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Evaluation of Lightweight High Performance Concrete in Bulb-T Beams and Decks in Two Bridges on Route 33 in Virginia

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16. Abstract:

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Each bridge has both normal weight and lightweight bulb-T beams. The decks on the lightweight beams are also lightweight. Two distinctly different high-strength lightweight concrete mix designs and curing procedures (steam cured versus moist cured) were used for the beams of the two bridges.

The results indicate that LWHPC with satisfactory strength and permeability can be achieved for beams and decks. These concretes are expected to be durable and cost-effective. The initial cost of LWHPC is higher than for conventional high performance concrete. However, the reduced dead load of LWHPC would result in longer spans, reduced number of piers or smaller piers, reduced substructure requirements, and easier transportation and erection of elements, leading to substantial savings, as was evidenced in this study.

The study recommends that the use of LWHPC should continue for beams and decks and possibly for accelerated construction with precast units in substructures or superstructures, especially for rehabilitation projects. Elements cast off site would be prepared under more controlled conditions and reduced traffic interruptions. In addition, handling and delivery would be easier than for conventional concrete because of the reduced weight.

If the improved quality through use of LWHPC resulted in a 10% increase in service life, large savings would occur. In Fiscal Years 2003 through 2008, the Virginia Department of Transportation spent an average of $10.68 million per year on prestressed concrete beams. Thus VDOT could save close to $1 million each year through the improvements expected with LWHPC.

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INTRODUCTION

The Virginia Department of Transportation (VDOT) regularly uses normal weight high performance concrete (NWHPC, or HPC) with high durability in all concrete and with high strength in beams (Ozyildirim, 1994; Ozyildirim and Gomez, 1996; Ozyildirim et al., 1996). VDOT also uses lightweight concretes (LWC) in various applications including the successful redecking of many functionally obsolete bridge structures posted with reduced load-carrying capacities (Holm, 1985; Ozyildirim, 2008a). Structural lightweight concrete is defined as having an air-dry density less than 115 lb/ft^3 (American Concrete Institute [ACI], 2000), with a fresh density usually less than 120 lb/ft^3. High-strength concrete has a 28-day compressive strength of 6,000 psi or higher (Kahn et al., 2004). High-strength LWC has limited applications because of the limited availability of the material and the uncertainty associated with particular material properties including tensile strength, modulus of elasticity, shrinkage, and creep. These properties are significant in structural behavior and design because of their considerable impact on shear strength, crack control, strand spacing, and prestress losses.

LWC specimens generally exhibit reduced tensile strength when compared to normal weight concrete (NWC). Air-dried cylinders demonstrate tensile strengths up to 30% less than NWC specimens (ACI 2003) although continuous moist curing may increase the strength of LWC (Lopez et al., 2003). The differences in tensile strength of LWC subjected to steam curing compared to moist curing are not well established. The tensile strength of LWC may be roughly one-tenth of the compressive strength (Vincent et al., 2004). The splitting tensile strengths of structural lightweight concretes vary from those of NWCs with equal compressive strength by approximately 75% to 100% (Holm and Ries, 2006). There are ways to increase the tensile strength of LWC. Lowering the water–cementitious material ratio (w/cm) results in higher strengths. Using normal weight fine aggregate with lightweight coarse aggregate also raises tensile strength (Holm and Ries, 2006).

Close estimation of the modulus of elasticity is important in the calculation of prestress loss and deflection. Generally, LWC has a modulus of elasticity of about one-half to three-fourths that of NWC (Lopez et al., 2003). Studies by Vincent et al. (2004), Sylva et al. (2004), and Lopez et al. (2003) reported the modulus of LWC as a percentage of NWC to be 45%, 67%, and 80%, respectively. The differences in mixture design and material could account for the variability. In the lightweight high performance concrete (LWHPC) test beams for the bridge on Route 106 over the Chickahominy River, the modulus of elasticity of the lightweight beams was about 65% that of the normal weight beams (Ozyildirim, 2005). ACI (2003) identified the expected modulus of elasticity range for high-strength LWC with natural sand aggregate as approximately 2,300 to 3,200 ksi. The modulus of elasticity values vary based on compressive strength, density, and aggregate amount and type (Holm and Ries, 2006).

LWHPC has either or both high strength and durability and has been used in bridge beams on a limited basis. These benefits are expected to result in increased longevity, a reduced number of beam lines, longer beams, and cost savings. The durability of concrete exposed to the harsh environment outdoors depends on low permeability to resist the ingress of aggressive solutions and a satisfactory air-void system to resist freeze-thaw deterioration. LWC can potentially demonstrate equal or superior durability to NWC because of the more continuous paste-aggregate bond, but proper selection of materials, proportioning, and placement and curing and the addition of air-entraining admixtures are essential. In addition, in LWC, the modulus of elasticity of the coarse aggregate is close to that of the paste matrix. This minimizes the large internal stress concentrations, reduces microcracking, and thus increases durability (Vaysburd, 1996). Internal moist curing attributable to the presence of moisture in the voids of aggregates is also an advantage of LWC that enhances durability (Bremner et al., 1984; Holm, 1980, 1985; Holm et al., 1984). Another issue related to durability is the wear or abrasion resistance of LWC. Most lightweight aggregates used in structural applications are composed of vitreous ceramic, comparable to quartz in hardness, and are expected to perform similar to NWC (Holm and Ries, 2006). The field experience of LWC in relation to wear and freeze-thaw deterioration resistance has been satisfactory in Virginia (Ozyildirim, 2008a).

Long-term concrete behaviors such as creep and drying shrinkage affect long service life requirements. They affect the extent of cracking, prestress loss, and warping. LWC typically exhibits higher levels of drying shrinkage than NWC. A good understanding of shrinkage and creep for varying density, strength, and curing method is needed for inclusion in structural design.

Although there is only a limited number of bridges that contain LWC beams, these bridges have generally performed successfully. The Florida Department of Transportation constructed the Sebastian Inlet Bridge in 1964, using 4,000 psi LWC in the decks and 5,000 psi LWC in the beams (Brown and Davis, 1993). An inspection showed the bridge to be in excellent condition after 40 years of service (Castrodale and Harmon, 2008). The Coronado Bridge (1969) in California and the Lewiston Pump-Generating Plant Bridge (1960) in New York each contain prestressed lightweight girders that demonstrate satisfactory performance (Expanded Shale Clay and Slate Institute, 2001). Norway has been an international leader in using LWHPC with compressive strengths exceeding 8,000 psi. The Raftsundet Bridge (1998) in Raftsundet Sound in Norway is a prominent project. Its long main span is constructed of 735 ft of high-strength lightweight aggregate concrete. The bridge has been performing successfully in the severe environment (Harmon, 2002).

In 2001, VDOT constructed an LWHPC bridge on Route 106 over the Chickahominy River near Richmond, Virginia, with a maximum fresh concrete density of 120 lb/ft^3 in the girders and deck (Ozyildirim, 2005). The LWHPC AASHTO Type IV beams had a minimum 28-day compressive strength of 8,000 psi and a maximum permeability of 1500 coulombs. The length of the beams is 84 ft with a 10-ft beam spacing. The bridge is three spans made continuous for live load. It was in very good condition with only minimal transverse deck cracking located over the interior piers (Ozyildirim, 2005). Successful use of LWHPC in this bridge led to VDOT building longer span LWC bridges. The LWHPC bridges over the Mattaponi and Pamunkey Rivers on Route 33 in Virginia use bulb-T beams, which are more efficient than standard AASHTO beams in spanning long distances (Rabbat and Russell, 1984).

