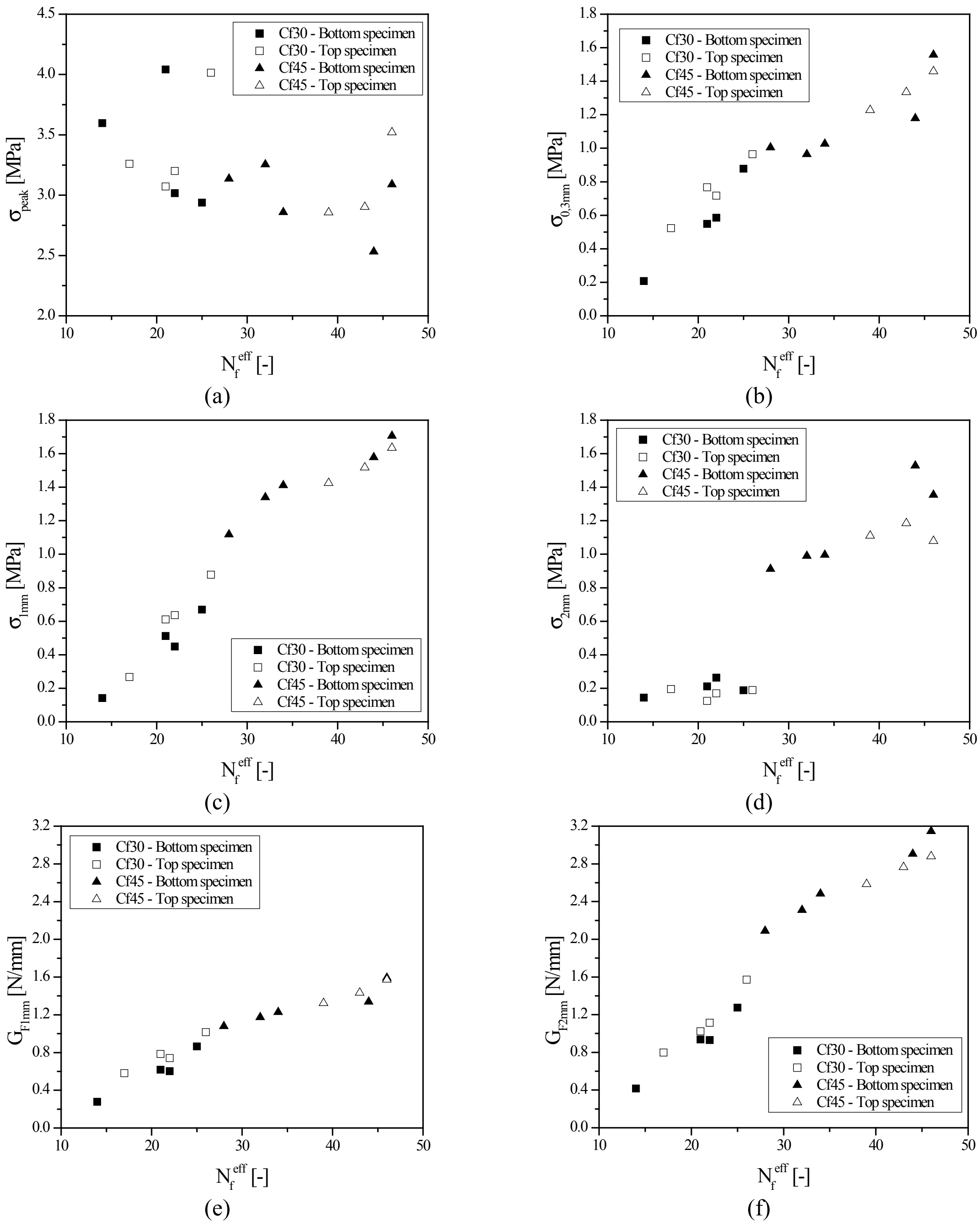

Figure 7 — Relationships between the number of effective fibers and the post-cracking parameters: (a) peak stress, (b), (c) and (d) stress at 0.3, 1 and 2 mm crack width, respectively; (e) and (f) dissipated energy up to 1 and 2 mm crack width, respectively

