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Use of Lightweight Concrete for Reducing Cracks in Bridge Decks

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16. Abstract:

Cracks in bridge decks can be due to many factors related to environmental effects, chemical reactions, and structural loads. Careful selection of materials and mixture proportions can minimize cracking to some degree. To reduce cracking, shrinkage must be reduced; however, cracking also depends on other factors such as modulus of elasticity, creep, tensile strength, and restraint. A low modulus of elasticity and high creep help to minimize cracking.

Lightweight concrete (LWC) has a lower modulus of elasticity, higher inelastic strains, a lower coefficient of thermal expansion, a more continuous contact zone between the aggregate and the paste, and more water in the pores of aggregates for continued internal curing when compared to normal weight concrete. These properties tend to reduce cracking in the concrete and are highly desirable in bridge decks. The Virginia Department of Transportation (VDOT) has been successfully using LWC in bridge structures. In most of these bridges, the coarse aggregate has been lightweight and the fine aggregate normal weight natural sand.

The purpose of this study was to investigate the effectiveness of LWC in reducing cracks in bridge decks. Seven bridges from six VDOT districts were included in the study. Three bridge decks each were constructed in 2012 and 2013, and one was constructed in 2014.

The results showed that bridge decks with fewer cracks than were typical of decks constructed with normal weight aggregate over the past 20 years or no cracks can be constructed with LWC mixtures. The study recommends that LWC with a maximum cementitious content of 650 lb/yd^3 be used in VDOT bridge deck concrete mixtures.

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ABSTRACT

Cracks in bridge decks can be due to many factors related to environmental effects, chemical reactions, and structural loads. Careful selection of materials and mixture proportions can minimize cracking to some degree. To reduce cracking, shrinkage must be reduced; however, cracking also depends on other factors such as modulus of elasticity, creep, tensile strength, and restraint. A low modulus of elasticity and high creep help to minimize cracking.

Lightweight concrete (LWC) has a lower modulus of elasticity, higher inelastic strains, a lower coefficient of thermal expansion, a more continuous contact zone between the aggregate and the paste, and more water in the pores of aggregates for continued internal curing when compared to normal weight concrete. These properties tend to reduce cracking in the concrete and are highly desirable in bridge decks. The Virginia Department of Transportation (VDOT) has been successfully using LWC in bridge structures. In most of these bridges, the coarse aggregate has been lightweight and the fine aggregate normal weight natural sand.

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The results showed that bridge decks with fewer cracks than were typical of decks constructed with normal weight aggregate over the past 20 years or no cracks can be constructed with LWC mixtures. The study recommends that LWC with a maximum cementitious content of 650 lb/yd^3 be used in VDOT bridge deck concrete mixtures.

FINAL REPORT

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INTRODUCTION

Bridge deck cracking is a major and costly problem as it often accelerates corrosion, increases maintenance costs, and shortens the service life of the deck. Cracks in bridge decks can be due to many factors related to environmental effects, chemical reactions, plastic shrinkage, drying shrinkage, and structural loads. Low permeability and a proper air void system do not always ensure durability if the concrete contains excessive cracks that facilitate the intrusion of aggressive solutions.

Effective control of early-age cracking can result in limited later-age cracking and can reduce chloride penetration and corrosion potential (Darwin and Browning, 2008). Careful selection of materials and mixture proportions can minimize cracking to some degree. Mixtures with high water and paste contents are prone to shrinkage cracks that occur over a period of time. Use of large-size aggregate and well-graded aggregates reduces the water and paste contents and minimizes shrinkage (Ozyildirim, 2007). To reduce cracking, shrinkage must be reduced; however, cracking also depends on other factors such as modulus of elasticity, creep, tensile strength, and restraint. A low modulus of elasticity and high creep help minimize cracking.

Lightweight concrete (LWC) has a lower modulus of elasticity, higher inelastic strains, a lower coefficient of thermal expansion, a more continuous contact zone between the aggregate and the paste, and more water in the pores of aggregates for continued internal curing when compared to normal weight concrete (NWC). These properties tend to reduce cracking in the concrete and are highly desirable in bridge decks. Weiss et al. (1999) established that a reduced modulus of elasticity can reduce the potential cracking of the concrete. Having a lower modulus of elasticity, a concrete can be considered more flexible than one with a greater modulus. Therefore, less rigidity of the concrete can provide better performance, reducing early-age cracking that is caused by thermal displacement, autogenous shrinkage, moisture loss, and restrained shrinkage. Further, NWC weighs about 150 lb/ft^3 as compared to structural LWC that weighs about 115 to 120 lb/ft^3. This is significant since using LWC decreases the dead load of NWC by about 20% (Ozyildirim and Gomez, 2005).

