Materials and Structures / Matériaux et Constructions, Vol. **37**, December 2004, pp 707-716

SCIENTIFIC REPORT

Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices

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ABSTRACT

In most cases, fiber reinforced concrete (FRC) contains only one type of fiber. The use of two or more types of fibers in a suitable combination may potentially not only improve the overall properties of concrete, but may also result in performance synergy. The combining of fibers, often called hybridization, is investigated in this paper for a very high strength matrix of an average compressive strength of 85 MPa. Control, single, two-fiber and three-fiber hybrid composites were cast using different fiber types such as macro and micro-fibers of steel, polypropylene and carbon. Flexural toughness tests were performed and results were extensively analyzed to identify synergy, if any, associated with various fiber combinations. Based on various analysis schemes, the paper identifies fiber combinations that demonstrate maximum synergy in terms of flexural toughness.

RÉSUMÉ

Dans la plupart des cas, le béton renforcé de fibres (BRF) contient seulement un type de fibre. L'utilisation de deux types ou plus de fibres dans une combinaison appropriée peut potentiellement non seulement améliorer les propriétés globales du béton, mais peut également avoir comme conséquence la synergie d'exécution. La combinaison des fibres, souvent appelée hybridation, est étudiée dans cet article pour une matrice de très haute résistance, d'une résistance à la pression moyenne de 85 MPa. Des composés hybrides de contrôle et à une, deux et trois fibres ont été moulés en utilisant différents types de fibre telles que les macrofibres et les microfibres d'acier, du polypropylène et du carbone. Des essais de ténacité en flexion ont été réalisés et les résultats ont été intensivement analysés pour identifier la synergie, le cas échéant, liée à de diverses combinaisons de fibres. Basé sur divers arrangements d'analyse, le papier identifie les combinaisons de fibres qui démontrent la synergie maximum en termes de ténacité en flexion.

1. INTRODUCTION

Concrete is a 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 be effective only 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 25 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.

Editorial note
Prof. Nemkumar Banthia is a RILEM Senior Member. He is the chairman of RILEM TC FRP 'FRP-concrete bond in structural strengthening and rehabilitation' and the Secretary of RILEM TC HFC 'Hybrid fibre concrete'.

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 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.
  Hybrids based on fiber dimensions are often distinguished according to the specific surface area (SSA) of fiber employed. The *SSA* can be defined as the surface area for a unit mass [5], and mathematically,

$$SSA_m = \frac{2(2l + d)}{ldD_f} \tag{1}$$

  When using fibers based on their size (micro or macro) alone, *SSA* can also be defined as the surface area for a unit volume, and can be written mathematically as,

$$SSA_v = \frac{2(2l + d)}{ld} \tag{2}$$

  where, l = length of a circular fiber, d = diameter of a circular fiber, and D_f = density of the fiber material. Arbitrarily, macro-fibers are defined as fibers with a *SSA* of roughly 10 cm^2/gm and micro fibers are defined as fiber with *SSA* exceeding 500 cm^2/gm. As their high *SSA*, and a small size would indicate, the micro-fibers reinforce cement paste and the mortar phases, thereby delaying crack coalescence and increasing 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.

This research investigation was designed based on a number of investigations in the past that have aimed at assessing the potential of fiber reinforcement, and in particular at identifying fiber combinations that produce the maximum synergy. Glavind *et al.* [7] tested steel and polypropylene fiber hybrids and reported that hybridization of these two fibers increased the ultimate compressive strain of the composite. Larsen *et al.* [8] combined steel and polypropylene fibers in cementitious composites and found that after 10 years of out-door exposure the fracture energy of composites containing two fibers increased by approximately 40%. Feldman *et al.* [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 are reported by Komlos *et al.* [10], by Qian *et al.* [11] and by Kim *et al.* [12]. Banthia *et al.* [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. In view of the above research findings, several control mixes with different V_f of steel and polypropylene were considered in this investigation to establish the effect of variation of fiber modulus on the behavior of concrete in flexural toughness. Mobasher *et al.* [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. More recently, Shah and Lawler [15] tested permeability characteristics of hybrid composites and demonstrated that fiber hybridization significantly increased the resistance to water ingress. More recently, Banthia *et al.* [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 synergy in toughness. 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 research findings further instigated the authors to investigate three-fiber hybrids with carbon and polypropylene micro fibers added to macro fibers. Further, Banthia *et al.* [16] showed that steel macro-fibers with highly deformed geometry produce better hybrids than those with a less deformed geometry. Finally, 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 V_f of fibers. In other words, FRCs with low toughness are better candidates for hybridization than composites with a higher toughness. Considering this, the V_f in the hybrids was a maximum of 1.3%.

Although the concept of hybrids has shown to have significant promise, almost all studies to date have focused on normal strength matrices. Gupta *et al.* [17] showed that the strength of the matrix plays a major role in the optimization of hybrid composites. In this paper, the influence of matrix strength is explored further by conducting tests on hybrid composites based on a very high strength matrix.

2. MATERIALS, MIXTURES AND FRESH PROPERTIES

2.1 Materials

CSA type-10 (ASTM Type I) cement and river sand was used with uniformly graded aggregates of 14 mm maximum size. Silica fume used conformed to the requirements of ASTM C 1240 [18]. The superplasticizer used was based on polycarboxylate chemistry and conformed to ASTM C 494 [19], which states the requirements for Type A water-reducing and Type F high-range water-reducing admixture. The air-entraining admixture used was a resin solution of sodium hydroxide and neutralized vinsol resin with a specific gravity of 1.037.

