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research report

Investigation of Fiber-Reinforced Self-Consolidating Concrete

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16. Abstract:

The rising cost of materials and labor, as well as the demand for faster construction, has prompted development of cheaper, faster alternatives to conventional building techniques. Self-consolidating concrete (SCC), a high performance concrete characterized by its ability to flow without segregation under its own weight, promises to speed construction while reducing the need for skilled labor. However, experience has shown that SCC may be prone to shrinkage cracking, which may compromise its durability. In conventional concrete, fiber reinforcement has been used to control cracking and increase tensile and flexural strength.

This study evaluated the feasibility of fiber-reinforced SCC (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 fibers. The results indicated that an SCC mixture can be prepared for use in transportation facilities that combines the properties of a high flow rate and some residual strength that would be beneficial for crack control. The residual strength is contributed by the internal fibers and provides load-carrying capacity after initial cracking of the concrete. At optimum fiber additions, FR-SCC mixtures can have the same fresh concrete properties as traditional SCC mixtures. FR-SCC also demonstrated a considerable improvement in the residual strength and toughness of a cracked section, which is expected to lead to the control of crack width and length. The improved performance of the FR-SCC cracked section indicated that it can be expected to have more durability in service conditions than would an identical SCC with no reinforcement.

The study recommends that the Virginia Department of Transportation's Structure & Bridge Division evaluate FR-SCC in field applications such as link slabs and closure pours in continuous concrete decks; formed concrete substructure repairs; or prestressed beams where end zone cracking has been an issue. In such applications, construction with FR-SCC has the potential to be faster than with SCC, as traditional steel reinforcement may be reduced or eliminated, yielding reduced labor and materials costs for reinforcement placement. Enhanced public and worker safety may result from the reduction of overall construction time and required maintenance of traffic. The next step toward implementation of this technology would involve coordination with VDOT's Materials Division and Structure & Bridge Division to create special provisions or standard specifications regarding the use of FR-SCC and to identify candidate projects for field trials.

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FINAL REPORT

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ABSTRACT

The rising cost of materials and labor, as well as the demand for faster construction, has prompted development of cheaper, faster alternatives to conventional building techniques. Self-consolidating concrete (SCC), a high performance concrete characterized by its ability to flow without segregation under its own weight, promises to speed construction while reducing the need for skilled labor. However, experience has shown that SCC may be prone to shrinkage cracking, which may compromise its durability. In conventional concrete, fiber reinforcement has been used to control cracking and increase tensile and flexural strength.

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INTRODUCTION

Self-Consolidating Concrete

Self-consolidating concrete (SCC) was first developed in Japan in 1986 by Okamura of the Koche University of Technology. Originally devised as a means to mitigate the growing costs of construction by reducing the amount of skilled labor necessary for the placement of concrete, SCC was revolutionary in its capability to flow and consolidate under its own weight without segregation of the mixture. Early SCC mixtures achieved fluidity through the addition of superplasticizers to conventional concrete mixtures while dramatically increasing the water–cementitious material (w/cm) ratio. The resulting SCC, although remarkably workable, exhibited significantly reduced strength and durability as compared to the conventional mixtures from which it evolved; this initially limited the use of SCC to applications with very low durability requirements (Vachon, 2002).

Since then, SCC technology enhancements have included the following:

- increasing fluidity while retaining a low w/cm and ordinary setting times by using a new generation of high-range water-reducing (HRWR) admixtures
- allowing for consolidation in congested areas by minimizing the maximum allowable size of the aggregate
- improving workability and permeability by using supplementary cementitious materials such as slag cements

- further increasing workability by incorporating a high fine-aggregate-to-coarse-aggregate ratio to reduce internal friction

- minimizing segregation by incorporating greater proportions of fine aggregate and adding viscosity-modifying admixtures to stabilize the concrete (ACI Committee 237, 2007).

The balance between workability and stability allows SCC to be placed without the necessity of mechanical vibration, even in situations that call for large amounts of reinforcing steel or complicated formwork. 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 et al., 2006).

SCC is ideal for many specialized applications and provides smooth surfaces. In conventional concretes, significant effort is required to achieve an acceptable finish, and it is often impossible to eliminate voids along cast surfaces enclosed by formwork. As a result, SCC is often a good choice where architectural or serviceability requirements call for smooth finishes and clean, sharp edges. SCC is also used to simplify casting in precast, prestressed concrete beams designed for structures such as bridges and parking garages, 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 increased.

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. The tendency of concrete to crack in service is accounted for in the structural designs, and, indeed, the cracking is actually necessary in some structural applications to transfer stresses and strains fully between the concrete and steel components of reinforced concrete. However, if cracks occur and remain open under loading, they can cause durability problems. Cracks allow water and other substances, such as deicing salts, to enter the concrete readily and corrode the steel reinforcement or react detrimentally with the concrete.

Fiber reinforcement 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). Fiber reinforcement is typically made of steel or synthetic filaments. In concrete applications, these fibers are generally 1 to 2 in 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 of an effect on the concrete permeability, slowing the corrosion process. In addition, because the fibers can, in some cases, be used as a replacement for traditional reinforcement, corrosion problems can be reduced or eliminated through the use of synthetic fibers that do not corrode in water (American Concrete Pavement Association, 2003).

Fiber Reinforcement in Self-Consolidating Concrete

Merging the benefits of fiber reinforcement with SCC technology may pay dividends in construction efficiency and durability of concrete elements. A problem with SCC is that the large amounts of fine material in the mixture have a comparatively large cumulative surface area onto which mix water will adhere. Subsequent redistribution or loss of this water may lead to excessive drying shrinkage. Shrinkage is the slow decrease of volume of concrete with time attributable to water loss. This poses a problem because in virtually any construction the concrete will be constrained, whether by connections to adjacent members, interaction with reinforcement, or interaction with the subgrade. These conditions will cause accumulation of internal stresses as the concrete shrinks, and against such restraint the stresses may eventually exceed the concrete tensile strength, resulting in cracks. This cracking will increase permeability and may lead to durability problems. Through the addition of reinforcing fibers, cracking may be controlled (Slag Cement Association, 2005).