PROBLEM STATEMENT

For NWC, design codes attempt to characterize material parameters. However, these code provisions do not directly translate to LWC, and provisions that specifically reference LWHPC are not established. There is only a limited number of field applications for LWC in beams, especially in high-strength applications spanning long distances. Actual field behavior is needed to provide more accurate information on the performance of LWHPC.

Poor soil conditions at the project bridge sites and span lengths exceeding 120 ft made the use of reduced-weight materials desirable. Although LWC itself is more expensive than NWC, the difference can be offset by increased durability, increased span length, smaller structural elements, reduced amount of reinforcing steel needed, reduced volume of concrete, and reduced transportation expenses (ACI, 2003; Ries and Holm, 2004).

PURPOSE AND SCOPE

The purpose of this research was to evaluate prestressed LWHPC bulb-T beams and decks in the two bridges on Route 33 over the Mattaponi and Pamunkey Rivers in Virginia. The beams were bulb-T beams with a height of 95.5 in. Different LWHPC mixture designs and curing procedures (steam cured versus moist cured at two plants) were used for the beams and segments of the bridges, enabling comparison of their performance. The concretes were tested for strength, elastic modulus, permeability, shrinkage, and creep. Some beams in each bridge were instrumented for evaluation of long-term strains and temperature. The LWC used in the decks in both structures was produced at the same plant with the same materials.

To determine the effects of additional curing, specimens from the Pamunkey Bridge that had been initially steam cured were subjected to different curing conditions (laboratory air, moist room, outdoors) for 1 year and the strength and elastic modulus values were compared.

METHODS

Overview

The study involved materials and structural testing of the bridge beams and decks. Both bridges over the Mattaponi and Pamunkey Rivers contain LWHPC decks and lightweight bulb-T beams set as simple spans made continuous for live load. Each bridge had two continuous spliced girder bulb-T units of 200-240-240-200-ft spans.

Description of Bridges

The Mattaponi Bridge is located near West Point, Virginia. It is 3,545 ft long with 2,195 ft of LWHPC beams and deck. The bridge opened to traffic in 2006. The Pamunkey Bridge is 5,354 ft long with 2,169 ft of LWHPC beams and deck. It opened to traffic in 2007. Both bridges have spliced LWHPC girders spanning 200 and 240 ft and simple spans made continuous for live load with LWHPC spanning 136 ft 4 in in the Pamunkey Bridge and 145 ft in the Mattaponi Bridge. The use of LWHPC in the beams and decks reduces the number of footings and piles, diminishes the environmental impact, and increases vehicular capacity from two lanes to four lanes (Nasser, 2008).

Specifications

The concretes were designed to comply with the requirements summarized in Table 1.

Table 1. Design Specifications for Lightweight Aggregate Concrete Mixtures

Property	Beams	Deck
Fresh Density (lb/ft^3)	123	120
Air Content[a] (%)	5.5 ± 1.5	6.5 ± 1.5
Maximum Slump[a] (in)	7	4
Compressive Strength, minimum 28 day (psi)	8,000	5,000
Splitting Tensile Strength, minimum 28 day[b] (psi)	580	360
Modulus of Elasticity, minimum (10^6 psi)	3.00	2.70
Creep Notional Coefficient, maximum	4.2	3.5
Shrinkage Notional Coefficient, maximum (microstrain)	450	550
Permeability, maximum (coulombs)	1,500	2,500

[a]The upper limit air content has been increased by 1% because of the addition of a high-range water-reducing admixture, and the slump increased to 7 in. A 9-in slump was permitted provided there was no segregation.
[b]The mixtures contained natural sand fine aggregate.

Mixture Proportions and Curing

The mixture proportions of beams and decks are given in Table 2. The proportions of the instrumented beams in each of the bridges were different mainly because of different curing procedures. In the Mattaponi Bridge, a rich mixture with a high cementitious material content was used since the beams were moist cured. The cementitious material was finely ground Type II cement and Class F fly ash. For coarse aggregate, No. 67 lightweight aggregate (expanded slate) and some normal weight coarse aggregate (granite) were used to maintain the density. The maximum aggregate size was ¾ in. Fine aggregate was normal weight natural sand. Corrosion-inhibiting (3.5 gal/yd^3), air-entraining, and regular and high-range water-reducing admixtures were used in the mixture.

In the Pamunkey Bridge, a lower amount of cementitious material was used and the beams tested were steam cured. Type III cement with slag having a slag activity index of 120 was used. The lightweight coarse aggregate in the mixture was from the same source and size used in the Mattaponi Bridge beams; no normal weight coarse aggregate was included. The fine aggregate was normal weight natural sand. Air-entraining, corrosion-inhibiting (2 gal/yd^3), high-range water-reducing, and water-retarding admixtures were used. Some of the beams used in the Pamunkey Bridge were also moist cured, but the data from those beams were not considered in this report.

The mixture proportions were the same for the decks for both bridges. Cementitious material was Type II cement and Class F fly ash. Lightweight coarse aggregate and normal weight natural sand were used. Air-entraining and water-reducing and water-retarding admixtures were added.

Table 2. Mixture Proportions for Lightweight Beams and Decks (lb/yd^3)

Material	Mattaponi Beams	Pamunkey Beams	Decks
Cement	750	480	588
Slag	-	320	-
Fly ash	185	-	147
NW coarse aggregate	250	-	-
LW coarse aggregate	800	950	950
NW fine aggregate	949	1193	1116
Water	287	248	294
w/cm	0.31	0.31	0.40

NW = normal weight; LW = lightweight.

Materials Testing

In the fresh state, concrete was tested for slump (ASTM C 143), air content (ASTM C 173), and density (unit weight) (ASTM C 138). Table 3 summarizes the tests conducted at the hardened state and the size of the specimens used. The age at which each test was conducted is provided in the "Results" section. Specimens for beams were cured in a manner similar to that for the actual beams except that an additional set of specimens from the Pamunkey Bridge was also moist cured.

For deck concrete, four batches, two from the Mattaponi Bridge and two from the Pamunkey Bridge, were tested. One set of the Pamunkey Bridge deck samples was tested only for hardened concrete properties. Deck concrete was placed using pumping, but the samples were obtained before pumping except for one set of samples that was obtained after pumping (Pamunkey B1). For the Mattaponi Bridge beams, a trial batch was made before the construction of the beams.

Table 3. Tests for Hardened Concrete

Tests	Specification	Size (in)
Compressive Strength	ASTM C 39	4x8
Splitting Tensile Strength	ASTM C 496	4x8
Elastic Modulus	ASTM C 469	4x8
Permeability[a]	ASTM C 1202	2x4
Freeze-thaw[b]	ASTM C 666	3x4x16
Drying Shrinkage	ASTM C 157	3x3x11
Creep	ASTM C 512	6x12

[a]When moist cured, 1 week at 73 F and 3 weeks at 100 F; tested at 28 days.
[b]At least 1 week of air drying prior to testing and 2% NaCl in test solution.

