FINAL REPORT

PERFORMANCE OF THE FIRST STRUCTURE BUILT WITH HIGH PERFORMANCE CONCRETE IN VIRGINIA

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ABSTRACT

This study evaluated the preparation and placement operations, concrete properties, cost-effectiveness, and performance over 5 years of the first bridge containing high performance concrete built by the Virginia Department of Transportation. High performance concrete was used in the prestressed beams and cast-in-place substructure and deck concrete. The concrete in the beams contained silica fume, and that in the cast-in-place substructure and deck contained slag. A high compressive strength was specified for the prestressed beams, normal strengths were specified for the cast-in-place substructure and deck concretes, and low permeability was specified for all the concrete.

Steam-cured specimens for the beams had high early strengths, but moist-cured specimens developed higher long-term strengths. The permeability was much lower than specified. Concretes were easily placed, and the strengths were higher than specified. The structure was monitored during construction and surveyed after construction and at 5 years. Some cracking occurred in the deck, but the cracks were tight.

The author recommends that high-strength concrete be used in beams if economically feasible. Temperature-matched curing should be used to determine the strength of elements where high temperature increases are expected, and pozzolans or slag should be used to reduce permeability.

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INTRODUCTION

Hydraulic cement concrete is a widely used material in transportation facilities and has served well in many applications. However, in certain applications, the deterioration of concrete structures necessitates costly repairs and results in inconvenience to the traveling public. Deterioration of reinforced concrete structures is caused mainly by four types of environmental distress: corrosion of the reinforcement, alkali-aggregate reactivity, freeze-thaw deterioration, and attack by sulfates.[1] In each case, water or solutions penetrating the concrete initiate or accelerate the damage.

High performance concrete (HPC) is now used to extend service life. The use of HPC is expected to enhance durability and/or strength.[2,3] Durable HPC exposed to the environment has low permeability, which is attained by using a low water–cementitious material ratio (w/cm) and pozzolans or slag.[4-7] HPC usually has high strength, and its use may contribute to more economical structures.[8] Initially, a reduction in construction cost is expected through increased span lengths and fewer beams; in the long term, reduced maintenance costs and increased service life are expected through increased durability.[9,10]

In the mid-1990s, at the beginning of their HPC program, the Virginia Department of Transportation (VDOT) enacted a special provision for low-permeability concrete, which included limits for permeability based on the rapid chloride permeability test (AASHTO T 277 or ASTM C 1202). The limits were a maximum of 1500 coulombs for prestressed concrete beams, 2500 coulombs for deck concrete, and 3500 coulombs for substructure concrete cast in place. Specimens were to be moist cured for 1 week at 73^{o} F (23° C) and then for 3 weeks at 100^{o} F (38° C). Further, to support the use of high-strength concrete in prestressed beams, the Virginia Transportation Research Council conducted a preliminary study.[11] Four prestressed beams, 31 ft (9.4 m) long, were prepared and tested to failure at the Federal Highway Administration's (FHWA) Structures Laboratory at the Turner-Fairbank Research Center. Satisfactory results were obtained, which allowed VDOT to design beams with high-strength concrete to be used for an HPC bridge.

PURPOSE AND SCOPE

This report documents the preparation and placement operations, concrete properties, cost-effectiveness, and performance over 5 years of the first bridge built by VDOT containing HPC.

METHODOLOGY

Overview

The bridge was built on Rte. 40 over Falling River in Campbell County, Virginia. It has four spans, each 80 ft (24.4 m) long and 44 ft (13.4 m) wide. The prestressed concrete beams were prepared at a prestressing plant in Bristol. The cast-in-place concretes for the substructure and the superstructure were furnished by a ready-mix concrete plant in Brookneal, 1.5 mi (2.5 km) from the job site. Condition surveys for cracking and scaling were conducted after the first and fifth years.

Materials, Proportioning, Placement, and Testing

Prestressed Beams

Twenty prestressed Type IV beams conforming to the requirements of AASHTO's standard specifications for highway bridges were prepared in July and August of 1995. A minimum 28-day compressive strength of 8,000 psi (55 MPa) and a release strength of 6,000 psi (41 MPa) were specified. The maximum permeability requirement was 1500 coulombs.

