Evaluation of High-Performance Fiber-Reinforced Concrete for Bridge Deck Connections, Closure Pours, and Joints

LEVON C. HOOMES, EIT
Bridge Designer
FIGG Bridge Group

H. CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist
Virginia Transportation Research Council

MICHAEL C. BROWN, Ph.D., P.E.
Associate Director
Virginia Transportation Research Council

Final Report VTRC 17-R15

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 17-R15	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Evaluation of High-Performance Fiber-Reinforced Concrete for Bridge Deck Connections, Closure Pours, and Joints		5. Report Date: January 2017
		6. Performing Organization Code:
7. Author(s): Levon C. Hoomes, H. Celik Ozyildirim, Ph.D., P.E., and Michael C. Brown, Ph.D., P.E.		8. Performing Organization Report No.: VTRC 17-R15
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS):
		11. Contract or Grant No.: 103752
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation Federal Highway Administration 1401 E. Broad Street 400 North 8th Street, Room 750 Richmond, VA 23219 Richmond, VA 23219-4825		13. Type of Report and Period Covered: Final
		14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

    Connections, closure pours, and joints in bridges are often sources of distress because of cracks and openings. Wide separation facilitates the penetration of harmful solutions that can lead to costly repairs. Cracks are caused by volumetric changes attributable to moisture and temperature and the application of service loads after the concrete has hardened. Poor bonding between the existing concrete and new concrete can lead to separation or opening. Wide cracks or openings within the material or at the interface and leaking joints allow the ingress of water and chemicals, causing damage to the bridge deck sections and the bridge substructure through corrosion of reinforcing steel, alkali-silica reactions, sulfate attack, and freeze-thaw damage.

    This study was designed to evaluate properties of fiber-reinforced concrete and cementitious composites in controlling cracking for bridge deck closure pours (i.e., link slabs). Plastic and hardened mixture properties of high-performance fiber-reinforced concrete (HPFRC) were evaluated, with emphasis on deflection hardening, flexural toughness, and bond strength. A secondary objective was to evaluate various bond strength tests for use in prequalification or quality assurance of mixtures. The addition of a small amount of discontinuous fibers to a conventional concrete matrix minimizes cracking, but the size of these cracks still permits the intrusion of harmful solutions. High volumes of suitable fibers used in HPFRC produce multiple very tight cracks (<0.1 mm wide), which do not allow for the ingress of water and other harmful solutions. Thus HPFRC offers a potential solution by controlling cracks and providing satisfactory bond strengths.

    The study recommends that VDOT's Structure and Bridge Division conduct field pilots of HPFRC mixtures that undergo deflection hardening to be used for closure pours (i.e., link slabs), and shear keys. The study also recommends that VDOT's Materials Division evaluate the California bond test (CA 551) for closure applications as part of field pilot projects. Pilots have already been initiated in VDOT's Staunton and Richmond districts.

17 Key Words: Fiber-reinforced concrete (FRC); engineered cementitious composite; ultra-high performance concrete (UHPC)		18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.	
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 25	22. Price:

Form DOT F 1700.7 (8-72)   Reproduction of completed page authorized

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Levon C. Hoomes, EIT
Bridge Designer
FIGG Bridge Group

H. Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist
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Michael C. Brown, Ph.D., P.E.
Associate Director
Virginia Transportation Research Council

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ABSTRACT

Connections, closure pours, and joints in bridges are often sources of distress because of cracks and openings. Wide separation facilitates the penetration of harmful solutions that can lead to costly repairs. Cracks are caused by volumetric changes attributable to moisture and temperature and the application of service loads after the concrete has hardened. Poor bonding between the existing concrete and new concrete can lead to separation or opening. Wide cracks or openings within the material or at the interface and leaking joints allow the ingress of water and chemicals, causing damage to the bridge deck sections and the bridge substructure through corrosion of reinforcing steel, alkali-silica reactions, sulfate attack, and freeze-thaw damage.

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INTRODUCTION

Cracking of concrete in connections, closure pours, and leaking joints in decks are often sources of permanent damage to bridges, which can lead to costly repairs. Jointless bridges are designed to alleviate these problems, and in the case of existing structures, deck joints may be eliminated through installation of closure pours, or link slabs. To extend the length of service of closure pours and connections, high-performance fiber-reinforced concretes (HPFRCs), which include high-performance fiber-reinforced cementitious composite mixtures, were investigated. HPFRC is expected to have high bond strength and high durability, and multiple cracks, should they occur, remain tight (<0.1 mm in width). Figure 1 shows the high ductility and tight multiple cracks in HPFRC. Cracks of this size do not readily allow water and other chemicals to penetrate the concrete.

One way to ensure that a fiber-reinforced concrete (FRC) or cementitious composite will exhibit tight cracks under bending and tension is through strain or deflection hardening. In strain or deflection hardening, as strain increases there is an increase of load carrying capacity past the point of yield (or initial cracking in the case of a cementitious composite) up to a peak load. Strain hardening is exhibited when the material is placed in tension, and deflection hardening when the material is in flexure. Figure 2 shows typical deflection hardening and softening behavior for a particular fiber combination.

