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16. Abstract

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This report describes the development and testing of concrete mixtures containing synthetic fibers in the laboratory and the plant and the placement in the deck of the bridge carrying Route 11 over the Maury River in Lexington, Virginia. The deck was on steel beams. FRC was placed over one of the four piers. Comparisons with the control section without the fibers over a 5-year period indicated that FRC has fewer and narrower cracks, even though higher shrinkage occurred in the FRC specimens.

Evaluation of fibers in continuous decks, especially over steel beams, should continue. However, particular attention must be devoted to mixture proportioning, slump, and air content. Further, the workability lost by the addition of fibers should be regained by the addition of a high-range water-reducing admixture, not water, or durability may decrease. Fibers can control cracking and minimize corrosion of the reinforcement in the concrete, thus extending the service life of the structure and reducing maintenance costs, leading to substantial savings.

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FINAL REPORT

HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE IN A BRIDGE DECK

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(A Cooperative Organization Sponsored Jointly by the
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ABSTRACT

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FINAL REPORT

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INTRODUCTION

Deterioration in reinforced concrete is related to four major types of environmental distress: corrosion of the reinforcement, alkali-aggregate reactivity, freezing and thawing deterioration, and attack by sulfates.[1] In each case, water and solutions, which can penetrate into the concrete through either the concrete itself or the cracks in the concrete, initiate or accelerate the distress. This distress can necessitate costly repairs. To reduce the penetration of liquids through the concrete, high-performance concrete (HPC) with low permeability is used.[2] However, because of low tensile strength and low strain capacity, concrete commonly cracks, particularly in bridge decks.[3]

It has been reported that one way to control cracking is to add reinforcing fibers to the concrete mixture. Fibers reportedly can control cracking due to plastic shrinkage, drying shrinkage, and settlement in unhardened concrete and due to loading and environmental factors in hardened concrete.[4-6] For example, in continuous decks, cracking is common over the piers because of the development of negative moments due to loads; these cracks may be mitigated by using fibers.

Adding fibers is expected to increase toughness, provide residual strength, and minimize the occurrence and width of cracks in concrete.[7] Fibers are produced from steel, glass, and a wide variety of organic polymers (known as synthetic fibers). The Virginia Department of Transportation (VDOT) used steel fibers in 1974 and 1996 for bridge deck overlays.[8,9] However, steel fibers exhibit corrosion on the surface. Although limited to the exposed fibers, corrosion may be considered unsightly to the traveling public. In addition, corroding fibers in the surface cracks could break or disintegrate and as a consequence could not provide the expected reinforcement. Although glass fibers do not corrode, they may contribute to problems with alkali-silica reactions. Therefore, this project focused on synthetic fibers.

There are many varieties of synthetic fibers. VDOT bridge and pavement projects have used polypropylene and polyolefin fibers.[9,10] Fibrillated polypropylene fibers were 0.75 in long and very fine with a high surface area. A high-fiber surface area increases the effectiveness of the fibers in improving the toughness of concrete but also increases mixing difficulty. This difficulty limited the amount of polypropylene fibers to 5 lb/yd^3 in the VDOT studies, thus restricting the improvement of hardened properties. The polyolefin fibers used were monofilament, had a large elliptical cross-section,[7] and could be mixed in large amounts with concrete (as high as 25 lb/yd^3 with the 2-in-long fiber). At such a high loading rate, improvement in toughness was achieved, but the concrete was difficult to place and finish.

In this project, a new structural fiber was used: high-tenacity synthetic fiber, designed to provide enhanced structural properties of concrete.[11] These fibers were 2-in-long monofilament fibers with an aspect ratio of 70 manufactured from a synthetic polymer blend of polypropylene and polyethylene resins. The monofilament fiber partially fibrillates during mixing, increasing the fiber surface area and strengthening the bond between the fiber and the concrete matrix. Mixing large quantities of this fiber is possible (about 10 lb/yd^3), resulting in enhanced toughness, impact and fatigue resistance, and control of plastic shrinkage cracking with minimal effect on concrete workability.

