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Evaluation of Bridge Deck With Shrinkage-Compensating Concrete

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HARIKRISHNAN NAIR, Ph.D., P.E.
Research Scientist

CELIK OZYILDIRIM, Ph.D., P.E.
Principal Research Scientist

MICHAEL M. SPRINKEL, P.E.
Associate Director

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530 Edgemont Road, Charlottesville, VA 22903-2454
www.VTRC.net

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16. Abstract:

Concrete bridge decks are susceptible to premature cracking and to corrosion of reinforcing steel. Low-permeability concrete does not always ensure durability if the concrete has excessive cracks that facilitate the intrusion of aggressive solutions. Cracks in concrete can occur when a restrained mass of concrete changes volume including drying shrinkage because of water loss. These types of shrinkage cracks can be counteracted with the use of shrinkage-compensating concrete (SC concrete). SC concrete is expansive cement concrete that when properly restrained by reinforcement can expand an amount equal to or slightly greater than the anticipated drying shrinkage.

The purpose of this study was to investigate the effectiveness of SC concrete using Type K expansive cement in reducing cracks in bridge decks. The bridge deck on the Route 613 Bridge over the South Fork Shenandoah River in Warren County in the Virginia Department of Transportation's Staunton District was selected for study. Restrained length change bar specimens showed expansion until the 7-day moist curing period (when tested in accordance with ASTM C878).

The results showed that a bridge deck with fewer transverse cracks than typically found in decks constructed with Type I/II cement can be constructed with Type K cement concrete. There were several longitudinal cracks (reflective cracks) caused by the differential movement of the beams at the keyway that could not be prevented by the use of SC concrete. No special construction equipment or techniques are required for satisfactory placement of SC concrete, but slump loss under hot weather conditions is a more serious problem in SC concrete than in normal portland cement concrete. Hence, for successful placement of Type K cement concrete, sufficient prior planning and proper mix design development are needed. Another concern is the availability and cost of Type K cement since it is not routinely used.

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FINAL REPORT

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Harikrishnan Nair, Ph.D., P.E.
Research Scientist

Celik Ozyildirim, Ph.D., P.E.
Principal Research Scientist

Michael M. Sprinkel, P.E.
Associate Director

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FINAL REPORT

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Harikrishnan Nair, Ph.D., P.E.
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INTRODUCTION

Early deterioration of concrete bridge decks has serious implications both financially and with regard to public safety. A shortened service life of the bridge deck, higher maintenance costs and frequency, and corrosion of reinforcing steel are some of the consequences of deck cracking. According to the Federal Highway Administration (2015), as of December 2014, there were more than 30,000 deficient bridges on the National Highway System. The dollar impact of corrosion on highway bridges is considerable. The average annual direct cost of corrosion for highway bridges was estimated to be $8.29 billion (Yunovich et al., 2005). Thus, the corrosion of the reinforcing steel (Virmani and Clemeña, 1998) mainly attributed to bridge deck transverse cracking and the application of deicing chemicals containing chloride is costly (McLeod et al., 2009).

Cracks in concrete can occur when a restrained mass of concrete changes volume. Drying shrinkage, autogenous shrinkage, plastic shrinkage, thermal shrinkage, and creep are the leading causes of volume change in concrete (Saadeghvaziri and Hadidi, 2002). Certain types of shrinkage can be counteracted with the use of shrinkage-compensating concrete (SC concrete). According to American Concrete Institute (ACI) Committee 223 (ACI 223R-10, 2010), SC concrete is expansive cement concrete that when properly restrained by reinforcement can expand an amount equal to or slightly greater than the anticipated drying shrinkage. Because of the restraint, compressive stresses will be induced in the concrete during expansion. Subsequent drying shrinkage will reduce these stresses. Ideally, a residual compression will remain in the concrete, minimizing the risk of shrinkage cracking (Mehta and Monteiro, 2014). Although the SC concrete will shrink as much as normal concrete once exposed to drying conditions, the net shrinkage will be negligible because the concrete started out with an initial expansion. Folliard et al. (1994) found that SC concrete will expand under restraint by approximately 0.04% to 0.06% during the moist-curing period and will shrink approximately equal to the initial dimension upon drying. It is assumed that shrinkage of conventional plain concrete ranges from 0.04% to 0.08% and that of reinforced concrete from 0.02% to 0.03% (Kosmatka et al., 2003).

Construction techniques involving SC concrete are critical for the development of proper expansion.

Two different SC concretes, which are commercially available, are based on calcium sulfoaluminate (Type K) and calcium oxide (Type G), respectively. The expansion in the Type K and Type G systems is driven by the formation of ettringite and calcium hydroxide, respectively. The main difference between Type K and Type G concretes is the rate of expansion: Type G concrete expands at a faster rate (Chaunsali et al., 2013).

Pittman et al. (1999) noted that the SC concrete bar specimens tested in their study exhibited significant early expansion during the first 7 days as long as moist-curing was maintained for this period. In addition, they compared the initial expansion of Type K cement, used for SC concrete, and Type I cement. When proper moist curing was used, Type K cement expanded up to 4 times as much as the Type I cement. The mechanism of expansion in the Type K cement concrete is a result of the early formation and stability of ettringite. The ettringite crystals need water to expand; therefore, moist curing must be used or else minimal expansion will occur.

PURPOSE AND SCOPE

The purpose of this study was to investigate the effectiveness of SC concrete using Type K expansive cement in reducing cracks in bridge decks.

The bridge deck on the Route 613 Bridge over the South Fork Shenandoah River in Warren County in the Virginia Department of Transportation's (VDOT) Staunton District was selected for the use of Type K cement concrete. The bridge has four prestressed box beam spans, each 80 ft long. The bridge has a width of 28 ft and has no skew. A 5-in-thick concrete overlay with corrosion-resistant reinforcement at a depth of 2.25 in from the top surface was used. Pre-blended Type K expansive cement was used rather than mixing the expansive additive with cement in the concrete mixing truck.

METHODS

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

1. A literature review was conducted to document the use of SC concrete in bridge decks.

2. Trial batches were made for the proposed Type K mix designs.

3. A pre-placement meeting was attended before construction.

4. Bridge deck placement details were documented.

5. Concrete mixtures were sampled and tested for fresh and hardened concrete properties.

6. Field evaluations of the bridge deck were conducted through crack surveys at varying intervals.

Literature Review

Relevant literature was identified by searching various databases such as TRID, TLCat, WorldCat, and the Transportation Research Board's Research in Progress (RiP) and Research Needs Statements (RNS) databases.

Trial Batches

To determine an optimal mix design, two initial trial batches were made at the concrete producer's plant in Winchester, Virginia. Total cementitious contents of the two batches were 658 lb/yd^3 and 715 lb/yd^3, respectively. Twenty percent of the total cementitious material was Class F fly ash. Complete mix designs are shown in Table 1. The water–cementitious materials ratio (w/cm) was 0.48. A higher w/cm is needed for Type K cement concrete for the ettringite formation and for maintaining workability.

Commercially available air-entraining, retarding, and water-reducing admixtures were used. 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). From the trial batches, hardened concrete specimens were subjected to compressive strength, elastic modulus, and permeability testing. The free shrinkage was measured in accordance with ASTM C157, and the restrained expansion was measured in accordance with ASTM C878. The dimensions of the test specimens for the latter are similar to the prism for the former. ASTM C878, however, differs from ASTM C157 in that the test specimen is restrained using a threaded low-carbon ¼-in-diameter rod and two end plates.

