Performance Synergy in Hybrid Fiber Reinforced Concrete Under Impact

Nemkumar Banthia[*1], Vivek Bindiganavile[2]

[1]Department of Civil Engineering, University of British Columbia, Canada
[2] Department of Civil and Environmental Engineering, University of Alberta, Canada
[*1]banthia@civil.ubc.ca; [2] vivek@ualberta.ca

***Abstract*- In most cases, Fiber Reinforced Concrete (FRC) contains only one type of fiber. However, 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 process of combining two or more fibers, often called hybridization, is investigated in this paper under quasi-static flexure and impact flexure conditions. Besides a reference plain mix, single-fiber and two-fiber hybrid composites were cast using diverse combinations of two types of macro-steel fibers and a micro-cellulose fiber. Quasi-static and impact flexural tests were performed and the results were analyzed to identify synergy, if any, associated with various fiber combinations. The paper identifies fiber combinations that demonstrate maximum synergy under impact.**

Keywords- Concrete; Fiber Reinforced Concrete; Toughness; Steel Fiber; Cellulose Fiber; Hybrid Composites; Strength; Energy Absorption; Flexure Impact; Synergy

I. INTRODUCTION

Concrete, as is well-known, is a brittle material with a low strain capacity. Fortunately, it is also well established that reinforcing concrete with short randomly distributed fibers can address some of the concerns related to concrete brittleness and its poor resistance to crack growth [1]. Although fracture in concrete is a multi-scale process [2] requiring improvements in the toughening mechanisms at various dimensional levels, in practice, most concrete contains only one type of fiber. The gradual and multi-scale nature of fracture in concrete even when it is fiber reinforced implies that a given fiber can provide reinforcement only at one level and within a limited range of strains. For an optimal response, therefore, different types of fibers must be combined. Such fiber reinforced concrete (FRC) with a combination of different types of fibers is often called Hybrid FRC, abbreviated as HyFRC.

A brief summary of published research on HyFRC is provided in Table 1. In spite of these efforts, experience shows that clearly, our understanding of what exactly constitutes an optimal combination of fibers capable of producing maximum synergy in performance remains quite limited. Furthermore, most previous studies have focused on quasi-static load application, and there is no available data to demonstrate the performance of HyFRC under impact. Accordingly, this paper is the outcome of studies undertaken at the University of British Columbia that examined possible synergy between fibers in FRC subjected to flexural loads under impact.

TABLE 1 STUDIES ON HYBRID FIBER REINFORCED CONCRETE (P: POLYPROPYLENE; S: STEEL; G: GLASS; AS: ASBESTOS; CA: CARBON, PVA: POLY VINYL ALCOHOL; GS: GALVANIZED STEEL; AL: ALUMINA; PE: POLYETHYLENE; CMP: CARBON MESOPHASE PITCH-BASED, CIP: CARBON ISOTROPIC PITCH-BASED)

Reference	**Hybrid Fibers Investigated**	**Major Findings**
Walton et al. [3]	P, N, G, As, Ca	Organic and inorganic fibers work together to produce improvement in both tensile and impact properties.
Glavind et al. [4]	S, P	Hybridization of these two fibers increased the ultimate compressive strain of the composite.
Larsen et al. [4]	S, P	After 10 years of out-door exposure, fracture energy of hybrid composite increased by approximately 40%.
Feldman et al. [6]	S, P	Stiffer steel fibers improved the ultimate strength; ductile polypropylene fibers improved post-peak strain capacity
Komlos et al. [7]	S, P	HyFRC with polypropylene fibers showed better post-crack responses and higher impact strengths.
Qian et al. [8]	S, P	Hybrid Composites had a higher K_{IC} but the synergy disappeared in the large displacement range.
Kim et al. [9]	S, P	The resistance to the initiation of the first crack and the toughness improved remarkably due to hybridization.
Horiguchi et al. [9]	S, PVA	HyFRC showed greater first crack deflection for the same flexural toughness.
Soroushian et al. [10]	P, Pe	Hybrids were beneficial in impact loading and for improving

