Low Cracking Concretes for the Closure Pours and Overlays of the Dunlap Creek Bridge

http://www.virginiadot.org/vtrc/main/online_reports/pdf/18-r10.pdf

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

HARIKRISHNAN NAIR, Ph.D., P.E.
Senior Research Scientist

Final Report VTRC 18-R10

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454

vtrc.virginiadot.org

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 18-R10	2. Government Accession No.:	3. Recipient's Catalog No.:

4. Title and Subtitle: Low Cracking Concretes for the Closure Pours and Overlays of the Dunlap Creek Bridge	5. Report Date: October 2017
	6. Performing Organization Code:
7. Author(s): Celik Ozyildirim, Ph.D., P.E., and Harikrishnan Nair, Ph.D., P.E.	8. Performing Organization Report No.: VTRC 18-R10
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.: 106061
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219 Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final
	14. Sponsoring Agency Code:

15. Supplementary Notes:

16. Abstract:

Joints, wide cracks, and poor-quality concretes facilitate the intrusion of chlorides, causing corrosion in bridge decks and substructures. In this study, joints were replaced with closure pours (link slabs) consisting of low permeability fiber-reinforced concretes resistant to wide cracking; overlays consisted of concretes with a low cracking potential and low permeability. Closure pours and overlay concretes had portland cement and a supplementary cementitious material for low permeability. Three different fibers, polyvinyl alcohol, polypropylene, and steel, were used in the closure pours; a compressive strength of 3,000 psi at 24 hours was sought. Latex-modified concrete with Rapid Set cement but without fibers was also included since it is commonly used in closure pours.

In the overlays, five different materials were used: (1) latex-modified concrete with Rapid Set cement, (2) silica fume concrete (SFC) alone, (3) SFC with shrinkage reducing admixture, (4) SFC with lightweight coarse aggregate, and (5) SFC with lightweight fine aggregate. A compressive strength of 3,000 psi at 3 days was sought. Two parallel bridges located on Route 64 over Dunlap Creek in Alleghany County, Virginia, each with five simple spans, were selected for study. The performance of the closure pours and overlay concretes was observed after two to three winters.

Fiber-reinforced concretes with the desired strength and low permeability were achieved in the closure pours. The surveys after two to three winters indicated mostly tight cracks (<0.1 mm [0.004 in] in width) that would resist penetration of solutions. The overlays also achieved the specified strength and low permeability. There were minimal tight cracks except in one section with the latex-modified concrete with Rapid Set cement in the left lane of the westbound bridge. There were extensive cracks in that section that were attributed to plastic shrinkage from adverse weather conditions at placement and the fact that a truck had caught fire in that lane.

The study recommends that fiber-reinforced concretes be used when early strengths are needed. Further experimental installations with different fibers would indicate the optimum type and amounts for crack control. SFC overlays with shrinkage reducing admixture, with lightweight coarse aggregate, or with lightweight fine aggregate are ready for implementation in the field.

17 Key Words: Fiber-reinforced concrete, early strength concrete, steel fibers, polypropylene fibers, PVA fibers, ECC, concrete overlays, SRA, lightweight concrete, internal curing, Rapid set LMC	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: 33	22. Price:

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

FINAL REPORT

LOW CRACKING CONCRETES FOR THE CLOSURE POURS AND OVERLAYS OF THE DUNLAP CREEK BRIDGE

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Harikrishnan Nair, Ph.D., P.E.
Senior Research Scientist

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportations
and the University of Virginia since 1948)

Charlottesville, Virginia

October 2017
VTRC 17-R10

DISCLAIMER

ABSTRACT

Joints, wide cracks, and poor-quality concretes facilitate the intrusion of chlorides, causing corrosion in bridge decks and substructures. In this study, joints were replaced with closure pours (link slabs) consisting of low permeability fiber-reinforced concretes resistant to wide cracking; overlays consisted of concretes with a low cracking potential and low permeability. Closure pours and overlay concretes had portland cement and a supplementary cementitious material for low permeability. Three different fibers, polyvinyl alcohol, polypropylene, and steel, were used in the closure pours; a compressive strength of 3,000 psi at 24 hours was sought. Latex-modified concrete with Rapid Set cement but without fibers was also included since it is commonly used in closure pours.

In the overlays, five different materials were used: (1) latex-modified concrete with Rapid Set cement, (2) silica fume concrete (SFC) alone, (3) SFC with shrinkage reducing admixture, (4) SFC with lightweight coarse aggregate, and (5) SFC with lightweight fine aggregate. A compressive strength of 3,000 psi at 3 days was sought. Two parallel bridges located on Route 64 over Dunlap Creek in Alleghany County, Virginia, each with five simple spans, were selected for study. The performance of the closure pours and overlay concretes was observed after two to three winters.

Fiber-reinforced concretes with the desired strength and low permeability were achieved in the closure pours. The surveys after two to three winters indicated mostly tight cracks (<0.1 mm [0.004 in] in width) that would resist penetration of solutions. The overlays also achieved the specified strength and low permeability. There were minimal tight cracks except in one section with the latex-modified concrete with Rapid Set cement in the left lane of the westbound bridge. There were extensive cracks in that section that were attributed to plastic shrinkage from adverse weather conditions at placement and the fact that a truck had caught fire in that lane.

The study recommends that fiber-reinforced concretes be used when early strengths are needed. Further experimental installations with different fibers would indicate the optimum type and amounts for crack control. SFC overlays with shrinkage reducing admixture, with lightweight coarse aggregate, or with lightweight fine aggregate are ready for implementation in the field.

FINAL REPORT

LOW CRACKING CONCRETES FOR THE CLOSURE POURS AND OVERLAYS OF THE DUNLAP CREEK BRIDGE

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Harikrishnan Nair, Ph.D., P.E.
Senior Research Scientist

INTRODUCTION

Corrosion of reinforcing steel in bridge decks and substructure elements results in costly repairs. Leaking joints have been instrumental in distress in the substructure. Joints can be replaced with closure pours, also known as link slabs, to reduce substructure distress. It is important that closure pours do not exhibit large cracks that facilitate infiltration of chlorides. Fiber-reinforced concrete (FRC) that attains strain and deflection hardening can undergo large deflections exhibiting multiple tight microcracks less than 0.1 mm (0.004 in) in width instead of wide localized cracks. Such tight cracks hinder the penetration of chlorides (Lawler et al., 2002; Wang et al., 1997). Strain hardening is obtained in the tension test and deflection hardening in the flexure test; an increase in the load carrying capacity occurs with further deformation after the first crack (Naaman, 1998). Another benefit of fibers is that they reduce plastic shrinkage cracking in the unhardened concrete by preventing water from leaving the fresh concrete, thereby reducing bleeding and segregation (Banthia and Gupta, 2006).

Engineered cementitious composite (ECC) with polyvinyl alcohol (PVA) fibers was developed by Li and can undergo large deformations while exhibiting multiple tight cracks (Li, 2003; Li and Lepech, 2009; Sahmaran and Li, 2010). The unique design of an ECC mixture allows it to withstand uniaxial tension strains up to 4% and deflection and strain harden, keeping crack widths under 0.004 in (Sahmaran and Li, 2010). The very tight cracks also facilitate a self-healing process (Li and Lepech, 2009). PVA fibers are hydrophilic and bond tightly to the concrete matrix, so in ECC they are coated with a thin layer of hydrophobic oiling agent to allow for pull-out, leading to high tensile strain. In addition to PVA fibers, FRCs with steel (S) fibers or polypropylene (PP) fibers are also available that can exhibit high ductility.

Closure pours are reinforced with continuous bars, and the inclusion of fibers improves concrete's crack resistance and post-crack behavior (Blunt and Ostertag, 2009; Mobasher et al., 2015). The high residual strengths achieved in concrete may be sufficient to control cracking without the need for strain or deflection hardening since primary reinforcement is also present.

The high permeability concrete that was used in older bridges enables the intrusion of salt solutions that can accelerate the corrosion of the reinforcement in the deck. In addition, cracks in decks facilitate the intrusion of salt solutions. Overlay concretes containing silica fume or latex modifiers with portland cement or Rapid Set cement with normal weight aggregate are widely used to protect decks because of their low permeability. Cracking of these overlays does occur, and options are desired that will reduce or eliminate cracking while maintaining the low permeability. Such options include silica fume concrete (SFC) overlays with shrinkage reducing admixture (SRA), lightweight coarse aggregate, or lightweight fine aggregate that allow for internal curing.

SRAs reduce shrinkage and are included in the 2016 VDOT *Road and Bridge Specifications* for low cracking bridge decks (VDOT, 2016). Lightweight concretes (LWCs) are also included in the 2016 VDOT *Road and Bridge Specifications* as low cracking concretes (VDOT, 2016). LWC has advantages over normal weight concrete: a more continuous contact zone between the aggregate and the paste, enabling better bonding in LWC, and the presence of water in the pre-wetted lightweight aggregate voids, contributing to internal curing (Bentz and Weiss, 2011; Bremner et al., 1984; Holm et al., 1984). Another advantage of LWC with lightweight coarse aggregate is the low modulus of elasticity. In addition, for a given deformation, concretes with lower modulus of elasticity have lower stresses, resulting in lower cracking potential. Internal curing can also be achieved by replacing a portion of the fine aggregate by pre-wetted lightweight fine aggregate. Internal curing can potentially increase strength, reduce porosity and permeability, and mitigate shrinkage cracking (Bentz and Weiss, 2011). One other advantage of LWC is its lower coefficient of thermal expansion compared to normal weight concrete.

RESEARCH SIGNIFICANCE

Joints, cracks, and high permeability concretes facilitate the intrusion of chloride solutions that often lead to costly corrosion damage in bridge substructures. Water and harmful solutions can also cause degradation of the concrete by processes such as alkali-aggregate reactions, sulfate attack, and damage attributable to cycles of freezing and thawing. Replacement of joints by closure pours (link slabs) and control of cracks through fibers would extend the service life of structures. Supplementary cementitious materials are also added to reduce the permeability of concrete and resist the infiltration of chlorides.

PURPOSE AND SCOPE

The purpose of this study was to investigate the use of innovative concretes in closure pours and overlays to reduce chloride infiltration into bridge substructures and bridge decks. For this study, two bridges on I-64 over Dunlap Creek in Alleghany County, Virginia, were selected (Figure 1). The westbound bridge is 578 ft long and has five spans, each 30 ft 8 in wide; the three middle spans are each 115 ft 6 in long; and the two end spans are each 115 ft 9 in long. The eastbound bridge is 536 ft long and has five spans, each 30 ft 8 in wide; the two end spans are each 101 ft 9 in long, a second span is 101 ft 6 in long, and the third and fourth spans are each 115 ft 6 in long.