Trial batches were also made at the Virginia Transportation Research Council (VTRC) to evaluate fresh and hardened concrete properties further for the final mix design.

Table 1. Trial Batch Mix Designs

Ingredient	Trial Batch 1 (658 lb cementitious)	Trial Batch 2 (715 lb cementitious)
Cement (lb)	526	572
Fly ash (lb)	132	143
Coarse aggregate (lb)	2080	2080
Sand (lb)	838	713
Water (lb)	321	349
w/cm	0.48	0.48
Admixtures	Retarding and water-reducing	Retarding and water-reducing
	Air-entraining	Air-entraining

Pre-Placement Meeting

A pre-placement meeting was organized by the VDOT Staunton District and was attended by district construction and materials staff, a contractor representative, the concrete producer, VTRC research staff, and a Type K cement manufacturer's representative.

Field Placement Documentation and Fresh Concrete Properties

Bridge deck construction details were documented, including the concrete placement method (pumping and other possible methods as a backup). Concrete temperature, air temperature, relative humidity, and wind speed were also monitored throughout the project.

Hardened Concrete Properties of Field Samples

Concrete mixtures were collected from different truck loads, and specimens were prepared for hardened concrete testing. Table 2 provides a list of the hardened concrete properties tested and their respective specification. Three specimens each were used for testing compressive strength, elastic modulus, splitting tensile strength, restrained expansion, and drying shrinkage. Two samples each were used for freeze-thaw and permeability testing. Drying shrinkage and restrained expansion test 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 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 2. 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)
Restrained expansion	ASTM C878	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 the bridge deck 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

Literature Review

An AASHTO study that polled U.S. state departments of transportation on their use of Type K cement for bridge decks produced variable results (AASHTO, unpublished data). Of the 26 states that responded, only Kentucky allowed the use of Type K cement without special approval. Those states that did not allow the use of Type K cement cited reasons such as a high w/cm, high permeability, poor freeze-thaw durability, and marginal crack reduction for the higher cost of the product.

Based on a review of the Ohio Turnpike Commission's bridge deck construction practices regarding the mixing, hauling, and placing of SC concrete using Type K cement, which were refined by the commission over an 11-year period, a pre-placement meeting to address the batching, mixing, hauling, and placement of the SC concrete is imperative (Phillips et al., 1997). As SC concrete loses slump faster than Type I portland cement concrete (PCC) mixtures, a plant slump of 7 in is recommended to achieve a placement slump of 4 in to 6 in (Phillips et al., 1997). With its higher slump requirements, SC concrete with Type K cement can be easier to place and finish, which may reduce labor costs, especially for decks of 300 yd^3 or more (Grunner and Plain, 1993).

Construction practices are of chief concern during the placement of SC concrete as it has several properties that will cause its crack-reducing capabilities to fail if they are not addressed during placement (Ramey et al., 1997). To ensure proper mixing, Type K cement should be mixed for 70 revolutions or for a timed 5-minute period at mixing speed (Ramey et al., 1997). The increased water content makes SC concrete susceptible to slump loss; therefore, pre-soaking of the aggregate is imperative, especially when high absorption aggregates such as gravel or lightweight aggregate are used and during hot weather (Phillips et al., 1997). Failure to do so will reduce slump, accelerate setting time, cause plastic shrinkage, and may increase the temperature of the mixture. In addition, special attention must be paid to determine accurately the free surface water of the aggregate before and during placement (Lindquist et al., 2008). Because of the higher cohesion of SC concrete mixtures as compared with PCC mixtures and the additional space required for proper mixing, the concrete must be proportioned such that the volume is at least 2 yd^3 less than the capacity of the mixing truck (Phillips et al., 1997).

Air entrainment of SC concrete is not appreciably different from that of PCC and air losses attributable to pumping are not unusual (Phillips et al., 1997). Neither special construction equipment nor special techniques are required for satisfactory placement of SC concrete; however, SC concrete is much more sensitive to continuous wet curing, which should be initiated very early (Ramey et al., 1997). In addition, the rate of slump loss is greater for SC concrete and thus renders it more sensitive to delays at the jobsite and long haul distances when ready-mixed concrete is used. The ability of SC concrete to minimize cracking depends on water curing for 7 days. It is essential that water curing and protection of the concrete are provided as discussed in ACI 301 and ACI 308.1 (ACI 223R-10, 2010). SC concrete will exhibit little or no bleed water; therefore, care must be taken to begin finishing operations as early as possible (Grunner and Plain, 1993). SC concrete with Type K cement is more cohesive than PCC mixtures, and therefore resists the tendency to segregate, and pumps more easily. Because of its higher slump, reduced tendency to segregate, and greater sensitivity to time delays, it is highly recommended that SC concrete with Type K cement be placed by pumping (Phillips et al., 1997).

Trial Batch Test Results

Fresh and hardened concrete properties of the trial batch prepared at the plant are shown in Table 3. Cylinders were tested for compressive strength at 7 and 28 days. Trial Batch 1 did not meet the strength criterion of 4,000 psi at 28 days. Both trial batch mixtures had low permeability attributed to the addition of Class F fly ash. The full amount of mixing water was not added since both mixtures showed good workability, and hence the effective w/cm was about 0.46. The concrete temperature was 70 °F. Restrained expansion testing was not performed on these mixtures.

Additional trial batches were made in the VTRC concrete laboratory on 2/26/14 and 6/10/14 using 715 lb/yd^3 cementitious material and a w/cm of 0.48. The results are shown in Table 4. A restrained expansion test was performed on Batch 4 specimens (in accordance with ASTM C878). Specimens were removed from the mold after 6 hours, and initial readings were taken. The average 7-day restrained expansion was 0.037% with a maximum expansion of 0.04% (after 1 day). The 28-day drying shrinkage tested in accordance with ASTM C878 and ASTM C157 showed low values. The initial slump value for Trial Batch 4 was 6.5 in, which after 45 minutes decreased to 4.25 in. The concrete temperature was 73 °F for Trial Batch 4. It was decided by the research team to use mixture with 715 lb/yd^3 cementitious material for field placement because of workability and to ensure sufficient expansion.

Table 3. Type K Trial Batch Test Results

Parameter	Trial Batch 1 (658 lb cementitious) 2/4/14	Trial Batch 2 (715 lb cementitious) 2/4/14
Compressive Strength (psi)		
7 Days	2780	4140
28 Days	3850	5710
Elastic Modulus, 7 days (*10^6 psi)	4.13	4.63
Permeability (coulomb, C)	925	475
Fresh Concrete Properties		
Slump (in)	7	8
Air content (%)	6.4	6.0
Unit weight (lb/ft^3)	146.8	147.0

Table 4. Additional Trial Batch Test Results

Parameter	Trial Batch 3 (715 lb cementitious) 2/26/14	Trial Batch 4 (715 lb cementitious) 6/10/14
Compressive Strength (psi)		
7 Days	2720	2880
28 Days	3940	4040
Elastic Modulus (*10^6 psi)		
7 Days	3.31	3.33
28 Days	3.81	4.01
Permeability (coulomb, C)	1156	1299
Restrained Expansion (%) 7 days	-	0.0373[a]
Maximum Expansion	-	0.0407 (1day)
Drying Shrinkage (%) (ASTM C878), 28 days	-	0.0023
Drying Shrinkage (ASTM C157), 28 days (%)	-	-0.0187[b]
Fresh Concrete Properties		
Slump (in)	4.8	6.5 (after 15 min), 5 (after 30 min), 4.2 (after 45 min)
Air content (%)	7.2	5.1
Concrete temperature (°F)	73	73
Unit weight (lb/ft^3)	153.6	152.4

[a] Positive sign indicate expansion.
[b] Negative sign indicates shrinkage.

