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Fiber-Reinforced Concrete Overlays for Bridge Structures

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FINAL REPORT

FIBER-REINFORCED CONCRETE OVERLAYS FOR BRIDGE STRUCTURES

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ABSTRACT

The common distresses in bridge decks are the loss of surface texture due to traffic, and cracks and spalls because of the reinforcement corroding. The common repair procedure for such distresses is removing the top surface of the deteriorated concrete and placing a low-permeability concrete overlay. Sometimes, these overlays exhibit cracks, diminishing the intended purpose of resisting the penetration of water and chloride solutions. Such cracks can occur in concrete overlays at early and late ages. However, the selection of ingredients, proportioning, and the addition of fibers to concrete can control cracks. Fiber-reinforced concretes (FRC) achieve varying levels of strength and ductility by adjusting the mixture design, including the types and amounts of fibers to address cracking occurring at different ages. This research emphasized the potential of using FRC as a versatile construction material, enabling tailored strength and durability properties to specific situations. Two groups of concretes with fibers were investigated—one with some residual strengths denoted as FRC and the other with deflection hardening properties denoted as high-performance FRC, or HPFRC. The findings of this research contribute to the understanding of FRC performance and guide the selection of optimal mixture designs with fibers to control cracking and improve the longevity and performance of concrete overlays. The practical outcome of this study is the recommendation that the Virginia Department of Transportation should use FRC to control cracking in overlays as needed, feasible, and practical.

FINAL REPORT

FIBER-REINFORCED CONCRETE OVERLAYS FOR BRIDGE STRUCTURES

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INTRODUCTION

The common distresses in bridge decks are the loss of surface texture, cracks, and spalls. Loss of texture results from many years of heavy traffic and poor concrete mixture proportioning, consolidation, surface finishing, and curing practices. Cracks and spalls are mainly due to corrosion, which is the main deterioration mechanism in bridge decks. Salt solutions infiltrating to the level of reinforcing steel through the concrete with high permeability and cracks in the concrete initiate and propagate corrosion that leads to delamination and further cracking and spalling (Balakumaran et al., 2017a; Balakumaran et al., 2017b). The common repair procedure for decks is the removal of the deteriorated concrete on the top surface and placement of rigid, low-permeability overlays (Ozyildirim and Nair, 2017; Sprinkel, 1999). Thin, rigid overlays are generally from 1.5 to 2 inches thick, with a specified minimum thickness of 1.25 inches. The overlay is expected to improve the surface texture and resist the penetration of water and harmful salt solutions into concrete. Sometimes the extent of deterioration in the reinforcement and the depth of chloride contamination requires exposing reinforcement, removing rust, and placing the concrete at least an inch below the level of reinforcement.

The Virginia Department of Transportation (VDOT) has used latex-modified concretes and concretes with portland cement and supplementary cementitious materials (SCMs), mainly silica fume that provides low permeability concretes, successfully in thin rigid overlays (Sprinkel, 1992, 2000, 2009; Sprinkel and Ozyildirim, 1999). Considering the importance of limited traffic interruption, VDOT has also been using very early strength latex-modified concrete overlays (LMCVE) so that traffic can be permitted on the overlay after 3 hours (Sprinkel, 1999). LMCVE contains rapid setting (RS) cement. VDOT's thin rigid overlays have a maximum water-cementitious materials ratio (w/cm) of 0.40. VDOT has also used a special overlay containing 13% silica fume and 15% Class F fly ash with a w/cm of 0.25 that provides very low permeability in a much thinner 3/4-inch thickness (Sprinkel, 2009; Sprinkel and Ozyildirim, 1999, 2000). This very thin overlay and the other overlays with latex-modified concrete, SCMs (including the currently used 7% silica fume), and some with fibers were placed on the Route 60 twin bridges in 1996, with the researchers paying close attention to proper surface preparation, and placement, consolidation, finishing, and curing of concrete. All the overlays with and without fibers performed satisfactorily until 2018, when the twin bridges were replaced, because of the poor substructure. Fibers used were 2 inches long made either of polyolefin at 25 lb/yd^3 or of polypropylene (PP) at 5 lb/yd^3 or were hooked-end steel at 50 lb/yd^3. A vibrating roller screed was used for consolidation and finishing, and for effective curing, the deck surface was covered with wet burlap immediately after screeding. The prompt curing eliminated the common plastic shrinkage cracking that occurs at an early age.

Cracks can result from environmental factors such as temperature and moisture change and from the loads imposed on the structure. Cracks caused by environmental factors at early ages can be minimized by proper selection of ingredients, proper proportioning of concrete mixtures, and proper construction practices of consolidation and curing (Nair et al., 2016). Synthetic fibers are available to prevent cracking at early ages, including plastic shrinkage cracking. Drying shrinkage is a common cause of cracks in decks and overlays that occurs at late ages and can be controlled by mixture proportioning and a shrinkage-reducing admixture (Nair et al., 2016). Cracks can also occur because of loading at any age. Fiber-reinforced concretes (FRCs) can prevent or reduce the occurrence of cracks caused by loading (ACI, 2009). Using concretes that strain and deflection harden can limit the widths of the cracks to tight cracks less than 0.1 mm in width (Naaman, 2007). Cracks that are tight resist the penetration of water and salt solutions (Lawler et al., 2002; Wang et al., 1997). In cases when bonding to steel is possible, use of FRC with some high residual strength and not necessarily the hardening behavior is expected to achieve tight cracks because of the contribution of the reinforcement. Different levels of residual strength would control the occurrence and width of cracks to various degrees at the hardened state in late ages.

Recently, VDOT has been experimenting with FRC containing synthetic polyvinyl alcohol (PVA) and PP, or steel fibers to control cracking in link slabs (closure pours) over bridge piers (Ozyildirim and Nair, 2017). In the link slabs of the twin bridges on I–64 near Covington, VA, PVA fibers at 44 lb/yd^3 (2% by volume of concrete) in the engineered cementitious composite (ECC), PP at 15 lb/yd^3 (1%) and 18 lb/yd^3 (1.2%), hooked end steel fibers at 66 lb/yd^3 (0.5%) and 80 lb/yd^3 (0.6%) were used. ECC was developed by Victor Li at the University of Michigan (Li, 2003). During a 5-year field exposure, concretes with the PVA and steel fibers performed well with tight cracks. However, the PP fibers exhibited wider cracks with age, attributed to low elastic modulus and high creep (Ozyildirim et al., 2020).