		flexural strength and toughness.
Mobasher et al. [11]	Al, Ca, P	Peak load increased by as much as 75% compared to composite containing only polypropylene.
Stroeven et al. [12]	Ca, S, P	Hybridization improved the composite toughness and pull-out resistance of steel fibers.
Ramanalingam et al. [13]	PVA (micro and macro), S	Hybridization provided significant increases to both ultimate load and post-peak ductility.
Sun et al. [14]	S, P, PVA	Combining various lengths of steel fibers lowers the shrinkage strains. Permeability decreased in other HyFRC.
Hua et al. [15]	Ca, P	Fatigue properties of concrete were improved by using the carbon + polypropylene hybrids.
Lawler et al. [16]	S, P	Hybridization was shown to reduced the permeability of cracked hybrid fiber reinforced mortar under load
Banthia and Sheng [17]	Ca, S	In hybrids, steel fibers contributed to strengthening and carbon fiber to toughening.
Banthia and Soleimani [18]	S, CMP, CIP, P	Flexural toughness tests on normal strength concrete indicate CIP fiber with its greater strain capacity produced higher performance HyFRC than the CMP fiber.
Banthia and Gupta [19]	S, CMP, P	Very high strength matrices were investigated for flexural toughness and only in some cases synergy was noted. .
Banthia and Sappakittipakorn [20]	S (various diameters)	Large diameter crimped steel fibers were hybridized with smaller diameter crimped steel fibers.

II. EXPERIMENTAL PROGRAM

A. Materials, Mixtures and Specimens

Three types of fiber—two of steel and one of cellulose—as shown in Table 2— were investigated. The Hooked-End (HE) fiber is a well-known deformed steel fiber produced by Bekaert Corporation. The Double-Deformed (DD) fiber is a relatively recent steel fiber described in details elsewhere (21). The fiber has two deformations—one sacrificial and one for drag enhancement.

TABLE 2 FIBERS INVESTIGATED

Fiber	Type	Length, (mm)	Dia. (mm)	Picture	E (GPa)	Tensile Strength (MPa)	Density (kg/m^3)
HE	Hooked-End Steel	30	0.5		212	1200	7850
DD	Double Deformed Steel	30	0.5		212	1150	7850
C	Cellulose Fiber	2.3 mm	16 µm		35	300	1100

The Cellulose fiber (C) used was a virgin, fully purified plantation softwood fiber produced by Buckeye Corporation. This fiber was chosen because of its small length (2.3 mm) and because, alone it is found to be good only for microcracks and not effective to enhance flexural toughness at medium to large crack openings. These hydrophilic fibers are collated in the form of a chip and carry a surface treatment applied to enhance their alkali tolerance and their bond with concrete. They absorb water during mixing which then becomes available for internal curing and pore refinement especially at the fiber-matrix interface.

In all ten mixtures—one plain and the other nine reinforced with fibers— were investigated (see Table 3 for details). Mixture proportions were as follows: Sand = 557 kg/m^3; Coarse Aggregate (14 mm maximum size) = 1113 kg/m^3; Cement = 400 kg/m^3 and Water = 180 kg/m^3. ASTM Type I normal Portland cement, saturated surface-dry (SSD) clean river sand (fineness modulus = 2.5), and crushed gravel were used. When appropriate, a commercially available Glenium-based high range water reducing admixture "RHEOBUILD 3000FC" (Glenium Polycarboxylate) was also used to achieve adequate workability. It is commonly known that in fiber reinforced concrete proper fiber dispersion may be challenging especially at high fiber dosages. In this study, a high shear mixer was used. The cellulose fiber was added to the cement paste as it was being mixed at high speed. Next the mixer speed was reduced and aggregates and high range water reducing admixture were introduced. Finally, the steel fibers were added and mixing continued. From each mixture, ten 100 mm x100 mm x 350 mm prismatic specimens and six 100 mm x 200 mm cylinders were cast using a vibrating table. Specimens were de-moulded 24 hours after casting and stored for an additional 27 days under controlled conditions at 23±3 ℃ and 100% RH.

