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Evaluation of Ultra-High-Performance Fiber-Reinforced Concrete

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16. Abstract:

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The Virginia Department of Transportation (VDOT) is experimenting with UHPC to determine the possibility of using it in transportation structures. The first bridge in Virginia to use UHPC beams was the bridge on Route 624 over Cat Point Creek in Richmond County. The specified minimum 28-day compressive strength was 23 ksi and the specified maximum water–cementitious material ratio was 0.2. UHPC with high strength and very low permeability was used in five beams in one of the 10 spans of the bridge.

The purpose of this study was to evaluate the use of UHPC in the Route 624 Bridge. This was achieved by (1) observing the casting of UHPC beams; (2) evaluating the material properties of the UHPC; (3) testing a test beam to failure; (4) measuring strains in beams; and (5) noting any deck cracking.

The results of the study indicated that the use of the UHPC led to very high strength and high durability attributable to a very low water-cementitious material ratio, low permeability, high resistance to cycles of freezing and thawing, and very tight cracks under load, all of which should provide for a much longer service life compared to the use of conventional concrete. However, because of the high cost of UHPC, more efficient shapes, design requirements, and material and construction specifications need to be developed to make UHPC practical for beams and other uses. The study recommends that UHPC be considered for use in closure pours and beams with optimized cross sections.

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FINAL REPORT

EVALUATION OF ULTRA-HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE

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In Cooperation with the U.S. Department of Transportation
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(A partnership of the Virginia Department of Transportation
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ABSTRACT

Recently, a new ultra-high-performance fiber-reinforced concrete (UHPC) was introduced into construction. The fibers in UHPC provide tensile capacity across cracks, resulting in high shear capacity in bending members. Typically, additional reinforcement for shear is not required.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) routinely uses high-performance concrete (HPC) in its structures. *HPC* may be defined as any concrete that provides enhanced performance characteristics for a given application (Zia et al., 1993). Improvement in concrete properties such as workability, durability, strength, and dimensional stability should result in long-lasting, safe, and economical structures. Durability ensures that structures continue to serve for long periods of time without any major maintenance, which promotes cost-effectiveness.

One method of improving durability is to lower the permeability of the concrete (Ozyildirim, 1993). VDOT has requirements for permeability (VDOT, 2010). Low-permeability concretes have high durability and are obtained with pozzolans or slag and a water–cementitious material ratio (w/cm) less than 0.45 (Ozyildirim, 1999). At a w/cm less than 0.40, high strength (above 6,000 psi) is expected. High strength could result in more economical structures through increasing span lengths, reducing the number of beam lines, and decreasing transportation and erection costs (Lane and Podolny, 1993).

Recently, a new ultra-high-performance fiber-reinforced concrete (UHPC) was introduced. UHPC can achieve compressive strengths exceeding 30,000 psi and sustain large deformations before failure (Association Française de Génie Civil, 2002). It is virtually impermeable to water and solutions (Graybeal, 2006a). The high strength and low permeability of UHPC are attributed to a very dense packing of fine material and a low w/cm (Graybeal, 2006a). There is no coarse aggregate. Fine sand, typically between 150 and 600 µm, is the largest particle size, followed by cement, crushed quartz, and silica fume (Graybeal, 2006a). The optimum gradation allows for tight packing of these particles. Steam curing at a high temperature (195 °F for 2 days) yields a strong material with minimal shrinkage. Without steam curing, the mortar mixture has a higher shrinkage of approximately of 800 microstrains (Graybeal, 2006a). The fibers in UHPC provide tensile capacity across cracks, resulting in high shear capacity in bending members. Typically, additional reinforcement for shear is not required (Graybeal, 2006b). The improved tensile strength is also due to the use of fibers. Small brass-coated steel fibers, with a diameter of 0.007 in (0.185 mm) and a length of 0.55 in (14 mm), are commonly used as fiber reinforcement in UHPC. Synthetic fiber, poly-vinyl alcohol (PVA), has also been used (Parsekian et al., 2008).

VDOT has built bridges having standard AASHTO I-beams (Precast/Prestressed Concrete Institute, 1997) or bulb-T beams with 28-day design compressive strengths as high as

10,000 psi. However, these designs are not efficient when the concrete strength is greater than 10,000 psi (Bruce et al., 1994). To realize the benefits of the very high strength of UHPC, special shapes are being researched; in Iowa, a bridge was built using a π-shaped cross section expected to be more cost-effective (Wipf et al., 2011). The first bridge with UHPC beams was constructed in Wapello County, Iowa (Moore and Bierwagen, 2006). The three 110-ft beams were modified 45-in Iowa bulb-T beams. To save material in the beam section, the web width was reduced by 2 in, the top flange by 1 in, and the bottom flange by 2 in. The bridge opened to traffic in February 2006.

Research regarding additional UHPC bridge structures is currently underway. Garcia (2007) detailed UHPC flexural behavior and offered a design methodology for two-way ribbed, precast bridge decks with this material. Under the Federal Highway Administration's (FHWA) Highways for LIFE Program, a two-lane bridge on a secondary road in Wapello County, Iowa, will be constructed of prestressed concrete girders and 14 UHPC deck panels (Heimann and Schuler, 2010). UHPC has also been used as a cast-in-place cementitious material in joints (Perry and Royce, 2010).

VDOT is experimenting with UHPC to determine the possibility of using this high-quality concrete with excellent durability in transportation structures. The first bridge in Virginia to use UHPC beams was the bridge on Route 624 over Cat Point Creek in Richmond County.

