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Toughness enhancement in steel fiber reinforced concrete through fiber hybridization

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Abstract

Crimped steel fibers with large diameters are often used in concrete as reinforcement. Such large diameter fibers are inexpensive, disperse easily and do not unduly reduce the workability of concrete. However, due to their large diameters, such fibers also tend to be inefficient and the toughness of the resulting fiber reinforced concrete (FRC) tends to be low. An experimental program was carried out to investigate if the toughness of FRC with large diameter crimped fibers can be enhanced by hybridization with smaller diameter crimped fibers while maintaining workability, fiber dispersability and low cost. The results show that such hybridization indeed is a promising concept and replacing a portion of the large diameters crimped fibers with smaller diameter crimped fibers can significantly enhance toughness. The results also suggest, however, that such hybrid FRCs fail to reach the toughness levels demonstrated by the smaller diameter fibers alone.

Keywords: Concrete; Crimped steel fibers; Flexure; Toughness; Workability; Strength; Cost

1. Introduction

Concrete is a quasi-brittle material with a low strain capacity. Reinforcement of concrete with short randomly distributed fibers can address some of the concerns related to concrete brittleness and poor resistance to crack growth. Fibers, used as reinforcement, can be effective in arresting cracks at both micro- and macro-levels. At the micro-level, fibers inhibit the initiation and growth of cracks, and after the micro-cracks coalesce into macro-cracks, fibers provide mechanisms that abate their unstable propagation, provide effective bridging, and impart sources of strength gain, toughness and ductility [1,2].

Almost all FRCs used today commercially involve the use of a single fiber type. Clearly, a given type of fiber can only be effective in a limited range of crack opening and deflection. The benefits of combining organic (polypropylene and nylon) and inorganic fibers (glass, asbestos and carbon) to achieve superior tensile strength and fracture toughness were recognized nearly 30 years ago by Walton and Majumdar [3]. After a long period of relative inactivity there appears to be a renewed interest in hybrid fiber composites and efforts are underway to develop the science and rationale behind fiber hybridization.

In well-designed hybrid composites, there is positive interaction between the fibers and the resulting hybrid performance exceeds the sum of individual fiber performances. This phenomenon is often termed "Synergy". Many fiber combinations may provide 'Synergy' with the most commonly recognized being [1,4]:

Hybrids based on fiber constitutive response: One type of fiber is stronger and stiffer and provides reasonable first crack strength and ultimate strength, while the second type of fiber is relatively flexible and leads to improved toughness and strain capacity in the post-crack zone.

Hybrids based on fiber dimensions: One type of fiber is smaller, so that it bridges micro-cracks and therefore controls their growth and delays coalescence. This leads to a higher tensile strength of the composite. The second fiber is larger and is intended to arrest the propagation of macro-cracks and therefore results in a substantial improvement in the fracture toughness of the composite. Fibers of small size (often called

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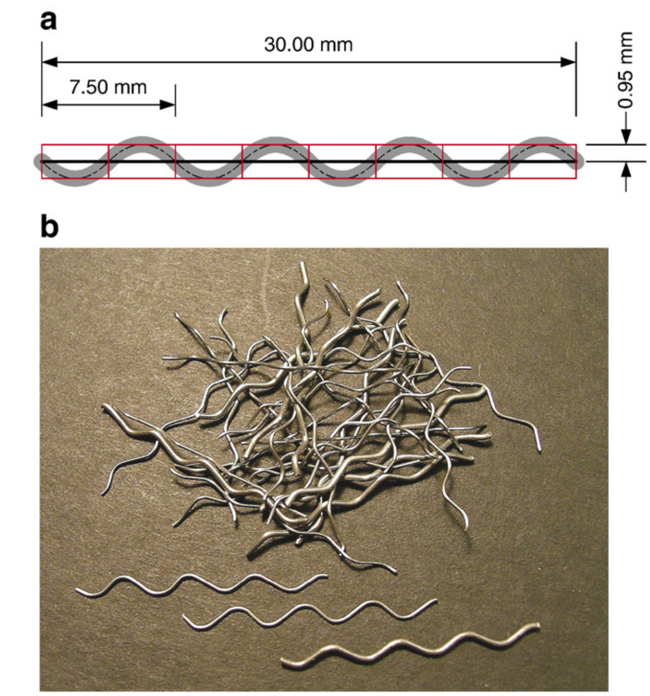

Fig. 1. a. Geometry of crimped steel fiber. b. Crimped fibers of various diameters investigated for hybridization.

micro-fibers) delay crack coalescence in the cement paste and mortar phases and increase the apparent tensile strength [5,6] of these phases.