Figure 1. Bridges on I-64 Over Dunlap Creek

Each bridge has four closure pours for a total of eight closure pours for the two bridges. There are four materials in the closure pours: (1) latex-modified concrete (LMC) with Rapid Set cement (RSLMC), (2) ECC with PVA fibers, (3) concretes with PP fibers, and (4) concrete with S fibers, as indicated in Figure 2. The contractor used RSLMC in mobile mixers as the control for the closure pours.

There are 10 spans total between the two bridges, also shown in Figure 2. The five overlay materials used included (1) latex-modified concrete with Rapid Set cement, (2) silica fume concrete (SFC) alone, (3) SFC with shrinkage reducing admixture, (4) SFC with lightweight coarse aggregate, and (5) SFC with lightweight fine aggregate.

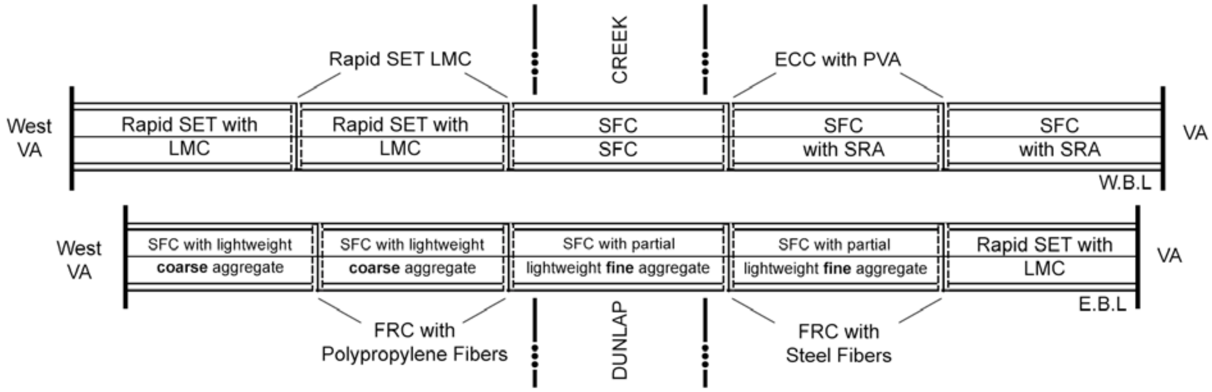


Figure 2. Closure Pour Locations, Overlays, and Material Types. Rapid Set LMC = latex-modified concrete with Rapid Set cement; ECC = engineered cementitious composite; PVA = polyvinyl alcohol; VA = Virginia; SFC = silica fume concrete; SRA = shrinkage reducing admixture; W.B.L = westbound lane; E.B.L = eastbound lane; FRC = fiber-reinforced concrete.

METHODS

In 2014, the westbound bridge was rehabilitated beginning with replacement of the closure pours. Then the top surface of the deck was removed by hydro-demolition, and then the overlays were placed. Overlays did not cover the closure pours but butted them. Although it is a common practice to cover the joint closure while placing the new overlay, joint closures were brought all the way up to the riding surface to facilitate future evaluation of the closure alternatives. In 2015, the eastbound bridge was rehabilitated in the same manner. To minimize traffic interruption, one lane was always kept open. The closure pour was required to achieve a strength of 3,000 psi in 24 hours; the overlays were required to achieve a strength of 3,000 psi in 3 days before opening to traffic. Concretes were tested at the fresh state for air content (ASTM C231), slump (ASTM C143), slump flow for ECC (ASTM C1611), density (ASTM C138), and temperature (ASTM C1604). Table 1 lists the ASTM test methods and specimen sizes for the tests on hardened concrete.

In mixtures with fibers, flexural strength was determined and load versus deflection was plotted to determine the post-cracking behavior. Post-cracking behavior is indicative of the contribution of the fibers to the control of the cracks. Permeability test (ASTM C1202) specimens were subjected to moist curing at room temperature for the first 7 days followed by curing at 100 °F for 3 weeks.

Table 1. Hardened Concrete Tests

Test	ASTM Test	Specimen Size (in)
Compressive strength	C39	4x8
Elastic modulus	C469	4x8
Splitting tensile strength	C496	4x8
Flexural strength	C1609	4x4x14
Permeability[a]	C1202	2x4
Drying shrinkage[b]	C157	3x3x11
Freeze-thaw durability[c]	C666	3x4x16

[a] Permeability specimens were moist cured 1 week at room temperature and 3 weeks at 100 °F.

[b] Drying shrinkage beams were moist cured for 7 days and then dried in the laboratory.

[c] Specimens for freeze-thaw durability testing were moist cured for 2 weeks and then air dried for at least 1 week. The test water contained 2% NaCl. The freeze-thaw test was run for 300 cycles, and the weight loss, durability factor, and surface rating were determined.

Closure Pours

The FRC closure pour mix design was a part of the rehabilitation project for the two bridges. Multiple FRC laboratory mixtures with PVA, PP, or S fibers were prepared in the laboratory at the Virginia Transportation Research Council (VTRC) and tested prior to construction. The amounts of the ingredients, including the accelerating admixture, the fiber type and percentage, and the water–cementitious material ratio (w/cm), were varied to achieve the desired strength and low permeability.

Material and Proportions

The FRC mixtures included one of two types of synthetic fibers, PVA or PP, or one type of S fiber with a hook end for better anchorage. PVA fibers were 0.375 in long and 1.5 x 10^{-3} in in diameter; they had a tensile strength of 240 ksi. The PP fibers were 2 in long and 0.027 in in diameter; they had a corrugated surface design and a tensile strength of 80 ksi. The S fibers were 2.36 in long and 0.035 in in diameter; they had a tensile strength of 330 ksi and a fiber ductility of about 6%. The amount of PP and S fibers was varied. The RSLMC mixture contained No. 8 coarse aggregate, and FRC mixtures with PP or S fibers contained No. 78 coarse aggregate.

Table 2 shows the mixture proportions. A commercially available air-entraining admixture and a high-range water-reducing admixture (HRWRA) were used in varying amounts to achieve the specified air content and workability. The ECC was not air entrained. However, earlier work has shown that ECC provides satisfactory resistance to freezing and thawing without air entrainment (Ozyildirim and Vieira, 2008).

Table 2. Mixture Proportions for Fiber-Reinforced Concrete (lb/yd^3)

Ingredient	Rapid Set With LMC	FRC PVA (ECC)	FRC PP	FRC S	
				Batch 1	Batch 2
Total cementitious content	658	2114	900	682	678
Rapid Set cement	658	-	-	-	-
Type I/II portland cement	-	961	723	542	628
Class F fly ash	-	1,153	177	140	SF50[a]
Natural sand	1,529	725[b]	1,193	1,463	1,613
Coarse aggregate	1,232	-	1,337	1,493	1,493
Latex	206	-	-	-	-
Water	146	571	328	233	264
w/cm (maximum)	0.39	0.27	0.36	0.34	0.39
PVA microfibers (% by volume)	-	44 (2.00%)	-	-	-
PP fibers (% by volume)	-	-	15-18 (1%-1.2%)	-	-
S fibers (% by volume)	-	-	-	80 (47) (0.60%)	66 (39) (0.50%)

LMC = latex-modified concrete; FRC = fiber-reinforced concrete; PVA = polyvinyl alcohol; ECC = engineered cementitious composite; PP = polypropylene; S = hook end steel fiber; - no data; w/cm = water–cementitious material ratio.

[a] Silica fume was used since fly ash was not available.

[b] Mortar sand.

Placement

RSLMC was placed using a mobile mixer in two closure pour sets and at the bridge ends above the abutments. All other mixtures with fibers were prepared in a ready-mixed concrete truck. Each pour included a lane-wide closure pour, a shoulder, and a curb (shown in Figure 3) and required 2 to 3 yd^3 of material. The dimensions of each pour were 16 ft long, 4 ft wide, and 8 to 10 in deep, and the dimensions of the curb were 9 in high and 7 in wide. Two pours, both on the same bridge and of the same material, were completed each day. For each FRC mixture, a total of 4 to 6 yd^3 concrete was used. While construction was ongoing in one lane, traffic flow was maintained in the other lane.

Figure 3. One Closure Pour Before Placement (*left*) and After Placement (*right*)

The concrete was deposited into the closure pours from a truck chute, as shown in Figure 4. ECC was self-consolidating, but the other FRC mixtures were consolidated using internal vibrators. After finishing, the closure pours were covered with wet burlap and plastic. When test results indicated a strength of 3,000 psi, wet burlap and plastic were removed and a curing compound was applied. When the curing compound dried, the lane was opened to traffic. The temperature of the slab and the specimens was monitored continuously until the specified strength was achieved.

Figure 4. Concrete Placement in Closure Pours

LMC With Rapid Set Cement

The LMC with Rapid Set cement was prepared in the mobile mixer and deposited immediately into the closure pour.

ECC

In the fall of 2014, three ECC batches were mixed for two sets of closure pours: 3 yd^3 and 1 yd^3 for the first set, and 4 yd^3 for the second set. The two closure pour sets were mixed and placed 1 week apart. An accelerating admixture and an SRA were also added. The SRA was used to control shrinkage because of the high amount of cementitious material, mixture water, and paste content. The ECC mixing sequence in the ready-mixed concrete truck was as follows:

1. About 5% of water was saved for any potential adjustments at the job site.
2. About 70% of the water with the required admixtures (HRWRA, SRA, and accelerator) was added.
3. The cement, fly ash, and mortar sand were added.
4. The remaining water was added, and the mixture was mixed at a high number of revolutions per minute for at least 5 minutes to obtain proper flow and homogeneity of the material.
5. PVA fibers were added, and the mixture was mixed at a high number of revolutions per minute for at least 5 additional minutes until the material achieved homogeneity.
6. For correction of flow and workability, the remainder of the water and more HRWRA were added at the job site.

For the second set of ECC closure pours, i.e., Batch 3, the amount of accelerating admixture was reduced from 30 to 15 oz/cwt.

FRC With PP Fibers

The FRC with PP fibers was placed in the summer of 2015. Concretes were prepared in the truck mixer. For Batch 1, all concrete ingredients and admixtures were added first, and a workable mixture was achieved. The PP fibers were added at the end in 2-lb dissolvable bags. Significant balling of fibers was observed, and only about 1% of fibers by volume (15 lb/yd^3) was used for Batch 1. The closure pour placement occurred after noon. Because of a high air temperature of about 93 °F, only a reduced amount of accelerating admixture (16.5 oz/cwt) was added to achieve high early strength. In spite of individual intertwined fiber bundles that had balled up, the rest of the fibers appeared to be well dispersed in the mixture. During the closure pour placement, the fiber bundles were removed. Fibers removed because of clumping appeared to be less than 5% of the total fiber amount and based on field observations did not affect the performance of the closure pours since tight cracks were observed.

