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Lightweight High-Performance Concrete Bulb-T Beams With Self-Consolidating Concrete in a Bridge Structure

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In this study, self-consolidating LWHPC with slag cement was used in the prestressed bulb-T beams for the bridge on Route 17 over Route 15/29 in Fauquier County, Virginia. The deck has LWHPC with slag cement. The bridge has two spans, each 128 ft long. Test beams 65 ft long with the same cross section as the actual beams were cast and tested prior to the fabrication of the bridge beams. The LWHPC provided satisfactory strength and permeability in the test beams and bridge beams that were also SCC. The bridge deck concrete had satisfactory strength and durability with no cracks after two winters.

The study recommends that lightweight SCCs with pozzolans or slag cement be considered in beams when there are long spans, poor soil conditions, and congested reinforcement. It is also recommended that lightweight concretes be considered for reducing deck cracking.

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

The Virginia Department of Transportation (VDOT) widely uses normal-weight high-performance concrete (HPC) with pozzolans (Class F fly ash or silica fume) and slag cement for cost-effective structures. These structures have high strength, high durability, or both. High durability leads to extended service life, and high compressive strength allows for a reduction in the number of beams per span, a reduction in the beam cross section, and/or longer spans, leading to cost savings (Ozyildirim, 1994; Ozyildirim and Gomez, 1996). Beyond the economics, additional benefits may be realized by reducing the dead load weight of the structures. For example, many bridge structures have been posted with reduced load-carrying capacities, making them functionally obsolete (Holm, 1985). However, lightweight concrete (LWC) can be used on superstructures while retaining the existing substructure because of reduced dead load.

LWC prestressed beams have been used on a limited basis. The Florida Department of Transportation reported the use of LWC for prestressed concrete bridge beams for two bridges built in 1964 (Brown and Davis, 1993). One of the advantages of LWC over normal-weight concrete (NWC) is the existence of a more continuous contact zone between the aggregate and the paste, enabling better bonding in LWC. In addition, the presence of water in the pre-wetted LW aggregate voids contributes to internal curing (Bentz and Weiss, 2011; Bremner et al., 1984; Holm et al., 1984). Water supplied by internal curing maximizes hydration and minimizes self-desiccation and its accompanying stresses that may produce early-age cracking (Bentz and Weiss, 2011). Another advantage in minimizing cracking is the low modulus of elasticity; since lower stresses occur for a given deformation when the modulus of elasticity is reduced. Cracking concern is more for decks rather than beams, which are usually in compression because of prestressing. For prestressed girders, the reduced modulus of elasticity must be considered in the design because it results in greater cambers and increased elastic shortening losses.

In 2001, VDOT constructed a LWHPC bridge on Route 106 over the Chickahominy River near Richmond, Virginia. This bridge contains LWHPC AASHTO (American Association of State Highway and Transportation Officials) Type IV beams (Precast/Prestressed Concrete Institute, 1997), 84 ft in length, with a minimum 28-day compressive strength of 8,000 psi and a maximum permeability of 1500 C. The bridge also has a LWC deck (Ozyildirim and Gomez, 2005). Recently, VDOT used bulb-T beams, which are more efficient in spanning long distances compared to the AASHTO beams. After the successful application of LWHPC on

Route 106, LWHPC bulb-T beams were used on two long bridges on Route 33 near West Point (Ozyildirim, 2009). The decks above the LWHPC beams are also LWC. LWHPC was used to provide improved concrete properties and overcome the poor soil conditions.

Self-consolidating concrete (SCC) is a new technology that has very high workability. SCC easily fills the congested spaces between the reinforcement (both mild reinforcement and prestressing steel) and the formwork under the influence of its own mass and without any additional consolidation. Eliminating the large air voids enhances the strength and reduces the permeability of the concrete, which is essential for longevity. In conventional concrete, consolidation would be needed to eliminate these large air voids. Easy flowing SCC permits convenient and fast concrete placement and easy elimination of large air voids. SCC has been used in Japan and Europe advantageously since the early 1990s (Okamura and Ouchi, 1999). Some of the benefits are reduced labor requirements and increased construction speed, improved mechanical properties and durability characteristics, ease of placement in the heavily reinforced and congested areas common in beams with strands and shear reinforcement, consolidation without vibration and without segregation, and reduced noise level at manufacturing plants and construction sites. However, there are some concerns with SCC: degree of uniformity, potential for segregation and increased shrinkage, quality of the air-void system and the protection from cycles of freezing and thawing, and bond quality between strands and concrete. VDOT used normal-weight SCC in the bridge beams on Route 33 over the Pamunkey River (Ozyildirim, 2008).