PURPOSE AND SCOPE

VDOT used five 45-in-tall bulb-T beams with UHPC in the bridge on Route 624 over Cat Point Creek. The bridge has ten 81.5-ft spans. One of the spans (Span I, the ninth span from the east end) contained UHPC beams. The steel fibers provided adequate shear resistance, so the UHPC beams did not contain the conventional stirrups normally used as shear reinforcement; however, there is confinement steel at the beam ends. The specified minimum 28-day compressive strength was 23 ksi, the specified maximum w/cm was 0.2, and the minimum release strength was 12 ksi. The UHPC beams had the same cross section as the other beams in the structure with a strength requirement of 8,000 psi. Thus, the very high strength of UHPC was not used in the design. There are no design specifications to handle such high strengths.

The objectives of the study were:

1. *Observe the casting of the UHPC beams.*

2. *Evaluate the UHPC material properties.* Concrete samples were obtained for tests at the fresh and hardened states.

3. *Test a beam to failure.* In addition to the actual bridge beams, a test beam with the same cross-sectional area as the bridge beams was cast and subjected to a concentrated load at the FHWA's Structures Laboratory at the Turner-Fairbank Highway Research Center in McLean, Virginia.

4. *Measure the strains in beams.* Strain gages were placed in two beams to determine strains with time. During service, the gages provided continuous measurements.

5. *Observe the deck cracking.* There were three conditions that could affect the cracking in the deck.

    - *There were different reinforcing steel arrangements throughout the deck.* The deck contains No. 5 transverse bars from Abutment A to Bent 5 and No. 4 transverse bars from Bent 5 to Abutment B. The transverse bars are located closest to the top surface of the deck. The deck has No. 4 longitudinal bars throughout. Additional 40-ft lengths of No. 6 bars were placed over Bents 1, 2, 5, 7, and 9. Forty-foot lengths of No. 5 bars replaced the typical No. 4 longitudinal bars over Bents 3 and 6. Forty-foot lengths of No. 6 bars replaced the typical No. 4 longitudinal bars over Bents 4 and 8.

    - *There were two different beam sets: conventional HPC and UHPC.* The conventional HPC beams had a minimum 28-day design strength of 8,000 psi. UHPC is stiffer and is not expected to undergo measurable volumetric change. UHPC beams were in Span I.

    - *There were temperature differences during placement.* Deck concrete was placed between December 21, 2007, and July 18, 2008, during which time there was a wide temperature range. Placement started at the east end (Span A).

METHODS

Before the construction of the bridge beams, a UHPC test beam was planned. Since there were several fabrication problems with the first test beam because of non-uniform mixing and an insufficient amount of available material to complete the top flange, the first test beam was discarded. Because of time constraints, the new test beam was cast together with three of the five bridge beams on December 7, 2007. The remaining two bridge beams were cast on December 13, 2007. The bridge opened to traffic on October 31, 2008. The deck cracking was monitored for 2 subsequent years.

The following sections summarize the casting of the beams including instrumentation and curing; materials testing; structural testing of the test beam; bridge deck concrete; and condition surveys of the deck.

Casting of Beams

The contractor was required to choose a plant that was prequalified for UHPC. During production of the beams, a representative from the manufacturer of the UHPC material was required to be present. UHPC beams were manufactured from prepackaged material at a precast, prestressing plant. The premix contained cementitious and fine material. At the conveyor belt, the sack bottom was cut and the material was transferred into the stationary mixer. The steel fibers and the high-range water-reducing admixture (50 lb/yd^3) in liquid form were added manually. Wind was blowing the fibers, and wind containment was needed. The mixture proportions of UHPC beams are shown in Table 1. Table 1 also includes the HPC beams used in the remaining 9 spans. HPC beams contained air-entraining admixture, retarding admixture, and a high-range water-reducing admixture.

Mixing was done in 4-yd^3 loads in a stationary 6-yd^3 twin shaft mixer at the batch plant. The mixer discharged the concrete to ready-mix concrete trucks. The prestressing bed was next to the central plant. Mixing time was longer than for conventional mixtures. The loading time, extended mixing for thorough blending, and discharge into the truck took about 20 to 25 min for each batch. Although the twin-shaft mixer is very efficient in providing thorough mixing, cement balls as large as 9 in (shown in Figure 1) were seen during the discharge from the truck. The cement balls were attributed to the exposure of the bags to moisture during storage, causing prehydration. The large cement balls were hand picked and discarded, and the small ones had a tendency to rise to the surface of the beam as shown in Figure 2.

Before the batching area was left, samples were obtained from the truck for flow measurements and specimens were cast for tests at the hardened state. The flow measurements were done on the flow table in accordance with ASTM C 1437 (ASTM, 2007). Static flow is the average diameter, measured at two perpendicular dimensions, of the concrete spread formed when the flow cone is raised. For the dynamic flow, the flow table was dropped 20 times and the diameter was measured again. A minimum dynamic flow of 230 mm (9 in) was sought for satisfactory workability of the mixture.

The mixture was discharged into one end of the beam molds from the trucks. It was very cohesive but was able to flow without the need for consolidation; i.e., it was self-consolidating. However, to eliminate surface blemishes, expedite the flow, and minimize delays, limited external vibration was applied, each time with a 1- or 2-sec duration. Vibration was limited because of concerns with fiber orientation and dispersion. During removal of the steel forms it was noted that extra UHPC flowing to the top of the form had bonded strongly to the form after hardening, making the removal of the form very difficult, as shown in Figure 3. Fibers protruding at the finished surface required careful handling.

Table 1. Mixture Proportions of UHPC and HPC Beams (lb/yd^3)

Material	UHPC	HPC
Premix	3700	
Steel fiber	263	
Portland cement		510
Slag		340
Coarse aggregate		1508
Fine aggregate		1324
Water	219	255

UHPC = ultra-high-performance concrete; HPC = high-performance concrete.