Because of the mixing issues with Batch 1, for Batch 2 the 15 lb/yd^3 of PP fibers was added in 2-lb dissolvable bags first with the water and admixtures. Then, the rest of the concrete mixture components, fine and coarse aggregate, cement, and fly ash, were mixed in. As a result, significantly less balling was observed for this batch. Then, an additional 3 lb/yd^3 of PP fibers was added, resulting in a total of 1.2% of fibers by volume in the mixture. However, when the last 3 lb/yd^3 of fibers was added to the ready-mixed concrete truck, the 2-lb PP dissolvable fiber bags were opened and fibers were directly added to the ready-mixed concrete truck to facilitate dispersion of fibers. Some balling of the fibers still occurred, but to a much lesser extent than for Batch 1. The closure pour placement occurred at about 11 A.M. The air temperature was close to 84 °F, and it was decided to increase the amount of accelerating admixture to 24 oz/cwt for early strength gain. Despite the balling of fibers in both batches, the rest of the fibers were well dispersed, and the mixtures achieved a homogeneous state.

FRC With S Fibers

The FRC mixture with S fibers was placed during the summer of 2015 and was used for the last two sets of closure pours. The mixing sequence consisted of mixing all of the ingredients first, then adding 0.60% by volume (80 lb/yd^3) of the S fibers, and then mixing for at least 5 additional minutes. The placement of the closure pour occurred at about 10 A.M., and the air temperature was 79 °F. The 24 oz/cwt of accelerating admixture was added to achieve the required compressive strength of 3,000 psi in 24 hours. The air content was 5.5%, as shown in Table 3.

Table 3. Mixture Proportions of Overlay Concretes (lb/yd^3)

Material	RSLMC	SFC	SFC With Lightweight CA	SFC With Lightweight FA
Type I/II portland cement	-	508	632	612
Rapid Set cement	658	-	-	-
Class F fly ash	-	102		
Silica fume	-	25	48	46
Lightweight CA, ½ in	-		790	----
Normal weight CA, No. 78	1,232	1481	----	1600
Sand	1,529	1451	1486	645
Latex	206	-	-	-
Lightweight FA			----	495
Water	146	267	272	272
w/c	0.39	0.44	0.40	0.41
AEA (oz/cwt)	-	0.4	0.4	0.4
Retarder (oz/cwt)	-	3	3	3
WRA (oz/cwt)	-	Varies	Varies	Varies
HRWRA 190-2100	-	3.5	3.5	3.5
SRA (gal)	-	1.5	1.5	1.5
Air (%)	-	7	6.5	6.5

RSLMC = latex-modified concrete with Rapid Set cement; SFC = silica fume concrete; CA = coarse aggregate; FA = fine aggregate; w/cm = water–cementitious material ratio.

For Batch 2, silica fume was substituted for the fly ash material used in Batch 1 since fly ash was not available. The amount of S fibers was reduced to 0.50% by volume (66 lb/yd^3). No accelerating admixture was added to this batch because of the addition of silica fume and a higher portland cement content. The same mixing procedure was followed for Batch 2. The slump was measured to be 4.0 in at the plant, which was reduced in delivery; therefore, additional HRWRA was added to retain the 4.0-in slump at the job site to improve workability and facilitate placement and finishing. The distance from the plant to the job site was about 10 miles, or within 20 minutes.

Tests

For all three FRCs with different fibers, six cylinders and two beams were placed over the closure pour under the burlap and plastic coverings until the lane was opened to traffic. The rest of the samples, six to eight cylinders and two to four beams, were taken to the laboratory at the concrete plant for curing at room temperature. Temperature development in the field within the closure pour, in a 4 by 8 in cylinder, and in the outside environment was recorded from the time of casting until the lane was opened to traffic. The laboratory environment and the temperature of one 4 by 8 in cylinder kept in the laboratory were also monitored. There was a significant difference in temperature development between the two environments, affecting the rate of the strength development. A higher fresh concrete temperature and curing temperature increase the rate of strength gain, resulting in higher early strengths (Kosmatka and Wilson, 2011).

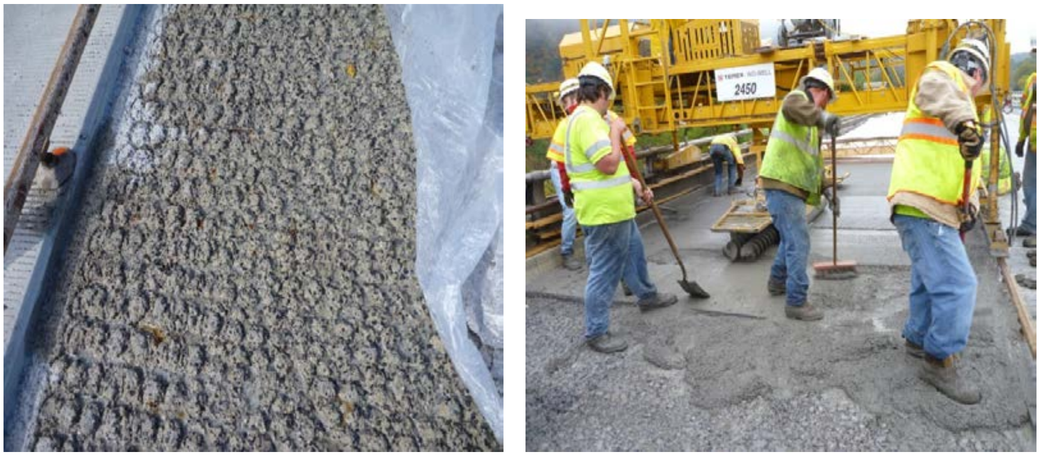
Overlays

Overlays were placed after the closure pours. About 1 3/4 in of the surface of the old deck was removed using hydro-demolition. The concrete was mixed and delivered in ready-mixed concrete trucks except for RSLMC, for which a mobile mixture was used. Silica fume was added in dissolvable bags. In the early mixtures when the bags were added toward the end of the addition sequence, the bags did not dissolve and many pieces were removed by hand during placement. Later, the sequence of addition was moved to the beginning and bags did dissolve with a few pieces in the concrete. Silica fume added in dissolvable bags can leave bag pieces in concrete. The overlays were placed using a vibratory screed, which provided consolidation and leveling of the surface. The overlays were immediately covered with wet burlap and plastic.

The overlays with RSLMC had the same mixture proportions used in the closure pours given in Table 2 and repeated in Table 3. In 2014, SFC with SRA and SFC without SRA (similar mixture proportions but SFC with SRA had 1.5 gal of the admixture for 1 cubic yard) were used in the westbound bridge. The mixture proportions are shown in Table 3. SFC had ternary cementitious material composed of portland cement, Class F fly ash, and silica fume. A commercially available air-entraining admixture and an HRWRA were used in varying amounts to achieve the specified air content and workability. In 2015, the SFC with lightweight coarse aggregate and the SFC with lightweight fine aggregate were used in the eastbound lanes, and the proportions are also given in Table 3. For SFC with lightweight fine aggregate, the lightweight aggregate added was approximately 53% of the volume of the fine aggregate.

The LWC mixtures with the lightweight coarse aggregate and the natural normal weight sand had a maximum density of 120 lb/ft^3. For the mixtures with lightweight fine aggregate, there was no density requirement; the lightweight fine aggregate was used to provide internal curing.

Both RSLMC and SFC overlays were covered with wet burlap and plastic promptly after placement. Figure 5 shows the details of the overlay placement.



(a) Hydro-demolished surface **(b) Placing overlay**

(c) Screed and finishing **(d) Wet burlap and plastic placement**

Figure 5. Overlay Placement Details for Dunlap Creek Bridge

RESULTS AND DISCUSSION

Closure Pours

LMC With Rapid Set Cement

Both batches of the LMC with Rapid Set cement met the VDOT specifications, as shown in Table 4, with a slump of 4.5 in and an air content of 3.7% and 4%, respectively. Table 5 shows that the mixtures can attain the required 3,000 psi strength within 3 hours. The test was conducted at 3 hours because of the distance to the testing facility; the 3,000 psi may be attained at an even earlier time. This is consistent with work done extensively in Virginia; LMC with Rapid Set cement with high early strengths has been used in bridge deck overlays successfully (Sprinkel, 2014). Batch 1 did not achieve the early strength requirement, attributed to mixture proportions, and the closure pour from that batch was replaced. Batches 2 and 3 yielded expected results, and the closure pours from those batches were accepted. The permeability of the mixture was satisfactory and significantly below the 2500 C limit for bridge decks (Table 5).

Table 4. Fresh Concrete Properties for Closure Pours

	RSLMC		ECC PVA			FRC PP		FRC S	
Property	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 3**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**
Air content (%)	3.7	4	2	1.75	2.5	5.3	5.3	5.5	5.2
Density (unit weight) (lb/ft^3)	-	-	125.0	124.0	122.0	-	137.6	146.2	146.4 (2345)
Slump (in)	4.5	4.5	-	-	-	8.5	4.75	7.5	4.0
Slump flow (in)	-	-	24	18	20	-	-	-	-
Mix temperature (°F)	-	-	92	92	79	90	91	80	95
Air temperature (°F)	-	-	-	-	86	85	84	79	96
Relative humidity (%)	-	-	-	-	-	49	48	64	51

RSLMC = latex-modified concrete with Rapid Set cement; FRC = fiber-reinforced concrete; ECC = engineered cementitious composite; PP = polypropylene; PVA = polyvinyl alcohol; S = hook end steel fiber; - = no data.

Table 5. Hardened Concrete Properties for LMC With Rapid Set Cement

Test	Age	Batch 1 (Rejected)	Batch 2	Batch 3
Compressive strength, psi	3 hours	2,780	3,660	-
	4 hours	-	-	4,060
	6 hours	2,600	4,400	-
	1 day	2,810	-	-
	28 days	3,870	6,400	6670
Elastic modulus, 10^6 psi	28 days	2.82	3.92	3.87
Permeability (C)	28 days	1947	499	468

LMC = latex-modified concrete; - = no data.

ECC

The fresh concrete properties of ECC are given in Table 4, which shows workable concretes with low air since there was no air entrainment. The density was low, ranging from 122.0 to 125.0 lb/ft^3.

Table 6 shows the hardened concrete properties for the three ECC batches. None of the laboratory-cured cylinders kept at room temperature at the plant reached 3,000 psi in 24 hours; however, a number of samples from Batch 3 left in the field and cured over the closure pour under the burlap and plastic covering achieved the specified strength within 24 hours.

Table 6. Hardened Concrete Properties for ECC

Test	Age	Batch 1 (3 yd^3)	Batch 2 (1 yd^3)	Batch 3 (4 yd^3)	
		Lab Cured	**Lab Cured**	**Lab Cured**	**Field Cured**
Compressive strength, psi	1 day	2,480	2,100	2,770	3,440
	7 days	4,230	3,890	4,380	5,300
	28 days	6,380	6,140	6,520	6,730
First-Peak / Peak flexural strength, psi	28 days	710/1,375	675/1,260	695/1,245	750/1,060
Elastic modulus, 10^6 psi	28 days	1.96	2.06	2.43	2.59
Permeability (C)	28 days	402	330	169	129

ECC = engineered cementitious composite.

