Reducing Cracks in Concrete Bridge Decks Using Shrinkage Reducing Admixture

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Final Report VTRC 16-R13

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
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www.VTRC.net

Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 16-R13	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Reducing Cracks in Concrete Bridge Decks Using Shrinkage Reducing Admixture		5. Report Date: March 2016 6. Performing Organization Code:
7. Author(s): Harikrishnan Nair, Ph.D., P.E., Celik Ozyildirim, Ph.D., P.E., and Michael M. Sprinkel, P.E.		8. Performing Organization Report No.: VTRC 16-R13
9. Performing Organization and Address: Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903		10. Work Unit No. (TRAIS): 11. Contract or Grant No.: 103636
12. Sponsoring Agencies' Name and Address: Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	Federal Highway Administration 400 North 8th Street, Room 750 Richmond, VA 23219-4825	13. Type of Report and Period Covered: Final 14. Sponsoring Agency Code:
15. Supplementary Notes:		

16. Abstract:

Restrained shrinkage cracking of concrete bridge decks creates a significant durability problem. Major admixture suppliers in the United States have introduced a new category of chemical admixtures called shrinkage reducing admixtures (SRAs). SRAs work by reducing the surface tension of pore water and thereby decreasing the capillary stress and shrinkage induced by drying. Several studies have reported that using SRAs in concrete mixtures is one of the most effective ways of reducing shrinkage cracking.

The purpose of this study was to investigate the effectiveness of SRAs in reducing drying shrinkage in Virginia Department of Transportation (VDOT) concrete mixtures and thus reducing cracks in bridge decks. Nine bridges located in VDOT's Northern Virginia, Staunton, and Fredericksburg districts were selected for study. Three different SRA products were used. With the exception of one mixture, the maximum cementitious content was limited to 600 lb/yd^3. Fresh and hardened concrete properties were determined for each mixture, and field placement details were documented.

The results showed that low cementitious concrete with SRA was effective in minimizing bridge deck cracking. The study showed that bridges with fewer and narrower cracks or no cracks can be constructed and that proper construction practices are needed to reduce bridge deck cracking.

The study recommends the use of SRA with a lower cementitious content in VDOT bridge deck concrete mixtures. A VDOT special provision was developed for the future use of SRA in concrete mixtures.

17 Key Words: Shrinkage reducing admixture, bridge deck cracking, drying shrinkage, bridge decks, SRA		18. Distribution Statement: No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.	
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages: 47	22. Price:

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FINAL REPORT

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

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

Charlottesville, Virginia

March 2016
VTRC 16-R13

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ABSTRACT

Restrained shrinkage cracking of concrete bridge decks creates a significant durability problem. Major admixture suppliers in the United States have introduced a new category of chemical admixtures called shrinkage reducing admixtures (SRAs). SRAs work by reducing the surface tension of pore water and thereby decreasing the capillary stress and shrinkage induced by drying. Several studies have reported that using SRAs in concrete mixtures is one of the most effective ways of reducing shrinkage cracking.

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FINAL REPORT

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INTRODUCTION

Cracking in concrete exposed to the environment creates a significant durability problem. Cracking can result from loads, moisture loss, temperature variation, and chemical reactions. The moisture loss in hardened concrete, i.e., drying shrinkage, is one of the major causes of bridge deck cracking. The cracks in bridge decks provide avenues for water, de-icing chemicals, sulfates, and other corrosive agents to penetrate the concrete and substantially diminish the concrete's service life because of premature corrosion of the reinforcement.

Shrinkage-induced cracking of bridge decks can be affected by many factors such as (1) material properties, (2) type of restraint, (3) construction methods, and (4) environmental conditions. If cracking attributable to concrete shrinkage could be eliminated, the service life of bridge structures could be increased and costly maintenance and repairs could be avoided.

Major U.S. admixture suppliers have introduced a new category of chemical admixtures called shrinkage reducing admixtures (SRAs). SRAs work by reducing the surface tension of pore water and thereby decreasing the capillary stress and shrinkage induced by drying. When pores lose moisture, a meniscus forms at the air-water interface. Surface tension in this meniscus pulls the pore walls inward, and the concrete responds to these internal forces by shrinking. Several studies have reported that using SRAs in concrete mixtures is one of the most effective ways of reducing shrinkage cracking (American Concrete Institute, 2010; Weiss and Berke 2003). Earlier research indicated that concrete containing SRAs generally shows less cracking because of a lower rate of shrinkage and a reduction in the overall magnitude of shrinkage (Shah et al., 1998).

Lura et al. (2007) studied the development of plastic shrinkage cracks in mortar containing SRA. In their study, mortars containing SRA showed fewer and narrower plastic shrinkage cracks than plain mortars when exposed to the same environmental conditions. They further proposed that the lower surface tension of the pore fluid in the mortars containing SRA results in less evaporation, reduced settlement, reduced capillary tension, and lower crackinducing stresses at the topmost layer of the mortar. Weiss and Berke (2003) reported that concretes containing SRA generally have lower shrinkage, lower or equal chloride penetration indexes, reduced sorptivity, and reduced cracking potential, despite having similar or slightly lower strength, modulus of elasticity, and fracture toughness when compared to plain concrete. Shah and Weiss (2000) reported that reduction in shrinkage depends mainly on the concentrations of SRA used. Shah et al. (1992) reported a reduction in pore volume depending on the composition of the SRA.

Several studies have reported on the influence of SRA on the mechanical properties of concrete, and the results are variable. Shah et al. (1992) tested three SRA compositions and found a reduction in compressive strength at 5% SRA additions (2% by weight of cement); however, this reduction was not found at lower SRA additions (1% by weight of cement). Cope and Ramey (2001) reported that the compressive strength and elastic modulus were reduced by approximately 10% and the splitting tensile strength was reduced by 8% (with 1.5% SRA by weight of cement). Studies performed with slabs restrained at both the base and the ends indicated that the use of SRA can substantially increase the distance between cracks (thus permitting larger joint spacing) (Weiss et al., 1998). Other studies reported similar values for the rapid chloride permeability in concrete with and without SRA in uncracked sections (Cope and Ramey, 2001).

According to Sant et al. (2007), the addition of SRAs does not appear to change the total loss of water. However, SRAs lower the surface tension of water, which in turn lowers shrinkage strain at a low relative humidity. Chaunsali et al. (2013) noted that a reduction in free drying shrinkage of approximately 50% was achieved with high dosages of SRA. At the same time, a 10% reduction in compressive strength was observed at high dosages of SRA, but this reduction was not significant at lower dosages. Weiss (1999) showed that the addition of SRAs significantly reduces autogenous shrinkage of high-performance concrete measured from the time of set. Approximately 50% of shrinkage was reduced at 90 days. In a different study, autogenous shrinkage of cement mortar with a water–cementitious material ratio (w/cm) of 0.35 was reduced substantially with the addition of SRA (Bentz et al., 2001).

Premature cracking is a primary concern for state departments of transportation throughout North America (Triandafilou, 2008). Concrete elements that have large surface-to-volume ratios, such as bridge decks, are vulnerable to cracking as a result of drying shrinkage.

Transverse cracking attributable to drying shrinkage is common in bridge decks and has been observed in many of the bridge decks newly constructed by the Virginia Department of Transportation (VDOT). Transverse bridge deck cracking was observed on the U.S. 15 bridge crossing the James River soon after its construction in 2000. The bridge deck was placed in three phases with standard VDOT Class A4 concrete. A recent technical assistance study (Saloman and Moen, 2015) generated a transverse crack map (Figure 1) for Unit 1 of the bridge deck and found a measured average crack width of 0.10 in and an average crack spacing of 5.38 ft (crack density of 0.186 ft/ft^2). The authors concluded that early-age drying shrinkage was the primary cause of the transverse cracking and that these full-depth cracks will result in a predicted service life reduction of up to 40% for the epoxy-coated reinforcing bar used in the bridge.

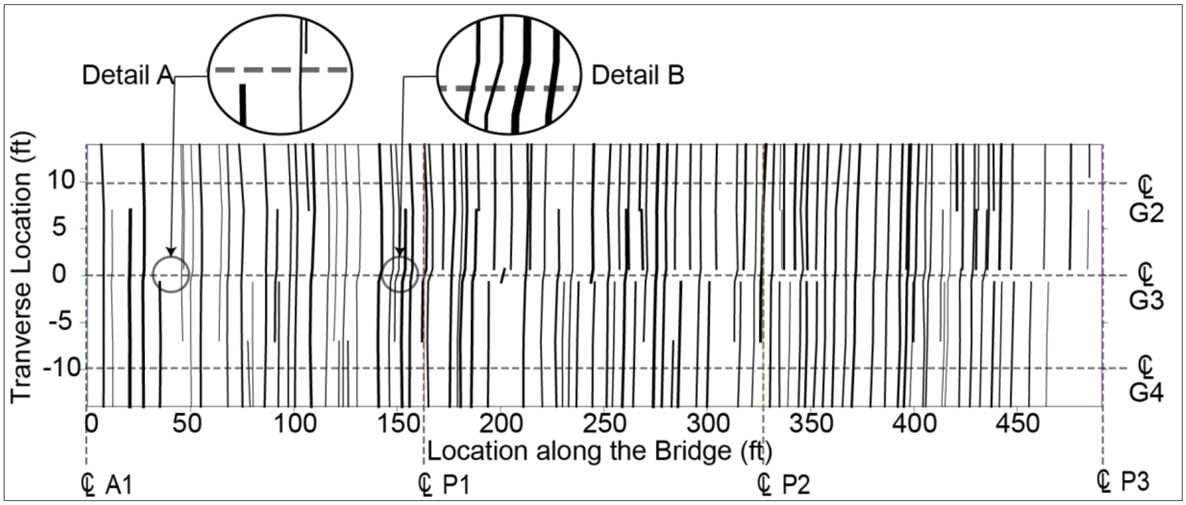

Figure 1. U.S. 15 Unit 1 Bridge Deck Crack Map. Heaviest line weight corresponds to 0.162 in average width along a crack; lightest line weight corresponds to 0.058 in along a crack (Saloman and Moen, 2015).

Sharp and Moruza (2009) documented transverse cracks on two bridges on U.S. 123 over the Occoquan River, which was completed in 2007 and used VDOT Class A4 concrete. Cracks were present on both decks, and visual analysis of the underside of the decks indicated that water was able to penetrate to the bottom of the concrete (Figure 2). The average full-depth crack spacing was 16.0 ft, and the crack density was 0.0624 ft/ft^2.

Figure 2. Underside of Route 123 Bridge Deck Showing Cracking (Sharp and Moruza, 2009)

PURPOSE AND SCOPE

The purpose of this study was to investigate the effectiveness of SRA in reducing drying shrinkage in VDOT bridge decks. Nine bridges from three VDOT districts were included in the study.

METHODS

Five tasks were performed to fulfill the purpose of the study.

1. *Several VDOT bridges were selected for the use of concrete mixtures with SRA.*

2. *Trial batches of the proposed mix designs were made to compare the properties of the concretes with and without SRA and to approve mixtures for use in the decks.*

3. *Bridge deck placement details were documented, with emphasis on the concrete and air temperatures at the time of placement and during the first 24 hr of the concrete curing period.* Thermal contraction of the concrete is more likely to contribute to the incidence of cracking as the difference between the temperatures of the concrete and the beams increases. Babaei and Fouladgar (1997) suggested that maintaining the concrete/beam differential temperature under 22 °F for at least 24 hr after the concrete is placed can minimize thermal shrinkage cracking. A comparison of the concrete and air temperatures provides a reasonable approximation of the concrete/beam temperatures.

4. *Concrete mixtures were sampled to determine fresh concrete properties, and specimens were prepared to determine hardened concrete properties to allow comparison of the properties of the concretes with and without SRA.* ASTM C157 provides a standard test method for shrinkage.

5. *Crack surveys were conducted at different intervals to allow comparison of the frequency and width of cracks in the decks constructed with SRA to those of decks constructed in the last 20 years without SRA.* Both drying shrinkage and thermal contraction can contribute to the incidence of cracking.

Bridge Details

The bridges were located in VDOT’s Northern Virginia, Staunton, and Fredericksburg districts. All of the bridges in the Northern Virginia (NOVA) District were part of the I-95 Express Lanes project. Details of the bridges, including length, width, type of beam, and skew angle (if any), are shown in Table 1.