Pre-Placement Meeting

At the pre-placement meeting, it was decided by the district construction staff to do a dry run to determine deck depths and steel clearance and to raise the concrete finish grade by 1 in over plan elevation to maintain the required 5-in minimum overlay depth. The concrete producer decided to run a test batch before placement to check the slump loss over time and to determine admixture dosages. Contingency plans for a breakdown of equipment during placement were discussed. Allowable slump range was adjusted to 4 in to 6 in, and the maximum concrete temperature was limited to 85 °F.

A field inspection was performed prior to the deck placement. During the field inspection, it was found that epoxy resin used to apply fiber strips to the box beam joints was spread out beyond the edge of the strips (Figure 1). Sand was not applied to the excess epoxy and the cured epoxy without sand would not allow for good bonding of the SC concrete overlay. To provide a better bonding surface, grooves (approximately 1/8 in wide) were made through the epoxy with a 4-in grinder. Reinforcing steel for the overlay was designed to have 2.75-in clearance above the box beams. This clearance was not met at many locations, and in some locations the reinforcing steel was touching the box beams. Plastic chairs were used to correct the rebar depth over the box beams.

Figure 1. Box Beam Joints With Fiber Strips

Field Placement Documentation and Fresh Concrete Properties

Initial placement was scheduled on 7/16/14. The concrete was placed by pumping. The contractor used a 5-in-diameter slickline that was reduced to a 4-in diameter to pump the concrete. Blockage occurred in the slickline, and pumping was stopped. In addition, the concrete at the end of the slickline showed heavy segregation and the entire mixture was removed. At the truck, the mixture looked cohesive and no segregation was found. A severe slump loss and a temperature gain of 10 °F occurred between the plant and the jobsite. The concrete mixture had a temperature of 85 °F. It was further noted that the temperature of the aggregate stock pile was 94 °F.

It was decided by the contractor to use a continuous pump line diameter of 5 in with a higher pumping capacity. It was also decided by the research team and concrete producer to use a hydration stabilizer and a high-range water-reducing admixture. Proper mixing of the stockpile during watering may aid in the cooling of the aggregate for future projects.

A 4 yd^3 trial batch was made using hydration stabilizing admixture (instead of retarding admixture) and a high-range water-reducing admixture. The trial batch had an initial slump of 7.5 in, an air content of 11%, and a temperature of 80 °F. After 45 minutes, the slump was recorded to be 4 in and the temperature had risen to 82 °F. To increase the slump, 1 gal/yd^3 of water was added to the mixture (of 2 gal/yd^3 water withheld). After the withheld water was added, the trial batch had a slump of 5 in, an air content of 8.4%, and a temperature of 85 °F. After 1 hour and 15 minutes and after the remaining withheld water of 1 gal/yd^3 was added, the trial batch had a slump of 5.5 in and a temperature of 84 °F. Based on the results, it was decided by the research team to use this mix design for the remaining placements.

The second placement occurred on 7/25/14. Figure 2 shows concrete placement by pumping, and Figure 3 shows wet burlap placement immediately after screeding and compaction. Each truckload contained 8 yd^3 of concrete (2 yd^3 less compared to A regular concrete mix truck load). The average w/cm was 0.47. At the plant, the average slump was 8 in, the average air content was 7.7%, the average concrete temperature was 61 °F, and the average unit weight was

146.0 lb/ft^3. Field levels were as follows: an average slump of 5.6 in, an average air content of 7.4%, and an average concrete temperature of 70 °F. The evaporation rate at the site averaged 0.017 lb /ft^2/hr, and slump loss averaged 2.4 in from the plant to the site. Detailed evaporation rates and fresh concrete properties are shown in Tables 5 and 6, respectively.

Figure 2. Concrete Placement by Pumping

Figure 3. Wet Burlap Placement Immediately After Screeding and Compaction

Table 5. Evaporation Rate Calculated for Pour on 7/25/14

Truck Load	Air Temperature (°F)	Concrete Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Evaporation Rate (lb/ft^2/hr)
1	65	66	1.0	86	0.009
2[a]	64	65	0.0	86	0.006
3	66	68	1.2	89	0.009
4[a]	64	71	1.4	92	0.017
5	65	70	4.4	88	0.026
6	64	72	2.6	89	0.029
7	63	74	0.0	90	0.018
8	62	72	0.0	93	0.014
9	63	72	1.5	94	0.025
10	63	71	1.8	89	0.024
11	66	73	0.0	85	0.015
12	74	69	1.6	65	0.014

[a]Samples were taken for hardened concrete testing.

Table 6. Fresh Concrete Properties for Pour on 7/25/14

Truck Load	Slump (in)	Air Content (%)	Concrete Temp (°F)	Unit Weight (lb/ft^3)
1	7.5	7.8	66	143.2
2	6.8	8.7	65	144.4
3	6.2	8.0	68	145.6
4	6.0	9.0	71	143.2
5	6.0	7.0	70	148.0
6	5.2	6.2	72	148.8
7	4.5	7.2	74	147.6
8	4.0	5.8	72	149.2
9	4.2	7.2	72	146.0
10	4.5	7.2	71	148.8
11	5.0	6.4	73	148.0
12	7.0	8.5	69	145.6

The third placement occurred on 7/30/14. The average w/cm was 0.47. At the plant, the average slump was 7.3 in, the average air content was 8.2%, the average concrete temperature was 66 °F, and the average unit weight was 147 lb/ft^3. Field levels were as follows: an average slump of 5.6 in, an average air content of 6.1%, and an average concrete temperature of 68 °F. The evaporation rate at the site averaged 0.021 lb/ft^2/hr, and the slump loss averaged 1.7 in from the plant to the site. Detailed evaporation rates and fresh concrete properties are shown in Tables 7 and 8, respectively. The fresh concrete properties measured at the plant are shown in Appendix A for the 7/25/14 and 7/30/14 concrete placements.

For the concrete temperatures below 68 °F measured at the plant, the slump loss was below 4 in. Thus, if the slump values are kept above 8 in at the plant, a minimum of 4 in would be achieved at the jobsite, which is satisfactory for placement. SC concrete finished easily at these slump values.

Table 7. Evaporation Rate Calculated for Pour on 7/30/14

Truck Load	Air Temperature (°F)	Concrete Temperature (°F)	Wind Speed (mph)	Relative Humidity (%)	Evaporation Rate ($lb/ft^2/hr$)
1	56	65	0	75	0.016
2	55	65	0	89	0.014
3[a]	51	67	0	86	0.020
4	51	68	0	89	0.021
5	51	68	1.6	95	0.035
6[a]	52	68	1.8	94	0.034
7	53	69	0	97	0.020
8	51	68	0	95	0.020
9	54	69	0	95	0.019
10	52	68	0	96	0.019
11	57	68	0	92	0.015
12	56	73	0	82	0.026
13	57	70	0	85	0.019

[a]Samples were taken for hardened concrete testing.