The concretes were prepared with materials normally available at the plant. The cementitious material was a combination of Type I cement and silica fume. Typical chemical and physical analyses of the portland cement are given in Table 1. The silica fume conformed to the requirements of ASTM C 1240 and was used in the slurry form. The coarse and fine aggregates were crushed limestone, and their characteristics are given in Table 2. The coarse aggregate had No. 67 grading with a nominal maximum size of 0.75 in (19 mm). Commercially available air-entraining admixture (AEA); water-reducing and retarding admixture (WR + R) conforming to the requirements of ASTM C 494, Type D; and a high-range water-reducing admixture (HRWRA), a combination of melamine and naphthalene condensates, conforming to the requirements of ASTM C 494, Type F, were used.

For each beam, four batches, each 4 yd^3 (3 m^3), were prepared. Nine beams were steam cured and the forms stripped the next day, and 11 were moist cured for 3 days. Moist-cured beams were cast on a Friday and stripped on Monday. From each type of cure, two batches were tested: B1 and B2 were steam cured, and B5 and B6 were moist cured. The mixture proportions were the same, except for the amount of admixtures, and are given in Table 3.

Table 1. Chemical and Physical Analyses of Portland Cement for Beam

Chemical	%
SiO_2	20.43
Al_2O_3	5.41
Fe_2O_3	3.21
CaO	63.54
MgO	1.39
SO_3	2.63
Na_2O Eq.	0.77
C_3A	10.12
Physical	**%**
Blaine fineness (m^2/kg)	376

Table 2. Characteristics of Coarse and Fine Aggregates

Aggregate	Specific Gravity	Los Angeles Abrasion (%)	Absorption (%)	Fineness Modulus	%Voids
Beams					
Coarse	2.78	19.8	0.5	3.1	52.3
Fine	2.75		1.5		
Substructure and Bridge Deck					
Coarse	2.72	26.1	0.2	2.8	51.3
Fine	2.63		0.4		

Table 3. Mixture Proportions for Prestressed Beams

Material (lb/yd^3)	B1, B2	B3	B4	B5, B6	B7
Portland cement	752	611	611	752	752
Silica fume	55	45	45	55	---
Coarse aggregate	1675	1700	1700	1675	1800
Fine aggregate	1425	1450	1450	1425	1300
Water	255	210	216	255	275
w/cm	0.32	0.32	0.33	0.32	0.37
HRWRA (oz/cwt)	25.0	30.0	30.0	25.0	11.3
WR + R (oz/cwt)	3.0	3.8	3.8	3.8	3.4

1 lb/yd^3 = 0.5935 kg/m^3; 1 oz/cwt = 0.6519 mL/kg.

Concretes were tested in the freshly mixed state for air content (ASTM C 231), slump (ASTM C 143), and temperature (ASTM C 1064). Specimens were cast for tests in the hardened state as indicated in Table 4. Specimens, except the temperature-matched cure (TMC) specimens, were steam cured along the beams cast in the pretensioning bed. In the TMC system, the temperature of the concrete member is monitored and the temperature of the cylinder is matched to that of the member by the heating element in the cylinder mold. For the initial batches, the presteaming period was longer than the initial time of setting because steam is turned on when the last batches of concrete attain the initial time of set. Specimens for moist-cured beams were kept moist for 3 days. After steam curing or initial moist curing, specimens were kept outdoors.

Compressive strength was determined in accordance with AASHTO T 22 using neoprene pads. TMC cylinders were tested at the end of steam curing or after 3 days for moist curing. For

Table 4. Tests and Specimen Sizes

Tests	Specification	Age (d)	Size (in)
Compressive strength	AASHTO T 22	*	4 x 8
Flexural strength	ASTM C 78	28	3 x 3 x 11¼
Splitting tensile strength	ASTM C 496	28	4 x 8
Elastic modulus	ASTM C 469	28	6 x 12
Permeability	AASHTO T 277	28, 1 yr	2 x 4
Drying shrinkage	ASTM C 157	6 mo	3 x 3 x 11¼

*At 1, 3, 7, and 28 days and 1 year for cast-in-place, moist-cured specimens. At 1 (steam cured), 3 (moist cured), 28, and 56 days and 1 year for prestressed concrete specimens. In addition, three temperature-matched cured specimens were prepared for steam-cured concretes. 1 in = 25.4 mm.

the permeability test, the top 2 in (50 mm) of cylinders measuring 4 by 4 in (100 by 100 mm) was cut and tested. The drying shrinkage specimens were stored outdoors for 4 months and then air-dried in the laboratory for an additional 8 months.