PROBLEM STATEMENT

Bridge structures are subjected to severe environmental conditions; however, HPC containing pozzolans or slag cement has high durability and provides the necessary characteristics to resist harsh environments. The lightweight characteristic of LWHPC is helpful in reducing the dead load placed on substructures. The high strength capacity of the concrete allows for a reduction in the number of beams or extensions in the span lengths. SCC is used because of its relatively high level of workability. With the use of self-consolidating LWHPC, cost savings are expected because of the reduced weight, ease of construction, reduced number of beams or long spans, and increased durability.

PURPOSE AND SCOPE

The purpose of this study was to evaluate prestressed self-consolidating LWHPC bulb-T beams and the LWHPC deck in the bridge structure on Route 17 over Route 15/29 in Fauquier County, Virginia. The bridge has two spans, each 128 ft long, made continuous for live load with a cast-in-place pier diaphragm. The bridge has a 27-degree skew. There are four 61-in-deep bulb-T beams in each span.

The LWHPC for the beams had a target unit weight of 120 lb/ft^3 with a maximum acceptable value of 123.4 lb/ft^3. It was designed to yield a slump flow of 25 ± 3 in. The required air content was 5.5% ± 1.5%. The 28-day minimum specified design compressive strength for the beams was 8,000 psi, with a release strength of 6,000 psi. The diameter of the strands was 0.6 in. The specified maximum permeability was 1500 C.

The deck consisted of LWHPC with a specified maximum unit weight of 120 lb/ft^3, a specified minimum compressive strength of 4,000 psi, and a specified maximum permeability of 2500 C. The required air content was 6.5% ± 1.5%. This concrete was designed with a conventional slump (i.e., it was not SCC).

The study was conducted in two phases. In the first phase, a test beam was fabricated and tested to failure. In the second phase, the actual bridge was constructed.

METHODS

Overview

The study involved materials and structural testing. Initially, trial batches were made to develop the lightweight SCC for beams at a precast prestressing plant (Plant 1). Then, a test beam similar in cross section to the actual beams in the structure was cast at Plant 1 to determine if lightweight SCC could be successfully placed and if the beam could meet the design criteria. The beam was loaded to failure at Virginia Tech (Dymond et al., 2009). The successful results allowed the casting of the actual bridge beams. The contractor selected a different precast prestressing plant (Plant 2) to fabricate the eight girders for the bridge. The beams were trucked to the site. After the beams were erected and deck forms were installed, the LWC deck was placed.

The mixtures used in the beams and decks were optimized for the local ingredients based on the trial batches. The following sections explain the steps taken in developing the mixtures and the placement procedures for the successful completion of the unique application of high-strength (exceeding 8,000 psi) lightweight SCC. These proportions and procedures may need to be altered for future projects because of changes in the available materials and placement procedures at different plants.

The density of concretes used in beams and decks was approximately 120 lb/ft^3 because of the densities of the ingredients. The density of future beams and decks will depend on the mixture ingredients and proportions. Density must be specified so that concrete mixtures can be developed to comply with specifications.

Materials Testing

The concrete properties were determined in the fresh and hardened states. In the fresh state, the concretes were tested for slump flow (ASTM C1611) (ASTM, 2009); air content (ASTM C173) (ASTM, 2012b); and density (unit weight) (ASTM C138) (ASTM, 2013). The hardened concrete specimens were subjected to the tests listed in Table 1.

Table 1. Hardened Concrete Tests and Specimen Sizes

Test	Specification	Size, in
Compressive strength	ASTM C39 (ASTM, 2012)	4 x 8
Elastic modulus	ASTM C469 (ASTM, 2010)	4 x 8
Splitting tensile strength	ASTM C496 (ASTM, 2011)	4 x 8
Permeability	ASTM 1202 (ASTM, 2012c)	2 x 4
Drying shrinkage	ASTM C157 (ASTM, 2008a)	3x 3 x 11.3
Freeze-thaw durability	ASTM C666 (ASTM, 2008b)	3 x 4 x 16

Trial Batches for Test Beam

Before the test beam was cast, small trial batches of 1.5 ft^3 were made in the laboratory and then a larger batch of 4 yd^3 was made at Plant 1. During fabrication, the mixture used for the test beam exhibited loss in workability (slump loss), and the mixture was no longer SCC. At this plant, a ready-mix truck was used to deliver the load mixed in the stationary mixer to the prestressing bed. The mixture proportions for the trial batch made at Plant 1 are provided in Table 2.