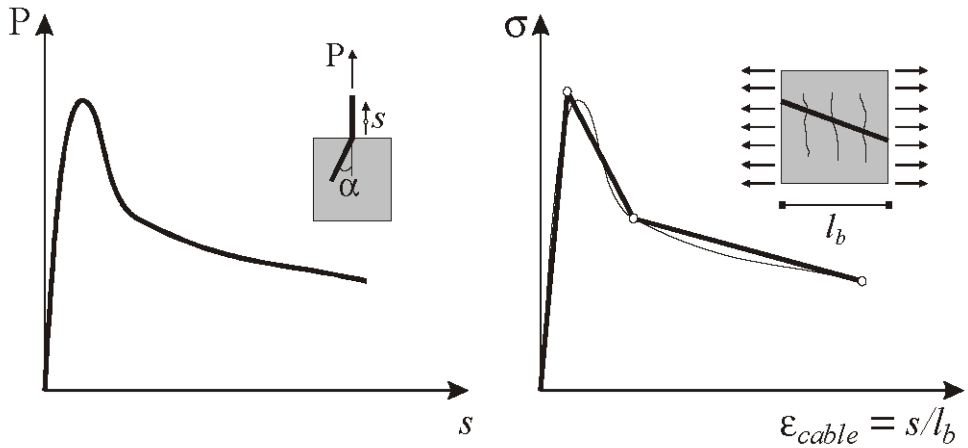

Figure 8 — Determination of the embedded cable's stress-strain diagram based on the experimental pullout force-slip relationship

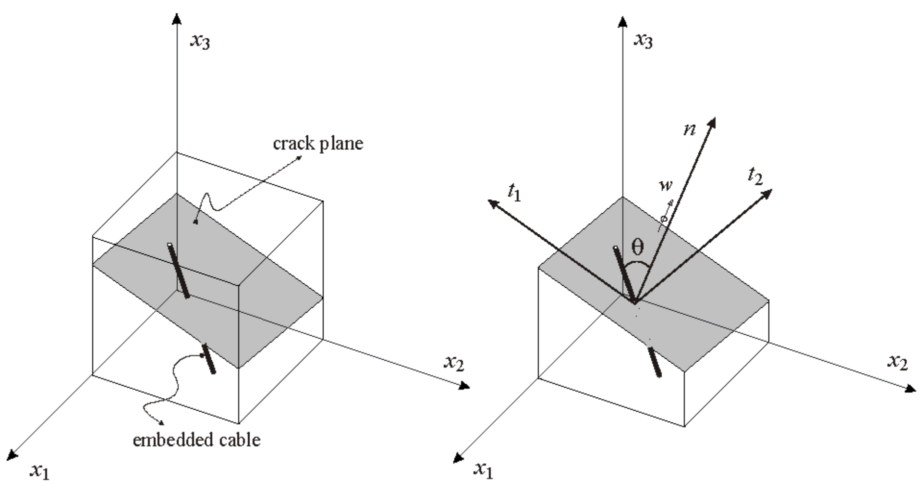

Figure 9 — Three-dimensional scheme of the embedded cable intersecting an active crack (n is the vector normal to the crack plane)