PURPOSE AND SCOPE

The purpose of this research was to evaluate the ability of polypropylene-polyethylene blend fibers to control cracking in a continuous concrete deck. The structure selected for the study was the bridge carrying Route 11 over the Maury River in Lexington, Virginia. Fibers were added to the deck concrete over one of the four piers. The deck concrete had a specified minimum 28-day compressive strength of 4,000 psi and a maximum permeability of 2500 coulombs.

METHODOLOGY

Overview

The bridge has five continuous steel plate girder spans; the inside spans are 138 ft long and the end spans are 105 ft long. The width of the bridge is 80 ft, and it carries traffic in both directions. In the southbound lanes, the 26-ft-wide section of the deck concrete over the fourth pier included 8.75 lb/yd^3 of synthetic fibers. The remainder of the deck was made with concrete without fibers. The deck over the first pier was symmetric and identical with the section over the fourth pier; therefore, this section was used as the control. A flexural strength of 600 psi and a residual strength of 400 psi were specified for the fiber-reinforced concrete (FRC). The properties of concrete with and without the fibers were evaluated. The deck was placed in December 2000, and the bridge was opened to traffic on April 16, 2001. The evaluation of field performance was based on a visual survey of surface distress and was conducted after placement and yearly until 2005.

Construction of the Deck

The deck was constructed in three phases: (1) trial batches were prepared in the laboratory with varying fiber dosages, (2) trial batches were made at the plant, and (3) the bridge deck was placed. The fresh and hardened concrete properties were determined in the trial batches and in the actual bridge deck.

Laboratory Trials

The laboratory trial phase used five different fiber batches. Batches 1, 2, and 3 were made using fly ash; and batches 4 and 5 were made using slag. A commercially available air-entraining admixture (AEA) and a water-reducing admixture (WRA) in compliance with the requirements of ASTM C 494, Type A, were used. The mix designs of the different batches are shown in Table 1. The only other variable from batch to batch was the fiber content.

In the laboratory trial phase, the fresh concrete properties of slump (ASTM C 143), time of flow through inverted slump-cone (ASTM C 995), air content (ASTM C 231), and unit weight (ASTM C 138) were determined. The hardened specimens were tested for compressive strength, elastic modulus, flexural strength, permeability, drying shrinkage, freeze-thaw resistance, and residual strength, as listed in Table 2. Beams cast for residual strength determination were tested in accordance with ASTM C 1018, and the residual strength was determined at the deflection values given in ASTM C 1399.

Table 1. Laboratory Trial Mix Design

Material	Batch Number	
	1, 2, 3	**4, 5**
Cement (lb)	508	394
Fly Ash (lb)	127	0
Slag (lb)	0	262
Water (lb)	286	286
Coarse Aggregate (lb)	1868	1831
Fine Aggregate (lb)	1196	1153
Fiber (lb/yd^3)	5, 10, 15	6, 9

Table 2. Test and Specimen Sizes

Tests	Age	Specifications	Size, in
Compressive Strength	28 d, 56 d, 1 yr	AASHTO T 22	4 x 8
Splitting Tensile Strength	28 d	ASTM C 496	4 x 8
Permeability	28 d	AASHTO T 277, T 259[a]	2 x 4, 12 x 12
Drying Shrinkage	64 wk	ASTM C 157	3 x 3 x 11.25
Freeze-thaw	300 cycles	ASTM C 666	3 x 4 x 16
Residual Strength	28 d	ASTM C 1018, C 1399	4 x 4 x 14

[a]Moist cured 1 week at 73°F and 3 weeks at 100°F.

Plant Trials

Table 3 shows the mixture proportions for trial batches prepared at a concrete plant on September 15, 2000. The concrete was fabricated in two batches in ready-mix concrete trucks and cast in a 12 ft x 12 ft x 6 in slab. The purpose of casting a slab prototype was to determine the placement and finishing characteristics of concrete with fibers. Both trial batches contained 9 lb/yd^3 of synthetic fibers. These batches included an AEA, WRA, and HRWRA.

Table 3. Plant Trial Mix Design

Material	lb/yd^3
Cement	395
Slag	263
Water	286
Coarse Aggregate	1830
Fine Aggregate	1152
Fibers	9

In the plant trial phase, the fresh concrete properties of slump (ASTM C 143), inverted slump (ASTM C 995), and air content (ASTM C 231) were determined. The hardened specimens were subjected to the tests shown in Table 2. In addition, sample beams were tested for residual strength at the Virginia Transportation Research Council (VTRC). The tests were preformed in accordance with ASTM C 1018, using the deflections given in ASTM C 1399 to determine the residual strength. The rate of displacement was controlled through the movement of the actuator of the testing machine.