Table 1. Details of Bridges That Used Shrinkage Reducing Concrete in Deck Concrete Mixtures

Bridge No./Name	Length (ft)	Width (ft)	No. of Spans	Type of Beam Support	Skew Angle (Degrees)
Northern Virginia District (I-95 Express Lanes)					
B607/Telegraph Road	313	40	2	Steel	19
B609/GHS Ramp	448.3	30	2	Steel	0 (curved)
B603/JHS Ramp	541	30	3	Steel	0 (curved)
B602/Ramp	558	30	3	Steel	0 (curved)
B601/Ramp	964	30	9	Concrete (1 span)/Steel	0 (curved)
Staunton District					
Route 633 Covington	340	26	3	Steel	0
Route 1421 Linville Creek	260	29.67	4	Prestressed concrete box beams	15
Route 250 Ramseys Draft	65	40	1	Prestressed concrete box beams	30
Fredericksburg District					
Route 600 Herring Creek	99	40	1	Steel	17

Trial Batches

The decks were constructed with mixtures containing different cementitious contents; aggregates; and admixtures, including SRAs.

I-95 Express Lanes, NOVA District

A single mix design was used for all five bridges in the NOVA District. As mentioned previously, all five bridges were part of the I-95 Express Lanes project. The mixture proportions (per cubic yard) used for the bridge decks are shown in Table 2. The concrete contained 600 lb/yd^3 of cementitious material, 50% of which by weight was slag cement. A commercially available SRA from Producer 1 (Eclipse 4500) was added at a rate of 1.50 gal/yd^3. The maximum w/cm for these decks was 0.45. Commercially available air-entraining, water-reducing, and high-range water-reducing admixtures were also used.

Route 633 Covington, Staunton District

The concrete mixture contained 580 lb/yd^3 of cementitious material with 20% fly ash. SRA from Producer 2 (Sika Control 40) was used at a dosage rate of 1.0 gal/yd^3. The w/cm was 0.45. The mixture proportions are shown in Table 2. Commercially available air-entraining, water-reducing, and high-range water-reducing admixtures were also used.

Route 1421 Linville Creek, Staunton District

The concrete mixture contained 650 lb/yd^3 of cementitious material with 50% slag. SRA from Producer 2 was used at a dosage rate of 1.5 gal/yd^3. The w/cm was 0.40. The mixture proportions are shown in Table 2. Fibers were also used in the mixture at a dosage rate of 3 lb/yd^3. Commercially available air-entraining and high-range water-reducing admixtures were also used.

Route 250 Ramseys Draft, Staunton District

The concrete mixture contained 600 lb/yd^3 of cementitious material with 20% fly ash. SRA from Producer 3 (Masterlife SRA 20) was used at a dosage rate of 1.5 gal/yd^3. The w/cm was 0.44. The mixture proportions are shown in Table 2. Commercially available air-entraining, water-reducing, and high-range water-reducing admixtures were also used.

Route 600 Herring Creek, Fredericksburg District

The concrete mixture contained 600 lb/yd^3 of cementitious material with 20% fly ash. SRA from Producer 2 was used at a dosage rate of 1.5 gal/yd^3. The w/cm was 0.43. The mixture proportions are shown in Table 2. Commercially available air-entraining, water-reducing, and retarding admixtures were also used.

Table 2. Concrete Mix Designs for All Bridges

Ingredient	I-95 Express Lanes (600 lb cementitious)	Route 633 Covington (580 lb cementitious)	Route 1421 Linville Creek (650 lb cementitious)	Route 250 Ramseys Draft (600 lb cementitious)	Route 600 Herring Creek (600 lb cementitious)
Cement (lb)	300	464	325	480	480
Fly ash (lb)		116		120	120
Slag (lb)	300		325		
Coarse aggregate (lb) No. 57	2019	1823	1985	1124	1715
Sand (lb)	1103	1213	1023	1909	1320
Water (lb)	271	262	260	262	258
Fiber			3 lb (Fibermesh No. 650)		
SRA dosage	1.5 gal/yd^3	1 gal/yd^3	1.5 gal/yd^3	1.5 gal/yd^3	1.5 gal/yd^3

SRA = shrinkage reducing admixture.

Bridge Deck Placement and Fresh Concrete Properties

Bridge deck construction details were documented for each bridge, including the concrete placement method (pumping, etc.). Concrete temperature, air temperature, relative humidity, and wind speed were also monitored throughout the project. By use of these values, the concrete evaporation rate was calculated and used for determining the requirements of fogging systems. To reduce the amount of water loss during construction and to avoid plastic shrinkage for overlays, VDOT requires that the evaporation rate during construction be below 0.1 lb/ft^2/hr. Temperature sensors were installed in several bridges to measure concrete temperature, which is important in curing and thermal contraction. In the fresh state, the concretes were tested for slump (ASTM C143); air content (ASTM C231); and density (unit weight, ASTM C138). Corrosion-resistant reinforcement was used in all bridges. All decks were wet cured for 7 days. After completion of the wet curing, a curing compound was applied to the surface of the decks. Then, the decks were grooved.

Hardened Concrete Properties

Concrete mixtures were collected from different truck loads, and specimens were prepared for hardened concrete testing. Table 3 lists the hardened concrete properties tested and their respective specifications. Three specimens each were used for testing compressive strength, elastic modulus, splitting tensile strength, and drying shrinkage. Two samples each were used for freeze-thaw and permeability testing. Drying shrinkage specimens were subjected to 7 days of moist curing. Permeability specimens were subjected to an accelerated moist cure for 1 week at room temperature and then 3 weeks at 100 °F. The resistance to cycles of freezing and thawing was determined in accordance with ASTM C 666, Procedure A, except that the specimens were air dried at least 1 week before the test and the test water 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 of 3 or less.

Table 3. Hardened Concrete Tests and Specimen Sizes

Test	Specification	Size, mm (in)
Compressive strength	ASTM C39	100 x 200 (4 x 8)
Elastic modulus	ASTM C469	100 x 200 (4 x 8)
Splitting tensile strength	ASTM C496	100 x 200 (4 x 8)
Permeability	VTM 112	50 x 100 (2 x 4)
Drying shrinkage	ASTM C157	75 x 75 x 280 (3 x 3 x 11)
Freeze-thaw durability	ASTM C666	75 x 100 x 400 (3 x 4 x 16)

Crack Surveys

Crack surveys were performed on all bridge decks at different intervals. The crack survey procedure included measuring crack length and width. Crack density was also calculated (total crack length divided by area of deck).

RESULTS AND DISCUSSION

Trial Batch Test Results

I-95 Express Lanes, NOVA District

A trial batch was performed at the concrete producer’s facility using a laboratory mixer. A control mixture (without SRA) using the same mixture proportions was batched at the Virginia Transportation Research Council (VTRC) laboratory. In the SRA mixture, mixture water was replaced by the amount of SRA dosage used by volume. Specifications for VDOT Class A4 concrete for a bridge deck are shown in Table 4. A total cementitious content of 600 lb/yd^3 was used instead of the specification minimum of 635 lb/yd^3. The fresh and hardened concrete properties of the trial batch are shown in Table 5.

Table 4. Specifications for VDOT Class A4 Concrete

Minimum compressive strength (psi)	4,000
Nominal maximum aggregate size (in)	1
Minimum cementitious material content (lb/yd^3)	635
Maximum water–cementitious material ratio	0.45
Slump (in)	2-4
Air content (%)[a]	6.5 ± 1.5

Source: Virginia Department of Transportation, *Road and Bridge Specifications*, Richmond, 2007.
[a] When a high-range water-reducing admixture is used, the upper limit for entrained air may be increased by 1% and the slump must not exceed 7 in.

Table 5. Trial Batch Results for I-95 Express Lanes

Property	**Control Mixture (600 lb cementitious material) 2/28/13**	**Mixture With Shrinkage Reducing Admixture (600 lb cementitious material) 2/26/13**
Compressive Strength (psi)		
3 days	2700	2410
7 days	4410 (11days)	3850
28 days	6070	6260
Elastic Modulus (*10^6 psi)		
7 days	4.6 (11days)	4.75
28 days	5.3	5.10
Splitting Tensile Strength, 28 days (psi)	640	580
Permeability (coulomb, C)	543	638
Drying Shrinkage (%)		
28 days	-0.0353	-0.0323
63 days	-0.0410	-0.0393
455 days	-0.0557	-0.0533
Freeze-Thaw Durability		
Durability factor	105	105
Surface rating	1.11	0.61
Weight loss (%)	1.55	1.65
Fresh Concrete Properties		
Slump (in)	2	6
Air content (%)	7.2	8.1
Concrete temperature (°F)	72	68
Unit weight (lb/ft^3)	149.6	146.8

From Table 5 it can be seen that the 28-day compressive strength, splitting tensile strength, and elastic modulus values were comparable between the control and SRA concrete mixtures. The permeability value for the SRA mixture was increased by 17% compared to the control mixture; however, the values were very low for both concretes. A significant reduction in shrinkage values was not observed for the SRA mixture (reduction was less than 10%). However, it should be noted that the control mixture also had a low cementitious content of 600 lb/yd^3 (50% slag) compared to a typical VDOT Class A4 concrete mixture, which usually has a cementitious content above 635 lb/yd^3. The mixture with SRA was very workable (6-in slump) compared to the control mixture. Even with a higher dosage of high-range water-reducing admixtures (compared to the SRA mixture), the control mixture achieved only a 2-in slump. Both the SRA and control mixtures showed excellent freeze-thaw durability.

Route 633 Covington, Staunton District

Trial batch results are shown in Table 6. Trial batches were made at VTRC using a laboratory mixer. An additional trial batch was made on 8/30/12 using a concrete truck mixer to check the workability and finishing characteristics of the mixture because it used a low cementitious content (580 lb/yd^3). Several sample concrete slabs were prepared at the jobsite, and no issues were found. The SRA mixture was highly workable compared to the control mixture. When the laboratory mixtures were compared, the SRA mixture showed a 15% decrease in 28-day compressive strength. However, the Batch 3 truck mixture showed a decrease in strength of less than 7%. In addition, the laboratory SRA mixture (1 gal/yd^3 dosage) showed a 58% reduction in 28-day drying shrinkage compared to that of the control mixture. The corresponding reduction at 455 days was 30%. However, a similar reduction in drying shrinkage for the Batch 3 SRA mixture was not observed when compared to that of the control mixture. Freeze-thaw durability was excellent for all mixtures.

Table 6. Trial Batch Results for Route 633 Covington

Property	Trial Batch 1 (600 lb cementitious material) Control Mixture 5/1/12	Trial Batch 2 (600 lb cementitious material) Mixture With SRA 5/22/12	Trial Batch 3 (600 lb cementitious material) Mixture With SRA 8/30/12
Compressive Strength (psi)			
7 days	3750	3440	3810
28 days	5000	4210	4670
Elastic Modulus (*10^6 psi)			
7 days	2.91	2.85	3.07
28 days	3.22	Not tested	3.51
Splitting Tensile Strength, 28 days (psi)	Not tested	405 (7 days)	465
Permeability (coulomb, C)	603	631	791
Drying Shrinkage (%)			
28 days	-0.0307	-0.0127	-0.0320
63 days	-0.0433	-0.0193	-0.0357
455 days	-0.0567	-0.0387	-0.0563
Freeze-Thaw Durability			
Durability factor	102	106	105
Surface rating	0.58	0.36	0.15
Weight loss (%)	0.56	0.47	0.03
Fresh Concrete Properties			
Slump (in)	1.75	5	3.25
Air content (%)	6	7.3	6.9
Concrete temperature (°F)	76	72	82
Unit weight (lb/ft^3)	147.2	144.4	144.8

Route 1421 Linville Creek, Staunton District

Trial batch results are shown in Table 7. This mixture used a cementitious content of 650 lb/yd^3 in which 50% was slag. Trial batches were performed at VTRC using a laboratory mixer. This mixture also used fibers; however, no fibers were included in the trial batch. The SRA trial mixture showed a 19% decrease in 28-day compressive strength. Overall, the 28-day compressive strength was high in both mixtures because of a low w/cm of 0.40. Permeability values were higher for the SRA mixture, but both mixtures had very low values. The SRA mixture showed only a 13% reduction in the 28-day drying shrinkage value as compared to the control mixture. No durability issues were observed after freeze-thaw testing. Slump values for the SRA mixture with fibers were higher than those of the control mixture. It should be noted that the addition of fibers can further reduce workability.