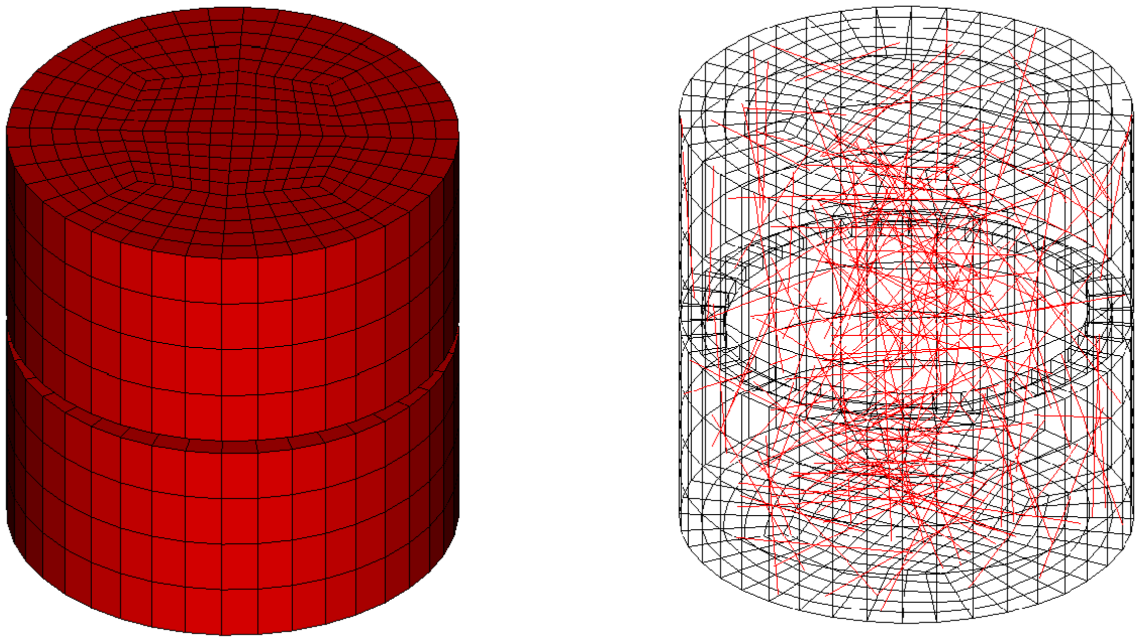

Figure 10 — Three-dimensional finite element mesh: (a) concrete phase and (b) concrete + fibers phases (Cf30 series; red lines represent the fibers)