The Virginia Department of Transportation (VDOT) has been successfully using LWC in bridge structures. In most of these bridges, the coarse aggregate has been lightweight and fine aggregate normal weight natural sand. In general, the resistance to cycles of freezing and thawing and the wear resistance of these concretes have been satisfactory (Ozyildirim, 2008). In 1979, VDOT constructed a bridge deck with LWC that had coarse aggregate with a very high absorption of 18%. This 212-ft-long bridge is located on old Route 60 (now Route 269) over the Cowpasture River. It has two lanes and two spans with a continuous deck on steel beams. Cylinders tested during construction had an average 28-day compressive strength of 5,100 psi (Ozyildirim, 2008). In 2013 a visual survey indicated the deck was still in very good condition after 34 years of service. It had no transverse cracks (common on continuous bridges), no visible cracks, and very limited wear. It had some shallow pop outs exposing the coarse aggregate in some areas, as shown in Figure 1. Another bridge on Route 60 over the Maury River also had an LWC deck, and no cracks were found in as 2013 survey after 30 years of service.

Early-age cracking of concrete bridge decks can have several detrimental effects on long-term behavior and durability. It is imperative that bridge deck concrete be proportioned and placed so as to minimize early-age cracking.

Full-depth transverse cracking is typically observed in VDOT's newly constructed bridge decks. Figures 2 and 3 shows transverse cracks found on Nimmo Parkway (Hampton Roads District) and Route 61 over the New River in VDOT's Salem District constructed in 2014 using standard VDOT Class A4 NWC.

Figure 1. Lightweight Concrete Bridge Deck at Route 269 After 34 Years

Figure 2. Transverse Cracks on Nimmo Parkway (Hampton Roads District)

Figure 3. Transverse Cracks on Route 61 Over New River (Salem District)

Transverse bridge deck cracking with a crack density of 0.186 ft/ft^2 was also observed on the U.S. 15 bridge crossing the James River soon after its construction in 2000 (Saloman and Moen, 2015). Sharp and Moruza (2009) documented transverse cracks with a crack density of 0.0624 ft/ft^2 on two bridges on U.S. 123 over the Occoquan River that were completed in 2007. Both bridge decks were placed with standard VDOT Class A4 NWC.

PURPOSE AND SCOPE

The purpose of this study was to investigate the effectiveness of LWC in reducing cracks in bridge decks. Seven bridges from six VDOT districts were included in the study. Three bridge decks each were constructed in 2012 and 2013, and one was constructed in 2014.

METHODS

Four tasks were conducted to fulfill the purpose of the study.

1. Several VDOT bridges were selected for using LWC mixtures.

2. Bridge deck placement details were documented with emphasis on the concrete and air temperatures at the time of placement and during the first 24 hours of the concrete curing period.

3. Concrete mixtures were collected to determine fresh concrete properties, and field samples were prepared and tested for hardened concrete properties. Testing in accordance with ASTM C157 provides an accepted indication of shrinkage.

4. Field evaluations of the bridge decks were conducted through crack surveys at varying intervals to allow comparison of the frequency and width of cracks in the decks constructed with lightweight aggregate to typical values of decks constructed in the last 20 years with normal weight aggregate. Both drying shrinkage and thermal contraction can contribute to the incidence of cracking.

Bridge Details

The seven study bridges were located in VDOT's Northern Virginia, Staunton, Lynchburg, Culpeper, Richmond, and Fredericksburg districts. Details of the bridges including length, width, type of beam and skew angle (if any), and construction year are shown in Table 1.

Mix Design

The decks were constructed with mixtures containing different cementitious contents (635 to 705 lb/yd^3), fine aggregates, and mineral admixtures. Expanded slate lightweight coarse aggregate was used in all mixtures. Commercially available air-entraining, water-reducing, and retarding admixtures were also used. The LWC mixture proportions (per cubic yard) used for the bridge decks are shown in Table 2.

Table 1. Details of Study Bridges That Used Lightweight Concrete in the Deck

Route No./District	Length (ft)	Width (ft)	No. of Spans	Type of Beam Support	Skew Angle (Degrees)
Construction Year 2012					
Route 657, Senseny Road, Winchester/ Staunton	249	32	4	Steel	0
Route 128, Chandlers Mountain Road, Lynchburg/Lynchburg	264	36	4	Steel	0
Route 15, Opal/Culpeper	256	28	2	Lightweight concrete beams	27
Construction Year 2013					
Route 49, The Falls Road, Crewe/ Richmond	175	42	3	Steel	0
Route 646, Aden Road, Nokesville/Northern Virginia	167	32	3	Prestressed concrete slab	0
Route 3, Piankatank River, Mathews County/Fredericksburg	4186	28	30	Steel	0
Construction Year 2014					
I-95 HOV Lane, Stafford/Northern Virginia	159	48	1	Steel	0

Table 2. Lightweight Concrete Mix Designs (Lightweight Mixture Proportions per Cubic Yard)

Ingredient	Route 657 Winchester	Route 128 Lynchburg	Route 15 Opal	Route 49 Crewe	Route 646 Nokesville	Route 3 Matthews County	I-95 HOV Lane Stafford
	705 lb cementitious 25% fly ash	**635 lb cementitious 50% slag**	**660 lb cementitious 50% slag**	**696 lb cementitious 24.5% fly ash**	**675 lb cementitious 20% fly ash**	**635 lb cementitious 20% fly ash**	**660 lb cementitious 50% slag**
	8/14/12	**9/26/12**	**10/24/12**	**10/22/13**	**8/21/13**	**11/8/13**	**2/20/14**
Cement (lb)	529	318	330	525	540	508	330
Fly ash (lb)	176	-	-	171	135	127	-
Slag (lb)	-	317	330	-	-	-	330
Fine aggregate (sand) (lb)	1358	1268	1285	1161	1295	1365	1305
Coarse aggregate (Stalite) (lb)	824	900	893	891	837	850	850
Water (lb)	267	286	292	313	292	286	292
w/cm	0.38	0.45	0.44	0.45	0.43	0.45	0.44

w/cm = water–cementitious material ratio.