A strong bond between the HPFRC closure material and the deck concrete is also critical to prevent the ingress of harmful solutions to other components of the bridge. To ensure the longevity of bridge structures, crack control, a good bond, and prevention or elimination of leaking joints are needed.
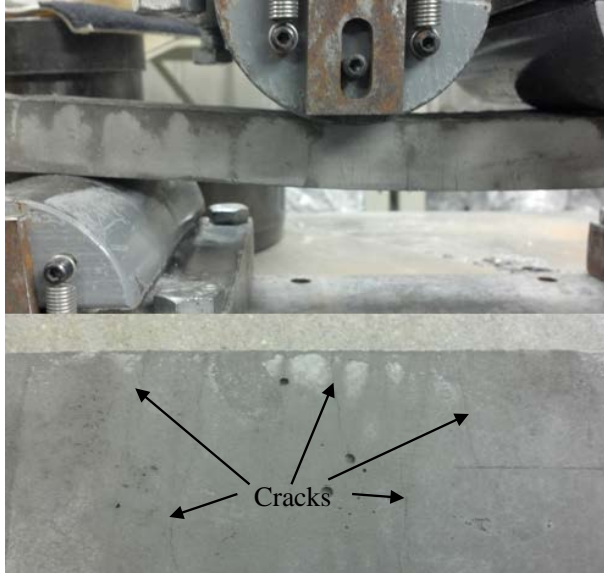
Figure 1. Ductility and Tight Cracks in High-Performance Fiber-Reinforced Concrete
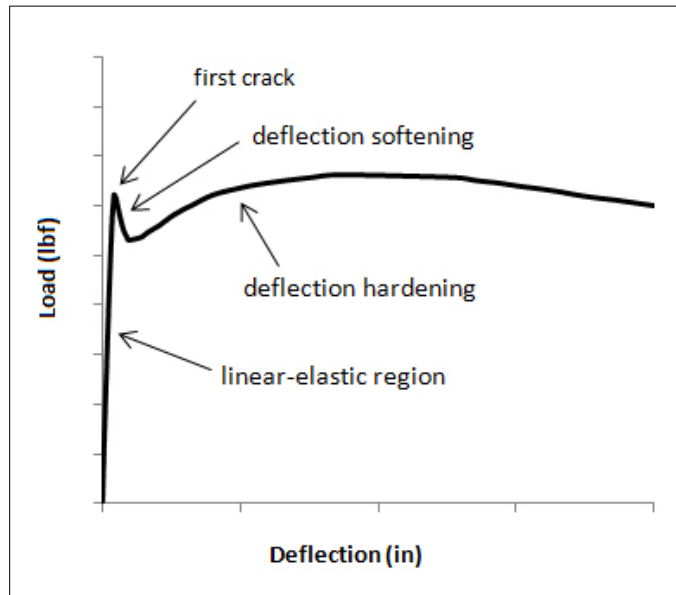

Figure 2. Typical Deflection Softening and Hardening Behavior of High-Performance Fiber-Reinforced Concretes

PURPOSE AND SCOPE

The purpose of this study was to evaluate properties of FRC and cementitious composites in controlling cracking for bridge superstructure link-slab connections and deck closure pours. A secondary objective was to evaluate various bond strength tests for use in prequalification or quality assurance of mixtures. A series of laboratory tests was used to complete a preliminary study of feasible mixtures.

METHODS

Overview

Cementitious mixtures were developed employing discrete steel or synthetic fibers or a combination of both. Tests were performed of mixtures in the fresh and hardened states to determine the properties of various HPFRC and high-performance fiber-reinforced cementitious composite systems. Each system was checked using preliminary small laboratory batches to ensure the desired properties were attained, including minimum compressive strength of 3,000 psi at 7 days and deflection hardening determined by flexural testing of beams measuring $4 \times 4 \times 14$ in with a gage length of 12 in. Then, larger laboratory batches were prepared, as described later. The variability of various bond strength tests was investigated. The crack widths and fiber lengths were measured and given in SI units, and the mechanical properties were reported in customary units.

Four tasks were conducted to achieve the study objectives:

1. review of the literature focused on applicable test methods to evaluate the bond of HPFRC mixtures to standard VDOT Class A4 base concrete

2. determination of potential mixtures for crack control and good bond

3. preliminary batching of various mixtures in the laboratory

4. materials testing of HPFRC.

Literature Review

Bond strength between the HPFRC materials and a concrete substrate was of critical importance for use of the subject materials in closure pours and joints. A literature review was conducted of available tests to evaluate bonds. Both standard and more recently developed non-standard tests were considered. The various tests for bond strength were the direct tension bond test, guillotine shear test, splitting prism test, slant shear test, and California Test 551.

Determination of Potential Mixtures

Different HPFRC systems were tested: engineered cementitious composite (ECC); hybrid fiber-reinforced concrete (HyFRC) systems, including both steel and synthetic discontinuous fibers; HyFRC including only synthetic fibers; and ultra-high performance concrete (UHPC) with steel fibers.

ECC

ECC has low permeability, contains no coarse aggregate, and is generally classified as a mortar mixture. ECC contains cement, fly ash, sand, and polyvinyl alcohol (PVA) microfibers (2% by volume) in order to achieve high ductility (Sahmaran et al., 2007). This system was previously mixed using locally available materials, tested, and proven to exhibit strain hardening in the laboratory (Ozyildirim and Vieira, 2008).

HyFRC (Steel and Synthetic Fibers)

A HyFRC system with both steel and synthetic discontinuous fibers can achieve strain hardening (Blunt and Ostertag, 2009). In contrast to ECC, coarse aggregates are typically used in HyFRC mixtures. The presence of coarse aggregate reduces paste requirements, which is expected to decrease the amount of shrinkage of the material and be less costly. In unpublished work conducted at the Virginia Transportation Research Council (VTRC) using locally available materials, HyFRC also displayed deflection hardening behavior. Gravel with a maximum nominal size of 3/8 in was used. Low permeability is also characteristic of this system.

HyFRC (Synthetic Fibers)

A HyFRC system with different synthetic fibers (but excluding steel fibers) has the advantage of easier handling and high corrosion resistance. A variety of combinations of fibers is possible; one system investigated at VTRC contained only PVA macrofibers and microfibers, and a second system had 50-mm polypropylene fibers in addition to PVA fibers. These mixtures were explored in an attempt to eliminate the use of steel fibers yet maintain the flexural and crack control characteristics seen in the HyFRC and ECC mixtures. This system also used 3/8-in maximum nominal size gravel.