Table 8. Fresh Concrete Properties for Pour on 7/30/14

Truck Load	Slump (in)	Air Content (%)	Concrete Temp (°F)	Unit Weight (lb/ft^3)
1	7	7.8	65	144.8
2	7	7.0	65	146.0
3	6.75	7.4	67	144.4
4	6.25	6.0	68	146.8
5	6.75	6.6	68	146.8
6	5.75	6.2	68	147.6
7	5.5	5.4	69	149.6
8	5.25	5.8	68	150.0
9	4	6.0	69	149.2
10	4.5	6.2	68	148.4
11	7	6.0	68	148.4
12	2.25	5.0	73	-
13	4.75	5.0	70	150.0

Hardened Concrete Properties of Field samples

The hardened concrete properties for each batch are shown in Table 9. The average values for two batches each day were as follows. The average 28-day strengths were 3,370 psi (average of Field Batches 1 and 2) and 4,450 psi (average of Field Batches 3 and 4) for Placements 1 and 2, respectively. The concrete strength was low in Field Batches 1 and 2 because of high air contents of 8.7% and 9.0%, respectively. The average elastic modulus and splitting tensile strength values were $3.37 * 10^6$ psi and 460 psi, respectively. Permeability values were low and ranged from 403 C to 1031 C, with an average value of 662 C. Average 28-day strengths for the district materials quality assurance samples (from three different truckloads) for Placement 1 were 4,060 psi, 4,010 psi, and 4,030 psi. The compressive strengths are expected to be lower than conventional deck concretes because of a higher w/cm; increased air contents also contributed to marginal strengths. The corresponding permeability values were 1057 C, 1055 C, and 1013 C, respectively. All specimens showed excellent results after freeze-thaw durability testing (Table 10). Figure 4 shows an example of specimens after 300 cycles of freeze-thaw testing.

Table 9. Hardened Concrete Properties of Field Batches

Property	Field Batch 1 (7/25/14)	Field Batch 2 (7/25/14)	Field Batch 3 (7/30/14)	Field Batch 4 (7/30/14)
Compressive Strength (psi)				
3 Days	1530	2220	2050	2730
7 Days	2280	2700	3010	3660
28 Days	3290	3440	4170	4720
Splitting Tensile Strength, 28 Days (psi)	465	505	415	-
Elastic Modulus ($*10^6$psi)				
7 Days	3.15	3.42	3.39	3.98
28 Days	3.06	-	3.32	3.75
Permeability (coulomb, C)	524	403	1031	691

Table 10. Freeze-Thaw Testing Results of Field Batches

Batch No.	Weight Loss (%)	Durability Factor	Surface Rating
1	2.44	111	1.09
2	1.96	105	1.10
3	0.83	102	0.53
4	1.35	103	0.83

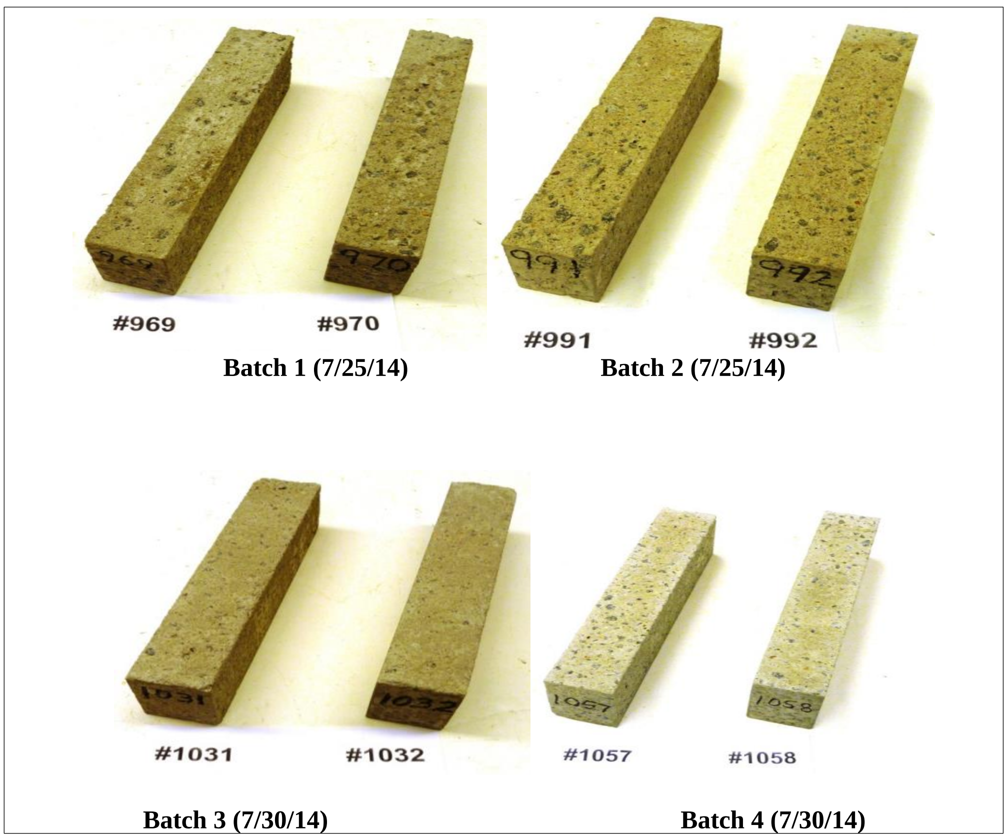

Figure 4. Specimens After 300 Freeze-Thaw Cycles

Specimens were tested in accordance with ASTM C878 and ASTM C157 for length change. The expansion results during the moist curing period are shown in Figures 5 and 6. The ASTM C157 samples were initially measured in 1-day increments for 7 days, starting with 24 hours after sampling. The ASTM C878 samples were initially measured 6 hours after sampling and then on the same 1-day increments as the ASTM C157 samples. Batch 2 specimens showed a lower expansion compared to others. The average 7-day expansion was 0.025%, with a maximum average value of 0.03%. ASTM C157 specimens showed less expansion. Although both length change test methods show initial expansion during the first 7 days, testing in accordance with ASTM C878 provides a more accurate representation of the expansion because of the initial measurement 6 hours after sampling. Most of the expansion happens immediately after placement, so the early measurement is critical in capturing the expansion.

After 7 days, all samples were subjected to drying, and the length change results are shown in Figures 7 and 8. Normal shrinkage occurs when water starts to evaporate from the concrete surface. The results of the ASTM C878 test method showed that the drying shrinkage values after a 28-day drying period for all specimens were below 0.01%. For all specimens, 230-day shrinkage values were below 0.04%. Corresponding values in accordance with the ASTM C157 test method were 0.04% and 0.06%, respectively.