TABLE 3 MIXTURE PROPORTIONS AND PROPERTIES

Mixture	Fiber Type			f'_c (*averaged*)	VeBe, *s*
	HE	**DD**	**C**	**MPa**	**s**
	Fiber Volume Fraction (%)				
1	---	---	---	56	2
2	0.3	---	---	55	3
3	0.3	---	0.5	54	7
4	---	0.3	---	51	3
5	---	0.3	0.5	58	7
6	0.5	---	---	52	4
7	0.5	---	0.5	61	9
8	---	0.5	---	49	4
9	---	0.5	0.5	46	8
10	---	---	0.5	59	5

B. Tests on Hardened Concrete

The cylinders were tested as per ASTM C39 [24] to obtain compressive strengths. The prismatic specimens were tested for flexure, five replicates each under quasi-static and impact loading, as per the procedures outlined below:

C. Flexural Tests

Specimens were tested for flexural toughness as per ASTM C1609 [25], Figure 1. As was seen, a special yoke was used to support the LVDTs, and the net deflections were recorded devoid of extraneous deflections arising from support settlement and load point crushing. The output from the ASTM C1609 test is in the form of a load versus deflection curve, which was then further analyzed to obtain a measure of energy absorption or 'toughness' of the material. ASTM 1609 requires the calculation of various toughness parameters from the load versus deflection curve at various fractions of the span. An alternate method often adopted to analyze the same curve is the Japan Society of Civil Engineers (JSCE) method using flexural toughness factor, FT_{δ} [26].

Fig. 1 Flexural tests per ASTM C1609

$$FT_{\delta} = \frac{T_{b,\delta} L}{\delta b d^2} \tag{1}$$

where, FT_{δ} = Flexural toughness factor at a beam displacement of δ, $T_{b,\delta}$ = Area under the curve to a bean displacement of δ, L = span, b = width and d = depth of the beam.

Given that JSCE analysis technique is better at capturing the overall trends in toughness (and a similar parallel approach has also been suggested by ASTM C1609), the same was adopted here.

D. Impact Tests

There are currently no standardized test procedures available for impact tests. Here, a technique developed at the University of British Columbia [called the UBC Method, Ref. (23)] was adopted. An instrumented drop-weight impact-testing machine was used, details of which can be found elsewhere [27]. Briefly, the 1.5 kJ capacity machine is capable of dropping a 60 kg mass from heights of up to 2.5 m on to a beam specimen supported on two anvils. The test is fully instrumented [23]. For the tests reported here, a hammer drop height of 0.45 m and a beam span of 300 mm were chosen. This produced an average stress-rate of 28830 MPa/s (corresponding strain rate ≈ 0.71/s). When compared with the quasi-static stress-rate generated in most standardized tests, impact loading generated a stress-rate that was 2 x 10^6 times greater. The setup for impact tests is shown in Figure 2.

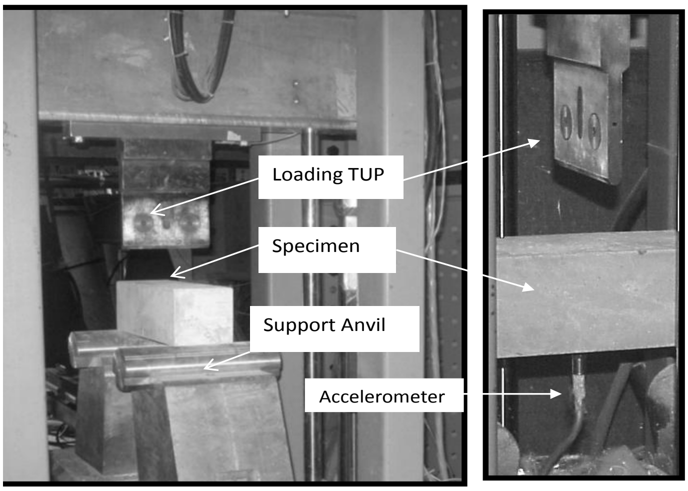

Fig. 2 Setup for impact tests

E. Impact Analysis

Based on previous observations [23], acceleration distribution along the length of the beam can be assumed to be linear with the maximum value at the center.