The selection of type and amount of fibers depends on the extent and age the cracking is expected. Many states use FRC that consists of conventional concrete with a limited amount of synthetic and steel fibers. However, the Federal Highway Administration (FHWA) promotes using UHPC, which is a specialty high-performance FRC (HPFRC), containing high amounts of steel fibers, typically 2% by volume of concrete. HPFRC has very low permeability, high ductility, high tensile strength and exhibits deflection hardening, which is effective in keeping cracks tight. VDOT also used another HPFRC called very high-performance concrete (VHPC) mainly in Virginia Adjacent Member Connections (Kedar et.al., 2017; Ozyildirim and Sharifi, 2022). VHPC contains a high percentage of hooked end steel fibers, 2% by volume, with a typical low w/cm of 0.25. That mixture leads to high tensile and flexural strengths, which are close to values expected from UHPC.

Fibers are expected to control cracking in bridge deck overlays. However, the type and dosage rates should be investigated for various stress levels and age.

Problem Statement

Decks are subject to cracking and spalling mainly because of the corrosion of their reinforcement. Also, surface scaling and texture loss can occur, attributed to high traffic volume and weather conditions. After the removal of deteriorated concrete, low permeability overlays can be placed to protect the deck and improve the ride quality. Overlay placement must follow specific surface preparation for proper bonding to the deck and proper consolidation and curing for satisfactory performance. Field experience has shown that even with good material selection and proportioning, overlays can still crack because of weather conditions, construction practices, structural design, and loading that can adversely affect long-term performance.

PURPOSE AND SCOPE

The research team investigated conventional FRC and HPFRC as in ECC, VHPC, and UHPC to control cracks in bridge deck overlays. The team also conducted a literature survey to determine the extent of fiber use in concretes applicable to overlays. This research also included laboratory investigation of concretes having different mixture proportions and various types and amounts of fibers as well as concretes with portland and RS cements.

METHODS

Initially, a literature survey was conducted to determine the fibers other research and state departments of transportation (DOTs) use that are applicable to overlays. Then, laboratory concretes were prepared and tested for workability and satisfactory strengths to resist cracking occurring at early and late ages of the overlays. The concretes were divided into two groups. The first group of concretes contained low to moderate amounts of fibers for ductility and to attain higher tensile and flexural strengths compared with the conventional concretes without fibers. Those concretes were denoted as FRCs and exhibited varying levels of residual strengths after the first crack. Concretes without fibers do not exhibit residual strengths. The second group included concretes with high amounts of fibers. Those concretes exhibited higher tensile and flexural strength than the concretes in the first group. The second group also exhibited deflection hardening and were denoted as HPFRC.

Literature Survey

Even though steel and synthetic fibers have been commonly used in bridge structures during the past few decades (Barman and Hansen, 2018), no uniformly applied fiber dosage rate exists for bridge decks and overlays.

Conventional Concretes with Fibers

Typical ranges used in the past bridge deck overlays were from 3 to 7.5 lb/yd^3 for synthetic polyolefin fibers, such as PP or polyethylene and from 20 to 90 lb/yd3 for steel fibers, corresponding to volume percentages from 0.2 to 1% (Amirkhanian and Roesler, 2019). Such low amounts of fibers are expected to control cracks occurring at the early fresh state and some at the hardened state. Synthetic fibers, especially at low amounts of about 1 to 1.5 lb/yd^3, 0.1%

by volume, are mainly used for controlling plastic shrinkage cracks (Naaman et al., 2005). The fibers are generally short microfibers. At the hardened state to increase residual flexural strength, macro fibers and steel fibers are used.

Concrete mixtures with a high volume (5.0 to 7.5 lb/yd^3) of macro synthetic fibers (typically with lengths from 1.5 to 2.25 inch) may require more cementitious material (from 20 to 50 lb/yd^3) and more fine aggregate for workability because of the large surface area of the fibers compared with their volume (Amirkhanian and Roesler, 2019). Such mixtures benefit from well-graded aggregates to minimize the increases in cementitious materials content and the fine aggregate at a given w/cm. Also, a regular or high-range water reducing admixture can be used to offset any loss in workability, especially for fiber dosages 5.0 lb/yd^3 and greater (Harrington and Fick, 2014). Steel fibers, used in addition rates from 20 lb/yd^3 to 90 lb/yd^3, also were expected to reduce the occurrence and width of some cracks in the hardened concretes. However, concretes with such addition rates of fibers are not expected to provide strain or deflection hardening such that tight cracks occur.

State DOTs use varying amounts and types of fibers in decks, overlays, and even pavement (Table 1), all which are applicable for overlay use. The California Department of Transportation (Caltrans) in a special provision recommends the use of 1 lb/yd^3 of microfibers and 3 lb/yd^3 of macro fibers for concrete bridge deck applications (Caltrans, 2019). Colorado DOT (2017) uses 3–4 lb/yd^3 of macro polyolefin fibers in bridge decks. Delaware DOT recommends using synthetic nonferrous reinforcement fibers at a rate of 1.5 lb/yd^3 (Cohan and McCleary, 2016). Florida DOT permits a variety of fiber types, including synthetic, steel, and basalt to achieve an average residual strength of no less than 215 psi tested in accordance with American Society for Testing and Materials (ASTM) C1399 (Florida DOT, 2014). Hawaii DOT recommends the use of at least 3 lb/yd^3 of polypropylene or polyethylene fibers. Also, required is a minimum average residual strength of no less than 150 psi tested in accordance with ASTM C1399 (Hawaii DOT, 2007).