UHPC With Steel Fibers

Like ECC, UHPC is a mortar mixture. UHPC with steel fibers has been used for field-cast connections for precast deck panels (Graybeal, 2012). The UHPC evaluated was a prepackaged proprietary material; water and high-range water-reducing admixture (HRWRA) are added and mixed thoroughly before the addition of 14-mm-long (0.6-in-long) brass-coated steel fibers.

This mixture has high compressive and bond strengths and is very durable, with high resistance to chloride ion penetration, freeze-thaw damage, and chemical attack. This UHPC uses brass-coated steel microfibers for reinforcement, which reduces plastic shrinkage cracking and is said to increase strain-hardening capabilities.

Preliminary Batching of Mixtures in the Laboratory

For each potential mixture, small trial batches of 0.7 ft^3 were prepared and 2-in mortar cubes and 4 × 8 in cylinders were cast and tested for compressive strength; beams were cast and tested for flexural strength and strain-hardening behavior.

ECC

Two small batches of ECC were produced, each with a different type of sand. In ECC, no coarse aggregate is used, so that sand comprises the largest particles in the cementitious matrix.

HyFRC

HyFRC mixtures including varying amounts of steel and synthetic fibers similar to those developed in California (Blunt and Ostertag, 2009) but with locally available materials were produced. These mixtures closely resembled standard VDOT mixtures except that they included fibers; therefore, trial batches were not prepared for them.

The HyFRC mixtures containing only synthetic fiber required much experimentation in order to achieve strain hardening and tight crack control. Different fiber combinations, paste contents, and water–cementitious materials ratios (w/cm) by weight were tried until a satisfactory mixture was obtained. Three types of synthetic fibers were used: (1) an 8-mm-long (0.375-in-long) PVA fiber, which functions on the micro-level to prevent the propagation of microcracks; (2) a 30-mm-long (1.25-in-long) PVA fiber, which was meant to control the growth of macrocracks that form when microcracks coalesce into larger cracks; and (3) a 50-mm-long (2-in-long) polypropylene fiber, which was expected to improve the post-crack performance of concrete. Both PVA fibers have a specific gravity of 1.3, and the polypropylene fiber has a specific gravity of 0.91.

At the beginning of the process of developing a satisfactory HyFRC mixture, only PVA fibers were used. In the first HyFRC mixture, a 2:1 ratio of PVA macrofibers to PVA microfibers was used. Subsequent mix designs were developed to improve on the preceding mixture by varying the fiber volume, type, w/cm, and paste content. The results of ASTM International (ASTM) flexural tests, i.e., ASTM C1609 (ASTM, 2013a) and ASTM C78 (ASTM, 2010a), governed the alterations made for the subsequent mix design. This process was complicated by the large volume of fibers and the hydrophilic nature of the PVA microfibers. To include the large amount of fibers (up to 2% by volume), the paste content of the concrete was increased and HRWRA was used.

UHPC

One trial batch of UHPC using three bags of premix was mixed in the laboratory, which equates to a 1.1 ft^3 batch. Compressive strength, flexural strength, and the deflection hardening capacity of the specimens were tested for the preliminary test batches. Fresh mixture properties were determined for ECC and HyFRC mixtures.

Materials Testing

Tests

Fresh and Hardened Concrete Tests

The fresh concrete tests included air content (ASTM C231) (ASTM, 2010b); density (ASTM C138) (ASTM, 2013b); and three types of slump tests: slump cone test (ASTM C143) (ASTM, 2005a) for base VDOT Class A4 concrete, mini–slump flow test (ASTM C230) (ASTM, 2014) for ECC mixtures, and inverted slump cone test (ASTM C995) (ASTM, 2001) for FRC mixtures. ASTM withdrew ASTM C995 in 2008 without replacement because of limited use; however, the results of the test are still valid.

Hardened concretes were tested for compressive (ASTM C39) (ASTM, 2005b), flexural, and bond strengths. For the flexure test, $4 \times 4 \times 14$ in beams were cast and the deflection hardening properties were determined (ASTM C1609); thin beams of 1-in thickness were tested to observe crack control. In addition, specimens were tested for shrinkage (ASTM C157) (ASTM, 2008).

Bond Strength Tests

For bond strength, several methods were evaluated, including the following:

- *Direct tension bond test (ASTM C1404) (ASTM, 1998).* ASTM withdrew ASTM C1404 in 2010 because of limited use. In 2013, ASTM introduced another similar test, ASTM C1583 (ASTM, 2013c).

- *Guillotine shear test (American Concrete Institute, 1998).*

- *Splitting prism test.* The splitting prism test is a modification of the splitting tensile test for cylindrical specimens (ASTM C496) (ASTM, 2011)

- *Slant shear test (ASTM C882) (ASTM, 2013d).*

- *California Test 551 (CA 551) (California Department of Transportation, 2009).*

Laboratory Batches

Two 2-ft^3 batches were mixed for each system with the use of a pan-type mixer. To determine the variability, at least three specimens were tested for each test value.

Class A4 Concrete Mixture Proportions

Base concretes for the bond tests were regular VDOT Class A4 bridge deck concrete, which has a minimum 28-day strength of 4,000 psi. The Class A4 concrete mixture had a total cementitious material content of 635 lb/yd^3 with 20% Class F fly ash and a 0.45 w/cm. Base

concrete specimens for different tests were prepared and cured for at least 28 days. The base specimens were aged in the VTRC moisture room for at least 56 days, and the surface of each base concrete specimen intended to serve as the bond surface was sandblasted 1 day before placement of the test mixture on the saturated-surface dry surface.

HPFRC Mixture Proportions

The results of laboratory evaluations of HPFRC mixtures including ECC, UHPC, and two HyFRC variants are reported here. Mixture proportions for the materials evaluated are provided in Table 1, and details about each mixture follow.