Since the trial batches lost workability and had lower density and lower strengths than anticipated, the proportions for the concrete used in the test beam were changed; the amount of air-entraining admixture was decreased to address density and strength, and the cementitious content and water–cementitious material ratio (w/cm) was increased to address the workability of the mixture, as shown in Table 3. An increase in the w/cm would lower the strength of the concrete; however, strength values within the specified strengths were still expected for these mixtures.

To improve the slump retention and to maintain the SCC properties of the mixture for a longer time, more mixtures were tried in the laboratory after the test beam. However, the contractor chose another precast plant, Plant 2, to cast the bridge beams. Plant 2 also prepared a trial batch before casting the eight bridge beams, but this mixture also lost workability. However, Plant 2 was able to deliver and deposit the concrete within a relatively short period of time and avoided the consequences of the slump loss.

Table 2. Mixture Proportions (lb/yd^3) of Trial Batch for Test Beam Cast at Plant 1

Ingredient	Amount
Portland cement	520
Slag cement	330
Lightweight coarse aggregate (¾ in maximum size)	850
Natural sand	1,251
Water	242
Water–cementitious material ratio	0.28
Air (%)	5.5 ± 1.5
Calcium nitrite (gal/yd^3)	2

The mixture contained an air-entraining, a water-reducing, and a high-range water-reducing admixture.

Test Beam

On October 24, 2006, a test beam was cast at Plant 1 with the proportions given in Table 3. The amount of portland cement, slag cement, water, and calcium nitrite was increased compared to the trial batch (see Table 2 for previous values). The quantity of calcium nitrite was increased to improve the strength development. Because of slump loss, limited internal and external vibration of 1 to 2 sec was used to ensure proper consolidation. The test beam was steam cured. It was transported to Virginia Tech for flexural and shear strength tests (Dymond et al., 2009). The 65-ft test beam contained draped strands with a cast-in-place lightweight deck. Each end was tested to failure in different loading configurations to characterize the shear and moment resisting behavior.

Table 3. Mixture Proportions (lb/yd^3) of Test Beam Cast at Plant 1

Ingredient	Amount
Portland cement	540
Slag cement	360
Lightweight coarse aggregate (¾ in maximum size)	850
Natural sand	1,158
Water	279
Water–cementitious material ratio	0.31
Air (%)	5.5 ± 1.5
Calcium nitrite (gal/yd^3)	3

The mixture contained an air-entraining, a water-reducing, and a high-range water-reducing admixture.

Trial Batches After Test Beam Was Cast

After the test beam was cast, more laboratory batches were made to develop a stable and easily flowing SCC with the needed slump retention during placement. This time, the volume and size of lightweight coarse aggregate was reduced and the volume of fine aggregate was increased to improve stability. To achieve the required density, lightweight fine aggregate was used in addition to the natural sand. More water was also added. The mixture proportions are given in Table 4.

Two laboratory batches were prepared on December 12, 2006. Because of the success of these batches, three more batches were made on September 18, 2007, to ensure that the mixtures

Table 4. Mixture Proportions (lb/yd^3) of Laboratory Trial Batch After Test Beam Was Cast

Material	Amount
Portland cement	540
Slag cement	360
Lightweight coarse aggregate (1/2 in maximum size)	650
Natural sand	1,109
Lightweight fines	250
Water	300
Water–cementitious material ratio	0.33
Air (%)	5.5±1.5
Calcium nitrite (gal/yd^3)	3

The mixture contained an air-entraining, a water-reducing, and a high-range water-reducing admixture.

could be reproduced with satisfactory properties. The specimens were kept in the environmental chamber in the laboratory where the temperature was raised at a rate of 20 °F per hour until it reached 160 °F, where it was held for 8.5 hr to simulate steam curing or accelerated curing at the plant.

Structural Testing of Test Beam

The reinforcement was outfitted with vibrating wire strain gauges and thermocouples to monitor the strain and temperature changes in the beam (Dymond et al., 2009). Concrete was placed on October 24, 2006, and steam cured overnight. Prestress was transferred to the beam by cutting the strands early on October 25, 2006, after approximately 16 hr. The 65-ft-long prestressed bulb-T beam arrived at the Virginia Tech Structures and Materials Laboratory for testing on December 13, 2006. On January 9, 2007, the concrete deck was formed and placed onto the beam, forming a composite concrete system. Additional instrumentation was installed prior to the initial shear testing, which took place on February 20, 2007.