Table 7. Trial Batch Results for Route 1421 Linville Creek

Property	Control Mixture (650 lb cementitious material) 11/19/12	Mixture With SRA (650 lb cementitious material) 11/19/12
Compressive Strength (psi)		
3 days	4290	2690
7 days	5780	4280
28 days	8380	6760
Elastic Modulus (*10^6 psi)		
7 days	3.80	3.51
28 days	4.23	3.66
Splitting Tensile Strength, 28 days (psi)	735	430
Permeability (coulomb, C)	566	648
Drying Shrinkage (%)		
28 days	-0.0423	-0.0367
63 days	-0.0503	-0.0443
455 days	-0.0600	-0.0567
Freeze-Thaw Durability		
Durability factor	107	107
Surface rating	0.54	1.06
Weight loss (%)	1.47	2.76
Fresh Concrete Properties		
Slump (in)	2.25	5.25
Air content (%)	8.5	9
Concrete temperature (°F)	76	76
Unit weight (lb/ft^3)	142.4	140

SRA = shrinkage reducing admixture.

Route 250 Ramseys Draft, Staunton District

Trial batch results are shown in Table 8. The trial batch was made at the concrete producer's facility using a truck mixer. Only an SRA mixture was batched. It was found that use of this SRA type greatly reduced the air content, which in turn necessitated a higher dosage of air-entraining agent. However, no durability issues were observed after freeze-thaw testing since the final mixture had an air content of 7%. The magnitude of the 28-day drying shrinkage value was very low. Previous trial batches in the laboratory with this SRA type (using a different aggregate source) showed a 40% reduction in the 28-day drying shrinkage value compared to that of the control mixture. Permeability values were very low, and the concrete had acceptable compressive strength.

Table 8. Trial Batch Results for Route 250 Ramseys Draft

Property	Mixture With SRA (600 lb cementitious material) 5/1/14
Compressive Strength (psi)	
3 days	
7 days	4280
28 days	5510
Elastic Modulus (*10^6 psi)	
7 days	5.66
28 days	6.27
Splitting Tensile Strength (psi)	Not tested
Permeability (coulomb, C)	506
Drying Shrinkage (%)	
28 days	-0.0157
63 days	-0.0240
Freeze-Thaw Durability	
Durability factor	101
Surface rating	0.48
Weight loss (%)	1.63
Fresh Concrete Properties	
Slump (in)	5.25
Air content (%)	7
Concrete temperature (°F)	80
Unit weight (lb/ft^3)	145.6

SRA = shrinkage reducing admixture.

Route 600 Herring Creek, Fredericksburg District

Table 9 shows the trial batch results. The trial batch was made using a truck mixer. Compressive strength and elastic modulus values were comparable for the SRA and control mixtures.

Table 9. Trial Batch Results for Route 600 Herring Creek

Property	Control Mixture (600 lb cementitious material)	Mixture With SRA (600 lb cementitious material)
Compressive Strength (psi)		
7 days	4940	4940
28 days	6330	6440
Elastic Modulus (*10^6 psi)		
7 days	5.05	5.02
28 days	5.35	5.24
Permeability (coulomb, C)	604	709
Drying Shrinkage (%)		
28 days	-0.0337	-0.0267
63 days	-0.0450	-0.0397
455 days	-0.0470	-0.0487
Freeze-Thaw Durability		
Durability factor	105	105
Surface rating	0.30	0.33
Weight loss (%)	0.33	0.33
Fresh Concrete Properties		
Slump (in)	2.75	3.5
Air content (%)	5.8	4.7
Concrete temperature (°F)	88	88
Unit weight (lb/ft^3)	145.6	147.2

Permeability values were very low for both mixtures, although the permeability of the SRA mixture was higher. The SRA mixture showed a 20% reduction in the 28-day drying shrinkage value compared to that of the control mixture. However, later age shrinkage values were similar. The resistance to cycles of freezing and thawing was satisfactory for both mixtures.

Bridge Deck Placement Details

I-95 Express Lanes, NOVA District

As mentioned earlier, all five of the bridge decks (B607, B603, B602, B609, and B601) in the I-95 Express Lanes project used the same mix design. B607 (Telegraph Road) is a two-span bridge constructed on 8/30/13 in a single placement. The concrete mixture was placed by pumping. The mixture was highly workable, and there was no difficulty during screeding and finishing operations. In the deck, the ends and the edges where the screed could not reach were hand finished. The average slump was 4.3 in, and the average air content was 5.9%. The average fresh concrete and air temperatures were 77.0 °F and 74 °F, respectively. The average evaporation rate during construction was 0.021 lb/ft^2/hr. The fresh concrete properties for the two truck batches tested are shown in Table 10. The rate of evaporation was low.

Concrete temperature results from the thermocouples installed in the bridge deck are shown in Appendix A (Figure A1). Data showed that the temperature at placement was 79 °F and the maximum temperature was 107 °F at 13.5 hr. The temperature logger in the southwest part of the bridge was activated about 2 hr earlier than the one in the northeast part. Temperature data from both locations showed no change during placement, indicating that the contractor maintained the plasticity of the concrete throughout the placement. The ambient air temperature was not monitored through the sensors. Weather data were collected from Weather Underground (2014). The maximum air temperature recorded at this location on the deck placement date was 84 °F. The data showed that the temperature difference between the air and the concrete was below 22 °F. According to Babaei and Fouladgar (1997), the level of restrained thermal shrinkage in the deck depends on the difference between the peak concrete temperature and the temperature of the supporting beam at the time of peak temperature. The temperature of supporting beams is usually equal to the ambient temperature, so a comparison of the concrete and air temperatures provides a reasonable approximation of concrete/beam temperature. Babaei and Fouladgar (1997) suggested that restrained thermal shrinkage should be limited to 150 microstrain. They further suggested that this can be achieved by maintaining the concrete/beam differential temperature under 22 °F for at least 24 hr after the concrete is placed.

The bridge deck on B603 (JHS Ramp) was placed on 9/18/13 and 9/27/13. The concrete mixture was collected on 9/18/13, and the fresh concrete properties are shown in Table 10. The mixture was placed by pumping. Concrete temperature data are shown in Appendix A (Figure A2). The maximum concrete temperature was 93 °F. Weather data were collected from Weather Underground (2014). The data showed that the temperature difference between the air and the concrete never exceeded 22 °F. The concrete evaporation rate was very low. Construction records showed that for the second placement, the average slump was 5.3 in and the average air content was 6.6%. The average fresh concrete and air temperatures were 74 °F and 52 °F, respectively.

The B602 Ramp was placed in five placements. Samples were collected on 11/19/13. The fresh concrete properties are shown in Table 10. The mixture was placed by pumping. Temperature data for each placement are shown in Appendix A (Figure A3). Concrete temperatures varied among different days of placement. The maximum concrete temperature was 95 °F. The measured difference in temperature was less than 22 °F. The rate of evaporation was low.

Concrete samples from B609 were collected on 4/1/14 and 4/8/14. Fresh concrete properties are shown in Table 10. The rate of evaporation was low.

B601 is 964 ft long and was placed in five placements (2/26/14, 6/6/14, 6/13/14, 6/21/14, and 6/26/14). Concrete mixture samples were collected on 6/26/14, and the fresh concrete properties are shown in Table 10. The concrete mixture was placed by pumping. Placements were divided into two units. In B601, the first span used prestressed concrete beams and the remaining span used steel girders. Unit 1 was placed on 2/22/14, and the concrete temperature data are shown in Appendix A (Figure A4). The maximum temperature recorded was 123 °F after 20 hr from the time of placement. The concrete temperature at placement was 68 °F. The concrete temperature differential within different depths of the bridge deck showed higher values, with a maximum value of 39 °F. Mean and maximum air temperatures on the placement days were 46 °F and 62 °F, respectively; hence, the maximum temperature differential between air and concrete was as high as 50 °F to 60 °F. Unit 2 (total of four placements) was placed in June 2014. Temperature data for all four placements are shown in Figure A5 (Appendix A). The maximum concrete temperature was below 110 °F. The temperature differential with depth of deck was below 22 °F. The average air temperature during these four periods varied from 68 °F to 80 °F with the maximum temperature varying from 75 °F to 89 °F. Temperature differentials between the air and the concrete were below 22 °F during Unit 2 placement. The average evaporation rate during construction was low.

Average slumps for the I-95 Express Lanes varied from 3.8 to 6 in, and the air content ranged from 5.8% to 7.4%. The average evaporation rate varied from 0.028 lb/ft^2/hr to 0.078 lb/ft^2/hr. The unit weight of concrete ranged from 144.8 lb/ft^3 to 152 lb/ft^3. The concrete temperatures at delivery were maintained below 85 °F for all placements. With the exception of the B601 Unit 1 placement, the differential temperature remained less than 22 °F after the concrete was placed. After concrete placement, the bridge deck was covered with wet burlap and plastic sheets. Wet curing was maintained with an automated system, which runs for 15 min and then rests for the next 30 min. Proper concrete placement procedures were followed in all five bridge deck placements. Overall, excellent quality control was maintained in all placements. The evaporation rates were low.

Table 10. Fresh Concrete Properties for I-95 Express Lanes

Property	Telegraph Road (B607) 8/30/13		JHS Ramp (B603) at MP 150 9/18/13		B602 Flyover Ramp I-95 11/19/13		B609 Flyover Ramp I-95 4/1/14		B609 Flyover Ramp I-95 4/8/14		B601 Flyover Ramp I-95 6/26/14	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Unit Weight, lb/ft^3	151.0	152.6	147.6	-	152.0	151.6	148.8	147.6	144.8	146.4	-	-
% Air	5.8	6.0	6.8	7.4	5.8	6.8	5.9	5.6	6.2	6.8	5.8	5.8
Slump, in	5.0	3.75	4.75	6.00	4.0	4.5	6.0	5.5	6.0	5.0	5.00	4.75
Temperature (°F)												
Concrete	76	78	74	77	65	65	63	63	72	72	78	81
Air	74	74	48	48	45	41	51	51	66	66	78	78
% Relative Humidity	88	87	49	-	34	39	32	32	69	59	65	65
Wind, mph	1.3	2.9	1.7	-	3.0	4.0	4.3	2.0	5.7	0	1.3	1.5
Evaporation Rate, lb/ft^2/hr	0.014	0.028	0.066	-	0.065	0.078	0.070	0.046	0.060	0.020	0.029	0.039

- = not tested

Route 633 Covington, Staunton District

The bridge deck was cast in four placements in 2012, as indicated in Table 11. The initial planned deck placement sequence is shown in Figure 3. However, Placements D and C were combined into one placement during the construction of the deck.

Concrete placement occurred in December, and placement started each day when the surface temperatures of the concrete forms were a minimum of 40 °F. Concrete placement was performed by conveyor (Figure 4) for Placements A and B, and a standard concrete pump truck was used for Placements C, D, and E. A fogging system was used to keep evaporative loss to a minimum. For protection from cold weather, the underside of the bridge was wrapped in tarps and a heating system was used to keep the beam and deck temperatures high, as shown in Figure 5. The total cementitious content in the mixture was 580 lb/yd^3. The mixture was highly workable (Figure 6), and there was no issue with screeding and finishing operations. For curing, the concrete was covered with burlap, soaker hoses, and plastic. The surface of the placed concrete was also covered with standard concrete curing blankets. A heating system in which hot water was circulated in hoses (Figure 7) was used to provide heat as necessary to maintain a minimum 60 °F cure temperature and to expedite heating of the forms.