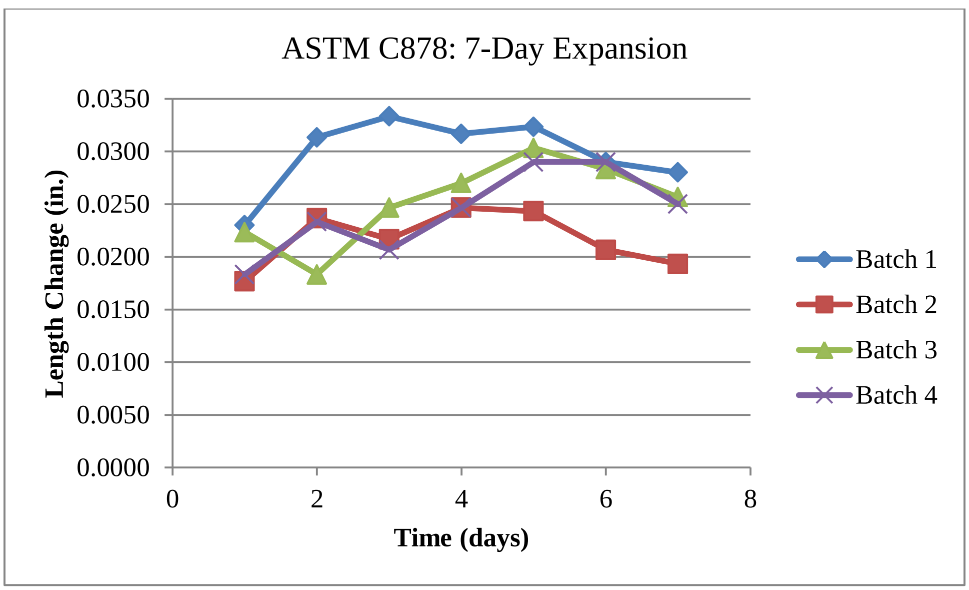

Figure 5. Expansion Results in Accordance With ASTM C878

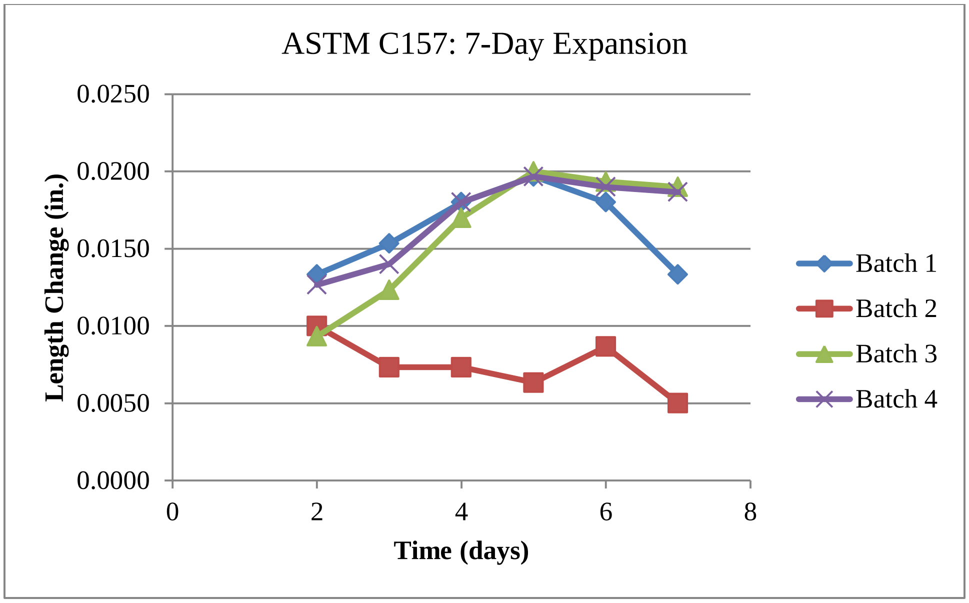

Figure 6. Expansion Results in Accordance With ASTM C157

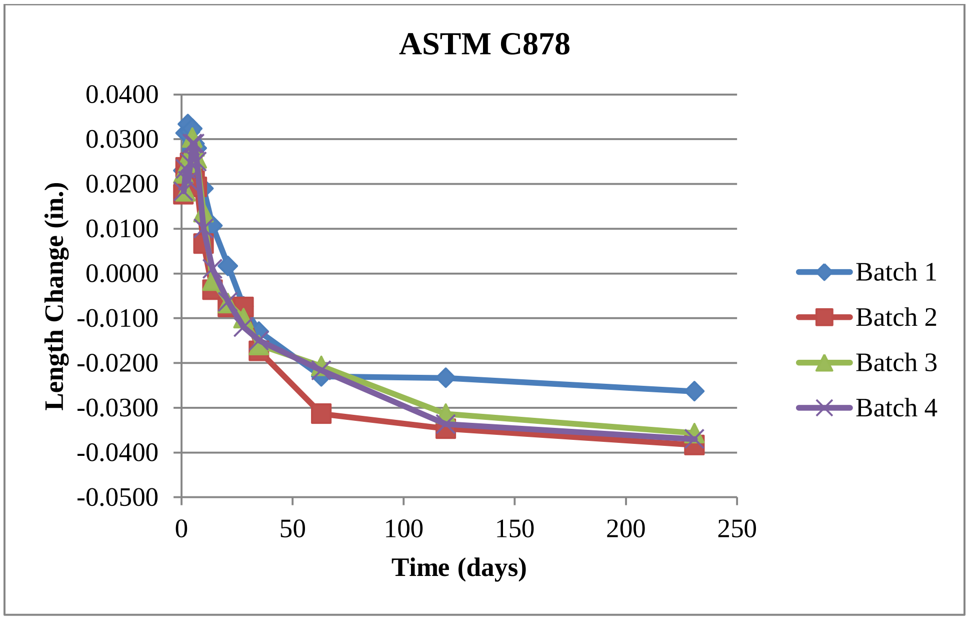

Figure 7. Shrinkage Results in Accordance With ASTM C878

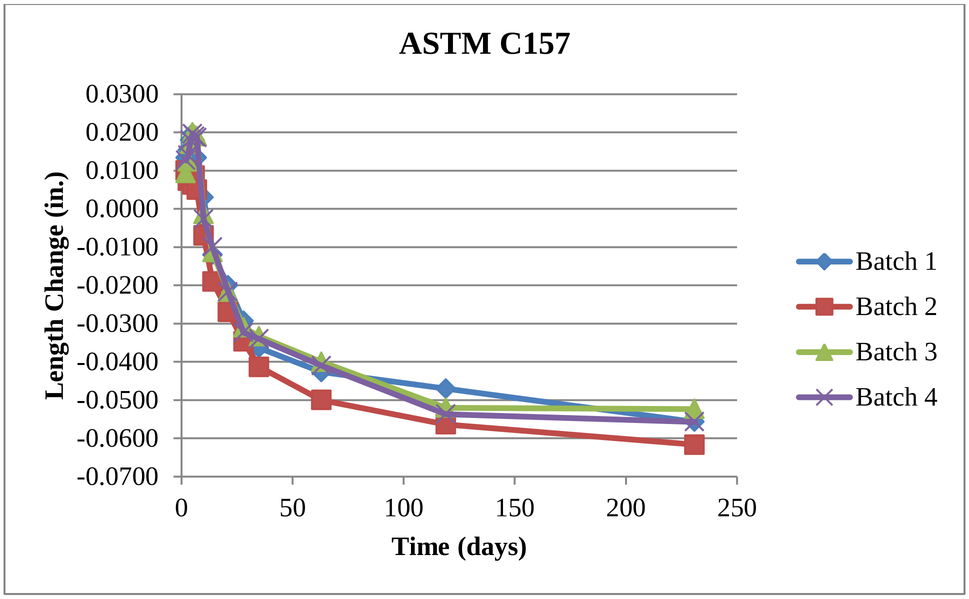

Figure 8. Expansion Results in Accordance With ASTM C157

Crack Surveys

The concrete placements were considered successful except for the initial placement because of the difficulty with the pump and the slickline. After curing was completed and the forms were removed, there was spalling of the concrete on one edge of the bridge (Figure 9).