Bridge Beams

The contractor chose Plant 2 for the production of the bridge beams. Eight bridge beams were cast, and concrete properties at the fresh and hardened states were determined. The beams were covered with an insulating blanket and cured overnight using a radiant heat cure until the release strength was achieved. The specimens were placed on top of the beams inside the insulating blankets.

A trial batch was prepared and tested at the plant prior to the casting of the bridge beams; the mixture proportions are given in Table 5.

Table 5. Mixture Proportions (lb/yd^3) of Trial Batch for Bridge Beam Cast at Plant 2

Ingredient	Amount
Portland cement	637
Slag cement	213
No. 8 normal-weight coarse aggregate	334
No. 8 lightweight coarse aggregate	870
Natural sand	919
Water	279
Water–cementitious material ratio	0.33
Air (%)	5.5 ± 1.5
Calcium nitrite (gal/yd^3)	2

The mixture contained an air-entraining, a water-reducing and retarding, and a high-range water-reducing admixture.

Bridge Deck

LWC with a minimum desired 28-day compressive strength of 30 MPa (4,350 psi) was used in the bridge deck. A trial batch was prepared on October 3, 2012. A commercially available air-entraining admixture and water-reducing admixture were used. Upon satisfactory results, the LWC deck was placed in three placements: Span A was placed on October 24, 2012; Span B on October 25, 2012; and the 9-ft-long closure pour on November 2, 2012. On October 24, 2012, the concrete was sampled by the Virginia Center for Transportation Innovation and Research (VCTIR) to determine the fresh and hardened properties. On each placement day, VDOT's inspectors also tested the concrete. The mixture proportions are shown in Table 6.

The concrete was pumped from the road below the bridge. In the deck, the ends and the edges where the screed could not reach were hand finished. Finishing by screed or hand was no different than for any other concrete placement. The pumping operation and the screed on the bridge are shown in Figure 1. The concrete was tested at the truck before pumping.

Table 6. Mixture Proportions (lb/yd^3) of Lightweight Concrete Bridge Deck

Ingredient	Amount
Portland cement	330
Slag cement	330
Natural sand	1285
Lightweight coarse aggregate (¾ in maximum size)	893
Water	292
Water–cementitious material ratio	0.44
Air (%)	6.5 ± 1.5

Figure 1. Concrete Placement and Screeding

Condition Survey

After placement, the bridge deck was visually surveyed periodically for two winters. Inspection after the first winter was on September 27, 2013, and after the second winter on February 24, 2014. Any excessive beam and deck deflection attributable to loads or the deformations attributable to environmental (moisture and temperature) effects could result in stresses that could cause deck cracking and was investigated during the surveys.

RESULTS

Trial Batches for Test Beam

The fresh and hardened concrete properties for the trial batches for the test beam done at Plant 1 are given in Table 7.

The concrete specimens were either steam or moist cured. After steam curing overnight, some were left for air drying and some were placed in the moist environment for the 28-day tests. The trial batch results at the plant indicated low strengths. Different curing conditions resulted in similar strengths at 28 days.

The length change data are summarized in Table 8. The results indicate variations in shrinkage values; however, they are 600 microstrain or less after 1 year. In bridge deck concretes, a maximum value of 700 microstrain at 4 months is considered satisfactory (Babaei and Fouladgar, 1997).

Table 7. Fresh and Hardened Concrete Properties of Trial Batch Cast at Plant 1

Property	Value
Slump flow (in)	26.0
Air (%)	7.5
Density (lb/ft^3)	106.6
Concrete temperature (°F)	76
Compressive Strength (psi)	
1-day steam	3,960
1-day moist	2,510
28-day steam + air	3,970
28-day steam + moist	4,050
28-day moist	4,030
Splitting Tensile Strength (psi)	
28-day steam + air	470
28-day steam + moist	480
28-day moist	465

The mixture contains an air-entraining, a water-reducing, and a high-range water-reducing admixture.

Table 8. Length Change Results

	Trial	Test Beam	Trial After Test Beam	Trial After Test Beam
Cure	**Moist**	**Moist (1446-1448)**	**Steam B8**	**Steam B10**
Cast Date	**9/21/06**	**10/24/06**	**9/18/07**	**9/18/07**
28 days (microstrain)	425	47	135	345
112 days (32 weeks) (microstrain)	565	333	355	575
224 days (64 weeks) (microstrain)	600	403	445	595

Steam-cured specimens were cured overnight and then air cured. Moist-cured specimens were cured for 7 days.