Figure 1. Large Cement Balls Were Seen During Discharge From Truck

Figure 2. Small Cement Balls Rose to Surface

Figure 3. Extra Ultra-High-Performance Concrete Stuck to Form After Hardening

Another concern was the interruption in the continuous placement of the UHPC, which can cause cold joints, thus adversely affecting the integrity of the beam. Vibration that can eliminate the cold joint is not permitted because of concerns with altering the random distribution of the fibers.

Instrumentation

Prior to placement of the concrete, vibrating wire strain gages (VWGs) were installed longitudinally at the midspan of the top and bottom flanges to monitor longitudinal strains and temperature under service. There were two VWGs at the level of the top strands located 2 in from the top of the beam and two at the level of the bottom strands located 2¼ in from the bottom of the beam. At each level, two VWGs were used to provide redundancy. The strains in the beam were measured for 2 years.

Curing

Beams were cured in forms at 105°F ± 10°F for the first 40 hours. The release strengths were attained, and the strands were detensioned. Afterward, beams were steam cured 48 more hours at 195°F ± 10°F. Temperature fluctuations were gradual to avoid any thermal shock to the beams.

Materials Testing

Specimens prepared for hardened properties were subjected to the same two curing cycles as the beams. Cylinders, 3 by 6 in, were tested for compressive strength. Cylinders, 4 by 8 in, were used to determine splitting tensile strength, modulus of elasticity, and Poisson's ratio.

Tests to determine resistance to cycles of freezing and thawing were conducted on beams 3 by 4 by 16 in. Specimens were not consolidated.

The compressive strength was determined in accordance with ASTM C39 (ASTM, 2009) with the load rate increased to 150 psi/sec, a modification commonly used in the compression testing of UHPC. The cylinder ends were ground and verified to be within 0.5 degree of parallel prior to testing.

The splitting tensile strength was determined in accordance with ASTM C496 (ASTM, 2004) with an increased load rate of 500 psi/min. The cracking strength and peak strength were determined. The cracking strength is the stress at first crack, and the peak strength is the ultimate strength of the specimen. The compressive and splitting tensile strength tests were conducted at about 8 months after casting.

The resistance to cycles of freezing and thawing was determined from two batches of concrete in accordance with ASTM C 666, Procedure A (ASTM, 2003a), except that the test solution contained 2% NaCl. 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 (ASTM C 672) (ASTM, 2003b) of 3 or less.

Small beams measuring 4 by 4 by 14 in were cast to determine load versus deflection. The test involved a four-point (third-point) flexural loading of the beam specimens. The specimens had a span length of 12 in. The apparatus increased the load on the specimen, and the corresponding deflection was measured using linear variable differential transformers attached to a yoke. Small beams measuring 1 by 3 by 12 in were cast to show the tight cracking pattern under flexural load.

Virginia Test Method (VTM) 112 (VDOT, 2007) is used to test permeability or penetrability. It is based on ASTM C 1202 (ASTM, 2007) where the charge passed through the specimen is determined. VTM 112 has minor variations and includes the accelerated wet curing of 1 week at room temperature and 3 weeks at 100 °F.

Structural Testing of Test Beam

The 20-ft test beam with the cross section of the actual beams was prestressed with strands but did not contain mild steel reinforcement. The beam was tested in four-point bending on a 19-ft span. The load points were located symmetrically 18 in from the midspan, thus providing a 3-ft constant moment region and two 8-ft shear spans. Testing was done at the FHWA's Structures Laboratory.

Bridge Deck Concrete

The bridge had 10 spans. The deck concrete was a typical VDOT A4 concrete with a minimum 28-day compressive strength of 4,000 psi and a maximum permeability of 2500 coulombs. The mixture proportions of the deck concrete are given in Table 2. Commercially available air-entraining, retarding, and water-reducing admixtures were used. Each span was cast in a separate day with the adjacent closure slab.

Table 2. Mixture Proportions of Deck Concrete

Material	lb/yd^3
Portland cement	536
Class F fly ash	134
Sand	1085
CA crushed stone	900
CA gravel	900
Water	258

CA = coarse aggregate.

Condition Surveys of Deck

Surveys were conducted to evaluate the condition of the deck. Visual surveys were conducted for cracking and scaling, and chain drag was used to detect delaminations.

RESULTS

Curing of UHPC Beams

The temperature data from the prestressing bed displayed in Figures 4 and 5 show that the specified curing was attained for the test beams.

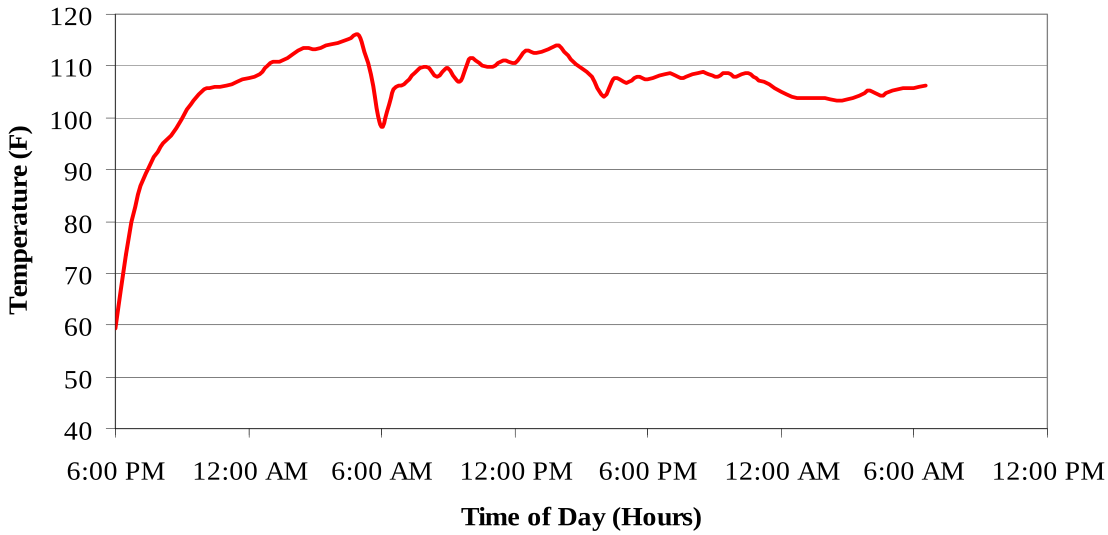

Figure 4. Temperature of Enclosure After Casting During Initial Steam Curing Before Detensioning

