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Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear

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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 has the potential to improve the mechanical properties of concrete, and result in performance synergy. This combining of fibers, often called hybridization, is investigated in this paper under flexure and direct shear. Along with a reference plain concrete mix, several single-fiber reinforced concrete mixes and two-fiber reinforced hybrid composite mixes were cast using diverse fiber combinations. Two types of macro-steel fibers and a micro-cellulose fiber were examined. Flexural and direct shear tests were performed and the results were analyzed to identify synergy, if any, associated with various fiber combinations. The paper highlights the influence of load configuration on fiber synergy.

1. Introduction

Concrete is a brittle material with a low strain capacity. Fortunately, reinforcement of concrete with short randomly distributed fibers can address some of the concerns related to concrete brittleness and its poor resistance to crack growth [1]. Yet, fracture in concrete is a multi-scale process [2] and merits improvement to the toughening mechanisms at various dimensional levels. The use of conventional reinforcing bars addresses crack arrest at only specific sections and at a single scale. While fiber reinforcement ensures a random distribution of crack arrest zones within concrete, most fiber reinforced concrete (FRC) mixes are reinforced at only a single scale, containing as they do, only one type of fiber. A summary of the published research on concrete reinforced with multiple fiber types is provided in Table 1. The collection of papers reviewed conveys that the gradual and multi-scale nature of fracture in concrete necessitates that a given fiber can provide reinforcement only at one level and within a limited range of strains. In order to obtain an optimal response, therefore, different types of fibers varying in constitutive response, size or function, must be combined. The resulting fiber reinforced concrete mix is often called hybrid FRC and abbreviated here as HyFRC.

In spite of these efforts, 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 flexural load application, and there is no available data to demonstrate the performance of HyFRC under direct shear, where fibers are known to be most efficient in concrete. There is also a great deal of current interest in natural fibers such as cellulose, and its performance in HyFRC has never been investigated. Accordingly, this study was undertaken to combine steel and cellulose fibers in HyFRC and to assess the response under flexure and direct shear.

2. Research significance

Fracture in concrete is a gradual, multi-scale process, occurring at both the micro and the macro levels. For fiber reinforced concrete, therefore, it is very limiting when only one type and dimension of fiber is used as reinforcement. Such a reinforcement clearly restricts crack growth at its own scale and has little or no influence on fracture processes at other scales. For maximum

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Table 1
Sample of studies on HyFRC (P: Polypropylene; S: Steel; G: Glass; As: Asbestos; C: 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 and Majumdar [3]	P, N, G, As, C	Organic and inorganic fibers work together to produce improvement in both tensile and impact properties
Glavind and Aarre [4]	S, P	Hybridization of these two fibers increased the ultimate compressive strain of the composite
Larson and Krenchel [5]	S, P	After 10 years of out-door exposure, fracture energy of hybrid composite increased by approximately 40%
Feldman and Zheng [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 and Stroven [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 and Sakai [10]	S, PVA	HyFRC showed greater first crack deflection for the same flexural toughness
Soroushian et al. [11]	P, Pe	Hybrids were beneficial in impact loading and for improving flexural strength and toughness
Mobasher and Li [12]	Al, C, P	Peak load increased by as much as 75% compared to composite containing only polypropylene
Stroeven et al. [13]	C, S, P	Hybridization improved the composite toughness and pull-out resistance of steel fibers
Ramanalingam et al. [14]	PVA (micro and macro), S	Hybridization provided significant increases to both ultimate load and post-peak ductility
Sun et al. [15]	S (various lengths), P, PVA	Combining various lengths of steel fibers lowers the shrinkage strains. Permeability decreased in other HyFRC
Hua et al. [16]	C, P	Fatigue properties of concrete were improved by using the carbon + polypropylene hybrids
Lawler et al. [17]	S, P	Hybridization was shown to reduced the permeability of cracked hybrid fiber reinforced mortar under load
Banthia and Sheng [18]	C, S	In hybrids, steel fibers contributed to strengthening and carbon fiber to toughening
Banthia and Soleimani [19]	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 [20]	S, CMP, P	Very high strength matrices were investigated for flexural toughness and only in some cases synergy was noted
Banthia and Sappakittipakorn [21]	S (various diameters)	Large diameter crimped steel fibers were partially replaced with smaller diameter crimped steel fibers. This hybrid resulted in a significantly higher toughness

reinforcing efficiency, fibers of various sizes and moduli must be combined in a rational manner, and the limited amount of work that has been carried out in this area has for the most part considered flexural loading only. In this paper, hybrid FRC mixes carrying various combinations of steel and cellulose fibers were studied under flexure and direct shear, and any synergy in fiber performance has been identified.

3. Experimental program

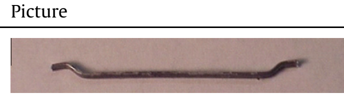
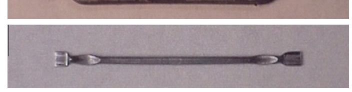
3.1. Materials, mixtures and specimens

Three types of fibers—two of steel and one of cellulose—as shown in Table 2—were investigated. The Hooked-End fiber (HE), a well known deformed fiber, has been in commercial use extensively since the 1970s. The Double-Deformed fiber (DD) is a relatively recent development described in detail elsewhere [22]. This fiber has two types of deformations—one of which is sacrificial, known as the 'dead' anchor and the other for drag enhancement. The cellulose fiber (C) used was a fully purified plantation softwood fiber. This fiber was chosen because of its small length (2.3 mm) and because of its ability to enhance flexural toughness at micro and meso scale crack opening displacements [23]. These hydrophilic fibers are collated in the form of a chip and carry a surface treatment applied to enhance their alkali tolerance and bond with concrete. Upon mixing, each chip may potentially disperse into 30,000 individual fibers. It is suggested that they absorb water during mixing which then becomes available for internal curing and pore refinement especially at the fiber–matrix interface [24].

In all, ten concrete mixtures—one plain and nine fiber reinforced concrete—were investigated (see Table 3 for details). All of these mixtures had the same amount of sand, aggregate, water and cement. The only difference was the amount and/or the type of fibers and their combination. The mix proportions were as follows: Sand = 560 kg/m^3; Coarse Aggregate (14 mm maximum size) = 1110 kg/m^3; Cement = 400 kg/m^3 and Water = 180 kg/m^3. An ordinary Portland cement, classified as Type GU [25], along with a saturated surface-dry (SSD) washed river sand (fineness modulus = 2.5) and crushed gravel were used. When appropriate, a commercially available high range water reducing admixture derived from a polycarboxylate ether was used to achieve adequate workability.

From each mix, fifteen prism specimens, 100 mm × 100 mm × 350 mm in dimension, and six cylinders, 100 mm × 200 mm, were

Table 2
Fibers investigated.

Fiber	Type	Length (mm)	Diameter (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

Note: 25.4 mm = 1 in; 1 MPa = 0.145 ksi; 1 GPa = 145 ksi; 1 kg/m^3 = 1.66 lb/yd^3.