Table 1. Mix Design for HPFRC[a]

Mixture Component	ECC	UHPC	HyFRC-A	HyFRC-G
Cement	961	-	508	490
Fly ash (Class F)	1,153	-	127	210
Pre-bagged mix	-	3,700	-	-
Mortar sand	767	-	-	-
Concrete sand	-	-	1,587	1,176
3/8-in Gravel	-	-	1,223	1,454
Water (Part 1)	570	219.1	289	315
Water (Part 2)	86	-	-	-
PVA microfibers (8 mm)	44 (2.00%)	-	4.4 (0.20%)	7.3 (0.33%)
Steel fibers (30 mm)	-	-	66.1 (0.50%)	-
Steel fibers (60 mm)	-	-	105.8 (0.80%)	-
PVA macrofibers (30 mm)		-	-	11.0 (0.50%)
Polypropylene macrofibers (50 mm)		-	-	17.9 (1.17%)
Brass-coated steel fibers	-	262.9 (2.00%)	-	-
HRWRA 1	5.4 oz/cwt	-	-	-
HRWRA 2	-	19.4 oz/cwt	-	-
HRWRA 3	-	-	2.1 oz/cwt	1.9 oz/cwt
w/cm	0.31	-	0.45	0.45
Total fiber content (%)	2.00	2.00	1.50	2.00

HPFRC = high-performance fiber-reinforced concrete; ECC = engineered cementitious composite; UHPC = ultra-high performance concrete; HyFRC-A = hybrid fiber-reinforced concrete; HyFRC-G = hybrid fiber-reinforced concrete; PVA = polyvinyl alcohol; HRWRA = high-range water-reducing admixture; w/cm = water–cementitious materials ratio.
[a]Units are in lb/yd^3 unless otherwise stated.

ECC. To achieve the proper viscosity in ECC before the addition of fibers, the amount of water was split into two components, as seen in the mix design in Table 1. The proper mixture consistency was somewhere between stiff and wet to enable good mixing of fibers. After the addition of fibers, the remaining water was added to enable a flowing consistency that did not need vibration for consolidation.

For a satisfactory ECC mixture with well-dispersed fibers, the following mixing sequence was followed (Zhou et al., 2012):

1. Part 1 of the water (87%) was mixed with solid materials for approximately 2 minutes so that a dough-like consistency was reached.

2. Fibers were added and mixed for 8 minutes.

3. The remaining water was added and mixed for another 6 minutes.

The mini–slump flow test was performed before the addition of fibers with the use of a miniature brass slump cone as specified in ASTM C230.

HyFRC (Synthetic and Steel): (HyFRC-A). Mixtures developed in California using synthetic and steel fibers were prepared with locally available materials (Blunt and Ostertag, 2009). Fibers used were PVA microfibers and 30-mm-long (1.2-in-long) and 60-mm-long (2.4-in-long) hooked-end steel fibers. This mixture is hereinafter referred to as HyFRC-A.

All components except for the fibers were mixed for 1 to 2 minutes before the addition of fibers. Since fibers reduce the workability of the mixture, water-reducing admixture was added to improve the workability.

HyFRC (Synthetic Only): (HyFRC-G). Three sizes of synthetic fibers were used in the mixtures designated as HyFRC-G mixtures: 8-mm-long PVA microfibers, 30-mm-long PVA macrofibers, and 50-mm-long polypropylene macrofibers. The mixture proportions are given in Table 1.

UHPC. Fresh mixture properties were not determined for UHPC since the ingredients are predetermined. The mixture was self-consolidating but had high viscosity and flowed slowly.

RESULTS AND DISCUSSION

Literature Review

Direct Tension Bond Test

The direct tension bond test, conducted in accordance with ASTM C1404-98 (ASTM, 1998), measures the bond strength in direct tension (perpendicular to the plane of the interface). This test is performed on a composite cylindrical specimen of either 4-in or 3-in diameter. The length of the cylinder is at least 4 in, and the cylinder is composed of a base portion and an overlay portion. A steel cap with eyebolt is bonded to each end of the specimen with epoxy at least 24 hours before testing. For this experiment, 4-in-diameter specimens were used in order to increase the area of the bond surface with the intent of improving the accuracy of the results. The specimen was always oriented so that the base portion of the specimen was on the bottom. The test setup is shown in Figure 3.

Figure 3. Setup for Direct Tension Bond Test

For the test, caps with eyebolts were bonded by an epoxy to the ends of the specimens. In some cases, the specimen failed at the epoxy-bond interface (at the cap) instead of the overlay-to-base bond interface. The failure could also occur entirely in either the overlay material or the base material. The location of the failure was determined by the location in the specimen with the least tensile capacity or the location with the highest stress concentration. In order to obtain the actual strength of the overlay-to-base bond, the failure must occur at the bond interface. Failure at another location simply means either that the strength of the overlay-to-base bond was higher than the recorded failure tensile capacity of the specimen or that the highest concentration of stresses did not occur at the bond interface.

Although care was taken to center the end caps for this test, the stress distribution may be uneven if the cap is horizontally skewed to the end of the specimen or if the cap is not exactly on center. Thus, the average strength reported by this test may not provide an accurate measurement of the strength of the bond.

Guillotine Shear Test

The guillotine shear test, the development of which is attributed to the Brookhaven National Labs (American Concrete Institute, 1998), measures the shear bond strength of overlays. The test requires a cylindrically shaped specimen consisting of two different materials (a base material and an overlay or bonding material) that is sheared at the interface by a guillotine-like jig that has a base to hold the specimen and a falling head that induces the shear under the force of a load frame. The test setup is shown in Figure 4.