Field Placement Documentation and Fresh Concrete Properties

Bridge deck construction details were documented including the concrete placement method (pumping, etc.). Concrete temperature, air temperature, relative humidity, and wind speed were also monitored throughout the study. The concrete properties were determined in the fresh and hardened states. In the fresh state, the concretes were tested for slump (ASTM C143), air content (ASTM C173), and density (unit weight, ASTM C138).

Hardened Concrete Properties

Concrete mixtures were collected from different truckloads, and specimens were prepared for hardened concrete testing. Table 3 provides a list of 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 test specimens were subjected to 7 days of moist curing. Permeability (reported as coulomb values) 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 C666, 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 (in)
Compressive strength	ASTM C39	4 x 8
Elastic modulus	ASTM C469	4 x 8
Splitting tensile strength	ASTM C496	4 x 8
Permeability	VTM 112	2 x 4
Drying shrinkage	ASTM C157	3 x 3 x 11
Freeze-thaw durability	ASTM C666	3 x 4 x 16

Crack Surveys

Crack surveys of the bridge decks were conducted at different intervals. The crack survey procedure included measuring the crack lengths and widths. Crack density was also calculated (as the sum of all crack lengths divided by the area of the deck).

RESULTS AND DISCUSSION

Field Placement Documentation and Fresh Concrete Properties

The bridge decks for Route 657 Winchester, Route 128 Lynchburg, and Route 15 Opal were constructed in 2012. The fresh concrete properties are shown in Table 4. LWC mixture was placed by pumping for all three bridges. For all three bridges, the fresh concrete properties met VDOT specifications. Average slumps ranged from 4 to 8 in, and air content ranged from 5.5% to 8%. For Route 657 Winchester, the LWC mixture contained a total cementitious content of 705 lb/yd^3, of which 25% was fly ash. Route 128 Lynchburg and Route 15 Opal used LWC mixtures with cementitious contents of 635 and 650 lb/yd^3, respectively, of which 50% was slag. The water–cementitious materials ratio (w/cm) was 0.38, 0.45, and 0.44, respectively, for Route 657 Winchester, Route 128 Lynchburg, and Route 15 Opal. To reduce the amount of water loss during construction and to avoid plastic shrinkage, VDOT requires that the evaporation rate during construction be below 0.1 lb/ft^2/hr. The concrete evaporation rates were very low (less than 0.1 lb/ft^2/hr) in all three cases. 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.

Table 4. Fresh Concrete Properties for Route 657 Winchester, Route 128 Lynchburg, and Route 15 Opal

Fresh Property	Route 657 Winchester 8/14/12		Route 128 Lynchburg 9/26/12		Route 15 Opal 10/24/12	
	Batch 1	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**
Unit Weight, lb/ft^3	120.9	117.2	115.6	114.2	-	-
% Air	6.2	8.0	7.1	6.8	5.5	7.6
Slump, in	5.0	8.0	5.5	6.75	4.0	5.0
Temperature (^{o}F)						
Concrete	86	79	69	68	69	68
Air	73	79	58	58	61	-
% Relative Humidity	73	69	86	79	84	-
Wind, mph	0.0	0	1.5	3.0	0.6	-
Evaporation rate, lb/ft^2/hr	0.021	0.025	0.03	0.04	0.0	-

The bridge decks for Route 646 Nokesville, Route 49 Crewe, and Route 3 Matthews County were constructed in 2013. The fresh concrete properties are shown in Table 5. Route 646 Nokesville, Route 49 Crewe, and Route 3 Mathews County used total cementitious contents of 675, 696, and 635 lb/yd^3, respectively, with 20%, 25%, and 20% fly ash, respectively. Corresponding w/cms were 0.43, 0.45, and 0.45, respectively. For Route 646 Nokesville and Route 3 Mathews County, the LWC mixtures were placed directly from the truck mixer. For Route 49 Crewe, the LWC mixture was placed by pumping. The concrete slump, air content, and evaporation rate met VDOT specifications. All three bridges decks were placed in multiple pours.

Each lane of Route 646 Nokesville was cast in 2 days. The eastbound lane, Spans 2 and 3, excluding the closure pour, were constructed on 8/21/13, and Span 1 and both closure pours were placed on 8/27/13. All three spans of the westbound lane excluding the two closure pours were placed on 10/19/13, and the closure pours were placed on 10/22/13. The closure pours were 4 ft wide, centered on the piers.