Test Beam

The fresh and hardened concrete properties of the test beam cast at Plant 1 are given in Table 9 and Table 10, respectively.

Slump flow values were on the low side, and compressive strengths exceeded the specified strength of 8,000 psi at 28 days. Permeability values were low even with the inclusion of calcium nitrite. Calcium nitrite interferes with the test because of its conductive nature.

Table 9. Fresh Concrete Properties of Test Beam Cast at Plant 1

Property	B4	B5
Slump flow (in)	23	20
T_{20} (sec)	7	7
Air (%)	4.0	-
Density (lb/ft^3)	120.0	116.8
Concrete temperature (°F)	56	56

T_{20} = the time it takes for the concrete spread to reach 20 in in diameter after lifting the slump cone.

Table 10. Hardened Concrete Properties of Test Beam Cast at Plant 1

Property	Age (days)	B4	B5
Compressive strength (psi)	1	8,917	7,752
	28	9,230	8,690
	365	9,740	9,100
Splitting tensile strength (psi)	1	626	558
	28	665	640
	56	700	640
Elastic modulus (x 10^6 psi)	1	3.64	3.55
	28	3.65	3.12
	56	3.55	3.39
	90	3.21	3.4
Permeability (C)	28	1820	1610

Specimens were cured in the same way as the test beam: steam cured overnight with the beam and then air dried.

Trial Batches After Test Beam Was Cast

The fresh and hardened concrete properties of the trial batches prepared in the laboratory after the test beam was cast are given in Table 11 and Table 12, respectively.

The trial batches after the test beam was cast had satisfactory strengths, with every value exceeding the minimum 28-day strength of 8,000 psi. Permeability values were very low, even with the inclusion of calcium nitrite.

Table 11. Fresh Concrete Properties of Trial Batch After Test Beam Was Cast

Beam No.	**B6**	**B7**	**B8**	**B9**	**B10**
Cast Date	**12/12/06**	**12/12/06**	**9/18/07**	**9/18/07**	**9/18/07**
Slump flow (in)	24.0	30.0	31.5	25.5	20.0
T_{20} (sec)	3.8	2.0	6.0	5.4	4.9
Air (%)	-	-	2.0	4.8	5.0
Density (lb/ft^3)	118.4	120.0	127.6	121.2	120.4
Concrete temperature (°F)	77.0	77.0	77.0	77.0	77.0
Visual stability index	0.5	0.0	-	-	-

T_{20} = the time it takes for the concrete spread to reach 20 in in diameter after lifting the slump cone; - = not tested.

Table 12. Hardened Concrete Properties of Trial Batch After Test Beam Was Cast

Beam No.	**Age (day)**	**B6**	**B7**	**B8**	**B9**	**B10**
Cast Date		**12/12/06**	**12/12/06**	**9/18/07**	**9/18/07**	**9/18/07**
Compressive strength (psi)	1	7,500	7,290	8,440	7,090	6,710
	7	-	-	9,530	9,050	8,730
	28	10,300	9,690	10,600	10,030	9,320
Splitting tensile strength (psi)	28	715	775	855	780	770
Elastic modulus (x 10^6 psi)	1	-	3.16	-	-	-
	28	3.47	3.35	3.91	3.31	3.24
Permeability (C)	28	922	1142	870	990	472

Specimens were cured in the same way as the test beam: steam cured overnight with the beam and then air dried. - = not tested.

Structural Testing of Test Beam

Structural testing of the composite system at Virginia Tech consisted of shear testing on one end of the girder and a flexure-shear test on the other end (Dymond et al., 2009). Testing indicated that LWSCC can be successfully used in prestressed beams. Current AASHTO or ACI (American Concrete Institute) standards are adequate for use in the design of bridge beams (Dymond et al., 2009).

Bridge Beams

The test beam exhibited satisfactory results, which provided confidence in using the LWSCC in actual bridge beams.

Trial Batch for Bridge Beams

The fresh and hardened properties of the trial batch of the bridge beams cast on February 8, 2012, at Plant 2 are summarized in Table 13.

These values, indicating satisfactory results, were obtained when the ambient temperature was low (49 °F). Therefore, the question was raised if similar results could be replicated and the slump flow be retained during placement at higher temperatures during warmer weather. Plant 2 ensured that placement would be done quickly and workability would be maintained during placement.