Figure 6 shows the temperature development over 24 hours of the ECC closure pour, field and laboratory cylinders, and field and laboratory environments. Higher temperatures result in an increased rate of strength gain. The closure pour had a much higher temperature development than the field- and laboratory-cured cylinders. Therefore, it was concluded that the closure pour reached the required strength sooner than the field and laboratory cylinders. In addition, the maturity method (ASTM C1074 and ASTM C918) was used to estimate the in-place concrete strength. From the maturity test results, ECC and other FRC closure pour systems reached the strength above 3,000 psi in less than 24 hours. All ECC batches had very low permeability and met the specified coulomb value of 2500 C (Table 6)**.**

Typical flexural strength graphs for field and laboratory ECC samples are presented in Figure 7. The flexural testing was conducted in accordance with ASTM C1609, as indicated in Table 1. The samples exhibited multiple tight cracks, and deflection hardening behavior was observed. These results are consistent with the extensive work done on FRC in Michigan by Li (Li and Lepech, 2009; Sahmaran and Li, 2010).

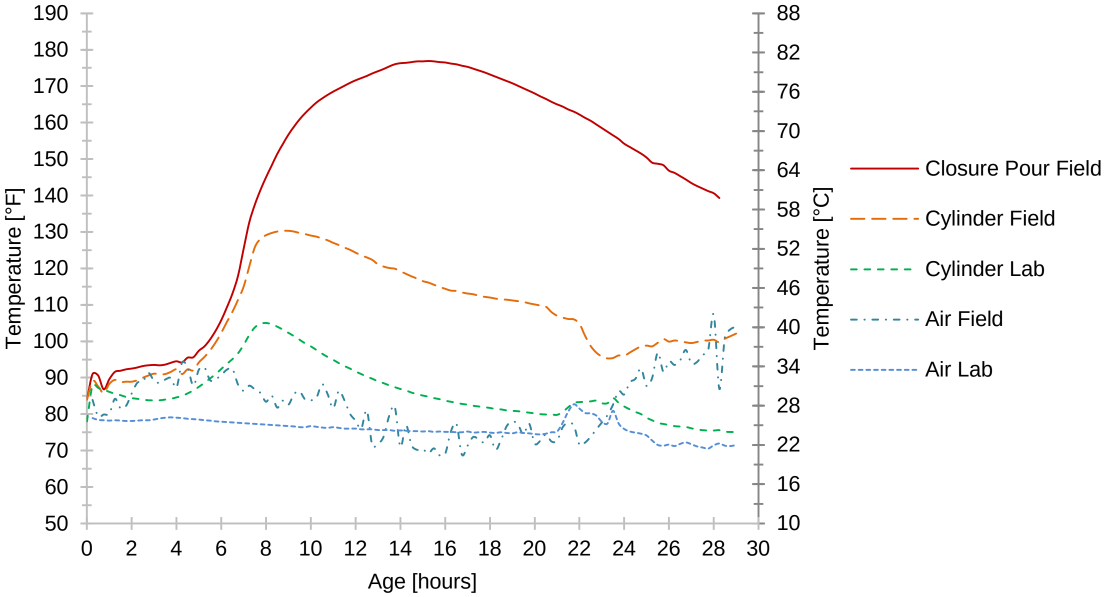


Figure 6. Temperature Development vs. Age for ECC (Batch 3). ECC = engineered cementitious composite.

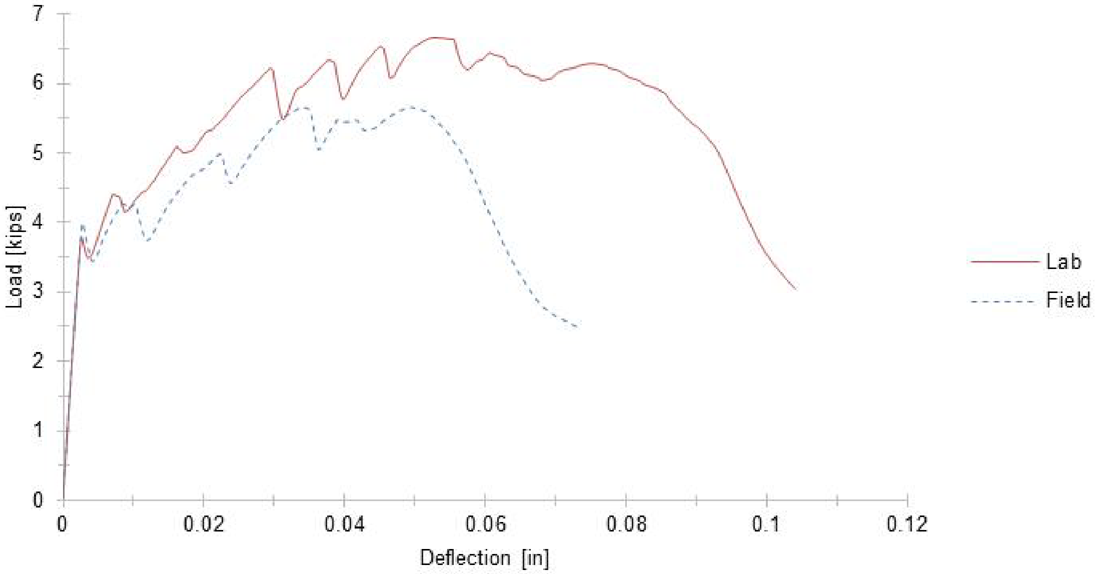


Figure 7. Load-Deflection Curves for ECC at 28 Days (Batch 3). ECC = engineered cementitious composite.

FRC With PP Fibers

The measured air content was 5.3% for both batches of FRC with PP fibers; the slump was 8.5 and 4.75 in for Batches 1 and 2, respectively, as shown in Table 4. The hardened concrete properties are presented in Table 7. Batch 1 contained 15 lb/yd^3 of fibers, and Batch 2 contained 18 lb/yd^3. Both batches reached 3,000 psi in about 24 hours, and the traffic lanes were opened later that day. The flexural test results for the FRC with PP fibers are shown in Figure 8. The FRC with PP fibers had significant residual strength but no clear deflection hardening behavior. The permeability values for the mixture were satisfactory and were below the 2500 C limit for bridge decks (Table 7).

Table 7. Hardened Concrete Properties for FRC With PP Fibers

Test	Batch 1 (6 yd^3)			Batch 2 (6 yd^3)		
	Age	**Field**	**Lab**	**Age**	**Field**	**Lab**
Compressive strength, psi	21 hours	-	3,100	27 hr	-	3,170
	24-27 hours	3,020	3,090	31 hr	3,010	3,280
	7 days	-	4,650	7 d	4,090	4,400
	28 days	5,640	6,140	28 d	5,130	5,390
First-peak flexural strength, psi	1 day	490	620	1 d	390	480
	7 days	-	720	7 d	-	670
	28 days	720	810	28 d	700	795
Elastic modulus, 10^6 psi	28 days	3.31	3.39	28 d	2.94	3.10
Permeability, C	28 days	976	643	28 d	1293	933

FRC = fiber-reinforced concrete; PP = polypropylene; - = no data.

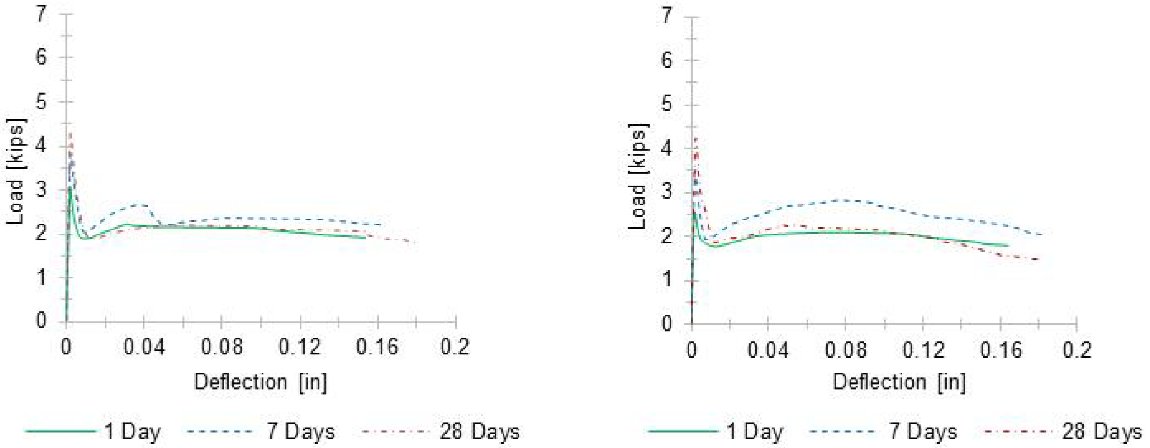


Figure 8. Load-Deflection Curves for FRC With PP Fibers (Batches 1 and 2). FRC = fiber-reinforced concrete; PP = polypropylene.

FRC With S Fibers

The Batch 1 mixture was workable, with a slump of 7.5 in as shown in Table 4; fibers were well dispersed; and no balling was observed. For Batch 2, the slump was 4.0 in, as shown in Table 3.

There were some differences between the two FRC batches with S fibers: the amounts of fiber and accelerating admixture and the substitution of fly ash with silica fume. Nevertheless, both batches had satisfactory results and reached the required strength of 3,000 psi in less than 24 hours. Table 8 shows the hardened concrete properties. The permeability test (ASTM C1202) was not conducted because of the presence of conductive S fibers that would have affected the test results.

The flexural strength results for the FRC with S fibers are given in Figure 9. The FRC with S fibers performed better than the FRC with PP fibers, with higher first peak and ultimate flexural strengths and deflection hardening behavior. The first-peak flexural strength was on average 24% higher compared to that of PP fiber systems.

Table 9 shows the toughness and residual strength values obtained for the specimens that were laboratory cured at the plant. The results for the field-cured specimens are presented in Table 10. The values were calculated in accordance with ASTM C1609. There were differences between the field and laboratory results, but they could be attributed to the variability between the specimens. The flexural strength results for the ECC with PVA fibers and FRC with S fibers were comparable. These two concretes had significantly higher toughness values compared to the FRC with PP fibers. Similar trends were observed for the residual strengths at L/600 and L/150 deflection values. Further, the equivalent flexural strength ratio was determined, which characterizes the increased flexural and ultimate load capacity after the first crack. The flexural capacity of the ECC after the first crack was the highest at 149%, followed by FRC with S fibers at about 86% on average, and FRC with PP fibers at 58% on average for the laboratory-cured specimens.