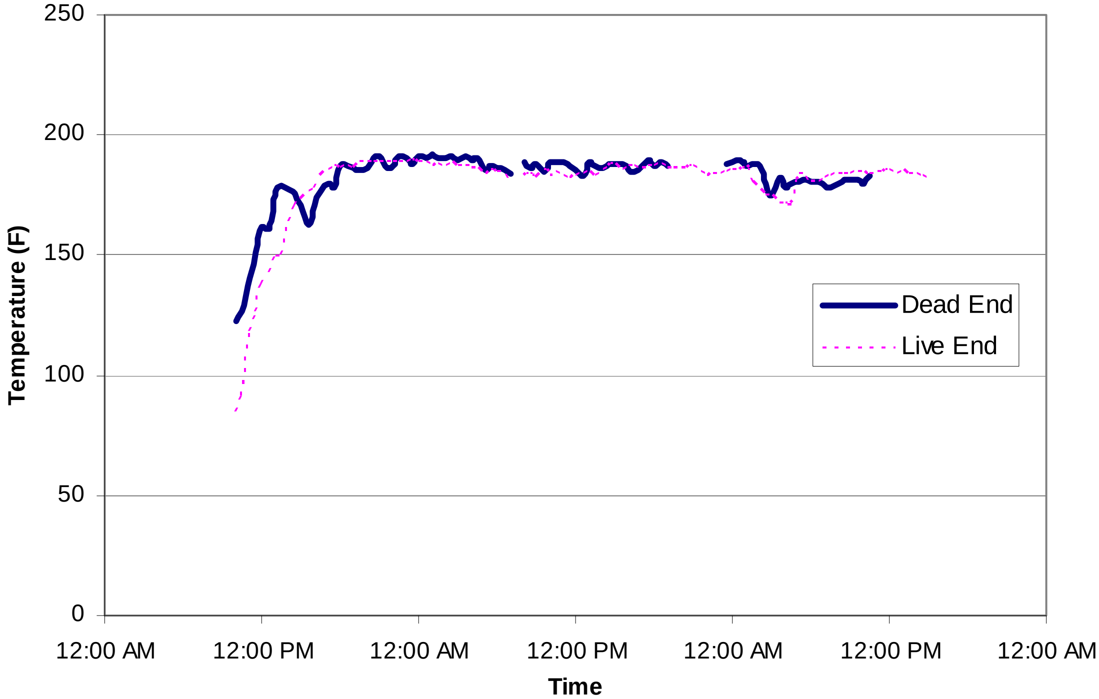

Figure 5. Temperature of Enclosure After Detensioning

Materials Testing of UHPC

The static and dynamic flow values of fresh concrete are given in Table 3 for both casting dates. The results indicated that most of the dynamic flow values were 9 in (230 mm) or more, as desired.

Fourteen UHPC cylinders representing the five beams from Span I of the bridge were tested in compression at about 8 months; the results are given in Table 4. The average compressive strength was 31.4 ksi with a standard deviation of 2.4 ksi. The compressive strength of all cylinders exceeded the specified 23 ksi. Forty-seven HPC cylinders, 4 by 8 in, representing beams from the rest of the nine spans were tested in compression at 28 days. The 47 cylinders were divided into 12 groups. Each group except 2 had four cylinders, one-half from the live end and one-half from the dead end of the bed. In one of the exceptions, there were five cylinders, and in the other two cylinders. The average of each group was determined, and the results are given in Table 4. The average of the groups was 9.8 ksi with a standard deviation of 0.5 ksi. The values were in excess of the specified compressive strength of 8 ksi.

The modulus of elasticity (E) and Poisson's ratio of UHPC are summarized in Table 5. The modulus of elasticity was 8,180 ksi or higher, with an average of 8,813 ksi and a standard deviation of 465 ksi. The average Poisson ratio was 0.18.

The splitting tensile strength of UHPC is shown in Table 6. The average splitting tensile strength is measured when the specimen exhibits first crack, which is the discontinuity in the load-displacement curve caused by an instantaneous decrease in load (Graybeal, 2006a). The

Table 3. Static and Dynamic Flow Measurements

Batch	Static Flow (mm)	Dynamic Flow (mm)
Cast 12/7/07		
1	220	255
2	200	220
3	210	237
4	195	225
5	230	250
6	210	235
7	208	229
8	200	230
9	215	235
10	215	240
11	225	250
Average	212	237
Std. Dev.	11	11
Cast 12/13/07		
1	235	255
2	225	240
3	223	241
4	214	243
5	207	240
6	214	240
7	215	240
8	215	245
Average	219	243
Std. Dev.	9	5

Note: The measurements were taken in metric units; 25.4 mm = 1 in.