Bridge Deck Concrete

The bridge is 2 miles from the plant. The concrete deck with fibers was cast on December 11, 2000, and the control section was cast 3 days later. Both the fiber mix and the control mix were pumped. Fresh concretes were tested for air content and slump before and after pumping The pump was located 40 ft below the deck. The boom stretched another 30 to 40 ft above the deck. Specimens for tests at the hardened state were taken from the pumped concrete below the deck except for a cylinder with control concrete cast on the deck for the air void parameters. The pump boom swiveled away from the deck and allowed a small amount of concrete to freefall through the boom down to a wheelbarrow on the ground. The properties of the on-deck sample are expected to be more representative of the actual bridge concrete since pumping decreases the amount of air in the concrete.[12]

The two sections had the same mix design except that the fiber section included 8.75 lb/yd^3 of synthetic fiber. The mix design for the actual bridge deck, given in Table 4, had the same proportions as the plant trial batch except that slightly fewer fibers were used (due to availability). The batches again included AEA, WRA, and a HRWRA.

Table 4. Bridge Deck Mix Design

Material	lb/yd^3
Cement	395
Slag	263
Water	286
Air	6.5%
Coarse Aggregate	1830
Fine Aggregate	1152
Fibers	8.75

The samples obtained for both the control and fiber batches were tested for the same fresh and hardened concrete properties as were the plant trial batches. The residual strength of the FRC was determined by VTRC and the producer. At VTRC, the deflection of the specimen was controlled through the actuator; the producer controlled the displacement rate through the specimen.

Condition Survey

Four field visits were made to the bridge: on June 29, 2001; July 11, 2002; May 2, 2003; March 5, 2004; and June 14, 2005. The overall condition of the two test sections was determined. Scaling, in addition to the length and width of the cracks, was compared between the two test sections.

RESULTS AND DISCUSSION

Laboratory Trials

Fresh Concrete Properties

In the laboratory trial batches, workability was determined using the inverted slump test and the regular slump test. Table 5 shows these properties and the air content and unit weight for each batch. Increasing the amount of fibers resulted in a reduction in the workability and air content.

Table 5. Laboratory Trial Freshly Mixed Properties

Test	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Specified
Fiber (lb/yd^3)	5.1	10.3	15.1	6.2	8.9	-
Time of flow (sec)	5.5	8.1	27.6	9.3	7.6	-
Slump (in)	3.5	1.75	0.5	---	---	2-4
Air (%)	10	6.4	2.6	3.7	5.1	5-8
Unit Weight (lb/ft^3)	138	143.2	148.4	148.4	145.6	-

Hardened Concrete Properties

Table 6 summarizes the compressive strength, flexural strength, and permeability for the laboratory trial batches. The flexural strength and residual strength (see Figure 1) improved with additional fiber content; however, permeability also increased from Batch 2 to Batch 3 due to the reduced workability of Batch 3, which had a very low slump and high flow time in the inverted slump test.

Table 6. Laboratory Trial Hardened Concrete Properties

Test	Age	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Specified
Compressive Strength (psi)	28 d	3380	4690	4770	7060	5850	$\geq$4000
Flexural Strength (psi)	7 d	520	550	535	---	---	-
	28 d	605	600	640	1000	525	-
Permeability (coulombs)	28 d	1436	1404	2473	781	727	$\leq$2500