Table 11. Fresh Concrete Properties for Route 633 Covington

	12/4/12		12/7/12	12/13/12	12/19/12
Property	**Placement A, Batch 1**	**Placement A, Batch 2**	**Placement B, Batch 3**	**Placements C and D, Batch 4**	**Placement E, Batch 5**
Unit weight, lb/ft^3	Not tested	Not tested	142.8	144.4	146.4
% Air	6.4	4.5	6.7	5.6	5.5
Slump, in	3.5	4.5	5	2.5	3.5
Temperature (°F)					
Concrete	71	68	70	73	68
Air	48	60	50	52	53
% Relative Humidity	91	80	63	42	52
Wind, mph	1.4	1.4	0	2.4	8.5
Evaporation rate, lb/ft^2/hr	0.044	0.025	0.030	0.073	0.121

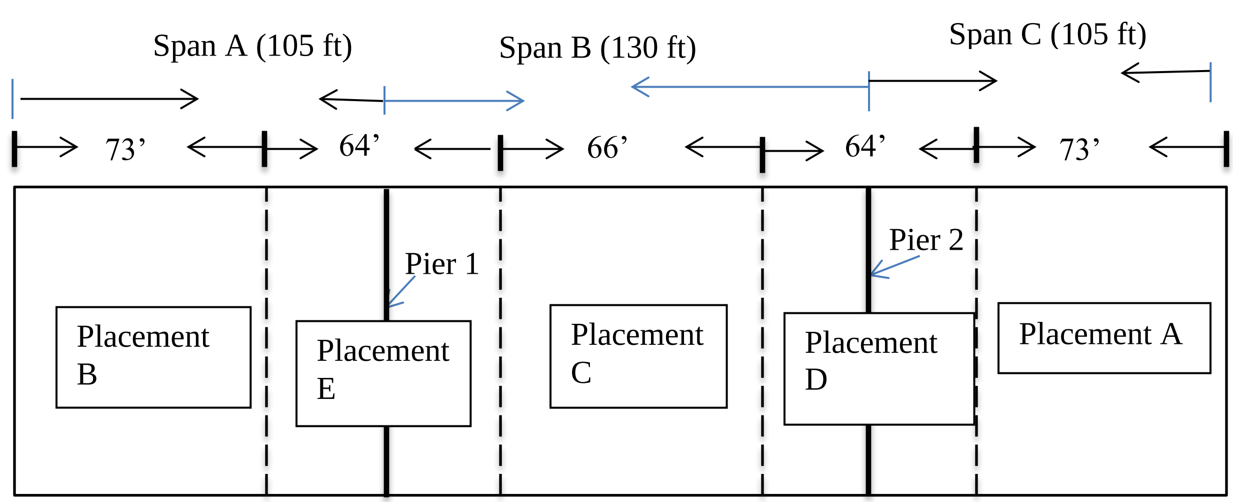

Figure 3. Planned Placement Sequence for Route 633 Covington (not to scale)

Figure 4. Conveyor Belt System for Placing Concrete for Route 633 Covington

Figure 5. Concrete Protection and Heating System for Route 633 Covington


Figure 6. Concrete Mixture With SRA for Route 633 Covington

Figure 7. Heating System Used for Placements B, C, D, and E for Route 633 Covington

Deck and beam temperatures were monitored after each placement and are shown in Table 12. In addition, thermocouples were installed for Placement E, and the results are shown in Figure A6 (Appendix A). For Placements A and B, it can be seen that temperature differential between the beam and the deck was less than 22 °F. Figure A6 shows that for Pour E, the temperature differential within the depth of concrete and between the deck and beam was 22 °F. The air temperature was very low during and after the placement.

Table 12. Temperatures of Deck and Beams for Route 633 Covington

Date	Time (A.M.)	Temperature (°F)			
		Middle of Deck	Edge of Deck	Interior Beams	Exterior Beams
Placement A					
12/5/12	7.30	98.5	80	Not checked	Not checked
12/6/12	7:10	73	50	66	66
12/7/12	7:25	68	60	58	52
12/8/12	10:36	65	59	52	49
12/10/12	8:12	56	53	54	51
12/11/12	7:45	44	45	45	43
Placement B					
12/8/12	7:10	101	92	86	78
12/10/12	7:20	68	63	71	67
12/11/12	7:32	60	52	58	54
12/12/12	9:20	56	47	46	43
12/13/12	7:45	55	50	52	52
12/14/12	7:45	55	47	56	50
Placements C and D					
12/14/12	7:20	70	67	-	-
12/17/12	7:30	67	57	-	-
12/18/12	8:35	66	61	-	-
12/19/12	7:30	59	48	-	-
12/20/12	7:30	53	53	-	
Placement E					
12/20/12	7:35	90	71	-	-

- = not measured.

Route 1421 Linville Creek, Staunton District

The deck was placed on 12/4/12 above prestressed box beams. The deck thickness was 5 in with reinforcement in the middle (Figure 8). Kevlar fiber fabric was used above longitudinal shear keys and transverse joints. Epoxy was used to install the fabric, and sand was used on the surface to get a good bond with the overlay.

Figure 8. Box Beams and Reinforcement for Route 1421 Linville Creek

The deck temperature was 47 °F when the placement started. The concrete was placed by pumping. Early on, fibers in the concrete were piled up in the hopper gate of the pump truck. The mixer chute was raised to correct the flow into the hopper. The fresh concrete properties are shown in Table 13. The average slump was 4 in, and the average air content was 7.6%. The concrete evaporation rate was low.

Table 13. Fresh Concrete Properties for Route 1421 Linville Creek, Route 250 Ramseys Draft, and Route 600 Herring Creek

Property	Route 1421 Linville Creek 12/4/12		Route 250 Ramseys Draft 8/21/14	Route 250 Ramseys Draft 11/24/14	Route 600 Herring Creek 8/30/13	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Unit Weight, lb/ft^3	138.0	-	145.4	146.7	147.6	146.8
% Air	7.4	7.8	6.4	6.3	5.5	4.9
Slump, in	4.5	3.5	4.8	5.6	3.8	2.5
Temperature (°F)						
Concrete	66	70	77	64	78	76
Air	48	63	63	57	69	73
% Relative Humidity	74	63	91	76	87	89
Wind, mph	0.0	2.7	0.0	3.5	0.6	0.0
Evaporation Rate, $lb/ft^2/hr$	0.024	0.044	0.022	0.034	0.024	0.010

Route 250 Ramseys Draft, Staunton District

The concrete deck was placed in two placements. The eastbound lane was placed on 8/21/14, and the westbound lane was placed on 11/24/14. The concrete deck was placed on prestressed box beams. Similar to Route 1421 Linville Creek, fiber fabric was used above longitudinal shear keys and transverse joints. Reinforcement was placed in the middle of the 5-in-thick deck overlay. The concrete mixture was placed directly from the truck mixer. The average slump was 5.2 in, and the average air content was 6.3%. However, SRA was affecting the air content, and hence a higher dosage of air-entraining agent was used to achieve the specified air content. It was noted that the air-entraining dosage was almost 10 times higher than the typical dosage for this brand of SRA. The fresh concrete properties are shown in Table 13. The rate of evaporation was low.

Route 600 Herring Creek, Fredericksburg District

The bridge deck was placed in a single placement on 8/30/13. The concrete was placed using a bucket as shown in Figure 9. The fresh concrete properties are shown in Table 13. The average slump was 3.2 in, and the average air content was 5.2%. Figure A7 (Appendix A) shows the temperature data from the sensors installed in the bridge deck. Sensors were installed on the top, middle, and bottom of the bridge deck in two locations (center and edge). The peak temperature was 130 °F. The temperature differential for the depths of the deck was less than 15 °F. The rate of evaporation was low.

Figure 9. Concrete Placement Using a Bucket for Route 600 Herring Creek

Hardened Concrete Properties

I-95 Express Lanes, NOVA District

The hardened concrete properties for the five bridges in the I-95 Express Lanes project are shown in Table 14. The average 28-day strength ranged from 3,960 psi to 5,450 psi. The average strength for the five bridges was 4,850 psi with a standard deviation (SD) of 460 psi. The average elastic modulus and splitting tensile strength values were $4.73*10^6$ psi and 517 psi, respectively. Permeability values ranged from 611 C to 1291 C, with an average value of 864 C. All specimens showed excellent freeze-thaw resistance.

Figure 10 shows an example of specimens after 300 cycles of freeze-thaw testing. The drying shrinkage results for the five bridge mixtures are shown in Figure 11. The drying shrinkage values after the 28-day drying period for most of the specimens were close to 0.035%. For all specimens, ultimate shrinkage values were below 0.06%. Babaei and Fouladger (1997) suggested that the 28-day shrinkage should be under 0.04% to control shrinkage-induced transverse cracking. However, Maggenti et al. (2013) suggested that a target 28-day shrinkage value below 0.030% would significantly limit or eliminate early-age shrinkage cracking. Gaines and Sheikhizadeh (2013) suggested a maximum 28-day drying shrinkage of 0.032% (based on AASHTO T 160) to control bridge deck cracking.

Table 14. Hardened Concrete Properties for I-95 Express Lanes

Property	Telegraph Road I-95, B607 8/30/13		JHS Ramp at MP 150, B603 9/18/13		B602 Flyover Ramp I-95 11/19/13		B601 Flyover Ramp I-95 6/26/14		B609 Flyover Ramp I-95 4/1/14	
	Batch 1	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**
Compressive Strength, psi										
3-day	2150	1810	1800	1420	1640	1400	2560	2460	1500	1550
7-day	2880	2750	2600	2030	3020	2680	3730	3210	2720	2660
28-day	4970	4550	4390	3960	5450	5300	5160	5190	4670	4860
Elastic Modulus (*10^6 psi)										
7-day	3.72	3.60	3.47	3.53	4.12	4.10	-	-	-	-
28-day	4.53	4.42	4.44	3.98	5.49	5.21	5.11	4.91	4.90	4.37
Splitting Tensile Strength, psi	530	495	490	460	595	500	520	500	550	530
Permeability, coulomb, C	1237	1291	611	926	625	743	674	-	983	873
Freeze-Thaw Durability										
% weight loss	3.8	3.3	1.5	2.5	0.5	1.1	1.21	1.10	2.8	2.7
Durability factor	104	107	108	109	110	111	107	111	107	107
Surface rating	1.55	1.31	1.06	1.25	0.80	0.91	0.74	0.95	1.19	0.95
Drying Shrinkage (%)										
28 days	-0.035	-0.035	-0.035	-0.033	-0.036	-0.036	-0.034	-0.034	-0.034	-0.042
4 months	-0.051	-0.049	-0.044	-0.044	-0.043	-0.043	-0.048	-0.048	-0.045	-0.053

Figure 10. B607 Freeze-Thaw Beam Specimens After 300 Cycles

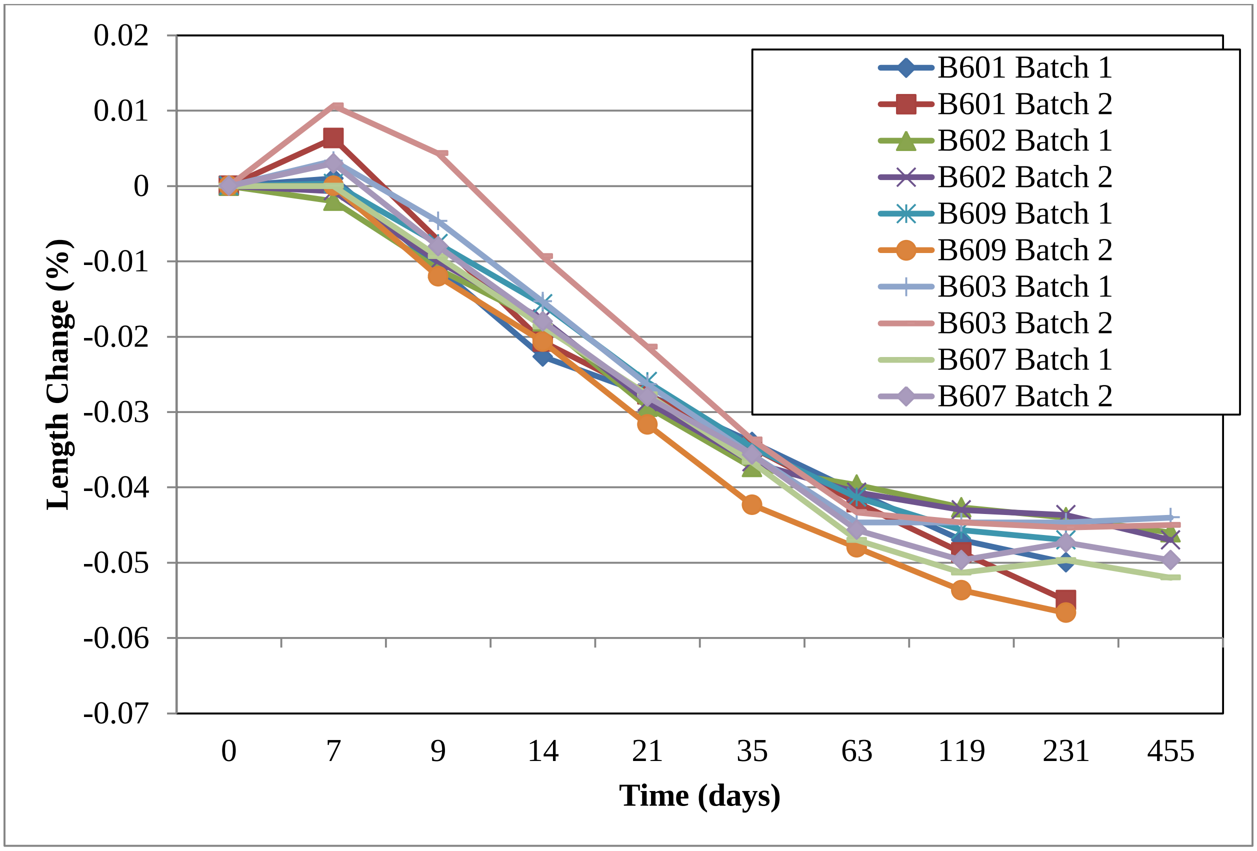

Figure 11. Drying Shrinkage Results for I-95 Express Lanes

Route 633 Covington, Staunton District

The hardened concrete properties are shown in Table 15. The average 28-day compressive strength was 4,600 psi with an SD of 500 psi. The compressive strength results for field-cured cylinders are shown in Table 16. The average 28-day elastic modulus was 3.48 * 10^6 psi. This value is lower and close to the elastic modulus of lightweight concrete.