As has been shown before [23, 27], the generalized inertial load can be obtained as:

$$P_i(t) = \rho A.\ddot{u}_o(t)\left[\frac{l}{3} + \frac{8(ov)^3}{3l^2}\right] \tag{2}$$

where, ρ = mass density, A is cross-sectional area of the beam, $P_i(t)$ = the generalized inertial load acting at the center of the beam, l = clear span of the beam, ov = length of overhanging portion of the beam, $\ddot{u}_o(t)$ = mid-span acceleration of the beam at time t

The generalized bending load, $P_b(t)$, can then be obtained from the equation of dynamic equilibrium using the measured t up load, $P_t(t)$:

$$P_b(t) = P_t(t) - P_i(t) \tag{3}$$

Once the acceleration history at the load-point is known, the velocity and displacement histories at the load-point can be obtained from it by integrating with respect to time.

$$\dot{u}_o(t) = \int \ddot{u}_o(t).dt \tag{4}$$

$$u_o(t) = \int \dot{u}_o(t).dt \tag{5}$$

where, $u_o(t)$ = mid-span deflection of the beam at time t,

$\dot{u}_o(t)$ = velocity at the load-point,

Using $P_b(t)$ and $u_o(t)$, the applied (stressing) load vs. load-point displacement plots can be obtained, which can then be compared directly with the static load-displacement plots obtained from the companion slow-rate beam tests as per ASTM C1609 described before.

III. RESULTS AND DISCUSSION

A. Quasi-static Loading

Representative plots between the load and deflection (averaged over the 5 replicates in each case) for the various composites are given in Figure 3. In Figure 3(a), composites based on the HE (Hooked End) fiber are presented and in Figure

3(b), composites based on the DD (Double Deformed) Fiber are presented.

As is seen in Figures 3(a) and 3(b), the cellulose fiber by itself is unable to impart toughness (the curves of plain concrete and composite 0.5C are almost identical). The likely reason is the small length of the cellulose fiber which provides insignificant post-crack bridging. Also, cellulose fibers are hydrophilic and well bonded to concrete and so the cellulose fiber presumably fractures across a matrix crack and fails to provide post-crack ductility. Both steel fibers, on the other hand, can be seen to be very effective in enhancing toughness.

To further analyze the curves and understand the effectiveness of fiber hybridization, flexural toughness factors (FT_{δ} in Equation 1) were calculated for beam deflections (δ) of 0.5 mm, 1 mm and 1.5 mm.

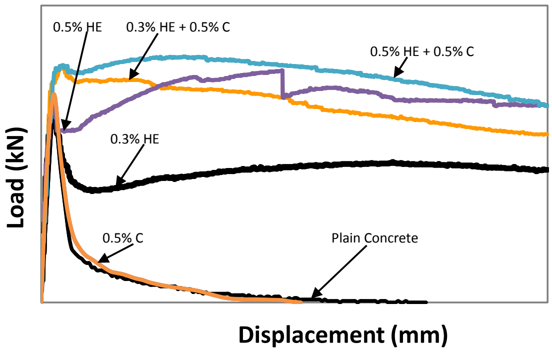

Fig. 3a Quasi-static flexural response, HE Fiber

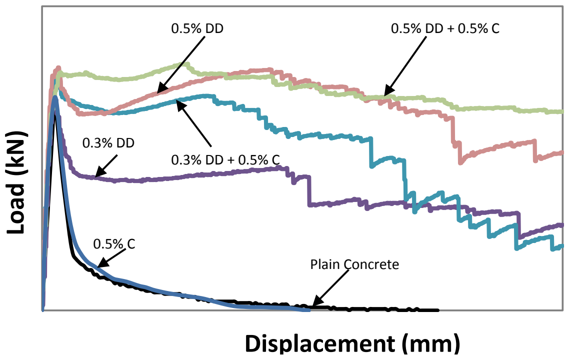

Fig. 3b Quasi-static flexural response, DD Fiber

B. Impact Loading

Representative plots of the average load and deflection for the various composites are given in Figure 4. In Figure 4(a), composites based on the HE (Hooked End) Fiber are presented and in Figure 4(b), composites based on the DD (Double Deformed) Fiber are presented. Again, the plots in Figure 4 suggest that cellulose fiber by itself is unable to enhance impact toughness and the curves for plain concrete and the composite with 0.5% cellulose fiber are almost identical. To further analyze the curves and understand the effectiveness of fiber hybridization, absorbed energy values to ultimate impact deflection were computed.