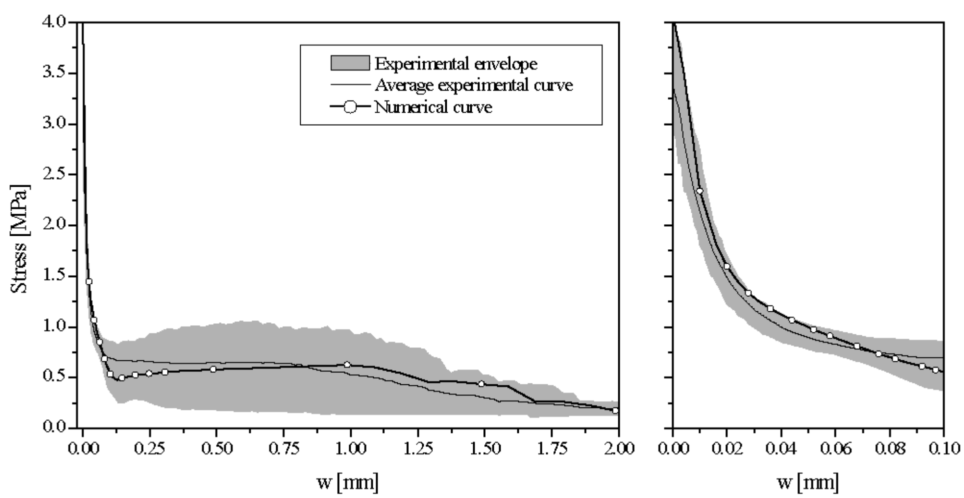

Figure 11 — Numerical simulation of the Cf30 series' uniaxial tension tests

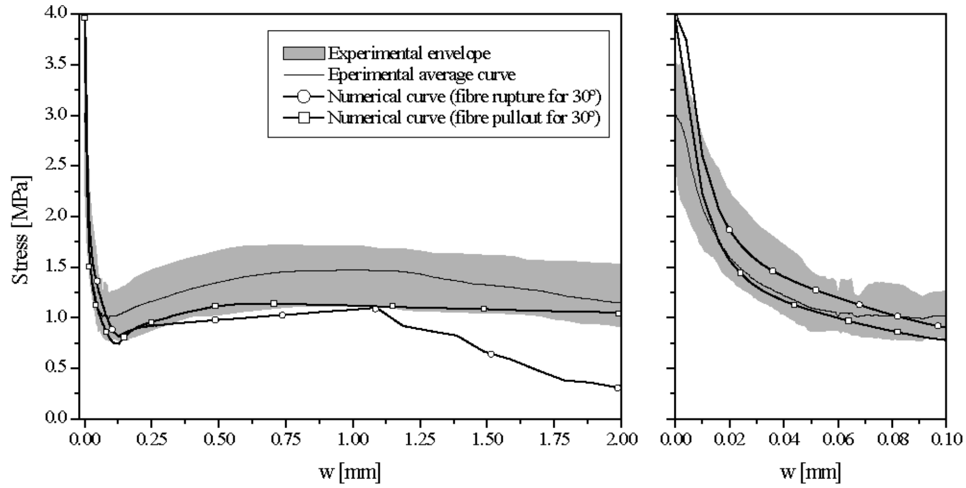

Figure 12 — Numerical simulation of the Cf45 series' uniaxial tension tests

Investigation of Steel and Polymer Fiber-Reinforced Self-Consolidating Concrete

by M. C. Brown, H. C. Ozyildirim, and W. L. Duke

Synopsis: Self-consolidating concrete (SCC) promises to shorten construction time while reducing the need for skilled labor. However, experience has shown that SCC may be prone to shrinkage cracking, which may compromise durability. In conventional concrete, fiber reinforcement has been used to control cracking and increase post-cracking tensile strength and flexural toughness. These benefits could be achieved in SCC without compromising the workability or stability, provided that the amount of fiber reinforcement is optimized.

This project sought to evaluate the feasibility of fiber reinforced self-consolidating concrete (FR-SCC) for structural applications. Tests were conducted in the laboratory to assess the fresh and hardened properties of FR-SCC containing various types and concentrations of fiber. The results indicate that SCC with high flowability and some residual strength beneficial for crack control can be prepared for use in transportation facilities. The results of the experiments further show that, at optimal fiber additions, FR-SCC mixtures can have the same fresh concrete properties as traditional SCC mixtures. FR-SCC also demonstrates a considerable improvement in the residual strength and toughness of a cracked section. Though not specifically measured, increase in residual strength and toughness is expected to lead to control of crack width and length (ACI 544.1R, 1996). The increase in the FR-SCCs' cracked section performance indicates that it can be expected to have better durability in service conditions than an identical SCC without fibers. In transportation structures FR-SCC can be used in link slabs, closure pours, formed concrete substructure repairs; or prestressed beams where end zone cracking has been an issue.

Keywords: concrete; crack control; fiber-reinforced concrete; residual strength; self-consolidating concrete; strength; toughness

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INTRODUCTION

Self-Consolidating Concrete

Self-consolidating concrete (SCC) was first developed in Japan in 1986 by Professor Hajime Okamura of the Kochi University of Technology (Ozawa et al, 1989). SCC mixtures can have a high workability and stability allowing them to be placed without the necessity of mechanical vibration, even in situations which require large amounts of reinforcing steel or complicated formwork (Vachon, 2002). The technology also assists in cutting costs by speeding up construction while also reducing the amount of skilled labor necessary to complete the job (Koehler, 2005).

SCC can provide smooth surfaces making it desirable in architectural applications. In transportation structures SCC can simplify casting in precast, prestressed concrete beams designed for bridge structures where long spans between supports are ideal. These beams are characterized by very heavy reinforcement that is densely packed, which make the consolidation of conventional concrete mixtures very difficult, leading to unwanted large voids in concrete. A properly designed SCC mixture eliminates the need for additional consolidation energy (vibration and compaction) and both the economy and the durability of the beams can be improved (ACI 237R, 2007).

Fiber-Reinforced Concrete

Concrete is by nature a heterogeneous and brittle material. Concrete does not perform well in tension because it fractures easily. The resulting cracks, once induced, can propagate quickly under structural or thermal loading or under restraint in cases of concrete shrinkage or other dimensional instability. Cracks allow water and other substances, such as deicing salts, to readily enter the concrete and corrode the steel reinforcement or react detrimentally with the concrete, reducing the durability of concrete.