Instrumentation

In the Mattaponi Bridge, four of seven beams in Span I of Unit B were instrumented with vibrating wire gauges (VWG) for strain measurements. The center beam (I B4), the one adjacent (I B5) to the center, and the end beams (I B1 and I B7) each had four VWGs. For redundancy, two VWGs were on top as shown in Figure 1 and two were at the bottom at midspan. In the Pamunkey Bridge, two beams in Unit F, Span FF (FF B4 and FF B5); two pier segments (34 B4 and 34 B5); and two beams in Unit G, Span HH (HH B4 and HH B5; HH B5 was broken during delivery and recast) were instrumented in a fashion similar to that for the beams in the Mattaponi Bridge. Each of the beams instrumented was a middle beam or the beam adjacent to the middle. VWGs were placed right after the reinforcement during the casting operation.

The Mattaponi Bridge beams were not steam cured; I B5 and I B7 were 2 days old and I B4 was 3 days old at release of strands. At release, a minimum concrete strength of 6,000 psi was needed. Until transfer, the beams were covered to retain moisture; after release, the cover was removed and the beams were left to dry. Specimens followed the same curing procedure. In the Pamunkey Bridge, release strength was achieved overnight due to steam curing. As described previously, specimens were also steam cured except for the one set that was moist cured.

VWGs provided data on concrete strains and internal concrete temperature. Type T thermocouples were also attached at mid-depth in the web to measure the temperature of the concrete. The VWGs and thermocouples were continuously monitored with a data acquisition system.

Figure 1. Vibrating Wire Gauges Located at Top of Beam

RESULTS AND DISCUSSION

Fresh Concrete Properties

The properties at the fresh state are summarized in Table 4 for the Mattaponi Bridge beams, in Table 5 for the Pamunkey Bridge beams, and in Table 6 for the bridge decks.

Table 4. Fresh Concrete Properties of Mattaponi Bridge Beams

Property	FF B4	FF B5
Cast Date	1/4/2005	1/5/2005
Slump (in)	7.5	6.5
Air (%)	6	5
Density (lb/ft^3)	118.7	122.7

Table 5. Fresh Concrete Properties of Pamunkey Bridge Beams

Property	FF B4	FF B5	Pier Segment 34 B4	Pier Segment 34 B5	HH B4	HH B5
Cast Date	1/10/06	1/10/06	2/28/06	3/2/06	3/30/06	4/21/06
Slump (in)	9.0	9.0	8.5	--	9.5	9.0
Air (%)	5.5	--	5.5	5.0	3.5	4.7
Density (lb/ft^3)	116.0	117.2	115.2	114.8	118.8	118.8

Table 6. Fresh Concrete Properties of Decks

Property	Mattaponi Bridge		Pamunkey Bridge
	B1	B2	B1 (after pump)
Cast Date	10/27/05	10/27/05	10/19/06
Slump (in.)	7.8 in	6.5 in.	4.5
Air (%)	7.0	5.2	5.0
Density (lb/ft^3)	115.0	113.5	118.8

Samples were obtained from the trucks. Workable concretes with satisfactory air and density were obtained. The slump values for the Pamunkey Bridge were at the upper limit or slightly above it. There was no apparent segregation, and these batches were placed easily. With slump values at the lower end of the specification limits, it was difficult to place and consolidate the concretes.

Hardened Concrete Properties

The hardened concrete properties are given in Tables 7 through 9 for the Mattaponi Bridge beams, Pamunkey Bridge beams, and deck concrete, respectively.

The beams and samples from the Mattaponi Bridge were kept moist by covers for the first 2 or 3 days. Then they were uncovered and exposed. The beams and samples from the Pamunkey Bridge were steam cured and then exposed. The early strengths of the beam samples from the Pamunkey Bridge were higher than those from the Mattaponi Bridge, as was expected because of the steam curing. At 28 days, beam samples from both bridges had similar strength. At 1 year, the strengths of beams from the Pamunkey Bridge were lower than those from the Mattaponi Bridge; even though both were satisfactory. Steam curing accelerated the early strength development, but ultimate strengths were lower. The splitting tensile strengths at 28 days were also similar. Splitting tensile strength values were lower than obtained for the NWC used in the Pamunkey Bridge (Ozyildirim, 2008b). The reduction in splitting tensile strength was as expected and can be addressed by additional reinforcement.

The samples from decks were continuously moist cured until testing. They had high 28-day compressive strengths exceeding 6,000 psi, and their 1 year strengths were approaching that of the steam-cured Pamunkey Bridge beams. Similar behavior was observed with the splitting

Table 7. Hardened Concrete Properties for Mattaponi Bridge Beams

Property	Age (days)	FF B4	FF B5
Cast Date		1/4/05	1/5/05
Compressive Strength (psi)	1	3629	4850
	28	8300	9180
	365	9040	9900
Elastic modulus (10^6) (psi)	28	3.23	3.51
	365	3.3	3.5
Splitting Tensile (psi)	28	640	565
Permeability (coulombs)	6 mo	356	334

tensile strength; deck concretes had lower values at 28 days but closer values at 1 year. Continuous moist curing helped improve strength.

The elastic modulus values of the samples from the Pamunkey Bridge were lower than for the Mattaponi Bridge. The continuously cured deck samples had a higher elastic modulus than the higher strength beam concretes. Moist curing for extended periods improved the elastic modulus for a given strength. NWCs for the Pamunkey Bridge had higher elastic modulus values (Ozyildirim, 2008b). The expected reduction in stiffness attributable to the lower elastic modulus can be compensated for by selecting the appropriate section modulus.

To investigate the effect of curing conditions after initial steam curing on the strength and elastic modulus, specimens from HH B5 of the Pamunkey Bridge were kept in the laboratory air, a moist room, and outdoors for 1 year and tested. The results are given in Table 10. The strength values were similar, but the elastic modulus values were different. The moist-cured specimens had the highest elastic modulus values followed closely by those kept outdoors and then by the ones left in the laboratory air. Those specimens were capped with sulfur mortar, and the other specimens tested in this study were capped with neoprene pads in an extrusion ring.

Permeability depends on the type and amount of supplementary cementitious material, curing method, and w/cm. At the same w/cm, the moist-cured specimens of the Mattaponi Bridge with Class F fly ash had lower permeability values than the Pamunkey Bridge samples; however, both had satisfactory values. Beams in both bridges had calcium nitrite, which affects the permeability test results, but values were still low or very low. The deck concrete with fly ash with a higher w/cm than the beams also had low permeability values.

Freeze-Thaw Results

Concretes for the beam showed varying results regardless of the curing condition (Tables 11 and 12), and some specimens did not meet the acceptance criteria because they had a low durability factor or high weight loss. However, concrete specimens for the deck (Table 13) had satisfactory results. This behavior is not uncommon since concrete for beams has lower air content requirements and the test is conducted under very severe conditions. In practice, the beam concretes have been doing well in the field mainly because they do not become critically saturated since they are low-permeability concretes and have been protected from the environment by the deck.