Figure 4. Setup for Guillotine Shear Test

The guillotine shear test was developed as a method for determining the shear bond strength of overlay materials. The configuration of this test has very particular specimen size requirements. The test frame (the guillotine) has a hole that is just large enough for a 4-in-diameter specimen. Any irregularities in the specimen cross section may alter the result of the test. If specimens slightly smaller than 4 in in diameter are placed in the guillotine, the unsupported portion of the specimen may tilt downward and cause the failure plane to be skewed away from the bond interface by an amount proportional to the angle at which the specimen tilts. One of the major benefits of the test is the tendency of the failure to occur at or near the bond interface. Issues with specimen skew may be solved by creating a female mold that fits inside the guillotine and holds the specimen tightly in the circular hole.

Splitting Prism Test

As discussed previously, the splitting prism test is a modification of the splitting tensile test for cylindrical specimens (ASTM C496). Instead of cylindrical specimens consisting of a single material, composite rectangular prism specimens are used (see Figure 5).

Figure 5. Setup for Splitting Prism Test. Note in left photograph that the base and high-performance fiber-reinforced concretes contain aggregate of several different colors and the interface plane is aligned with the axis of the slitting tensile loading head.

A loading bar is placed along the top surface of the bond interface and loaded, inducing a splitting tensile force perpendicular to the bond plane. Hardened specimens measuring 3 in wide × 4 in deep × 16 in long were cut in half lengthwise as base concrete. Then the closure pour materials were cast against the base segments in the original mold. After 7 days of curing, the specimens were removed from the moist room and cut into four segments so that the dimensions of the remaining four composite sections were 3 in wide × 4 in deep × 4 in long (see Figure 5).

The splitting prism test provides a large failure surface (4 × 4 in) and promotes failure at the bond interface when the specimen is loaded directly along the edge of the bond. However, if the specimen is not loaded directly along the bond line, the compressive strength of either the overlay or base material may influence the results as the portion of the specimen supporting the majority of the load begins to crush in compression. During the test, when the bond fails, the sustained compressive load only slightly decreases before continuing to increase as the separated base and overlay components continue to resist the compressive force. This can sometimes be confused with minor fluctuations in load resistance that are observed as the wooden loading strips are crushed, making it challenging to obtain an accurate reading. This issue may affect the accuracy of this test.

Slant Shear Test

Another available bond test is the slant shear test, ASTM C882. In this test, the bond strength is determined by use of the epoxy system to bond together two equal sections of a portland cement mortar cylinder. A variation of this test can be used to determine the bond strength where the experimental concretes are cast over the hardened base concrete. This test was not used because of high variability; the precision statement in ASTM C882 (ASTM, 2013d) indicates an effective coefficient of variation [CoV] over 20% is to be expected.

CA 551

CA 551 includes a method for testing the bond strength between a concrete overlay and a portland cement concrete (PCC) base (California Department of Transportation, 2000). This method requires that a 3 × 3 × 11-in composite specimen be cast with one half containing the base material and the other half containing the overlay or bonding material. The bond interface is located at the middle of the specimen lengthwise, as shown in Figure 6.

CA 551 determines the tensile bond strength at the overlay-to-base interface by calculating the force in the tension face when the composite beam specimen is placed in flexure. The specimen under this test, unlike in the splitting prism test and guillotine shear test, undergoes an immediate failure as the bond fails. The capacity of the specimen immediately drops sharply upon fracture at the bond. CA 551 also promotes failure at the bond (as opposed to in the overlay material or the base material) by using a center point load configuration.

Figure 6. Setup for California Test 551

VDOT Class A4 Bridge Deck Concrete

For VDOT Class A4 bridge deck concrete, the average slump for the base mixture was 3.5 in, the average air content was 5.5%, and the average density was 144 lb/ft^3. The compressive strength after 28 days of curing was tested to ensure that the mixture would achieve the desired minimum strength of 4,000 psi. The average 28-day compressive strength of the Class A4 bridge deck concrete used in the base for the ECC and HyFRC-A mixtures was 4,740 psi, which is higher than the 4,000 psi specified. The average compressive strength of the Class A4 base mixture used to test HyFRC-G and UHPC was 5,240 psi.

HPFRC Mixtures

ECC mixtures were workable and self-consolidating, and the fibers were well disbursed. The HyFRC mixtures were workable but required consolidation; the fibers were well disbursed. UHPC premix was self-consolidating and very workable. Steel fibers for UHPC were mixed in easily; however, upon failure of the beam specimens, the cut cross sections revealed that steel fibers had settled to the bottom of the mixture.

The hardened properties are summarized in Table 2. The deflection hardening capacity of each system is quantified by dividing the average peak stress by the average yield stress, or first cracking stress, for each mixture. Thus, if the quantity is 1.0, deflection hardening was not achieved. For numbers exceeding 1.0, deflection hardening was achieved.

Table 2. Hardened Properties of Class A4 Concrete and HPFRC

Test / No. of Days		VDOT Class A4[a]	ECC (Batch 1)	ECC (Batch 2)	HyFRC-A	HyFRC-G	UHPC
Compressive Strength (psi)	7	4,000	4,315	4,780	-	-	15,355
	28		6,920	7,865	6,115	4,400	22,180
Elastic Modulus (ksi)		3,000-6,000	2420		3,820	2,780	8,200
Flexural Behavior							
Flexural stress at first yield (psi)	7	600	670	645	-	-	1,835
	28		895	835	760	580	2,290
Peak flexural stress (psi)	7		1,070	1,190	-	-	1,835
	28		1,440	1,465	1,160	725	2,290
Deflection hardening capacity	7		1.60	1.84	-	-	1.00
	28		1.61	1.75	1.53	1.25	1.00
Flexural toughness (lb-in)	7		260	280	-	-	400
	28		340	330	980	580	460
Bond strength							
Guillotine shear test (psi)	7		560	760	720	515	1,120
	28		990	1,065	690	625	1,170
Splitting prism test (psi)	7		800	800	700	510	1,260
	28		935	1,100	990	555	1,225
California bond test (psi)	7		590	625	785	500	690
	28		825	755	895	525	1,050
Direct tension bond test (psi)	7		340	310	425	325	245
	28		285	295	380	330	455

VDOT = Virginia Department of Transportation; HPFRC = high-performance fiber-reinforced concrete; ECC = engineered cementitious composite; UHPC = ultra-high performance concrete; HyFRC-A = hybrid fiber-reinforced concrete; HyFRC-G = hybrid fiber-reinforced concrete.
[a] The specification requirement for 28-day strength was 4,000 psi (VDOT, 2017). The expected elastic modulus varies between 3,000 and 6,000 ksi depending on the compressive strength, and the flexural strengths are expected to be more than 600 psi.