Fiber Reinforced Concrete (FRC) may mitigate this problem in two ways; fibers restrain cracks from opening and act as a substitute or supplement for conventional steel reinforcement within the concrete (Maingay, 2004; ACI 544.1R, 1996). Fiber reinforcement for concrete is typically made of either steel or synthetic filaments. In most concrete applications, these fibers are generally 1 to 2 inches (25 to 50 mm) in length and designed to be added during the mixing process. Because the fiber reinforcement is added during mixing, it provides uniform tensile reinforcement throughout the concrete member. Even if this reinforcement is not relied upon for structural strength, it serves to hold a cracked concrete section tightly together during loading. By keeping the cracks from opening as wide, the cracks have less effect on the concrete permeability, slowing the corrosion process. Also, because the fibers can, in some cases, be used as a replacement to traditional reinforcement, corrosion problems can be reduced or eliminated through the use of synthetic fibers which do not corrode in water (Concrete Paving Assoc., 2003). Steel fibers in cast-in-place concrete slabs and pavements, or various shotcrete applications, can improve flexural toughness, impact resistance and flexural fatigue endurance (ACI 544.1R, 1996). Synthetic fibers have been incorporated into concrete slabs on grade, floor slabs and stay-in-place forms or precast elements for multi-story buildings (ACI 544.1R, 1996).

Fiber Reinforcement in Self-Consolidating Concrete

Merging the benefits of fiber reinforcement with self-consolidating concrete technology may pay dividends in construction efficiency and durability of concrete elements. A problem with SCC is that it may have large amounts of fine material and small maximum coarse aggregate size. The resulting comparatively large cumulative surface area onto which mix water will adhere may lead to greater water demand and, subsequently, excessive drying shrinkage. However, SCC mixtures are often designed with low water content for stability, which can serve to reduce potential for drying shrinkage. Thus, the shrinkage characteristics of the SCC mixtures will depend upon mixture proportions and the intended application. If shrinkage occurs, restrained stresses may result, which exceed the concrete tensile strength, resulting in cracks. This cracking will increase the permeability and may lead to durability problems. Through the addition of reinforcing fibers, cracking may be controlled (Slag Cement Assoc., 2005).

Construction with Fiber Reinforced Self-Consolidating Concrete (FR-SCC) may even be faster than with SCC because the need for traditional steel reinforcement could potentially be reduced or eliminated. In pavements and bridge decks designed with FR-SCC, the elimination of secondary reinforcing steel can lead to sections that can be built faster than those built with conventional construction techniques (Concrete Paving Association, 2003). These benefits have positive implications for reducing costs, through reduction of labor and materials for reinforcement placement, and possible public and worker safety enhancement through the reduction of overall construction times and required maintenance of traffic.

PURPOSE AND SCOPE

The purpose of this study was to investigate the properties of self-consolidating concrete containing fibers and to determine the feasibility of using such concretes in transportation facilities. Synthetic polymer and steel fibers were used at varying concentration in SCC.

METHODOLOGY

This section describes the mixture compositions and test methods. SCC mixtures with fibers were prepared in the laboratory in two phases. In the first phase, four different mixtures of fiber reinforced self-consolidating concrete (FR-SCC) were tested against a control mixture of regular SCC. Although American Concrete Institute (ACI) suggests 22 in slump flow as adequate for most structural applications, for this research, slump flow values exceeding 20 in were sought, which is sufficient for many typical transportation applications (ACI 237R, 2007). In the second phase, mixture proportions and fiber content were refined, and some alternate fibers were also investigated.

Mixtures

Concrete mixture proportions are given in Table 1 for Phases 1 and 2. They are expected to provide a minimum compressive strength of 4,000 psi and meet the requirements of Virginia Department of Transportation (VDOT) Class A4 concrete, common for bridge decks.

Table 1 Mixture Proportions for Phase 1 and 2 in lb/yd3 (kg/m^3)

Ingredient	Source	Phase 1	Phase 2
Cement	Type I/II	439 (260)	439 (260)
Slag Cement	Grade 120	236 (140)	236
Coarse1	Lime stone (SG=2.81)	1535 (911)	
Coarse2	Granite (SG=2.80)		1436 (852)
Fine1a	Natural sand (SG=2.60)	704 (418)	
Fine1b	Natural sand (SG=2.60)	704 (418)	
Fine2	Natural sand (SG=2.61)		1436 (852)
Water		290 (172)	287 (170)
Air (%)		6%	6%