The bridge deck for I-95 HOV Lane Stafford was constructed in 2014. Table 6 shows the fresh concrete properties. The LWC mixture was placed by a conveyer system. The cementitious content of the mixture was 660 lb/yd^3, of which 50% was slag. A w/cm of 0.44 was used.

Table 5. Fresh Concrete Properties of Route 646 Nokesville, Route 49 Crewe, and Route 3 Mathews County

Fresh Property	Route 646 Nokesville Lightweight Deck		Route 49 Crewe Lightweight Pour		Route 3 Mathews County	
	8/21/13		10/22/13		11/8/13	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Unit Weight, lb/ft^3	114.0	122.0	115.6	115.2	114.7	114.7
% Air	5.5	5.2	5.2	5.2	6.3	8
Slump, in	5.0	5.0	6.25	6.5	6.0	6.5
Temperature (^{o}F)						
Concrete	80	84	71	73	66	70
Air	70	68	28.9	28.8	52	45
% Relative Humidity	90	93	82	74	53	40
Wind, mph	0.0	1.2	0.6	0	6.7	7.3
Evaporation rate, lb/ft^2/hr	0.02	0.04	0.03	0.03	0.09	0.13

Table 6. Fresh Concrete Properties for I-95 HOV Lane Stafford

Fresh Property	2/20/14	
	Batch 1	Batch 2
Unit Weight, lb/ft^3	117.6	118.4
% Air	6.5	6
Slump, in	6.0	5.0
Temperature (^{o}F)		
Concrete	64	64
Air	53	54
% Relative Humidity	23	23
Wind, mph	3.1	5.9
Evaporation rate, lb/ft^2/hr	0.06	0.09

Hardened Concrete Properties of Field Samples

The hardened concrete properties for all three bridge decks constructed in 2012 are shown in Table 7. The average 28-day strength for Route 657 Winchester ranged from 5,320 psi to 5,450 psi. The average 28-day strength for two batches for Route 128 Lynchburg and Route 15 Opal were 5,480 psi and 5,920 psi, respectively. Even though the Route 657 Winchester LWC mixture had a higher cementitious content and a lower w/cm compared to the other two bridges, strength results were comparable, which indicates that a w/cm higher than 0.38 was used for Route 657 Winchester. The average elastic modulus ranged from $3.09 * 10^6$ psi to $3.43 * 10^6$ psi. Permeability values ranged from 395 C to 1174 C. All specimens showed excellent resistance to cycles of freezing and thawing.

The drying shrinkage values for all three bridge mixtures are shown in Figure 4. The drying shrinkage values after a 28-day drying period for all specimens were below 0.03% except for Route 657 Winchester (values were approximately 0.05%). It can be seen that as cementitious content increases, drying shrinkage values also increase. Lower cement, water, and paste contents are always desirable to lower cracking including those related to drying shrinkage. The hardened concrete properties for Route 128 Lynchburg confirm that decks can be successfully placed using LWC with a cementitious content below 650 lb/yd^3 while meeting strength and permeability requirements. The industry also accepts that LWCs with a maximum cementitious material content of 650 lb/yd^3 can be prepared and placed successfully.

Table 7. Hardened Concrete Properties for Route 657 Winchester, Route 128 Lynchburg, and Route 15 Opal

	Route 657 Winchester		Route 128 Lynchburg		Route 15 Opal	
	8/14/12		9/26/12		10/24/12	
Hardened Property	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**	**Batch 1**	**Batch 2**
Compressive Strength, psi						
3-day	3640	3600	2060	1870	2730	2630
7-day	4130	4000	3470	3370	4040	3620
28-day	5320	5450	5470	5490	5940	5890
Elastic Modulus (10^6 psi)						
7-day	2.96	2.95	2.82	2.82	2.84	2.82
28-day	3.09	3.17	3.43	3.29	3.22	3.29
Splitting Tensile Strength, psi	425	490	515	470	435	475
Permeability, coulomb, C	914	874	395	419	1174	766
Freeze-Thaw Durability						
% Weight loss	1.59	5.25	4.1	4.8	6.6	7.5
Durability factor	106	101	101	104	114	116
Surface rating	0.53	1.28	1.0	1.0	1.5	1.6