Concrete was truck mixed and placed in the beam mold by bucket. In each beam, concrete was placed in layers. Each layer was internally vibrated. At the same time, a vibrator moving along the side of the beam mold provided external vibration. The beams were hand finished and covered with wet burlap. The burlap was then covered with insulating material.

During the placement of the HPC beams, Type II beams with a minimum compressive strength of 5,000 psi (35 MPa) fabricated in accordance with AASHTO's standard specifications for highway bridges were prepared for another VDOT project. The mixture proportions for this conventional concrete are given as B3 and B4 in Table 3. Even though the concrete was a conventional design, it had the same w/cm as the HPC beams and contained the same cementitious material, although less. These beams were steam cured.

Six beams corresponding to batches B1 through B6 were instrumented with thermocouples to determine the temperature development.

In VDOT mixtures, pozzolans or slag is routinely used. VDOT requires that the alkali content of cement be 0.45 percent (previously 0.40 percent) or less for resistance to alkali-silica reaction (ASR). For higher alkali contents, a pozzolan or slag must be used. In addition, the permeability requirements can be met more easily with the use of pozzolans or slag. To demonstrate the effectiveness of a pozzolan in reducing permeability, silica fume concrete supplied to another state was sampled for compressive strength and permeability. The mixture proportions for this non-air-entrained batch, B7, are given in Table 3.

One of the 20 beams was subjected to a load test at the prestressing plant. A load test indicates if a specified amount of residual deflection occurs in the beam after removal of a maximum load of 95 percent of the calculated load to cause a flexural crack.

Substructure and Bridge Deck

The substructure concrete had a minimum 28-day design compressive strength of 3,000 psi (21 MPa), and the bridge deck concrete had a minimum of 4,000 psi (28 MPa). The maximum permeability requirement for the substructure was 3500 coulombs and for the bridge deck was 2500 coulombs at 28 days.

The cementitious material was a combination of Type II cement with ground-granulated blast furnace slag (slag). The coarse aggregate was an arch marble, No. 57, with a nominal maximum aggregate size of 1 in (25 mm); the fine aggregate was a natural sand. The characteristics of the aggregates are given in Table 2, and the mixture proportions are given in Table 5. The contractor chose a lower w/cm than normally used, 0.05 lower than the maximum permissible, to ensure that the permeability specification was met. Three batches of concrete representing the substructure (A31, A32, and A33), and four batches of concrete for the bridge deck (A41 through A44) were tested. The concretes contained an AEA, a WRA, and a naphthalene-based HRWRA, except for A31, which did not contain the HRWRA.

Concretes were tested at the freshly mixed state for slump, air content, and temperature. Specimens were prepared for tests (Table 4) at the hardened state.

Specimens for strength testing were kept moist until tested. A set of two permeability specimens was kept moist at 100° F (38° C) the last 3 weeks for testing at 28 days. Additional sets were moist cured at 73° F (23° C) for tests at 28 days and 1 year. Curing the last 3 weeks at a higher temperature was performed to accelerate the reduction in permeability to determine at 28 days the level of permeability that would occur at later ages.[6]

The concrete was mixed and delivered in ready-mix concrete trucks. At the job site, concrete was discharged into a bucket for placement in the substructure and was pumped for the bridge deck. Concrete was consolidated by internal vibrators. Bridge deck concrete was screeded by a vibratory roller screed. After screeding, the surface was kept from drying by fogging until the application of wet burlap covered with plastic and an insulating blanket for 7 days. The bridge deck was placed in December. To protect concrete from cold weather, the contractor provided heat to the deck from the underside by using heaters placed on the pier caps.

Table 5. Mixture Proportions for Substructure and Deck

Materials (lb/yd^3)	Substructure	Deck
Portland cement	353	329
Slag	235	329
Coarse aggregate	1773	1773
Fine aggregate	1254	1173
Water	259	263
w/cm	0.44	0.40
HRWRA (oz/cwt)	0-8	2-3
WR + R (oz/cwt)	8-10	10

1 lb/yd^3 = 0.5935 kg/m^3; 1 oz/cwt = 0.6519 mL/kg.

The sides and bottom of the deck were covered with plastic enclosing the heaters. After 7 days, burlap was removed, and the deck was sprayed with a white-pigmented curing compound. Transverse grooves were cut on the hardened concrete several weeks after the placement.

The bridge deck was placed in 2 days. Each day, two batches of concrete were sampled. Specimens were kept under the blanket near the deck. The temperatures of a cylinder and a slab measuring 8.5 by 12 by 12 in (215 by 300 by 300 mm) kept under the blanket and a cylinder left outside the blanket were monitored for 1 day using thermocouples.

