FINAL REPORT

DESIGN OF HIGH-PERFORMANCE CONCRETE MIXTURES AND TEST BEAMS FOR A BRIDGE IN VIRGINIA

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16. Abstract

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Results showed that high-strength and low-permeability air-entrained mixtures could be designed. Concretes with a 28-day strength exceeding 69 MPa (10,000 psi), a minimum release strength of 70% of the 28-day strength, and coulomb values below 1,500 at 28 days can be produced with a water–cementitious material ratio (W/CM) of about 0.30 or below. Achieving such a low W/CM requires large amounts of cementitious material, proper selection of aggregates, and high dosages of high-range water-reducing admixtures. Thorough mixing is necessary, and good construction practices must be followed during placement, consolidation, and curing. To achieve high early strengths, proper temperature management is also needed.

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

The main objective of this study was to develop concretes with a compressive strength of 69 to 83 MPa (10,000 to 12,000 psi) at 28 days and a high early release strength (within 20 hr) exceeding 70% of the 28-day strength. The properties of the high-performance concretes (HPC) tested included compressive strength, flexural strength, splitting tensile strength, and permeability. Four prestressed concrete AASHTO Type II beams were fabricated with HPC at a prestressing plant and load tested to failure. This test program was undertaken to support the field application of HPC in Virginia.

Results showed that high-strength and low-permeability air-entrained mixtures could be designed. Concretes with a 28-day strength exceeding 69 MPa (10,000 psi), a minimum release strength of 70% of the 28-day strength, and coulomb values below 1,500 at 28 days can be produced with a water–cementitious material ratio (W/CM) of about 0.30 or below. Achieving such a low W/CM requires large amounts of cementitious material, proper selection of aggregates, and high dosages of high-range water-reducing admixtures. Thorough mixing is necessary, and good construction practices must be followed during placement, consolidation, and curing. To achieve high early strengths, proper temperature management is also needed.

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INTRODUCTION

High-performance concretes (HPC) have enhanced specific properties such as workability, durability, strength, and dimensional stability.[1] Improved durability is expected to extend the service life of transportation facilities with minimal maintenance requirements. Low permeability, a satisfactory air void system, and good wear resistance are important characteristics of durable concretes. When exposed to water and aggressive solutions, durable concretes must also have low permeability. For low permeability, low water–cementitious material ratios (W/CM) and pozzolanic materials are used. Such practices also lead to strengths higher than those of ordinary concretes. The potential benefits of high-strength concrete in bridge structures include increased girder spacing, longer pile and girder lengths, increased rigidity, and lower prestress losses, leading to reduced overall cost.[2-6] To use high-strength concrete effectively, prestressing strands with a diameter of 15 mm (0.6 in), rather than 13 mm (0.5 in), are necessary to generate additional prestressing force.[3]

In 1992, to extend service life, the Virginia Department of Transportation (VDOT) reduced the maximum W/CM specification for prestressed concrete members from 0.49 to 0.40. VDOT also requires the use of pozzolans or ground granulated blast furnace slag (slag) in the cementitious material to reduce alkali-silica reactivity when cements with an alkali content exceeding 0.40% are used. (The maximum alkali content permitted in portland cements is 1.0%.) These changes have resulted in low permeability and high ultimate strengths. VDOT has been revising its specifications to take full advantage of these benefits.

The VDOT specification for regular prestressed concrete requires a minimum compressive strength of 35 MPa (5,000 psi) at 28 days. Higher strengths and low permeability were specified for a four-span bridge on Rte. 40 over the Falling River at Brookneal in VDOT's Lynchburg District constructed in 1995. It has AASHTO Type IV prestressed concrete beams with a minimum compressive strength of 55 MPa (8,000 psi) at 28 days. The number of beams was reduced from 7 to 5 for each span because of the higher strength and resulted in lower material, construction, and transportation costs. Fewer beams are also more aesthetically pleasing. The deck is 215 mm (8.5 in) thick, 13 mm (0.5 in) thicker than usual, to allow a larger spacing of 3 m (10 ft) between beams. The low permeability of the concretes used should extend the service life of the bridge.

Even with the requirement for low-permeability concretes, the bridge construction unit cost per square foot (0.09 square meter) was $49, which was less than the 1994 average cost of $58 for 34 bridges in the federal-aid highway system in Virginia. The unit cost is determined by dividing the total cost of the bridge by the deck area. The initial cost savings was estimated to be $30,000, approximately 4% of the total bridge cost. Additional savings are expected over the life of the structure because of the anticipated longevity and low maintenance requirements.

Before the construction of the Brookneal bridge, an experimental project was conducted to support the design of high-strength, low-permeability, prestressed concrete bridge girders using the larger diameter strands. The results of this project are presented in this report.

PURPOSE AND SCOPE

The objectives of this research were:

1. Develop concrete mix designs for compressive strengths of 69 to 83 MPa (10,000 to 12,000 psi) at 28 days and high early release strengths (within 20 hr) exceeding 70% of the 28-day strength. These design strengths were higher than originally planned for the Brookneal bridge to provide information for use with this bridge and future bridges designed with higher strengths.

2. Determine the properties of HPC, i.e., compressive strength, flexural strength, splitting tensile strength, and permeability.

3. Fabricate four full-size beams, two with a 28-day compressive strength of 69 MPa (10,000 psi) and two with a compressive strength of 83 MPa (12,000 psi), with strands 15 mm (0.6 in) in diameter spaced 51 mm (2 in) apart.

4. Test the beams for transfer length, development length, and maximum load carrying capacity.

METHODOLOGY

Materials and Proportioning

To obtain HPC, strong aggregates with the proper gradation are required. Usually, the maximum size is limited to 13 mm (0.5 in) to provide a better bond between the aggregates and paste.[7] A low W/CM is needed to obtain high early and ultimate strengths and is achieved by a high cement content, proper selection of aggregates, and large amounts of a high-range water-reducing admixture (HRWRA). However, a large amount of portland cement in concretes may cause thermal cracking and increase cost. Pozzolanic materials, fly ash and silica fume, and slag can be added to reduce the amount of portland cement needed. These materials also improve the ultimate strength and durability of concretes. HPC have low permeability and an improved bond between the aggregate and paste. In this study, different cementitious materials, aggregates, and admixtures were tested.