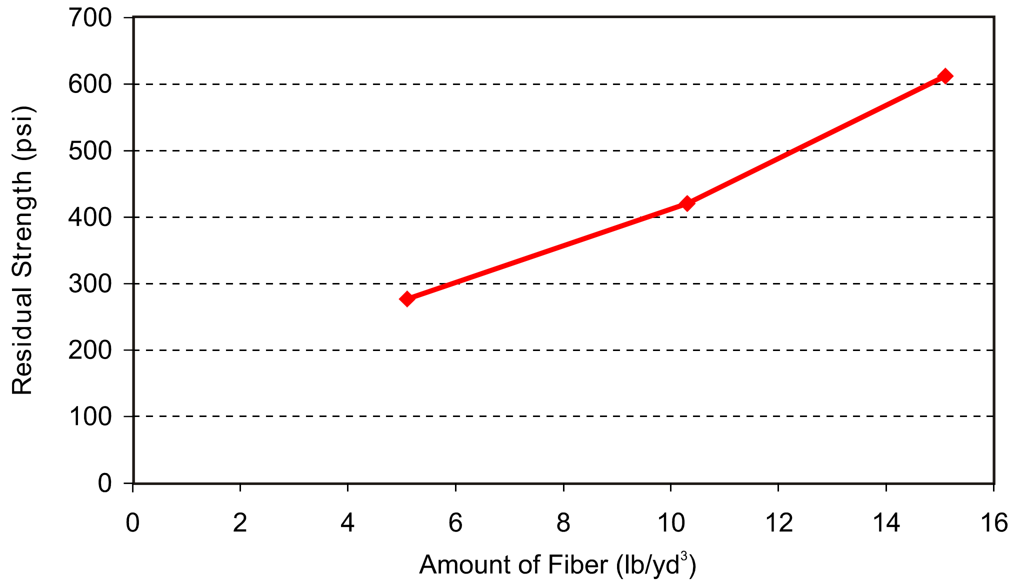

Figure 1. Residual Strength vs. Fiber Dosage for Fly Ash Concrete

Plant Trials

Fresh Concrete Properties

Air content and workability as determined using the time of flow through inverted slump-cone test and the regular slump test are summarized in Table 7. Both batches were workable, with Batch 2 being more workable than Batch 1, and had higher air contents, in general greater slump values, and lower flow times compared to those of the laboratory mixtures.

Table 7. Plant Trial Fresh Properties

Test	Batch 1	Batch 2	Specified
Time of flow (sec)	6.5	3.2	-
Slump (in)	2.5	4.5	2-4
% Air	10.9	10.6	5-8

Hardened Concrete Properties

The strength, permeability, and length change data are summarized in Table 8. The compressive strength and the flexural strength were below the required values. The failure to reach the required strength was attributed to the higher air content and extra water. Adding fibers reduced the workability of the mixture. It appears that excess water was added to compensate for the lost workability, which also increases consistency and the air content. The drawbacks to this addition were increased permeability (high level) and length change in the hardened concrete. Improvements in workability by adding HRWRA rather than water would enable the attainment of the specified strength and permeability.

Table 9 shows the residual strength data obtained for the trial samples. Values were above the minimum 400 psi residual strength specified.

Table 8. Plant Trial Hardened Concrete Properties

Test	Time	Batch 1	Batch 2	Specified
Compressive Strength (psi)	28 d	3700	3800	≥4000
Flexural Strength (psi)	7 d	525	505	-
	28 d	590	---	-
Permeability (coulombs)	28 d	8055	8781	≤2500
Shrinkage (microstrain)	28 d	750	840	-

Table 9. Residual Strength Data From Plant Trial Batch

	Beam No.	Modulus of Rupture (psi)	Residual Stress (psi)				
			0.02 in	0.03 in	0.04 in	0.05 in	Average
VTRC	617	561	418	459	488	496	465
	618	615	522	592	636	654	601

Bridge Deck Concrete

FRC

Fresh Concrete Properties

The fresh concrete properties for the fiber section are shown in Table 10. There were 9 loads of concrete, but only 2 of them were tested before and after pumping and are designated as B1 and B2. The pumped concrete had a significantly lower air content when compared to the concrete before pumping (68 percent and 57 percent reduction for B1 and B2, respectively);