Fibers investigated are described in Table 1 and some of them can be seen in Fig. 1. Notice that the fibers included three macro-fibers: flat-ended steel (S1), crimped polypropylene (P1) and self-fibrillating polypropylene (P2). The micro-fibers included: a 12.5 mm chopped, mesophase pitch-based carbon fiber (c), a 2-denier micro-polypropylene fiber (p1) and a 3-denier micro-polypropylene fiber (p2).

2.2 Mixture proportions and specimens

Mixture proportions of the base matrix are given in Table 2. Slight modifications to the base matrix were necessary to maintain workability when fibers were added. Fiber dosages for all the mixes including those with a hybrid combination of fibers are given in Table 3. For each mix, six concrete cylinders and six beams were cast according to ASTM C 192 [20]. The cylinders were 100 mm in diameter and 200 mm in height, and the beams were 100 mm x 100 mm in section and 350 mm in length.

2.3 Fresh properties of mixtures

As is well known, slump is not an ideal measure of FRC workability; FRC mixes need to be characterized using VeBe time measurements [21]. In a VeBe test, workability is measured in terms of the time required in seconds for compaction in the presence of vibration. A higher VeBe time therefore indicated a less workable mix. In this test program, therefore, VeBe times were measured along with density and air content values for most of the mixes. Air content was measured using an air meter as per ASTM C 231 [22]. Results are given in Table 4. Notice that the VeBe times varied between 0 and 10 seconds. All two-fiber and three-fiber hybrid mixes, with the exception of Mix N7 (0.3%S1+0.2%p1), had longer VeBe times (7-10 seconds). Except for Mixes N4 (1.0%S1) and N5 (1.0%P1), all other single fiber mixes had lower VeBe times (0-6 seconds).

A constant dosage (1.3 ml/kg of cementitious material, Table 2) of air-entraining agent resulted in air content in mixes that were tested between 5% (for Mix N10-0.5%S1+0.25%p2) and 8.8% (for Mix N4). The sources of entrapped air were the added fibers and the air-entraining agent, but since the content of air-entraining agent was constant, the change in air content for different mixes can be attributed to the variation in fiber

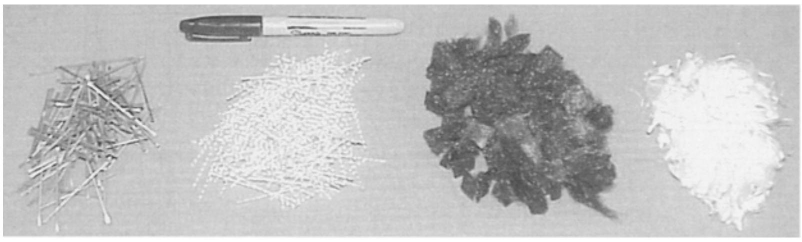

Fig. 1 - Some of the Fibers used in this Investigation (From left to right: S1, P1, c and p1; see Table 1 for details).

Table 1 - Properties of fibers investigated**

Fiber code	Type	Dimensions			Cross sectional shape
		L (mm)	D	Geometry	
S1	Flat-ended steel	50	1 mm	Flat-end	Circular
P1	Macro polypropylene	50	1mm	Crimped	Rectangular
P2	Self fibrillating Polypropylene	50	1 mm	Straight	Fibrillated
c	Carbon fiber (Mesophase Pitch-based)	12.5	9-11 μm	Straight	Circular
p1	Micro polypropylene	12.5	2-denier	Straight	Circular
p2	Micro polypropylene	12.5	3-denier	Straight	Circular

****S1**: *Novotex fiber by SI Corporation;* **P1**: *HPP fiber by SI Corporation;* **P2**: *Self-fibrillating fiber by Dow Chemical Company;* **c**: *Carbon micro-fiber with sizing by Conoco-Phillips Inc.;* **p1**: *Polypropylene micro fiber by Dow Chemical Company,* **p2**: *Stealth fiber by SI Corporation*

Table 2 - Mixture proportions of the base matrix

Cement (kg/ m^3)	Sand (kg/ m^3)	Gravel-14mm (kg/m^3)	Water (kg/ m^3)	Silica fume (kg/ m^3)	Super-plasticizer (ml/kg of cement)	Air Entrain. (ml/kg of cement)
435	643	1029	128	43.5	8	1.3

Table 3 – Volume fraction of fibers used in various mixes

Mix	Type of mix	Volume of various fiber types (%)						Total V_f
		S1	P1	P2	c	P1	p2	
N1	Plain	-	-	-	-	-	-	0
N2	Single-fiber composites	0.5	-	-	-	-	-	0.5
N3		0.75	-	-	-	-	-	0.75
N4		1.0	-	-	-	-	-	1.0
N5		-	1.0	-	-	-	-	1.0
N6		-	-	1.0	-	-	-	1.0
N7	Two-fiber composites	0.3	-	-	-	0.2	-	0.5
N8		0.3	-	-	-	-	0.2	0.5
N9		0.5	-	-	-	0.25	-	0.75
N10		0.5	-			-	0.25	0.75
N11		0.75	-	-	-	0.25	-	1.0
N12		0.75	-	-	-	-	0.25	1.0
N13	Three-fiber composites	-	0.5	-	0.25	0.25	-	1.0
N14		-	0.5	-	0.25	-	0.25	1.0
N15		-	1.0	-	0.15	0.15	-	1.3
N16		-	1.0	-	0.15	-	0.15	1.3
N17		-	-	0.5	0.25	0.25	-	1.0