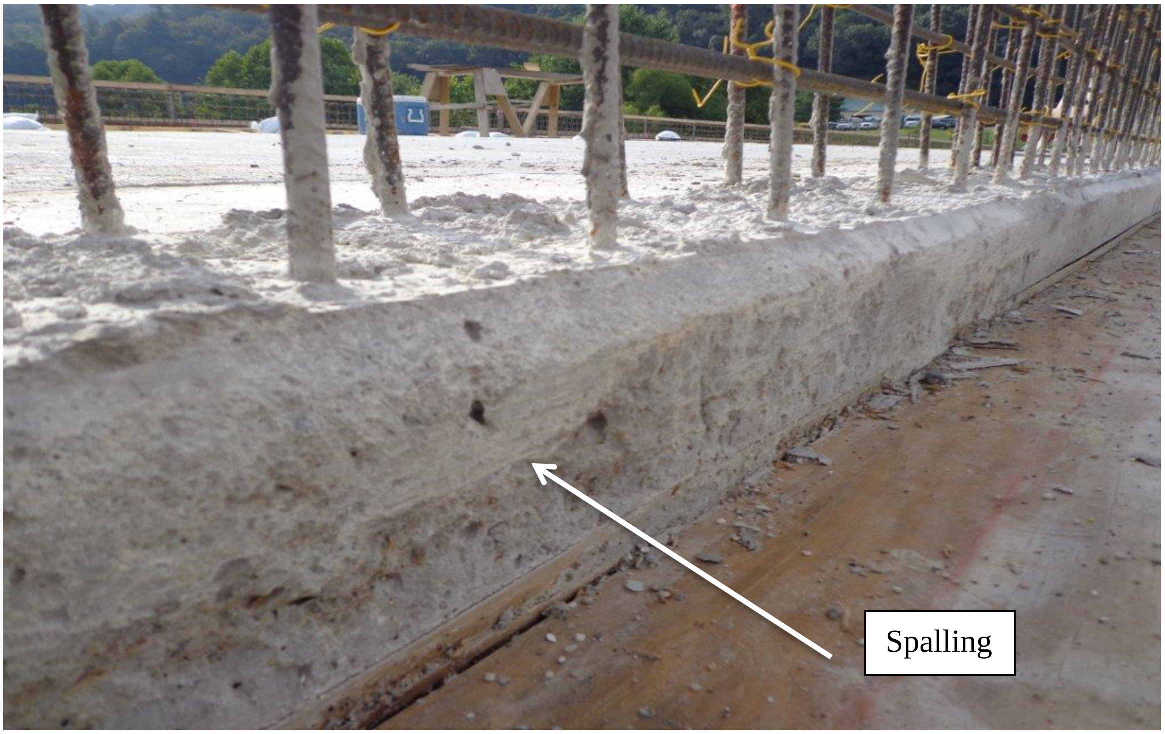

Figure 9. Spalling Along Edge of Route 613 Bridge During Form Removal

This occurred along an approximately 50-ft section. Spalling may have occurred because of segregation when the first placement over Spans C and D were vibrated for consolidation and screeded because of the higher slump. As a suggested remedy, District bridge staff recommended the application of an EP-3 sealer to the outside surface of the beams in lieu of patching the concrete surface with a grout that could possibly delaminate in the future. Treating the entire 320-ft span would provide a uniform appearance below the railing and seal the outer surface of the deck to match the beams below.

A field survey of the bridge deck was performed on 9/3/14 (6 weeks) to monitor cracking. During the inspection, two transverse cracks were found above Pier 1 and Pier 3. No other cracking was found at that time. A second field survey was performed on 12/16/14 (4.5 months) to monitor cracking in the bridge deck overlay. Several longitudinal cracks were found in the bridge spans. An additional transverse crack was also found above Pier 2. The location data, as well as lengths and widths, of the longitudinal and transverse cracks are described in Table 11. Approximate locations of longitudinal and transverse cracking in plan view and in cross section are shown in Figures 10 and 11, respectively. Based on the locations of the cracks in the bridge deck overlay (directly above box beam connections), reflective cracking is considered to be the cause of the longitudinal cracking. This type of cracking appears to be caused by the differential movement of the beams at the keyway and this relative movement between adjacent box beams is quite common.

Another condition survey was conducted on 10/29/15 at an age of 15 months. There were longitudinal cracks (reflective cracks) along the entire length of the bridge. Figure 12 shows reflective cracks directly above box beam connections. The average widths of these cracks ranged from 0.1 mm to 0.3 mm. Map cracking was found in a couple of locations in the deck surface. More transverse cracks over the piers were observed (crack width of 0.1 mm to 0.2 mm) compared to the previous survey.

Table 11. Crack Location Data

	Transverse Distance[a]	**Longitudinal Distance[b]**	**Length of Crack**	**Width of Crack**
Longitudinal				
Span A	20 ft 0 in	62 ft 0 in	13 ft 0 in	0.2 mm
Span B	16 ft 1 in	80 ft 0 in	18 ft 0 in	0.2 mm
	16 ft 2 in	119 ft 0 in	14 ft 4 in	0.2 mm
	16 ft 2 in	142 ft 0 in	9 ft 0 in	0.2 mm
Span D	16 ft 3 in	270 ft 0 in	5 ft 4 in	0.2 mm
Transverse				
Pier 1		80 ft 0 in	36 ft 0 in	0.2 mm
Pier 2		160 ft 0 in	36 ft 0 in	0.2 mm
Pier 3		240 ft 0 in	36 ft 0 in	0.2 mm

[a] Measured from eastern edge of bridge and across bridge width.
[b] Measured from southern end of bridge and along bridge length to starting point of crack.

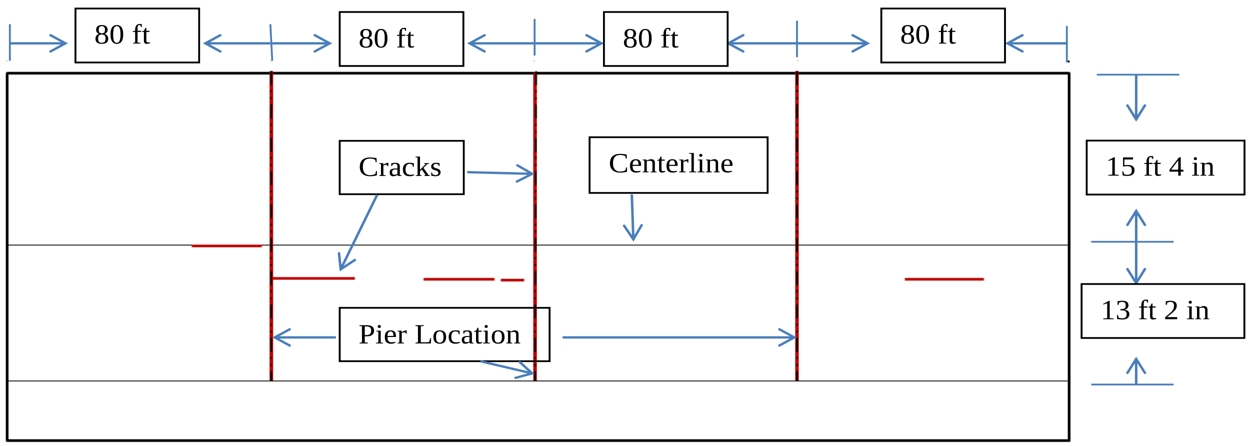

Figure 10. Approximate Locations of Longitudinal and Transverse Cracking in Plan View