Hybrids based on fiber function. One type of fiber is intended to improve the fresh and early age properties such as ease of production and plastic shrinkage, while the second fiber leads to improved mechanical properties. Some such hybrids are now commercially available where a low (<0.2%) dosage of polypropylene fiber is combined with a higher (~0.5%) dosage of steel fiber.

Attempts have been made in the past at identifying fiber combinations that produce the maximum synergy. Glavind and Aarre [7] tested steel and polypropylene fiber hybrids and reported that hybridization of these two fibers increased the ultimate compressive strain of the composite. Larsen and Krenchel [8] combined steel and polypropylene fibers in cementitious composites and found that after 10 years of outdoor exposure the fracture energy of composites containing two fibers increased by approximately 40%. Feldman and Zheng [9] combined steel and polypropylene fibers and noted that a stronger and stiffer steel fiber improved the ultimate strength, while the more flexible and ductile polypropylene fibers improved toughness and strain capacity in the post-crack zone. Similar findings were reported by Komlos et al. [10], by Qian and Stroeven [11] and by Kim et al. [12]. Banthia and Sheng [13] combined low modulus pitch-based carbon and high modulus steel fibers and found that the steel fiber led to a more prominent improvement in strength and the carbon fiber led to a more pronounced improvement in toughness. Mobasher and Li [14], investigated hybrids based on alumina, carbon and polypropylene fibers. In their tests, the load versus CMOD response showed that the peak load increased by as much as 75% compared to composite containing only polypropylene fibers. On the durability side, Shah et al. [15] tested permeability characteristics of cracked hybrid composites under tensile loading condition and demonstrated that fiber hybridization significantly increases the resistance to water ingress. More recently, Banthia and Soleimani [16] tested several types of hybrids in normal strength concrete and showed that hybrids based on polypropylene and mesophase carbon fiber produced the highest level of fracture energy synergy. Likewise, a hybrid combination of two types of carbon fibers—low modulus, isotropic pitch-based carbon fiber and high modulus, mesophase pitch-based carbon fiber—showed significant promise. These authors also investigated three-fiber hybrids with carbon and polypropylene micro-fibers added to macro-steel fibers and showed that steel macro-fibers with highly deformed geometry produce better three-fiber hybrids than those with a less deformed geometry. Also, composites with a lower volume fraction (V_f) of fiber reinforcement were seen as having a better prospect for hybridization than composites with a high volume fraction V_f of fibers. In other words, FRCs with low toughness are better candidates for hybridization than composites with a higher toughness. Finally, Banthia and Gupta [17] showed that the strength of the matrix plays a major role in the optimization of hybrid composites.

The use of crimped steel fibers in concrete and shotcrete for both new construction and repair remains popular around the world. In most instances, however, large diameter crimped fibers are specified as these fibers are inexpensive, disperse in concrete easily, do not reduce the workability excessively and finish

Table 1
Mix proportions of concrete matrix

Materials	(kg/m^3)
ASTM Type 1 Portland cement	437
Silica fume	50
Sand	1495
Gravel 3/8″	368
Water	292
W/C	0.6

Table 2
Different composites investigated

Mix	Crimped steel fiber (V_f, %)			Compressive strength (MPa)	Modulus of rupture (MPa)
	0.80 mm	0.45 mm	0.40 mm		
1	0.75			37.1	3.803
2	0.50			36.2	3.801
3		0.75		35.6	3.975
4		0.50		34.2	3.911
5	0.25	0.25		37.0	3.210
6	0.50	0.25		34.5	3.565
7			0.75	35.6	3.815
8			0.50	35.4	3.862
9	0.25		0.25	38.9	3.587
10	0.50		0.25	35.8	3.265
11	0.25	0.50		36.2	3.800
12	0.25		0.50	34.2	3.566