Table 8. Hardened Concrete Properties for Pamunkey Bridge Beams

Property	Age (days)	FF B4	FF B5	Pier Segment 34 B4	Pier Segment 34 B5	HH B4	HH B5 Steam	HH B5 Moist	HH B5 (Redo) Steam
Cast Date		1/10/06	1/10/06	2/28/06	3/2/06	3/30/06	4/21/06	4/21/06	10/26/06
Compressive Strength (psi)	1	7320	7040	5790	8040	5760	7210	5930 (3d)	7327
	7	8050	8050	7060	7860	7910	8150	7490	7860
	14	8370	8360	--	9730	8070	--	--	8550
	28	9020	9020	8420	8800	8500	9010	8880	8510
	365	8810	8610	8290	8440	8690	8980	--	--
Elastic Modulus (10^6 psi)	1	3.46	3.32	3.23	3.37	3.15	3.16	2.86 (3d)	--
	7	3.32	3.27	3.10	3.04	3.13	3.26	3.34	3.75
	14	3.36	3.17	--	--	2.54	--	--	3.45
	28	3.26	3.16	3.02	3.18	3.15	2.98	3.76	3.98
	365	2.80	2.77	2.70	2.88	2.92	3.16	--	--
Splitting Tensile Strength (psi)	1	--	--	--	--	--	505	465 (3d)	--
	7	525	510	460	480 (5d)	485	555	540	560
	28	550	515	560	540	570	695	705	585
	365	670	670	640	700	620	600	--	--
Permeability (coulombs)	28	1453	2245	1375	1216	2010	1228	--	1163
	365	498	712	1068	830	848	--	--	--

Table 9. Hardened Concrete Properties for Bridge Decks

Property	Age (days)	Mattaponi		Pamunkey	
		B1	B2	B1	B2
Cast Date		10/27/05	10/27/05	10/19/06	2/27/07
Compressive Strength (psi)	1	---	---	2360	2010
	3	---	---	4470	2800
	4	3220	3110	---	
	7	4370	4320	---	4150
	28	6110	6310	7060	6040
	56	---		7550	7280
	90	---		8000	7400
	365	7950	8110	9050	7710
Elastic Modulus (10^6 psi)	1	---	---	2.34	2.66
	3	---	---	2.81	2.64
	4	2.76	2.84	---	
	7	2.86	2.83	2.76	2.96
	28	3.32	3.24	4.03	3.33
	56	---	---	4.45	3.80
	90	---	---	3.88	4.30
	365	---	---	3.87	4.05
Splitting Tensile (psi)	28	535	410	660	520
	56	---	---	520	540
	90	---	---	590	720
	365	---	---	645	
Permeability (coulombs)	28	939	976	1411	1940

Table 10. Hardened Property Variation From Storage Condition for Pamunkey Bridge

Sample	Compressive Strength			Elastic Modulus		
	Lab Air	Moist Room	Outside	Lab Air	Moist Room	Outside
1	9030	7560	8060	3.08	3.82	4.05
2	8670	8220	7980	3.35	4.18	3.83
3	7360	7720	7640	3.05	4.14	4.13
4	8180	8630	6960	3.11	4.07	3.51
5	7820	7740	7480	3.50	4.11	3.56
6	6585	8060	7780	2.94	4.15	3.31
7	6880	8060	8060	3.39	4.04	3.45
8	7880	7660	7700	3.10	3.83	3.54
9	7990	7600	7700	3.24	3.86	3.82
10	7880	8300	7840	3.10	3.81	3.96
Average	7828	7955	7720	3.19	4.00	3.72
Std. Dev.	743	356	326	0.18	0.15	0.28

Table 11. Freeze-Thaw Data for Mattaponi Bridge Beams

Property	Batch 1	Batch 2
Cast Date	1/4/05	1/5/05
Durability Factor	76	17
Weight Loss (%)	0.7	2.5
Surface Rating	0.6	0.8

B1-1 completed 300 cycles, B1-2 broke at 300 cycles, B2-1 broke at 100 cycles, and B2-2 broke at 150 cycles.

Table 12. Freeze-Thaw Data for Pamunkey Bridge Beams

Property	FF B4	FF B5	Pier Segment 34 B4	Pier Segment 34 B5	HH 2 Steam	HH 2 Moist
Cast Date	1/10/06	1/10/06	2/28/06	3/2/06	4/21/06	10/26/06
Durability Factor	28	22	30	21	87	107
Weight Loss (%)	9.1	25.7	31.7	54.0	11.6	0.0
Surface Rating	1.3	3.8	3.9	5.0	1.9	0.9

FF B4-1 broke at 200 cycles; FF B4-2 broke at 150 cycles; FF B5-1 and 2 broke at 150 cycles; Pier 34 B4-1 and 2 broke at 250 cycles; Pier 34 B4-1 and 2 broke at 150 cycles; HH 2 steam and HH 2 moist completed 300 cycles.

Table 13. Freeze-Thaw Data for Bridge Decks

Property	Mattaponi		Pamunkey
	Batch 1	Batch 2	Batch 1
Cast Date	10/27/06	10/27/06	10/19/06
Durability Factor	102	103	107
Weight Loss (%)	6.6	2.9	6.1
Surface Rating	1.5	0.9	1.0

Mattaponi Batch 1completed 300 cycles; Mattaponi Batch 2 broke at 150 cycles; Pamunkey Batch 1 completed 300 cycles.

Length Change Results

The length change data summarized in Table 14 and displayed in Figures 2 and 3 indicate that shrinkage values for beam and deck concretes were less than those recommended for deck concretes. The values were less than 400 microstrain at 28 days and 700 microstrain at 4 months, which are the recommended maximums for satisfactory performance for bridge decks (Babaei and Fouladgar, 1997). The Federal Highway Administration's (FHWA) definition of HPC has three performance grades for shrinkage. Specimens are dried for 6 months, and values between 800 and 600 microstrain are Grade 1; 600 to 400 microstrain is Grade 2; and less than 400 microstrain is Grade 3 (Goodspeed et al., 1996). The values are in Grade 2 for the LWCs tested and are assumed to be satisfactory. The steam-cured beam concretes had lower water contents than the deck concretes and, in general, lower shrinkage values. The shrinkage values for the LWCs were higher than for the NWCs, which had values of 328 and 320 microstrain at 112 days (Ozyildirim, 2008b).

Creep Results

The Mattaponi trial batch had a 28-day compressive strength of 10,680 psi, an elastic modulus of 3.85×10^6, and a permeability of 644 coulombs. Cylinders measuring 6 x 12 in were sent to the company furnishing the admixtures for creep testing in accordance with ASTM C512. The 90-day creep coefficient of 0.57 was determined by dividing the 90-day creep strain of 421 $\mu\varepsilon$ by the initial elastic strain of 738 $\mu\varepsilon$. The 180-day creep coefficient was determined in a similar fashion to be 0.69. These creep coefficient values are approaching an ultimate creep coefficient that is well within the specified limits for lightweight bridge beams. The creep coefficient can also be expressed by multiplying the elastic modulus by the specific creep. The specific creep value is calculated from the following equation:

Table 14. Shrinkage Data (microstrain)

	Span FF B4	Span FF B5	Segment 34 B4	Segment 34 B5	Beam HH B5	Beam HH B5 (Redo)	Pamunkey Deck B1 (After Pump)	Pamunkey Deck B2
Cure Type:	**Steam**	**Steam**	**Steam**	**Steam**	**Steam**	**Steam and Moist**	**Moist**	**Moist**
Cast Date:	**1/10/2006**	**1/10/2006**	**2/28/2006**	**3/2/2006**	**4/21/2006**	**10/26/2006**	**10/19/2006**	**2/27/2007**
28 Days	327	373	327	377	333	200	340	323
112 Days	407	453	370	430	410	393	553	523
224 Days	363	417	410	453	487	423	480	583
448 Days	453	497	483	577	467	497	557	556