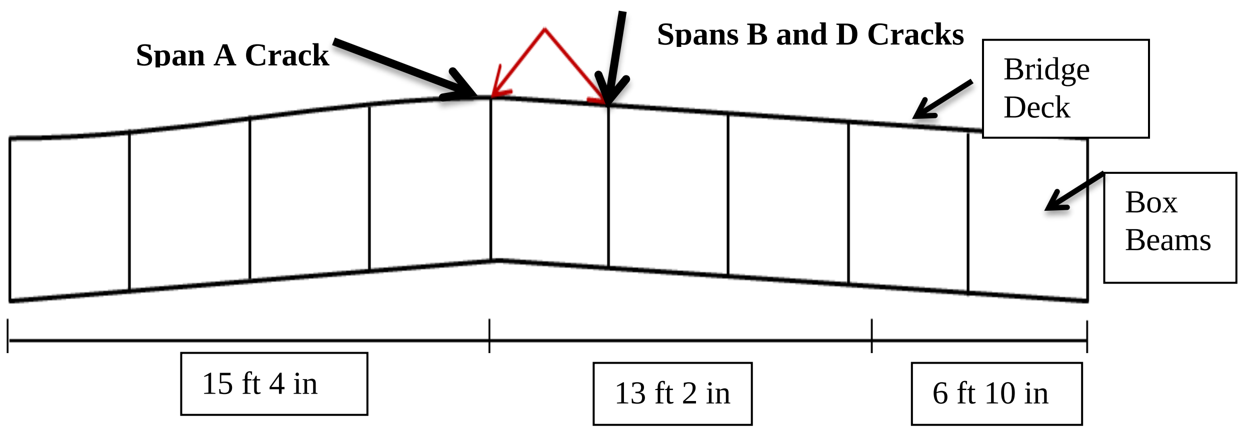

Figure 11. Approximate Locations of Longitudinal Cracking in Transverse Cross-Section View

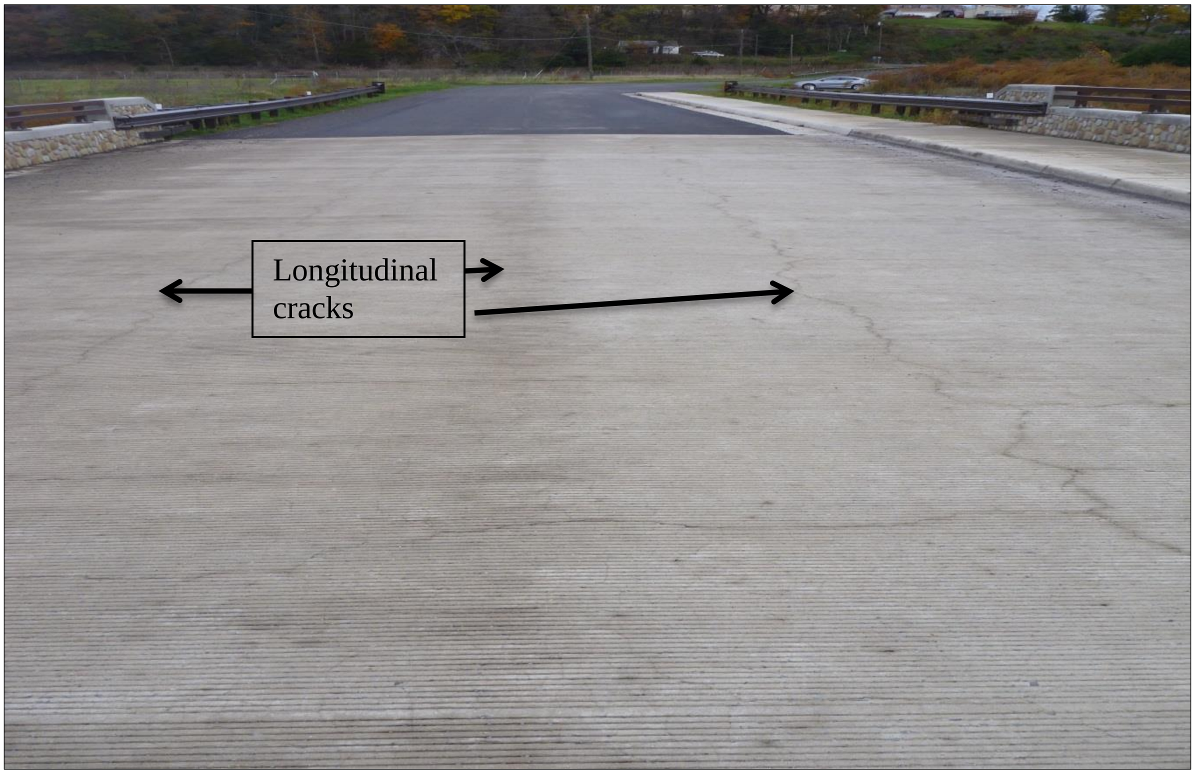

Figure 12. Longitudinal Cracks in Deck

CONCLUSIONS

- *For successful placement of Type K cement concrete, proper mix design development, 7-day moist curing, and sufficient prior planning are needed.*

- *Action must be taken to address slump loss under hot weather conditions. In this study, if the slump at the plant was kept above 8 in and the concrete temperature was kept below 68 °F, slump at the jobsite was above 4 in, which enabled satisfactory placement when a hydration controlling admixture was used.*

- *No special construction equipment or placement techniques are required for satisfactory placement of SC concrete, and the concrete is finished easily.*

- *The SC concrete length change bar specimens exhibit early expansion (first 7 days) as long as the concrete mixtures are exposed to moist curing. The expansion is followed by shrinkage after a 7-day wet cure period.*

- *The crack surveys indicated cracking with age that was attributed to reflective cracking over the longitudinal keyways between beams and the joints between the ends of the beams over the piers; however, cracks appear to be tight after 1 year of exposure. SC concrete cannot be expected to prevent reflective cracks over keyways and joints, which are typical in box beam bridges.*

- *Since the expansion starts very early in SC concrete, the length change tested by restrained concrete prisms (ASTM C878) provides a better indication of shrinkage than the length changed determined in accordance with ASTM C157.*

- *Concrete made with Type K cement and Class F fly ash can achieve permeability values below the specified limit of 2500 C.*

- *The 28-day compressive strength of concrete with Type K cement is lower than that of conventional concretes because of the higher w/cm.*

RECOMMENDATION

1. *VDOT's Materials Division and Structure and Bridge Division should continue to allow the use of Type K cement concrete in bridge deck concrete mixtures in accordance with the special provision provided in Appendix B as an option in the low-cracking deck provisions.*

BENEFITS AND IMPLEMENTATION

Benefits

By minimizing concrete cracking, the time between repair and rehabilitation of concrete structures can be increased for both new and existing structures. Reducing cracks in bridge decks benefits VDOT by providing longer lasting bridges. SC concrete made with Type K cement can be used to minimize or eliminate shrinkage cracking. Because full-depth transverse cracks allow water and chloride leakage through the deck to the supporting superstructure and substructure units below, fewer, shorter, and tighter cracks along with corrosion-resistant reinforcement will extend the service life of bridge decks and reduce maintenance costs.

