post-cracking load–deflection characteristics of the composites.

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 [1–7].

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 have 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. No attempt has so far been made to study the effect of fiber hybridization in size and quantities of carbon fiber on flexural properties of cement-composites except for the incomplete research works that can be found in the technical literatures [8–13]. Although dimensional and modular hybrids using steel fiber and polystyrene fiber on crack growth resistance of hybrid fiber reinforced cement composites have been studied earlier, it is necessary to assess and optimize the characteristics of the optimal fiber system [14].

This investigation is, therefore, aimed at generating information on the overall response of flexural behavior of cement composite reinforced with different fiber length and percentage of carbon fibers. Flexural tests on cement composite panels of size 200×400 mm (7.87×15.75 in.) containing fiber of 0.0, 0.5, 1.0

* Corresponding author at: Graduate School of Bioresources, Mie University, 1577 Kurimamachiya, Tsu, Mie 514-8507, Japan. Tel./fax: +81 592319578.
E-mail address: zakaria@bio.mie-u.ac.jp (M.Z. Hossain).

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and 1.5% by weight with fiber lengths of 3 mm (0.12 in.), 6 mm (0.36 in.) 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 studied and depicted in tabular and graphical form for the sake of convenient design of carbon fiber cement composites in structural applications.

2. Research significance

Dimensional hybrid and amount of carbon fibers in cementitious composites can be effective in arresting cracks at both macro and micro levels. The problem of failure mechanism and bearing capacity of fiber reinforced concrete (FRC) under various loading conditions has been studied quite extensively in the past. In spite of the volume of information available, relatively very little or no research work is reported in the technical literature on the flexural response of thin cementitious composites containing carbon fibers of dimensional hybridization with varying quantities although it presents considerable versatility towards the development of cementitious composites for structural applications. Most of the FRC used today involves the use of a single fiber type. This implies that a given fiber can provide reinforcement only at one level and within a limited range of strain or crack opening. For an optimal response, therefore, different sizes and amount of fibers may be combined to produce hybrid fiber-reinforced cementitious composites. The purpose of this research is to investigate the flexural behavior of hybrid fiber-reinforced cementitious composites and to identify synergistic effects between dimensions and quantities, if present.

3. 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, 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 (0.12 in.), 6 mm (0.36 in.) and combination of 3 mm (0.12 in.), 6 mm (0.36 in.) fibers in 50:50 ratios. 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 to 30 mm (1.2 in.) for all the specimens to investigate the effectiveness of both length and amount as well as hybridization of fibers in cement composites.

4. Materials and methods

4.1. Carbon fibers

The carbon fibers used in this research work is commercially available in Japan and was obtained from the Japanese company. Locally, this carbon fiber is popularly known as 'donacarbo' with grade number S-331. It is made of petroleum or coal pitch diameter of which varies from 10 μm (0.00039 in.) to 18 μm (0.00071 in.). The fibers are generally sized by either cutting or by chopping, and therefore it is also known as chopped carbon fiber in Japan. Common lengths of chopped carbon fiber are 3 mm (0.12 in.), 6 mm (0.36 in.). The properties of carbon fibers are given in Table 1. The physical appearance of the carbon fiber used in this investigation is shown in Fig. 1.

Table 1
Properties of carbon fibers.

Tensile strength	2500–3500 MPa	161.61–225.31 tsi
Elastic modulus	200–600 GPa	12931.41–38974.24 tsi

Fig. 1. Physical appearance of short carbon fibers.

4.2. Mortar–fiber mixture

In this study, ordinary Portland cement and river sand with fineness modulus of 2.33 were used. The water to cement ratio and cement to sand ratio were kept as 0.5 by weight in all the mixes. In each casting, two elements of plain mortar of size 100 × 200 mm (3.94 × 7.87 in.) with thickness 30 mm (1.18 in.), and three cylinders of diameter 100 mm (3.94 in.) and length 120 mm (4.72 in.), were 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 2. The required amount of sand, cement and carbon fiber were dry mixed manually in a pan 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 10–15 min were required to obtain a homogeneous mortar–fiber mixer. For the workability of carbon fiber mortar mix, slump tests were performed (Fig. 2). For all the mixes, the value of slump was found as 70–95 mm without any admixture. Mix proportions of mortar–fiber mixtures are given in Table 3.

4.3. Casting of panels

The test panels were cast in wooden moulds with open tops as shown in Fig. 3. 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. After 28 days of curing the specimens were air-dried for 2 days in room temperature at about 15 °C (59 F) with relative humidity of about 40%.

4.4. 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 (14.17 in.) (Fig. 4). The distance between the two loading points is 120 mm (4.72 in.) with moment arms of 120 mm (4.72 in.) at both sides of the loading points. The tests were performed with a loading speed of 1.0 mm per minute and the readings were taken at an interval of 0.1 kN (22.44 lbs). At various stages of loading, the deflections were measured with the mechanical dial gauges having a least count of 0.01 mm (0.00039 in.) at the mid-section of the element. A proving ring of 50 kN (11224.49 lbs) capacities was used for accurate measurement of the applied loads. Before testing, all the elements were painted white for clear observation of the cracking patterns. In order to observe the crack propagation phenomena, the tests were carried out with the tension side up. In general, most of the elements produced initial cracks (visible to the naked eye) without any cracking noise. The failure patterns of some tested elements in flexure are shown in Figs. 5–7.

4.5. Crack-stress of cement composites

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

$$\sigma_{cr} = \frac{LtP_{cr}}{12I} \quad (1)$$