RESULTS AND DISCUSSION

Prestressed Beams

Concrete Properties

The air content, slump, concrete temperature, and duration of steam curing are given in Table 6. All mixtures met the air content requirement of 5.5 →1.5 percent for prestressed concrete with an HRWRA. Slump values were high, enabling easy consolidation. The presteaming and the steam duration were within 19 hours, which would enable fabricating, stripping, and moving the beams within 24 hours, enabling daily production in the pretensioning bed.

The temperatures in the steam enclosure, the TMC cylinder, and the beam containing B2 at 2 ft (600 mm) from the end and 6 in (150 mm) from the bottom are given in Figure 1. Because of the heat of hydration, the temperature rose continuously in the beam and, after a peak, gradually decreased. The TMC molds were covered to protect them from the environment. The temperature rise in the molds was higher than in the beam.

The temperature rise in the cylinders cured along the beam in the enclosure was expected to be less than in the beam because of size. The enclosure temperature and the temperature of the cylinder within the enclosure alongside the beam containing B4 are given in Figure 2. The temperature of the cylinder followed that in the enclosure. The temperature rose continuously in the beam and then dropped gradually, even though sudden changes occurred in the temperature in the enclosure. The strength difference between the TMC and regular cylinders in the enclosure in concretes representing B3 and B4 was higher than with B1 and B2. This larger difference, more than 2,000 psi (14 MPa), was attributed to the higher cement factor and the higher enclosure temperature for B1 and B2. The location of cylinders with respect to the member and the steam ducts would also have an effect.

Table 6. Characteristics of Freshly Mixed Concrete for Beams

Items	B1	B2	B3	B4	B5	B6	B7
Air content (%)	4.5	6.5	7.2	7.5	6.2	5.7	---
Slump (in)	6.3	7.0	6.0	6.5	5.8	6.8	5.8
Concrete temperature (° F)	91	89	83	82	92	91	81
Presteaming + steam time (hr)	8 + 10	7 + 10	7 + 12	6.5 + 12	MC	MC	9 + 12

1 in = 25.4 mm; ° F = (° C*1.8) + 32.