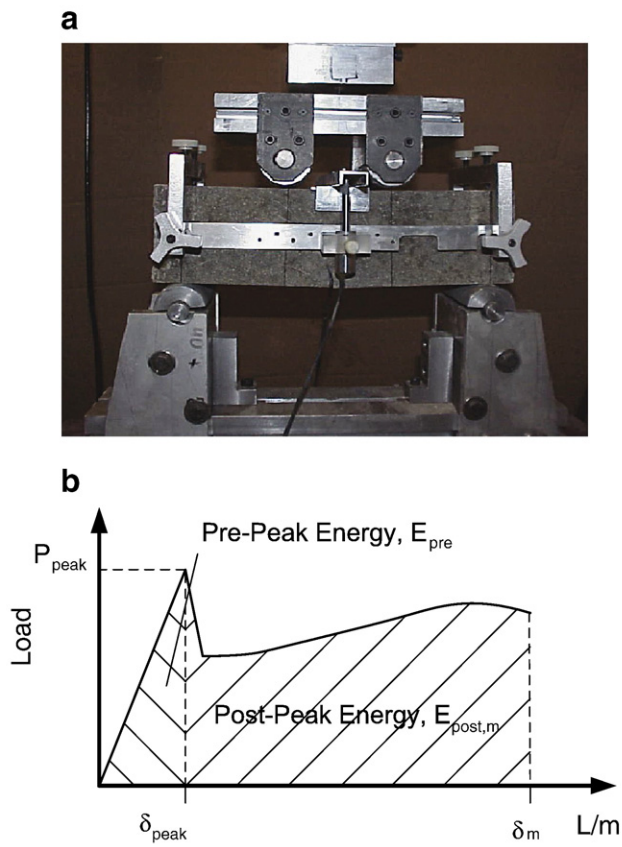

Fig. 2. a. ASTM C1018 toughness test. b. PCS analysis on a FRC beam.

without difficulty. Unfortunately, such fibers also provide a low toughness. A test program was conducted here to investigate if the flexural toughness could be enhanced by replacing a part of the large diameter fibers with smaller diameter fibers while maintaining fiber dispersability and workability.

2. Experimental program

The geometry of the fiber investigated is shown in Fig. 1a. Three diameters of this fiber were investigated: one large 0.8 mm diameter fiber and two smaller 0.4 mm and 0.45 mm diameter fibers (Fig. 1b). FRCs with 0.8 mm fiber were treated as the 'base' composite and smaller diameter fibers were introduced into the 'base' composite for hybridization while keeping the volume fraction constant.

A 35 MPa concrete matrix (Table 1) was used. The matrix was reinforced at variable fiber addition rates to produce single fiber and hybrid fiber composites as described in Table 2.

From each mix, four cylinders (100 × 200 mm) and four beams (100 mm × 100 mm × 350 mm) were cast in Plexiglas moulds. These were demoulded 24 h later and cured in lime-saturated water for 7 days before testing. The cylinders were tested in compression as per ASTM C-39 [18] using a 2.8 MN load-controlled compression testing machine. Only the peak loads were recorded, and converted to compressive strengths by using an elastic analysis. The compressive strength values are given in Table 2.

Beams (100 mm × 100 mm × 350 mm) were tested for flexural toughness in a closed-loop arrangement as per ASTM C1018, Fig. 2a [19]. As is well known [20], during a flexural toughness test, the supports settle in the direction of load application, and concrete crushing occurs at the load points. In order to eliminate these spurious specimen deflections, a "yoke" was installed around the specimens as shown in Fig. 2a. With such an arrangement, only the net deflection of the neutral axis is measured which relates well with the theoretical deflection arising from bending and shear in the specimen [20]. During a test, both the applied load and the specimen deflection in the direction of the applied load were recorded. The deflections were measured by two linear variable displacement transducers (LVDTs) placed on both sides of the specimen and the results from which were averaged as the feed-back signal to the servo-valve.