Table 10. Fiber Deck Fresh Concrete Properties

Before Pumping					
Load	**Air (%)**	**Slump (in)**	**Concrete Temp. (°F)**	**HRWRA (fl oz/cwt)**	**Unit Weight (lb/ft^3)**
1	6.5	3.5	70	10	----
2	5.3	4.5	61	12.5	----
3	6.5	4.8	60	14.5	----
4 (B1)	7.2	7.0	54	14	152
5	9.0	7.3	60	14	----
6	8.0	7.0	60	14	----
7 (B2)	7.0	7.3	60	14	154
8	7.6	7.3	60	12.5	----
9	7.0	7.5	60	12.5	----
Note: The air temperature was 40°F.					
After Pumping (Under Bridge)					
Load	**Air (%)**	**Slump (in)**	**Concrete Temp. (°F)**	**HRWRA (oz/cwt)**	**Inverted Cone (sec)**
4 (B1)	2.3	4.8	60	14	5
7 (B2)	3.0	5.8	60	14	7

however, the air contents after pumping may not be indicative of the actual concrete placed on the deck because of the method of sampling. Usually, concrete in the ready-mix trucks is sampled after discharge. Here the effect of the pumping operation was considered and samples were obtained after pumping. However, for convenience, the samples were not obtained on the deck except for a cylinder for air content determination at the hardened state. After placing a load of concrete on the deck, the pump boom swiveled away from the deck and allowed a small amount of concrete to freefall through the boom down to a wheelbarrow on the ground for collection below the bridge. The freefall and the impact of the concrete landing in the wheelbarrow may have caused the bubbles to break, resulting in a significant amount of air loss.[12] In addition, concrete was not flowing continuously, as was expected during deck placement.

Hardened Concrete Properties

Table 11 shows the hardened concrete properties for the FRC portion of the bridge deck. The 28-day compressive strength for both batches tested was above the required 4000 psi. The length change in the deck concrete was higher than the recommended limit of 400 microstrain at 28 days[13] but much less than the values for the plant trial batches. Permeability values were within the specified limits (less than 2500 coulombs at 28 days of age).

The results of the testing of the FRC for resistance to freezing and thawing are listed in Table 12. Both samples exceeded the acceptable weight loss of 7 percent, were below the minimum durability factor of 60, and had surface ratings higher than the minimal criterion of 3. Therefore, the concrete samples failed the freeze-thaw test. This failure may be due to the sampling method. Permeability values were low, indicating good resistance to infiltration of solutions.

Table 11. Fiber Deck Hardened Concrete Properties

Test	Age	Load 4 (B1)	Load 7 (B2)
Compressive Strength (psi)	1 d	730	820
	3 d	2260	2340
	7 d	3740	3510
	28 d	5570	5260
	1 yr	7150	7110
Permeability (coulombs)	28 d	1915	1722
Shrinkage (microstrain)	28 d	585	555
	4 mo	700	685

Table 12. Fiber Deck Freeze-Thaw

Number	Weight Loss (%)	Durability Factor	Surface Rating
B1	30.4	57	4
B2	32.5	23	4

Table 13 displays the results of a linear traverse analysis of Batch 2 (ASTM C 457). The air bubbles less than 1 mm in diameter are spherical air-entrained bubbles, and the air bubbles greater than 1 mm in diameter are entrapped air. Properly consolidated concrete should contain less than 2 percent entrapped air, which is due to a lack of consolidation and excess water in the system.[14] The specific surface was lower than the minimum 24 mm^{-1}, and the spacing factor was higher than the maximum 0.20 mm recommended for concrete exposed to a severe environment[15] The poor results were attributed to the low air content.

The residual strength analysis for the actual deck concrete was conducted at both VTRC and the producer. Both facilities conducted the analysis in accordance with ASTM C 1018, except that the rate of deflection was measured in different ways. At VTRC, the rate of deflection of the actuator was held constant; the producer followed the recently updated ASTM 1018 test procedure that requires the beam deflection rate to be held constant. The difference in beam deflection for the two methods is shown in Figure 2. Figure 3 shows the difference in residual stress at the two laboratories. Holding the actuator deflection constant resulted in higher residual strengths than did keeping the rate of deflection of the beam constant. Residual strengths determined by VTRC were higher than those determined by the producer and higher than the minimum 400 psi. The values obtained by the producer were below the 400 psi limit except for those of one sample. Table 14 shows that after 1 year, there was no considerable increase in the residual strength, although the modulus of rupture increased slightly.