Idaho DOT special provision for silica fume concrete bridge deck overlays requires a minimum dosage rate of 1.5 lb/yd^3 of fibrillated fibers (Bilderback and Giard, 2018). Illinois DOT has a specification for fiber types and dimensions. The synthetic fiber shall be a monofilament or bundled monofilament with a minimum length of 1 inch and a maximum length of 2-1/2 inch. The quantity of synthetic fibers added to the concrete mixture shall be sufficient to have a residual strength ratio (R150, 3) of 20%, according to Illinois Modified ASTM C1609 (Illinois Bureau of Materials, 2019). The maximum dosage rate is 5 lb/yd^3, unless the manufacturer can demonstrate through a field demonstration that the concrete mixture will be workable and that fiber clumping is not a problem as determined by the engineer. Illinois DOT has used 7.5 lb/yd^3 of microfibers in pavements (Riley, 2010). The Louisiana Department of Transportation and Development has a special provision for patching with steel fibers, with a nominal length not less than 1 inch or no greater than 1-1/2 inches and a dosage rate of 85 to 90 pounds per cubic yard of concrete (LaDOT, 2016).

Table 1. Fibers in Bridge Deck and Overlay Applications by Departments of Transportation

State	Fiber Type	Notes
California	1 lb/yd^3 of microfibers and 3 lb/yd^3 of macro fibers	N/A
Colorado	3–4 lb/yd^3 of macro polyolefin fibers	N/A
Delaware	Synthetic nonferrous reinforcement fibers at a rate of 1.5 lb/yd^3	N/A
Florida	synthetic, steel, and basalt	average residual strength of no less than 215 psi tested in accordance with ASTM C1399
Hawaii	3 lb/yd^3 of polypropylene or polyethylene fibers	average residual strength of no less than 150 psi tested in accordance with ASTM C1399
Idaho	1.5 lb/yd^3, Fibrillated fibers (ASTM C1116)	
Illinois	4–7.5 lb/yd^3 of synthetic fibers	1–2-1/2-inch length, maximum aspect ratio of 150; residual strength ratio ($R_{150, 3}$) of 20%
Louisiana	Steel fiber (85–90 lb/yd^3)	1–1-1/2-inch length
Maryland	Synthetic fibers at amounts recommended by the fiber manufacturer	1/2–1-1/2-inch length
Michigan	Polypropylene collated fibers at 2 lb/yd^3 for silica fume modified concrete overlays. Polypropylene fibers at 1–3 lb/yd^3, 3/4 inch long that meet the requirements of ASTM C1116, Type III	N/A
Minnesota	Synthetic fibers with minimum dosage rate of 4 lb/yd^3	The fibers are a combination of micro- and macro non-metallic fibers to provide crack control and improve the long-term performance of the bridge decks.
New Hampshire	Synthetic fiber reinforcement shall be a product as included on the Qualified Products List. Dosage should be 7 lb/yd^3 unless otherwise approved, in writing, by the engineer.	N/A
Virginia	Summarized in the introduction	N/A

N/A = not applicable.

Maryland DOT's specification requires 1/2 to 1-1/2-inch-long synthetic fibers. The quantity of fibers used and their point of introduction into the mixture conforms to the fiber manufacturer's recommendations (Maryland DOT, 2017). Michigan DOT has two specifications related to the FRC overlays. The specification for silica fume modified concrete overlays requires the use of polypropylene collated fibers at 2 lb/yd^3. Other specification requires use 1–3 lb/yd^3 of polypropylene fibers, 3/4 inch long that meet the requirements of ASTM C1116, Type III (Amirkhanian and Roesler, 2019). Minnesota DOT has a special provision for FRC in bridge decks and overlays that requires use of synthetic fibers with a minimum dosage rate of 4 lb/yd^3 (Barman and Hansen, 2018). The fibers are a combination of micro and macro synthetic fibers. Minnesota DOT claims that these fibers provide crack control and improve the long-term performance of the bridge decks.

High-Performance Fiber-Reinforced Concretes

Low amounts of synthetic polyolefin fibers (less than 7.5 lb/yd^3) appear to be satisfactory for most applications. However, when high tensile stresses occur in locations such as the negative moment areas over the piers or reflective cracking in decks, torsional stresses in skewed bridges, improvements in the structural capacity of the decks, and for short splice lengths in connections require using higher amounts of fibers. These concretes, known as HPFRCs, exhibit strain and deflection hardening. Currently, FHWA is promoting the use of UHPC to address the cracking in hardened concrete overlays (Haber et al., 2017). UHPC generally has 2% steel wire fibers to attain high strength, very low permeability, and ductility that provides crack control, structural strengthening, and stiffness (Binard, 2017; FHWA, 2018; Graybeal, 2006; Schmidt and Fehling, 2005). UHPC also has a very low w/cm, ranging from 0.17 to 0.25. According to FHWA (2018), UHPC-class materials are cementitious-based composite materials with discontinuous fiber reinforcement, compressive strengths above 21.7 ksi, tensile strengths above 0.72 ksi, and enhanced durability because of their discontinuous pore structure. However, this definition is not universally used. American Concrete Institute 239 uses only a minimum compressive strength of 150 MPa (21.7 ksi) in defining UHPC. ASTM C1856 indicates a minimum compressive strength of 17,000 psi for UHPC. UHPC that regularly achieves compressive strengths of 24 to 30 ksi has been produced (DHS, 2011).

The first UHPC bridge deck overlay in the United States was completed in May 2016 on a reinforced concrete slab bridge in Brandon, IA, in Buchanan County (FHWA, 2018; Wibowo and Sritharan, 2018). Afterward, UHPC was used in overlays in Delaware and New York State. Other HPFRCs that deflection harden and can be used in overlays are ECC and VHPC (Ozyildirim and Sharifi, 2022).

Laboratory Mixtures

The project researchers prepared and tested two groups of concretes. The first group, commonly used in Virginia, comprise conventional concretes with fibers, FRCs, typically containing low to moderate dosages of synthetic PP or steel fibers. Those concretes also include RS cement to achieve conventional compressive strength within hours. These FRCs have higher tensile and flexural strength than the conventional concretes without fibers.

The second group comprise the HPFRCs because of its hardening property and high content of cementitious materials and PVA or steel fibers. That high content with fibers and low w/cm contributed to the expectation that this concrete group would provide greater strength than the first group. HPFRCs are usually prepackaged materials for convenience because some of the ingredients may not be readily available to purchase individually.