Table 4. 28-day Compressive Strength

UHPC		HPC	
Specimen	**Strength (psi)**	**Specimen Group**	**Strength (psi)**
1	32532	1	9209
2	32669	2	9675
3	34036	3	10746
4	30909	4	9748
5	33821	5	9181
6	30477	6	10102
7	27173	7	10153
8	26414	8	9575
9	32051	9	10534
10	31265	10	8992
11	34254	11	9827
12	32476	12	9527
13	31204	13	-
14	29760	14	-
Average	31360	Average	9772
Std. Dev.	2353	Std. Dev.	537

UHPC = ultra-high-performance concrete; HPC = high-performance concrete.

Table 5. Modulus of Elasticity and Poisson Ratio of UHPC

Sample	E (ksi)	Poisson's Ratio
1	8470	---
2	8700	0.18
3	9170	0.18
4	9610	0.18
5	8780	0.19
6	8780	0.20
7	8180	0.17
Average	8813	0.18
Std. Dev.	465	0.01

UHPC = ultra-high-performance concrete.

Table 6. Splitting and Peak Strength of UHPC

Specimen	Tensile Cracking Strength (ksi)	Peak Strength (ksi)
1	1.37	3.24
2	1.83	3.13
3	1.93	3.48
4	1.14	2.94
5	1.51	3.56
6	1.01	2.92
Average	1.47	3.21
Std. Dev.	0.37	0.27

UHPC = ultra-high-performance concrete.

average value of splitting tensile strength was 1.47 ksi with a standard deviation of 0.37 ksi. The average apparent peak strength, maximum or ultimate strength, was 3.21 ksi with a standard deviation of 0.27 ksi.

The permeability values were 19 and 35 coulombs, which indicate negligible permeability. The presence of steel fibers in UHPC did not interfere with the electrical conductivity and the test results because steel fibers were discontinuous and the cementitious matrix surrounding the fibers was very dense.

The freeze-thaw data are summarized in Table 7. The samples had a very high resistance to cycles of freezing and thawing. The UHPC was not air-entrained during mixing. The high resistance without the addition of an air-entraining admixture during mixing was attributed to the very low permeability, which prevented critical saturation.

The typical flexural strength data from 4-in-thick beams are displayed in Figures 6 and 7. Each figure shows two lines that each represents a beam. Figure 6 shows specimens tested at 2 months, and Figure 7 at 2.5 years. The specimens tested at 2.5 years had higher flexural strengths, because of the age.

