

Tensile Behavior of Cement-Based Composites with Random Discontinuous Steel Fibers

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In this paper, the tensile properties of cement-based composites containing random discontinuous steel fibers are reported. Direct tensile tests were performed to study the effects of fiber length (hence fiber aspect ratio), interfacial bonding, and processing conditions on composite properties. Composite tensile strength and ductility are highlighted and discussed.

I. Introduction

FIBER reinforcement has been employed in various concrete structures in the past few decades. In thin sheet products, fiber reinforcement is often employed to improve flexural performance.¹ For bulk structures, fibers have been largely used for the suppression of plastic shrinkage cracking.^{2,3} Fibers have also been used to increase impact resistance in concrete structures.^{4,5} Improvements in tensile properties are often related to enhancement of fracture toughness associated with tension softening and fiber pull-out across an opening crack. Composite tensile or compressive strength, and tensile ductility, typically remain unchanged.²

In 1971, Aveston *et al.*⁶ demonstrated that composite tensile strength and ductility can be significantly enhanced by the use of aligned continuous fibers. Since then, many experimental results have shown this pseudo-strain-hardening behavior in composites using both continuous and discontinuous fibers. For discontinuous fiber composites, the fiber volume fraction used typically is high (e.g., SIFCON⁷). Recent theoretical modeling of pseudo-strain-hardening in discontinuous random fiber reinforced composites^{8,9} provides guidelines for selection of individual materials constituents (fiber, matrix, and interface) and fiber geometry (fiber diameter and aspect ratio) to achieve desirable composite performance.

In this paper, direct tensile test results of cement-based matrix composites reinforced with short random steel fibers are reported. Special attention is given to composite tensile strength and ductility. Ductility in this paper refers to the strain value at ultimate tensile stress, and as such, is a material property independent of measurement gage length. The composite constituent parameters under study include fiber volume fraction, fiber length, and interface bond strength. These preliminary results suggest that it is possible to achieve strain-hardening in steel-fiber-reinforced concrete with moderately small fiber volume fraction. However, these test results also indicate to us

that direct tension test results must be carefully interpreted, and improved testing procedures are suggested.

II. Experimental Program

A series of tests were carried out to study the effects of microparameters on composite tensile behavior as discussed above. Fiber length is controlled by the use of a laboratory fiber cutting machine and adjusting the cutter speed on a continuously fed wire. Interfacial bond properties are controlled by the addition of a coupling agent to the mix and by the use of variable vibration frequency during casting. More details of the coupling agent and vibration frequency will be given later. Direct tensile tests were performed using coupon tensile specimens. The plain matrix materials were also tested for pertinent information. At least three tensile plate specimens were tested in each case.

(1) Materials

The mix proportion of the matrix and the composite are shown in Table I. All of the mix proportions are by weight of the ingredients. Discontinuous steel fibers (trade name Dramix) with various fiber lengths and volume fractions are employed in this study. This steel fiber is brass-coated with a diameter of 150 μm ; fiber properties are tabulated in Table II.

(2) Specimen Preparation

The tensile specimen is in the form of a rectangular coupon of size 304.8 mm \times 76.2 mm \times 12.7 mm. The molds used to cast the specimens are made of plexiglass. The mixing procedure of the composite materials consists of the following steps:

(A) *Premixing Stage:* In this stage the matrix is carefully prepared in the regular Hobart type of mixer. The silica fume (in solution form) is first mixed either by hand or by a small mixer to make a uniform mixture and poured into the mixing bowl. The cement is added next. The water and the superplasticizer are mixed together along with a coupling agent if necessary. The dosage of the coupling agent used in this study is 0.25% by weight of the cement. This mixture is then slowly added while the cement and silica fume are mixed at a slow speed. This procedure takes 3–5 min and results in a uniform fluid matrix. The bottom of the mixing bowl may be scraped manually to ensure that no material sticks to the bottom. After such scraping the matrix may be mixed at a higher speed for 1 min before addition of fibers.

(B) *Addition of Fibers:* The fibers are added manually as the matrix is mixed at a slow speed. To ensure proper distribution, the fibers must be added slowly over a period of about 10 min for high fiber loading such as 7% by volume of the 6-mm-long fibers. For the fiber length used in this study, visual inspection of the mix at the end of fiber addition reveals good fiber dispersion.