During the development of the trial batches, materials other than those normally used at the plant were also tested. Regular Type III cement was used in all laboratory batches and two plant batches. At the plant, for both trial batches and job mixes, Type II modified portland cement (finely ground) was used. Slag was used in most batches and the job mixes. Silica fume was also added to some batches. Table 1 provides typical analyses of the cements, slag, and silica fume. Different coarse and fine aggregates were also used so that the material would be cleaner with a better particle shape for a reduced water demand. The maximum size of the coarse aggregate used in the beams was the usually recommended 13 mm (½ in), but in trial batches 25 mm (1 in) coarse aggregate was also used to lower the water demand. The characteristics of the aggregates used are given in Table 2. The fine aggregates were natural sand, and the coarse aggregates were crushed rock. Figures 1 and 2 show the gradations of the aggregates used in the test beams. The chemical admixtures were also varied. Regular water reducers and HRWRA from two sources were used. In one batch, a melamine-based HRWRA was used, and in the remaining batches, a naphthalene-based HRWRA was used.

Table 1. Chemical and Physical Analysis of Cementitious Material (%)

Analysis	Type II MF	Type III	Slag	Silica Fume
Chemical SiO_2	20.7	20.4	35.2	94.6
Al_2O_3	4.8	4.5	10.7	0.3
Fe_2O_3	3.2	2.1	1.0	0.1
CaO	62.8	63.3	37.9	0.5
MgO	3.2	2.8	13.0	0.4
SO_3	3.4	3.8	0.8	
Na_2O Eq.	0.58	0.57		
C_3A	7.3	9.2		
Physical Blaine Fineness (m^2/kg)	504	562	494	

Table 2. Characteristics of Coarse and Fine Aggregates

Location and Classification	S.G.	L.A. Abr.	Absorp. (%)	F.M.	% Voids
Coarse Aggregate Garrison Gr.	2.98	17.8	0.4		
Red Hill Gr.	2.83	26.5	0.5		
Petersburg Bi.,Gn.,Gr.	2.67	26.2	0.6		
Manassas Db.	2.92	17.4	0.9		
Fine Aggregate Rappahann.	2.60		0.9	2.9	50.2
Providence Forge	2.64		0.1	2.8	47.9
La Plata	2.62		1.2	2.8	47.9
Petersburg	2.59		0.4	2.6	48.8
Kingsland Reach	2.61		0.8	2.7	50.3

Note: The coarse aggregate from Garrisonville and the fine aggregate from Rappahannock were the plant material. Gr.-granite, Bi.-biotite, Gn.-gneiss, Db.-diabase.

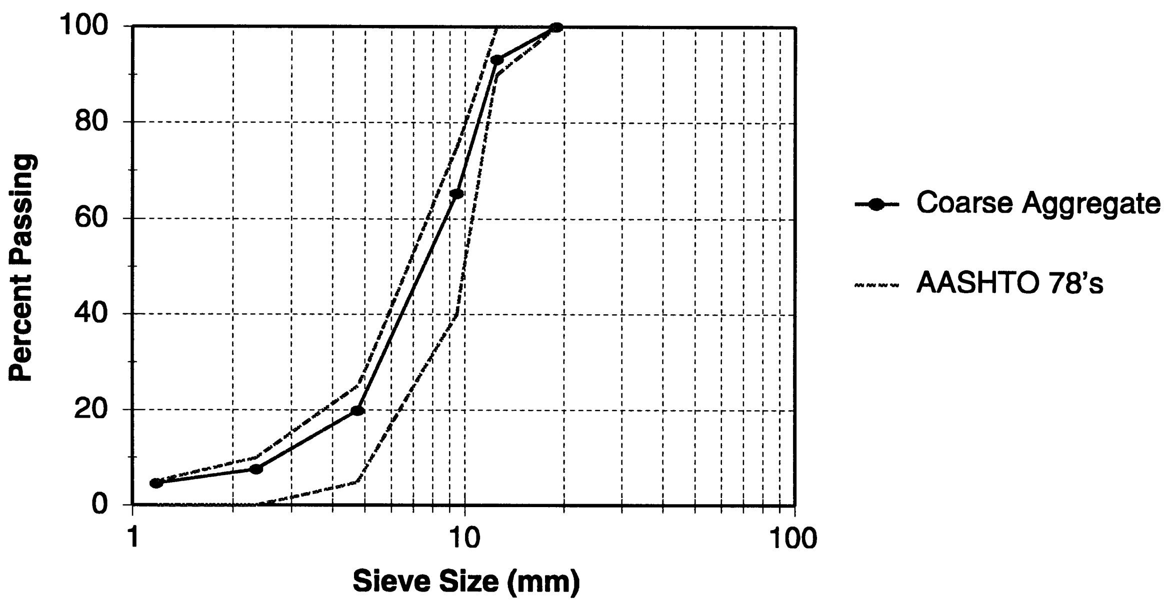


Figure 1. Gradations of Aggregates Used in Test Beams

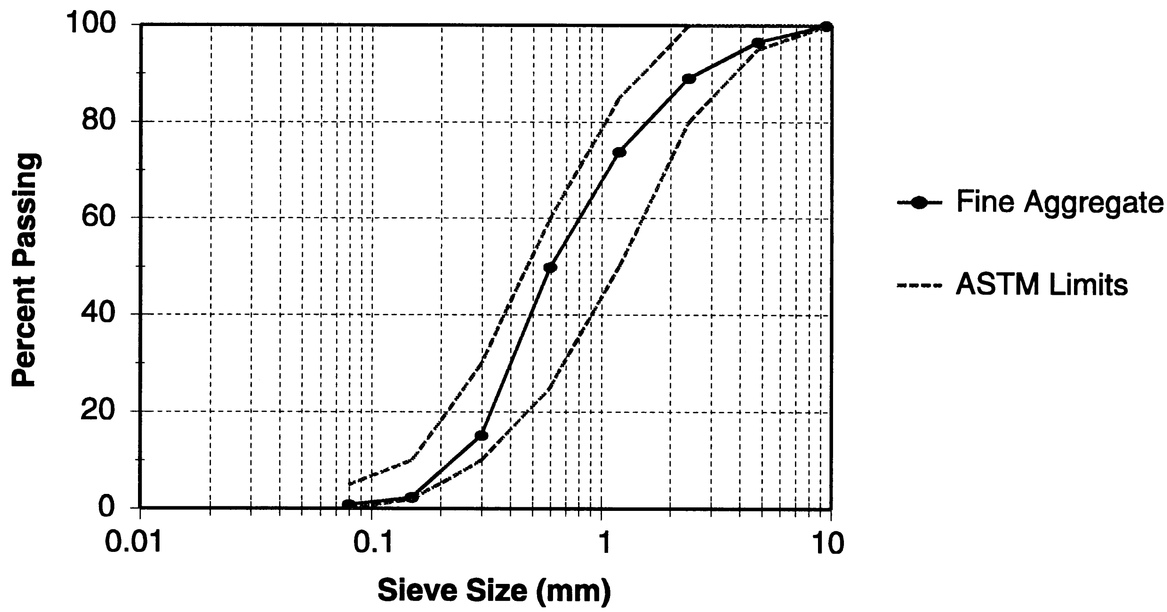


Figure 2. Gradations of Aggregates Used in Test Beams

Concretes were proportioned in accordance with ACI 211, with one exception. A fixed amount of coarse aggregate, 1068 kg/m^3 (1,800 lb/yd^3), was used in most trial batches and job mixes. Alkali-aggregate reactivity was addressed by including pozzolans and slag in the mixtures. These mineral admixtures were also used to develop a high ultimate strength and low permeability. In the concrete for the prestressed beams, a coulomb value of 1,500 or less (in accordance with AASHTO T277) was sought at 28 days to restrict the intrusion of aggressive solutions into the concrete.