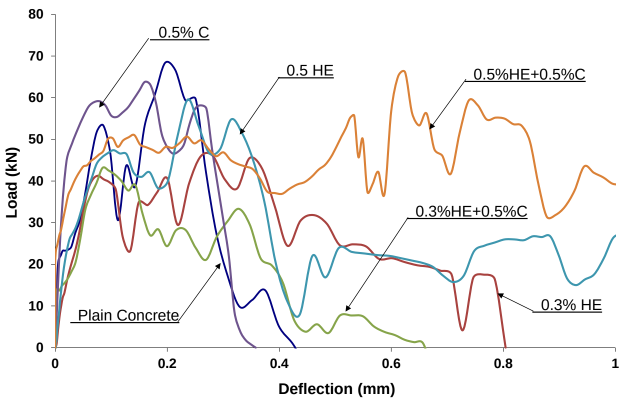

Fig. 4a Impact response, HE Fiber

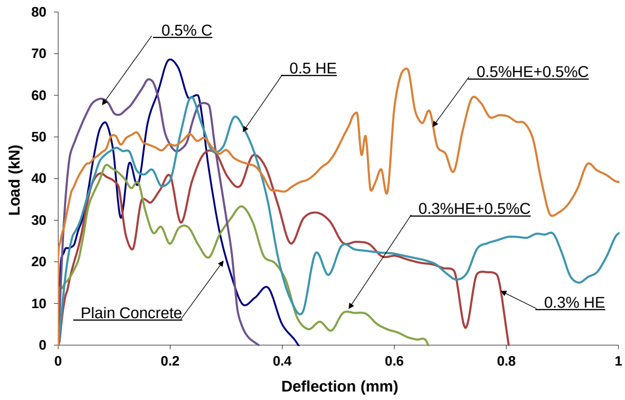

Fig. 4b Impact response, DD Fiber

C. Assessment of Synergy

It is critical to calculate synergy for the various hybrid mixes to understand if indeed hybridization is successful. For the purpose of this study, *Synergy* was evaluated using Eq. (6).

$$Synergy = \frac{\left(X_{Hybrid(a+b)} - X_{plain}\right) - \left[\left(X_a - X_{plain}\right) + \left(X_b - X_{plain}\right)\right]}{\left[\left(X_a - X_{plain}\right) + \left(X_b - X_{plain}\right)\right]} \tag{6}$$

Where 'X' is the property under consideration (FT_δ for example), $X_{Hybrid\,(a+b)}$ is the property for the hybrid carrying fibers *a* and *b*, X_a or X_b is the value of the property when either fiber *a* or fiber *b* only is present, and X_{plain} is the property in question for plain concrete. The idea behind the approach is that a positive *Synergy* (>0) is realized when a hybrid combination of fibers improves a property so that the value is numerically greater than the sum of the value associated with that property produced by the individual fibers. A zero value of *Synergy* means that the synergy is absent, and a negative value indicates that the hybrid in question is performing poorer than the sum of its parts.

The *Synergy* noted in quasi-static flexure (based on FT_δ values) is plotted in Figure 5. Notice that in all instances, there is an indication of positive synergy. Remarkably, cellulose fiber which does not add much to the toughness by itself was effective in contributing to toughness in the presence of steel fibers. The *Synergy*, however, in all cases decreased as the beam displacement increased from 0.5 mm to 2.0 mm. This implies that hybridization is more effective at small crack openings. This may be the consequence of hybridizing a fiber of smaller length with one with a longer length.