The fibers used in various mixtures were 2-inch-long macro synthetic, polypropylene, or 8-mm-long PVA, and hooked-end steel fibers that were 1.4 inch long with an aspect ratio of 45 (S1), 1.2-inch long with an aspect ratio of 55 (S2), and 0.5 inch-long steel wire with an aspect ratio of 62 (S3)—content commonly used in UHPC. The fibers with high aspect ratio (length and diameter) are effective in increasing the tensile and flexural strengths; thus, for a given diameter, long fibers are more effective in controlling cracking than short fibers (ACI, 2009). For overlays with a minimum thickness of 1.25 inches, 2-inch-long flexible synthetic fibers can be used. However, because of the limited thickness of the overlay, domestic steel fibers with lengths restricted to 1.4 inches were used. The short fibers are easy to mix and have little clumping tendency. Some of the mixtures had fine aggregate and 3/8-inch nominal maximum-size coarse aggregate as in conventional concretes or VHPC, and some had only fine aggregates as in ECC or UHPC. SCMs were added for low permeability and improved durability. The prepackaged materials also included SCMs. The tensile strength was determined with the splitting tensile strength test method, ASTM C496, and the flexural strength by ASTM C1609. Splitting tensile strength is generally greater than direct tensile strength and lower than flexural strength. All concretes have a certain level of ductility depending on the mixture proportioning and the fiber type and content.

Fiber-Reinforced Concretes

Two sets of FRC were investigated. The basis for the first set was the 28-day strength and designated as late age strength. The basis for the second set was early strengths attained within hours, described as early age strength.

Late Age Strength

Researchers prepared eight batches, as shown in Table 2. The batches have moderate amounts of total cementitious materials content (635, 658 lb/yd^3) and low amounts of synthetic PP fibers (0.2–0.5% by volume) (3–7.5 lb/yd^3) or low-to-moderate amounts of steel fibers (0.2–1.0% by volume) (50–130 lb/yd^3). PP fibers were 2 inches long. Steel fibers, S1, had hooked ends with an aspect ratio of 45 and were 1.4-inch-long loose fibers.

Table 2. Mixture Proportions for Conventional Late Age Strength Fiber-Reinforced Concretes (lb/yd^3)

Batch No.	Cement (Type I/II) (lb.)	Fly Ash (lb.)	Silica Fume (lb.)	Total Cementitious Material (lb.)	w/cm	Fiber (Type, Vol %)
C1	508	102	25	635	0.42	(PP, 0.2)
C2	508	102	25	635	0.42	(PP, 0.3)
C3	527	105	26	658	0.40	(PP, 0.3)
C4	508	102	25	635	0.42	(PP, 0.5)
C5	508	102	25	635	0.42	(S1, 0.4)
C6	508	102	25	635	0.42	(S1, 0.6)
C7	508	102	25	635	0.42	(S1, 0.8)
C8	508	102	25	635	0.42	(S1, 1)

PP = polypropylene; S1 = short steel fibers; w/cm = water-cementitious materials ratio. Notes: All mixtures had 1,238 lb/yd^3 of #8 coarse aggregate and 1,675 lb/yd^3 of fine aggregate. C in batch number indicates conventional concrete.

Early Age Strength

LMCVE attains minimum compressive strength of 2,500 psi within 3 hours and exhibits very low permeability. In this study, mixtures using 658 lb/yd^3 of RS cement with or without latex and three with a polymer admixture as shown in Table 3 that can achieve early strengths within 3 hours were tested. Typically, mixtures with RS cement have short setting times about 25 minutes in the laboratory. However, the setting time can be extended by adding citric acid, which is a retarding admixture for RS cement. LMCVE contains a minimum of 15% styrene butadiene latex by weight of cement (3.5 gallons per bag of cement, or 24.5 gallons per cubic yard of concrete) and a maximum w/cm of 0.40. Polymer admixture was used in much smaller amounts, about 10 oz/cwt, with the expectation to reduce permeability as does the addition of latex in LMCVE.

Table 3. Mixture Proportions of Early Age Strength Fiber-Reinforced Concretes (lb/yd^3)

Batch No.	Variable	Citric Acid (%)	Fiber (Type, Vol %)	w/cm
B1	RS	0.30	(S1, 0.9)	0.40
B2	RS, Latex[a]	0.12	(S1, 1.2)	0.40
B3	RS, Latex[a]	0.30	(S1, 1.5)	0.40
B4	RS, Latex[a]	0.30	(PP, 0.3)	0.40
B5	RS, P[b]	---	---	0.40
B6	RS, P[b]	---	---	0.40
B7	RS, P[b]	---	---	0.40
B8	RS	---	---	0.40

PP = polypropylene; RS = rapid setting; S1 = 1.4-inch short steel fibers; w/cm = water-cementitious materials ratio; --- = not added to the mixture. [a] 24.5 gal/yd^3 of latex was added. [b]10 oz/cwt of polymer admixture was added. Note: Total cementitious materials content was 658 lb/yd^3 and contained only RS cement.

Typically, LMCVE does not contain fibers. However, fibers were added to increase the tensile and flexural strengths to enable crack control and improve durability. B1 had a moderate amount, 0.9%, and B3 had a high amount, 1.5% by volume short loose steel fibers S1. B1 through B4 contained citric acid to extend the setting time at the amounts shown in Table 3. Lower amounts of citric acid were used in B2. In B2 through B4, the effect of latex on strength and permeability was determined. B5, B6, and B7 contained the polymer instead of latex for low permeability. Also, those batches did not contain fibers but were added to the test to determine the effect of the polymer admixture on the permeability. B8 was prepared with no fibers added to study the effect of temperature on strength development. Two sets of samples were prepared from the same batch of concrete. In the first batch, samples were cured in the laboratory at 74°F; and in the second batch, samples were refrigerated at 40°F to simulate the cold temperature.

High-Performance Fiber-Reinforced Concretes

The HPFRC group included ECC, VHPC, and UHPC and had high tensile and flexural strengths compared with the FRC group. In addition to deflection hardening for tight cracks, VHPC and UHPC had higher strengths than other concretes for structural improvement. Table 4 shows the mixture proportions of ECC. They contained portland cement (Type I/II), Class F fly ash, and fine aggregates. Different amounts of PVA fibers were added to the regular ECC mixtures to see the effect on the properties, especially the flexural strength.