Table 8. Hardened Concrete Properties for FRC With S Fibers

Test	Batch 1 (6 yd^3)			Batch 2 (6 yd^3)		
	Age	Field	Lab	Age	Field	Lab
Compressive strength, psi	24 hours	-	3,440	21 hr	3,430	-
	31 hours	3,930	3,330	29 hr	4,020	4,080
	7 days	5,160	5,520	7 d	5,380	5,610
	28 days	6,440	6,790	28 d	6,600	7,100
First-peak / Peak flexural strength, psi	1 day	570/600	585/640	1 d	685/815	640
	7 days	-	835/925	7 d	-	840/910
	28 days	895/940	980/1270	28 d	1,090	999
Elastic modulus, 10^6 psi	28 days	3.63	3.85	28 d	4.32	4.42

FRC = fiber-reinforced concrete; - = no data.

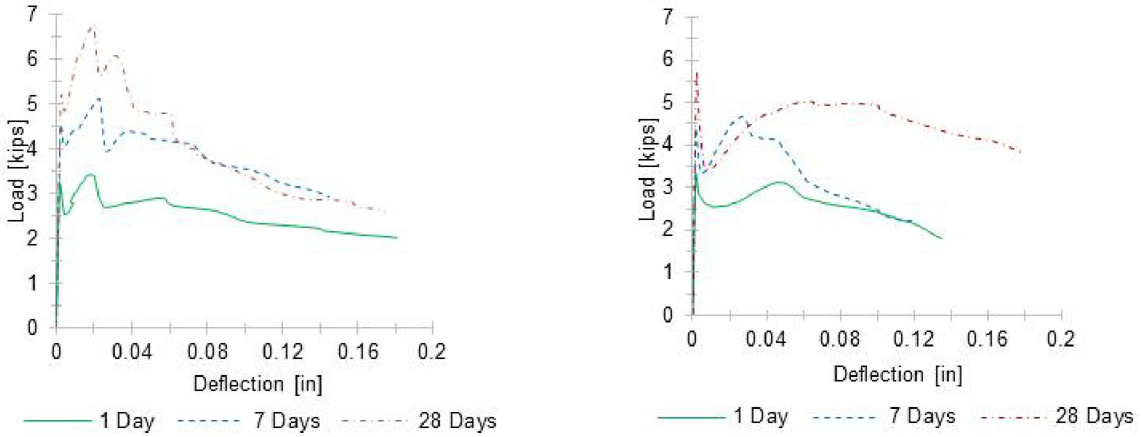


Figure 9. Load-Deflection Curves for FRC With S Fibers (Batches 1 and 2). FRC = fiber-reinforced concrete S = steel.

Table 9. 28-Day Flexural Strength Results for FRC (Lab Cured)

Test	ECC PVA	FRC PP		FRC S	
	Batch 3	Batch 1	Batch 2	Batch 1	Batch 2
Toughness, T_{150}^{D}, in-lb	450	210	190	400	350
Equivalent flexural strength ratio, $R_{T,\ 150}^{D}$,%	149.5	61.5	54.5	96.5	75.5
Residual strength, f_{600}^{D}, psi	990	370	370	1265	745
Residual strength, f_{150}^{D}, psi	1145	410	410	710	930

FRC = fiber-reinforced concrete; ECC = engineered cementitious composite; PP = polypropylene; PVA = polyvinyl alcohol; S = hook end steel fiber.

Table 10. 28-Day Flexural Strength Results for FRC (Field Cured)

Test	ECC PVA	FRC PP		FRC S	
	Batch 3	Batch 1	Batch 2	Batch 1	Batch 2
Toughness, T_{150}^{D}, in-lb	340	180	210	350	340
Equivalent flexural strength ratio, $R_{T,\ 150}^{D}$, %	105.5	60.0	71.5	93.0	83.0
Residual strength, f_{600}^{D}, psi	895	380	400	740	730
Residual strength, f_{150}^{D}, psi	425	500	535	820	925

FRC = fiber-reinforced concrete; ECC = engineered cementitious composite; PP = polypropylene; PVA = polyvinyl alcohol; S = hook end steel fiber.

Closure Pour Shrinkage Results

Shrinkage results for all FRC and RSLMC mixtures are shown in Figure 10. The LMC with Rapid Set cement had very low shrinkage values, less than 0.02% at 4 months (ASTM C157). Because of the high cementitious material and water contents of the ECC mixture, substantial shrinkage occurred. Length change values of up to 0.182% were found at 4 months. Length change values of about 0.085% were measured at 4 months for FRC with PP fibers. For FRC with S fibers, length change values of about 0.077% at 4 months were also found.

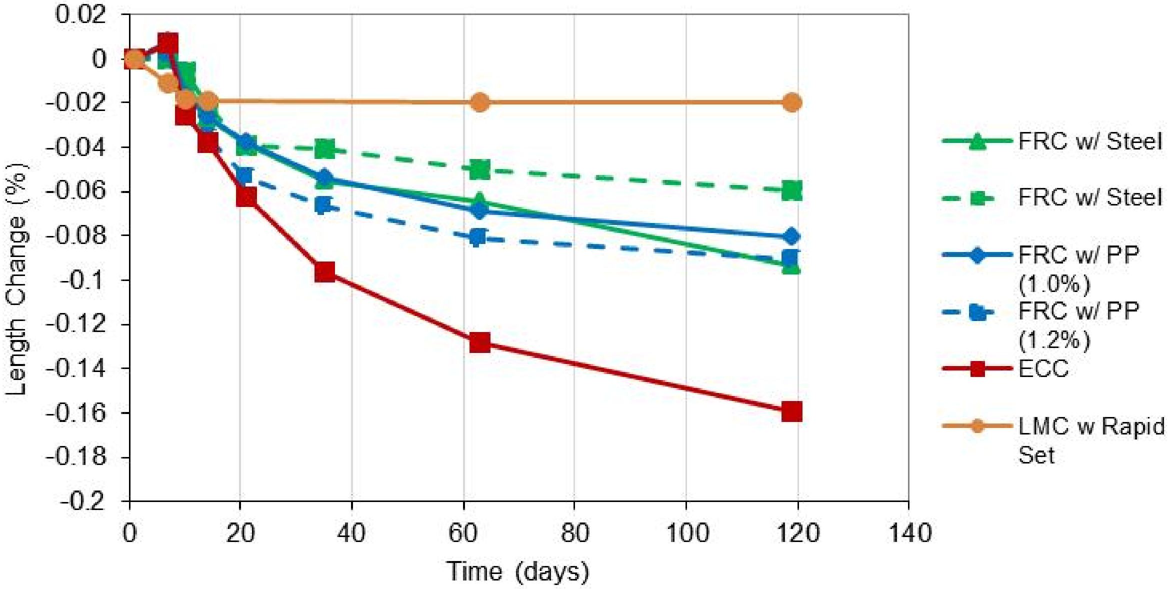


Figure 10. Drying Shrinkage Data for FRC and RSLMC Mixtures. LMC = latex-modified concrete; FRC = fiber-reinforced concrete; ECC = engineered cementitious composite; PP = polypropylene;

Overlays

The overlay concretes for the westbound bridge were placed 1 year before those for the eastbound bridge. The fresh and hardened properties of these overlays were determined. The fresh concrete properties for the westbound bridge are summarized in Table 11, which also includes the weather data for some of the mixtures; the properties for the eastbound bridge are summarized in Table 12. Workable concretes with satisfactory air contents were obtained.

The hardened concrete properties are summarized in Table 13 for the westbound bridge and in Table 14 for the eastbound bridge. The specified strength of 3,000 psi can be achieved in 3 days. Concrete with lightweight aggregate achieved 3,000 psi in 1 day. This was attributed to a relatively low w/cm and internal curing. The 28-day compressive and splitting tensile strengths were satisfactory, and permeability was low or very low. The elastic modulus was similar and above 3 million psi at 28 days. LWCs also had an elastic modulus above 3 million psi, similar to that of the concretes with normal weight aggregate for this study. In general, LWCs with low densities have a lower elastic modulus than the normal weight concretes.

The freeze-thaw durability results given in Tables 13 and 14 indicate that all concretes had a satisfactory durability factor. The acceptance criteria at 300 cycles are a weight loss of 7% or less, a durability factor of 60 or more, and a surface rating of 3 or less. The weight loss was within acceptance limits for the SFC with normal weight aggregate and the SFC with lightweight aggregate. The SFC with SRA and the RSLMCs had high weight loss, but the durability factors were satisfactory indicating sound internal structure.

Table 11. Fresh Concrete Properties of Overlays for Westbound Bridge

Test	RSLMC1	RSLMC2	SRA1a	SRA1b	SRA2a	SRA2b	SFC1	SF2
	9/12/14	10/8/14	9/15/14	9/16/14	10/10/14	10/10/14	9/15/14	10/10/14
Air, %	5	4.2	6.1	7	5.2	6.8	6.4	6.4
Density, lb/ft^3	142	141.6	-	143.2	-	141.2	142.8	142.8
Slump, in	7.5	8.5	6	7	7	6	5.5	5
Concrete temp., °F	83	71	75	70	68	73	75	70
Air temp., °F	73.6	74	-	-	51	-	-	64.4
RH, %	80.4	36	-	-	90	-	-	-
Wind, mph	0	10	-	-	1	-	-	-

RSLMC = latex-modified concrete with Rapid Set cement; SRA = shrinkage reducing admixture; SF = silica fume; RH = relative humidity.

Table 12. Fresh Concrete Properties of Overlays for Eastbound Bridge

Test	LWC1		LWC2		LWF1	LWF2		RSLMC1	RSLMC2
	7/20/15		8/3/15		7/22/15	8/4/15		7/23/15	8/5/15
	B1	B2	B1	B2	-	B1	B2	-	-
Air, %	7.5	6	7.7	1	8.4	6	5.5	4.5	3.25
Density, lb/ft^3	120.4	-	-	116.8	133.2	136.8	138	-	-
Slump, in	5	5	2.25	3.75	2.5	3.5	3	4.5	5
Concrete temp., °F	82	-	74	75	-	85	85	83	83
Air temp., °F	-	-	-	-	-	-	-	77	-

LWC = concrete with lightweight coarse aggregate; LWF = concrete with lightweight fine aggregate; RSMLC = latex-modified concrete with Rapid Set cement; B = batch; - no data.

Table 13. Hardened Concrete Properties of Overlays for Westbound Bridge

Test	Age, days	RSLMC1	RSLMC2	SRA1a	SRA2a	SF1	SF2
		9/12/14	10/8/14	9/15/14	10/10/14	9/15/14	10/10/14
Compressive strength, psi	1	4,000	4,710	2,030	-	2,120	-
	3	5,620	5,240	3,040	2,980	3,110	2,810
	7	5,850	5,605	-	-	3,800	-
	28	6,740	6,180	5,300	4,770	5,110	5,260
E x 10^6 psi	28	3.52 (3d)	3.69	3.82	2.70 (3d)	3.71	2.79 (3d)
Splitting tensile strength, psi	28	690	580	500	530	500	555
Permeability, C	28	348	292	638	905	507	841
Freeze-thaw durability at 300 cycles							
WL, %		22.6	21.8	-	22.7	0.8	7.3
DF		75	81	-	87	102	105
SR		2.5	2.8	-	3.6	0.7	2.0

RSLMC = latex-modified concrete with Rapid Set cement; SRA = shrinkage reducing admixture; SF = silica fume; E = modulus of elasticity, 3d: 3 days; WL = weight loss; DF = durability factor; SR = surface rating.