PURPOSE AND SCOPE

The objectives of this study were to determine how fiber reinforcement may alter the properties of SCC and to investigate the types and concentration of fibers that are feasible for use in the Virginia Department of Transportation’s (VDOT) concrete mixtures.

The study was conducted in two phases. In Phase 1, four mixtures of fiber-reinforced SCC (FR-SCC) were tested against a control mixture of regular SCC. The scope of this phase was limited to the study of fibrillated structural synthetic fiber (PF1). In Phase 2, five mixtures with fibers and a control mixture were used. This phase employed a synthetic polymer structural fiber (PF2) and two coated steel fibers: one twisted with a triangular cross section and one round with hooked ends.

METHODS

Overview

SCC mixtures with and without fibers were prepared. The properties at the fresh and hardened states were determined and compared. Several tests were conducted to characterize the fresh properties of the mixtures, including standard slump or flow tests and the U-box flow test, and the temperature, air content, and unit weight (density) were monitored. Once a mixture met the target values for fresh concrete properties, cylinders and beam specimens were cast. These specimens included 4-in by 4-in by 16-in prisms to determine flexural and residual strength and toughness (ASTM C1609) and 4-in by 8-in cylinders to determine compressive strength (ASTM C39) and splitting tensile strength (ASTM C496). Flexural strength and toughness were determined on a closed loop servo-controlled loading frame with a four-point loading apparatus and "Japanese yoke" affixing two linear variable displacement transducers (LVDTs) to measure deflection at mid-span of the beam specimen. Specimens were cured in a moist room.

Hardened specimens were tested for compressive strength, residual strength, flexural strength, splitting tensile strength, and permeability (ASTM C1202). The specimens were tested at various ages, primarily 7 and 28 days.

Mixture Design

The SCC control mixture was based on a design that had been tested by the Virginia Transportation Research Council (VTRC) and would yield a minimum of 4,000 psi at 28 days. This design was chosen because it had undergone a series of successful tests and could be counted on to perform adequately. Table 1 lists the weight and volume of the materials used in the Phase 1 control SCC mixture, and Table 2 lists the weight and volume of the materials used in the Phase 2 control mixture, which was similar except for the substitution of alternate local coarse and natural fine aggregate sources. A w/cm ranging between 0.40 and 0.45 is typical for high performance concrete used in bridge decks; the chosen mixture design set the w/cm to 0.43.

There are many material trade-offs to consider in the design of SCC mixtures. Mixtures containing fibers had the same mixture proportions as the controls, except that fibers were added.

Table 1. Mixture Proportions for Phase 1

Ingredient	Source	Quantity
Cement	Type I/II	439 lb/yd^3
Slag cement	Grade 120	236 lb/yd^3
Coarse aggregate	Limestone (SG = 2.81)	1535 lb/yd^3
Fine aggregate 1	Natural sand (SG = 2.60)	704 lb/yd^3
Fine aggregate 2	Natural sand (SG = 2.75)	704 lb/yd^3
Water		290 lb/yd^3
Air		6%

SG = specific gravity.

Table 2. Mixtures Proportions for Phase 2

Ingredient	Source	Quantity
Cement	Type I/II	439 lb/yd^3
Slag cement	Grade 120	236 lb/yd^3
Coarse aggregate	Granite (SG = 2.80)	1436 lb/yd^3
Fine aggregate	Natural sand (SG = 2.61)	1436 lb/yd^3
Water		287 lb/yd^3
Air		6%

SG = specific gravity.

Fibers

Several fiber types were used, including a steel fiber and two polymer fibers. One of the polymer fibers (PF1) was a 2-in-long monofilament fiber with an aspect ratio of 70 and a 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. Mixing large quantities (about 10 lb/yd^3) of this fiber is possible, resulting in enhanced toughness, impact and fatigue resistance, and control of plastic shrinkage cracking with minimal effect on concrete workability. The second synthetic fiber (PF2) is a monofilament fiber made of a polypropylene/polyethylene blend with a specific gravity of 0.92, a fiber length of 1.6 in, and an aspect ratio of 90.

The fiber concentrations of fiber reinforcement PF1 included 0.2%, 0.3%, 0.4%, and 0.6% by volume (3.0, 4.5, 6.0, and 9.0 lb/yd^3). The fiber concentrations used in the Phase 2 mixtures were 0.2% to 0.3% by volume (3.0 to 4.5 lb/yd^3) for the polymer fiber and 0.3% to 0.5% by volume (40 to 66 lb/yd^3) for the steel fibers.

Cementitious Materials

Type I/II portland cement and slag cement were used as the cementitious material. Slag cement can increase the concrete's resistance to sulfate attack and alkali-silica reactivity and, more important for SCC, can increase workability and lower permeability (ACI Committee 233, 2003; Cement Americas, 2001). When used, slag cement comprised 35% of the total cementitious material.

Aggregate Proportions

A high ratio of fine-to-coarse-aggregate materials was used, as shown in Tables 1 and 2, to ensure satisfactory workability and stability. For a better grading that would enable high stability, fine aggregate from two stockpiles with different gradations were used in Phase 1.

Chemical Admixtures

A polycarboxylate-based HRWR admixture was used, which is essential to attain the desired flow properties of an SCC mixture. A vinsol resin air-entraining admixture (AEA) was also added to stabilize air voids in the concrete (Miller, 2005).