Table 13. Linear Traverse Analysis of Fiber Batch 2

Air Content (%)			Specific Surface (mm^{-1})	Spacing Factor (mm)
<1 mm	>1 mm	Total		
2.65	0.67	3.32	21	0.29

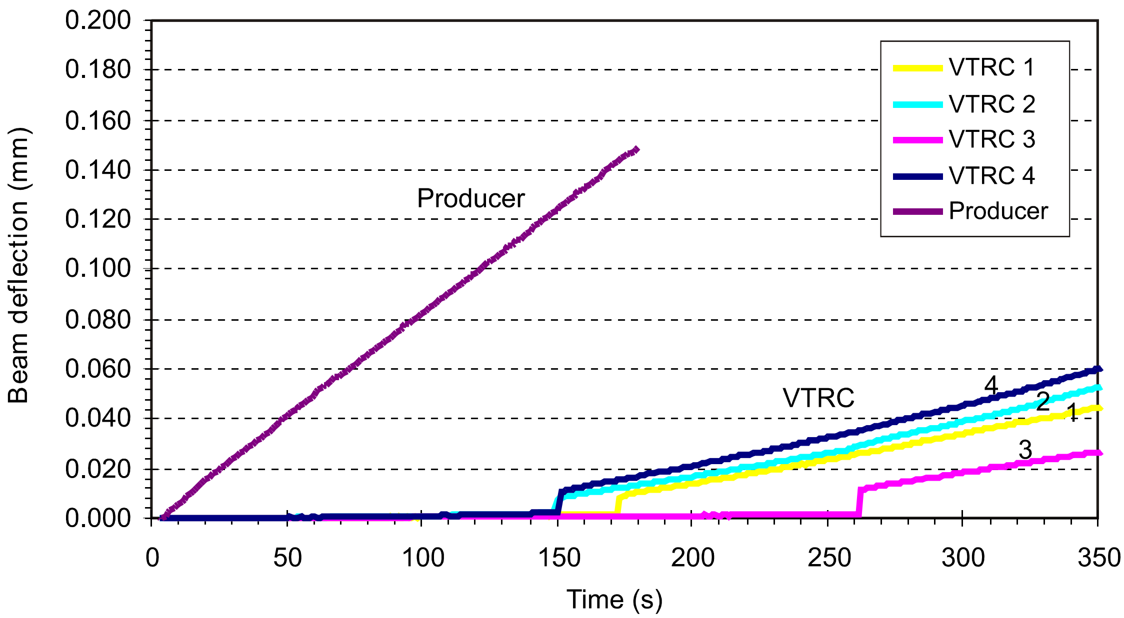

Figure 2. Rate of Deflection Comparison

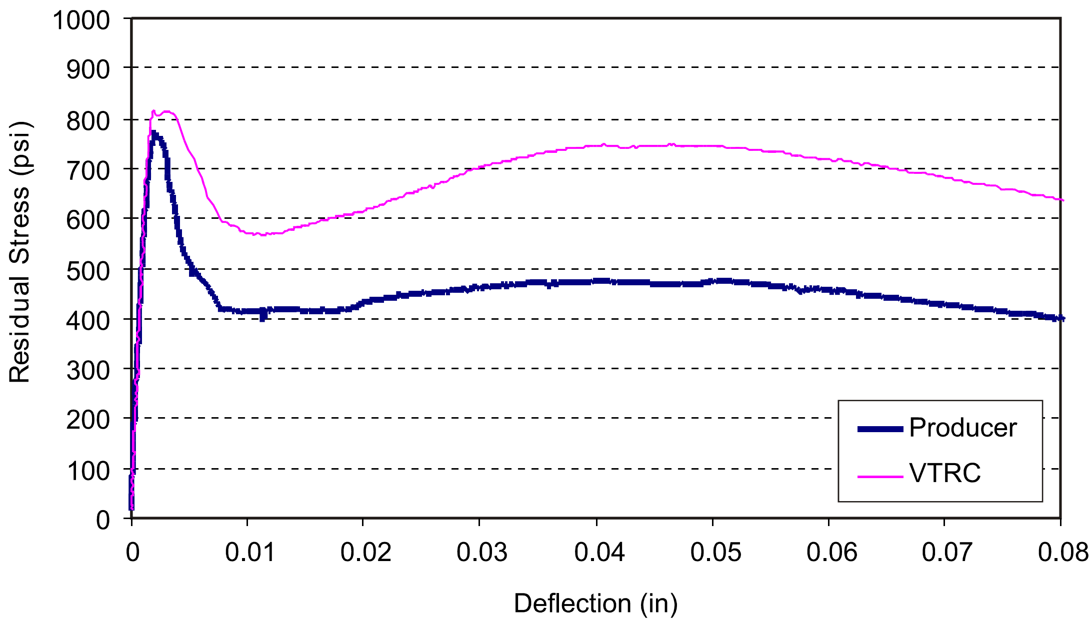

Figure 3. Relationship of Data and Testing Method

Table 14. Fiber Deck Residual Strength Data

Batch	Age	Lab	Sample	Modulus of Rupture (psi)	Residual Stress (psi)				
					0.02 in	0.03 in	0.04 in	0.05 in	Average
B1	7 d	VTRC	1	814	615	696	750	750	703
B2	7 d	VTRC	1	733	464	565	611	641	570
			2	797	422	476	472	447	454
B1	28 d	Producer	1	776	413	455	464	472	451
			2	641	363	388	388	384	380
		VTRC	1	750	519	620	674	662	619
B2	28 d	Producer	1	733	350	354	350	346	350
			2	662	316	295	287	253	288
		VTRC	1	814	531	611	666	679	622
B1	1 yr	Producer	1	930	394	413	412	405	406
B2	1 yr	Producer	1	918	403	403	396	381	396
			2	898	291	291	268	216	266

Control

Fresh Concrete Properties

The fresh concrete properties for the control batches were tested in a manner similar to that of the FRC batches except that samples from Loads 9 (B5) and 10 (B6) were taken at the deck. The results are listed in Table 15. Similar to the FRC batches, the control concrete pumped into the wheelbarrow below the deck had a significant decrease in air content (76 percent and 47 percent reductions for B3 and B4, respectively). However, the concrete pumped only up to the deck (B5 and B6) did not undergo air loss.

Table 15. Control Deck Fresh Properties

Before Pumping				
Load	**Air Content (%)**	**Slump (in)**	**Concrete Temp. (°F)**	**Unit Weight (lb/ft^3)**