Concrete Testing

Trial Batches

Trial batches were prepared in the laboratory and at the plant before the beams were cast. Specimens were tested for slump (ASTM C143), air content (ASTM C231), setting time (ASTM C403), compressive strength (AASHTO T22, using neoprene pads in steel caps), and permeability (AASHTO T277). For compressive strength and permeability tests, each test value was taken as an average of two specimens. In the laboratory, specimens were cast in plastic molds with caps and placed in a Styrofoam insulating box or an oven to cure at high temperatures. At the plant, the high temperatures were achieved by either using an insulating box or keeping specimens in the steam-curing beds. Specimens cured in the boxes were tested at 1 day. The steam-cured specimens were tested at the end of steaming, which ranged from 16 to 20 hr, including the preset times (presteaming period). After steam curing, specimens were kept in the laboratory in open air.

Test Beams

Concrete mixes for the test beams were tested for slump and air content in the plastic state. Specimens were prepared for tests in the hardened state (Table 3). The samples were steam cured in prestressing beds by setting them in the recesses in the side forms. At the end of steaming, they were cured outdoors. Before testing, the beams for flexure testing were soaked in lime-saturated water for 24 hr because drying of the surface induces tensile stresses in the extreme fibers that will markedly reduce the strength (ASTM C78 and ASTM C192).

Table 3. Test and Specimen Sizes

Tests	Specifications	Size (in)
Compressive Strength	AASHTO T 22	4 x 8, 6 x 12
Flexural Strength	ASTM C 78	3 x 3 x 11¼
Splitting Tensile Strength	ASTM C 496	4 x 8
Elastic Modulus	ASTM C 469	6 x 12
Permeability	AASHTO T 277	2 x 4

Compressive strengths were determined at the end of the steam-curing period, at 28 days, and at 56 days. Each test value was taken as an average of two 100 x 200 mm (4 x 8 in) cylinder strengths. At 28 days, 150 x 300 mm (6 x 12 in) cylinders were also tested. The tests on the 100 x 200 mm (4 x 8 in) cylinders were conducted in accordance with AASHTO T22 using neoprene pads in steel end caps. The 150 x 300 mm (6 x 12 in) cylinders were capped with high-strength sulfur-mortar. The elastic modulus of the concretes was determined in accordance with ASTM C469 using the 150 x 300 (6 x 12 in) cylinders. Flexural strength was determined in accordance with ASTM C78 using 75 x 75 x 285 mm (3 x 3 x 11¼ in) prisms, and the splitting tensile strength was determined in accordance with ASTM C496 using 100 x 200 (4 x 8 in) cylinders.

For the permeability test, the top 50 mm (2 in) of the 100 x 100 mm (4 x 4 in) cylinders was cut and tested at 28 days. The specimens were tested in accordance with AASHTO T277 or ASTM C1202.

Beam Design and Structural Testing

Four prestressed concrete AASHTO Type II test beams, each containing 10 strands 15 mm (0.6 in) in diameter, 2 on top and 8 across the bottom, were fabricated at a prestressing plant in Virginia. They were designed in accordance with AASHTO and VDOT specifications. Strands conforming to the requirements of ASTM A416-90a for Grade 270 strands were placed with a 51-mm (2 in) center-to-center spacing. Two of the bottom strands were draped, as shown in Figure 3. Shear reinforcement was uncoated Grade 60 steel conforming to the requirements of ASTM A615-92b. Two of the beams were prepared with concrete to develop a 28-day compressive strength of 69 MPa (10,000 psi), and the other two to develop a compressive strength of 83 MPa (12,000 psi). Trial batches were prepared at the plant and in the laboratory before the field concretes were prepared for the test beams. The beams were steam cured to obtain 70% of the compressive strength within 24 hr. Two of the beams, B1 and B3, were instrumented to determine the temperature profile at different locations during steam curing (Figure 4).

The test beams were instrumented to measure the transfer length and the end slip of the prestressing strands. Brass studs, spaced at intervals of 100 mm (4 in), were embedded on the outside surface of the beams along the path of the bottom and draped strands. Measurements were taken with a Whittemore gage before and just after detensioning and at 1 day, 7 days, 14 days, and 28 days from the time of concrete placement. The difference between the initial reading and the readings after detensioning, normalized with respect to the initial reading,