Table 7. Freeze-Thaw Data at 300 Cycles

Batch	Weight Loss (%)	Durability Factor	Surface Rating
1	0.1	97	0.1
2	0.1	97	0.1

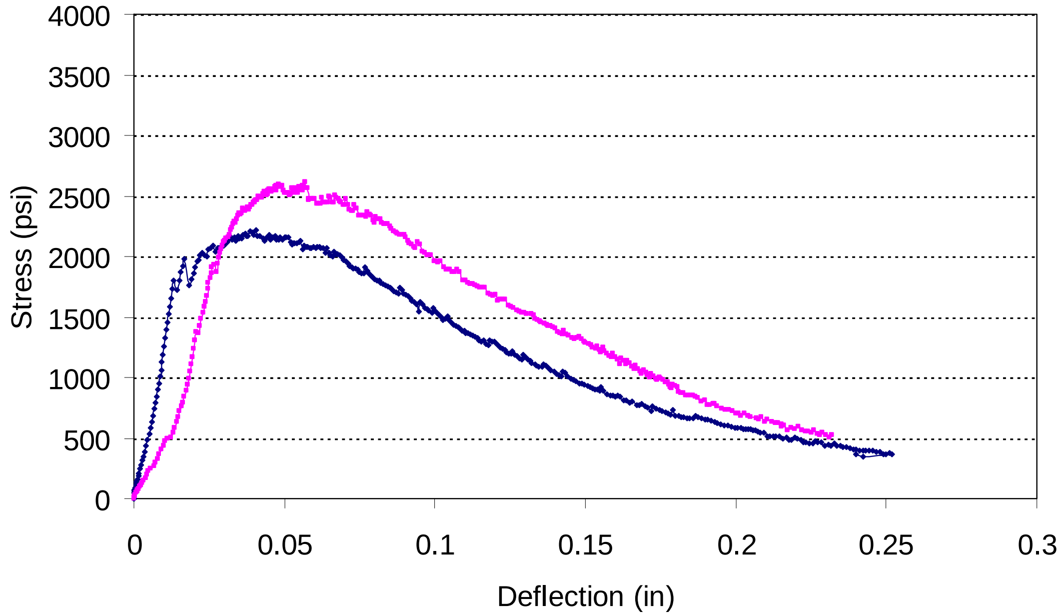

Figure 6. Flexural Strength of Two 4-in-Thick Beams Tested at 2 Months

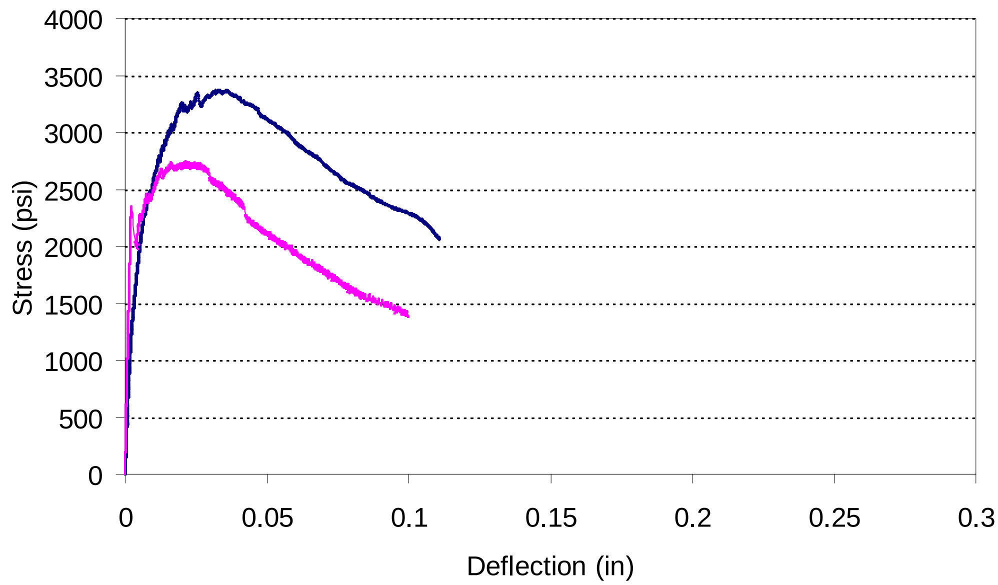

Figure 7. Flexural Strength of Two 4-in-Thick Beams Tested at 2.5 Years

The testing of the small beams measuring 1 by 3 by 14 in indicated that UHPC with fibers had very tight cracks, as shown in Figure 8. The beam was loaded to failure and a large crack developed; however, many tight cracks formed until failure, as shown in Figure 8. The tight cracks were less than 0.1 mm in width; such tight cracks would hinder the penetration of chlorides. UHPC undergoes deflection hardening, as shown in Figures 6 and 7, and in such behavior, tight cracks occur. In deflection hardening, an increase in stress occurs as deflections increase after the first crack.

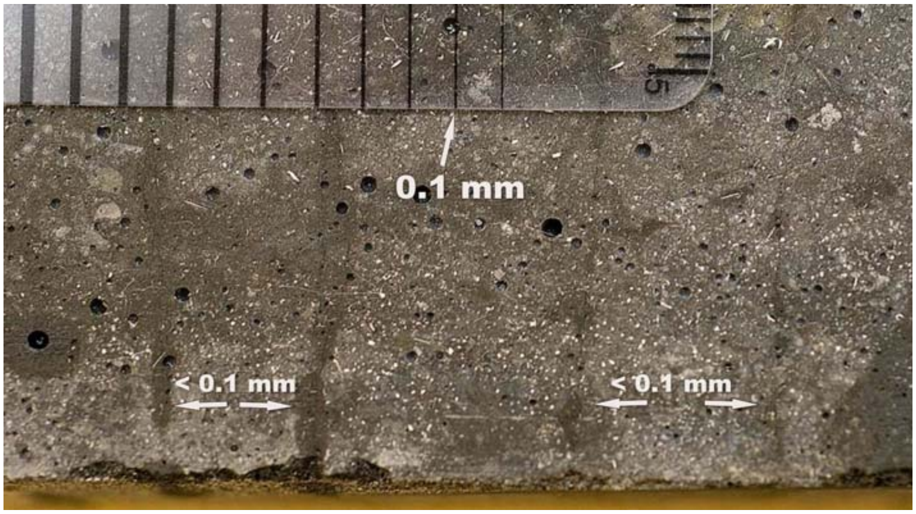

Figure 8. Tight Cracks From 1-in-Thick Beam. 1 in = 25.4 mm.

Structural Testing

Initial cracking of the test beam was observed at an applied load of approximately 330 kips, which corresponds to an applied moment of 1,430 kip-ft. The continuing flexural cracking of the beam resulted in a gradual decrease in the flexural stiffness at an applied load of approximately 500 kips, corresponding to an applied moment of 2,100 kip-ft. The applied flexural capacity of this beam was 2,760 kip-ft at an applied load of 672 kips and a midspan deflection of 0.54 in. Additional flexural cracks continued to appear, and individual cracks became wider until fiber pullout began across a dominant crack at midspan. At an overall midspan deflection of 0.87 in, the fiber reinforcement lost tensile capacity and the bonded prestressing strands ruptured. No shear cracking in the web of the girder was observed under load.

The behavior of this beam was analyzed through a strain compatibility analysis. The observed flexural cracking of the bottom flange of the girder equates to a tensile cracking strength of approximately 1.0 ksi. The flexural capacity of the girder without any UHPC post-cracking tensile capacity would have been approximately equal to the cracking moment. A rough approximation shows that the UHPC provided approximately 0.7 ksi of sustained tensile capacity throughout the tensile region of the cross section after cracking.

Bridge Deck Concrete

The high and low air and concrete temperatures during placement of the deck concrete are summarized in Table 8. The fresh and hardened properties of the concrete for different spans are summarized in Table 9. The slump values ranged from 3.0 in to 4.5 in. The air content varied from 5.0% to 7.3%. Three cylinders were tested to obtain an average compressive strength for each span. They exceeded the 4,000 psi minimum specified strength at 28 days. The average of the 19 sets of strength values was 5,581 psi with a standard deviation of 595 psi. The permeability test was conducted on 2-in slices from the top of 4-in-diameter cylinders. The permeability values were much lower than the maximum 2500 coulombs specified. They averaged 857 coulombs with a standard deviation of 189 coulombs.