The mixture for phase 1 was based on a concrete mixture used at a nearby precast plant for precast concrete pipe and manhole structures. It includes two types of fine aggregate with the same specific gravity, but from two different sources for a better grade distribution. The ingredients were obtained from the precast plant. The scope of the first phase was limited to the study of fibrillated structural synthetic fiber (PF1), a 2-in-long monofilament fiber with an aspect ratio of 70 and specific gravity of 0.92, manufactured from a synthetic blend of polypropylene and polyethylene resins. The monofilament fiber partially fibrillates during mixing, increasing the fiber surface area and strengthening the bond between the fiber and the concrete matrix. In the first phase, PF1 was used at 0.2%, 0.3%, 0.4% and 0.6% by volume (3.0, 4.5, 6.0 and 9.0 lb/yd^3 or 1.8, 2.7, 3.6 and 5.3 kg/m^3). It is recognized that, "Higher volume percentages of fibers have been found to offer significant property enhancements to the [synthetic] FRC, mainly increased toughness after cracking and better crack distribution with reductions in crack width." (ACI 544.1R-96) Thus, researchers posited that mixing large quantities of this fiber may be possible, resulting in enhanced toughness, impact and fatigue resistance, and control of plastic shrinkage cracking with minimal effect on concrete workability.

In the second phase, the concrete mixture incorporated ingredients available in the laboratory. To achieve the high flow rates, a polycarboxylate-based high range water-reducing (HRWR) admixture was used. Mixtures also contained a vinsol resin for air entrainment to achieve an adequate air void system to resist freezing and thawing, as suggested by ACI (ACI 544.1R, 1996). An alternate synthetic polymer structural fiber (PF2) and two coated steel fibers were evaluated. The second synthetic fiber (PF2), employed in phase 2, is a monofilament fiber made of a polypropylene/polyethylene blend with a specific gravity of 0.92, fiber length of 1.6 inches, and aspect ratio of 90. It does not fibrillate. The polymer fiber (PF2) was added at 0.2% to 0.3% by volume (3.0 to 4.5 lb/yd^3 or 1.8 to 2.7 kg/m^3). The two coated steel fibers, one with twisted, triangular cross-section and one round with hooked ends, were used at concentrations of 0.3% to 0.5% by volume (40 to 66 lb/yd^3 or 24 to 39 kg/m^3).

Tests

Fresh concrete properties determined included standard slump or flow tests, mixture temperature, air content and unit weight (density). In the slump flow (ASTM C 1611) an inverted cone was used. Once a mixture met the target values for the fresh concrete properties, cylinders and beam specimens were cast for hardened concrete tests. These specimens included 4"×4"×16" (102 mm×102 mm×406 mm) prisms for flexural and residual strength and toughness (4 samples per mixture) (ASTM C 1609) and 4"×8" (102mm×204mm) cylinders for compressive strength (2 samples per mixture) (ASTM C 39) and splitting tensile strength (3 samples per mixture) (ASTM C 496), and 4"×4" (102mm×102mm) in cylinders for permeability (2 samples per mixture) (ASTM C 1202). Specimens were cured in the moist (100% humidity) room until the tests were carried out. Flexural strength and toughness were tested on a closed loop servo controlled loading frame with 4-point loading (third point loading) apparatus and "Japanese yoke" affixing 2 linear-variable displacement transducers (LVDTs) to measure deflection at midspan of the beam specimen. The toughness can be calculated from the load-deflection curves by integrating the area under the curve up to the specified endpoint, in this case L/150 (0.08 in or 2 mm).

RESULTS AND DISCUSSION

The results for each phase are explained under separate headings.

Phase 1

Fresh Concrete Properties – The fresh concrete properties of the mixtures are summarized in Table 2. At fiber concentrations of 6 and 9 pounds per cubic yard (3.6 and 5.3 kg/m^3), stable self-consolidating concretes were not possible. To retain the stability of the mixtures, workability was compromised, and the resulting concrete was treated as normal fiber-reinforced concrete (not SCC). SCC mixtures at these levels of fiber content were deemed infeasible.