Table 4. Engineered Cementitious Composite Mixture Proportions

Batch No.	PC (lb/yd^3)	FA (lb/yd^3)	FA (%)	PVA (lb/yd^3)	PVA (%)
E1	961	1,153	55	40	1.8
E2	961	1,153	55	33	1.5
E3	634	1,480	70	33	1.5
E4	740	1,374	65	33	1.5
E5	740	1,374	65	44	2.0
E6	740	1,374	65	22	1.0
E7	740	1,374	65	11	0.5

FA = fly ash; PC = portland cement; PVA = polyvinyl alcohol. Note: Water-cementitious materials ratio for all batches were 0.27.

VDOT uses VHPC and UHPC for crack control and short splice lengths in connections (Ozyildirim and Sharifi, 2022). FHWA promotes UHPC in overlays for durability and structural improvement. VHPC can be used for similar purposes because they have high tensile and flexural strengths and high ductility close to UHPC. VHPCs can be prepared from individual ingredients during batching (referred to as in-house mixtures) or by using prepackaged materials. In-house VHPC mixtures contain high amounts of cementitious materials and high amounts of various steel fibers (1.2–2% by volume) as Table 5 shows. UHPC used in Virginia is from prepackaged materials.

Table 5. In-House VHPC Prepared in the Laboratory

Batch No.	Portland Cement (lb.)	Fly Ash (lb.)	Total Cementitious Material (lb.)	w/cm	Fiber (Type, %)
VHPC1	786	139	925	0.29	(S1, 1.2)
VHPC2	1,120	480	1,600	0.25	(S2, 2)

S = steel fibers; VHPC = very high-performance concrete; w/cm = water-cementitious materials ratio.

Some of the prepackaged materials has fibers and dry admixtures in the pre-blend, and in some packaged mixtures, fibers and admixtures are added during mixing. Several commercially available prepackaged VHPC and UHPC mixtures also were tested, as Table 6 shows. None of the prepackaged VHPC and UHPC used had fibers in the bag. Two percent fibers were added to all these mixtures.

Table 6. Prepackaged VHPC and UHPC Tested in the Laboratory

Materials	Fiber
VHPC-E1	S2
VHPC-E2	S1
VHPC-R	S3
UHPC-A1	S3
UHPC-A2	S2

S = steel fibers; UHPC = ultra high-performance concrete; VHPC = very high-performance concrete.

RESULTS

Fiber-Reinforced Concretes

Late Age Strengths

Table 7 shows the compressive strength, splitting tensile strength, and permeability test results of FRC. The 1-day strengths ranged from 2,250 psi to 3,670 psi, and the 28-day strengths ranged from 6,170 to 9,380 psi. The splitting tensile strengths at 28 days ranged from 575 to 995 psi. The permeability values generally were very low, even though steel fibers would affect the electrical conductance and test results through an increase in values. For example, the mixture C8 with the highest amount of steel fibers had the highest permeability value attributed to the presence of steel fibers.

Table 7. Late Age Strength and Permeability Data for Fiber-Reinforced Concretes

Batch No.	Compressive Strength (psi)			Splitting Tensile Strength (psi)			Perm (C)
	1 day	7 days	28 days	1 day	7 days	28 days	28 days
C1	2,500	3,600	6,280	265	420	615	470
C2	3,490	6,260	8,990	395	605	725	360
C3	3,440	6,530	9,380	390	660	670	372
C4	2,440	4,860	7,140	280	---	575	1,793
C5	2,880	5,100	7,240	365	520	660	225
C6	3,320	5,660	7,930	415	620	845	335
C7	2,250	4,310	6,170	290	535	785	429
C8	3,670	6,240	9,340	525	815	995	2,340

C = coulombs; Perm = permeability; --- = not tested. Note: 28d modulus of elasticity for C2 is 4.1x106 psi.

Table 8 and Figure 1 show the flexural test data. Post cracking behavior indicated varying residual strengths with the highest one obtained in C8 with the highest addition rate of the steel fiber. Deflection hardening did not occur, but residual strengths and the ductility attained would enable crack control through reduced crack occurrence and width.

Table 8. Late Age Flexural Test Data for Fiber-Reinforced Concretes at 28 Days (psi)

Batch No.	Fiber Type, (lb/yd^3)	First Peak Strength	Residual Strength at Span/600	Residual Strength at Span/300	Residual Strength at Span/150
C1	PP, 3	615	101	129	---
C2	PP, 5	705	146	230	---
C3	PP, 5	835	182	272	300
C4	PP, 7.5	847	223	240	263
C5	S1, 50	977	299	276	219
C6	S1, 80	947	478	448	397
C7	S1, 100	665	479	462	372
C8	S1, 130	1,073	768	779	782

PP = polypropylene; S = steel fibers; --- = not tested.

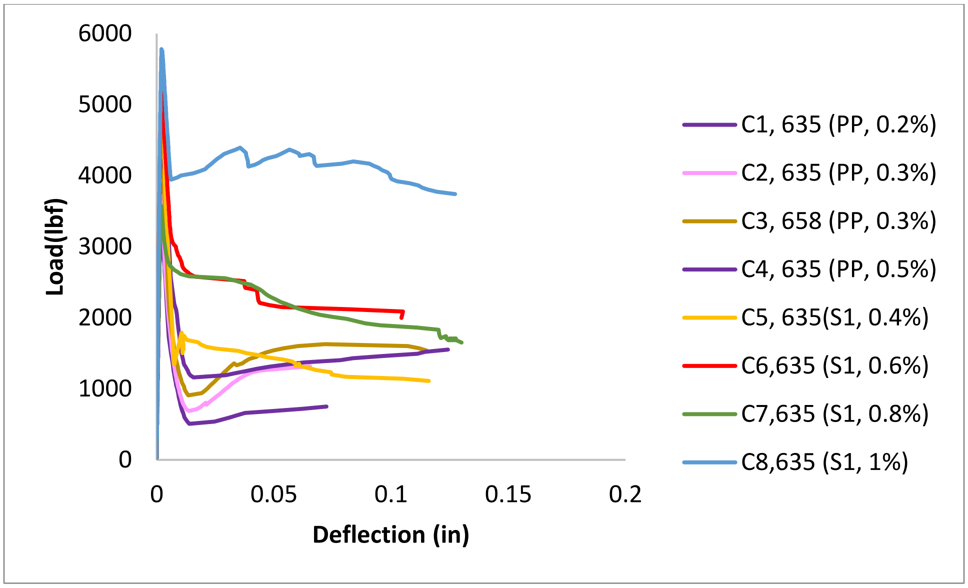

Figure 1. 28-Day Flexural Strength Data. PP = polypropylene; S = steel fiber; fiber amounts are in percent in parenthesis.