The average 28-day splitting tensile strength was 530 psi, and average permeability was 1300 C. All specimens met freeze-thaw durability criteria. Average drying shrinkage (Figure 12) values at 28 days of drying for all specimens were below 0.035%. For all specimens, ultimate shrinkage values were lower than 0.06%.

Table 15. Hardened Concrete Properties for Route 633 Covington

Property	12/4/12		12/7/12	12/13/12	12/19/12
	Span A, Batch 1	Span A, Batch 2	Span B, Batch 3	Span C, Batch 4	Span E, Batch 5
Compressive Strength, psi					
3-day	2470	2780	2650	3280	3130
7-day	3190	3300	3160	3890	3660
28-day	4200	4640	3970	5150	5030
Elastic Modulus (*10^6 psi)					
7-day	3.07	3.06	3.07	3.22	3.26
28-day	3.46	3.39	3.39	3.60	3.58
Splitting Tensile Strength, 28 days, psi	525	530	505	545	555
Permeability, 28 days, coulomb, C	1466	1213	1308	1251	1240
Freeze-Thaw Durability					
% Weight loss	0.3	0.37	0.03	0	0.4
Durability factor	103	103	106	108	103
Surface rating	0.63	0.6	0.41	0.14	0.5
Drying Shrinkage (%)					
28 days	-0.030	-0.030	-0.030	-0.037	-0.034
4 months	-0.043	-0.043	-0.043	-0.049	-0.051

Table 16. Concrete Field Cylinder Strength Results for Route 633 Covington

Compressive Strength (psi)	Placement A	Placement B	Placements C and D
3-day	2310	2470	-
4-day	-	-	2870
7-day	3070	-	-
10-day	-	3900	-

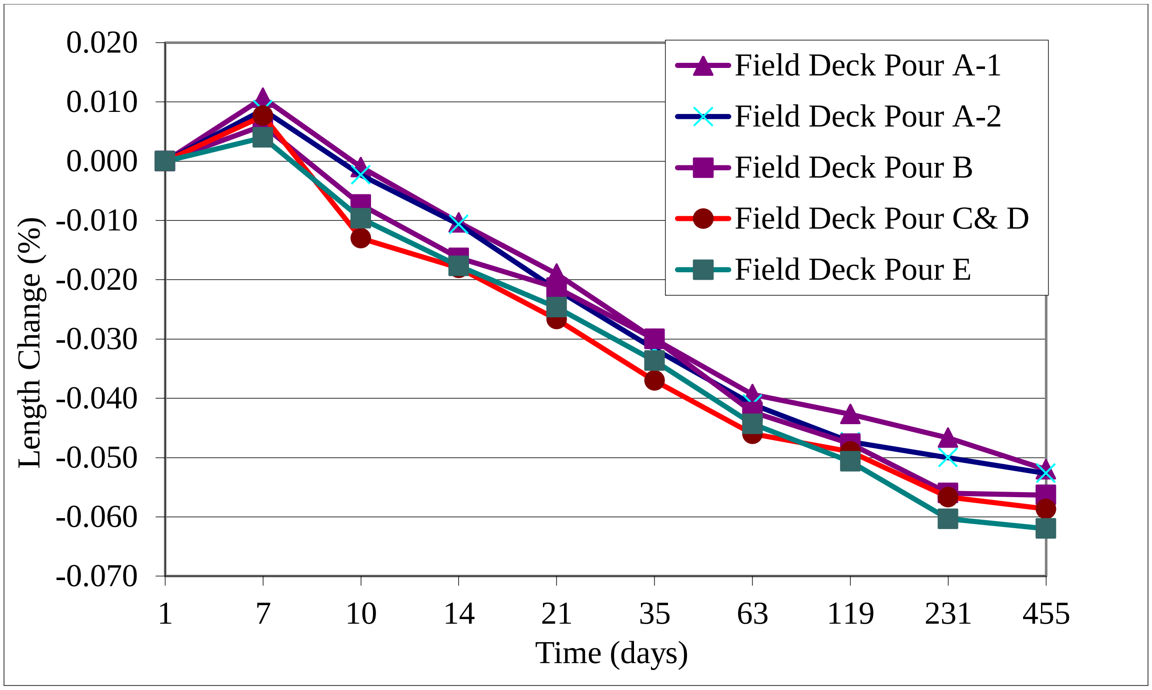

Figure 12. Drying Shrinkage Results for Route 633 Covington

Route 1421 Linville Creek, **Staunton District**

The hardened concrete properties are shown in Table 17. The average 28-day compressive strength was 4,340 psi, which is lower than for the trial batch. The decrease was attributed to an increase in water content. The trial batch had a w/cm of 0.40. Results indicate that a higher w/cm was used in the field placement. The higher w/cm also helped to achieve higher workability in the field, especially with fibers. A lower concrete strength and a lower modulus of elasticity are expected to reduce the occurrence of cracks in bridge decks. Lower modulus of elasticity values were also obtained for Route 633 Covington and are expected to lead to reduced cracking. The permeability values were below 1000 C. The average 28-day splitting tensile strength was 520 psi. Although a high water content was used, the 28-day drying shrinkage value (Figure 13) was 0.042%, and the value was below 0.06% for 4 months.

Route 250 Ramseys Draft, Staunton District

The hardened concrete properties are shown in Table 17. The average 28-day compressive strength and elastic modulus were 5,380 psi and $4.92 * 10^6$ psi, respectively. The drying shrinkage results are shown in Figure 14. The 28-day drying shrinkage value was less than 0.02%, lower than for other mixtures tested in this study. However, the freeze-thaw durability factor was 82% and the weight loss of 6.8% was higher than for other mixtures These values still met the freeze-thaw testing criteria needed for durability.

Table 17. Hardened Concrete Properties for Route 1421 Linville Creek, Route 250 Ramseys Draft, and Route 600 Herring Creek

Property	Route 1421 Linville Creek 12/4/12		Route 250 Ramseys Draft 8/21/14, 11/24/14		Route 600 Herring Creek 8/30/13	
	Batch 1	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**
Compressive Strength, psi						
3-day	1730	1600	3480	2830	3990	3560
7-day	2930	2470	4230	3920	4740	4360
28-day	4420	4250	5580	5180	5700	5520
Elastic Modulus (*10^6 psi)						
7-day	2.71	2.32	4.96	4.15	4.87	4.76
28-day	3.26	3.10	4.92	Not tested	5.47	5.41
Splitting Tensile Strength, psi	550	480	555	460	545	530
Permeability, coulomb, C	968	916	701	719	996	885
Freeze-Thaw Durability						
% Weight loss	2.06	1.49	6.66	6.90	0.00	0.03
Durability factor	101	101	89	76	104	103
Surface rating	1.26	0.98	2.01	1.30	0.25	0.35
Drying Shrinkage (%)						
28 days	-0.042	-0.042	-0.017	-0.021	-0.024	-0.027
4 months	-0.058	-0.058	-0.031	-0.031	-0.042	-0.044

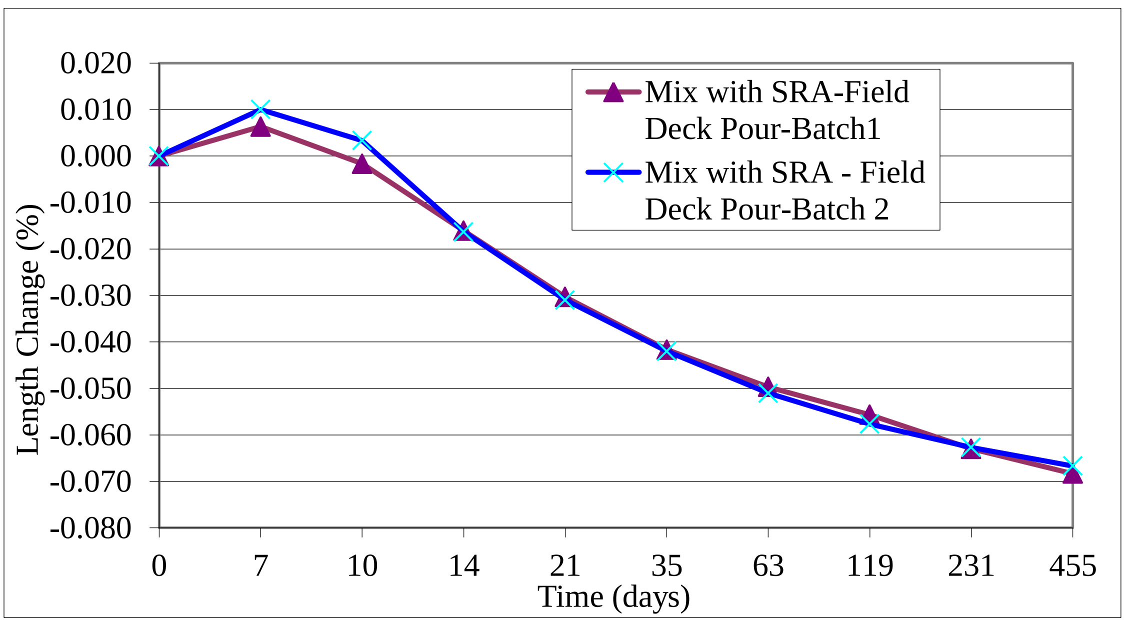

Figure 13. Drying Shrinkage Results for Route 1421 Linville Creek

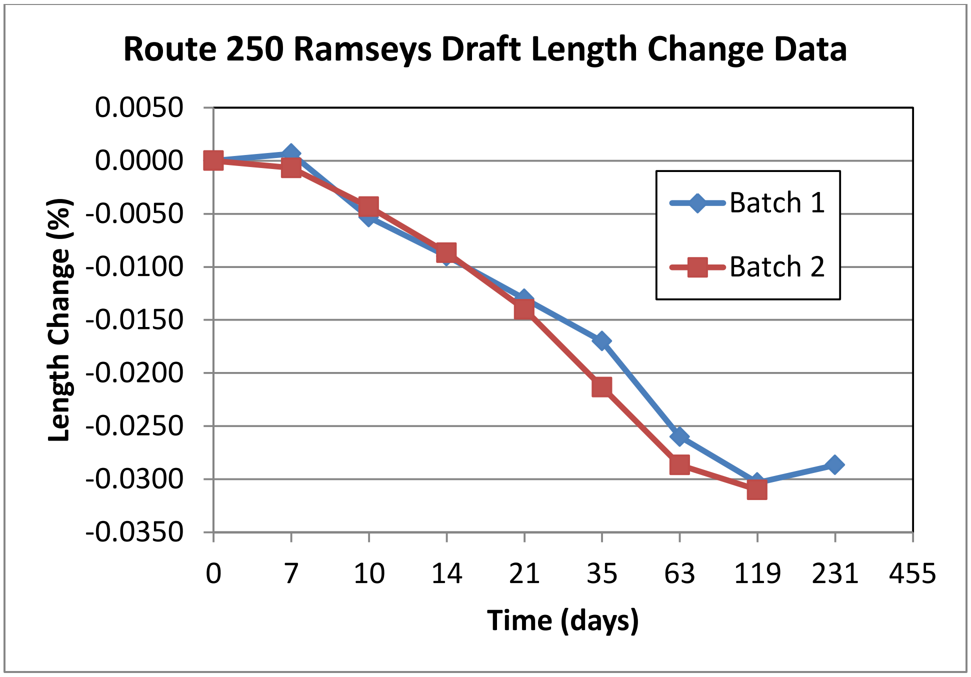

Figure 14. Drying Shrinkage Results for Route 250 Ramseys Draft

Route 600 Herring Creek, Fredericksburg District

The hardened concrete properties are shown in Table 17. The average 28-day compressive strength and permeability values were 5,610 psi and 940 C, respectively. The 28-day drying shrinkage value was less than 0.03%, and the ultimate shrinkage value was below 0.045% (Figure 15). The average splitting tensile strength was 540 psi, and specimens showed excellent freeze-thaw durability.