(C) *Casting Composite Materials:* The composite material is carefully placed in the mold and compacted. The casting

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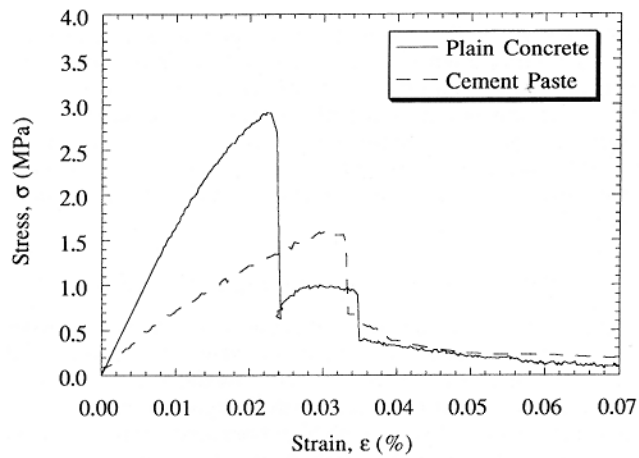


Fig. 2. Tensile behavior of plain matrix.

the plain matrix are 38%, 160%, and 400%, respectively, for $V_f = 3.6\%$, 7%, and 10%. Moreover, the ultimate strain capacities are enhanced 67%, 100%, and 833%, respectively, by adding fiber reinforcements.

(3) Effect of Aspect Ratio

Figure 4 shows the stress–strain curves for four composites with fiber lengths of 6, 12, 16, and 20 mm, corresponding to aspect ratios of 40, 80, 107, and 133, respectively. The specimens were cast under high-frequency vibration, the effect of which will be discussed in the next section. The fiber volume fraction for each fiber length was selected so as to maintain roughly the same workability and uniformity of the fresh mix without altering the properties of the matrix. As shown in Fig. 4, the reinforcement becomes more efficient as the fiber length is increased. For instance, by increasing the fiber length from 6 to 20 mm, the tensile strength of the composite (peak stress of stress–strain curve) was maintained at about 6 MPa although the fiber volume fraction was reduced from 7% to 1.3% (keeping in mind that the unreinforced matrix has a tensile strength about 1.5 MPa). In addition, all composites show a clear pseudo-strain-hardening behavior. Further, the longer fibers (16 and 20 mm) gave the composite a larger strain capacity. Multiple cracking (up to seven cracks by unaided visual examination) was also observed on these composites during

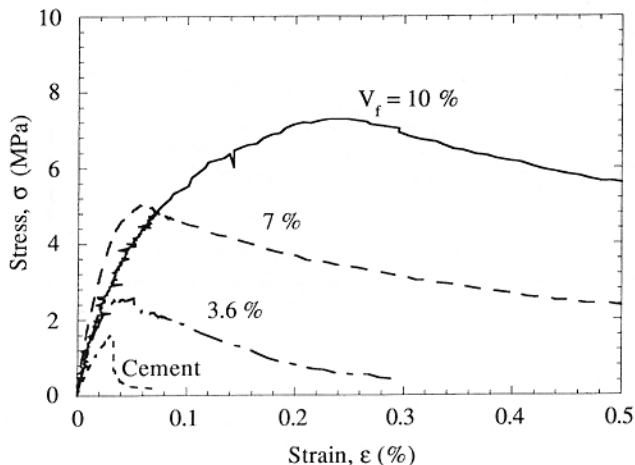


Fig. 3. Tensile stress–strain curves of plain and steel-fiber-reinforced cement with various fiber volume fractions ($L_f = 6$ mm). Specimens cast under normal-frequency vibration.

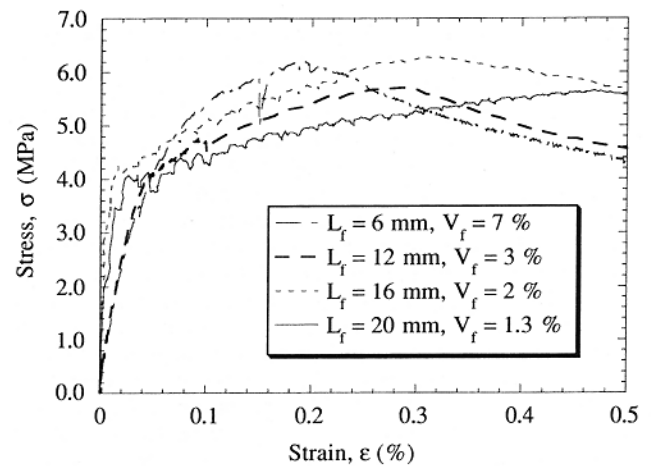


Fig. 4. Effect of fiber length (or aspect ratio) on tensile stress–strain behavior. Specimens cast under high-frequency vibration.

loading. This is quite remarkable given the low fiber volume fractions of these composites (less than or equal to 2%).

The longer fibers may produce a bias on fiber orientation. Since the specimen thickness is only 12.7 mm, the fiber orientation within the matrix for the 16 mm and the 20 mm fiber composites is mostly two-dimensional. However, theoretical calculation¹³ indicates that the effect of 2-D versus 3-D fiber orientation on tensile properties is relatively minor, making a difference of less than 10%.