Table 4 - Fresh properties				
Series	**Fiber Proportion (%)**	**VeBe Time (sec)**	**Density (kg/m³)**	**Air Content (%)**
N1	0	0	2366	6.0
N2	0.5S1	5	*	*
N3	0.75S1	0	*	*
N4	1.0S1	10	*	8.8
N5	1.0P1	10	*	*
N6	1.0P2	6	*	*
N7	0.3S1+0.2p1	6	*	5.9
N8	0.3S1+0.2p2	5	2508	*
N9	0.5S1+0.25p1	7	2298	7.5
N10	0.5S1+0.25p2	7	2460	5.0
N11	0.75S1+0.25p1	8.5	2337	8.2
N12	0.75S1+0.25p2	7.5	2465	7.0
N13	0.5P1+0.25c+0.25p1	10	*	7.8
N14	0.5P1+0.25c+0.25p2	*	*	*
N15	1.0P1+0.15c+0.15p1	*	*	*
N16	1.0P1+0.15c+0.15p2	*	*	*
N17	0.5P2+0.25c+0.25p1	10	2377	7.8

* *Values not recorded*

dosage and fiber combination. For all hybrid mixes (except for Mix N10), a correlation was observed between the air content and the workability of the concrete. For example, as seen in Table 4, the air content increased from 5.9% for N7 to 8.2% for N11 (0.75%S1+0.25%p1). The corresponding VeBe times for N7 and N11 were 6 and 8.5 sec, respectively, implying that a decrease in workability based on VeBe time occurred with an increase in the air content. This is somewhat counter-intuitive.

3. MEASUREMENT OF HARDENED PROPERTIES

3.1 Compressive strength and modulus of rupture (MOR)

The test specimens were prepared according to ASTM C 192 [20] and six cylinders per mix were tested in compression according to ASTM C 39 [23]. MOR values were averaged for six specimens for most mixes and were determined from the flexural toughness tests (described later) by following the procedure outlined in ASTM C 78. Accordingly, the peak loads supported by the 100 x 100 x 350 mm beams in four-point bending were converted to MOR values using linear elastic analysis.

3.2 Flexural toughness

In this study, the flexural toughness of various fiber reinforced concrete composites was evaluated by conducting the ASTM C1018 test [24], which is, in principle, similar to the JSCE SF-4 method [25]. In these tests, a beam is failed in four-point bending and the resulting load vs. deflection response is analyzed for toughness parameters. The test procedure in these two standards is identical—the only difference is in the way the resulting load vs. deflection curves is analyzed.

Fig. 2 shows ASTM C1018 test set-up used in this study. Notice that the linear variable displacement transducer was mounted in a yoke to exclude any spurious deflections caused by the crushing of concrete and rigid body movements of the beam and the supports. Thus only the net deflections characterized by the downward displacement of the neutral axis were recorded. The rate of deflection was 0.1 mm per minute. The load vs. deflection curves were recorded to a total deflection of approximately 2.5 mm at an acquisition rate of 1 Hz.

As has been previously shown [26, 27], both the C1018 test method [24] and the JSCE SF-4 method [25] suffer from a number of inadequacies and shortfalls. Consequently, although the tests were run as per ASTM C1018, the load vs. deflection responses in this program were analyzed by using a recently developed Post-Crack Strength (PCS) method proposed in [27]. It was shown previously [16, 17] that the PCS method provides a more suitable toughness characterization scheme for the hybrid composites because in this method, toughness values are determined based on the peak load as opposed to the point of first crack, which is subject to human judgment in the case of ASTM C1018 method. In the PCS method, values are determined at significant points of interest on a load vs. deflection curve. The PCS technique locates the peak load and divides the curve into two regions: pre-peak and post-peak (Fig. 3). The area under the curve is then calculated up to the peak load and termed

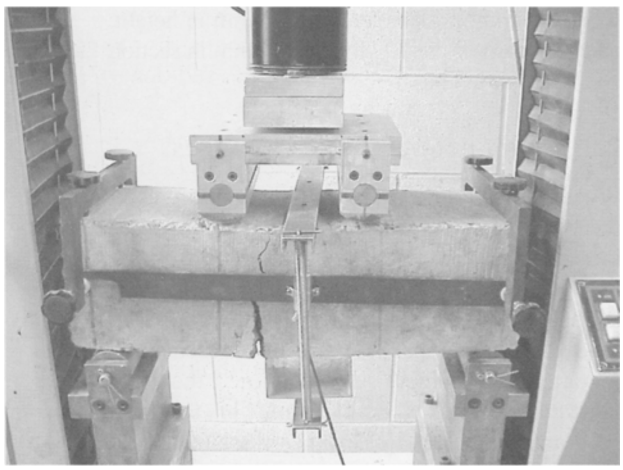

Fig. 2 - Set-up for flexural toughness test.

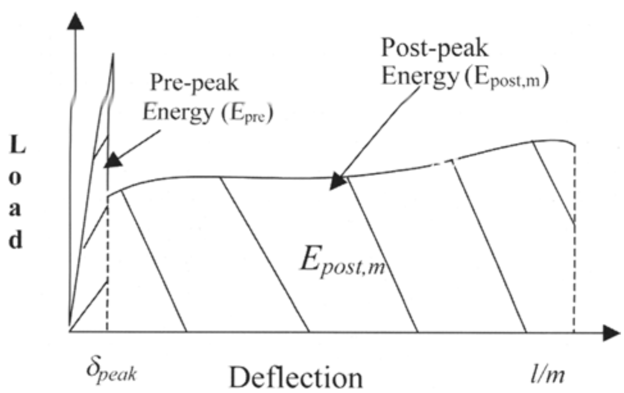

Fig. 3 - PCS analysis: pre-peak and post-peak regions.

"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 3000 to 150). The area under the curve up to a deflection of L/m is termed "total energy" ($E_{total,m}$). The pre-peak energy is subtracted from this total energy to obtain the post-peak energy values, $E_{post,m,}$ corresponding to a deflection of L/m.