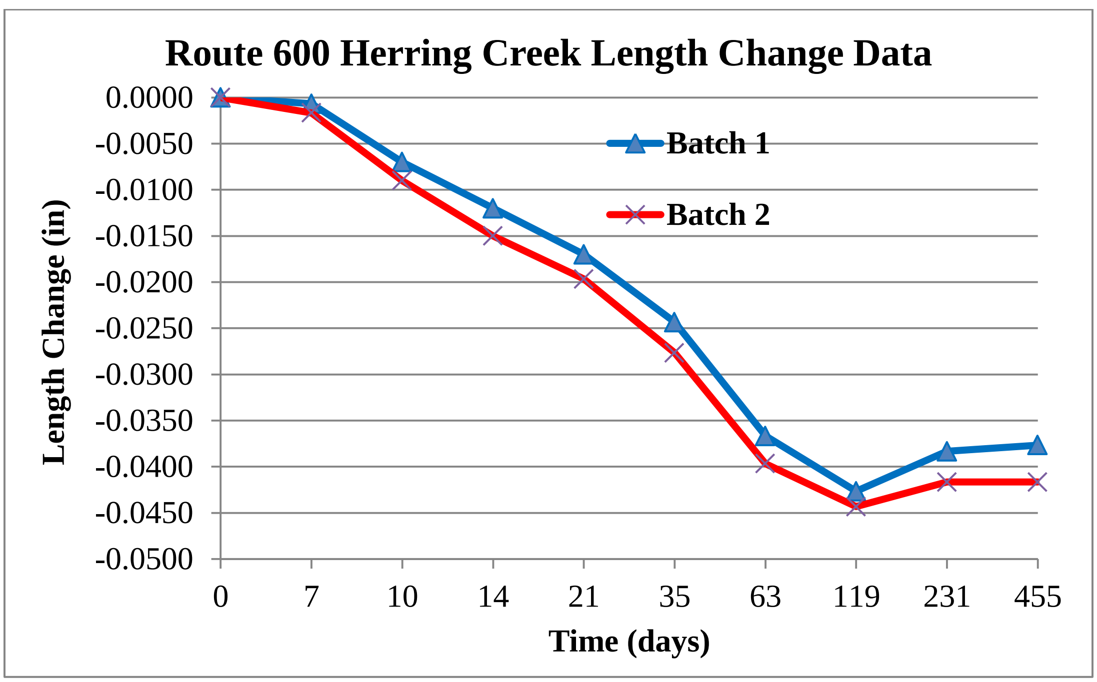

Figure 15. Drying Shrinkage Results for Route 600 Herring Creek

Crack Survey Results

I-95 Express Lanes, NOVA District

Initial bridge deck condition surveys for B607, B603, and B609 were conducted on 05/27/14 at an age of 9, 8, and 1 months, respectively. There was one large transverse crack in the span on B607 (36 ft long and 0.2 mm wide). B609 and B603 had no cracks on the deck. Additional surveys were conducted on 11/19/14 for all five bridges, and the data are shown in Table 18. The decks were 5 to 15 months old when the crack surveys were performed. Crack densities were very low compared to the VDOT Class A4 concrete without SRA used on U.S. 15 at 0.188ft/ft^2 and U.S. 123 at 0.0624 ft/ft^2 as reported in the "Introduction" section. The excellent performance of all five bridge decks was attributed to low drying shrinkage, a low temperature differential between the deck and beams, a lower elastic modulus of the concrete, and good construction practices.

All cracks on the B601 bridge deck were in the first 150-ft length. Cracks were sealed with epoxy. These may be temperature-related cracks rather than drying shrinkage cracks as the temperature differential was high (Figure 4).

Table 18. Crack Survey Results for I-95 Express Lanes

Bridge No.	Length of Bridge	No. of Cracks Length (ft) and Width (mm)	Age at Time of Survey (months)	Crack Density (ft/ft^2)
B607 (Telegraph Road)	313 ft	1 crack: 36 ft (0.2 mm)	15	0.0028
B609 (GHS Ramp)	448 ft	4 cracks: 3 ft (0.25 mm),15 ft (0.2 mm), 9 ft (0.3 mm),1 ft (0.25 mm)	7	0.0020
B603 (JHS Ramp)	542 ft	No cracks	14	0
B602 (Ramp)	558 ft	1 crack: 7 ft (0.2 mm)	13	0.0004
B601 (Ramp)	964 ft	20 short cracks: Average length: 4-5 ft	5	0.0049

Route 633 Covington, Staunton District

The initial condition survey of Route 633 Covington was conducted on 10/2/13 at an age of 10 months. An additional survey was conducted on 7/10/14 at an age of 19 months. A crack survey diagram is shown in Figure 16. As indicated in the figure, additional cracks were found in the second survey. The cracks on this deck were a combination of long and small transverse cracks. There were also a few very short transverse and longitudinal cracks (2 in to 5 in long) with widths less than 0.08 mm. These cracks are not shown in Figure 16 and were not considered in the crack density calculation. These cracks will have little if any impact on the performance of the decks.

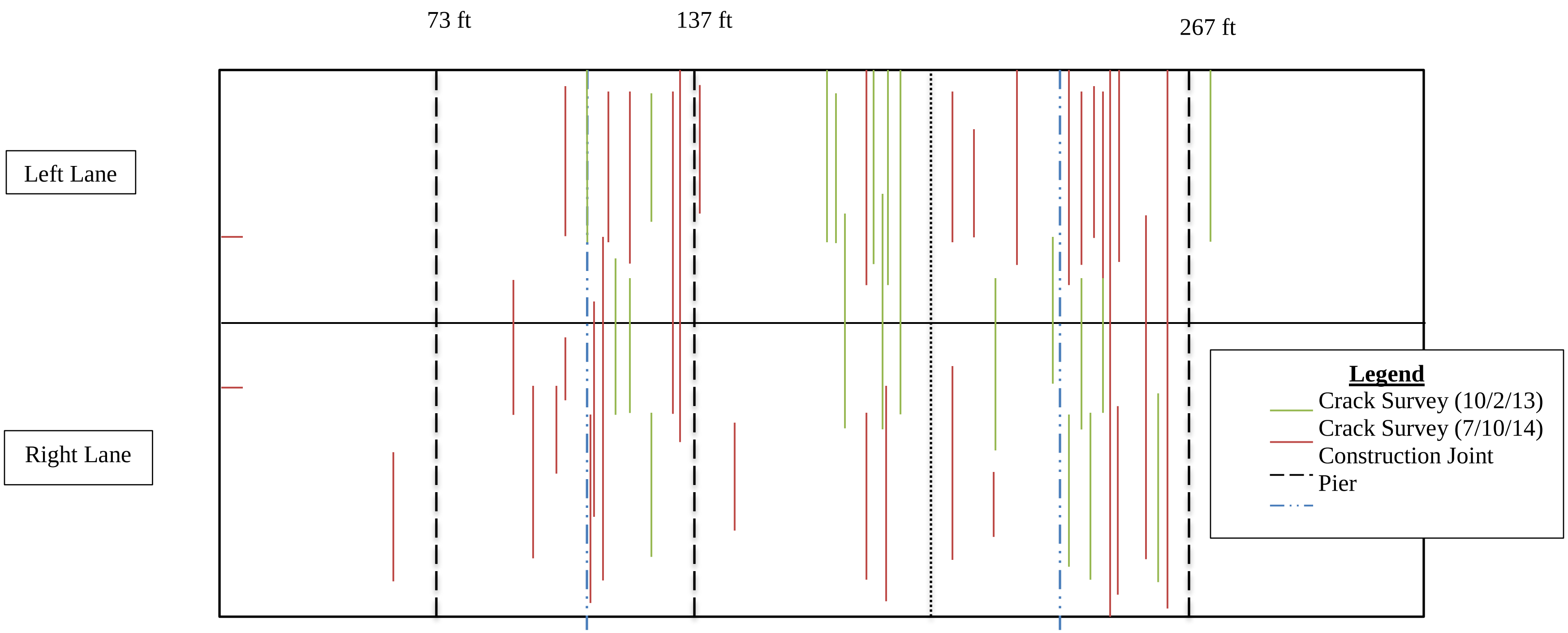

Figure 16. Crack Survey Plots for Route 633 Covington (not to scale)

Crack survey results from the first and second surveys are shown in Table 19. Table 20 shows crack survey details by Placements A, B, C, D, and E (based on 7/10/14 data). It can be seen from the table that most of the cracks occurred in Placements C, D, and E . The concrete had low compressive strength, drying shrinkage, and elastic modulus values. The modulus of elasticity is the linear correlation between stress and strain; the higher the modulus, the less strain the concrete can handle before the stresses surpass the tensile strength and cracking occurs. As mentioned earlier, Placements C and D were combined. For continuous span bridges, the deck construction sequence can contribute to transverse cracking. Positive moment areas should be placed before negative moment areas to minimize tensile stress in the concrete in negative moment areas (VDOT, 2009). Cracks were most likely caused by the addition of tensile stress induced by the live load to the stress in the concrete caused by the deck construction sequence and thermal contraction. Placements A and B were not affected by the construction sequence and had low crack densities.

Table 19. Crack Survey Results for Different Spans for Route 633 Covington

Parameter	Date	Span A		Span B		Span C	
		Left Lane	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane
Crack density (ft/ft^2)	10/2/13	0.0015	0	0.0441	0.0286	0.0591	0.0166
Crack density (ft/ft^2)	7/10/14	0.0079	0.0212	0.0663	0.0736	0.0575	0.0586

Table 20. Crack Survey Results for Different Placements for Route 633 Covington

Parameter	Placement A		Placement B		Placements C and D		Placement E	
	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane
Crack density (ft/ft^2)	0.0060	0	0.0015	0.0056	0.0392	0.0464	0.0337	0.0529
Total crack density(ft/ft^2)	0.0060		0.0071		0.0856		0.0866	

Route 1421 Linville Creek, Staunton District

The initial condition survey of Route 1421 Linville Creek was conducted at an age of 2 months. There were only three transverse cracks over each of the piers (crack width of 0.10 mm). Another condition survey was conducted on 02/04/14 at an age of 14 months. The same three cracks were found with an increased width of 0.3 mm. These types of transverse cracks over piers are common in bridges. The crack density was 0.0115 ft/ft^2. The excellent performance of this bridge deck was due to low drying shrinkage, lower compressive strength, the use of fibers in the mixture, and the low elastic modulus.

Route 250 Ramseys Draft, Staunton District

On May 13, 2015, the condition survey was conducted when the eastbound lane was 9 months old and the westbound lane was 6 months old. There were no cracks on the deck. The absence of cracks was attributed to the benefits of the lower dying shrinkage (the 28-day drying shrinkage value was 0.02%).

Route 600 Herring Creek, Fredericksburg District

The condition survey of Route 600 Herring Creek was conducted on 5/20/14 at an age of 9 months. The only cracks on the deck were short longitudinal cracks (total of five cracks) originating at the abutments. The crack length and width are shown in Table 21. The excellent performance of this bridge deck was due to low drying shrinkage (the 28-day drying shrinkage value was less than 0.03%).

Table 21. Crack Survey Results for Route 600 Herring Creek

Location	Length of Crack (ft)	Width of crack (mm)	Crack Density (ft/ft^2)
South Abutment	2.5	0.2	0.0062
	1.8	0.2	
North Abutment	9	0.2	
	2.5	0.2	
	9	0.2	

CONCLUSIONS

- *Bridge decks with fewer cracks than is typical of decks constructed over the last 20 years can be constructed.*
- *Cracks may occur when the differential temperature between the concrete and the beams, as reflected by air temperature, exceeds 22 °F, which is the value recommended by Babaei and Fouladgar (1997).*
- *Following a proper construction sequence and maintaining low temperature differentials are important for reducing cracks in bridge decks.*
- *The use of SRA along with a low cementitious content (600 lb/yd^3 maximum) is very effective in reducing cracks in bridge decks.*
- *For low-cracking decks, the 28-day drying shrinkage (per ASTM C157) should be kept below 0.035%.*
- *Concrete with SRA has slightly lower strength and higher permeability (than the control mixtures); however, the values are satisfactory for both.*
- *SRAs have varying effects on strength and air entrainment. A high amount of air-entraining admixture was added to meet the air content requirement for one of the SRA types used in this study.*
- *Mixture proportions must be determined with trial batches or historic data when SRAs are used in bridge deck concretes.*

- *SRA mixtures used in this study showed a reduction of 28-day drying shrinkage values ranging from 0% to 58% compared to corresponding control mixtures. However, it should be noted that the control mixtures used in this study also had low cementitious material and water contents for reduced shrinkage.*

- *A low permeability value for concrete can be achieved by using fly ash or slag.*

RECOMMENDATION

1. *VDOT's Materials Division and Structure and Bridge Division should continue to use SRA in bridge deck concrete mixtures along with a maximum cementitious content of 600 lb/yd^3 to reduce the 28-day shrinkage value below 0.035%. A suggested special provision is provided in Appendix B.*

BENEFITS AND IMPLEMENTATION

Benefits

Cracking continues to be the number one concern with respect to bridge deck construction. It is rare that a deck without cracks is constructed. Considerable time and effort go toward determining the cause of the cracking and making decisions on how to repair it. Considerable money is spent on concrete sealers, epoxy injection, crack sealing, and overlays to mitigate leaking cracks. More often than not these techniques do not stop leaking in some of the cracks. By limiting the rate of volume change over time, cracking can be reduced. This can lead to lower crack mitigation costs for new construction. A more durable concrete structure will last longer and require less maintenance during its service life, thereby reducing maintenance costs.

