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Self-consolidating hybrid fiber reinforced concrete: Development, properties and composite behavior

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HIGHLIGHTS

- A self-consolidating hybrid fiber reinforced concrete composite was developed.
- The composite exhibits high workability and deflection hardening behavior.
- Fibers ensure ductile response and internal confinement in compression.
- Reinforced composites tested in tension exhibit tension stiffening behavior.

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ABSTRACT

The workability of an existing Hybrid Fiber-Reinforced Concrete (HyFRC) composite is improved though the incorporation of concepts from the field of Self-Consolidating Concrete (SCC). The resulting composite, achieved through a described parametric study, allows for easier placement within areas of high reinforcement congestion while maintaining the desired mechanical performance benefits inherent to high performance hybrid fiber-reinforced concrete composites. Retention of the strengthening and ductility enhancement, characteristic of the original HyFRC, is gauged by material response to direct tension and four point bending tests. The designated goal of the SC-HyFRC mix is to provide an optimal structural material for construction in which concrete might be expected to face tension, compression and bending as part of a common service load and must be designed to withstand high levels of deformation under maximum credible earthquake or similar design scenarios. The ductility response of Self Consolidating Hybrid Fiber Reinforced Concrete (SC-HyFRC) to severe loading is then investigated through a comparison with conventional concrete by conducting reinforced compression and tensile tests. In both scenarios the presence of hybrid fiber reinforcement is shown to provide an improvement to the phenomena of internal confinement and tension stiffening, for compression and tension loading respectively, which allow for a significantly improved post cracking response.

1. Introduction

As a widely used structural material, the material properties of concrete are critical toward determination of structural ductility and reliability. Despite its popularity in large scale structures, concrete suffers material limitations; specifically with respect to its inability to carry moderate tension forces as experienced in flexural or direct tension loading. In compression loading, the maximum capacity and subsequent ductility can only be reached upon the addition of confining stress, commonly applied through reinforcing steel stirrups/spirals. To improve the intrinsic properties of concrete with respect to both tension loading and element ductility, fibers can be introduced into the mixing process. Introduction of fibers into the cement matrix provides additional energy absorption mechanisms to delay crack growth and element failure. Fibers present in the fracture process zone ahead of the crack tip can subdue and delay crack propagation, while fibers incorporated in the crack wake provide a load transfer path to maintain load carrying capacity and restrict crack growth. The addition of multi-scale fiber reinforcement optimizes fiber-crack interactions through the process of delaying macrocrack formation and providing post cracking ductility. The concept of multi scale fiber incorporation in concrete has started with Rossi [1] and described in [2] with studies focused on steel fiber and multi type fiber additions respectively. The mix developed and described by Blunt and Ostertag [3] and advanced in this study incorporating both steel and polyvinyl alcohol (PVA) fiber types shall hereafter be

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referred to as Hybrid Fiber-Reinforced Concrete (HyFRC). The steel fibers include two discrete hooked end fibers of differing lengths and aspect ratios for the purpose of macrocrack interactions, while a single type straight PVA microfiber was used to stabilize microcracks. Fiber hybridization incorporating a low volume fraction of PVA fibers has been shown experimentally in [2,4] to produce measurable improvements to composite strength in relation to fiber reinforced cementitious composites comprising solely macrofibers.

While the improved toughness property of fiber reinforced concrete is typically in direct relation to the included fiber content [5,6], the feasibility of high fiber volume inclusion has not been realized in a conventional concrete matrix. The reasons for this lie in the mixing and placement procedures for concrete which require workability, subjectively measured as an ability to adequately disperse all components and consolidate into formwork. Conventional fiber reinforced mix designs limit the allowable fiber content to less than two percent by volume [7], but even under these restrictions supplementary materials may be required to aid in the mixing process and extra care must be given to ensure satisfactory consolidation during placement. With the gaining popularity of Self-Consolidating Concrete (SCC) in construction practice, the potential for a marriage of concepts is expected to provide increased workability at currently evaluated levels of fiber volume fraction. The application of self-consolidating properties to fiber-reinforced concrete have been studied under a variety of different fiber mixes [8–12], however few studies have specifically focused on the integration of multi type fibers and the specific optimizations that must be taken to reduce the risk of segregation and ensure proper fiber dispersion. One of the objectives of this study was to apply the concepts of SCC to HyFRC and hence develop a Self-Consolidating Hybrid Fiber-Reinforced Concrete (SC-HyFRC) which maintains the cracking resistance of HyFRC while being workable enough to place without the external vibration techniques employed to consolidate HyFRC.