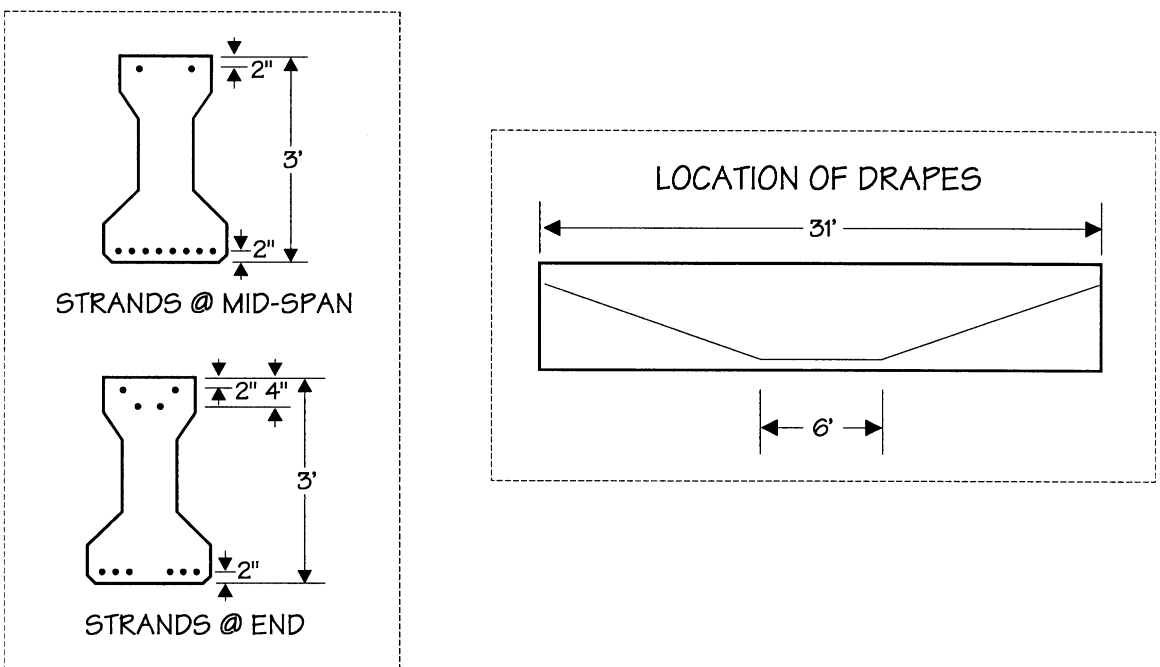


Figure 3. Schematic Showing Draped Bottom Strands

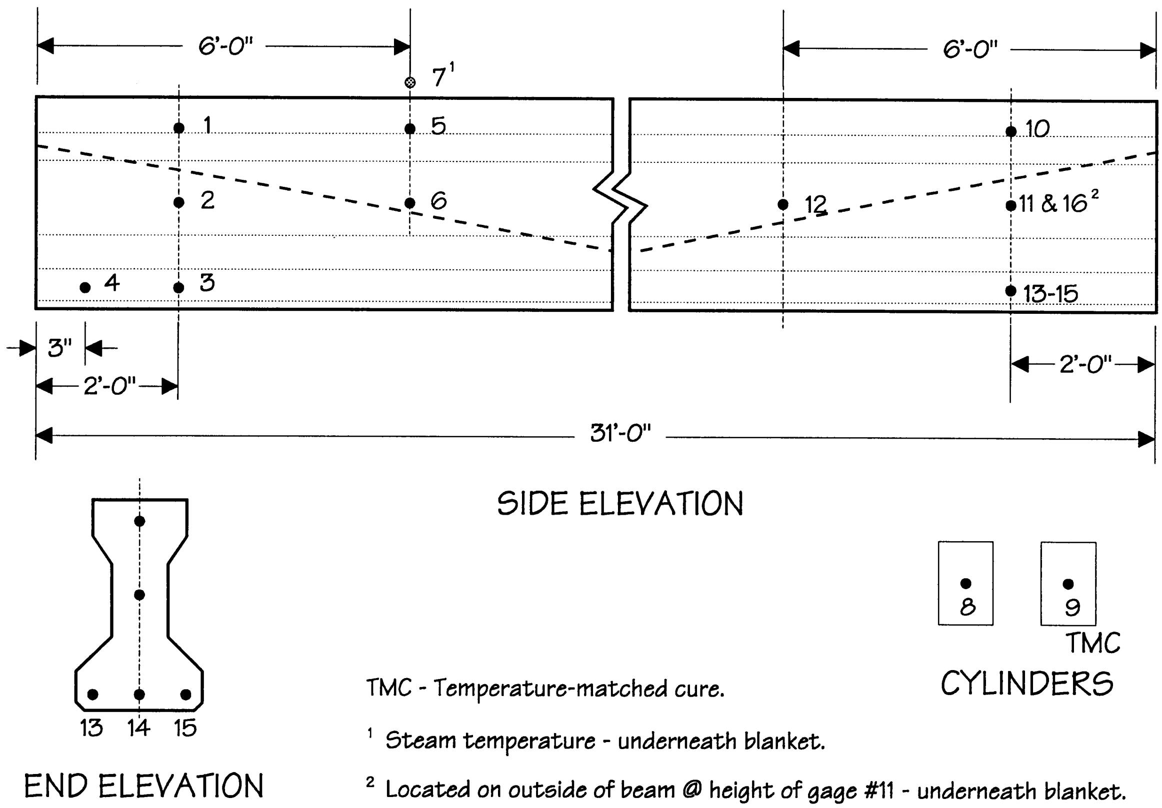


Figure 4. Instrumented Beams

yielded a strain profile along the face of the beam at the location of the brass studs. Ideally, this strain profile reaches a plateau, indicating the transfer of prestressing force from the strands to the concrete has occurred. The flexural bond length, or embedment length, can be determined experimentally, and by adding the transfer length, the total strand development length can be determined. Thus, AASHTO Equation 9-32 could be validated for the 15 mm (0.6 in) diameter strands.

RESULTS AND DISCUSSION

Trial Batches

The minimum cement content specified by VDOT for regular prestressed concretes is 377 kg/m^3 (635 lb/yd^3). For high-strength concretes, larger amounts are needed to obtain a low W/CM and thereby higher strength.

Set 1 at Plant

Most of these batches were prepared using large amounts of portland cement and silica fume, both in the dry-densified (I1 and I2) and slurry (I3-I6) forms (Table A-1). I7 had 504 kg/m^3 (850 lb/yd^3) of portland cement but no silica fume. Samples were either steam cured or moist cured. The steam-cured samples were tested within 20 hr, and the moist-cured samples at 24 hr and 7, 28, and 56 days. The W/CM ranged from 0.30 to 0.39.

The batches were prepared with materials available at the plant and contained an air-entraining agent and an HRWRA. VDOT specifications require an air content of 4% to 7% in prestressed concretes when an HRWRA is used. The air contents ranged from 3% to 5.6%, with 3 of 7 batches meeting the VDOT specification. The slump values were less than 65 mm (2.5 in), indicating stiff concretes. The 1-day strength of steam-cured specimens ranged from 34 to 55.7 MPa (4,930 to 8,080 psi). The mixtures with silica fume in the slurry form and the mixture with a low W/CM (0.30) with portland cement had 1-day compressive strengths exceeding 48 MPa (7,000 psi). This was the required release strength for the 69 MPa (10,000 psi) concrete, but all strengths were less than the 58 MPa (8,400 psi) needed for the 83 MPa (12,000 psi) concrete. The 1-day strengths of moist-cured specimens were less than those for steam-cured specimens. The 28-day strengths were all below 69 MPa (10,000 psi), though most were very close to that value. At 56 days, 4 of the 7 batches had strengths exceeding 69 MPa (10,000 psi). These test results indicate that a W/CM close to or lower than 0.30 is needed, and that steam curing helps develop high early strengths.