In this study, low cementitious concrete mixtures with SRA were effective in minimizing bridge deck cracking. Thus, bridges with fewer cracks can be constructed. Fewer and shorter cracks along with corrosion-resistant reinforcement will extend the service life of bridge decks and reduce maintenance costs.

The addition of SRA will increase the cost of concrete to about $40 to $50 per cubic yard. However, this increase is expected to be less than 10%, considering the per cubic yard cost for in-place concrete. When considered against the total cost of the bridge, the increase is less significant. These additional costs are expected to be offset by longer service life and the maintenance savings realized over the service life of the structure.

Implementation

The study recommended that VDOT's Materials Division and Structure and Bridge Division continue to use SRA in bridge deck concrete mixtures along with a maximum cementitious content of 600 lb/yd^3 to reduce the 28-day shrinkage value below 0.035%. This recommendation has been accepted and implemented. The special provision developed in the study (shown in Appendix B) was incorporated into the 2016 VDOT *Road and Bridge Specifications.* Several ongoing projects are currently using SRA in deck concrete mixtures.

ACKNOWLEDGMENTS

The authors thank Michael Burton, Ken Herrick, Lew Lloyd, and Andy Mills of VTRC and Gundars Buka and Mat Felts, formerly of VTRC, for their outstanding efforts in sample collection and testing. The assistance of Sam Heiberger, undergraduate research assistant, in compiling and analyzing data is also acknowledged. Appreciation is also extended to Linda Evans of VTRC for her editorial assistance. The authors thank staff of VDOT's Materials Division and Structure and Bridge Division, district materials engineers, and district bridge engineers. In addition, the authors thank Andrew Cantwell of VDOT's Staunton District and Bobby Turner of the NOVA District for their invaluable help throughout this project. The authors are also appreciative of the technical review panel for their expertise and guidance: Larry Lundy, Adam Matteo, and Chaz Weaver of VDOT and Shabbir Hossain of VTRC.

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APPENDIX A

TEMPERATURE DATA

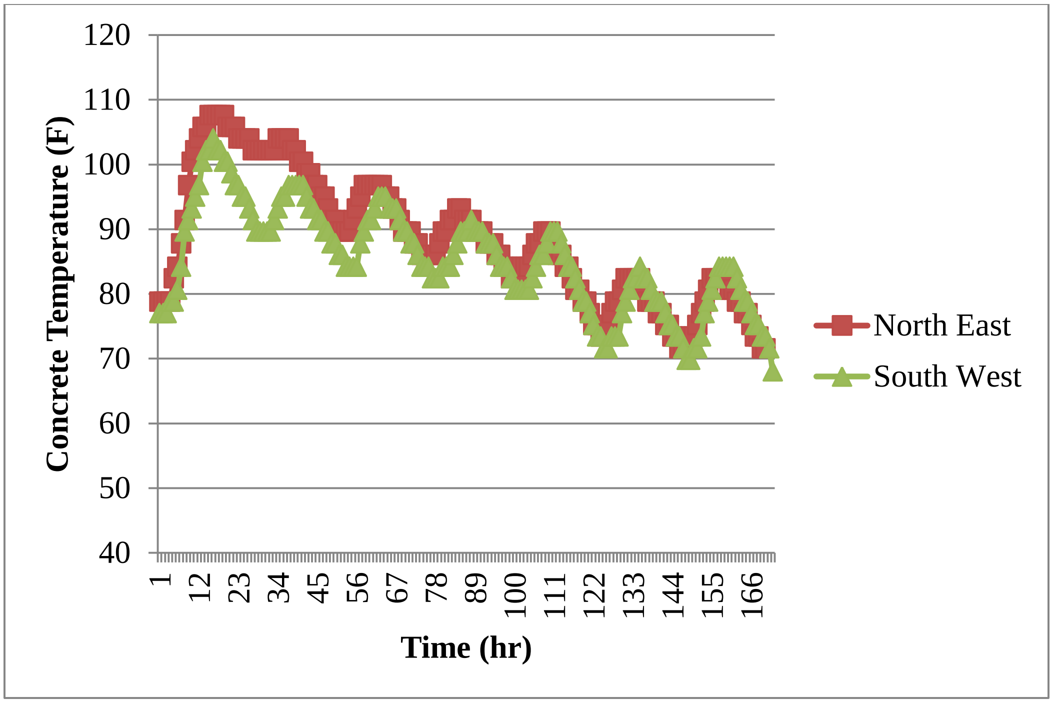

Figure A1. B607 Concrete Temperature Data

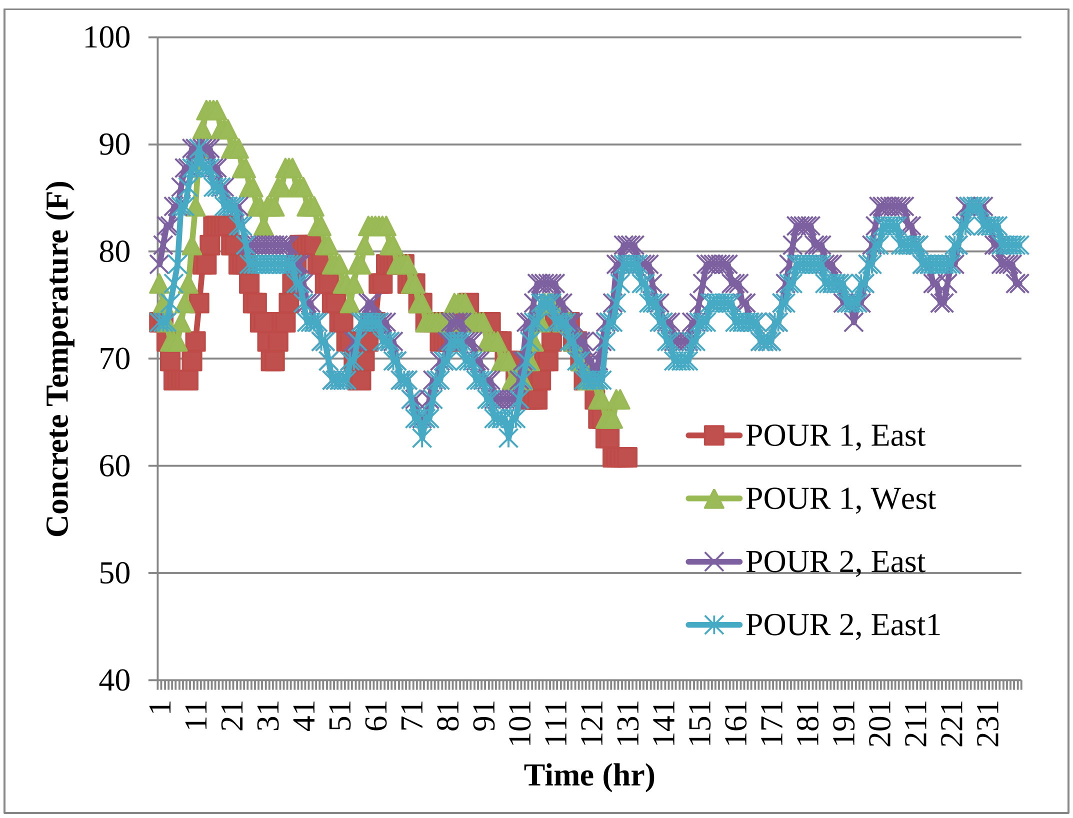

Figure A2. B603 Concrete Temperature Data

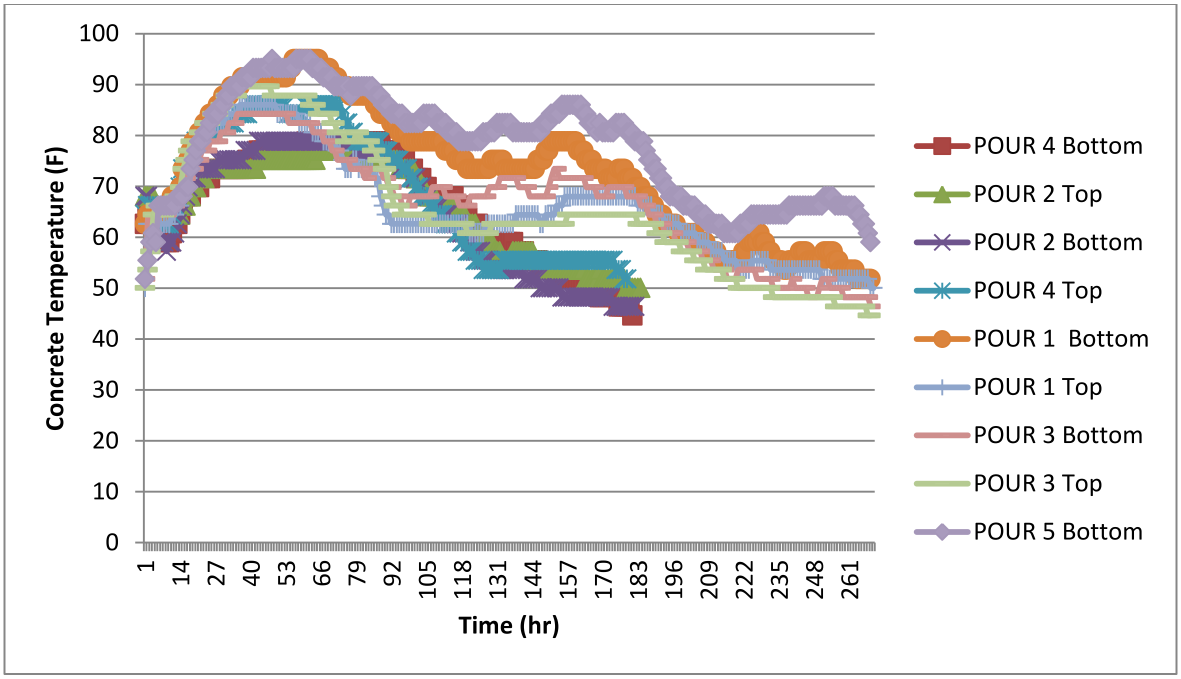

Figure A3. B602 Concrete Temperature Data

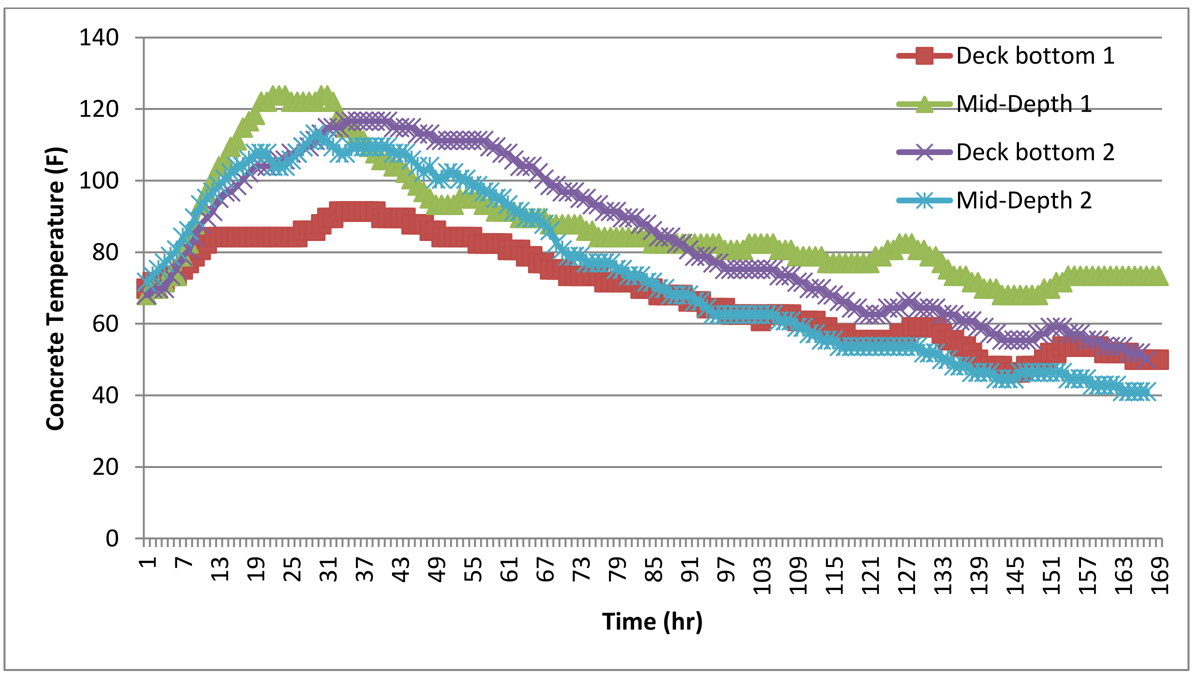

Figure A4. B601 Concrete Temperature Data (Unit 1)