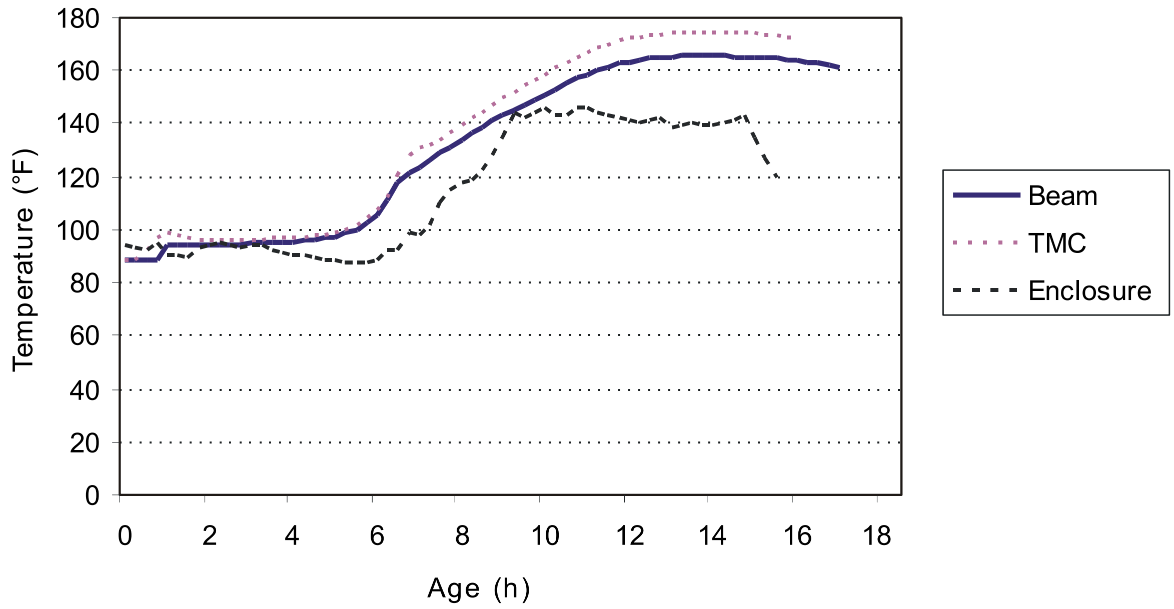

Figure 1. Temperature Rise for B2

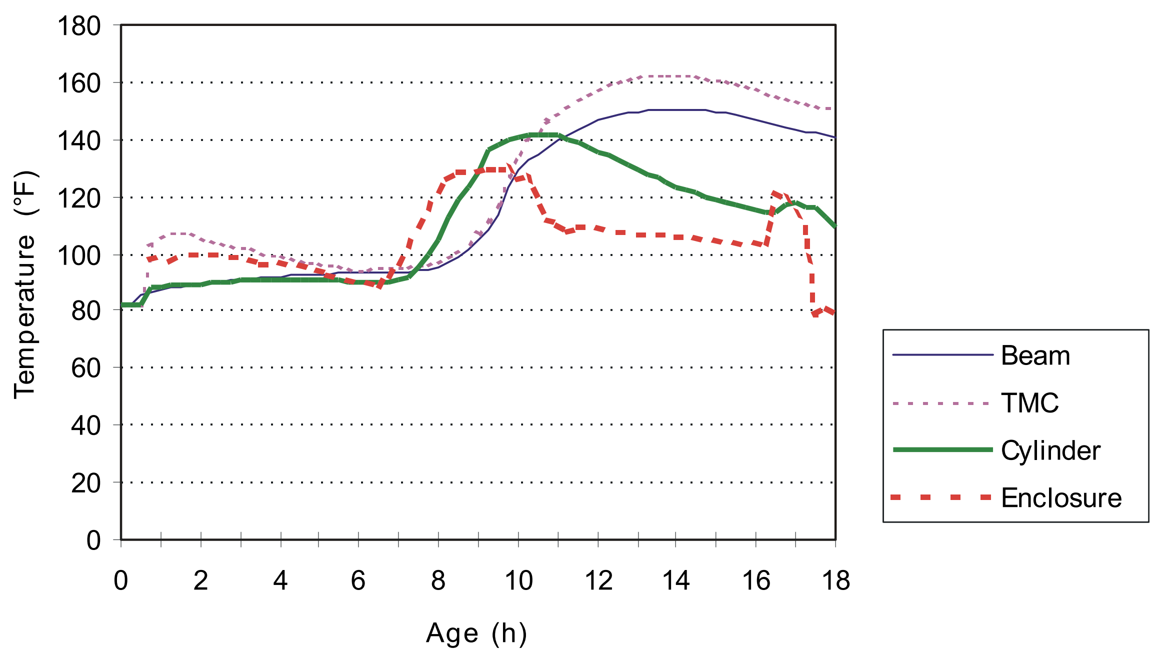

Figure 2. Temperature Rise for B4

The temperature development in the moist-cured beam B6 is given in Figure 3. The data indicated that the beams and TMC cylinders had a high temperature development, unlike the regular cylinders kept under the covers next to the beams. The results for the TMC cylinders indicate the possibility of attaining a release strength of 6,000 psi (41 MPa) with moist curing in 1 day.