For a beam with a width and depth, respectively of b and h, the post-crack strength PCS_m at a deflection of L/m is then given by:

$$PCS_m = \frac{(E_{post,m}) \times L}{(\frac{L}{m} - \delta_{peak}) \times b \times h^2} \tag{3}$$

for $L/m > \delta_{peak}$

Note that PCS_m has units of stress and at a deflection equal to δ_{peak}, the PCS_m would coincide with the MOR of the beam.

4. RESULTS AND DISCUSSION

4.1 Compressive strength and modulus of rupture

The average compressive strength values for all mixes are given in Table 5 along with the MOR values.

As expected, a minimal change in the compressive strength was observed due to the addition of various fibers, ranging from a maximum of 102.4 MPa to a minimum of 70 MPa. With the exception of Mix N8 (0.3%S1+0.2%p2), most mixes with polypropylene macro-fiber, P1, had lower compressive strengths. As the air content increased in the HyFRC mixes, a decrease in the compressive strength was also evident. The results showed that at 5.9% air, the strength was about 102 MPa, and at 8.8% air, the strength decreased to about 86 MPa.

Table 5 - Compressive strength and modulus of rupture values

Mix	Fiber Proportion (%)	Compressive strength (MPa)	MOR (MPa)
N1	0	80.8	7.3
N2	0.5S1	97.4	7.7
N3	0.75S1	92.6	8.4
N4	1.0S1	86.6	6.4
N5	1.0P1	84.3	6.5
N6	1.0P2	77.3	6.6
N7	0.3S1+0.2p1	102.4	8.3
N8	0.3S1+0.2p2	76.3	9.8
N9	0.5S1+0.25p1	83.2	8.4
N10	0.5S1+0.25p2	82.3	9.7
N11	0.75S1+0.25p1	97.0	10.2
N12	0.75S1+0.25p2	94.5	7.9
N13	0.5P1+0.25c+0.25p1	77.3	7.0
N14	0.5P1+0.25c+0.25p2	77.0	6.9
N15	1.0P1+0.15c+0.15p1	71.0	7.1
N16	1.0P1+0.15c+0.15p2	70.0	8.2
N17	0.5P2+0.25c+0.25p1	86.3	6.9

Even though no clear increases in the compressive strengths were noted with the addition of fibers, there was a clear increase in the MOR of the material due to the addition of micro-fibers. For the mixes containing steel macro-fibers, one can compare Mixes N9 (0.5%S1+0.25%p1) and N2 (0.5%S1), and Mixes N11 (0.75%S1+0.25%p1) and N3 (0.75%S1).

Similarly, among the mixes containing polypropylene macro-fibers (P1), Mixes N13 (0.5%P1+0.25%c+0.25%p1) and N15 (1.0%P1+0.15%c+0.15%p1) can be compared with Mix N5 (1.0%P1). For Mixes N9 and N2, an increase of about 9% can be observed in the value of MOR. When Mixes N13 and N15 are compared with their control N5, increases of about 8.5% and 10%, respectively, can be observed. Notice that MOR values also decreased with an increase in the air content.

4.2 Flexural toughness based on load-deflection plots

In this section, flexural responses of composites are compared based on the average load deflection curves, starting with the control single fiber mixes and followed by hybrid composites based on steel macro-fiber (S1) and polypropylene macro-fiber (P1, P2). Note that for most mixes the curves are an average of six specimens, a plot of "average load" plotted against the deflection. For determining average load values, at numerous deflection values, the corresponding load values for each specimen was "looked-up" from the acquired data and finally averaged. High strength matrices were studied in this investigation to establish the behavior of the hybrid mixes with different V_f before and after the peak load. From the load vs. deflection plots, the release of energy at the peak load could also be identified.

Fig. 4 compares mixes containing steel and polypropylene macro-fibers at 1% fiber V_f each. Notice the superior response of Mix N4, containing steel fiber over Mixes N5 and N6 containing macro-polypropylene fibers. Between the two polypropylene macro-fibers (self-fibrillating and crimped), the self-fibrillating fiber (P2) appears to perform better than the crimped fiber (P1).

Fig. 5 shows a comparison of mixes with different V_f of steel macro fiber. When the V_f of the steel fiber was increased from 0.5% to 0.75%, the load carrying capacity at the peak and after the peak was greater. However, when the V_f was further increased to 1.0%, performance declined probably due to lower compaction of Mix N4, which had lower workability.

Fig. 6 shows a comparison of mixes with steel macro-fiber and its two-fiber hybrids with the 2-denier polypropylene fiber, p1. Even though Mix N7 had the same total V_f as Mix N2, it resulted in a decreased load carrying capacity throughout the deflection range. When the total V_f of Mix N9 is compared to that of Mix N2 (both mixes have the same 0.5% V_f of steel macro-fiber, S1), synergy is clearly visible (shaded region in Fig. 6). Note that this statement is based on the assumption that composites with small V_f of micro-fibers alone have little or no flexural toughness.

Fig. 7 shows the comparison of mixes with steel macro-fiber alone and its two-fiber hybrids with the 3-denier

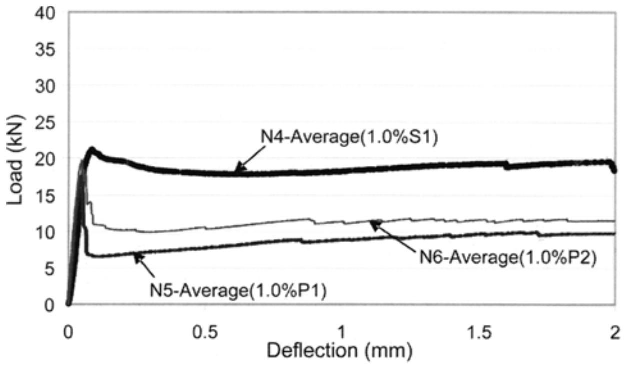

Fig. 4 - Comparison of mixes with steel (S1) and polypropylene macro-fibers (P1 and P2) at 1%.