Table 13. Fresh and Hardened Concrete Properties of Trial Batch Cast at Plant 2

Property	Value
Slump flow (in)	26.0
Slump flow with J-ring (in)	25.0
Density (lb/ft^3)	120.3
Concrete temperature (°F)	65
Compressive Strength (psi)	
1-day moist	5,956
28-day (1 day moist + 27 days air)	9,354

Casting of Beams and Tests

The casting of the beams started on August 7, 2012. The beams were bulb-T beams with a height of 61 in and a length of 127 ft 6 in. Two beams were made on each casting day, and the eight beams were completed in 4 days of casting. Beams were covered with insulating blankets and subjected to radiant heat cure. Specimens were prepared for each end of the casting bed. Specimens were placed over the beams under the blankets. The fresh and hardened concrete properties obtained at the plant are given in Table 14.

On August 9, 2012, additional specimens were prepared by VCTIR for hardened concrete tests shown in Table 15. In addition to the fresh concrete properties shown in Table 15, slump flow values tested by the J-ring were determined by VCTIR, as shown in Figure 2. The slump flow values with and without the J-ring were within 1 in, and there was no segregation. The concrete exhibited a slump flow loss of 2 in (from 29 in to 27 in) within 10 min. The placement

Table 14. Fresh and Hardened Concrete Properties of Bridge Beams

Beam No.	**Beam 1**	**Beam 2**	**Beam 3**	**Beam 4**	**Beam 5**	**Beam 6**	**Beam 7**	**Beam 8**
Casting Date	**8/7/12**	**8/7/12**	**8/9/12**	**8/9/12**	**8/14/12**	**8/14/12**	**8/16/12**	**8/16/12**
End Type	**DE**	**LE**	**DE**	**LE**	**DE**	**LE**	**DE**	**LE**
Slump flow (in)	24.5	28.0	28.0	27.0	25.0	24.5	27.0	26.5
Air content (%)	4.0	6.0	6.3	4.4	6.1	4.9	6.3	4.2
Concrete temperature (°F)	86	83	89	90	88	88	86	86
Density (lb/ft^3)	121.0	119.7	119.8	121.0	119.9	120.2	121.6	123.3
Compressive strength, 1-day (psi)	7,410	6,553	6,840	7,625	7,721	7,188	6,813	6,325
Compressive strength, 28-day (psi)	9,489	11,254	10,306	11,684	11,489	11,318	8,592	11,658

Specimens for compressive strength were air cured after a radiant heat cure. LE = live end; DE = dead end.

of the concrete into beam molds was accomplished within 4 to 5 min. Thus, the slump flow loss was not an issue in the production of the beams. Air content was tested using the volumetric method (ASTM C173) (ASTM, 2012b).

Table 15. Hardened Concrete Properties of Beam 3 and Beam 4 at 28 Days

Property	Beam 3	Beam 4
Compressive strength (psi)	10,580	11,700
Splitting tensile strength (psi)	670	765
Permeability at room temperature (C)	1634	1542
Permeability after 3 weeks at 100 °F (C)	769	761
Length Change (με)		
28 days	477	510
112 days (16 weeks)	543	600
224 days (32 weeks)	573	643

Figure 2. Slump Flow Tests of Self-Consolidating Concrete With and Without J-Ring

The stationary mixer discharged the SCC into the bucket in front of the forklift, as shown in Figure 3, which carried the SCC to the beam mold. There, the SCC was placed in another bucket that was attached to a ceiling crane. An operator directed the movement of the bucket along the length of the beam. Each load was emptied within 4 to 5 min.

Figure 3. Placement of Self-Consolidating Concrete Into Beam Molds

To ensure that the concrete was properly consolidated and that there were no lift lines, limited internal and external vibration was performed, as shown in Figure 4. The internal vibration from the top of the form assisted in consolidation since there was a small head pressure to help concrete flow. Both vibration methods were used for only short durations to avoid segregation.

The specimens were placed on top of the beams and were covered with insulating blankets. Both the beams and the specimens on top of the beam were subjected to radiant heat curing. This allowed the specimens to cure in the same environmental conditions as the beams. The next day, release strengths exceeding the specified value of 6,000 psi were achieved as shown in Table 14, and the beams were moved to storage. The specimens prepared by VCTIR were brought to the laboratory. The hardened concrete properties are summarized in Table 15 for specimens tested at VCTIR. The compressive strength was similar for those tested at the plant, as shown in Table 14: 10,580 psi compared to 10,306 psi for Beam 3 and 11,700 psi compared to 11,684 psi for Beam 4.