Table 2 Fresh Concrete Properties of Phase 1 Mixture

Fiber Concentration % by Vol.	(lb/yd^3)	[kg/m^3]	Unit Weight lb/ft^3 (kg/m^3)	Air Content (% by vol.)	Slump Flow Diameter in (mm)
Control 0%	(0)	[0]	142.4 (3.13)	5.6	22.0 (559)
0.2%	(3)	[1.8]	144.8 (3.18)	4.0	21.5 (546)
0.3%	(4.5)	[2.7]	146.0 (3.21)	3.5	22.0 (559)
0.4%	(6)	[3.6]	144.5 (3.18)	-	*
0.6%	(9)	[5.3]	145.2 (3.19)	3.6	*

*Concrete was not sufficiently workable to report flow values

Hardened Concrete Properties – The averaged results of the 28-day strengths, elastic modulus, and toughness are presented in Table 3. The compressive strengths were not affected by the fiber addition. Some observed differences were attributed to the inherent material variability of concrete mixtures. Similar behavior was observed with elastic modulus.

Table 3 Hardened Concrete Properties of Phase 1 Mixtures

Strength Property	Fiber concentration in lb/yd³(kg/m³)				
	0 (0)	**3 (1.8)**	**4.5 (2.7)**	**6 (3.6)**	**9 (5.3)**
Compression, psi (MPa)	8430 (58.1)	8963 (61.8)	8640 (59.8)	8560 (59.0)	8153 (56.2)
Elastic Modulus, $\times 10^6$ psi (GPa)	4.48 (30.9)	4.66 (32.1)	4.96 (34.2)	5.07 (35.0)	4.49 (31.0)
Splitting tensile, psi (MPa)	722 (4.98)	863 (5.95)	872 (6.01)	867 (5.98)	785 (5.41)
Flexural at peak, psi (MPa)	1028 (7.1)	1167 (8.0)	1078 (7.4)	1295 (8.9)	1055 (7.3)
Residual at δ=0.02 in (0.5mm), psi (MPa)	0 (0)	113 (0.78)	77 (0.53)	150 (1.03)	310 (2.14)
Residual at δ=0.08 in (2mm), psi (MPa)	0 (0)	144 (0.99)	173 (1.19)	246 (1.70)	135 (0.93)
Toughness at δ=0.08 in (2mm), in-lb (N-m)	3 (0.34)	60 (6.78)	73 (8.25)	97 (11.0)	123 (13.9)

In concretes containing fiber reinforcement, a limited increase in the splitting tensile strength of the concrete was observed, though no clear relation to fiber concentration could be identified. At high concentrations of fiber reinforcement, fibers often exhibit a tendency to clump together during mixing, which can influence concrete workability, fiber distribution and bond between fibers and cement paste. Also the reduction in workability could result in increased amounts of entrapped air.

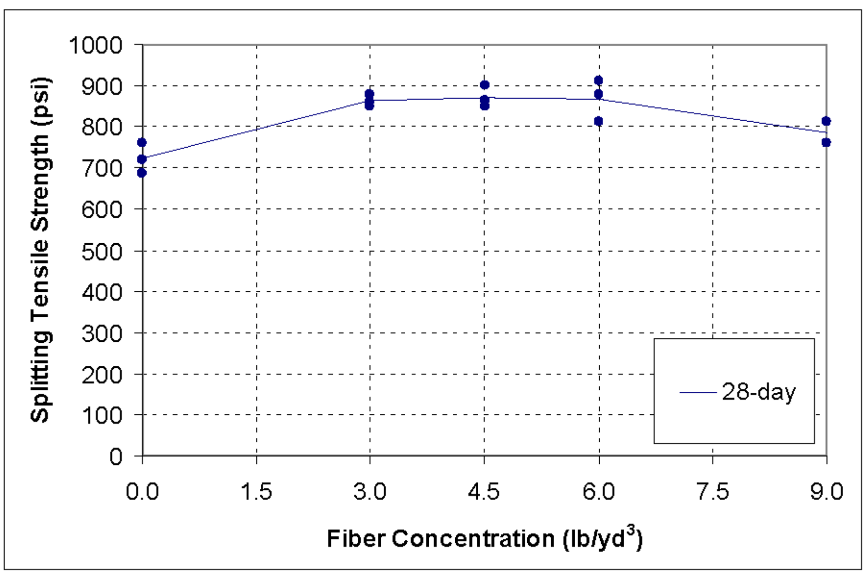

Figure 1 Splitting Tensile Strength versus Fiber Concentration

The flexural strength results, represented by individual sample points and the average as a line, show that the addition of fiber reinforcement in the tested range of concentration had no clear effect on the peak flexural strength of concrete.