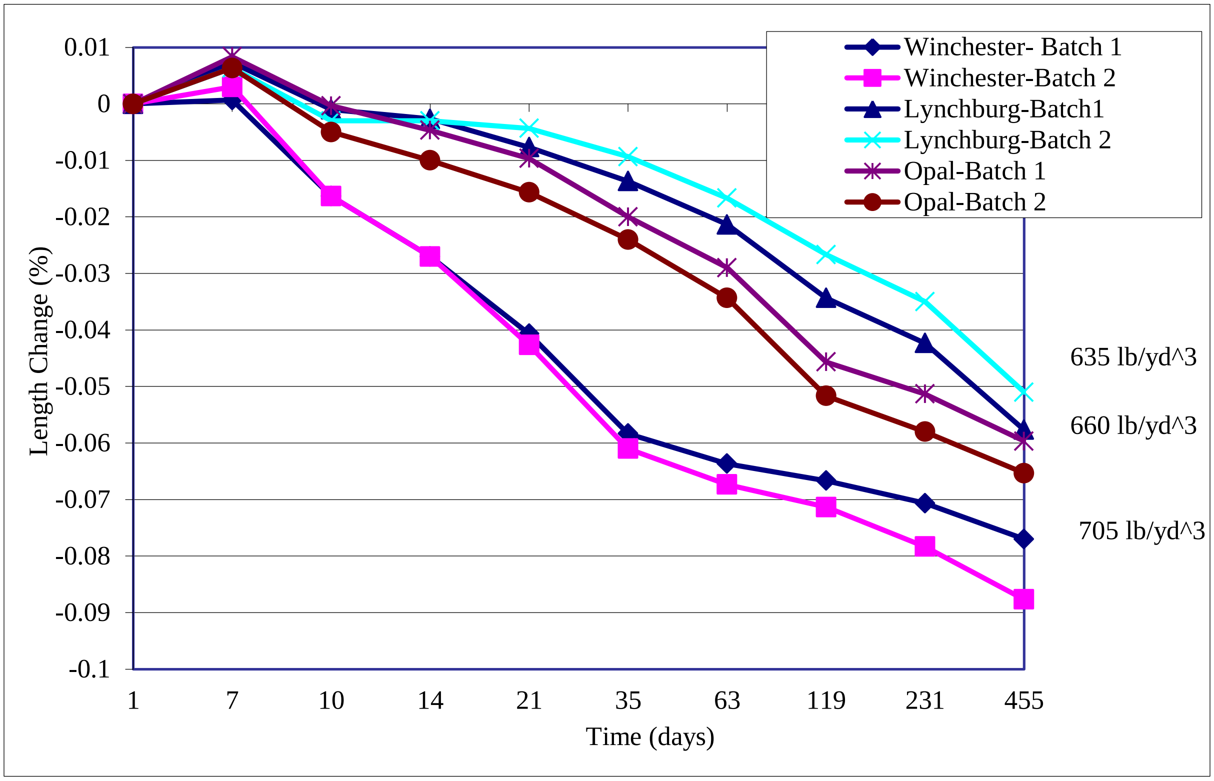

Figure 4. Drying Shrinkage Results for Route 657 Winchester, Route 128 Lynchburg, and Route 15 Opal

The hardened concrete properties of all three bridges constructed in 2013 are shown in Table 8. For Route 646 Nokesville, the average 28-day strength results for Batch 1 and Batch 2 showed large variation. As mentioned before, the deck for Route 646 Nokesville was placed on different days. For the eastbound lane, two batches of concrete were tested by the Virginia Transportation Research Council (VTRC), and the results are summarized in Table 8. Since this lane exhibited extensive cracking, more data were collected by the field personnel: 28-day strengths of 8,580 psi, 7,630 psi, and 6,990 psi were obtained. For LWC, it is very important to pre-soak the lightweight aggregate before mixing. The reason for the different average strength results was the lack of proper saturation of the lightweight aggregates.

For Route 49 Crewe and Route 3 Mathews County, the average 28-day strengths were 5,760 psi and 5,770 psi, respectively. All specimens showed excellent resistance to freezing-thawing. Permeability values ranged from 473 C to 964 C.

Table 8. Hardened Concrete Properties for Route 646 Nokesville, Route 49 Crewe, and Route 3 Mathews County

Hardened Property	Route 49 Crewe Lightweight Pour 10/22/13		Route 646 Nokesville Lightweight Deck 8/21/13		Route 3 Mathews County 11/8/13	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Compressive Strength, psi						
3-day	3720	3840	2870	5500	3910	3810
7-day	4200	4510	3770	6590	4710	4520
28-day	5490	6020	4870	8010	5840	5690
Elastic Modulus (10^6 psi)						
7-day	3.30	3.00	2.77	3.12	3.26	3.37
28-day	3.08	3.35	3.09	3.82	3.65	3.51
Splitting Tensile Strength, psi	510	550	450	475	540	570
Permeability, coulomb, C	522	473	732	638	912	964
Freeze-Thaw Durability						
% Weight loss	0.9	0.3	0.4	0.4	0.4	0.5
Durability factor	112	111	98	96	98	98
Surface rating	0.4	0.4	0.6	0.4	0.6	0.6

The drying shrinkage results for all three bridge mixtures are shown in Figure 5. The drying shrinkage values after the 28-day drying period for all specimens were close to 0.04%.

The bridge deck for I-95 HOV Lane Stafford was placed on 2/20/14 with a single placement. The average 28-day compressive strength and permeability were 4,620 psi and 497 C, respectively (Table 9). The drying shrinkage results are shown in Figure 6. The 28-day drying shrinkage was higher (≥0.05%) compared to other mixtures in this study.