Mixing

The same mixing procedure was followed for each of the five 1.5 ft^3 batches of concrete that were produced in Phase 1. The coarse and fine aggregates were added to the mixer and blended together. After approximately 1 min of blending the aggregates, one-half of the water was added, and mixing was allowed to continue. Once the aggregate and the water had mixed evenly, the cementitious materials were added. At this point, the AEA was added to the remaining water, and then the water was poured into the mixer. This was allowed to mix for a short period of time, and then the HRWR admixture was slowly added as mixing continued. After 3 min, the mixing was stopped for 2 min and then continued for an additional 2 min in accordance with ASTM C192, and the fresh concrete properties were tested. At this point, if the results of the fresh concrete testing were satisfactory, the fibers were added, if applicable.

The addition of fibers had immediate effects on the workability of the concrete. As a result, it was always necessary to add additional HRWR admixture to increase workability/flow of the mixture if fibers were used. Once this had been achieved, final tests of the workability, stability, air content, and unit weight were conducted and documented.

Fresh Concrete Testing and Specimen Casting

The fresh concrete properties of every mixture were tested to ensure that the workability, stability, and air content of each batch were within acceptable ranges. The workability was determined through an inverted slump cone flow test in accordance with ASTM C1611. A slump cone was inverted in the center of a flat board; this board had two concentric circles, the innermost measuring 20 in in diameter. The cone was filled to the top with concrete and then lifted straight up such that the concrete could flow by gravity out of the bottom of the cone. The time it took the concrete to spread to a diameter of 20 in (the first circle) was recorded, and the final diameter of the concrete spread was measured; this measurement is known as the slump flow diameter of an SCC mixture. A slump flow diameter of 20 in or more is generally acceptable for SCC, but when fibers are used, some reduction is expected. In this study, slump flow values of 18 in and greater were assumed to be satisfactory.

After the slump flow test, the concrete was inspected for signs of excessive bleeding or segregation. Excessive bleeding manifests itself in the form of a watery halo that extends a significant distance past the edges of the bulk of the concrete circle. Segregation is evident if larger aggregate has been left piled in the center of the circle and finer material has moved to the edges. Generally, these two problems occur simultaneously and are often caused by excess HRWR admixture or water in the mixture. If the segregation or bleeding is severe, the concrete will be rejected, although it may be possible to salvage the material using viscosity-modifying admixtures in cases where segregation and bleeding are not severe. A slump flow test of concrete that has failed this visual stability analysis can be seen in Figure 1. The watery halo around the edges of the concrete is an indication of bleeding problems, and the bare aggregate piled in the center is a sign of severe segregation problems. These issues must be addressed before this concrete can be accepted for use.

Once the workability and stability of a mixture were verified, the air content and unit weight were measured. The unit weight was expected to be between 140 and 150 lb/ft^3, but none of the mixtures was accepted or rejected on the basis of this property. The target value for the air content was 5% by volume, ±1.5%, which is specified for precast elements that are not exposed to a harsh environment. The air content was measured by a pressure meter in accordance with ASTM C231.

Figure 1. Slump Flow Test of Concrete Exhibiting Excessive Bleeding and Segregation

Testing

Hardened concrete tests included 7- and 28-day compressive strength and modulus of elasticity, 28-day splitting tensile strength, and 28-day peak and residual flexural strengths and flexural toughness. The beams used in the testing were subjected to third-point loading, but in Phase 1 testing, rigidity in the test apparatus restricted free rotation and induced apparent residual stresses. These stresses were accounted for, and the concrete flexural results are presented herein. In Phase 2, the apparatus was modified to remove rotational constraint.

RESULTS

Phase 1 Results

As stated previously, the focus of Phase 1 was evaluating the feasibility of determining the behavior of SCC while various concentrations of PF1 were incorporated. Five mixtures were prepared as indicated in Table 3. Fresh properties were used for primary screening, supplemented by tests of hardened concrete.

Fresh Concrete Properties

The fresh concrete properties of the mixtures are summarized in Table 3. Mixtures that failed the slump flow test (<18 in diameter) were not recorded. In achieving the workability requirements of SCC at fiber concentrations of 6 and 9 lb/yd^3, the stability of the mixtures was compromised to an unacceptable degree. Therefore, SCC mixtures at these levels of fiber content were deemed infeasible, and instead the stability was improved, at the expense of workability; thus, these mixtures were treated as traditional fiber-reinforced concrete mixtures.

Table 3. Total Admixtures Added and Fresh Concrete Properties of Phase 1 Mixtures

Fiber Concentration (% by Volume)	HRWR (mL)	AEA (mL)	Unit Weight (lb/ft^3)	Air Content (% by Vol.)	Slump Flow Diameter (in)
Control 0% (0 lb/yd^3)	85	2	142.4	5.6	22
0.2% (3 lb/yd^3)	115	2	144.8	4	21.5
0.3% (4.5 lb/yd^3)	105	2	146	3.5	22
0.4% (6 lb/yd^3)	175	2	144.5	-	-
0.6% (9 lb/yd^3)	-	2	145.2	3.6	-

HRWR = high-range water-reducing admixture, AEA = air-entraining admixture.

Compressive Strength and Modulus of Elasticity

The results of the 7- and 28-day compressive strength testing are presented in Figure 2. As expected, the level of fiber reinforcement did not have any significant or discernable effect on the 7-day compressive strength of the SCC. The inherent material variability of concrete is the best explanation for the minor differences in the average compressive strengths of the five mixtures. Figure 2 also demonstrates that there was no clear effect of fiber reinforcement on the 28-day compressive strength of the SCC.

Figure 3 presents the elastic modulus values, indicating that there was no relationship between either the 7- or 28-day elastic modulus values and the fiber concentration.