Although the tests were conducted as per the ASTM C1018 procedure, the curves were not analyzed as per the recommendations of this procedure. Instead, they were analyzed using the JSCE SF4 procedure [21] and the post-crack strength (PCS) procedure [20]. There is much greater confidence in parameters resulting from the JSCE SF-4 and the PCS procedures as compared to the ASTM procedure [20,22]. In the ASTM C1018 procedure, the difficulty of objectively identifying the exact location of 'first crack' on the curve affects ASTM 'toughness indexes' calculation [19].

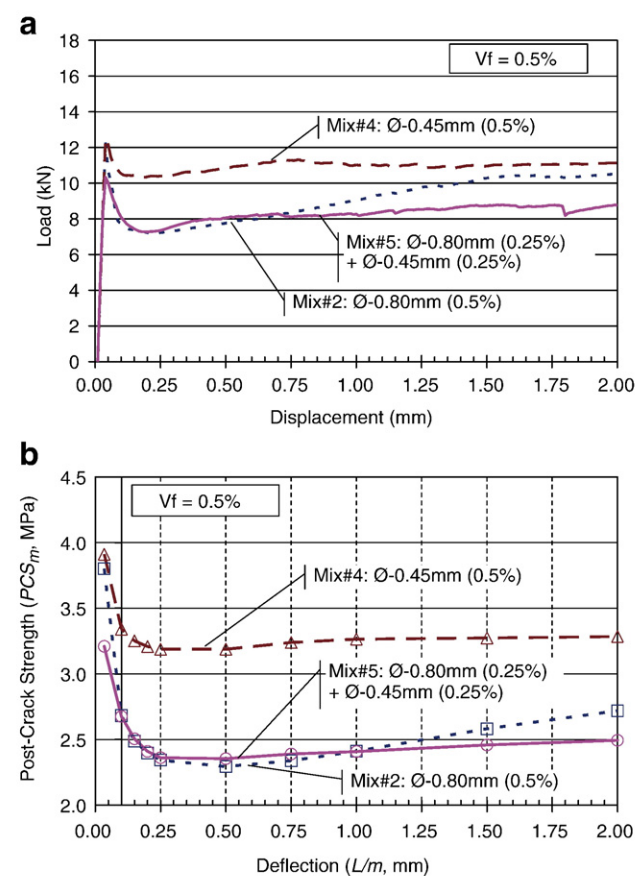

Fig. 3. a. Average flexural load–deflection curves for single and hybrid fibers with diameters of 0.80 mm and 0.45 mm at a volume fraction of 0.50%. b. Post-crack strength of single and hybrid fiber with diameter of 0.80 mm and 0.45 mm at a volume fraction of 0.50%.