Early Age Strengths

Setting times for the early age strength FRC containing RS cement and fibers varied from 30 minutes to an hour. Early compressive strengths exceeding the specified 2,500 psi in 3 hours of LMCVE were achieved in all mixtures as shown in Table 9. The 28-day compressive strengths ranged from 5,310 to 8,670 psi for the mixtures with no latex or polymer admixture to achieve greater strength. The splitting tensile strengths at 28 days ranged from 545 to 1,095 psi for the RS cement with fibers. B6 did not contain fibers and had the lowest splitting tensile strength of 437 psi. The permeability of these concretes containing 658 lb/yd^3 of RS cement even with the steel fibers were in the very low range when latex or polymer admixture was added. Those concretes were in the low or moderate range when only RS cement was used. The modulus of elasticity averaged 2,800 ksi in the two RS concretes, B2 and B4, with fibers.

Table 9. Properties of Mixtures for Early Age Strength Fiber-Reinforced Concretes

Batch No.	Variable	Set Time (min)	Compressive Strength (psi)			Splitting Tensile Strength (psi)			Perm (C)	E (10^6)
			3 hours	1 day	28 days	3 hours	1 day	28 days	28 days	28 days
B1	RS	45	4,890	---	8,670	790	---	1,095	2,129	---
B2	RS, Latex	40	2,630	3,790	5,310	465	565	790	593	2.81
B3	RS, Latex	60	2,780[a]	3,850	5,480	355[a]	450	735	---	---
B4	RS, Latex	45	2,760	4,400	5,620	350	485	545	536	2.79
B5	RS, P	30	5,120	5,910	---	---	---	---	---	---
B6	RS, P	30	4,860	5,180	5,450	330	---	437	229	---
B7	RS, P	30	5,850	6,050	---	340	---	---	---	---
B8	RS	30	5,530	---	7,780	---	---	---	1,449	---

E = modulus of elasticity; P = polymer admixture; RS = rapid setting cement; --- = not tested. [a] Five-hour compressive and splitting tensile strengths are 3,070 and 435 psi, respectively.

From B8, two sets of specimens were tested. One set were kept at 74°F and the other set at 40°F. Table 10 shows the strength data and temperature of these specimens during the test. A reduction in strength occurred when the specimens were cured in the cold environment of 40°F. However, strengths still exceeded 4,500 psi, even at 2 hours.

Table 10. Strength Data for Batch 8

Age (hour)	Laboratory (74°F)		Refrigerator (40°F)	
	Temp[a] (°F)	Compressive Strength (psi)	Temp. (°F)	Compressive Strength (psi)
2	102	4,710	89	4,590
2.5	98	5,100	85	4,950
3	98	5,530	78	4,990
5	88	6,270	59	5,370

[a] Temperature of the specimen at time of test.

Table 11 and Figure 2 shows the flexural strengths at 7 days except B3, which shows strengths at 28 days.

Table 11. Flexural Test Data for Early Age Strength Fiber-Reinforced Concretes at 7 Days (psi)

Batch No.	Fiber (Type, Vol %)	First Peak Strength	Residual Strength at Span/600	Residual Strength at Span/300	Residual Strength at Span/150
B1	(S1, 0.9)	848	684	656	701
B2	(S1, 1.2)	824	824	801	632
B3 (28 days)	(S1, 1.5)	931	880	869	728
B4	(PP, 0.3)	739	196	235	263

PP = polypropylene; S = steel fibers.

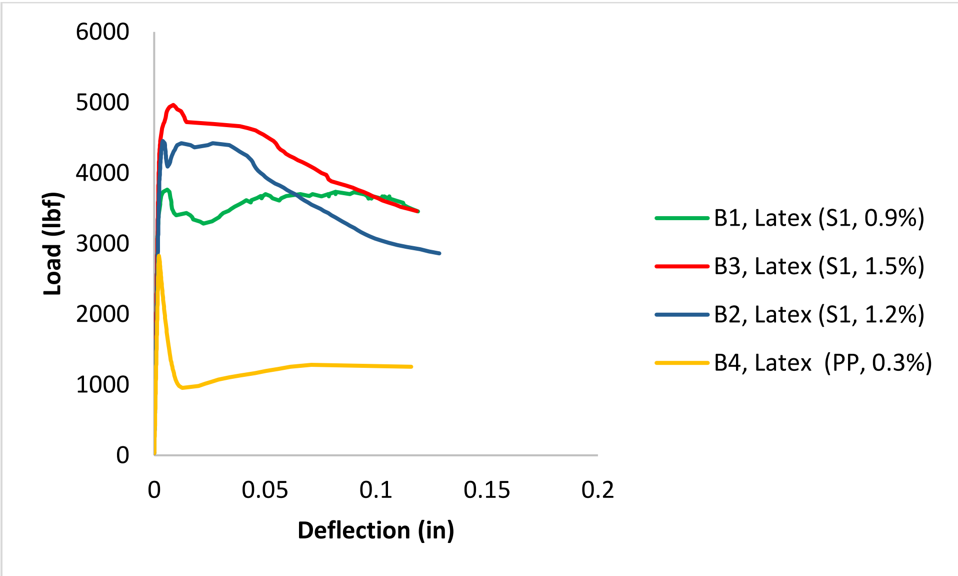

Figure 2. Flexural Strength Data at 7 Days except for B3 in Early Age Strength Fiber-Reinforced Concretes with Rapid Setting Cement and Fibers. S = steel fiber; PP = polypropylene; fiber amounts are in percent in parenthesis.