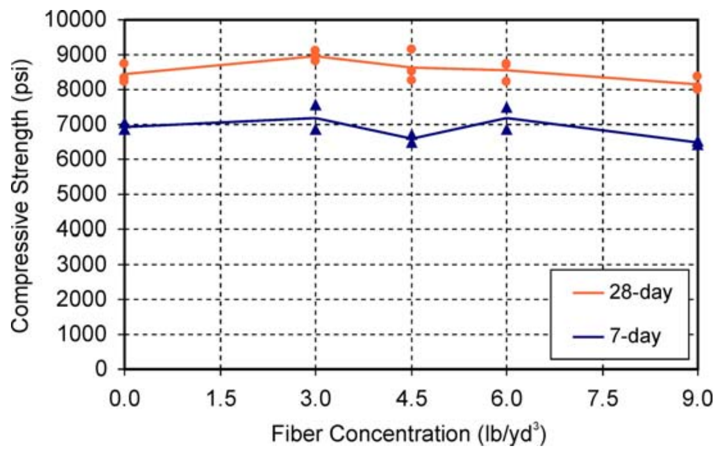

Figure 2. Compressive Strength Versus Fiber Concentration

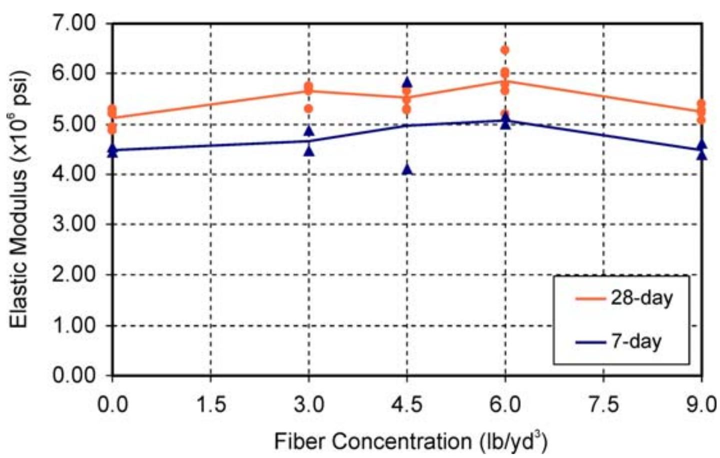

Figure 3. Elastic Modulus Versus Fiber Concentration

Splitting Tensile Strength

The results of the 28-day splitting tensile test are presented in Figure 4. It appears that fiber reinforcement did have a limited effect on the tensile strength of SCC. The effect was uniform until the levels of fiber reinforcement were very high (9 lb/yd^3), where the benefit appeared to be reduced, perhaps because of consolidation problems induced by the high fiber concentration. The trend is most likely explained by the brittle nature of concrete. Weak in tension, concrete is strengthened by the presence of the synthetic fibers, which have a considerable tensile strength and act as little reinforcing bars. However, to achieve this effect, the fibers must be evenly distributed and well anchored in the concrete. At high concentrations of fiber reinforcement, fibers often have a tendency to clump together during mixing, which can influence concrete workability, fiber distribution, and the bond between fibers and cement paste. In addition, the reduction in workability could have led to increased amounts of entrapped air. As a result, there was a reduction in the benefit of the fibers at very high fiber concentrations. Although the addition of fiber reinforcement appeared to have a positive effect on the tensile strength of SCC, the variability of the individual observations indicated that the difference as compared to the control was not expected to be large.

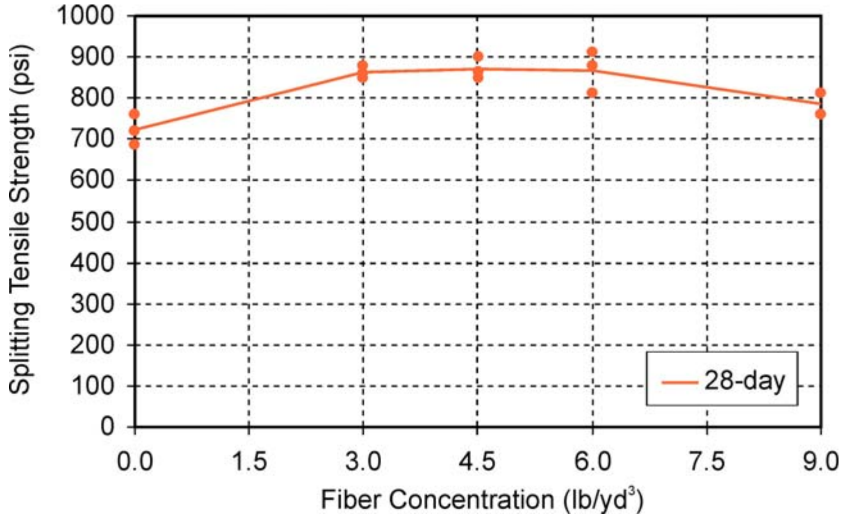

Figure 4. Splitting Tensile Strength Versus Fiber Concentration

Flexural and Residual Strengths and Toughness

The flexural strength data summarized in Figure 5 show that the addition of fiber reinforcement in the tested range of concentrations had no clear effect on the peak flexural strength of SCC. The flexural strength was determined when first crack occurred, which was the peak stress with the concretes tested. The flexural strength of brittle materials is governed by the material's tensile strength, so the addition of fibers may be expected to induce improvements, as seen in the tensile testing. However, at the volumes and type of fiber present, there may not be a discernible transfer of stress from the bulk concrete to the embedded fibers until after initial cracking of the concrete. This will be a function of the elastic moduli of the two materials, as well as the degree of bond and slip along their interface.