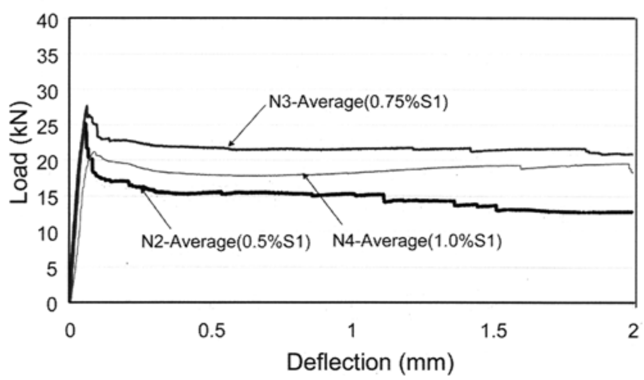

Fig. 5 - Comparison of mixes with different volume fractions of steel macro-fiber (S1).

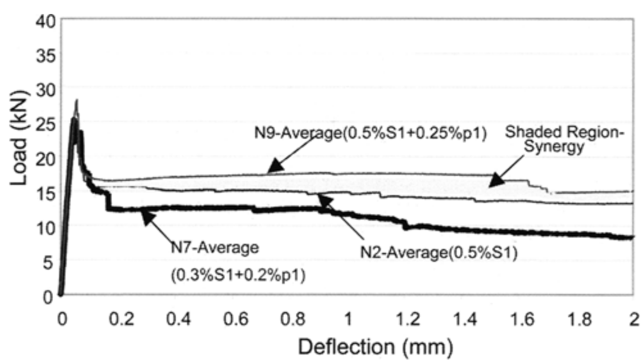

Fig. 6 - Comparison of mixes with steel macro-fiber (S1) and its two-fiber hybrids with polypropylene micro-fiber (p1).

polypropylene fiber, p2. Minimal enhancement in response was observed, except at large deflections.

Fig. 8 compares the performance of the two types of polypropylene micro-fibers (p1 and p2) with 0.75% S1. Here, Mix N3 is the control. A clear synergy was observed in the hybrid mix containing the 2-denier micro-fiber, p1, at least for beam deflections smaller than 1.4 mm. Note, once again that this statement implicitly assumes that small V_f of p1 or p2 fibers alone will not contribute to toughness. No synergy, however, was observed for Mix N12 with the 3-denier fiber, p2, for the entire deflection range.

In Fig. 9, hybrid mixes with p1 or p2 fiber themselves are compared with three different V_f of steel macro-fiber. Clearly Fiber p1 is seen to be more effective than fiber p2

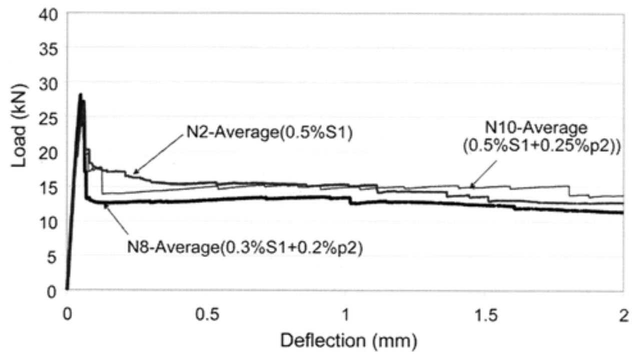

Fig. 7 - Comparison of mixes with steel macro-fiber (S1) and its two-fiber hybrids with polypropylene micro-fiber (p2).

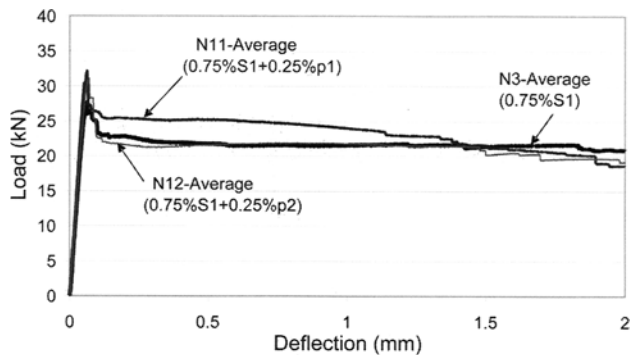

Fig. 8 - Comparison of two polypropylene micro-fibers (p1 and p2) for hybridization with 0.75% S1.

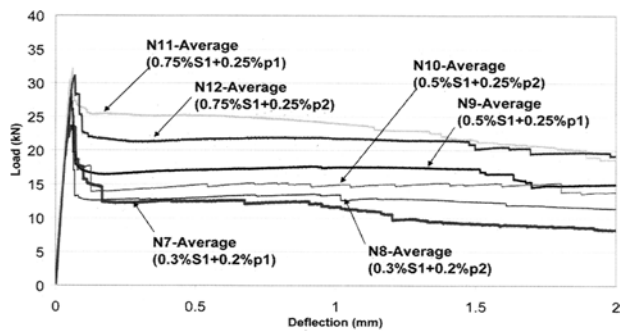

Fig. 9 - Comparison of various steel-polypropylene hybrids.

in all cases except at low total V_f (Mixes N7 and N8) where Fiber p2 is clearly better.