Table 14. Hardened Concrete Properties of Overlays for Eastbound Bridge

Test	Age, days	LWC1 7/20/15 B1	LWC1 7/20/15 B2	LWC2 8/3/15 B1	LWC2 8/3/15 B2	LWF1 7/22/15 B1	LWF2 8/4/15 B1	LWF2 8/4/15 B2	RSLMC1 7/23/15 -	RSLMC2 8/5/15 -
Compressive strength, psi	1	-	-	3,570	2,800	3,100	2,760	3,030	3,690	(3.5 hr) 3,020
	3	4,470	4,450	3,740	3,360	-	-	3,760	-	(6 hr) 2,950
	7	5,240	5,160	4,580	3,580	4,800	4,320	4,740	4,660	(8 hr) 3,460
	28	6,550	6,550	5,540	5,070	6,250	6,030	6,310	5,280	5,270
E x 10^6 psi	28	3.64	3.48	3.08	3.84	3.42	3.60	3.58	3.47	-
Splitting tensile strength, psi	28	490	560	420	410	625	640	630	475	515
Permeability, C	28	-	-	1359	1303	428	341	158	-	188
Freeze-thaw durability at 300 cycles										
WL, %		0.1	0.5	1.6	0.1	0	2.3	4.6	-	-
DF		104	104	93	102	98	98	97	-	-
SR		0.2	0.6	0.7	0.2	0.2	0.6	0.8	-	-

LWC = concrete with lightweight coarse aggregate; LWF = concrete with lightweight fine aggregate; RSLMC = latex-modified concrete with Rapid Set cement; B = batch; E = modulus of elasticity; WL = weight loss; DF = durability factor; SR = surface rating; - no data.

The shrinkage data are displayed in Figure 11 for both overlays. RSLMC had the lowest shrinkage values. SFC with SRA and SFC with lightweight coarse aggregate met the VDOT specification of 0.035% shrinkage at 28 days for low cracking bridge decks. Babaei and Fouladgar (1997) recommended a maximum shrinkage of 0.07% at 4 months. SFC with SRA and SFC with lightweight coarse aggregate also met this limit. SFC had shrinkage values above the limits set by VDOT (2016) or Babaei and Fouladgar (1997).

Surveys

First Survey

Closure pours and decks were surveyed right after the removal of burlap and plastic sheeting about 1 week after concrete placement. In the closure pours, the FRC had cracks less than 0.1 mm in width whereas the cracks in the RSLMC were larger than 0.2 mm. All cracks were in the direction of traffic. In the transverse direction, there were gaps between the closure pours and overlays. For LMC overlays, small gaps up to about 0.8 to 1.5 mm were formed along both edges of the closure pours with LMC with Rapid Set cement and the existing deck. For ECC, gaps of about 1 to 1.5 mm; for PP fibers, gaps of about 0.2 to 0.4 mm; and for S fibers, tight gaps of 0.1 mm were observed between the closure pours and the existing deck.

The gaps between the closure pours and the overlays in the transverse direction were wider at the ECC slabs than at the PP and the S slabs, following the same trend as the water contents. ECC had the highest water content followed by the FRC with PP and then the FRC with S fibers. The overlays were butted against the closure pours, eliminating edge gaps. The formed gaps along both edges of all closure pours were located 2 ft away from the former joint location on either side of the closure pour and thus were not expected to cause any leakage. In addition, the gaps were filled with epoxy material to ensure no leakage would take place. The longitudinal joints were also filled with epoxy. The overlays did not have any visible cracks.

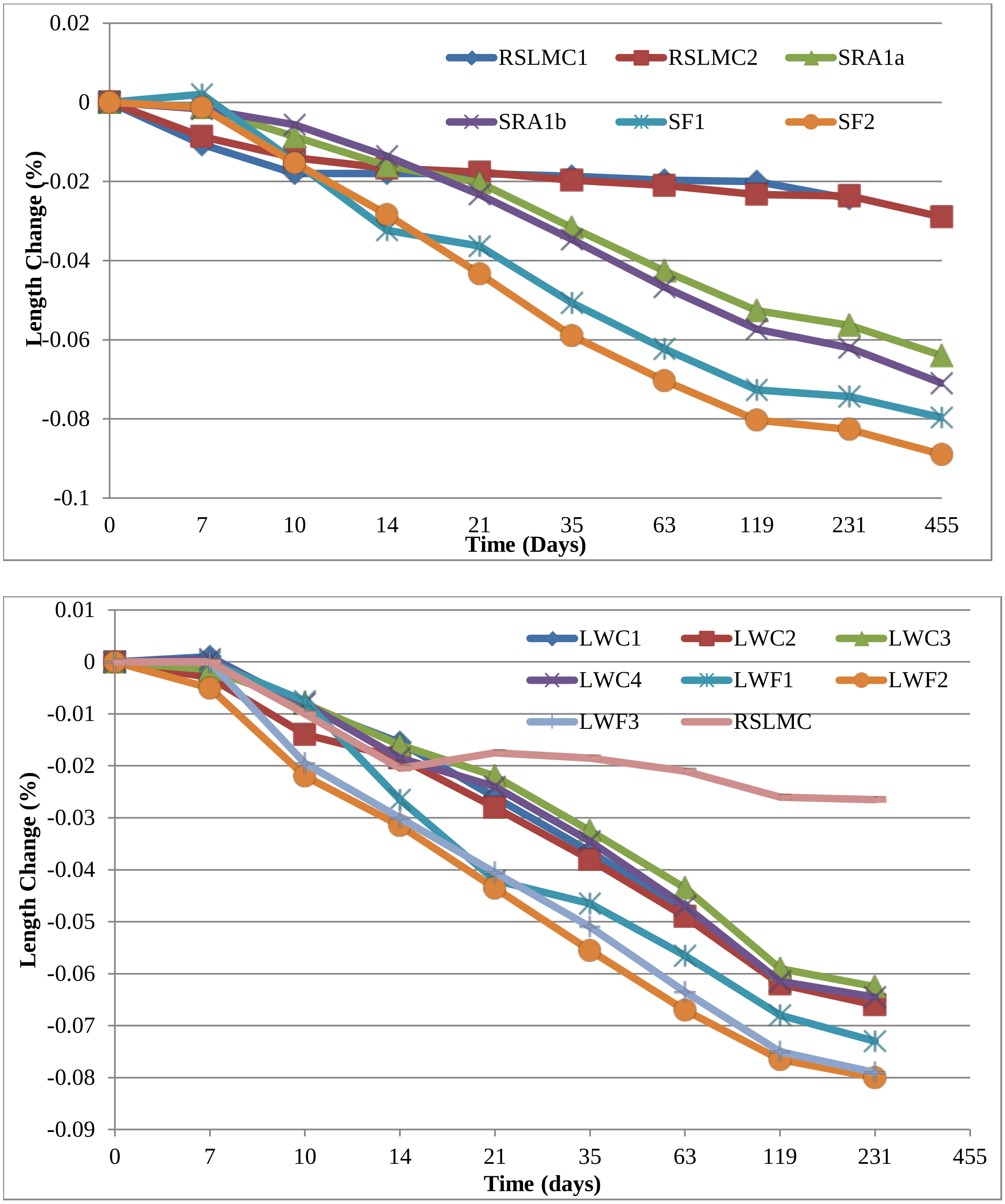


Figure 11. Shrinkage Data for Westbound (*top*) and Eastbound (*bottom*) Overlays. RSMLC = latex-modified concrete with Rapid Set cement; SRA = shrinkage reducing admixture; SF = silica fume; LWC = concrete with lightweight coarse aggregate; LWF = concrete with lightweight fine aggregate.

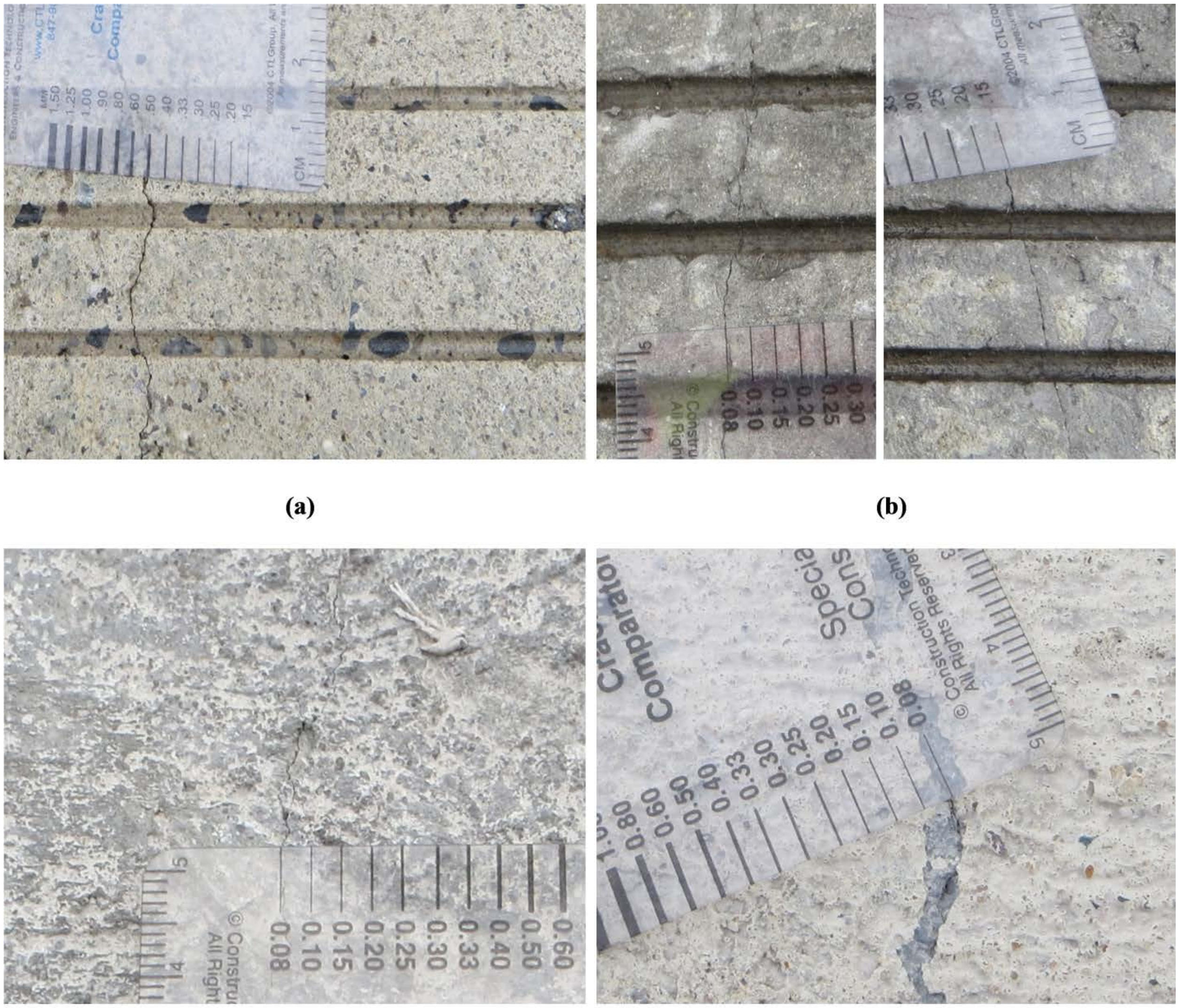
Second Survey

A later survey was conducted when the westbound bridge closure pours (RSLMC and ECC) and overlays (RSLMC, SFC with SRA, and SFC without SRA) were 1 year old and the eastbound bridge closure pours (FRC with PP fibers and FRC with S fibers) and overlays (SFC with lightweight coarse aggregate and SFC with lightweight fine aggregate) were 3 to 4 months old.