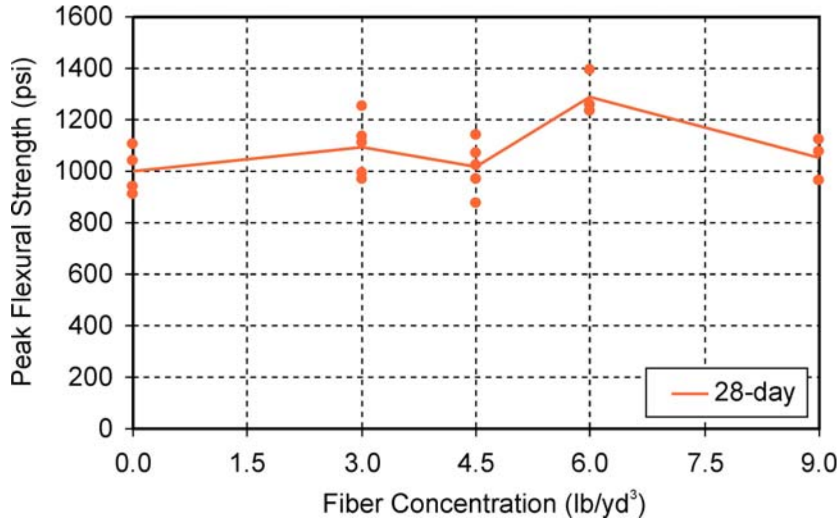

Figure 5. 28-Day Flexural Strength Versus Fiber Concentration

The conventional splitting tensile test, in accordance with ASTM C496, determines a single peak load value, from which the associated tensile strength is calculated. In contrast, the flexural toughness test is designed to evaluate and differentiate behavior beyond initial rupture of the concrete and peak stress, which may or may not occur at initial rupture, and enable the determination of the residual strength attributable to the fiber after initial rupture occurs. This gives a better overall indication of the amount of energy necessary to induce failure in fiber-reinforced concrete. Others have attempted a similar approach to assessing post-cracking performance in the splitting tensile strength test configuration, but there is no current standard for such a test. Hence, the initial tensile strength, from either splitting tensile tests or flexural tests at initial cracking, did not seem to be significantly affected by the fiber, but flexural toughness results indicated a clear difference in post-cracking behavior.

The addition of fiber reinforcement had a tremendous impact on the residual strength of the SCC control mixture. Figure 6 shows that the residual strength increased with fiber

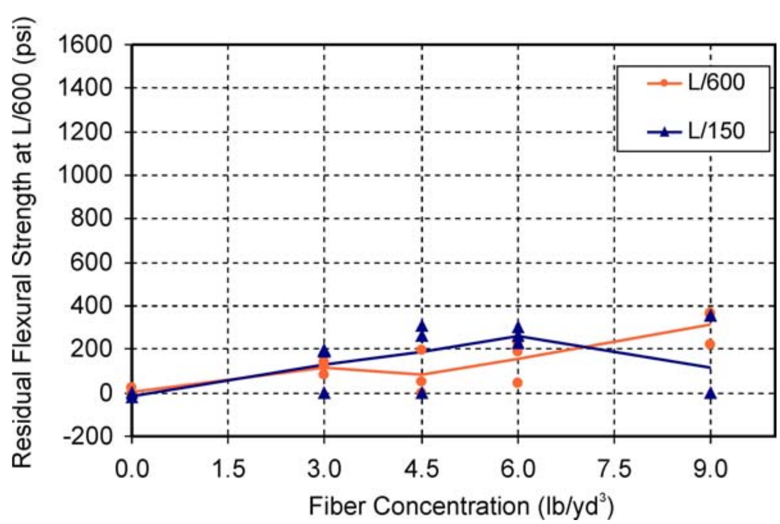

Figure 6. Average Residual Strength Versus Fiber Concentration at a Deflection of L/600 (0.02 in) and L/150 (0.08 in) at 28 Days

concentration, except with the highest fiber addition at the L/150 (0.08 in) deflection, which was attributed to poor consolidation.

Flexural toughness was closely related to the residual strength. As a result of this relationship, the flexural toughness increased with fiber concentration at a deflection of L/150 (0.08 in), as can be seen in Figure 7. The residual strength played the dominant role in the toughness of the test specimen, since the fibers absorbed considerable energy prior to the loss of stress capacity.

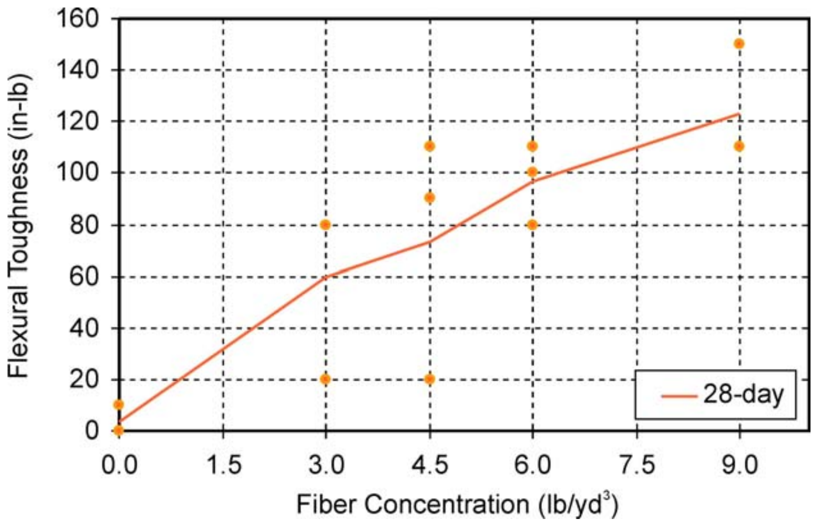

Figure 7. Flexural Toughness Versus Fiber Concentration at L/150 Deflection

Phase 2 Results

As stated previously, Phase 2 evaluated the effects of types and concentrations of fibers on fresh and hardened concrete properties.

Fresh Concrete Properties

Fresh properties evaluated included variations of unit weight, air content, and slump flow of the SCC mixture between the control mixture containing no fibers and the series of polymer and steel FR-SCC mixtures. Table 4 summarizes the amounts of chemical admixtures required to attain the slump and air values shown, as well as the resulting unit weight, air content, and slump-flow diameter results for the respective mixtures.