Fig. 10 shows a comparison of mixes with polypropylene (P1) macro-fiber and its three-fiber hybrids containing polypropylene (p1 and p2) and carbon micro-fibers (c). The three-fiber hybrids (Mixes N13 and N15) had better responses when compared with the control Mix N5. Here, Mix N13 resulted in significant positive synergy at a total V_f of 1% identical to Mix N5. In Mix N15, the total V_f of the fibers was 1.3%, higher than N5, but a further increase in toughness occurred.

Fig. 11 compares the Mix (N6) containing self-fibrillating polypropylene macro-fiber (P2) and its three-fiber hybrid (Mix N17). The hybrid composite produced a higher peak load, but had lower load carrying capacity beyond the peak. One reason for the poor performance of

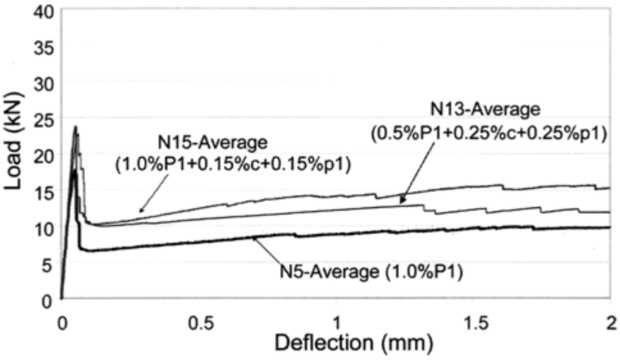

Fig. 10 - Comparison of three-fiber hybrids based on polypropylene macro-fiber (P1).

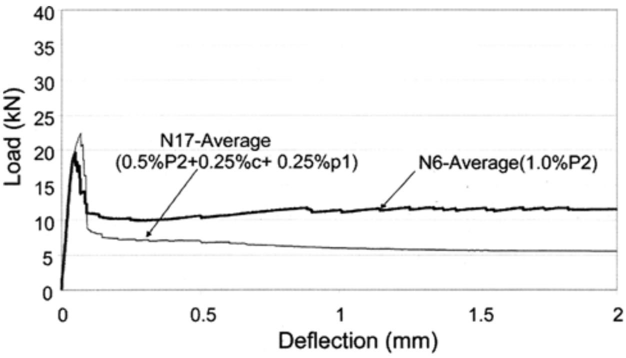

Fig. 11 - Comparison of three-fiber hybrids based on polypropylene macro-fiber (P2).

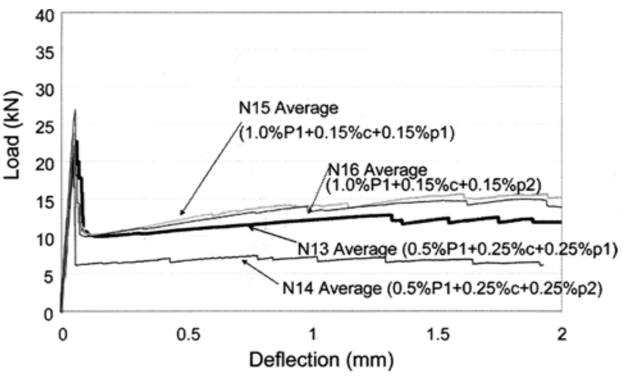

Fig. 12 - Comparison of various three-fiber hybrids based on polypropylene macro-fiber (P1).

the hybrid mix could be its poor workability indicated by a long VeBe time of 10 seconds.

Fig. 12 shows a comparison of different three-fiber hybrids that contained the polypropylene macro-fiber (P1). While the hybrid Mixes N13 and N15 contained the p1 type polypropylene micro-fiber, Mixes N14 and N16 contained the p2 type micro polypropylene fiber. Mixes N13 and N15 showed better performance when compared to Mixes N14 and N16, indicating quite clearly the greater effectiveness of finer 2-denier fiber, p1, over the coarser 3-denier fiber, p2.

4.3 Flexural toughness based on the PCS values

The PCS values at lower L/m ratios (between 0 and 0.3) can help identify the synergy (positive or negative) in the

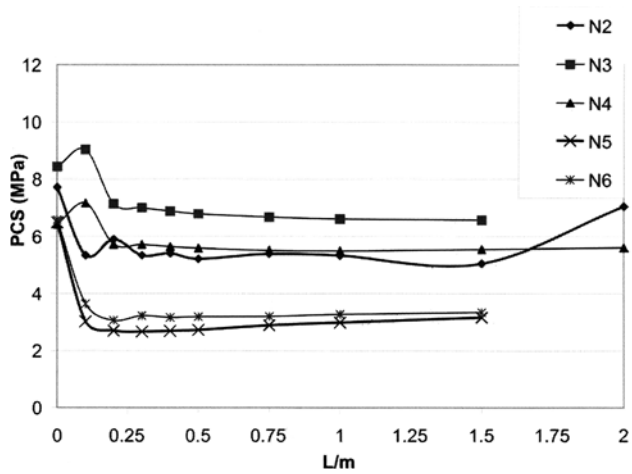

Fig. 13 - PCS Chart for Mixes N2-N6.

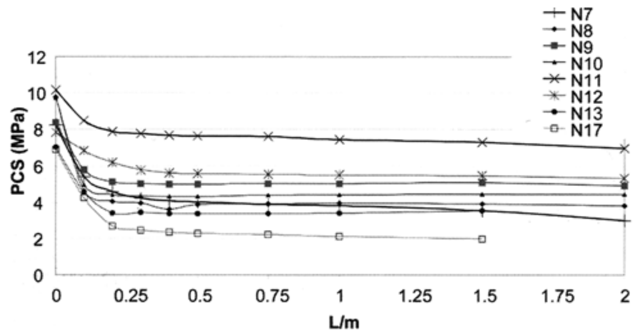

Fig. 14 - PCS Chart for Mixes N8-N13 and N17.

hybrids at low deflection values, which might otherwise be difficult to observe in the load vs. deflection curves. Also, for certain mixes, when the load vs. deflection responses are similar, the PCS plots help quantify the synergy, if present.