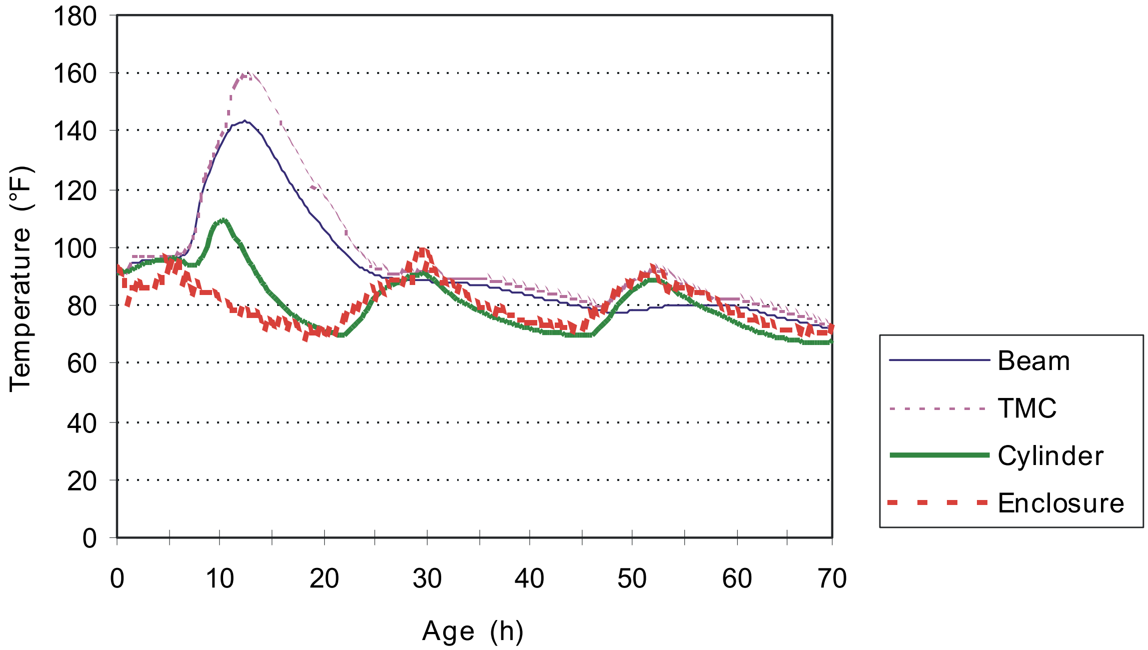

Figure 3. Temperature Rise for B6

The strengths of different batches are summarized in Table 7. High early strengths were obtained in 1 day by steam curing. Similar strengths were obtained in 3-day moist-cured or 1-day steam-cured specimens. The TMC cylinders tested after steam curing had higher strengths than the regular cylinders in the enclosure. This was as expected because of the higher temperatures developed in the TMC cylinders. The moist-cured concretes had higher 28-day strengths than the steam-cured specimens, demonstrating the adverse effect of a high initial curing temperature; however, all values were satisfactory.

The strengths of the HPC concretes, B1 and B2, versus those of the conventional concretes, B3 and B4, all steam cured, were similar at 28 days, as would be expected since they had a similar w/cm. At release, the same was the case for the TMC cylinders but not for the regular cylinders in the enclosure because of the lower temperature development in the small cylinders. The elastic modulus, splitting tensile strength, flexural strength, and permeability values are given in Table 7. They were all satisfactory. The modulus and strength values at 28 days were always higher and the permeability values lower for the moist-cured concretes.

The permeability of B7 with portland cement only was high, more than 3 times the specified maximum value of 1500 coulombs. This concrete had a low w/cm of 0.37 but had a high coulomb value, indicating the effect of not using silica fume to reduce permeability.

The drying shrinkage data for the beams are given in Table 8. The results indicate that shrinkage was within satisfactory levels, less than 700 microstrain, with steam-cured specimens having less shrinkage than moist-cured specimens.[12]

Table 7. Properties of Hardened Concrete for Beams

Property	Age	Cure	B1	B2	B3	B4	B5	B6	B7
Compressive strength (psi)	1 d	Steam	8170	7840	6010	5850			5440
	1 d	TMC	8430	8230	8040	8080			
	3 d	MC					7830	7830	
	3 d	TMC					8870	9030	
	28 d	Steam + Air	9850	9690	9850	9190			7210
	28 d	3 d MC + Air					12120	11960	
	56 d	Steam + Air	9890	9860					
	56 d	3 d MC + Air					12120	12130	
	1 yr	Steam + Air	9840	9720	9850	9170			
	1 yr	3d MC + Air					11830	11730	
E (10^6 ksi)	28 d	Steam + Air	5.98	5.85	6.11	5.76	6.21	6.22	
	56 d	Steam + Air	5.96	6.35			6.65	6.42	
Splitting tensile strength (psi)	28 d	Steam + Air	760	825			950	910	
Flexural strength (psi)	28 d	Steam + Air	970	865			1005	990	
Permeability (coulomb)	28 d	Steam + Air	254	290			178	188	4985
	1 yr	Steam + Air	280	300			119	184	

1 psi = 0.006895 MPa; 1 ksi = 0.006895 GPa.

Table 8. Drying Shrinkage (%)

Concrete Type	Sample Age			
	4 wk	8 wk	32 wk	64 wk
Beams				
Steam cured	0.0138	0.0048	0.0317	0.0303
Moist cured	0.0292	0.0208	0.0498	0.0488
Substructure (A3)	0.0193	0.0278	0.0392	
Deck (A4)	0.0286	0.0353		

Load Test

The beam was loaded up to 95 percent of the load that would cause a flexural crack. To measure the deflection of the beam, a scale was placed on one side of the beam behind a wire stretched between the supports. The maximum deflection was 1.5 in (38 mm). When the load was released, a recovery of 97.9 percent was instantaneous. This is the percent difference between the centerline deflection under load and after the load is removed. The result is assumed to be satisfactory if the recovery is 90 percent or more. After 30 minutes, the recovery was 100 percent. During the load test, the bottom of the beam was wetted to observe cracking easily. There were no visible cracks.