1	5.6	1.8	60	-----
2	7.4	3.3	58	-----
3 (B3)	6.2	3.8	59	153
4	6.8	3.5	---	-----
5 (B4)	5.5	3.0	60	149
6	6.0	4.3	58	-----
7	6.6	4.0	60	-----
8	7.0	3.8	59	-----
9	6.6	4.0	60	-----
10	7.0	3.8	55	-----
Note: The air temperature was 51°F.				
After Pumping				
Load	**Air Content (%)**	**Slump (in)**	**Concrete Temp. (°F)**	**Unit Weight (lb/ft^3)**
3 (B3)	1.5	3.5	59	-----
5 (B4)	2.9	3.0	60	-----
9 (B5)	6.0	-----	-----	-----
10 (B6)	7.6	-----	-----	-----

Hardened Concrete Properties

Table 16 shows the hardened deck concrete properties of the control batches, which exceeded the minimum compressive strength of 4,000 psi and the minimum flexural strength of 600 psi. Further, the control batches had low permeability and less shrinkage than did the FRC.

The results of the freezing and thawing tests for the control concrete are shown in Table 17. Batch B3 showed poor results, with the weight loss being 6.5 times the acceptable maximum and the surface rating being 4.2. Conversely, Batch B4 exhibited better results, with a good durability factor and marginal weight loss and surface ratings.

Table 16. Control Deck Hardened Concrete Properties

Test	**Age**	**Load 3 (B3)**	**Load 5 (B4)**
Compressive Strength (psi)	1 d	980	840
	3 d	2540	2410
	7 d	3190	2990
	28 d	5040	4460
	1 yr	6990	6390
Flexural Strength (psi)	28 d	860	830
Permeability (coulombs)	28 d	1937	1800
Shrinkage (microstrain)	28 d	400	380
	4 mo	570	515

Table 17. Control Deck Freeze-Thaw Data

Batch	Weight Loss (%)	Durability Factor	Surface Rating
B3	45.4	25	4.2
B4	11.0	98	3.9