Figure 7 shows typical flexural stresses as beam specimens undergo deflection under third point loading. All except the UHPC showed deflection hardening. The difficulty in UHPC may be attributed to the sinking of the fibers. During testing, the beam was placed sideways to provide smooth cast surfaces at the top and bottom. Thus, because of apparent settlement, fibers were concentrated in one-half of the cross section being tested. In the future, the viscosity of the mixture should be increased to minimize fiber segregation. HyFRC-G displayed lower yield stresses than the other systems but was able to achieve deflection hardening.
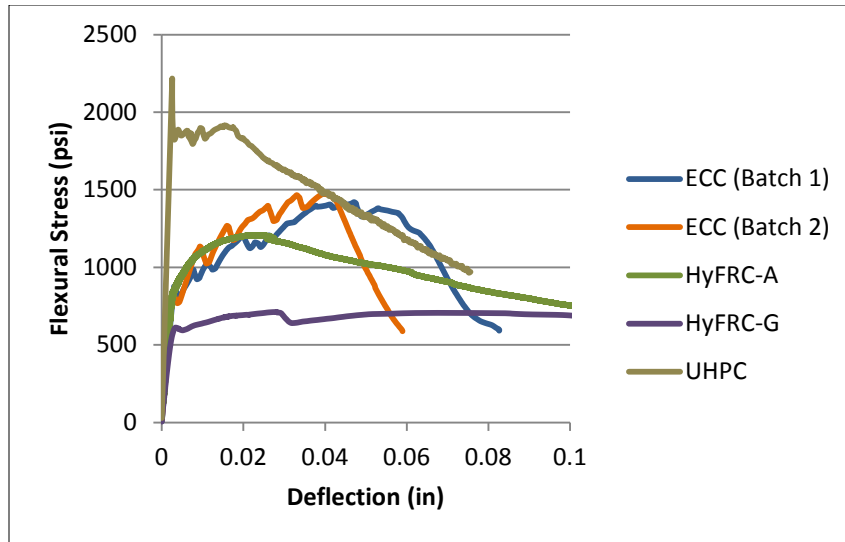
Figure 7. Flexural Performance of High-Performance Fiber-Reinforced Concrete Systems. Stresses are determined from the measured loads using the relationship applicable to the elastic region. ASTM C1609 (ASTM, 2013a) uses the same relationship to determine stresses after the elastic region. HPFRC = high-performance fiber-reinforced concrete; ECC = engineered cementitious composite; UHPC = ultra-high performance concrete; HyFRC-A = hybrid fiber-reinforced concrete; HyFRC-G = hybrid fiber-reinforced concrete.

Flexural Toughness

Typically, deflection hardening capacity is measured by calculating the flexural toughness. Several of the beam specimens in this study did not reach the required deflection (at least L/150 in) for the calculation of flexural toughness because of constraints set by the testing apparatus. Thus, the deflection limit for calculating flexural toughness was lowered from L/150 to L/220 for this study to enable comparison of the flexural toughness of each system.

Flexural toughness could be compared only between systems that used beam specimens with the same geometry. Thus, flexural toughness was compared between UHPC and ECC and between the two HyFRC mixtures. The average flexural toughness of UHPC at 7 days and 28 days was 400 lb-in and 460 lb-in, respectively. In comparison with the 260 lb-in and 340 lb-in for ECC, UHPC displayed much greater toughness. This means that greater energy is required to fail the specimen. UHPC did not achieve deflection hardening, but the high flexural strength reached before first crack coupled with the residual strength provided by the fibers contributed to the high flexural toughness of the system. This is a possible indication of crack control in this system. With regard to the FRC mixtures, HyFRC-A had higher average flexural toughness than HyFRC-G—as expected—because of the steel fibers in the matrix.

Deflection Hardening

For HyFRC-A, the point of first crack based on the load deflection curve was difficult to identify because deflection softening did not occur. To determine the point of first crack, the load deflection trend was observed and the first point, which expressed clear nonlinear behavior, was used to define first crack. This is appropriate because first crack in concrete separates linear elastic behavior from nonlinear inelastic behavior. Based on the results from this test regimen,

14

all of the systems being considered achieved some degree of deflection hardening with the exception of UHPC, which had a large drop in strength after first cracking. This behavior is attributed to the settling of the fibers in the UHPC. Although UHPC did not achieve deflection hardening, the material did not undergo brittle failure. Compared to the other systems, UHPC achieved very high stress at first crack, and the energy required to fail these specimens was high, as indicated by the modified flexural toughness.

The system that achieved the highest deflection hardening capacity based on these results was ECC Batch 2, which attained a peak flexural stress 75% higher than the stress at first crack. The compressive strengths and deflection hardening capacity were slightly higher than those of ECC Batch 1.

Bond Strength

The variability of the different bond tests is conveyed through range, standard deviation, and CoV, as shown in Table 3. The average values include the results for all mixtures. The standard deviation was large because of the small number of specimens. Table 3 shows the average parameters for each bond strength test after 28 days of curing. Although some tests seem to be less reliable than others for providing the actual bond strength of two materials, all of these tests yielded somewhat consistent results and can still be used as a means of comparing the bond strength of the systems being analyzed.