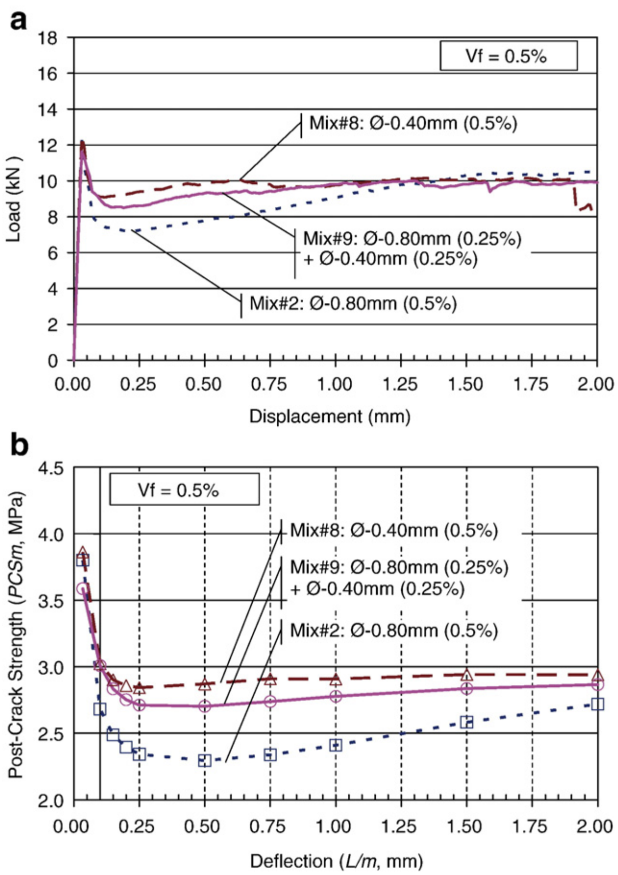

Fig. 4. a. Average flexural load–deflection curves for single and hybrid fibers with diameters of 0.80 mm and 0.40 mm at volume fraction of 0.50%. b. Post-crack strength of single and hybrid fiber with diameter of 0.80 mm and 0.40 mm at a volume fraction of 0.50%.

As per the JSCE method, the flexural toughness factor (σ_b) is given by [21]:

$$\sigma_{\mathrm{b}} = \frac{\tau_{\mathrm{b}}}{\delta_{\mathrm{tb}}} \times \left(\frac{L}{b \times h^2}\right) \tag{1}$$

where, L = span of the beam under test (300 mm in this study); δ_{tb} = deflection at the mid-span of beam (variable); τ_{b} = flexural toughness (energy absorption) up to a deflection of δ_{tb}; and b, h = width and depth of the beam under test (100 mm each, in our case).

As mentioned before, the load versus deflection curves were further analyzed by using a recently developed post-crack strength (PCS) method [20], which provides a more meaningful characterization scheme for FRCs [16,17]. The PCS Method is a method of converting a load–displacement curve into an effective (or equivalent) flexural strength curve using a simple energy equivalence. The technique thus generates "material" properties from a "structural" curve and such properties can then be used in analysis, comparative assessment and in design. Briefly, the technique (Fig. 2b) locates the peak load and divides the curve into two regions: pre-peak and post-peak. The area under the curve is then calculated up to the peak load and termed 'pre-peak energy', E_{pre}. In the post-peak region, points are located corresponding to deflections coinciding with various fractions of the span, L/m (where 'L' is the span of the beam, and 'm' has different values ranging from 150 to 3000). The area under the curve up to a deflection of L/m is termed "total energy" ($E_{\mathrm{total},m}$). The pre-peak energy is subtracted from this total energy to obtain the post-peak energy values, $E_{\mathrm{post},m}$ corresponding to a deflection of L/m.

For a beam with a width b and depth h, the post-crack strength PCS_m at a deflection of L/m is given by (Fig. 2b):

$$\mathrm{PCS}_m = \frac{\left(E_{\mathrm{post},m}\right)}{\left(\frac{L}{m} - \delta_{\mathrm{peak}}\right)} \times \left(\frac{L}{b \times h^2}\right). \tag{2}$$

The terms used in the above equation are described in Fig. 2b. Note that PCS_m has units of stress and at a deflection equal to δ_{peak}, the PCS_m value would coincide with the MOR of the beam.

In this study, for PCS calculations, nine deflection points (0.1, 0.15, 0.2, 0.25, 0.5, 0.75, 1.0, 1.5, and 2.0 mm) were selected in the deflection range of 0.1 to 2 mm. A starting deflection of 0.1 mm was chosen as the deflection at the peak load is always less than 0.1 mm. The PCS value at the peak load was replaced by the modulus of rupture (MOR) value calculated by replacing the term '$(E_{\mathrm{post},m})/(L/m-\delta_{\mathrm{peak}})$' in Eq. (2) with the peak load recorded in a test.