Very small dosages of AEA were required for the relatively small laboratory batches, and a few of the mixtures had a higher air content than anticipated. All Phase 2 mixtures were able to attain the minimum slump required for SCC concrete without segregation or excessive bleeding.

Table 4. Total Admixtures Added and Fresh Concrete Properties of Phase 2 Mixtures

Fiber Type	Fiber Concentration (% by Volume)	Unit Weight (lb/ft^3)	Air Content (% by Volume)	Slump Flow Diameter (in)
Control	0% (0 lb/yd^3)	144.4	6.2	21.5
PF2	0.2% (3 lb/yd^3)	140.8	8.0	20.5
	0.3% (4.5 lb/yd^3)	137.2	10.5	20.5
Twisted steel	0.3% (40 lb/yd^3)	142.4	6.0	23.5
	0.5% (66 lb/yd^3)	141.6	9.5	20.0
Hooked steel	0.5% (40 lb/yd^3)	143.6	6.8	21.0

Compressive Strength and Modulus of Elasticity

The compressive strength and modulus of elasticity results are presented in Tables 5 and 6, respectively. Compressive strength was consistent between the mixtures except for the batch containing 0.3% by volume polymer fibers (4.5 lb/yd^3) that had a lower average compressive strength, which could be attributed to lack of consolidation.

Elastic modulus values were similarly comparable, with the lowest values curiously corresponding to the two mixtures with the highest fiber concentrations (0.3% polymer and 0.5% twisted steel fibers) where the adverse effect of lack of consolidation would most likely occur.

Table 5. Compressive Strength of Phase 2 Mixtures at 28 days (psi)

Specimen	Control (0 lb/yd^3)	PF2 (3.0 lb/yd^3)	PF2 (4.5 lb/yd^3)	Twisted Steel (40 lb/yd^3)	Twisted Steel (66 lb/yd^3)	Hooked Steel (40 lb/yd^3)
1	7,720	7,220	7,500	8,040	6,720	8,100
2	7,280	7,200	5,290	7,480	7,700	7,960
3	7,660	7,300	5,950	8,120	7,220	-
Average	7,553	7,240	6,247	7,880	7,213	8,030

Table 6. Modulus of Elasticity for Phase 2 Mixtures at 28 days (×10^6 psi)

Specimen	Control (0 lb/yd^3)	PF2 (3.0 lb/yd^3)	PF2 (4.5 lb/yd^3)	Twisted Steel (40 lb/yd^3)	Twisted Steel (66 lb/yd^3)	Hooked Steel (40 lb/yd^3)
1	3.85	3.36	3.40	4.07	3.41	3.94
2	3.99	3.52	3.11	3.46	4.07	3.22
3	3.35	4.24	3.60	3.29	3.55	4.23
4	4.03	3.39	3.36	3.71	3.15	-
5	3.58	3.05	3.40	3.60	3.27	-
6	-	3.57	-	4.33	3.43	-
Average	3.76	3.52	3.37	3.74	3.48	3.80

Splitting Tensile Strength

By contrast to the compressive strength and modulus results, the results of the splitting tensile strength tests, indicated in Table 7, clearly showed the benefit of fibers. The trends illustrated a definite increase in tensile capacity attributable to higher fiber concentrations.

Table 7. Splitting Tensile Strength of Phase 2 Mixtures at 28 days (psi)

Specimen	Control ($0 lb/yd^3$)	PF2 ($3.0 lb/yd^3$)	PF2 ($4.5 lb/yd^3$)	Twisted Steel ($40 lb/yd^3$)	Twisted Steel ($66 lb/yd^3$)	Hooked Steel ($40 lb/yd^3$)
1	315	350	725	435	805	505
2	345	335	670	515	865	-
3	-	340	-	480	900	-
Average	330	342	698	477	857	505

Flexural and Residual Strengths and Toughness

Figure 8 shows a typical flexural toughness plot of load versus mid-span deflection for four-point bending of a beam containing no fibers. At the point of rupture, load capacity drops off immediately as the specimen deflects freely. The cyclic load-deflection curve about zero load reflects the resulting vibration in the system immediately after brittle failure.

By contrast, the load-deflection curve for a concrete beam reinforced with 0.3% polymer fiber by volume exhibited the behavior shown in Figure 9, wherein load dropped significantly at initial concrete rupture, but not completely to zero, but to a load corresponding to residual fiber strength. Continued loading at a constant strain rate resulted in the long strain plateau, which was continued under the test protocol past the target deflection of L/150, or 0.08 in.

A similar test of a concrete beam containing 0.5% twisted steel fibers revealed the behavior shown in Figure 10, where considerable residual strength was retained by the fibers and load capacity gradually tapered off under constant strain-rate loading until the target deflection was attained.

Flexural strengths of the various Phase 2 mixtures, as shown in Table 8, were generally consistent, although the average flexural strength of the polymer fiber at 3 lb/yd^3 concentration was a bit lower than that of the control and slightly higher at 4.5 lb/yd^3. The steel fibers appeared