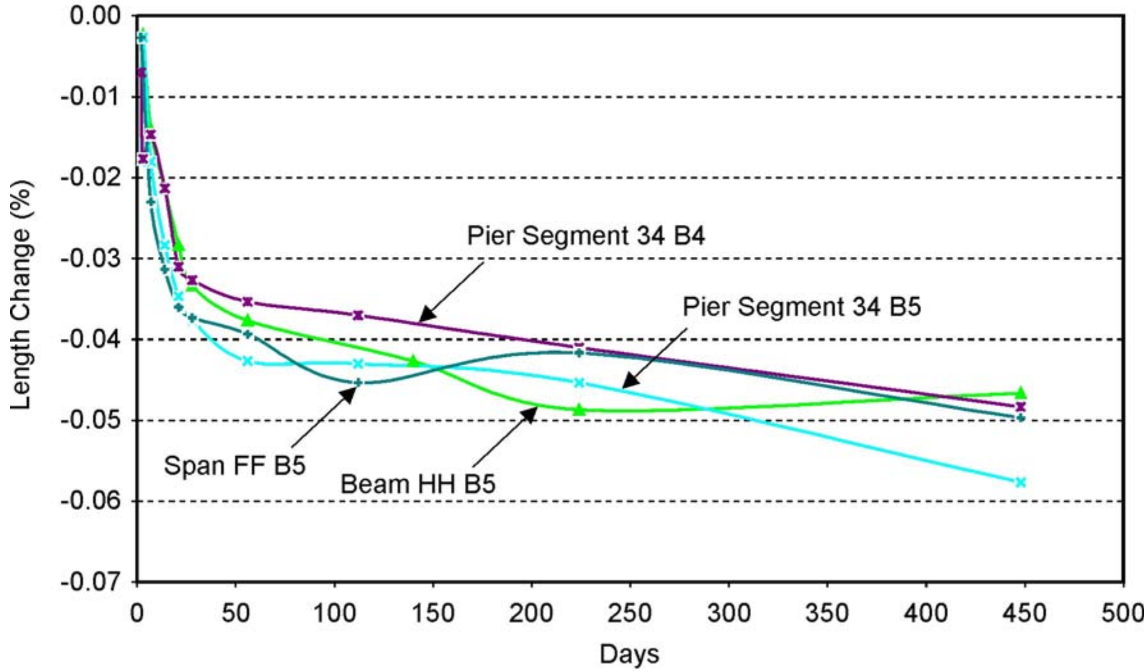

Figure 2. Pamunkey Length Change Data for Steam-Cured Specimens

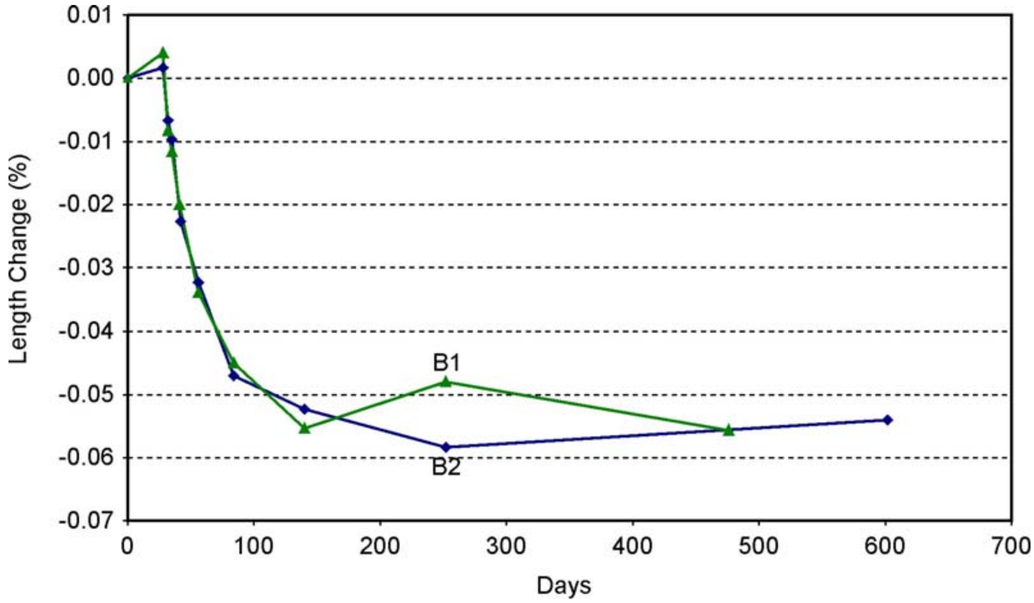

Figure 3. Pamunkey Deck Length Change Data for Moist-Cured Specimens

$$\varepsilon = (1/E) + F(K)\ln(t + 1)$$

where

ε = specific creep
E = instantaneous elastic modulus
F(K) = creep rate, slope of creep curve
t = time after loading.

This formula gives a 90-day specific creep value of 0.15×10^{-6} per psi. When multiplied by the elastic modulus, a 90-day creep coefficient of 0.57 is obtained. Figure 4 provides an example of the output of the creep testing procedure specified in ASTM C512.

Figure 5 illustrates the change in creep coefficient for the Mattaponi Bridge beams. Only one batch was tested for creep when the concrete reached 28 days of age. The creep coefficient for the Mattaponi Bridge beams was 0.61 at 134 days, which is significantly less than the maximum allowable creep coefficient of 4.2 for bridge beams. The majority of the creep strain occurred in the first 60 days of testing.

The Pamunkey Bridge beam cylinders were made during beam production because of time constraints. Cylinders were tested at 3, 28, and 91 days of age to evaluate the creep characteristics at various stages of hardening. The sustained load required by creep testing was 30% of the compressive strength. The variation in creep coefficient with time for each age is shown in Figure 6. The creep coefficients were well within the limits of the lightweight specifications.