Table 3. Parameters for 28-Day Bond Test Results (psi)

Test	Average	Range	Standard Deviation	Coefficient of Variation (%)
Direct tension bond test	366	94	37	10.1
California Test 551	801	154	86	10.7
Guillotine shear test	878	365	146	16.6
Splitting prism test	947	320	117	12.4

ASTM C496 states: "Splitting tensile strength is generally greater than direct tensile strength and lower than flexural strength (modulus of rupture)" (ASTM, 2011). This may suggest that the strengths determined by the splitting prism test should be greater than those of the direct tension bond test and less than those of CA 551. The results of the direct tension bond test and CA 551 were in accordance with this, but the results of the spitting prism test tended to be higher than those of CA 551. This may have been due to the aforementioned possibility that the compressive strength of either the base or overlay material could influence the results and produce higher strength results for the splitting prism test.

With the small numbers of samples tested, it is difficult to determine which test provided the most dependable results. The suitability of each test must be determined individually for each system being tested. Accuracy of bond strength tests was determined by comparing the results of the current study with results of previous research that had been completed with each test on similar materials. Research by Tayeh et al. (2013) to determine the strength of the bond between UHPC and normal concrete with a sandblasted surface indicated an average 28-day bond strength of approximately 510 psi for composite splitting tensile test specimens. Their test method most closely resembles the splitting prism test performed in this study. The average 28-day bond strengths for the splitting prism test ranged from 555 psi (for HyFRC-G) to 1,225 psi

(for UHPC). This range is higher than the average strengths found by others using this test. Momayez et al. (2005) found that results from the splitting prism test and pull-off tests (an in situ variant of the direct tension bond test) were lower than for other bond strength tests. This observation held true in the current study for the direct tension bond test, but the results for the splitting prism test were much higher than found by others. This further supports speculation about closure pour material or base material compressive strengths increasing the bond strength results for this test. In research by Shatnawi (2011), bond strengths of 400 psi to 500 psi were achieved using CA 551 to test the bond between two placements of standard PCC. The values obtained with that test for bond strength for the systems in the current study were larger, but this can be expected because of the high-performance characteristics of the HPFRC systems. No results of the guillotine shear test in which similar overlay materials were used were found.

Based on the average CoV, the direct tension bond test (ASTM C1404) provided the most consistent results in the current study, closely followed by CA 551. However, ASTM withdrew ASTM C1404 in 2010 because of limited use.

In the current study, CA 551 and ASTM C1404 were used for comparison with the other bond strength tests. The guillotine shear test results had the highest variability, but the bond strength values were similar to those with CA 551. The splitting prism test provided slightly more consistent results than the guillotine shear test, and the results were higher than those of the other tests discussed herein. All HPFRC systems met the lower quality limit for bond strength of 150 psi as specified in a VDOT special provision for overlays (VDOT, 2002). The lowest average bond strength was 366 psi.

Fresh Concrete Properties

Workability of cementitious mixtures can be critical for the performance of the structure, especially when the material is cast in a closure pour and reinforcement congestion limits methods of consolidation. Several observations were made about the workability of each system in this study.

ECC is highly workable and is self-consolidating, but the workability is critically dependent on the mixture sequence. The mini–slump flow test was performed before the addition of fibers with a miniature brass slump cone as described in ASTM C230. When the cone full of material was lifted, a spread diameter of 5 7/8 in was achieved, which indicates that the mixture is suitable for mixing with fibers. The air content was 3.0% and 3.6% for the first and second batches, respectively, and the average density for both batches was 120 lb/ft^3.

UHPC was also highly workable and self-consolidating, but there were issues with set time and settling of fibers. For both batches of UHPC, the specimens required 3 days to set before they were hard enough to be removed from the molds and placed in the moisture room to cure. The mixture proportions were in accordance with the supplied mix design. One potential source for the long set time may be the type of mixer used. A mixer with high shearing action can be used effectively for UHPC, but a pan-type mixer was used in the laboratory in the current study.

The workability of the HyFRC systems varied greatly. HyFRC-A with mainly steel fibers was workable and easily placed in the molds. External vibration was applied to consolidate the mixture in the molds. Internal vibration for FRC systems causes fibers to disperse from the location of the vibrator, which disrupts the even distribution of fibers throughout the mixture. Thus, internal vibration is avoided when FRC mixtures are consolidated. The average air content was 3.3%. The inverted slump test was performed, and the average time was 8.8 seconds. The final average unit weight was 147.2 lb/ft^3, which is slightly higher than for typical concrete, as expected, because of the added weight of the steel fibers in the mixture.

The workability of HyFRC-G with synthetic fibers was greatly reduced by the long fibers, and the system required more external vibration than the HyFRC-A mixture. The deformations along the long polypropylene fibers may have had an effect on the workability of this mixture. During mixing of the HyFRC-G mixture, it was observed that the long fibers were tangling together in clumps, affecting the uniformity of the mixture. Synthetic fibers had a more pronounced effect on reducing workability than the steel fibers, necessitating higher amounts of HRWRA. However, the excess admixture caused the fibers to segregate and ball and caused large amounts of entrained air. For the first batch, an air content of 4.3% was achieved, and the inverted slump test time was 19.3 seconds, which was far longer than expected. For the second batch, an air content of 6.4% was achieved. The inverted slump test time was 7.9 seconds, as desired, but there was some minor bleeding of the mixture. The densities were 125.2 lb/ft^3 and 136.4 lb/ft^3 for the first and second batches, respectively. The unit weight was expected to be lighter than for standard PCC because of the use of 2.0% synthetic fibers in the mixture.

Differences in Material Results

The two mortar systems (ECC and UHPC) had very high bond strengths because of a low w/cm, indicating strong paste. Although these two systems provided the highest bond strengths, the HyFRC systems provided a more economical solution to crack control and bond strength attributable to less paste.