The permeability specimens for conventional cast-in-place concretes tested at 28 days require accelerated curing. They are cured the first week at room temperature and the next 3 weeks at 100 °F, and tested at 28 days. However, steam-cured specimens are not subjected to the 3 weeks of 100 °F curing because of the high steam temperatures. The permeability values for the specimens were 1542 C for B4 and 1634 C for B3 at 28 days when kept at room temperature after the initial stay over the beams that were subjected to a radiant heat cure for the first night. Specimens were also tested after curing at 100 °F for 21 days in accordance with the accelerated curing. The permeability values were 761 C for B4 and 769 C for B3. Accelerated curing enables the determination of long-term permeability at an early age of 28 days. Pozzolans or slag cements in concrete show their effectiveness after the hydration reactions, which take time. In specimens subjected to a radiant heat cure overnight, high temperature may not be attained. Small specimens do not generate as high heat as the large beams. Large beams would exhibit higher temperatures than the small cylinders and may exhibit reduced permeability at early ages.

Figure 4. Internal and External Vibration of Self-Consolidating Concrete

Thus, it is important to test for permeability either by accelerated curing at 28 days, testing at a later age with standard curing, or matching the curing temperature of beams experiencing high temperatures. The bridge beams with LWSCC are shown in Figure 5.

Figure 5. Bridge Beams With Lightweight Self-Consolidating Concrete

Bridge Deck

The trial batch for the bridge deck concrete had an air content of 6.8% and a slump of 5.5 in; the concrete temperature was 70 °F.

The hardened concrete properties of the trial batch are shown in Table 16. The strengths given are the average values of three cylinders, and the permeability values given are the average values of two cylinders. Cylinders were moist cured until tested.

Since the trial batch met expectations, the mixture was used for the bridge deck in both spans and the closure pour. For Span A, two batches of concrete were tested by VCTIR on October 24, 2012. The first batch was sampled early in the placement, and the second one later. The fresh concrete properties are given in Table 17.

Table 16. Hardened Properties of Trial Batch

Property	Set 1	Set 2	Average
Compressive Strength (psi)			
7-day	2,980	2,890	2,935
14-day	4,110	4,310	4,210
28-day	5,210	5,270	5,110
Permeability (C)	1,091	947	1,019

Table 17. Fresh Concrete Properties of Actual Bridge Deck Batches

Property	Batch 1	Batch 2
Air content (%)	5.5	7.6
Slump (in)	4.0	5.0
Concrete temperature (°F)	69	68
Air temperature (°F)	61	---

The test results at the hardened state are summarized in Table 18. The values for strength are an average of three cylinders and the values for permeability are the average of two cylinders. Cylinders were moist cured until tested.

The 28-day strength of the cylinders was greater than the specified minimum of 4,350 psi, and the permeability values were very low. The elastic modulus values were low compared to those for NWCs. For NWC, the elastic modulus is expected to be greater than 4,000 ksi at 28 days for a compressive strength of 5,000 psi. A higher compressive strength would yield a higher elastic modulus.

The fresh concrete properties; strength; and permeability of samples from the deck pours on Span A and Span B and the closure pour were tested by VDOT inspectors. The values for the fresh concrete are shown in Table19 and for the hardened concrete in Table 20.

Table 18. Hardened Concrete Properties of Actual Bridge Deck Batches

Property	**Age (days)**	**Batch 1**	**Batch 2**
Compressive strength (psi)	3	2,730	2,630
	7	4,040	3,620
	28	5,940	5,890
Elastic modulus (ksi)	28	3,220	3,160
Splitting tensile strength (psi)	28	435	475
Permeability (C)	28	865	766

Table 19. Fresh Concrete Properties of Actual Bridge Deck Batches

Property	**Span A**		**Span B**		**Closure**
Batch	**1**	**2**	**1**	**2**	**1**
Air content (%)	5.5	7.0	5.2	7.5	8.0
Slump (in)	4.0	4.8	6.2	5.5	6.0
Concrete temperature (°F)	69	71	70	70	58
Air temperature (°F)	69	80	62	68	50

Table 20. Hardened Concrete Properties of Actual Bridge Deck Batches

Span	**Span A**		**Span B**		**Closure**
Batch	**1**	**2**	**1**	**2**	**1**
Date Cast	**10/24/12**	**10/24/12**	**10/25/12**	**10/25/12**	**11/2/12**
Compressive strength at 28 days (psi)	6,610	6,033	5,210	5,750	4,583
Permeability (C)	803	805	1270	1056	1171
Length Change (με)					
28 days	200	240	-	-	-
16 weeks (112 days)	457	517	-	-	-
32 weeks (224 days)	513	580	-	-	-

Length change values were obtained after a 7-day moist cure. Specimens for compressive strength were moist cured until tested. Permeability specimens were subjected to an accelerated moist cure: 1 week at room temperature and 3 weeks at 100 °F. - = not tested.