Fig. 13 shows the PCS values plotted against L/m ratios for single-fiber Mixes N2-N6. Fig. 14 shows the PCS values for the two-fiber and three-fiber hybrid Mixes N7-N13, as well as for Mix N17. Note that while the MOR for Mix N2 (Fig. 13) is higher than that of Mix N4, Mix N4 performs better at smaller L/m ratios (ratios between 0.25 and 1.75 approximately). This clearly indicates the usefulness of the PCS method of analysis, as these trends remain obscured when only the load-deflection curves are considered.

The values plotted in Figs. 13 and 14 are also shown in Table 6, where the average MOR and PCS values for mixes at nine different values of beam deflection are given. The PCS_{150} values for some of the mixes could not be calculated due to a loss of data at 2-mm beam deflections.

5. SYNERGY QUANTIFICATION

As previously stated, synergy associated with fibers is analyzed as follows. Micro-fibers at small dosages are assumed not to contribute to toughness, which is often the case. Secondly, mixes with the same total V_f of fiber can be compared, which is a conservative approach and underestimates synergy.

In this section, the synergy (in terms of the PCS) between the different mixes has been evaluated and

Table 6 - Average MOR and PCS

Mix	MOR (MPa)	Average PCS (MPa)								
		PCS_{3000}	PCS_{1500}	PCS_{1000}	PCS_{750}	PCS_{600}	PCS_{400}	PCS_{300}	PCS_{200}	PCS_{150}
N1	7.3	-	-	-	-	-	-	-	-	-
N2	7.7	5.3	5.9	5.3	5.4	5.2	5.4	5.3	5.0	-
N3	8.4	9.0	7.1	7.0	6.9	6.8	6.7	6.6	6.6	7.0
N4	6.4	7.2	5.7	5.7	5.6	5.6	5.5	5.5	5.6	5.6
N5	6.5	3.0	2.7	2.7	2.7	2.7	2.9	3.0	3.2	-
N6	6.6	3.6	3.1	3.2	3.1	3.2	3.2	3.3	3.3	4.7
N7	8.3	5.4	4.6	4.2	4.1	4.0	3.9	3.8	3.6	3.0
N8	9.8	4.6	4.1	3.9	3.6	3.9	3.9	3.9	3.9	3.8
N9	8.4	5.8	5.1	5.0	5.0	5.0	5.0	5.0	5.1	4.9
N10	9.7	5.0	4.4	4.4	4.3	4.3	4.4	4.4	4.5	4.5
N11	10.2	8.5	7.9	7.8	7.7	7.6	7.6	7.5	7.3	7.0
N12	7.9	6.8	6.2	5.8	5.6	5.6	5.5	5.5	5.5	5.4
N13	7.0	4.6	3.4	3.4	3.4	3.4	3.4	3.4	3.6	-
N14	6.9	3.2	3.1	3.1	3.1	3.1	3.2	3.3	3.4	3.5
N15	7.1	3.1	3.1	3.2	3.3	3.4	3.6	3.8	4.0	4.2
N16	8.1	3.0	3.0	3.1	3.2	3.3	3.4	3.6	3.8	4.0
N17	6.9	4.3	2.7	2.5	2.4	2.3	2.2	2.1	2.0	-

compared as a percentage. Table 7 compares the PCS value of some of the hybrid mixes to that of its control. Some of these are negative, implying that the hybrid mix has a poorer performance than its control. The values presented here have been plotted in the form of graphs in Figs. 15-17.

In Fig. 15, where the total V_f was compared, Mix N7 showed some positive synergy at L/m ratios less than 0.1 and negative synergy thereafter when compared with Mix N2. Similarly, when Mix N9 was compared with N2, there was positive synergy at small and large deflections and negative synergy elsewhere.

With a small addition of 0.25% of p1 fibers, significant positive synergy was observed for Mix N3 when compared with Mix N11. For most of the deflection range, more than 10% positive synergy was realized. Fig. 16 compares Mixes N2-N8, N2-N10, and N3-N12. Except for the MOR, no positive synergy was observed in any of these mixes.

The comparison of Mixes N6 and N17 (Fig. 17) containing polypropylene macro-fibers (P2) and polypropylene micro-fibers (p1), did not show any positive synergy (except for the MOR and L/m = 0.1).

The results for Mix N13 demonstrate significant positive synergy throughout the deflection range. Positive synergy of about 51%, gradually decreasing to about 12% with the increasing deflection, was evident for Mix N13, when compared with its control mix, N5.

An attempt is made here to identify hybrid fiber combinations that provide synergy in high strength matrices based on flexural toughness. The study identifies some composites (for example, those containing deformed polypropylene macro-fibers and polypropylene micro fibers) as developing higher synergy than others (for example, those containing deformed steel macro-fibers and polypropylene micro-fibers).