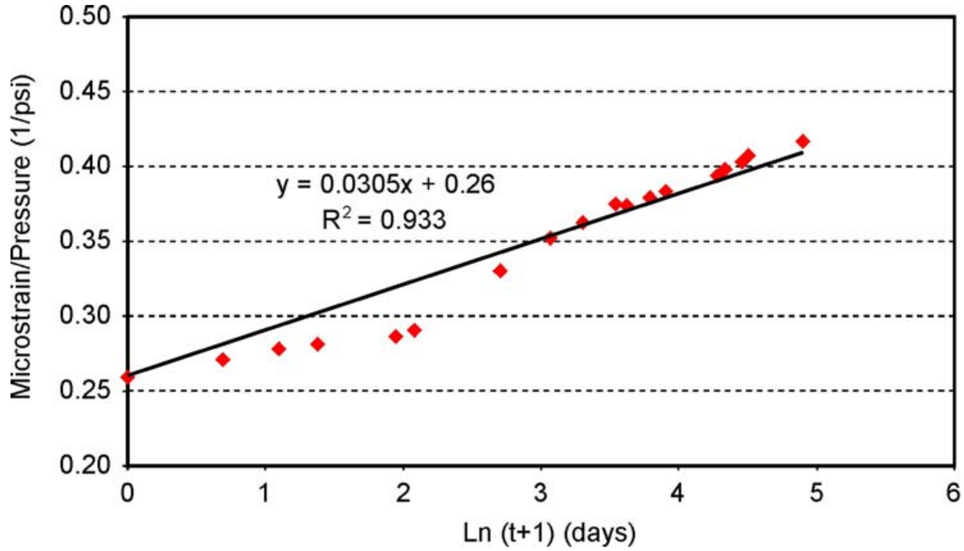

Figure 4. Creep Rate for Mattaponi Bridge Beams

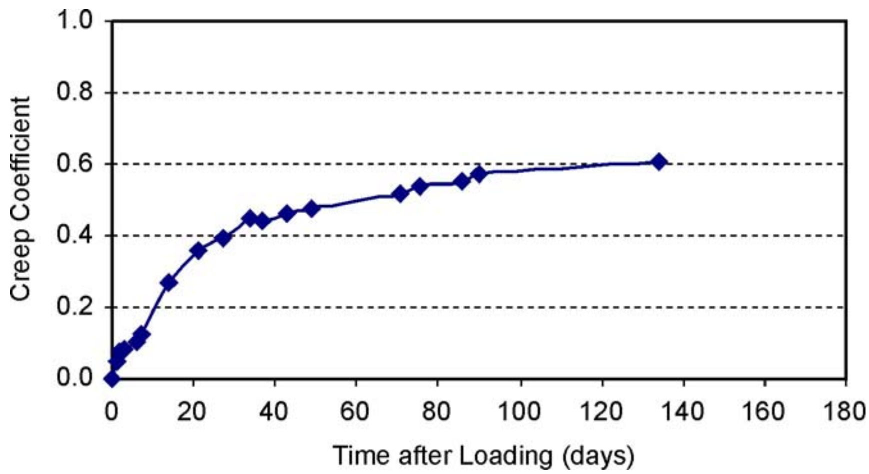

Figure 5. Creep Data for Mattaponi Bridge Beams

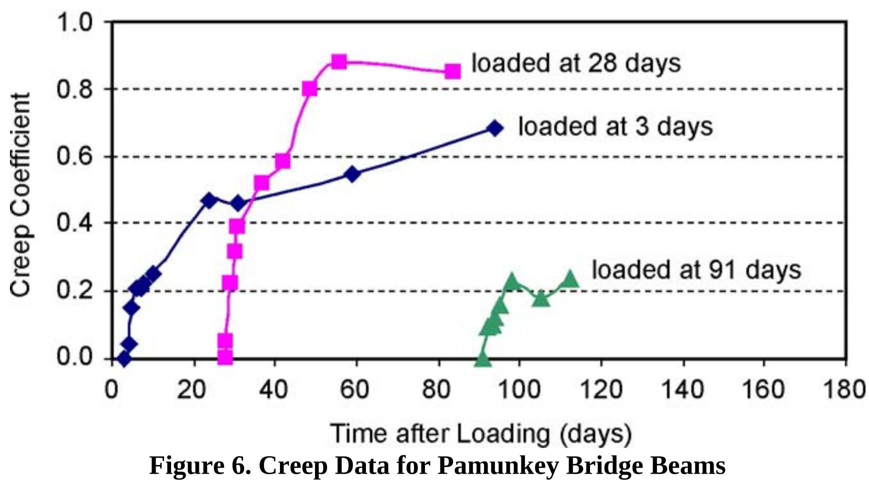

Figure 6. Creep Data for Pamunkey Bridge Beams

Creep testing for the deck concrete of the Mattaponi Bridge was conducted on materials shipped to the testing laboratory. Cylinders were made from a 5-1/2 ft^3 batch and tested in accordance with ASTM C512. The change in creep coefficient was plotted for cylinders loaded at 3, 28, and 91 days of age (Figure 7). The creep coefficient values appear to converge to a value well below the maximum allowable deck creep coefficient of 3.5.

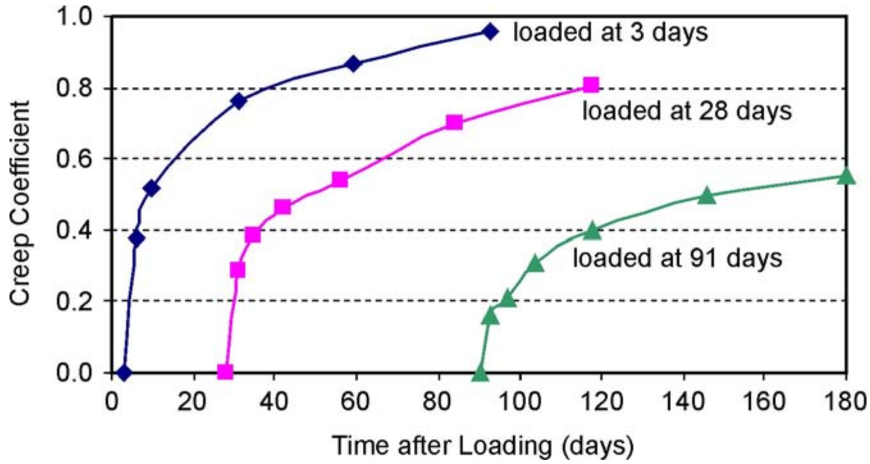

Figure 7. Creep Data for Mattaponi Bridge Deck

Strain Results

The strain data presented in Figures 8 through 12 are an average of the data from two gauges at each location. These beams experienced a large strain change at the time of prestress transfer and another large strain change at the time of deck placement. Then, the strains showed temperature fluctuations attributable to seasonal change but stayed constant in the long term. Ozyildirim and Davis (2005) also provided strain and camber data for the Mattaponi Bridge.