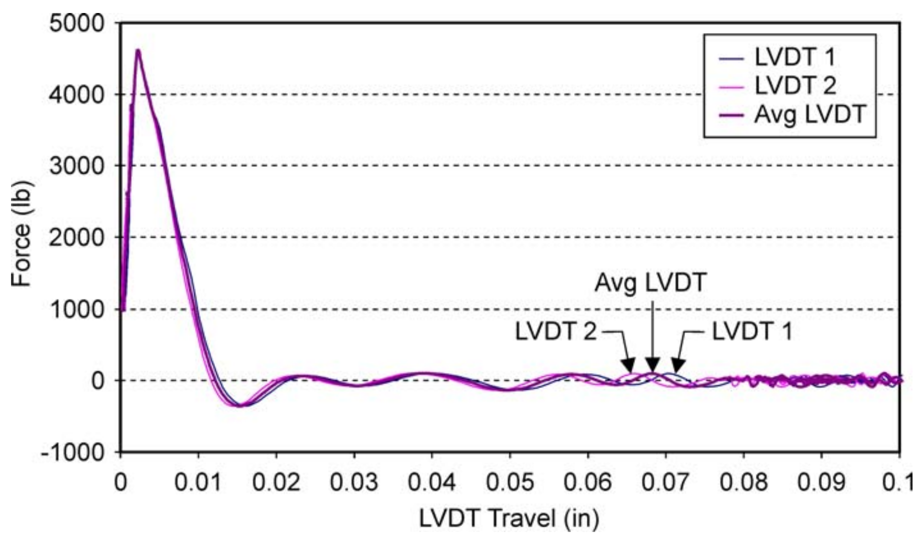

Figure 8. Example of Flexural Toughness Test of Beam with No Fibers

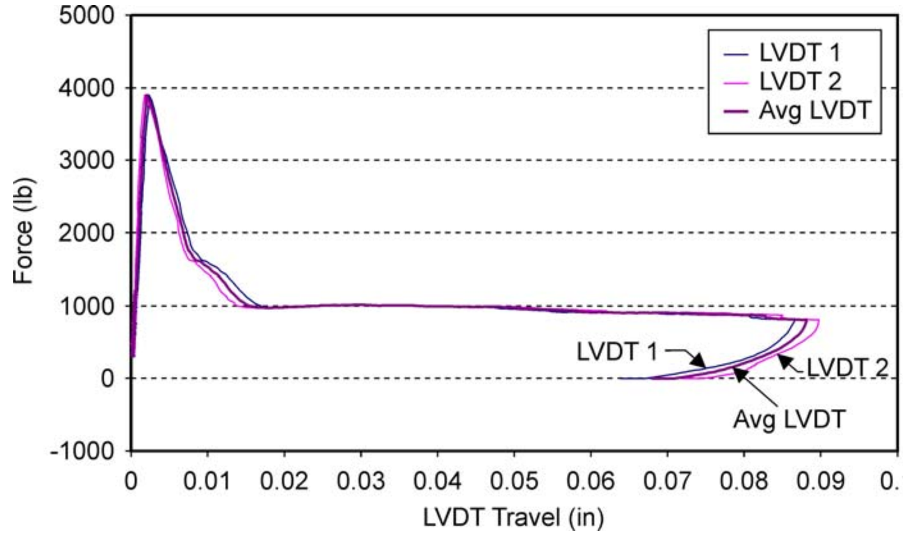

Figure 9. Example of Flexural Toughness Test of Beam with 0.3% Polymer Fibers

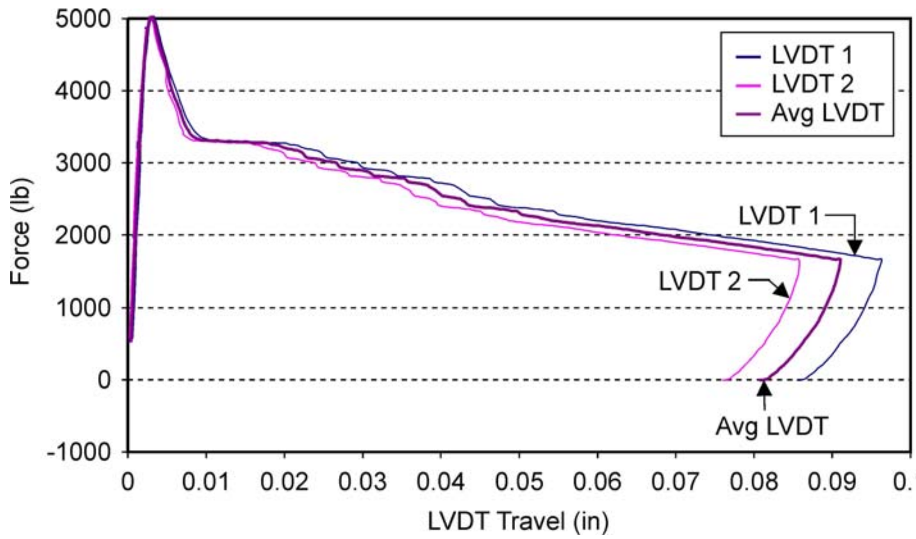

Figure 10. Example of Flexural Toughness Test of Beam with 0.5% Steel Fibers

Table 8. Flexural Strength (psi)

Specimen	Control ($0\ lb/yd^3$)	Polymer ($3.0\ lb/yd^3$)	Polymer ($4.5\ lb/yd^3$)	Twisted Steel ($40\ lb/yd^3$)	Twisted Steel ($66\ lb/yd^3$)	Hooked Steel ($40\ lb/yd^3$)
1	865	770	885	890	945	885
2	845	865	855	885	910	875
3	-	770	880	840	940	-
Average	855	802	873	872	932	880

to provide increasing strength above that of the control as fiber concentration increased, with both steel fibers attaining similar flexural strengths at the matching concentration of 40 lb/yd^3.

Residual flexural strengths at a deflection of L/600 (0.02 in) for Phase 2 mixtures are summarized in Table 9. The concept of residual strength for non-fiber controls is not applicable, so these values should be considered as zero. By comparison, the polymer fibers had a modest

Table 9. Residual Flexural Strength at L/600 Deflection (psi)

Specimen	Control	Polymer		Twisted Steel		Hooked Steel
	(0 lb/yd^3)	(3.0 lb/yd^3)	(4.5 lb/yd^3)	(40 lb/yd^3)	(66 lb/yd^3)	(40 lb/yd^3)
1	-30	125	270	430	605	395
2	5	30	210	495	585	540
3		130	265	480	765	
Average	-13	95	248	468	652	468

residual flexural strength, which, as was expected, increased with dosage. The steel fibers of both types showed comparable and considerable residual flexural strength at 0.3% by volume; an even higher strength at 0.5% is shown for the twisted fiber.