Table 8. Concrete and Air Temperatures

Span	Date	High Air Temp. (°F)	Low Air Temp. (°F)	Concrete Temp. (°F)
A	12/21/2007	47	39	60
B	1/31/2008	46	25	52
C	2/20/2008	53	27	50
D	3/21/2008	67	42	60/64
E	4/25/2008	78	61	76/78
F	5/15/2008	75	60	70/71
G	5/30/2008	83	59	76/79
H	6/24/2008	92	63	80
I	7/2/2008	91	69	82/80
J	7/18/2008	91	71	87

Table 9. Fresh and Hardened Properties of Deck Concrete

Span	Date	Slump (in)	Air (%)	Unit Weight (lb/ft^3)	Concrete Temp. (°F)	Strength	Permeability Age (days)	Permeability (coulombs)
A	12/21/07	4.0	5.9	142.4	60	5633	40	760
B	1/31/08	3.0	5.0	145.2	52	5880	40	707
B	1/31/08	3.0	6.0	143.2	52	6627	40	738
C	2/20/08	2.5	6.2	142.4	50	6033	37	644
C	2/20/08	3.0	5.6	144.4	50	6100	37	563
D	3/21/08	3.2	6.0	143.6	60	5830	35	827
D	3/21/08	3.0	5.6	144.8	64	6713	35	624
E	4/25/08	3.2	6.2	142.2	76	5533	40	951
E	4/25/08	4.5	7.3	139.2	78	4553	47	1304
F	5/15/08	3.7	5.6	142.8	70	5677	40	767
F	5/15/08	3.5	5.5	143.6	71	6107	40	838
G	5/30/08	3.0	6.2	140.8	76	5230	41	787
G	5/30/08	3.0	6.6	140.4	79	4890	41	808
H	6/24/08	3.0	6.0	142.4	80	4983	31	1131
H	6/24/08	3.5	5.4	142.8	80	5800	31	1132
I	7/2/08	3.2	7.1	140.0	82	4807	41	843
I	7/2/08	3.7	7.0	139.6	80	5193	41	994
J	7/18/08	2.5	6.4	142.0	87	5163	31	959
J	7/18/08	3.0	7.0	140.8	87	5277	31	911

Condition Surveys of Deck

A visual survey of the bridge deck on October 24, 2008, 1 week prior to opening to traffic, indicated that Spans A, B, C, and D had the fewest cracks; Spans E, F, G, H, and I had the most cracks; and Span J had a number of cracks between the two. On October 6, 2009, five spans were selected to study the cracking on the decks: Spans B, E, F, H, and I. They showed more cracks but trends similar to those of the 2008 survey. In the first survey, few cracks were present and the crack widths were small. In the second survey, more cracks had occurred and the crack widths had increased.

On June 15, 2010, another survey was conducted on all 10 spans; the data collected are shown in Tables 10 and 11. There were more and wider cracks than in the previous surveys. Table 10 shows that the number of cracks in spans increased with placement in warmer weather. Placement started with Span A, the first span on the east end, in cold weather in winter and ended in warm weather in summer. The east end was placed first and had less cracking than the west end placed last. The fresh concrete temperatures are summarized in Table 9. The transverse cracks occasionally had a diagonal tendency, especially on Spans G through J, which were placed on warmer days.

Different reinforcing steel arrangements over the bents did not appear to be important. The cracking pattern on either side of a bent and among different bents indicated a different number of transverse cracks, as indicated in Table 11. Even the same reinforcing pattern did show a difference in the number of cracks. Thus, the reinforcement difference over the bents did not seem to result in a different cracking pattern.

Span I contains beams made of UHPC. The cracks in Span I had a transverse cracking pattern similar to those of the adjacent spans containing regular HPC beams. Span I had 26 transverse cracks versus 22 and 25 in the adjacent spans. However, it appears that the wider cracks were prevalent in Span I. Therefore, an evaluation of the cracking severity was conducted by multiplying the crack width by the crack number and crack length, as shown in Table 10. The

Table 10. Number of Transverse Cracks and Widths in Each Span

Span			**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
Transverse Cracks in Central Portion			0	4	1	5	7	9	11	12	11	15
Total Transverse Cracks			1	8	11	13	14	19	19	22	26	25
Crack Width	**0.1 mm**	**Number**	0	0	0	0	0	0	0	1	0	1
		Total Length (ft)	0	0	0	0	0	0	0	10	0	40
	0.2 mm	**Number**	0	6	9	6	1	14	6	6	2	6
		Total Length (ft)	0	130	155	100	10	290	95	90	80	70
	0.3 mm	**Number**	1	2	1	4	11	5	5	10	10	14
		Total Length (ft)	35	60	20	100	315	175	140	310	275	370
	0.4 mm	**Number**	0	0	1	2	2	0	7	5	10	4
		Total Length (ft)	0	0	25	50	70	0	260	185	315	160
	0.5 mm	**Number**	0	0	0	1	0	0	1	0	4	0
		Total Length (ft)	0	0	0	35	0	0	35	0	160	0
Weighted Cracking Severity			11	192	295	298	1098	1075	1070	1409	2437	1898

Note: Weighted cracking severity is equal to the sum of the products of (crack width * crack number * crack length).

Table 11. Reinforcing Schedule Over Bents and Number of Transverse Cracks on East and West Sides of Bents

Reinforcing Schedule Over Bents[a]	**No. 4 & No. 6**		**No. 4 & No. 6**		**No. 5**		**No. 6**		**No. 4 & No. 6**		**No. 5**		**No. 4 & No. 6**		**No. 6**		**No. 4 & No. 6**	
	Bent 1		**Bent 2**		**Bent 3**		**Bent 4**		**Bent 5**		**Bent 6**		**Bent 7**		**Bent 8**		**Bent 9**	
	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W	E	W
	0	2	2	5	5	6	1	5	2	5	5	6	2	6	3	9	6	10

E = east, W = west.
[a] The reinforcing bars have a length of 40 ft and extend 20 ft in both directions.

variation in the cracking severity among the three spans (H, I, J) having similar temperature exposure) is within about 1 standard deviation (514) of the mean (1,915) and is not considered statistically significant.