(4) Effects of Bond Strength

(A) *Vibration Frequency during Casting:* In addition to fiber aspect ratio, high bond strength is another useful means of enhancing composite properties. One effective way of improving bond strength is by high-frequency vibration during casting, presumably due to better geometric packing. Figure 5 shows the tensile stress–strain curves of specimens with two different V_f (but the same fiber length of 6 mm) cast under two different vibration frequency compactations, namely normal- and high-frequency (60 and 120 Hz, respectively). In the cases of $V_f = 7\%$, significant strain increase (2.3 times) and moderate strength increase (24%) are achieved when high-frequency vibration is applied. The composites of $V_f = 10\%$ have shown increased strain capacity even when they are cast under normal-frequency vibration. For these composites ($V_f = 10\%$), the strength and strain are increased about 60% and 45%, respectively, when a high-frequency vibration is employed instead of normal-frequency. This gain in strength and strain is probably due to enhanced bond strength by the use of high-frequency vibration.

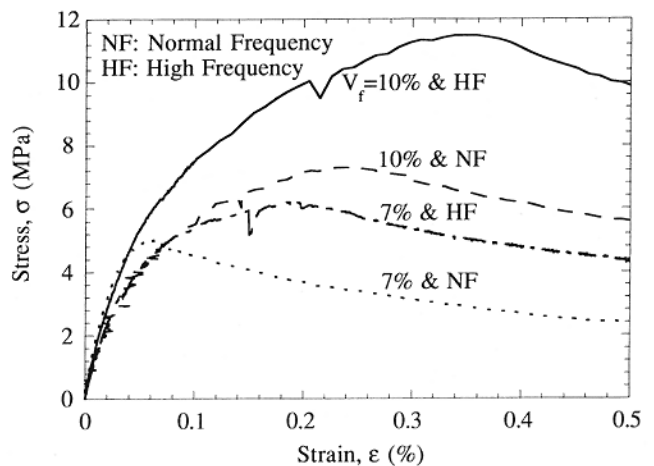


Fig. 5. Effect of vibration frequency during casting on tensile stress–strain curves for two different fiber volume fractions ($L_f = 6$ mm).

These results are consistent with recent single-fiber pull-out experimental findings¹⁵ that when the interfacial zone is compacted, the bond strength increases for brass fibers in cementitious matrices. In the work of Chan,¹⁵ compaction was achieved by the use of microfillers (silica fume and change in water/cement ratios) whereas compaction is achieved by higher vibration frequency in the present experiments.

(B) *Coupling Agent*: In our recent efforts toward enhancing interfacial bonding through fiber surface modification, a titanium-based coupling agent was used in the steel fiber composites. The coupling agent was added in an attempt to create

enhanced workability by the use of a coupling agent. In addition, the ultimate tensile strain increased by almost 50%. Further, the stress-strain curve for this composite clearly shows better performance in terms of ultimate tensile strength and strain capacity, when compared to typical stress-strain curves reported for plain concrete and steel-fiber-reinforced concrete¹⁶ of comparable fiber volume fractions (shown in dotted lines in Fig. 7).

IV. Further Discussions and Conclusions

It is concluded that in this paper that apart from fiber

modulus = 200 GPa; matrix modulus = 15 GPa; interface bond strength = 1.8 MPa) suggest that the short fiber with an aspect ratio of 40 could not possibly have achieved critical conditions for strain-hardening.¹⁷ It is therefore argued that the apparent "strain-hardening" behavior revealed in the macroscopic stress-strain curve is likely a result of stabilized edge crack propagation. This means that the instability of an edge crack is greatly delayed by the presence of the steel fibers as the edge crack propagates with *R*-curve behavior.¹⁸ To balance the rotational moment of an edge crack, a new edge crack is often created on the opposite side of the specimen, as a result of the rotational rigidity of the specimen grip.

While all composites show significant improvement in strength and "ductility," we conclude that only the longer fiber composites shown in Figs. 4 and 7 in this test series undergo pseudo-strain-hardening. Although multiple cracking was observed during the test of these composites, these cracks disappeared after specimen unloading. From this study, new insights into uniaxial testing of strain-hardening materials can be derived: (1) For tensile strength testing of brittle material, rotational rigidity is preferred. For strain-hardening material, complete rotational flexibility is preferred since by definition, the strain-hardening effect of the material should create multiple cracks to maintain rotational balance. In contrast, a brittle or quasi-brittle material with stabilized cracks will continue to open the first edge crack, leading to a distinct flexural failure mode which can be well detected from differential displacement measurements by LVDTs maintained on both edges of a specimen. (2) Techniques in damage pattern monitoring such as dye epoxy impregnation¹⁹ should be employed in order to freeze the multiple crack pattern while the specimen is still under load. Adopting these techniques should provide better means of distinguishing the mode of failure in these composites which are at the borderline between quasi-brittleness and quasi-ductility.

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