Closure Pours. The 1-year-old RSLMC had cracks up to 0.4 mm in width. The cracks were attributed to the high temperature generated in the thick slabs and not to moisture loss since very low shrinkage occurred in these concretes. The ECC had multiple tight cracks, and most cracks were less than 0.1 mm in width; a few were as wide as 0.2 mm. The 3- to 4-month-old FRCs with PP or with S fibers had very tight cracks less than 0.1 mm in width. The closure pours from Batch 1 of the FRC with PP fibers had no visible cracks, whereas the adjacent closure pours from Batch 2 had one crack in one closure pour and two cracks in the second closure pour. FRC with S fibers did not reveal any cracks exceeding 0.004 in [0.1 mm] in width, which is attributed to the lower water content than the other mixtures (233 and 264 lb/yd^3). The benefits of S fibers in reducing crack spacing and crack width are well documented (Bischoff, 2003; Lee et al., 2013; Tiberti et al., 2014).

It appears that the FRC with PP fibers did not deflection harden and is still performing well with tight cracks (less than 0.1 mm in width). This is attributed to the presence of primary reinforcement in the slabs. When continuous reinforcement and randomly distributed fibers are used together, concretes with residual tensile strength assist the primary reinforcement in keeping crack widths tight (Mobasher et al., 2015). Figure 12 shows the closure pour cracks for the LMC with Rapid Set cement, ECC, FRC with PP fibers, and FRC with S fibers from the second crack survey.

Overlays. The finished westbound deck is shown in Figure 13. SFC with SRA, SFC without SRA, or SFC with lightweight aggregate exhibited no cracks or very tight cracks; thus, they are performing satisfactorily. SFC with SRA and LWCs had low shrinkage and are expected to have minimal cracking. However, SFC had higher shrinkage than desired but still had tight cracks. This was attributed to good curing practices and favorable weather conditions. RSLMC performed well except that the left lane of the westbound bridge has extensive cracking, thought to be plastic shrinkage cracking (Figure 14). Even though good curing procedures were used, the weather conditions during placement were conducive to high evaporation rates, as shown with the high wind and low humidity in Table 11. This indicates the high sensitivity of RSLMC to curing conditions in adverse weather. In addition, a truck caught fire on that lane, possibly contributing to cracks.



(a) (b)

(c) (d)

Figure 12. Cracks: (a) LMC With Rapid Set Cement; (b) ECC; (c) FRC With PP fibers; (d) FRC With S Fibers. LMC = latex-modified concrete; FRC = fiber-reinforced concrete; PVA = polyvinyl alcohol; ECC = engineered cementitious composite; PP = polypropylene; S = steel fibers.


Figure 13. Finished Deck of Westbound Bridge


Figure 14. Plastic Shrinkage Cracking in RSLMC in Left Lane of Westbound Bridge. RSLMC = latex-modified concrete with Rapid Set cement.

Third Survey

A third condition survey was conducted on March 24, 2017. For each bridge condition survey, the traffic lane was closed to traffic. The cracks in closure pours and overlays and delaminations in overlays in the traffic lanes were observed and measured. The crack survey results for overlays are summarized in Table 15. In general, there were few cracks except for the RSLMC in the westbound lane. The high cracking density for the RSLMC that was also observed in the previous survey was attributed to the weather conditions. In addition, the truck catching fire in those spans would have affected cracking as noted before. The cracks were narrow, most with a width of 0.1 mm or less and a few as wide as 0.2 mm. The cracks were in both the longitudinal and transverse directions. The passing lane was observed for cracking from the traffic lane; however, measurements were not taken.

The results indicated that the overlays with LMC with Rapid Set cement and with SFC had spans with no cracking, but they also had cracks in other spans. This indicated the importance of curing in these overlays. There were also small spots repaired with epoxy mortar in the silica fume sections, as shown in Figure 15. These were due to the mixing sequence leaving silica fume bags in the mixture that necessitated removing the bag pieces and repairing the holes.

There were some delaminated areas indicated by chain drag and hammer soundings, especially in the spans with silica fume and lightweight fine aggregate, as indicated in Table 15. This was attributed to the poor surface preparation leaving puddles of water that weakened the bond between the base concrete and the overlay. The hydro-demolition used had provided a rough and clean surface to bond; however, water puddles would adversely affect the bond.

Table 15. Cracks and Delaminations in the Overlays

Overlay Type	**Cracks**					**Delaminations**		
	Transverse		**Longitudinal**		**Density (%)**			
	No.	**Length (ft)**	**No.**	**L (ft)**	**L/Area**	**No.**	**Area (ft^2)**	**%Area**
Westbound								
SFC+SRA	None	-	-	-	-	-	-	-
SFC+SRA	None	-	-	-	-	3	6	0.4
SFC	2	4	2	2	0.4	-	-	-
RSLMC	20	125.5	8	29.5	10.8	1	12	0.8
RSLMC	8	26.5	2	8	2.4	-	-	-
Eastbound								
SFC+LWCA	None	-	-	-	-	-	-	-
SFC+LWCA	7	11.5	-	-	0.8	-	-	
SFC+LWFA	1	1	-	-	0.7	3	40.5	2.8
SFC+LWFA	None	-	3	10.5	7.3	11	67	4.7
RSLMC	None	-	None	-	-	1	6	0.4

SF = silica fume; SRA = shrinkage reducing admixture; RSLMC = latex-modified concrete with Rapid Set cement; SFC = silica fume concrete; LWCA = lightweight coarse aggregate; LWFA = lightweight fine aggregate.

Figure 15. Small Dark Spots Attributable to Repair of Holes Left When Bag Pieces Were Removed From Bridge Deck

For the closure pours, cracks were in the longitudinal direction the length of the patch width. They were counted for both the traffic and passing lanes, as given in Table 16, but the width was measured in the traffic lane only since this lane was closed to traffic. There were more cracks in the traffic lane compared to the passing lane. The results indicated that cracks in the FRC were tight, mainly 0.1 mm, and the maximum width observed was in the section with the PP fibers at 0.25 mm. The RSLMC without fibers had cracks mainly above 0.3 mm, with some as high as 0.4 mm. Thus, FRC was controlling the crack width.

The results of the third survey were similar to those of the second survey conducted 1.5 years before, indicating that cracks had stabilized in the closure pours.

Table 16. Cracks in the Closure Pours

	Traffic Lane		Passing Lane
Fiber Type	**No.**	**Width (mm)**	**No.**
Westbound			
ECC	12	0.1	12
ECC	8	0.1-0.15 (most 0.1)	13
RSLMC	7	0.3-0.4 (most above 0.3)	5
RSLMC	5	0.15-0.4 (most above 0.3)	7
Eastbound			
FRC with PP fibers	6	0.1-0.2	-
FRC with PP fibers	4	0.1-0.25	1
FRC with S fibers	1	0.15	-
FRC with S fibers	1	0.2	3

ECC = engineered cementitious composite with polyvinyl alcohol fibers; RSLMC = latex-modified concrete with Rapid Set cement; PP = polypropylene fibers; S = steel fibers.

SUMMARY OF FINDINGS

Closure Pours

- RSLMC had very high early strengths; 3,000 psi was achieved within the first test age of 3 hours. Even though these concretes had low shrinkage, they exhibited cracks ranging in width from 0.1 mm to 0.4 mm in the closure pours; cracks above 0.2 mm facilitate the infiltration of harmful solutions. The wide cracks in RSLMC in closure pours were attributed to the lack of fibers in the mixture.

- Overall, the FRC mixtures reached the required strength of 3,000 psi in about 24 hours. Accelerators and high concrete temperatures helped in achieving early strengths. Specimens exhibiting higher temperatures had higher early strength. The closure pour had a higher temperature development than the test specimens, indicating that the specified early strength could be reached sooner.

- FRC can be prepared in a ready-mixed concrete truck. The sequence of the addition of silica fume and PP fibers, especially when bags are not discarded, requires attention. As indicated in this study, the bags added near the end of loading will not dissolve easily; therefore, they should be added toward the beginning of the loading. PP fibers added near the end will tend to clump. The silica fume in bags and the PP fibers must be placed in the drum at the beginning of the loading. Even then, silica fume bags may not dissolve completely. Trial batches would indicate if the bags will dissolve completely. S fibers were easier to mix than PP fibers.

- ECC was self-consolidating. The other mixtures with fibers and the overlay mixtures required consolidation.

- ECC with PVA and FRC with S fibers displayed deflection hardening behavior; FRC with PP fibers had high residual strength but did not exhibit deflection hardening.

- Proper mixing procedures are needed to achieve the desired fresh concrete properties, workability, and fiber dispersion.

- ECC displayed the highest shrinkage, followed by the concretes with PP fibers and then those with S fibers. Gaps between the overlays and the closure pours followed the same trend. These results are consistent with the water content for the mixtures: ECC had the highest water content followed by mixtures with PP fibers and then with S fibers. The gaps were closed by the subsequent overlay placements and were sealed with epoxy.

Overlays

- The SFC overlay attained about 3,000 psi in 3 days. The 3,000 psi gain in 1 day by the overlay concretes with lightweight aggregate was attributed to a relatively low w/cm and internal curing.

- The overlays had very tight cracks except for the RSLMC in the left lane of the westbound bridge, which had extensive cracks attributed to plastic shrinkage from adverse weather conditions at placement. In addition, a truck had caught fire on that lane, which may have contributed to the development of cracks.