The difference in beams did not reveal significant differences in the cracking pattern at the time of the survey. However, UHPC in Span I had a higher coefficient of thermal expansion (CTE) than those of the other concretes. The CTE of UHPC was given as 6.6 x 10^{-6}/°F by the French (Association Française de Génie Civil, 2002) and as 8.3 by 10^{-6}/°F by an FHWA study (Graybeal, 2006a). The CTE of UHPC is considerably higher than the CTE of conventional concrete (about 5.5 x 10^{-6}/°F [Graybeal, 2006a]) and could affect the cracking severity with time. Future performance evaluations would provide more insight into the cracking severity and its effects.

Plastic shrinkage cracks were observed in Spans G, H, I, and J, which were cast in warm weather. There were no delaminations. Scaling was observed in Span H and was attributed to the use of water to finish the surface in this span.

Beam Strains

Two beams were instrumented for strain measurements from the beginning of the casting operation. The data obtained during placement of concrete and the tensioning were lost because of the loss of the computer. Then, during the placement of the deck, the wires for one of the beams placed in the center were damaged. The remaining beam adjacent to the center beam was monitored for strains for 2 years. The data displayed in Figure 9 indicate that during the placement of the deck, a change in strain occurred as expected and then the strain values were cyclical in response to seasonal changes but were level with age, indicating a stable condition.

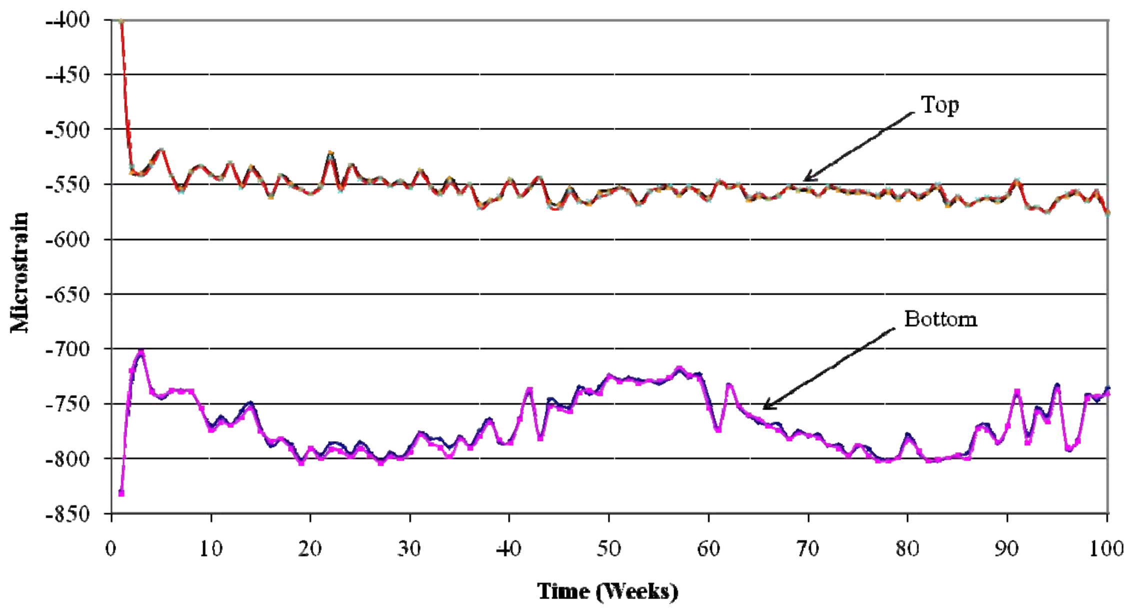

Figure 9. Strain Data for Top and Bottom Vibrating Wire Gages

CONCLUSIONS

- *UHPC can be satisfactorily produced at a precast prestressed concrete plant.* Material is delivered in bags and should be kept dry to avoid prehydration. Mixing of UHPC requires more time than with the conventional mixtures. UHPC is self-consolidating. However, to eliminate surface blemishes, expedite the flow, and minimize delays, a limited amount of external vibration was applied, each time with a 1- or 2-sec duration. Vibration was limited because of concerns with fiber orientation and dispersion.

- *UHPC has high strength and durability because of a low w/cm, low permeability, a high resistance to cycles of freezing and thawing, and very tight cracks under load.*

- *UHPC beams with steel fibers do not need shear reinforcement.*

- *Cracking in decks was influenced by the weather conditions at the time of placement.* Decks placed in warm weather had more cracking.

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should not use UHPC because of its high cost (as discussed in the next section).* More efficient shapes, design requirements, and material and construction specifications need to be developed to make the use of UHPC practical.

2. *VDOT's Structure and Bridge Division and Materials Division should support further research to evaluate the use of UHPC with fibers in closure pours because of the tight cracking pattern that would hinder the penetration of aggressive solutions.*

BENEFITS AND IMPLEMENTATION PROSPECTS

The use of UHPC beams can extend longevity. However, the casting of these beams requires extra attention in preparation and the materials used are proprietary and expensive, leading to a net cost increase in production. In this application, the contract unit price of the UHPC beams was more than 5 times the cost of the HPC beams. However, there were few UHPC beams, and this was the first application of these beams in Virginia. In certain applications, the higher cost may be justified because of the improved properties, extending service life with minimal or no maintenance. The cost savings from improved durability is certain and predictable. Replacing and repairing beams are difficult and costly because of the deck structure above them. Savings in cost are expected if shapes are optimized with minimal material, new design procedures are developed, and UHPC material with steel fiber is optimized for different applications. Work to optimize the shape is in progress at the Massachusetts Institute of Technology (Park et al., 2003). Other national organizations should also be encouraged to develop design procedures for UHPC beams.

Another application of UHPC can be in closure pours because of its tight cracking pattern. Tight cracks with widths less than 0.1 mm hinder the penetration of aggressive solutions and provide longevity.

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