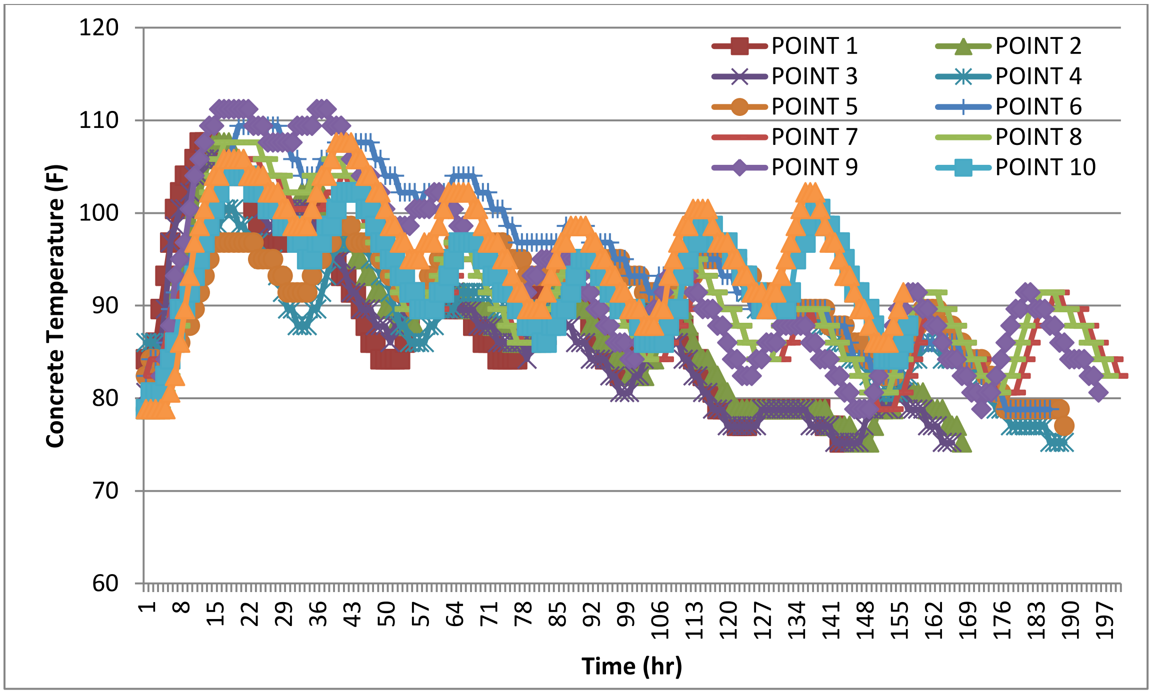

Figure A5. B601 Concrete Temperature Data (Unit 2)

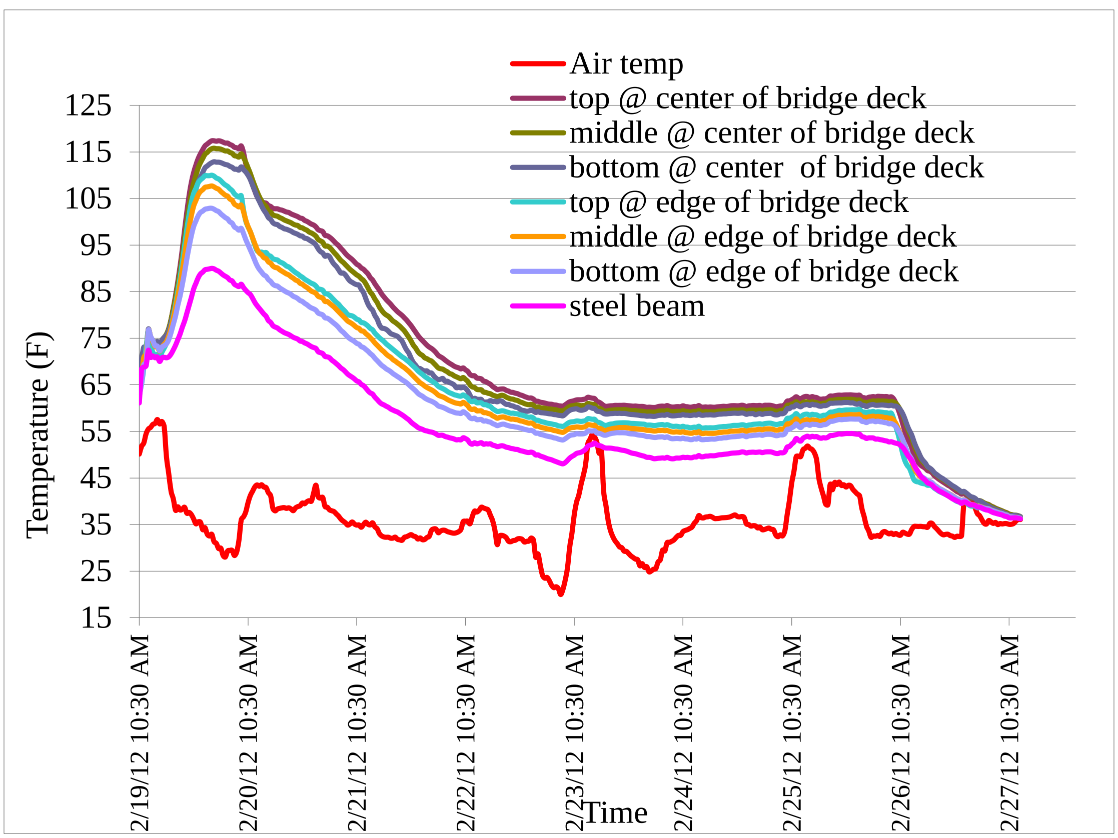

Figure A6. Temperature Data for Route 633 Covington (Placement E)

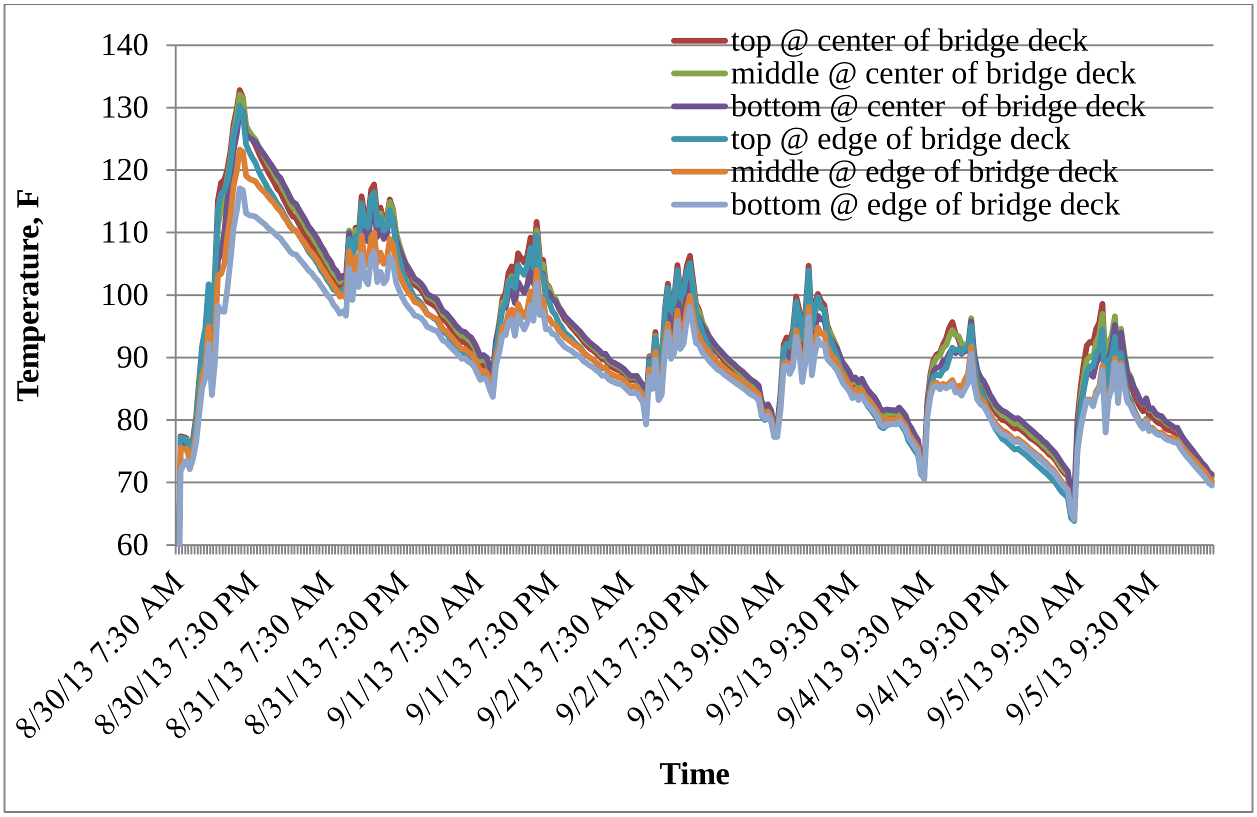

Figure A7. Temperature Data for Route 600 Herring Creek

APPENDIX B

SPECIAL PROVISION

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
CLASS A4 CONCRETE MODIFIED TO MINIMIZE CRACKING WITH SHRINKAGE REDUCING ADMIXTURE (SRA)

November 1, 2015

I. DESCRIPTION

This work shall consist of the construction of bridge decks using concrete modified as described herein, as shown on the plans and as directed by the Engineer.

II. MATERIALS

Hydraulic cement concrete used in the construction of bridge decks shall conform to the requirements of Section 217 of the Specifications for Class A4 and the following:

The cementitious materials content shall be $\leq$ 600 pounds per cubic yard. The use of high-early-strength hydraulic cement concrete as described in Section 217.08 (b) of the Specifications is not permitted.

The 28 day drying shrinkage shall be $\leq$ 0.035% (based on average of three specimens) when tested in accordance with ASTM C 157. Specimens shall be moist cured for 7 days prior to testing for drying shrinkage. A shrinkage reducing admixture shall be used unless the 28 day drying shrinkage is $\leq$ 0.035% without the admixture. With appropriate documentation, a fixed amount of SRA dosage can be used without additional drying shrinkage testing if approved by the Engineer.

III. QUALITY ASSURANCE TESTING

The Contractor, at the Contractor's expense, shall prepare a minimum 3 cubic yard trial batch of the mix at least 5 weeks prior to the proposed start date of production. The trial batch will be used to verify compliance with the shrinkage requirements listed herein and the minimum compressive strength, permeability, air void content, and slump listed in Table II-17. The Contractor shall prepare the trial batch with the same equipment to be used on the project. The Contractor shall obtain the services of a Department approved independent laboratory to perform the trial batch testing. Test results shall be furnished to the Engineer for review and approval. The Engineer will not authorize the Contractor to proceed with production of low shrinkage Class A4 modified concrete for the work required by the contract until the test results verify conformance with the requirements stated herein.

IV. MEASUREMENT AND PAYMENT

Class A4 concrete modified will be measured and paid for in accordance with Section 404.08 for deck slab concrete except that this price shall also include trial batch preparation and testing services.

Payment will be made under:

Pay Item	Pay Unit
Class A4 concrete modified	Cubic yard