The influence of a high matrix strength on achievable fiber synergy is not clear from the tests conducted here as low strength matrices were not tested for comparison purposes. While some such tests are currently underway, one can hypothesize that in high strength matrices an increased instability at the peak load would adversely affect some fiber types and in their cases the hybridization benefits would remain small. However, in the case of fibers with a weak fiber-matrix bond, an increase in the

Table 7 - Synergy assessment (%)

Mixes Compared	L/m ratios									
	MOR	0.1	0.2	0.3	0.4	0.5	0.75	1.0	1.5	2.0
Two-fiber hybrids- steel macro and polypropylene micro-fiber (p1)										
N2-N7	6.9	1.3	-21.9	-21.0	-24.5	-23.1	-28.2	-28.1	-29.6	-
N2-N9	8.8	8.4	-13.0	-5.7	-7.4	-3.8	-6.7	-5.3	0.9	-
N3-N11	20.7	-6.0	10.2	11.0	11.5	12.5	13.8	12.7	10.9	-0.2
Two-fiber hybrids- steel macro and polypropylene micro-fiber (p2)										
N3-N12	-6.9	-24.4	-13.4	-17.4	-18.2	-17.7	-17.1	-16.6	-16.7	-23.4
N2-N10	26.1	-7.3	-24.8	-18.2	-20.0	-16.8	-18.3	-16.8	-11.8	-36.6
N2-N8	26.4	-13.6	-31.2	-26.2	-33.2	-25.3	-27.3	-26.1	-22.6	-45.9
Macro polypropylene mixes and their three-fiber hybrids										
N5-N13	8.4	51.3	26.5	29.0	26.3	23.7	17.2	15.0	12.8	-
N5-N15	9.9	2.1	16.3	20.1	22.2	24.1	24.8	26.4	26.3	-
N6-N17	5.1	16.6	-11.6	-23.4	-25.5	-27.8	-30.1	-34.7	-40.1	-

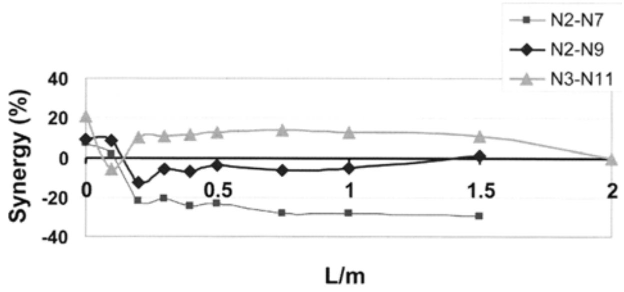

Fig. 15 - Synergy vs. L/m ratio for mixes containing steel macro-fiber and polypropylene micro-fibers (p1).

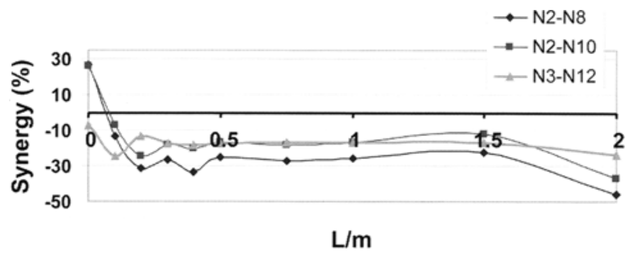

Fig. 16 - Synergy vs. L/m ratio for mixes containing steel macro-fiber and polypropylene micro-fibers (p2).

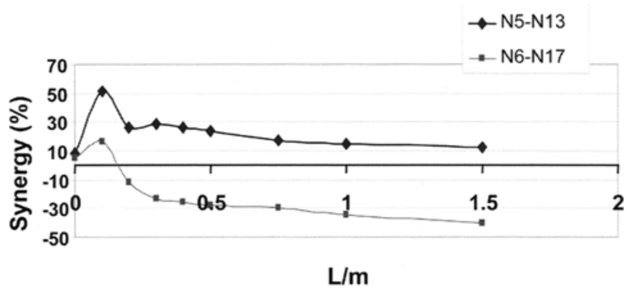

Fig. 17 - Synergy vs. L/m ratio for mixes containing polypropylene macro fibers (P1 & P2) and polypropylene micro-fiber (p1).

strength of the matrix may strengthen the bond and, in turn, provide increased reinforcement efficiency. It is possibly for this reason that in the study reported here, polypropylene macro-fiber with a hydrophobic nature and a weak interfacial bond demonstrated better synergy than steel fibers. These statements, however, need verification.

6. CONCLUSIONS

Based on tests performed here on high strength fiber reinforced concrete with an average compressive strength of 85 MPa, the following conclusions may be drawn:

1. While the addition of fibers does not enhance the compressive strength of the mix, the addition of micro-fiber clearly enhances the MOR.
2. At identical volume fractions, deformed steel macro-fiber provides better toughness than the crimped or self-fibrillating polypropylene macro-fibers. Between the two polypropylene macro-fibers, the self-fibrillating fiber performs better than the crimped macro-fiber.
3. Hybrids based on steel macro-fibers and polypropylene micro-fibers demonstrated some synergy. Hybridization of crimped polypropylene macro-fiber with micro-fibers of carbon and polypropylene, however, demonstrates maximum synergy. Finally, the composites based on self-fibrillating polypropylene macro-fiber show no synergy at all.
4. Of the two micro-polypropylene fibers investigated, the 2-denier fiber is clearly far more effective in producing synergy in hybrids than the 3-denier fiber. The effectiveness of the 2-denier micro-polypropylene fiber is further enhanced when carbon micro-fiber is added as the third fiber.
5. While hybrid fiber reinforced cement composites are promising, and have been used in several areas [28], there is much further research needed to develop the science and rationale necessary for their optimization.

ACKNOWLEDGEMENTS

The authors acknowledge NSERC for their continued support financial support. Thanks are also due to SI Corporation, The Dow Chemical Company, Conoco-Phillips, Lafarge North America Inc. and Master Builders Inc. for their contributions to this research.

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Paper received: August 7, 2003; Paper accepted: November 19, 2003