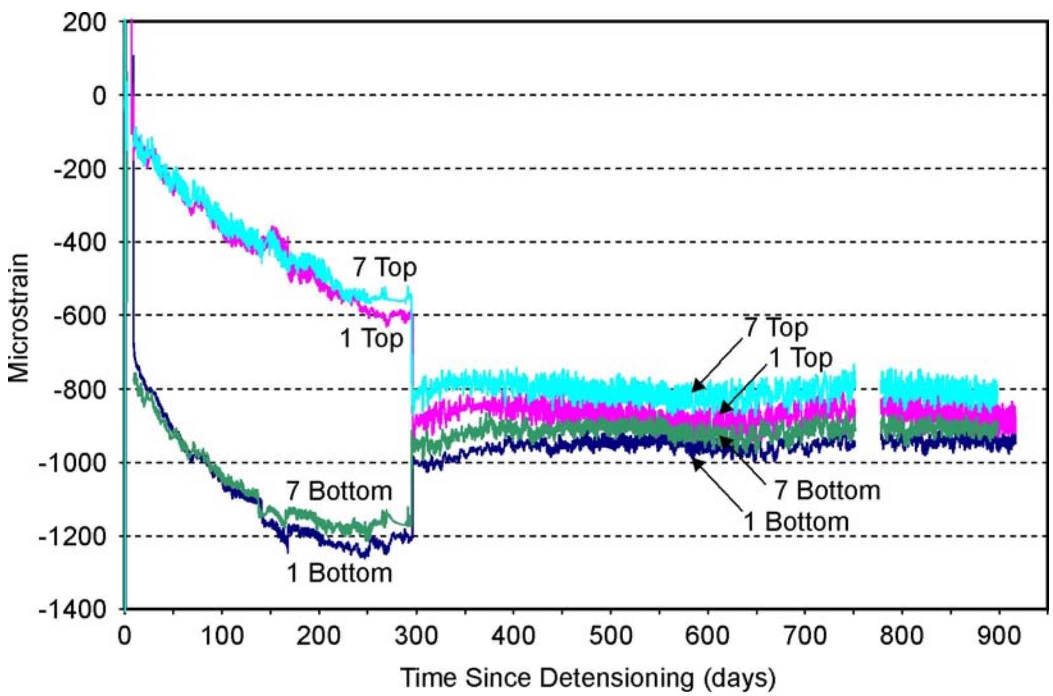

Figure 8. Strain Data for Span I Exterior Beams of Mattaponi Bridge

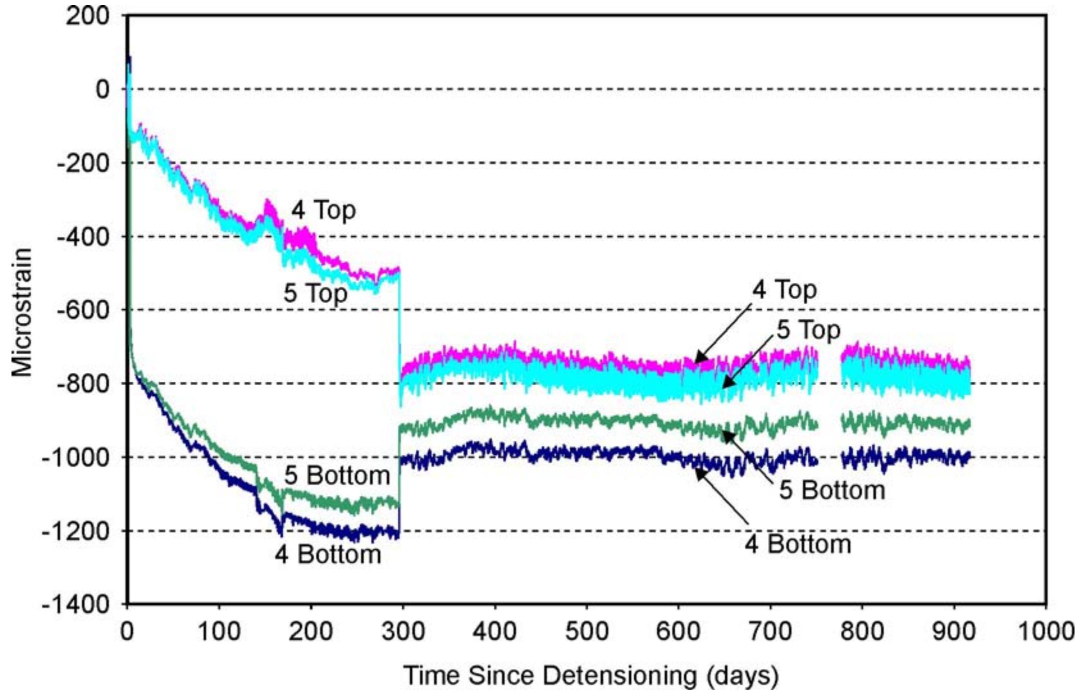

Figure 9. Strain Data for Span I Interior Beams of Mattaponi Bridge

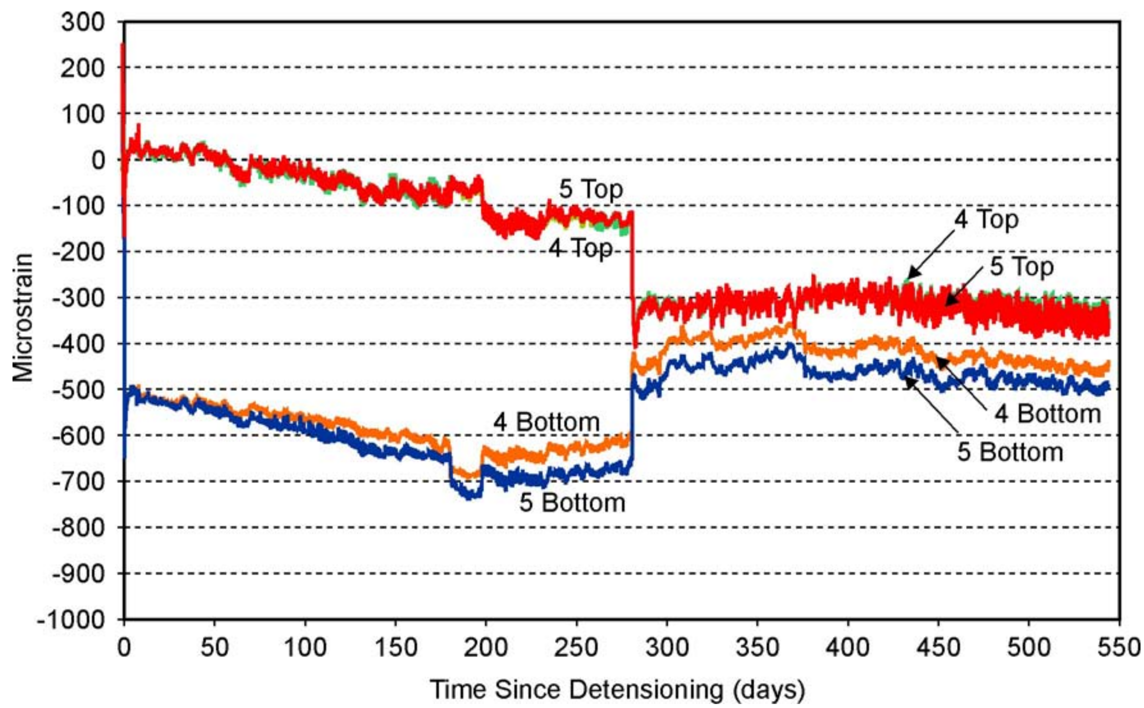

Figure 10. Strain Data for Span FF of Pamunkey Bridge

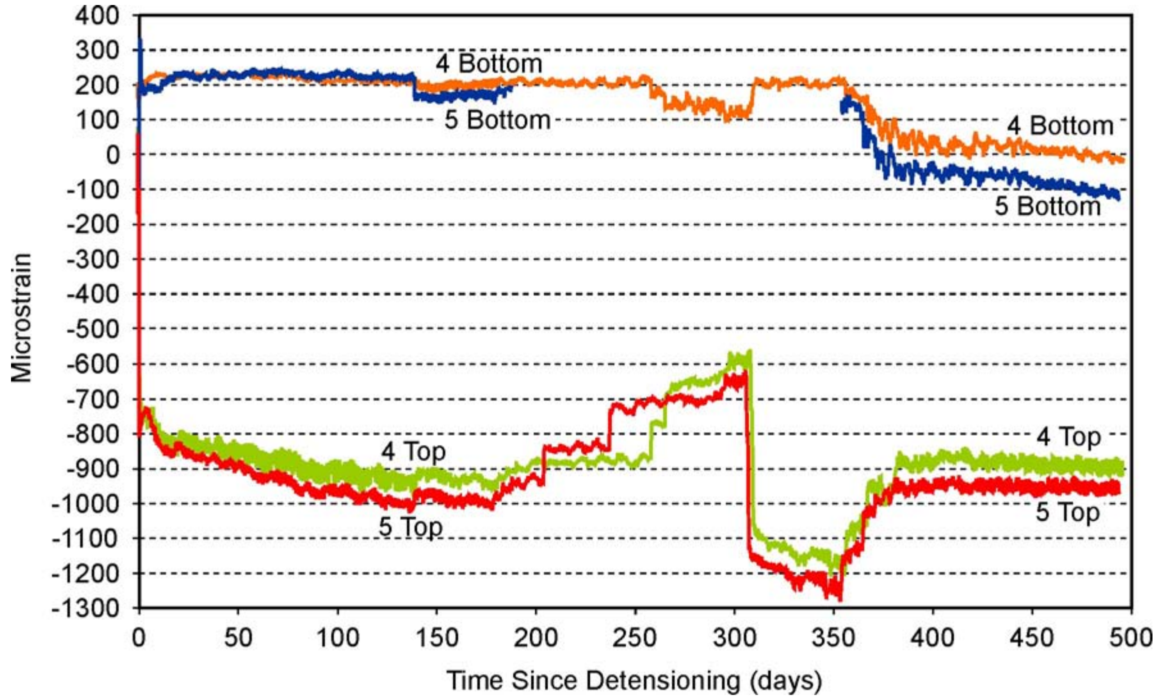

Figure 11. Strain Data for Pier Segment 34 of Pamunkey Bridge

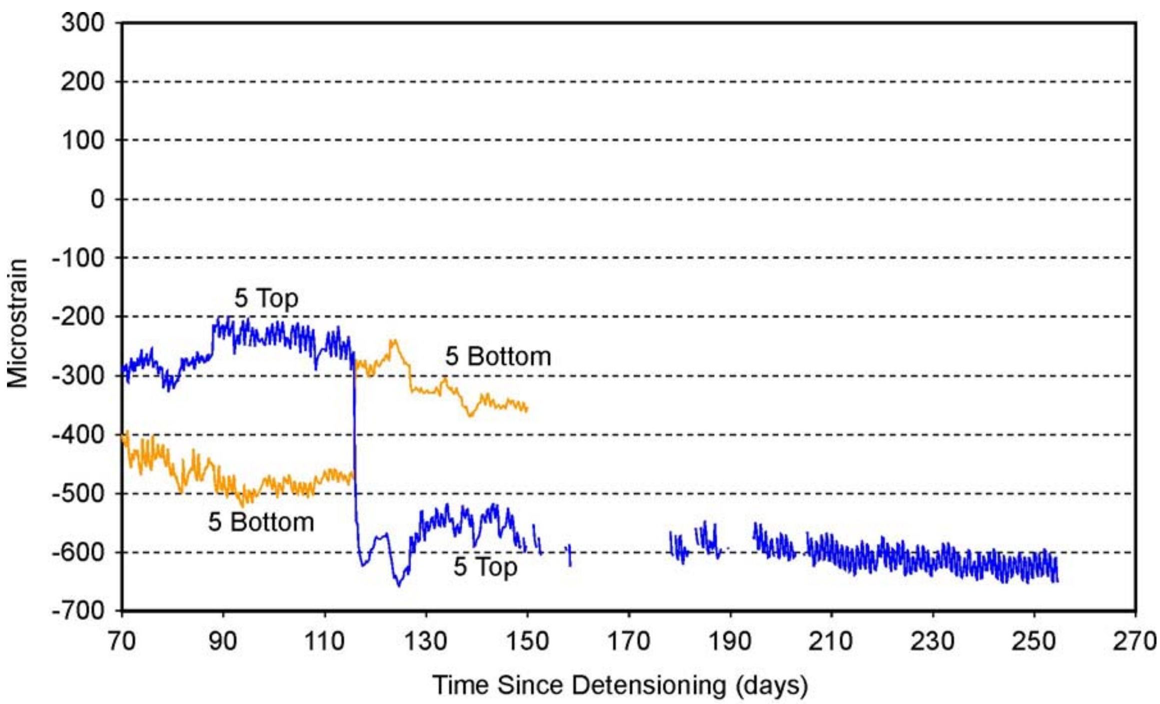

Figure 12. Strain Data for Beam HH5 of Pamunkey Bridge

SUMMARY OF FINDINGS

- LWHPC with satisfactory strength and permeability can be achieved.

- The freeze-thaw resistance of beam concretes with LWHPC was marginal but was satisfactory for the deck concretes. The beam concrete has a lower air content requirement than the deck concrete since it is expected to be protected by the overlying deck; it also has a lower w/cm; both make it difficult to critically saturate. Therefore, the harsh test does not necessarily indicate poor field performance and the performance is expected to be satisfactory.

- Steam curing accelerates early strength development but results in lower ultimate strengths.

- Specimens steam cured initially and then kept in the moist room had similar strengths at 1 year as specimens kept outdoors or left in the laboratory air; however, the elastic modulus values were different. The moist-cured specimens had the highest elastic modulus, followed closely by those kept outdoors and then those kept in the laboratory air. Thus, moist curing for extended periods improves the elastic modulus for a given strength.

- Permeability values were all satisfactory, either low or very low, even when calcium nitrite was added.

- The splitting tensile strength for the LWHPC was lower than for NWC, which was expected and can be addressed by adding sufficient reinforcement.

- The shrinkage values for the LWHPC were higher for the LWC compared to those for NWC; however, they were still in Grade 2 as defined by the FHWA.

- The creep coefficient for the LWHPC over the early age time interval appears similar to that for NWC, but the elastic modulus for the concrete is reduced from that for NWC as expected because of the low stiffness of the lightweight aggregate. Relationships developed between strength and elastic modulus for different LWCs can be used to select the appropriate section modulus to overcome the reduced stiffness attributable to reduced elastic modulus.