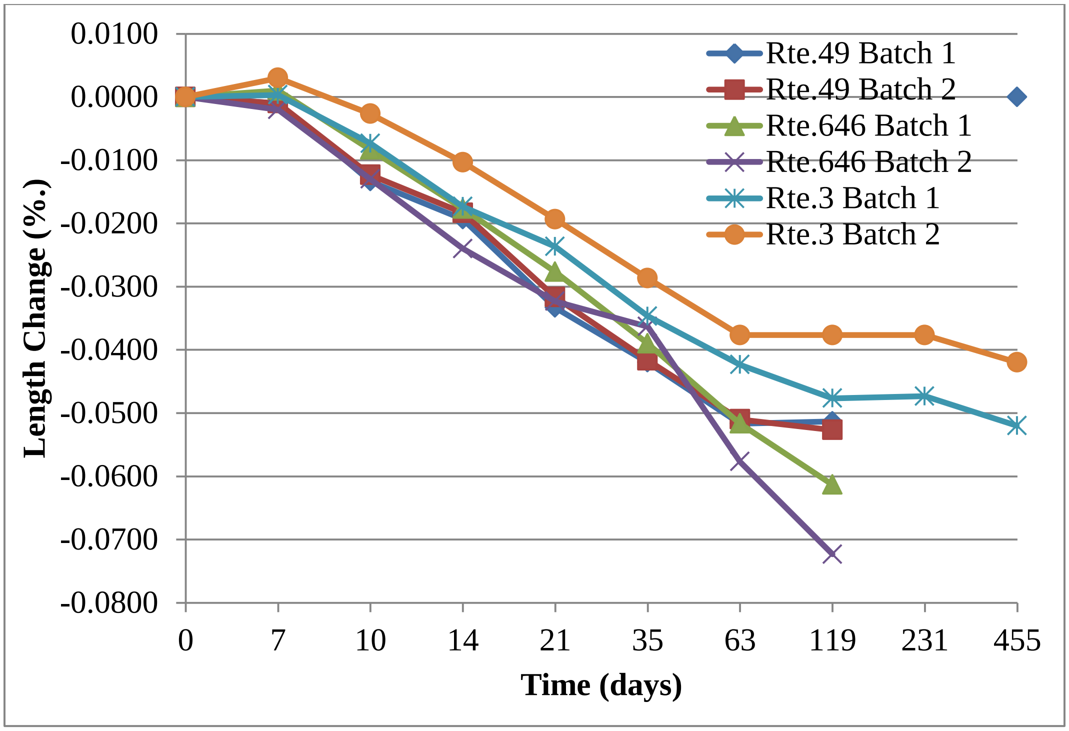

Figure 5. Drying Shrinkage Results for Route 646 Nokesville, Route 49 Crewe, and Route 3 Mathews County

Table 9. Hardened Concrete Properties for I-95 HOV Lane Stafford

Hardened Property	**2/20/14**	
	Batch 1	**Batch 2**
Compressive Strength, psi		
3-day	1120	1250
7-day	1850	2290
28-day	4380	4850
Elastic Modulus 28-day (10^6 psi)	2.78	2.83
Splitting Tensile Strength, psi	465	510
Permeability, coulomb, C	522	473
Freeze-Thaw Durability		
Weight loss (%)	6.2	5.2
Durability factor	109	108
Surface rating	0.6	1.1

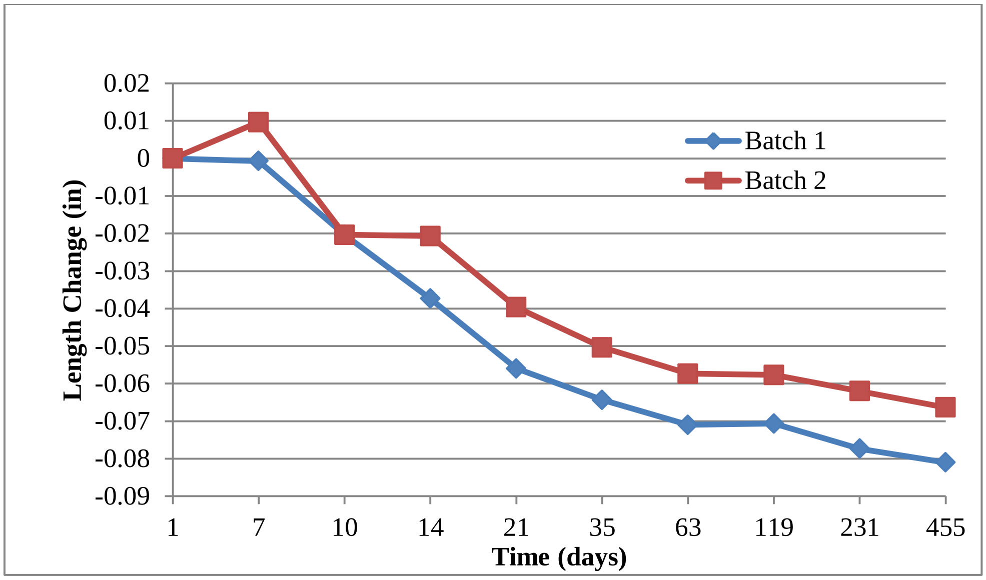

Figure 6. Drying Shrinkage Results for I-95 HOV Lane Stafford

Crack Surveys

Construction Year 2012

Route 657 Winchester

The condition surveys were conducted on 1/31/13 and 2/4/14. There were no cracks on the deck during either survey.