The other objective of the program was to study the composite response of the developed SC-HyFRC with conventional reinforcement. Investigating the composite response provides a measure of the stress distributions found within true reinforced concrete structures. For conventional concrete under high seismic demands, transverse reinforcement of slender elements such as bridge columns is required to generate confining stresses and ensure ductile response of the reinforced concrete beyond its intrinsic compressive strength and corresponding strain value [13]. To ensure this type of behavior the content of reinforcing steel in concrete is increased. Having previously observed ductile response with fiber reinforcement under direct compression loading [14,15], it is theorized that the internal confinement provided by fiber inclusions in SC-HyFRC can reduce the demand placed on transverse reinforcement and achieve the same composite ductile response at reduced confining steel reinforcement ratios. For conventional reinforced concrete under tensile loading, the contribution of tensile concrete is known as tension stiffening; it affects the member's stiffness after cracking and is an important consideration when designing for deflection and crack control at the serviceability limit states. However, due to the limited tensile strain capacity of conventional concrete, this stiffening effect is often confined to a small range of elastic strain and has no influence upon the composite response at the stage of reinforcement yielding [16,17]. Through the incorporation of fiber reinforcement, SC-HyFRC can sustain stress across developed cracks which allows the material to contribute to composite strengthening beyond conventional composite performance.

The paper first describes the parametric development of the SC-HyFRC mix. The ultimate goal was to design a SC-HyFRC that allows for easier placement within areas of high reinforcement congestion while maintaining the desired mechanical performance benefits inherent to the high performance hybrid fiber-reinforced concrete composite. The paper also provides information on the mechanical performance of SC-HyFRC by conducting reinforced compression and tensile tests. This information is essential for use of SC-HyFRC for structural applications. The multi-scale crack resistance due to fiber hybridization is expected to provide improved internal confinement and enhanced tension stiffening behavior for compression and tension loading respectively.

2. Materials and methods

2.1. Materials

Concrete materials for this project consisted of Quickcrete Portland cement conforming to ASTM C150 Type I/II, fly ash conforming to ASTM C618 Type F, pea gravel with a maximum size aggregate of 9.5 mm, and Vulcan sand with a measured fineness modulus of 3.2. Chemical admixtures were provided by BASF Admixtures, namely Glenium 3030NS polycarboxylate superplasticizer (SP) and Rheomac VMA 358, an organic viscosity modifying admixture (VMA), with a later product update to Rheomac VMA 362. Fiber reinforcement was provided by Dramix steel fibers produced by Bakaert and Kuralon PVA fibers produced by Nycon, with provided material and geometry properties listed in Table 1. Batch mix volumes ranged from 0.008 cubic meters for trial mix batches to 0.300 cubic meters for casting of scaled bridge column specimens simultaneously under investigation. SC-HyFRC production was carried out in pan-style mixers of appropriate size for their batch volumes. Steel fiber reinforcement was introduced into a wet concrete mix leaving approximately one quarter of each chemical admixture in reserve. After achieving steel fiber dispersion, PVA fibers were introduced in conjunction with the remaining admixture components and mixing continued until scoop sampling was shown to have dispersion of microfibers.

2.2. Self-consolidation measurement technique

Following ASTM C1611, the slump flow test was performed on all mixes which did not suffer from segregation problems within the mixing bowl. The slump flow test was carried out by filling a standard upright standing slump cone with freshly mixed concrete and measuring the diameter of concrete spread when the cone was lifted vertically. A rigid board of either plywood or plastic was used to provide a flat surface upon which to carry out the slump flow test. When using the wooden board, a cover sheet of plastic was placed over the board with the plastic contact surface being wiped clean with a wet sponge before each test. Concentric circles marked on the boards allowed for visual indication of strong preference for flow in a single direction. Flow diameters were measured along the longest axis of the resulting circle or ellipse and the axis perpendicular to it, with an average value reported. In general, to be considered viable for further investigation, a mix was required to achieve a diameter of similar scale in both directions. Later mixes also incorporated a measurement of the highest peak of concrete, with smaller heights indicating a more uniform spreading behavior. Ideal performance in the slump flow test is achieved when a pancake like form is attained with equivalent maximum spread diameters in orthogonal directions being greater than 600 mm and minimum peak height.

The slump flow test also allowed for determination of segregation tendencies of each mix by visual inspection of the spread behavior. If fine and coarse aggregates were not present in the outermost edge, the mix was determined to have undergone "concrete segregation". The flow behavior of fibers within concrete was analyzed by measuring the presence and concentration of fibers within the outermost 50 mm ring of spread and by inspection for "fiber clumping" behavior within the initial slump cone diameter leading to an interlocked fiber mound structure at the center of the concrete spread. Failing either of these visual measurements resulted in labeling of that trial mix as suffering "fiber segregation".

During later stages of development, the passing ability of promising trial mixes was measured through reinforcement cages designed to mimic the reinforcing ratios and clear spacing encountered in laboratory test specimens and structures. The two cage geometries were constructed to represent tight transverse tie reinforcement of rectangular reinforced concrete beams (Fig. 1a) and the hinging base section of circular reinforced columns (Fig. 1b), with both structure types having

Table 1
Fiber properties.

	Material	Aspect ratio (L/D)	Tensile strength (MPa)	Elastic modulus (GPa)
RC-80/60-BN	Steel	80	1050	200
ZP 305	Steel	55	1100	200
RECS 15	PVA	200	1600	43