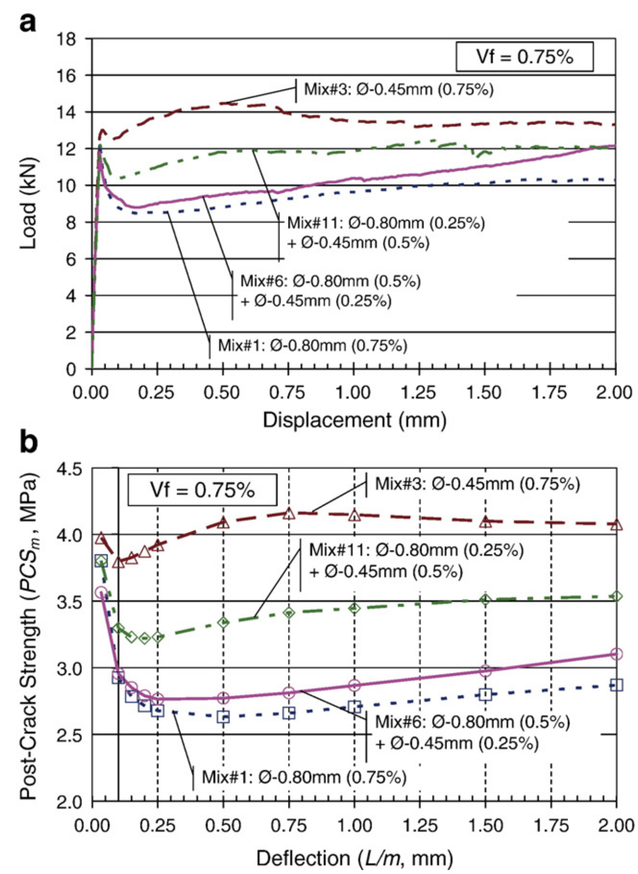

Fig. 5. a. Average flexural load–deflection curves for single and hybrid fibers with diameters of 0.80 mm and 0.45 mm at a volume fraction of 0.75%. b. Post-crack strength of single and hybrid fiber with diameters of 0.80 mm and 0.45 mm at a volume fraction of 0.75%.

3. Results

3.1. Fresh properties and compressive strengths

In Table 2, hardened properties (compressive strengths and moduli of rupture) are given. All mixes were well workable and proper fiber dispersion was achieved. This conclusion was drawn as there was no difficulty experienced in molding the specimens, fiber balling was not visible, mixes flowed easily under an external vibration, and there was no drop in the compressive strength due to fiber addition.

3.2. Flexural toughness

Results from flexural tests on single fiber and hybrid fiber composites with a total fiber content of 0.5% are given in Figs. 3 and 4. Similarly, results from flexural tests on single fiber and hybrid fiber composites with a total fiber content of 0.75% are given in Figs. 5 and 6. In Fig. 3a, the average flexural load–deflection curves (averaged over four specimens) for single fiber and hybrid fiber composites with 0.80 mm diameter fiber and 0.45 mm diameter fiber at a total volume fraction of 0.50% are given. In Fig. 3b, the curves in Fig. 3a are analyzed for PCS values. In Fig. 4a, the average flexural load–deflection curves (averaged again over four specimens) for single fiber and hybrid fiber composites with 0.80 mm diameter fiber and 0.40 mm diameter fiber at a total volume fraction of 0.50% are given. In Fig. 4b, the curves in Fig. 4a are analyzed for the PCS values.

In Fig. 5a, the average flexural load–deflection curves (averaged over four specimens) for single fiber and hybrid fiber composites with 0.80 mm diameter fiber and 0.45 mm diameter fiber at a total volume fraction of 0.75% are given. In Fig. 5b, the curves in Fig. 5a are analyzed for the PCS values. Finally, in Fig. 6a, the average flexural load–deflection curves (averaged over four specimens) for single fiber and hybrid fiber composites with 0.80 mm diameter fiber and 0.40 mm diameter fiber at a total volume fraction of 0.75% are given. In Fig. 6b, the curves in Fig. 6a are analyzed for the PCS values. Note that in all PCS curves, post-crack strengths values at various displacements between 0.1 mm–2.0 mm are given. The resulting flexural curves were also analyzed as per JSCE SF-4 procedure and the results are given in Table 3. These flexural toughness factors are plotted as a function of fiber volume fraction in Fig. 7. Notice in Figs. 3–6 and Table 3 that hybridization did not increase the peak loads carried by the beams in the flexural tests. In other words, no increases in the MOR values were noted.