- SFC with SRA and SFC with lightweight aggregate had low shrinkage values and had tight cracks. SFC had shrinkage values above those recommended but still had tight cracks attributed to good curing practices and favorable weather conditions.

CONCLUSIONS

- *Crack control leading to fewer and tighter cracks can be obtained by proper selection of the type and amount of ingredients, including fibers, and good construction practices.*

- *RSLMC achieves a compressive strength of 3,000 psi within 3 hours. Mobile mixers are needed for mixing and placing RSLMC.*

- *FRC with portland cements and supplementary cementitious materials that achieves a compressive strength of 3,000 psi within 24 hours can be produced in a ready-mixed concrete truck. Results also indicated that the specified early strength could be reached sooner than 24 hours in the field.*

- *Closure pours with FRC (ECC, PP, and S fibers) with tight cracks can perform well. RSLMC without fibers develop wide cracks.*

- *FRC can control crack width in closure pours. Even the FRC with PP that did not deflection harden had tight cracks. This is attributed to the presence of primary reinforcement in the closure pours. In general, a crack survey after three winters showed the following:*

  — *FRC with PP and S fibers:* no cracks or cracks < 0.1 mm wide
  — *ECC with PVA fibers:* cracks < 0.1 mm wide with a few as wide as 0.2 mm
  — *RSLMC:* cracks up to 0.4 mm.

- *FRC mixtures have high paste contents and had high shrinkage values exhibited in wide gaps between the overlay and the closure pour. Subsequent placement of overlay concrete closed the gaps. In addition, epoxy was applied to those construction joints. ECC had the highest shrinkage and gap.*

- *RSLMC overlay is one of the best options to achieve very early strengths using special cement that provides a compressive strength of 3,000 psi within 3 hours to limit lane closures and minimize inconvenience to the traveling public.*

- *Overlay concretes with portland cements and silica fume reach a compressive strength of 3,000 psi within 3 days and some within 1 day. Further research is needed to obtain high early strength concretes using portland cements that achieve a compressive strength of 3,000 psi within 10 hours.*

- *Silica fume overlays with SRA, SFC with lightweight coarse aggregate, and SFC with lightweight fine aggregate perform well with no or tight cracks.*

- *RSLMC overlays perform well when proper construction procedures are followed.*

- *Adding silica fume in bags early will minimize dark spots in overlays (repaired areas after removal of the pieces of the silica fume bag).*

- *Proper surface preparation practices are needed for overlay placement. Chain drag and hammer soundings indicated limited delaminated areas near the longitudinal joint attributed to surface preparation leaving water puddles.*

RECOMMENDATIONS

1. *VDOT's Materials Division and Structure and Bridge Division should consider using FRC in closure pours / link slabs to control crack width when early strength for opening to traffic is required.*

2. *VDOT's Materials Division and Structure and Bridge Division should consider using SFC with SRA, lightweight coarse aggregate, or lightweight fine aggregate as a partial replacement for normal weight fine aggregate in overlays to minimize cracking.*

BENEFITS AND IMPLEMENTATION

Benefits

Cracking continues to be the number one concern with regard to bridge decks and overlays. Cracks can facilitate the intrusion of chlorides, causing corrosion of the reinforcing steel. Considerable money is spent on concrete sealers, epoxy injection, crack sealing, and overlays to mitigate cracks. Cracking can be minimized and crack widths controlled by using fibers in closure pours. Low permeability concrete overlays with low cracking potential would lead to more durable concrete structures with minimal maintenance during their service life.

There are more than 13,000 bridge structures in Virginia (VDOT, 2015). The majority of these were built with an anticipated service life of 50 years. Currently, about 63.5% of VDOT's structure inventory is 40 years or older. Accordingly, a large number of bridges in Virginia that were built in the 1960s are now facing the end of their 50-year lifespan. This problem is particularly pronounced on the interstate system. To extend service life, preventative and proactive maintenance, major repairs, and rehabilitation are needed. The Dunlap Creek Bridge rehabilitation project may serve as an example to refer to in the future because of its use of innovative concretes. This project provides valuable experience in how to carry out the numerous interstate bridge rehabilitation projects that are expected to arise in the near future.

The benefit of implementing Recommendation 1 would be that cracking could be controlled by the use of FRC in conjunction with the primary reinforcement. Concretes with portland cements that are durable and easy to place and that achieve a strength of 3,000 psi within 24 hours are needed to minimize traffic interruptions and inconvenience to the traveling public in bridge repairs. These concretes usually have high cementitious material, water, and paste contents, making them prone to cracking. Controlling cracking by FRC would extend the life of structures. Recently, VDOT's Richmond District used FRC with polypropylene fibers in longitudinal closure pours; there are no visible cracks and no leakage after the first winter.

The benefit of implementing Recommendation 2 would be that silica fume concrete with SRA, lightweight aggregate concrete, or normal weight concrete with partial replacement by lightweight fine aggregate would minimize cracking and is expected to increase the service life of overlays.

Implementation

With regard to implementing Recommendation 1, VDOT's Structure and Bridge Division should adopt the use of FRC as an option in closure pours to control cracking whenever early strength is needed for opening to traffic. This could be accomplished by adding FRC to the *Manual of Instructions of the Materials Division* and the *Manual of the Structure and Bridge Division.* However, further field installations are needed to determine the type and amount of fibers in the field to control cracking, especially in the presence of the primary reinforcement. VTRC has initiated a new study to address accelerated strength development even in less than 24 hours. The objective is to develop FRC mixtures that will gain 3,000 psi in 10 hours using portland cements and SCMs in truck mixers or mobile mixers. Optimizing fiber contents further is also planned in the study. It is hoped that a new specification for the use of FRC mixtures in closure pours can be developed. The study will be completed by 2020.

With regard to implementing Recommendation 2, VDOT's Materials Division and Structure and Bridge Division should adopt SFC with SRA and SFC with lightweight aggregates as options for overlays. This will be accomplished by adding them to the *Manual of Instructions of the Materials Division,* the *Manual of the Structure and Bridge Division,* and the VDOT *Road and Bridge Specifications* within 1 year (by 2018).

ACKNOWLEDGMENTS

The authors thank VTRC and personnel of VDOT's Staunton District Structure and Bridge Section, especially Kim Ikhyeon and Rex Pearce; VDOT's Structure and Bridge Division and Materials Division; and the Federal Highway Administration. Particular thanks go to Deven

Barkley, Mary Bennett, Michael Burton, Liam Gallagher, Darrell Hayes, Kenneth Herrick, Evelina Khakimova, Andy Mills, Gail Moruza, William Ordel, Mary Sharifiasl, and Park Thompson.

REFERENCES

Babaei, K., and Fouladgar, A.M. Solutions to Concrete Bridge Deck Cracking. *Concrete International,* Vol. 19, No. 7, 1997, pp. 34-37.

Banthia, N., and Gupta, R. Influence of Polypropylene Fiber Geometry on Plastic Shrinkage Cracking in Concrete. *Cement and Concrete Research,* Vol. 36, No. 7, 2006, pp. 1263-1267.

Bischoff, P.H. Tension Stiffening and Cracking of Steel Fiber-Reinforced Concrete. *Journal of Materials in Civil Engineering,* Vol. 15, No. 2, 2003, pp. 174-182.

Blunt, J.D., and Ostertag, C.P. Deflection Hardening and Workability of Hybrid Fiber Composites. *ACI Materials Journal*, Vol. 106, No. 3, 2009, pp. 265-272.

Bremner, T.W., Holm, T.A., and DeSouza, H. *Aggregate-Matrix Concrete Subject to Severe Weathering.* FIB-CPCI International Symposium on Concrete Sea Structures in Arctic Regions, Calgary, Alberta, Canada, 1984.

Bentz, D.P., and Weiss, W.J. *Internal Curing: A 2010 State-of-the-Art Review.* NISTIR 7765. National Institute of Standards and Technology, Gaithersburg, MD, 2011.

Holm, T.A., Bremner, T.A., and Newman, J.B. Lightweight Aggregate Concrete Subject to Severe Weathering. *Concrete International*, Vol. 6, No. 6, 1984, pp. 49-54.

Kosmatka, S.H., and Wilson, M.L. *Design and Control of Concrete Mixtures*, 15th Edition. Portland Cement Association, Skokie, IL, 2011.

Lawler, J.S., Zampini, D., and Shah, S.P. Permeability of Cracked Hybrid Fiber Reinforced Mortar Under Load. *ACI Materials Journal,* Vol. 99, No. 4, 2002, pp. 379-392.

Lee, S.-C., Cho, J.-Y., and Vecchio, F.J. Tension-Stiffening Model for Steel Fiber-Reinforced Concrete Containing Conventional Reinforcement. *ACI Structural Journal,* Vol. 110, No. 4, 2013, pp. 639-648.

Li, V.C. On Engineered Cementitious Composites (ECC): A Review of the Materials and Its Applications. *Journal of Advanced Concrete Technology,* Vol. 1, No. 3, 2003, pp. 215-230.

Li, V.C., and Lepech, M.D. Application of ECC for Bridge Deck Link Slabs. *Materials and Structures,* Vol. 42, No. 9, 2009, pp. 1185-1195.

Mobasher, B., Yao, Y., and Soranakom, C. Analytical Solutions for Flexural Design of Hybrid Steel Fiber Reinforced Concrete Beams. *Engineering Structures,* Vol. 100, 2015, pp. 164-177.

Naaman, A.E. New Fiber Technology: Cement, Ceramic and Polymeric Composites. *Concrete International*, Vol. 20, No. 7, 1998, pp. 57-62.

Ozyildirim, C., and Vieira, M. *Exploratory Investigation of High-Performance Fiber-Reinforced Cementitious Composites for Crack Control.* VTRC 08-R12. Virginia Transportation Research Council, Charlottesville, 2008.

Sahmaran, S., and Li, V. Engineered Cementitious Composites: Can Composites Be Accepted as Crack-Free Concrete? *Transportation Research Record: Journal of the Transportation Research Board,* No. 2164, 2010, pp. 1-8.

Sprinkel, M.M. Very-Early-Strength Latex-Modified-Concrete Overlay. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1668, 2014, pp. 18-23.

Tiberti, G., Minelli, F., Plizzari, A.G., and Vecchio, F.J. Influence of Concrete Strength on Crack Development in SFRC Members. *Cement & Concrete Composites*, Vol. 45, October 2014, pp. 176-185.

Virginia Department of Transportation. *State of the Structures and Bridges Report, Fiscal Year 2015.* Richmond, 2015.

Virginia Department of Transportation. *Road and Bridge Specifications.* Richmond, 2016.

Wang, K., Jansen, D.C., Shah, S., and Karr, A.F. Permeability Study of Cracked Concrete. *Cement and Concrete Research,* Vol. 27, No. 3, 1997, pp. 381-393.