Observation of the residual flexural strengths at a deflection of L/150 (0.08 in), as seen in Table 10, revealed a comparable load capacity between polymer fibers at 0.2% by volume and steel fibers of both types at 0.3% by volume. Higher concentrations of both polymer and steel fibers provided modest increases in residual flexural strength at this level of deflection. However, the raw residual flexural strength at a given deflection was insufficient to depict the value of the fibers in resisting loads beyond the point of concrete cracking.

A more useful measure of the benefit of fibers to control cracking is that of toughness, which reflects the total energy necessary to strain or elongate the fibers after the concrete has cracked. 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). The flexural toughness of the Phase 2 specimens is summarized in Table 11. In this regard, it can be clearly seen that the twisted and hooked steel fibers had substantial toughness, although polymer fibers also provided a benefit over non-fiber concrete. The toughness values estimated for control concrete represent the relatively small deflection capacity of the concrete under flexural load and may reflect a minor amount of error induced by the test under brittle failure conditions.

Table 10. Residual Flexural Strength at L/150 Deflection (psi)

Specimen	Control	Polymer		Twisted Steel		Hooked Steel
	(0 lb/yd^3)	(3.0 lb/yd^3)	(4.5 lb/yd^3)	(40 lb/yd^3)	(66 lb/yd^3)	(40 lb/yd^3)
1	0	125	265	190	345	140
2	0	110	215	215	295	130
3		115	265	145	355	
Average	0	117	248	183	332	135

Table 11. Flexural Toughness (in-lb)

Specimen	Control	Polymer		Twisted Steel		Hooked Steel
	(0 lb/yd^3)	(3.0 lb/yd^3)	(4.5 lb/yd^3)	(40 lb/yd^3)	(66 lb/yd^3)	(40 lb/yd^3)
1	30	70	140	160	210	130
2	30	70	110	160	200	160
3		70	140	120	250	
Average	30	70	130	147	220	145

DISCUSSION

Implications of Test Results for the Construction Industry

The results indicate that FR-SCC can be easily produced at fiber-reinforcement concentrations at or below 4.5 lb/yd^3 of synthetic fiber or 66 lb/yd^3 of steel fiber. With this level of fiber reinforcement, FR-SCC could be expected to have a residual flexural strength that is 25% to 30% of the flexural strength at first crack with no negative effect on the workability or stability of the plastic concrete. Through field applications, the residual strengths that would limit the width of cracks and the accompanying improvements in resisting the penetration of chlorides can be determined. The residual strength of the FR-SCC should help control the cracking problems typically associated with concrete mixtures that are not fiber reinforced, including SCC. Through crack control, FR-SCC is a much more viable construction material, particularly for applications such as bridge decking, where a 75-year service life is expected from the structure.

Possible applications include link slabs and closure pours in continuous concrete decks; formed concrete substructure repairs; and prestressed beams where end zone cracking has been an issue, even with higher concentration of vertical stirrups (Dhonde et al., 2007).

Implications of Test Results for Future Research

In the immediate future, it would be beneficial to study the effects of other forms and types of fiber reinforcement on SCC. Long-term research projects should be planned to test the effectiveness of FR-SCC in the field. The results of the current project indicate that under laboratory conditions it is possible to develop an FR-SCC mixture that provides improvements in residual strength of the crack section. This does not necessarily mean that the same benefits can be expected in field conditions. There may be unforeseen issues involved with larger scale elements in actual field conditions. A field application where conventional and FR-SCC bridge deck concrete are placed side by side for an in-situ comparison of their strength and durability would provide a better understanding of the relative construction costs, time requirements, and performance of the two methods.

Broad Implications

If future research produces results similar to those of this laboratory investigation, the time and cost benefits of FR-SCC in improving durability through crack control would make it an attractive construction material. VTRC already recognizes that the use of SCC has the potential to provide initial savings because of the reduction in labor required to place the concrete (Ozyildirim and Lane, 2003). VTRC has stated that its “goal is to make the use of SCC standard practice, so that [VDOT is] producing it consistently day in and day out” (Federal Highway Administration, 2005). The development of an effective method of crack control is a critical step toward a more universal application of SCC in construction, and the results of this project suggest FR-SCC can accomplish that. With savings on new construction, public organizations such as VDOT could do more for the people they serve.

CONCLUSIONS

- *At optimum fiber additions, FR-SCC mixtures can have the same fresh concrete properties as traditional SCC mixtures.*

- *FR-SCC demonstrated a considerable improvement in the residual strength and toughness of a cracked section that is expected to lead to control of crack width and length. This indicates that FR-SCC can be expected to have better durability in service conditions than an identical SCC with no reinforcement.*

RECOMMENDATIONS

1. *VDOT's Structure & Bridge Division should use FR-SCC in field applications where cracking and workability are concerns.*

2. *VDOT's Materials Division and VTRC should prepare a specification addressing the design and construction of FR-SCC, including provisions for residual strength for crack control.*

BENEFITS AND IMPLEMENTATION PROSPECTS

Construction with FR-SCC may be even 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 (American Concrete Pavement 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.

FR-SCC combines the benefits of fiber-reinforced concrete with those of an SCC mixture. The result will be reduced labor and faster placement and finishing of reinforced concrete and extended service life attributable to control of cracking. The mixture may find application in a variety of structural applications where crack control and ease of placement are of concern. One potential application may be to limit the extent of cracking in the ends of prestressed beams that occur because of thermal stresses and time-dependent behavior of the mixtures during curing. Another application may be use in closure pours on continuous bridge decks. Other uses may include precast concrete components where fibers may reduce or replace secondary reinforcement for temperature and crack control.

The next step toward implementation of this technology would involve coordination with VDOT's Materials Division and Structure & Bridge Division to create special provisions or standard specifications and to identify candidate projects for field trials.

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