Substructure and Bridge Deck

Concrete Properties

The air content, slump, and concrete and air temperatures are given in Table 9. The air contents were within the specification limit of 6 → 2% for substructure and 6.5 → 1.5% for deck concrete, except that one of the batches for the deck concrete had a low value of 3.4%. The test samples were obtained from the middle third of each load. Acceptance tests were performed for concrete from the beginning of the load; all concrete complied with the acceptance criteria. Concretes were workable with high slump.

The strength of slag concrete for the A3 concrete used in the substructure was much higher than the minimum required strength of 3,000 psi (21 MPa) at 28 days, as shown in Table 10. The w/cm of the substructure concrete was 0.44, which is lower than the specified maximum of 0.49, to ensure the permeability requirement was met.

The strength of the A4 concrete for the deck was low at 1 day. The air temperature was also low, as shown in Figure 4. The specimens were covered with insulating blankets and kept near the structure. The temperatures of a cylinder under cover and a cylinder kept outside the cover and the slab under cover are displayed in Figure 4. The temperature of the cylinder left outside the cover follows the air temperature. The cylinder under the blankets retains its temperature and then shows a slight gradual increase. The slab had higher temperatures than the cylinders because of their larger size. The actual bridge deck is expected to have a higher temperature because of its size and heating from the underside. Thus, even though the cylinders had a low 1-day strength, a higher strength is expected in the deck concrete because of the higher heat generation. At 28 days, the compressive strength of deck concrete was more than twice the minimum required value of 4,000 psi (28 MPa). Batches A43 and A44 were brought to the laboratory on Monday, 3 days after casting on a Friday. They had low 3-day strengths because of cool temperatures.

The elastic modulus, splitting tensile, and the flexural strength were satisfactory, with deck concretes having higher values, as shown in Table 10.

The rapid chloride permeability values at 28 days of substructure concrete were low, and even lower when the concrete was cured at 100^{o} F (38° C) the last 3 weeks, as shown in Table 10. Similarly, the deck concretes had low values at room temperature and very low values when

Table 9. Characteristics of Freshly Mixed Concrete for Substructure and Deck

Property	A31	A32	A33	A41	A42	A43	A44
Air (%)	5.4	5.2	4.8	---	6.4	3.4	6.0
Slump (in)	4.5	4.5	3.8	5.5	4.8	4.3	4.3
Concrete temperature (° F)	72	90	90	53	53	61	61
Air temperature (° F)	67	92	92	56	56	67	67

1 in = 25.40 mm; ° F = (° C*1.8) + 32.