The addition of Type K cement will increase the cost of concrete to about $50 to $60 per cubic yard. When considered against the total cost of the bridge, the increase is less significant. These additional costs are expected to be offset by the maintenance savings realized over the service life of the structure. However, it should be noted that SC concrete requires special attention in placement in addition to the increased cost. VDOT has other options in addition to SC concrete for reduced deck cracking. For a given project, the designer has the option of selecting one among several options for optimized conditions. One other concern with Type K cement is the availability. Most ready-mixed plants do not have Type K cement at their plants and would not be interested in dedicating a silo to this special cement.

Other studies conducted at VTRC have found that the use of lightweight concrete or normal weight concrete with shrinkage reducing admixture is effective in minimizing bridge deck cracking and is expected to be a lower cost option compared to the use of concrete with Type K cement. However, since Type K concrete provides crack control, it is kept as a special provision and enables the contractor to select one among several options for optimized condition.

Implementation

The study recommendation was approved, and the special provision provided in Appendix B will be used for future projects using Type K cement.

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REFERENCES

American Concrete Institute. ACI 223R-10: Guide for the Use of Shrinkage-Compensating Concrete. Reported by ACI Committee 223. Farmington Hills, MI, 2010.

Chaunsali, P., Li, S., Mondal, P., Foutch, D., Richardson, D., Tung, Y., and Hindi, R. *Bridge Decks: Mitigation of Cracking and Increased Durability*. FHWA-ICT-13-023. Illinois Center for Transportation, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 2013.

Federal Highway Administration. Deficient Bridges by State and Highway System. 2015. http://www.fhwa.dot.gov/bridge/deficient.cfm. Accessed July 28, 2015.

Folliard, K.J., Ohta, M., Rathje, E., and Collins, P. Influence of Mineral Admixtures on Expansive Cement Mortars. *Cement and Concrete Research*, Vol. 27, No. 3, 1994, pp. 424-432.

Grunner, P.W., and Plain, G.A. Type-K Shrinkage-Compensating Cement for Bridge Deck Concrete. *Concrete International*, Vol. 15, No. 10, 1993, pp. 44-47.

Kosmatka, S.H., Kerkhoff, B., and Panarese, W.C. *Design and Control of Concrete Mixtures*, 14th Edition. Portland Cement Association, Skokie, IL, 2003.

Lindquist, W., D. Darwin, and J. Browning. *Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture optimization, and concrete production.* Project No. TPF-5(051) University of Kansas Center for Research, Inc., Lawrence. November, 2008**.**

McLeod, H.A., Darwin, D., and Browning, J. *Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Construction Methods, Specifications, and Resistance to Chloride Ion Penetration.* University of Kansas Center for Research, Inc., Lawrence, 2009.

Mehta, P.K., and Monteiro, P.J. *Concrete: Microstructure, Properties, and Materials.* McGraw Hill Education, New York, 2014.

Pittman, D.W., Ramey, G., Webster, G., and Carden, A. Laboratory Evaluation of Concrete Mixture Designs Employing Type I and Type K Cement. *Journal of Materials in Civil Engineering,* Vol. 11, No. 2, 1999, pp. 144-150.

Phillips, M.V., Ramey, G.E., and Pittman, D.W. Bridge Deck Construction Using Type K Cement. *Journal of Bridge Engineering,* Vol. 2, No. 4, 1997, pp. 176-182.

Ramey, G.E., Pittman, D.W., Webster , G., and Carden, A. *Use of Shrinkage Compensating Cement in Bridge Decks.* Auburn University, Department of Civil Engineering, Auburn, AL, 1997.

Saadeghvaziri, D.M., and Hadidi, R. *Cause and Control of Transverse Cracking in Concrete.* New Jersey Institute of Technology, Department of Civil Engineering, Newark, 2002.

Virmani, Y.P., and Clemeña, G.G. *Corrosion Protection—Concrete Bridges.* Federal Highway Administration, Washington, DC, 1998.

Yunovich, M., Thompson, N.G., and Virmani, Y.P. Corrosion Protection System for Construction and Rehabilitation of Reinforced Concrete Bridges. *International Journal of Materials and Product Technology*, Vol. 23, No. 3/4, 2005, pp. 269-285.

APPENDIX A

FRESH CONCRETE PROPERTIES

Load	Slump at Plant (in)	Air Content at Plant (%)	Concrete Temperature at Plant (°F)
1	8.5	7.2	58
2	9	7	58
3	8.25	9.4	60
4	8.25	9.5	62
5	8.25	7.8	60
6	8	7.6	62
7	7.25	8.2	NA
8	NA	NA	NA
9	7	NA	65
10	8	6.5	64
11	NA	6.4	NA

Load	Slump at Plant (in)	Air Content at Plant (%)	Concrete Temperature at Plant (°F)
1	8.75	7.2	62
2	8.75	6.6	62
3	8	10.9	63
4	8	10.1	63
5	7	9.8	65
6	7	8.7	67
7	7	7.8	67
8	6.5	7.5	67
9	7	7.8	67
10	NA	NA	NA
11	8	8	68
12	6	7.5	68
13	NA	NA	NA
14	6	7.4	68

APPENDIX B

SPECIAL PROVISION FOR
CLASS A4 CONCRETE MODIFIED TO MINIMIZE CRACKING WITH SHRINKAGE COMPENSATING CONCRETE

May 30, 2014

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:

Cement shall be Type K rather than Type I/II cement. Maximum w/c ratio should be 0.48. Fly ash and slag should be used to reduce permeability. Minimum slump during placement shall be 4 inches and there should be no segregation. During summer placement, necessary steps should be taken to avoid excessive slump loss.

Concrete shall be moist cured for 7 days. Moist curing shall be achieved by immediately applying wet burlap to the surface of the finish concrete, covering the wet burlap with plastic sheets and maintaining the burlap in a saturated condition during the 7 day curing period. The saturated condition shall be maintained by periodic wetting of the burlap or by placing soaker hoses over the burlap. Curing water shall be contained over the entire deck surface and shall be prevented from running off the deck.

The use of high-early-strength hydraulic cement concrete as described in Section 217.08 (b) of the Specifications is not permitted.

III. QUALITY ASSURANCE TESTING

At least 5 weeks prior to production, the Contractor shall prepare a trial batch of the mix, minimum of 3 cubic yards, to demonstrate compliance with the compressive strength, permeability, air void content, slump. Expansion test should be performed in accordance with ASTM C878. The Contractor shall prepare the trial batch with the same equipment to be used on the project. The Contractor shall obtain the services of an AMRL-accredited laboratory to perform the trial batch testing. Test results shall be furnished the Engineer for review. At 28 days the compressive strength shall be greater than 4,000 psi and permeability less than 2500 coulombs. The Contractor will not be authorized to proceed with concrete production for use in the construction of the bridge deck until the test results verify conformance with the requirements stated herein.

IV. MEASUREMENT AND PAYMENT

Class A4 Shrinkage-Compensating Concrete 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