Route 128 Lynchburg

The condition surveys were conducted on 3/13/13 and 2/21/14 at ages of 6 months and 17 months, respectively. There were no transverse cracks on the deck. Very small longitudinal cracks (2 to 3 in long with a width less than 0.08 mm) were found in the deck during the survey. These cracks will have little if any impact on the performance of the decks.

Route 15 Opal

During inspection after the first winter on 9/27/13, no cracks were visible on the deck. 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 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 11/11/13.

Another condition survey was conducted on 2/24/14. There were no cracks on the LWC deck; however, the cracks at the NWC approach slab were a similar length but a little wider than before; about 0.4 mm to 0.5 mm at the east end and 0.5 mm to 0.6 mm at the west end. The increase in width from the previous September survey was attributed mainly to the cooler temperature. One other observation was the apparent scaling at a portion of the closure pour that had LWC, as shown in Figure 7. Since it was restricted to a small area, it was attributed to poor finishing practices. The rest of the deck including the closure pour was in good condition.

Figure 7. Scaling at Closure Pour of Route 15 Opal Bridge at Lower Middle Portion of Photograph

Construction Year 2013

Route 49 Crewe

The initial condition survey was conducted on 5/20/14 at an age of 7 months. There were no cracks on the deck.

Route 646 Nokesville

As mentioned before, Route 646 Nokesville was constructed in two stages using four placements. The eastbound lane comprised Placements 1 and 2. The condition survey of Route 646 Nokesville was conducted on 6/5/14 at an age of 10 months. The crack survey (Figure 8) showed that the eastbound lane had serious cracking issues, including the closure pour. On the eastbound lane, Placement 1 (Spans 2 and 3) had crack density of 0.15 ft/ft^2 and Placement 2 (Span 3 and two closure pours) had a crack density of 0.13 ft/ft^2. In Spans 1 and 3, there were very large transverse cracks. Several longitudinal cracks were also found in the eastbound lane. The westbound lane was placed on a different day, and there were no cracks in the deck, including the closure pour. The cracks in the eastbound lane may be attributed to a lack of pre-saturation of lightweight aggregate prior to mixing, which resulted in inconsistent quality concrete with varying strengths.