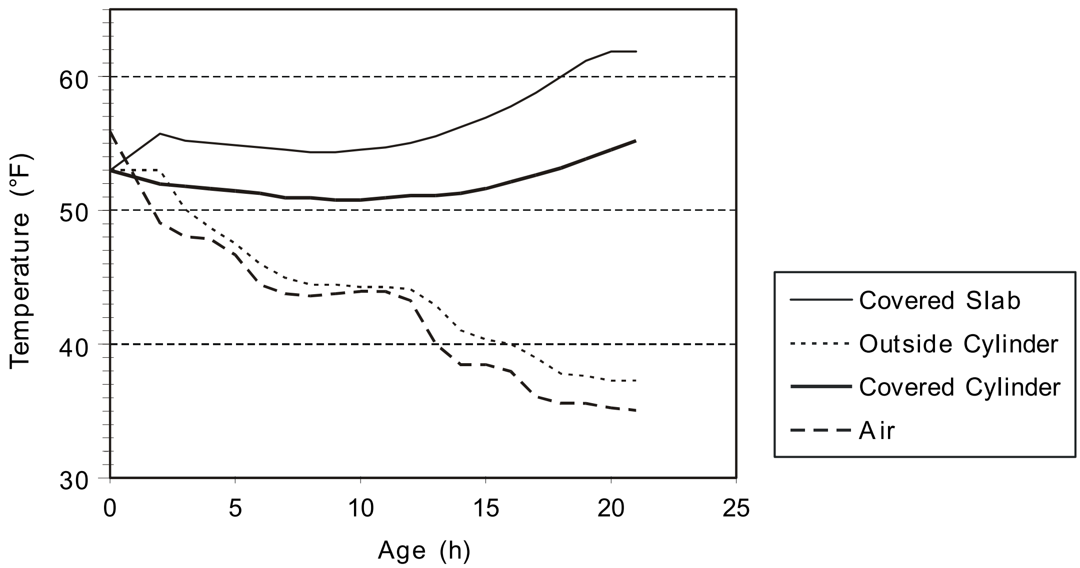

Figure 4. Temperature Rise of Deck Concrete

Table 10. Properties of Hardened Concrete for Substructure and Deck

Property	Age	Substructure			Deck			
		A31	A32	A33	A41	A42	A43	A44
Compressive strength (psi)	1 d	2120	1940	1480	590	420		
	3 d						1730	1660
	7 d	4190	4430	3900	5820	5440	5400	4890
	28 d	5820	6160	5800	8400	8100	9050	9290
	1 yr	6870	7320	6730	9510	9280	10680	10810
Elastic modulus (10^6 ksi)	28 d		4.83	4.73				
	1 yr	5.19			5.59	5.47	6.32	6.12
Splitting tensile strength (psi)	28 d	590	625	575	765	685	750	750
Flexural strength (psi)	28 d	835	815	740	875	830	1045	995
Permeability	28 d	1831	1347	1670	1428	1405	1256	1677
Permeability[a]	28 d	1323	883	1076	696	773	743	898
Permeability	1 yr	815	710	904	705	674	602	782

[a]Last 3 weeks cured at 100 °F (38 °C).
1 psi = 0.006895 MPa; 1 ksi = 0.006895 GPa.

cured at higher temperature. Substructure concrete with a w/cm of 0.45, which is the maximum specified w/cm for deck concrete, complied with the permeability requirement of deck concrete, indicating that lowering the w/cm of the deck concrete to 0.40 was unnecessary. Concretes with a w/cm of 0.45 compared to 0.40 are easier to place in the field and are less prone to cracking.

The drying shrinkage data for the substructure and deck concretes are given in Table 8. The results indicate satisfactory shrinkage, less than 700 microstrain.[12]

Cost Data

There were initial cost savings with this bridge even though a ½-in (13-mm) thicker deck (attributable to the wider beam spacing) and a higher quality concrete were used compared to regular bridge structures. The total cost of the bridge was $49.32/ft^2 ($530/m^2) of deck surface. This was lower than the average federal-aid cost of $58/ft^2 ($624/m^2) for bridges built that year. The savings were due to the use of fewer beams, eight less, resulting from the use of high strength concrete. All concrete met the low permeability requirements. Minimal maintenance is expected, which will result in further savings in the long term.

Condition Survey

At 1 and 5 years, generally, there was no scaling. At 1 year, 15 ft (4.5 m) of diagonal and 24 ft (7.5 m) of transverse cracks were observed in the deck. At 5 years, there were 60 ft (18.5 m) of diagonal cracks, mainly at the joints, with an average width of 0.010 in (0.25 mm), ranging from 0.008 to 0.020 in (0.2 to 0.5 mm); 100 ft (30.5 m) of transverse cracks with an average width of 0.06 in (0.15 mm), ranging from 0.004 to 0.010 in (0.1 to 0.25 mm); and 535 ft (163 m) of longitudinal cracks with an average width of 0.008 in (0.20 mm), ranging from 0.004 to 0.012 in (0.1 to 0.3 mm). Most of the longitudinal cracking occurred over the bridge beams. In general, the cracks were very tight and are not expected to have a great impact on the performance of the deck.

CONCLUSIONS

- Air-entrained HPC beams with low permeability and high early and 28-day strengths may be satisfactorily prepared using locally available materials.

- TMC cylinders are more representative of actual early beam strengths than regular cylinders. Cylinders cured near the beams under covers do not generate as much heat as a massive beam or the TMC cylinders and, therefore, do not develop the strength of the actual member. They underestimate the strength of the actual beam.

- Moist-cured specimens have lower early strengths but higher ultimate strengths than steam-cured specimens, indicating the adverse effect of a high initial temperature on long-term strength.

- The use of pozzolans or slag reduces the permeability of concretes.

RECOMMENDATIONS

1. Use high strengths in bridge beams if economically feasible.

2. Use TMC to determine the early strengths of concretes in beam.

3. Use pozzolans or slag to reduce the permeability of concrete.

ACKNOWLEDGMENTS

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