Shrinkage was another factor that was tested for each system. Large volumetric changes can cause cracking of the material and unwanted tensile forces at the bond interface between the closure pour and deck. The ECC systems exhibited the highest volumetric change, which was attributable to a high paste content. However, the high deflection hardening capacity of ECC allows for tight cracks in the system. The cracks were less than 1 mm as determined by a visual crack comparator. The shrinkage results are presented in Table 4.

Table 4. Average Drying Shrinkage of HPFRC

System	Shrinkage (microstrain)		
	7 Days	28 Days	16 Weeks
ECC	1,108	1,457	1,840
HyFRC-A	148	298	540
HyFRC-G	180	520	
UHPC	230	350	

HPFRC = high-performance fiber-reinforced concrete; ECC = engineered cementitious composite; UHPC = ultra-high performance concrete; HyFRC-A = hybrid fiber-reinforced concrete; HyFRC-G = hybrid fiber-reinforced concrete.

The UHPC system tested in the laboratory did not undergo deflection hardening but achieved very high stress at first crack compared to the other systems and had volume stability. The shrinkage properties of the HyFRC systems varied slightly from the typical range of volumetric change for normal weight concrete. The elastic modulus for most mixtures was within the typical range for portland cement mixtures except for UHPC, for which it was higher because of the extremely high strength of the system. ECC had high shrinkage values; however, it exhibited tight multiple cracks less than 0.1 mm, making intrusion of solutions difficult.

Summary of Findings

- ECC and HyFRC mixtures achieved deflection hardening with a high fiber content of steel or synthetic fibers. ECC achieved the highest deflection hardening capacity of all systems tested.

- Although UHPC attained the highest stress capacity, the material did not undergo deflection hardening; these results were partly attributed to the settling of the fibers to the bottom.

- Mixtures with high shrinkage values did not necessarily exhibit wide cracks. ECC had the highest shrinkage values yet showed deflection hardening and uniformly distributed multiple tight cracks instead of few wide cracks.

- The workability of mixtures with steel fibers was higher than for those with synthetic fibers.

- All mixtures achieved adequate bond strength for use in closure pours.

- Based on the different bond tests, different average values and variability were obtained such that no single test gave the most indicative measure of bond. The direct tension bond test and CA 551 provided the lowest CoV.

CONCLUSIONS

- *Fibers in cementitious composites and concrete mixtures can be effective in controlling crack widths, even in mixtures with substantial shrinkage.*

- *FRC mixtures that underwent deflection hardening exhibited a series of fine cracks instead of fewer wide cracks.*

- *Of the bond tests evaluated, the direct tension bond test and CA 551 provided the most consistent and satisfactory results.*

- *Bond tests (direct, flexure, shear, or splitting) must be selected in accordance with the stresses anticipated in application.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should conduct field pilots of HPFRC mixtures that undergo deflection hardening to be used for closure pours, link slabs, and shear keys, particularly in situations where a protective overlay will not be applied and the closure will be exposed to the environment, to achieve tight cracks (less than 0.1 mm in width).*

2. *VDOT's Materials Division should evaluate application of CA 551 in a series of field pilot projects to determine the bond strength of concretes for closure applications.*

BENEFITS AND IMPLEMENTATION

Benefits

The costs of fiber-reinforced cementitious composites and FRCs vary widely. FRC mixtures may cost as little as twice the materials unit cost of conventional concrete; ECC costs are reported to be 3 times that of conventional concrete (Zhang et al., 2015); and UHPC may cost as much as 20 times that of conventional concrete, particularly if small quantities are used (Ahlborn et al., 2008). Differences in cost can be attributed to the types and amounts of fibers employed, the amounts of other specialized ingredients including admixtures needed to achieve workable mixtures, and the proprietary nature of certain commercialized mixtures.

Based on the performance of each system and the respective costs, the HyFRC systems present an economical means of crack control and corrosion resistance in closure pours or link slabs in bridges. Of the mixtures evaluated in this study, the most economical and user-friendly system is expected to be the HyFRC-G system, but further field evaluation is necessary. HyFRC-G can be more easily mixed in large quantities than a mortar mixture. In addition, HyFRC-G lacks steel fibers that can cause minor injuries during handling and cause discoloration of the concrete surface in service. Each system has its own benefits and limitations, and the correct material must be chosen based on the application.

Regarding Recommendation 1, VDOT personnel will gain direct experience with application of the materials and develop a greater ability to tailor the mixtures to respective applications by conducting the recommended pilots.

With regard to Recommendation 2, the application of the suggested test method in a production field application will allow personnel of VDOT's Materials Division to evaluate the efficacy of the method for routine quality control and quality assurance purposes and determine whether the method is most suitable to be incorporated into standard specifications.

Implementation

With regard to Recommendation 1, ECC and HPFRC mixtures are being evaluated in a pilot project on two bridges carrying I-64 over Dunlap Creek near Covington, Virginia, and in

another project on the eastbound lane of I-64 over Route 33 in Henrico County to assess performance of the materials in link slabs. ECC was also evaluated by VDOT in shear key applications for voided slabs and box beams with satisfactory results and has become a routine material for shear keys. VTRC is working with VDOT's Structure and Bridge Division to develop guidance for materials selection related to closure pours and link slabs for the *Manual of the Structure and Bridge Division*. Designers are cautioned against placing overlays over the HPFRC closures without first evaluating their potential to crack or debond in the region of the closure. This effort is already well underway and is anticipated to be complete in 2017.

With regard to Recommendation 2, VTRC is working with VDOT's Materials Division to develop special provisions for pilot projects and ultimately to suggest appropriate modifications to VDOT's *Road and Bridge Specifications* relating to bond tests. This effort is anticipated to be complete in 2017.

ACKNOWLEDGMENTS

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