Set 2 at Plant

These batches, B1-B4, had a total cementitious material content of 593 kg/m^3 (1,000 lb/yd^3) with portland cement and slag but 623 kg/m^3 (1,050 lb/yd^3) when an additional bag of densified silica fume was used (Table A-2). The fine aggregate source was changed to use aggregates with a lower void content, resulting in a reduced water demand. A water-reducing and retarding admixture was used at a rate of 2.6 ml/kg (4 oz/cwt) including both the portland cement and slag. This dosage was not expected to cause excessive retardation in portland cement mixtures. An HRWRA was used at dosages higher than those recommended by the manufacturer, which is about 6.5 to 7.8 ml/kg (10 to 12 oz/cwt), including total cementitious material. Some cylinders were steam cured, and some were kept in an insulating box. At 24 hr, the concretes had not gained sufficient strength to enable removal from the molds without damage. The temperature profiles for these batches are shown in Figure 5 for steam cured and Figure 6 for those cured in the box. Figure 6 shows that these concretes were retarded and did not hydrate to an extent to generate a measurable heat of hydration, as evidenced by their delay in temperature rise for at least 1 day. As shown in Figure 5, the external heat through steam curing generated an early rise in temperature at about 8 hr, but early strengths were not achieved since measurable hydration was not occurring. Steam curing should begin at the initial time of setting, which was more than 1 day for this retarded mix.

After steam curing for 1 day, specimens were moist cured and tested at 3 and 28 days. At 3 days, only one batch (B1) that had 413 kg/m^3 (700 lb/yd^3) of portland cement, 178 kg/m^3 (300 lb/yd^3) of slag, and 30 kg/m^3 (50 lb/yd^3) of silica fume had a compressive strength exceeding 48

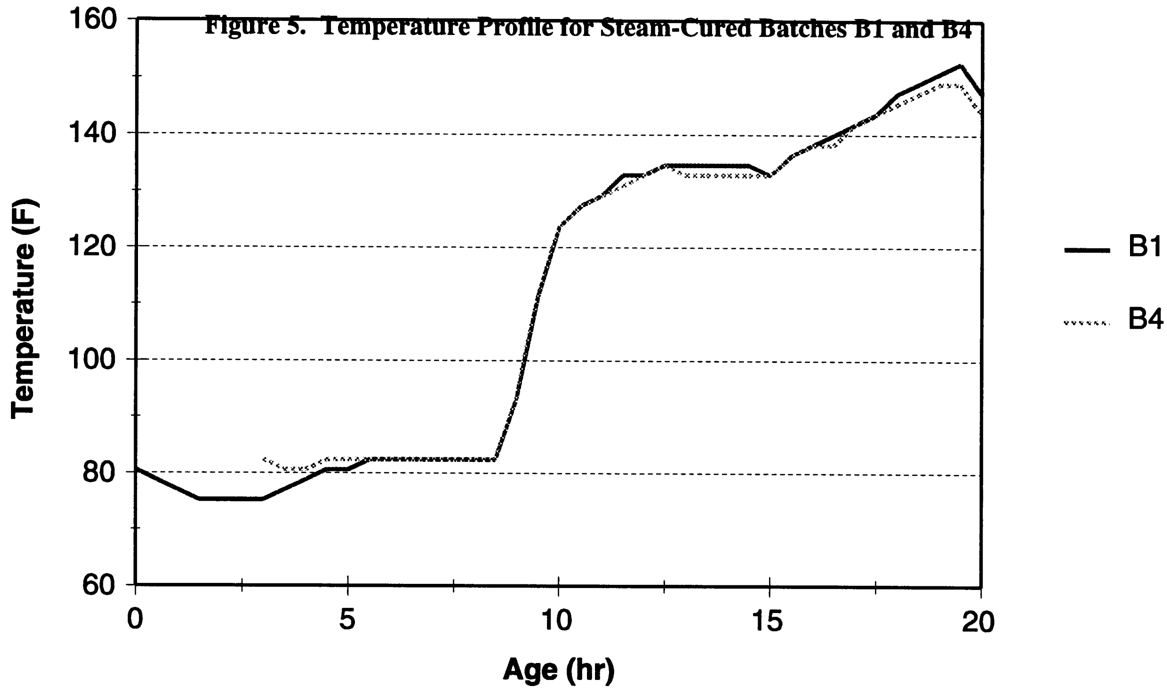


Figure 5. Temperature Profile for Steam-Cured Batches B1 and B4

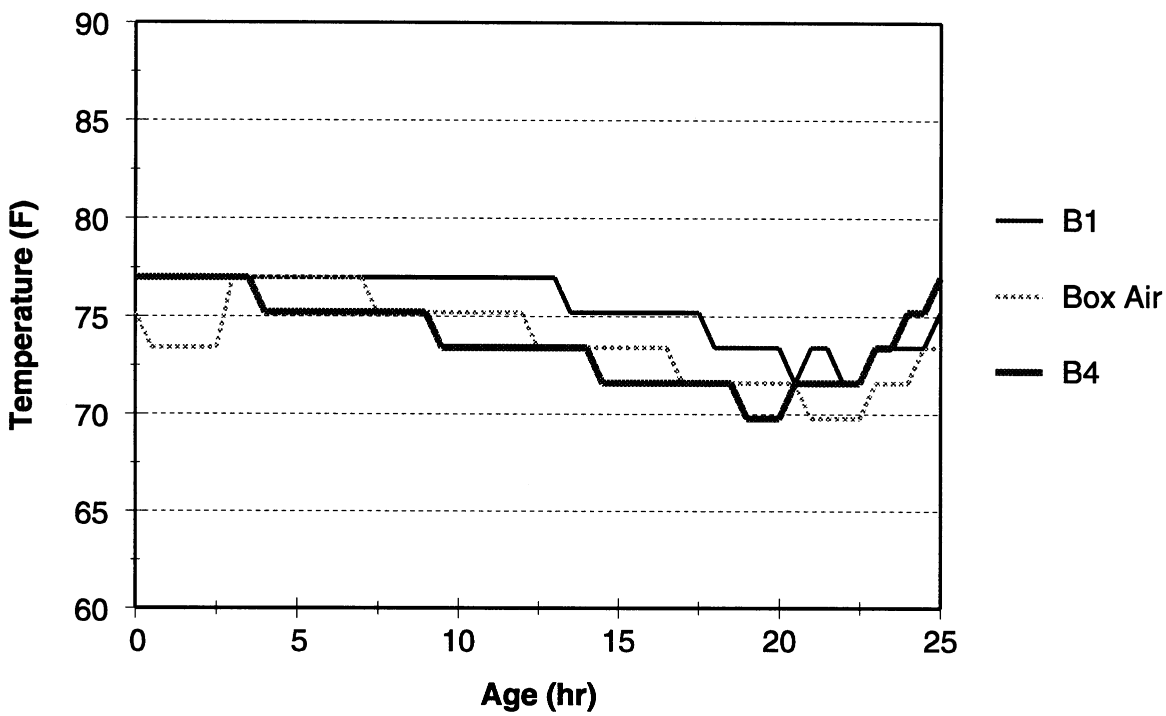


Figure 6. Temperature Profile for Batches B1 and B4 Cured in Box

MPa (7,000 psi). At 28 days, two of the concretes with 356 kg/m^3 (600 lb/yd^3) of portland cement and 237 kg/m^3 (400 lb/yd^3) of slag with or without silica fume had a strength exceeding 69 MPa (10,000 psi). The 28-day chloride permeability results ranged from 531 to 1,432 coulombs.