High-Performance Fiber-Reinforced Concretes

Among the ECC, VHPC, and UHPC, the highest ductility was achieved with ECC. However, VHPC and UHPC had high strengths in addition to ductility. All these concretes with high amounts of fibers exhibited deflection hardening that ensures tight cracks.

Table 12 shows ECC test data, in which E in the batch number indicates ECC. The 1-day compressive strengths ranged from 1,640 to 3,400 psi, and the 28-day strengths exceeded 5,500 psi. The 7-day splitting tensile strengths ranged from 515 to 1,085 psi, and at 28 days from 770 to 1,140 psi. E3 mixture had the lowest strengths and the highest ductility. The E3 sample was the mixture with the lowest amount of portland cement and highest amount of fly ash at 70% of the total cementitious materials content.

Table 12. Engineered Cementitious Composite Mixture Proportions

Batch No.	**PVA Fiber (lb/yd^3) (% by Volume)**	**Compressive Strength (psi)**			**Splitting Tensile Strength (psi)**	
		1 day	7 days	28 days	7 days	28 days
E1	40 (1.8%)	3,400	6,270	8,500	915	---
E2	33 (1.5%)	3,190	6,490	9,170	855	---
E3	33 (1.5%)	1,640	3,850	5,660	515	---
E4	33 (1.5%)	2,130	5,390	8,180	1,085	---
E5	44 (2%)	2,210	4,500	10,930	---	1,140
E6	22 (1%)	2,160	4,850	11050	---	985
E7	11 (0.5%)	1,830	4,580	10210	---	770

PVA = polyvinyl alcohol; --- = not tested. E in batch number indicates engineered cementitious composite.

Table 13 shows a summary of the flexural strength. Results in Figure 3 indicate that in all the mixtures containing at least 1.5% PVA, fibers deflection hardening occurred. When low amounts of fibers were used, as in E6 and E7, deflection hardening did not occur.

Table 13. Flexural Test Data for the Engineered Cementitious Composite at 7 Days (psi)

Batch No.	**PVA Fiber (Vol %)**	**First-Peak Strength**	**Residual Strength at Span/600**	**Residual Strength at Span/300**	**Residual Strength at Span/150**
E1	1.8	571	949	989	900
E2	1.5	485	846	835	525
E3	1.5	401	712	774	730
E4	1.5	389	924[a]	127	125
E5	2.0	643	1368	369	183
E6	1.0	649	543	204	---
E7	0.5	627	270	100	66

PVA = polyvinyl alcohol; --- = not tested. Note: Tested at Span/1200; E5-E7 were tested at 28 days.

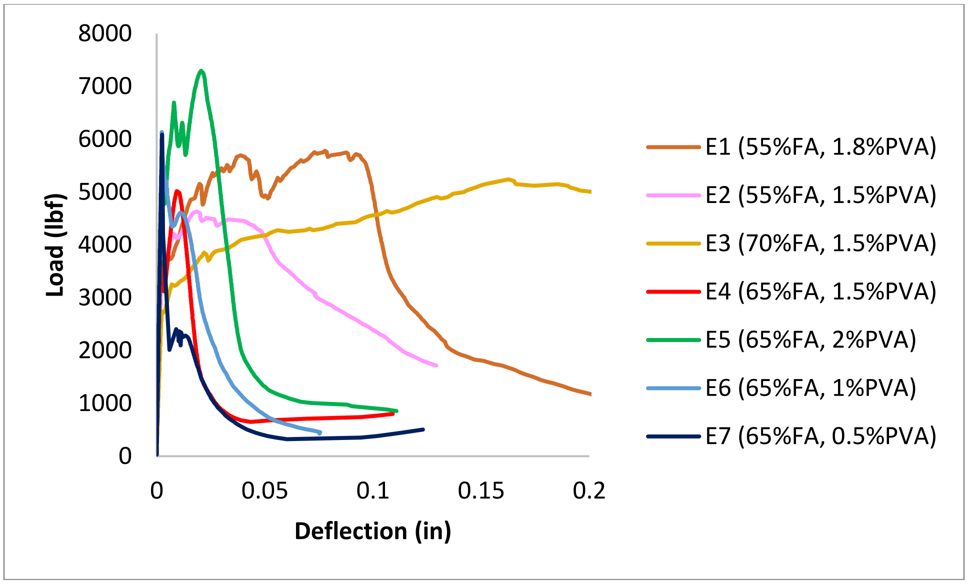

Figure 3. 7-Day Flexural Strength for Engineered Cementitious Composite Mixtures. FA = fly ash; PVA = polyvinyl alcohol; fiber amounts are in percent in parenthesis.

Table 14 shows VHPC and UHPC mixtures from in-house and prepackaged materials. The compressive strengths at 1-day ranged from 4,580 to 9,720 psi, which indicates that typically required strengths for overlays are possible within a day. At 7 days, VHPC 2 had the lowest compressive strength of 7,260 psi and splitting tensile strength of 1,200 psi. The rest of the 7-day strengths were 9,120 psi and above, and the splitting tensile strengths were above 1,290 psi. The 28-day highest compressive strengths ranged from 10,660 to 20,910 with UHPC. The 28-day splitting tensile strengths ranged from 1,360 to 2,790 psi with the UHPC mixtures again having the highest strengths. The modulus of elasticity for the VHPC was $4.82x10^6$ psi and was 5.94 and 6.02x106 psi at 28 days for UHPC mixtures.

Table 14. Laboratory Test Results for VHPCs and UHPCs

Material	Batch No.	Compressive Strength (psi)			Splitting Tensile Strength (psi)			E (psi)
		1 day	7 days	28 days	1 day	7 days	28 days	---
In-House	VHPC1	6,270	9,120	11,520	---	1,450	1,530	---
	VHPC2	4,580	7,260	10,660	980	1,200	1,360	---
Prepackaged	VHPC-E1	9,720	14,960	15,560	1,560	---	---	---
	VHPC-E2	5,980	9,610	10,420	945	1,290	1,495	---
	VHPC-R	5,600	11,860	13,580	---	1,640	1,890	4.82×10^6
	UHPC-A1	6,860	15,870	20,910	1,235	2,130	2,790	6.02×10^6
	UHPC-A2	7,490	15,930	20,640	1,600	2,115	2,335	5.94×10^6

E = modulus of elasticity; UHPC = ultra high-performance concrete; VHPC = very high-performance concrete; --- = not tested.