Table 18. Linear Traverse Analysis of Control Batch

Batch No.	Air Content (%)			Specific Surface (mm^{-1})	Spacing Factor (mm)
	<1 mm	>1 mm	Total		
B4a	5.2	0.7	5.9	29.7	0.16
B4b	4.4	0.9	5.3	24.4	0.20
B9 at deck	9.7	0.7	10.4	35.2	0.08

Two samples from Batch B4 were subjected to linear traverse analysis (ASTM C 457); the results are presented in Table 18. Even though the pressure method for testing air content yielded low values, the results from the analysis show that the total air content was within acceptable limits and the percentage of entrapped air (bubbles with a diameter greater than 1 mm) was below 2 percent, indicating proper consolidation.[14] In addition, the spacing factor in this batch was low and the specific surface exceeded the 24 mm^{-1} minimum, thus confirming the results from the freeze-thaw test. Similar results were obtained for sample B9, which was taken at the deck.

Condition Survey

The first field visit was made 2 months after the bridge was opened to traffic. During that visit, there were four tight cracks observed in the control section, none of which extended across the entire width of the deck. No cracks were noticeable in the fiber section.

During the subsequent visit 1 year later in 2002, the difference between the control and FRC sections became even more apparent. The FRC portion had 40 percent fewer cracks and had no transverse cracks across the full width of the section. On the other hand, the control portion had two full-width cracks, and the average crack was about 30 percent longer than the average crack in the FRC section. The crack widths were similar in both sections. Although both sections exhibited map cracking, the patterns in the FRC section were less frequent and had tighter cracks. Three additional site visits in each of the following 3 years reflected a continuation of this trend: the FRC section exhibited fewer, shorter, and narrower cracks, even though the FRC had higher shrinkage than the control. These results are presented in Table 19. There was minimal, very light scaling in both sections.

Table 19. Transverse Crack Length and Width

Year	Air Temp. (°F)	Deck	Length (ft)	Width (mm)
2002	68	Control	102	0.24
		Fiber	48	0.22
2003	69	Control	150	0.53
		Fiber	37	0.28
2004	55	Control	141	0.55
		Fiber	35	0.29
2005	85	Control	151	0.53
		Fiber	59	0.29

CONCLUSIONS

- *Adding fibers provides residual strength and controls cracking.* There were fewer and narrower cracks in the FRC even though the FRC had more shrinkage than the control. The residual strength is directly proportional to the fiber content.

- *Controlling deflection through the actuator or the beam affects residual strength.* The residual strengths were higher when the rate of deflection was controlled through the actuator.

- *Adding fibers decreases workability.*

- *Pumping in a vertically downward direction reduces the air content and slump of freshly mixed concrete.* However, concretes with reduced air content can provide satisfactory resistance to freezing and thawing if a satisfactory air void system is maintained.

- *Differences in slump and air content were observed before and after pumping depending on the location of the sample.*

- *The permeability of FRC is comparable to that of conventional concrete.*

RECOMMENDATIONS

1. VDOT's Structure & Bridge Division should continue evaluating FRC with different residual strengths over the piers in continuous decks, especially on steel girders.

2. VDOT inspectors should pay attention to mixture proportioning, slump, and air content.

3. VDOT inspectors should ensure that HRWRA is used instead of water to regain the workability lost by adding fibers.

4. VDOT inspectors should either test concrete at the point of placement or establish a relationship between the point of discharge from the mixer and the point of placement.

BENEFITS AND COSTS ASSESSMENT

The addition of synthetic fibers together with a WRA can increase the cost of concrete from 25 percent to 40 percent per cubic yard. However, this increase is expected to be less than 10 percent, considering the per cubic yard cost for in-place concrete. In the total cost of the bridge, the increase is much smaller. These costs are expected to be offset by the benefits realized over the service life of the structure.

Specifically, in this project, fibers were found to be effective in minimizing the severity and frequency of cracks over the piers. Fewer, narrower, and shorter cracks will minimize corrosion of the reinforcement within the concrete, thus extending the service life of the structure and reducing maintenance costs. This study has shown that the potential is there. However, the study also showed that particular attention must be devoted to mixture proportioning, slump, and air content or durability may decrease. If as little as a 10 percent increase in the service life were achieved, the savings would be greater than $20 million per year. Further work with fibers will allow for a refinement of the cost savings.

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