CONCLUSIONS

- LWHPC can be successfully produced and used in bridge beams and decks.

- Beam concrete can be steam cured or moist cured after casting.

RECOMMENDATION

1. *VDOT's Materials and Structure & Bridge Divisions should consider the use of LWHPC in bridge beams and decks and possibly for accelerated construction with precast units*

especially in rehabilitation projects. Such use will enable reduced dead loads leading to reduced substructure and longer spans, which together with improved durability will lead to cost savings.

COSTS AND BENEFITS ASSESSMENT

LWHPC costs more than NWHPC because of the up-front material cost for lightweight aggregates. The premium paid for LWC relative to NWC may range from 25% to 30% of the cost per cubic yard, which is expected to decrease with more use of this material. However, this increase is less than 10%, considering the per cubic yard cost for in-place concrete. In the total cost of the bridge, the increase is much smaller, within a few percentage points.

Several benefits of LWHPC are realized immediately and are expected to offset the increased lightweight material cost. The reduced dead load of LWHPC translates directly into longer spans, reduced number of piers or smaller piers, and reduced substructure requirements, resulting in a large cost savings, as was evidenced in the bridge structures described in this report. The costs of transporting and erecting LWHPC superstructure elements are significantly lower relative to those for NWC. In accelerated construction use of precast elements cast off site where more control in preparation is possible and less interruption to traffic occurs, LWC would be desirable for its reduced weight in handling and delivery to the jobsite. In bridge decks, the internal curing and the lower modulus of LWC are expected to minimize cracking. The enhanced durability of LWHPC is expected to lead to an extended service life with minimal maintenance costs.

This study indicates that LWHPC can be successfully used in bridge beams and decks. If the improved quality results in a 10% increase in service life, large savings would occur. In Fiscal years 2003 through 2008, VDOT spent an average of $10.68 million per year on prestressed concrete beams. Thus, VDOT could save close to $1 million each year through the improvements expected with LWC.

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