Table 15 and Figure 4 show flexural test data for VHPC and UHPC, both considered HPFRCs. All flexural strength data for the two HPFRC samples at 7 days indicate high ductility and high strengths with deflection hardening in all mixtures that contained 2% steel fibers by volume. VHPC-R was tested at 28 days and also showed high ductility and strength.

Table 15. Flexural Test Data for the In-House and Prepackaged VHPC and UHPC (psi)

Batch No.	Age (days)	First-Peak Strength	Residual Strength at Span/600	Residual Strength at Span/300	Residual Strength at Span/150
VHPC1	7	530	1,133	980	746
VHPC2	7	1,139	1,460	1,308	1,156
VHPC-E2	7	1,385	1,526	1,283	955
VHPC-R	28	1,667	2,192	2,210	1,712
UHPC-A1	7	1,364	1,997	2,093	1,716
UHPC-A2	7	1,473	2,058	2,210	1,847

UHPC = ultra high-performance concrete; VHPC = very high-performance concrete.

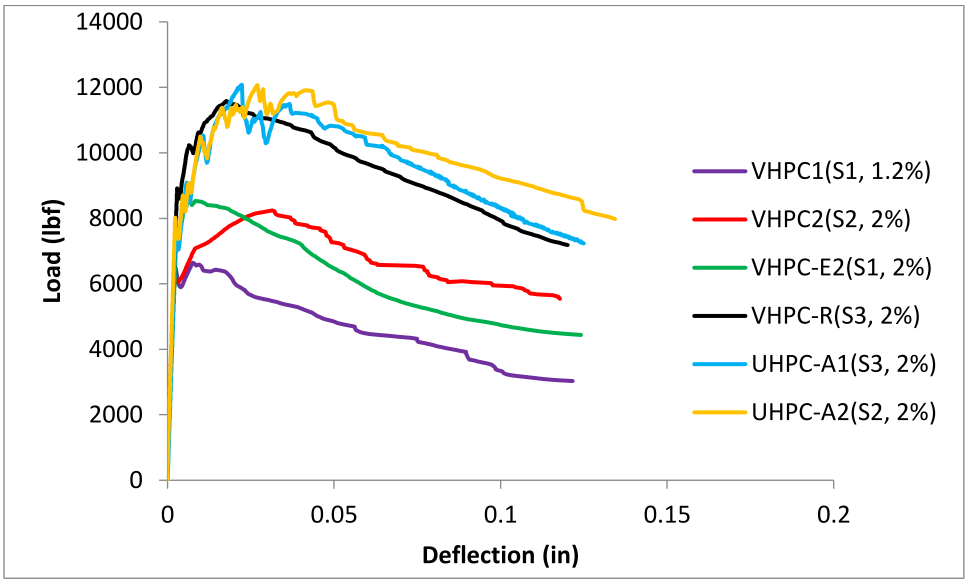

Figure 4. Flexural Strength for VHPC and UHPC at 7 Days Except for VHPC E2 at 28 days. S = steel fiber; UHPC = ultra high-performance concrete; VHPC = very high-performance concrete. Fiber amounts are in percent in parenthesis.

CONCLUSIONS

- *FRC provides varying levels of tensile and flexural strength for crack control, depending on the type and amount of fibers used.* A wide range of fiber combinations can be utilized with portland or RS cements, from the low amount of synthetic fibers to the high amount of steel fibers. These combinations are designed to deliver effective crack control based on the deformations and stresses specific to different overlay applications.
- *FRCs with RS cement can be prepared with high tensile strength and short setting times*. Those concretes can also provide high early strength to minimize traffic interruptions and crack control to improve durability.
- *HPFRC exhibits deflection hardening.* Deflection hardening enables tight cracks that resist infiltration of water and chloride solutions.
- *Low permeability is achieved by using SCM with portland cement and latex or polymer admixture with RS cement*. Low permeability is essential in reducing the infiltration of water and chloride solutions.

RECOMMENDATIONS

1. *VDOT's Materials, Structure and Bridge, and Construction Divisions should prepare special provision for FRC and HPFRC overlays*.

2. *VDOT's Materials, Structure and Bridge, and Construction Divisions with input from Districts should install FRC and HPFRC for bridge deck overlays in demonstration projects, including RS mixes to control cracking whenever needed, feasible, and practical.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments section) for the project collaborated to craft a plan to implement the study recommendations and to determine the benefits of doing so. This effort was undertaken to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The following sections describe the implementation plan and the accompanying benefits.

Implementation

With regards to Recommendation 1, The Materials Division and VTRC, with input from the Structure and Bridge Divisions, will develop a special provision for FRCs with low dosages of synthetic or steel fibers for early-age cracking and for HPFRCs with high tensile and flexural strengths to improve crack control and structural capacity within one year of the publication date of this report.

Regarding Recommendation 2, Structure and Bridge Division, Construction Division, Districts, and VTRC will collaborate and apply FRC with low dosages of synthetic fibers within 1 year; and HPFRC with high dosages of PVA or steel fibers within two years of the publication date of this report.

Benefits

Overlays are placed primarily to resist the infiltration of water and chloride solutions to the level of steel. For longevity, overlays must exhibit low permeability and have no cracks or tight cracks. Low permeability in concretes with RS cement is primarily achieved by adding latex or a polymer admixture, whereas it is achieved in portland cement concretes by incorporating SCMs. The proper selection of ingredients and fibers can control cracks. Cracks occur at different surface ages because of environmental factors and loads, and mixtures with fibers provide various crack resistance potential, depending on the type and amount of fibers and the level of deformations and stresses affecting the structure. Extending the service life would have positive economic impacts and reduce the inconvenience to the traveling public. Also, less maintenance due to improved durability reduces work zone activities, leading to improved safety.

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