Set 3 in Laboratory

These batches, L1-L7, were prepared as shown in Table A-3, with water-reducing admixtures from two different sources, one also being a retarding admixture. This time, the dosage of the water-reducing and retarding admixture was calculated with regard to the amount of portland cement only. The HRWRA also came from two sources. A regular Type III cement was used. Different aggregate sources were used, and workable concretes with slumps exceeding 150 mm (6 in) were prepared. However, large dosages of HRWRA were used. L1 and L2 had a high air content, exceeding 8.4%. The rest of the batches had an air content ranging from 2.4% to 5.5%. The specimens were kept in insulating boxes, one with thicker walls, and thus better insulating capabilities, than the other. The temperature profiles for L3-L7 are given in Figure 7. L3-L6 were in the thicker box.

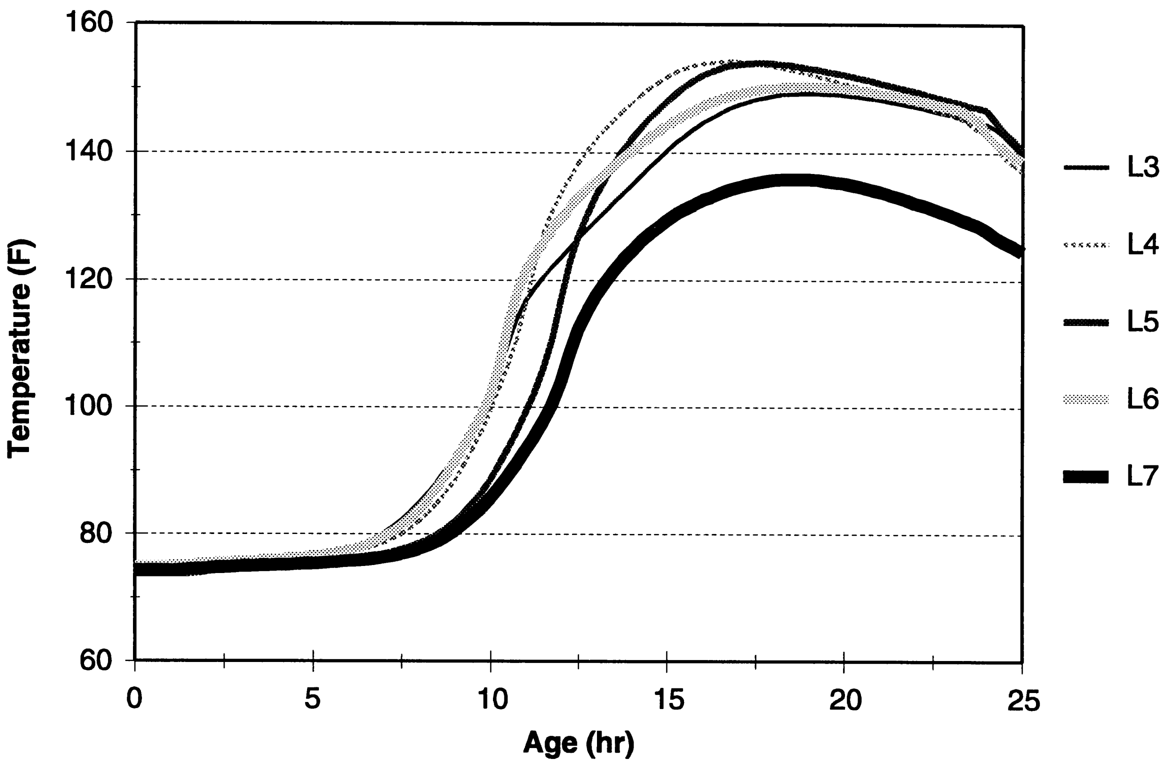


Figure 7. Temperature Profile for Batches L3-L7

Specimens in the thicker box (L3-L6) developed a higher heat. The maximum temperature of the specimens in the thicker box was 66 to 68 C (150 to 155 F) and for those in the other box about 57 C (135 F). L6 had a lower early strength than the other batches with a low or acceptable air content (L3-L7), even though the strength was almost 55 MPa (8,000 psi). L1-L7 had a setting time ranging from 7 to 9¼ hr. The W/CM was 0.28 in all except L1, which was 0.29. Some had early strengths exceeding 58 MPa (8,400 psi) (70% of 83 MPa [12,000 psi]). The 28-day strengths were higher than 69 MPa (10,000 psi) in most, but none had a strength higher than 83 MPa (12,000 psi). The chloride permeability of L2 was 374 coulombs at 28 days.

Set 4 at Plant

These batches, B5-B7, were prepared as indicated in Table A-4. The W/CM of B5 was 0.30, and that of the others was 0.28. Type II modified cement and aggregates available at the plant were used exclusively in B5. Type III cement was used in the remaining 2 batches. The temperature profiles of these 3 batches while in the steam bed are shown in Figure 8, and the profile for those in the insulating box are shown in Figure 9. The temperature rise was slow in both curing environments and slower for those in the box, especially for the Type II modified cement. Steam curing was intended to provide a temperature of 66 C (150 F), but did not. There was also a drop in temperature because of an interruption of steam, as shown in Figure 8. The highest early strength of the steam-cured specimens was only 52.8 MPa (7560 psi). However,