As can be seen from Figs. 3–7, hybridization of a large diameter fiber with a smaller diameter fiber appears to be a promising concept. By itself, the 0.8 mm diameter fiber performed inferior to the 0.40 mm and 0.45 mm diameter fibers. This may be partly due to a substantial increase in number of fibers crossing a section when the fiber diameter is decreased (for example, a halving of fiber diameter will increase the fiber count number four-fold). By replacing part of the 0.8 mm fiber with either a 0.45 mm fiber or a 0.40 mm fiber improved the performance significantly. The performance of such hybrids, however, stayed below that of the composites carrying 0.40 mm and 0.45 mm fibers alone. There was no discernible difference between the 0.45 mm and 0.40 mm fibers. In some rare instances at low dosage rates, the performance of

Table 3
Flexural results

Mix	Crimped steel fiber (%)			Peak load (kN)	Deflection at peak load (mm)	Post-crack strength at L/m = 2 mm (MPa)	JSCE flexural toughness at δ=2 mm (MPa)
	0.80 mm	0.45 mm	0.40 mm				
1	0.75			12.68	0.032	2.870	2.859
2	0.50			12.67	0.034	2.719	2.710
3		0.75		13.25	0.035	4.078	4.049
4		0.50		13.04	0.033	3.284	3.265
5	0.25	0.25		10.70	0.033	2.494	2.486
6	0.50	0.25		11.88	0.031	3.103	3.086
7			0.75	12.72	0.039	4.172	4.138
8			0.50	12.87	0.032	2.939	2.926
9	0.25		0.25	11.96	0.034	2.866	2.851
10	0.50		0.25	10.85	0.034	3.558	3.532
11	0.25	0.50		12.67	0.033	3.537	3.513
12	0.25		0.50	11.89	0.040	3.295	3.274

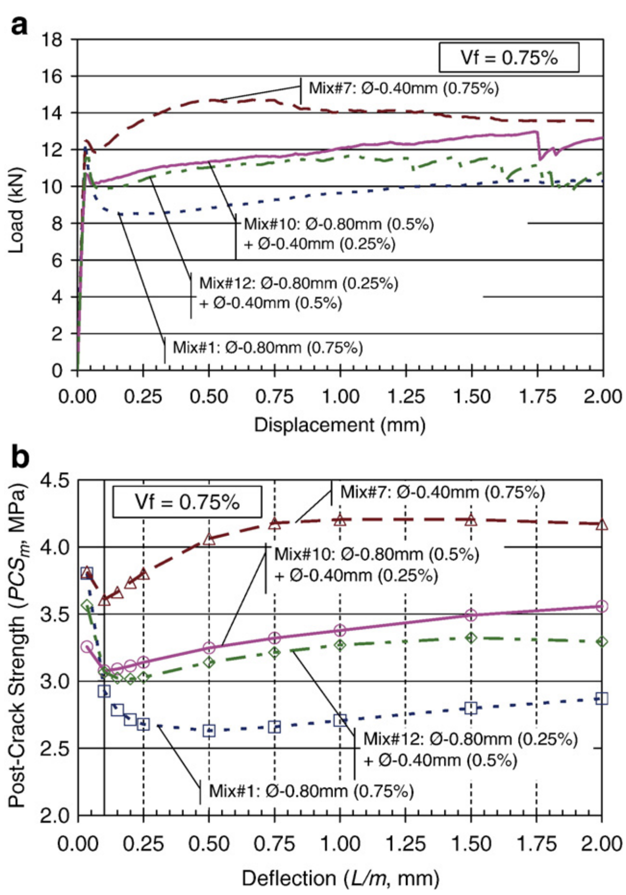

Fig. 6. a. Average flexural load–deflection curves for single and hybrid fibers with diameters of 0.80 mm and 0.40 mm at a volume fraction of 0.75%. b. Post-crack strength of single and hybrid fiber with diameters of 0.80 mm and 0.40 mm at a volume fraction of 0.75%.