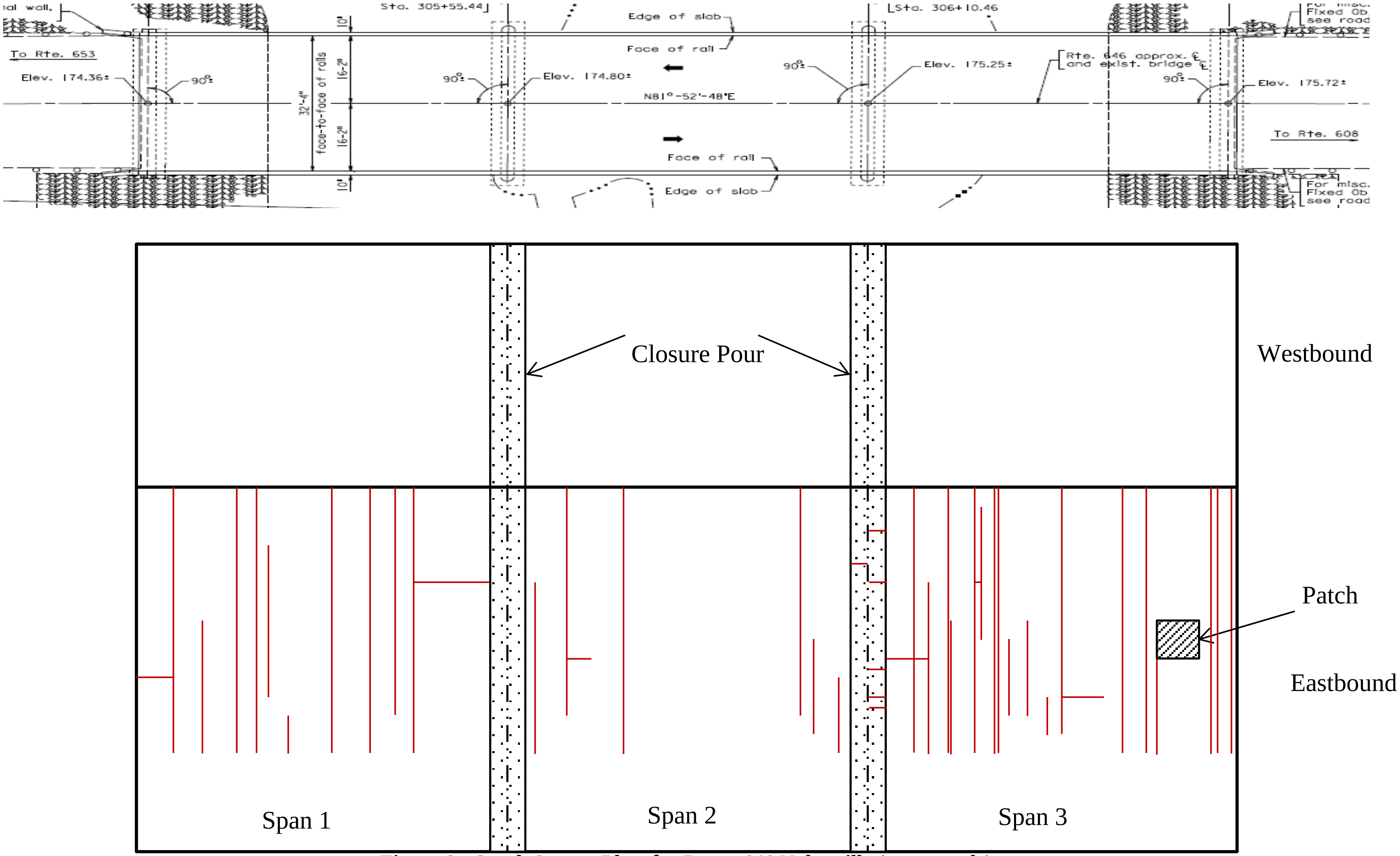

Figure 8. Crack Survey Plots for Route 646 Nokesville (not to scale)

Route 3 Mathews County

The initial condition survey of Route 3 Mathews County was conducted at an age of 22 months. The bridge was in good condition with no transverse cracks. However, there were a few cracks on the closure pour, which had also LWC.

Construction Year 2014

I-95 HOV Lane Stafford

The condition surveys of I-95 HOV Lane Stafford were conducted on 5/27/14 and 11/19/14 at ages of 3 months and 9 months, respectively. There were no cracks on the deck. However, several cracks were found in the approach slab, which had NWC.

CONCLUSIONS

- *Bridge decks with reduced or no cracks can be constructed with LWC mixtures.*

- *Properly air-entrained LWC made with high-quality lightweight aggregate provides satisfactory resistance to cycles of freezing and thawing.*

- *Pre-soaking of lightweight aggregate is very important in obtaining consistent quality LWC and reducing cracking.*

- *Low-permeability LWC can be produced with supplementary cementitious material.*

- *Reduced cracks or no cracks on the deck indicate the benefits of LWC.*

- *VDOT uses 0.035% at 28 days as the maximum shrinkage for the NWC used in bridge decks. However, the LWCs used in this study had values as high as 0.060% and did not crack. This shows the benefits of the lower elastic modulus, internal curing, and the lower coefficient of thermal expansion of LWC.*

- *Decks can be successfully placed using LWC with a cementitious content below 650 lb/yd^3 while meeting strength and permeability requirements. Lower cement, water, and paste contents are always desirable to lower cracking, including those related to drying shrinkage. The industry accepts that LWCs with a maximum cementitious material content of 650 lb/yd^3 can be prepared and placed successfully.*

RECOMMENDATIONS

1. *VDOT's Materials Division and Structure and Bridge Division should continue to use LWC in bridge deck concrete mixtures. Further, VDOT's Structure and Bridge Division should encourage the use of LWC in bridge decks by incorporating this recommendation into the Manual of the Structure and Bridge Division.*

2. *VDOT's Materials Division and Structure and Bridge Division should specify a maximum cementitious content of 650 lb/yd^3 and maximum fresh unit weight of 120 lb/ft^3 for LWC bridge deck mixtures.*

BENEFITS AND IMPLEMENTATION

Benefits

In 2002, a study estimated that the annual direct costs associated with corrosion of highway bridges totaled $8.3 billion. The indirect costs to the users were 10 times that value (Yunovich et al., 2002). Cracking in bridge structures is mainly attributable to moisture loss and temperature change. 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.

LWC is expected to be durable in bridge decks because of the reduced cracking attributed to the modulus compatibility between the paste and the lightweight aggregates, reduced elastic modulus, and internal curing. Another advantage of using LWC is the reduced weight, which allows widening of bridges without the need to reinforce or add substructure elements such as piles, which reduces both the cost and the environmental impact. The increased durability of LWC leads to a longer lasting material that will reduce future maintenance and repair costs.

Implementation

In Recommendation 1, the study recommended that VDOT's Materials Division and Structure and Bridge Division continue to use LWC in bridge deck concrete mixtures and that the Structure and Bridge Division should encourage the use of LWC in bridge decks by incorporating this recommendation into the *Manual of the Structure and Bridge Division*

In Recommendation 2, the study recommended that VDOT's Materials Division and Structure and Bridge Division specify a maximum cementitious content of 650 lb/yd^3 and a maximum fresh unit weight of 120 lb/ft^3 for LWC bridge deck mixtures. This recommendation has been accepted and implemented. The recommendation was incorporated into the 2016 VDOT *Road and Bridge Specifications.* Several ongoing projects are currently using LWC in bridge decks.

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