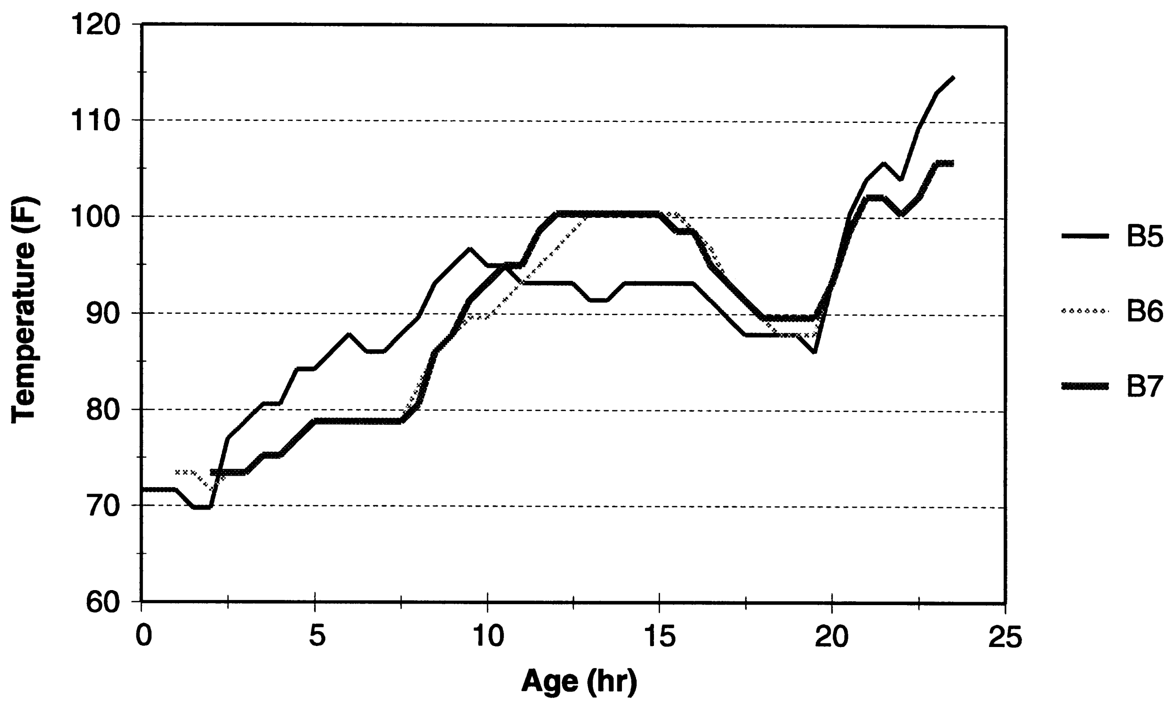


Figure 8. Temperature Profile for Steam-Cured Batches B5-B7

Figure 9. Temperature Profile for Batches B5-B7 Cured in Box

the early strengths of these specimens were higher than for those cured in the box. This demonstrates the importance of temperature management in achieving the desired temperature development for high early strength. The batches with Type II modified cement had more retardation and low strength when cured in the box but had strengths similar to those of the other batches when steam cured. The 28-day strength of one of the batches with the lowest W/CM and Type III cement was higher than 76 MPa (11,000 psi), whereas the strength of the other was a little more than 62 MPa (9,000 psi). The air contents of these two batches were low, the one with the highest 28-day strength being the lowest.

Set 5 in Laboratory

Batches L8-L11 were prepared with a higher cement content of 475 kg/m^3 (800 lb/yd^3) (Table A-5). The W/CM was either 0.27 or 0.28. The amount of water-reducing and retarding admixture was reduced to 1.3 ml/kg (2 oz/cwt), and 1 batch (L10) was prepared using a melamine-based HRWRA without a regular water reducer. Only L9 had Class F fly ash (ASTM C618) rather than slag. In this series, the initial setting time varied from 4¾ to 7¼ hr. Different admixtures and aggregates were used. Air content ranged from 4.2% to 6.6%, and slumps exceeded 150 mm (6 in). The temperature profile is given in Figure 10. Maximum temperatures were 66 to 68 C (150 to 155 F). The 1-day strengths ranged from 60.4 to 71 MPa (8,760 to

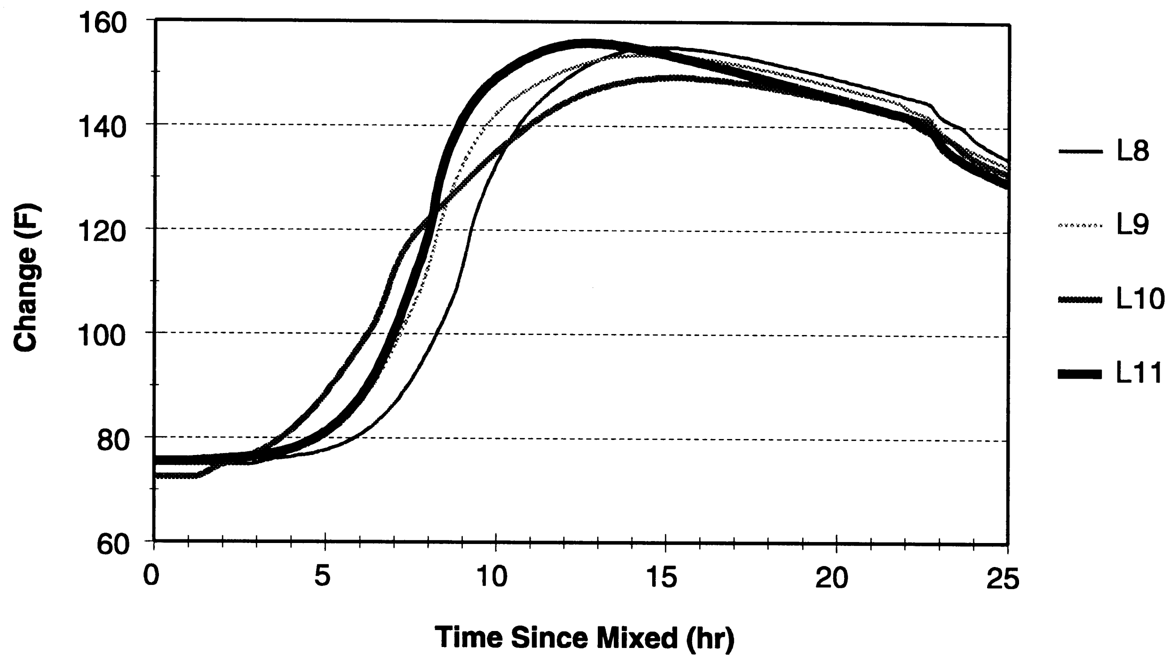


Figure 10. Temperature Profile for Batches L8-L11

10,300 psi), and the 28-day strengths from 70.7 to 80.8 MPa (10,260 to 11,720 psi). The values for all the concretes were satisfactory, indicating the importance of a low W/CM in achieving high strengths.

Batches L12-L14 were prepared with less portland cement since higher early strengths than needed were achieved in the previous batches (Table A-5). Aggregates from the plant were used. The initial setting time for L14 was more than 10 hr. Penetration resistance (ASTM C403) was 0.5 MPa (70 psi) at 10 hr. These batches were subjected to high temperatures (71 C [160 F]) in the oven within 45 min after mixing, thus before the initial set. With concrete tempera-ures reaching from 66 to 82 C (150 to 180 F), they developed 1-day strengths ranging from 55.6 to 59.2 MPa (8,060 to 8,580 psi). Even though they may not have reached their highest potential, these strengths were satisfactory. However, with the earlier batches, B1-B4, retardation was so excessive that satisfactory early strengths were not achieved. L14 had a greater amount of an HRWRA than the others. This setting delay can also be seen in the temperature profiles in Figure 11. These specimens were put in the oven after casting. The setting delay affected the early strength of L14, especially when cured in a box instead of an oven at 71 C (160 F). One-day strengths exceeding 55 MPa (8,000 psi) can be achieved if enough heat can be provided and retardation is not excessive. Some heat in the beginning helps reduce setting times.[8] The 28-day strengths varied from 68.9 to 80.9 MPa (9,990 to 11,730 psi). The concretes (L14) with the lowest early strength had the highest 28-day strength. L12 had the lowest 28-day strength and the highest W/CM (0.30 compared with 0.28 in the other two).