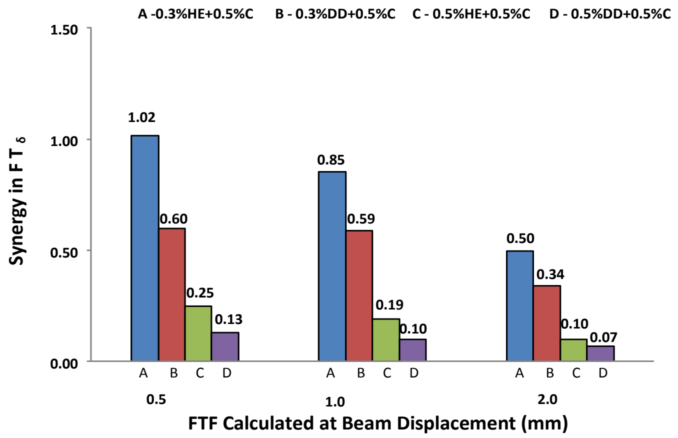

Fig. 5 Synergy in quasi-static flexure

When composites with Fiber HE are compared with those with Fiber DD, both fibers appear to be effective candidates for hybridization with cellulose. However, as mentioned earlier, with both these steel fibers, hybridization is less effective at higher dosage rates. Also, consistently, the DD fiber is less effective than the HE fiber. The *Synergy* noted under impact loading (based on the total impact energy absorbed regardless of the beam deflection) is plotted in Figure 6. Notice that for the four hybrid composites tested, only the one based on 0.3% of HE fiber did not show *Synergy* in impact—all others did. *Synergy*, when noted, was also numerically of the same order of magnitude as in quasi-static flexure (Figure 5). The fact that 0.3% of HE fiber did not show *Synergy* in impact is likely associated with the fact that such a composite also showed the greatest synergy under quasi-static loading where performance limits were already attained. For a composite that has been fully optimized under quasi-static condition with fiber stresses approaching material strengths, a brittle response under impact is often expected as fiber fractures would become apparent at high rates of loading. That is to say, this anomaly clearly requires further investigation using crack-growth studies and various other fiber combinations to ascertain what may be the real cause for this lack of synergy in 0.3% HE composite.

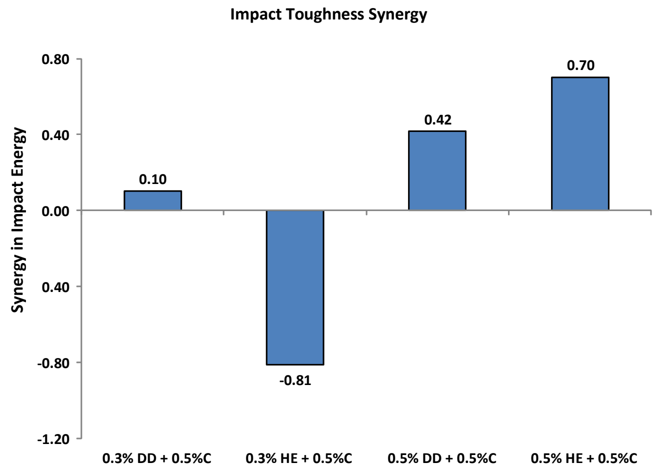

Fig. 6 Synergy in impact flexure

The choice of a hybrid mix must be made based on details of the structure and the expected loading. Whereas under quasi-static loading, the HE fiber was better than the DD fiber in providing synergy with cellulose fiber, under impact, one can conclude that the DD fiber at low dosages is an ideal candidate for hybridization with cellulose fiber.

IV. CONCLUSIONS

Based on the toughness measurements and *Synergy* quantification, the following conclusions can be drawn:

1. When by themselves, the two steel fibers demonstrate a comparable performance in quasi-static and impact flexure. The cellulose fiber, on the other hand, does not impart toughness under any mode of loading and this is likely due to its small length and an excessively strong bond with concrete.

2. For the hybrid composites, the following conclusions may be drawn:

i. Under quasi-static flexure (based on FTδ values), there is a clear indication of positive Synergy between steel and cellulose fibers in all combinations. Interestingly, cellulose fiber, which by itself does not add much to the toughness of plain concrete, is an effective contributor to toughness in the presence of a steel fiber. Synergy is more pronounced at smaller crack openings and at smaller dosage rates of steel fiber. While both Fiber HE and Fiber DD are effective candidates for hybridization with cellulose, Fiber DD is somewhat less effective than Fiber HE.

ii. Under impact loading, based on the total energy, most hybrid combinations demonstrated Synergy. The Synergy, when noted, was of the same order of magnitude as in quasi-static flexure.

iii. Overall, a hybrid combination of steel macro-fiber and cellulose micro-fiber appears to produce an excellent synergistic response in most cases and under both loading configurations.

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