The strength and permeability values collected by the inspectors were in close agreement with those of the samples taken by VCTIR. The strengths exceeded the specified strength of 4,350 psi. However, with each passing day, there was an appreciable decline in the strength values and a small increase in the permeability of concretes. The reduction was attributed to an increase in water content since for similar air contents strength was reduced. This raised questions on the uniformity of the concrete even though all values indicated satisfactory results. The length change values were less than the desired maximum value of 700 microstrain at 4 months.

Condition Survey

During inspection after the first winter on September 27, 2013, no cracks were visible on the bridge deck. The ambient temperature was 68 °F. The absence of cracks was attributed to the benefits of the lower elastic modulus and internal curing. Another contributing factor could be the reduced coefficient of thermal expansion of LWC, which was not measured. The bridge had not yet been opened to traffic.

Although the bridge deck showed no cracking, the inspection on September 27 indicated that cracking had appeared on both the east and west bridge deck approach slabs, which had the NWC. In the right-hand lane of the west approach slab, cracks appeared approximately 45 degrees from the centerline. One crack originated at the start of the approach slab and ran for 17 ft at a width of 0.30 mm before expanding to a width of 0.35 mm for another 3 ft. Another crack originated 12 ft from the start of the approach slab and ran for 8 ft at a width of 0.30 mm. On the east approach slab, there was one crack in the left-hand lane, originating approximately 13 ft from the start of the slab and running for 7.5 ft at a width of 0.25 mm. This crack ran about 45 degrees to the centerline. The bridge was opened to traffic on November 11, 2013.

On February 24, 2014, another condition survey was conducted (3 months after the bridge was opened to traffic). The air temperature was 46 °F. There were no cracks on the LWC deck; however, the cracks at the NWC approach slab were of similar length but a little wider than before: about 0.4 to 0.5 mm at the east end, and 0.5 to 0.6 mm at the west end. The increase in width from the previous September survey was attributed mainly to the cooler temperature and also to drying shrinkage. One other observation was the apparent scaling at a portion of the closure pour that had LWC, as shown in Figure 6. Since the scaling was restricted to a small area along the edge, it was attributed to poor finishing practices. The rest of the deck including the closure pour was in good condition, as shown in Figure 6.

Figure 6. Scaling at Lower Portion of Photograph

CONCLUSIONS

- *Lightweight SCC with a high compressive strength exceeding an average value of 10,000 psi and a low permeability of less than 1000 C can be produced at a precast plant using quality lightweight coarse aggregates and slag cement.*

- *Even in the presence of calcium nitrite, which interferes with the test because of its conductive nature, the values for the permeability test were very low or low. For permeability testing of LWCs with slag cement, accelerated curing where specimens are kept at 100 °F for 3 weeks is needed, as with NWCs, to observe the low permeability at the early age of 28 days.*

- *LWCs with slag cement for bridge decks can have compressive strengths exceeding 5,000 psi and very low permeability that is less than 1000 C.*

- *A decrease in the compressive strength values in the bridge deck concrete placements on successive days draws attention to the uniformity of the mixture and the need to control water content throughout the project.*

- *Shrinkage values were within the expected range for conventional concretes. In general, conventional concretes exhibit transverse cracks, especially over piers. However, there were no cracks on the deck after two winters, indicating the benefits of the lower elastic modulus and internal curing of LWCs.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division and Materials Division should consider the use of lightweight SCCs with pozzolans or slag cements to mitigate engineering challenges including weight of long beams, deflections in long spans, poor foundation conditions, and congested reinforcement.*

2. *VDOT's Structure and Bridge Division and Materials Division should consider the use of LWCs for reduced deck cracking.*

BENEFITS AND IMPLEMENTATION PROSPECTS

LWCs that have high workability, high strength, and low permeability can be produced using quality lightweight coarse aggregates and slag cement. The casting of beams with congested reinforcement is facilitated by the high workability of self-consolidating LWCs. In bridge structures, longer spans and durable beams are possible with the use of LWCs. For bridge sites with poor soil conditions, LWCs in beams and decks will be desirable for reducing the dead load. The LWCs are expected to eliminate deck cracking or at least reduce the number and width of cracks, which is important for extending the service life of decks.

High-performance LWCs with high workability, strength, and durability were successfully produced in this study and are expected to be used in future VDOT structures for reduced dead loads and improved durability.

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