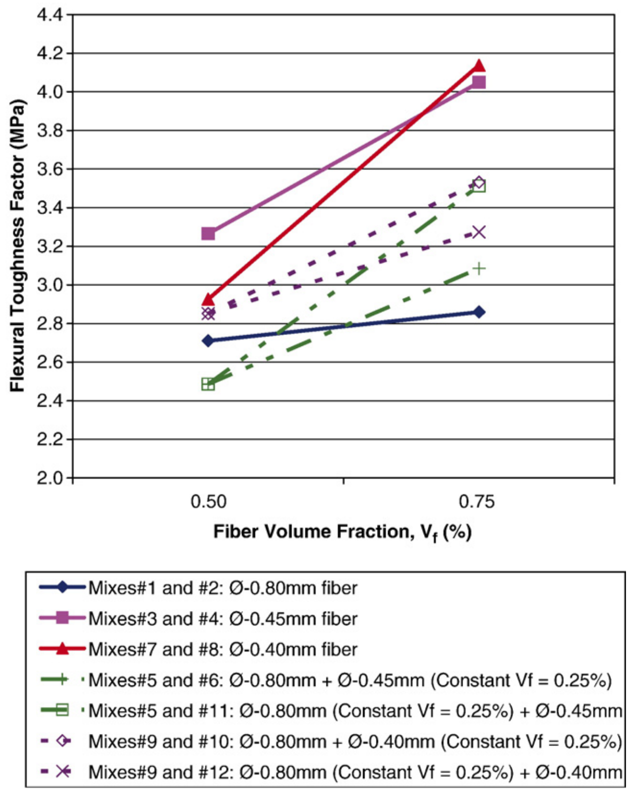

Fig. 7. JSCE flexural toughness factor of the fibers in the experiment.

the hybrids (based on the JSCE Factors, Fig. 7) was slightly below that of single fiber FRCs with 0.8 mm fiber alone.

In Figs. 3b–6b, the post-crack strength (PCS) results are shown. These demonstrate the equivalent strengths of various composites beyond cracking and provide data in the context of design with these materials. While they agree well with the load–deflection responses, they also help identify composites that may perform better from serviceability considerations. For example, PCS curves indicate that the small diameter fibers (0.4 and 0.45 mm) developed a healthy PCS response at low displacements whereas the large diameter fiber (0.8 mm fiber) started off with a lower PCS value which then rose gradually. PCS curves indicate that the efficiency of the small diameter fibers is greater at small deflections and hence one can expect an improved serviceability. Another benefit of the PCS analysis is that it can identity the presence or absence of strain-hardening in a composites that shows deflection-hardening in a flexural test. For example, both Mixes #3 and #11 demonstrated deflection-hardening, but only Mix #3 showed strain-hardening in the PCS analysis. Likewise, both Mixes #7 and #12 demonstrated deflection-hardening in the test curves, but only Mix #7 exhibited strain-hardening.

Interestingly, the toughness enhancements due to hybridization appear to be almost linearly related to the volume fraction of the smaller diameter fiber. This indicates that fibers of different diameters act more as additive phases in hybrid composites. In other words, fibers of different diameters fail to produce a synergistic response.

Notice the deflection-hardening response in FRCs with 0.75% by volume of 0.40 mm and 0.45 mm diameter fibers (Figs. 5a and 6a, Sets 3 and 7). While the 0.80 mm fiber failed to produce any deflection-hardening, there was some evidence of deflection-hardening in hybrid composites especially those carrying large amounts of smaller diameter fibers (Figs. 5a and 6a, Sets 6, 11, 10 and 12).

4. Conclusions

1. One can successfully enhance the flexural toughness of fiber reinforced concrete carrying large diameter crimped steel fibers by hybridizing it with smaller diameter crimped steel fibers of the same length. Such hybrids may even depict deflection-hardening which is generally not seen in composite with large diameter fibers alone.
2. Although hybridization appears to be a promising concept, hybrid FRCs with a combination of large and small diameter crimped fibers failed to reach the toughness levels demonstrated by FRCs with small diameter fibers alone.
3. There does not appear to be a universally applicable additive rule to hybrid composites involving small and large diameter fibers. In other words, replacing a larger portion of the large diameter fiber with the small diameter fiber may not always guarantee a better performance. Given that producing a lower diameter fiber is more expensive than producing a higher diameter fiber, one should integrate production costs into the decision process to arrive at the truly optimal hybrid composites.

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