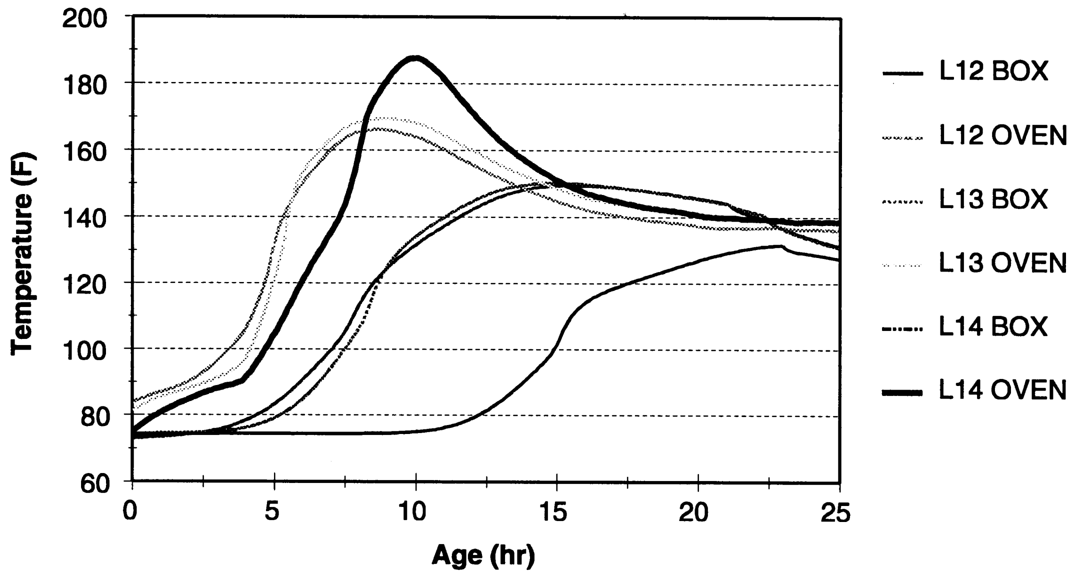


Figure 11. Temperature Profile for Batches L12-L14

Because of the high early strengths with a W/CM of 0.30, another batch (L15) was prepared with a lower portland cement content of 347 kg/m^3 (585 lb/yd^3), a slag content of 187 kg/m^3 (315 lb/yd^3), and a silica fume content of 30 kg/m^3 (50 lb/yd^3) (Table A-5). The concrete with the lower portland cement content was retarded, as shown in the temperature profile in Figure 12. The specimen in the box reached a strength of 48.2 MPa (6,990 psi), but the one in

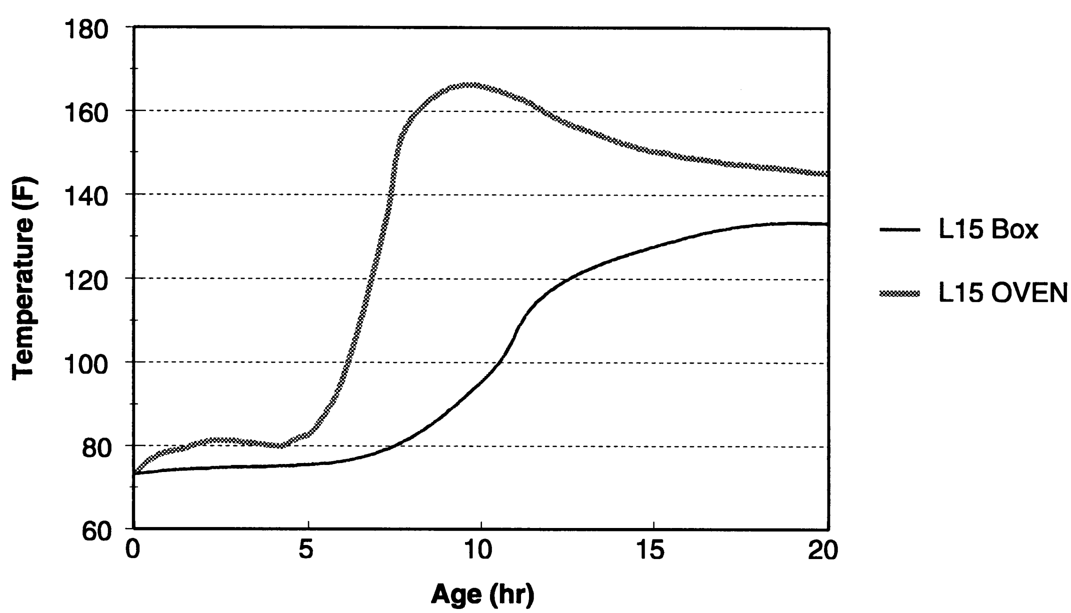


Figure 12. Temperature Profile for Batch L15

the oven reached 55.1 MPa (7,990 psi), similar to that of L14. The 28-day strength was 72.9 MPa (10,580 psi), lower than for L14, but the air content was higher.

Set 6 at Plant

These batches (B8-B11) were prepared as indicated in Table A-6. The W/CM ranged from 0.28 to 0.30. The amount of portland cement ranged from 347 to 445 kg/m^3 (585 to 750 lb/yd^3). B8 and B9 were placed in one bed and B10 and B11 in another bed for steam curing. B9 and B11 contained silica fume. B10 was similar to B11 except that B11 had silica fume replacing 30 kg/m^3 (50 lb/yd^3) of slag. Temperature profiles for B8 and B11 and each enclosure are shown in Figure 13A and 13B, respectively. B9 had the most portland cement and was in an enclosure where the temperature exceeded 60 C (140 F), reaching 71 C (160 F). Temperatures were below 60 C (140 F) in the other enclosure. Only B9 had a high early strength of 58.4 MPa (8,475 psi). The strengths of the others were less than 39.2 MPa (5,680 psi). B10 and B11 had similar 28-day strengths. The early (1-day) strength of B11 was about 10% higher, but this batch also had 1.6% less air. Based on the results from these mixtures, it was determined that the desired high strengths are achieved if low W/CM ratios are obtained irrespective of whether slag is used alone or in combination with silica fume. Since silica fume is an additional expense, and the desired properties were achieved without it, it was not included in the final mix design.

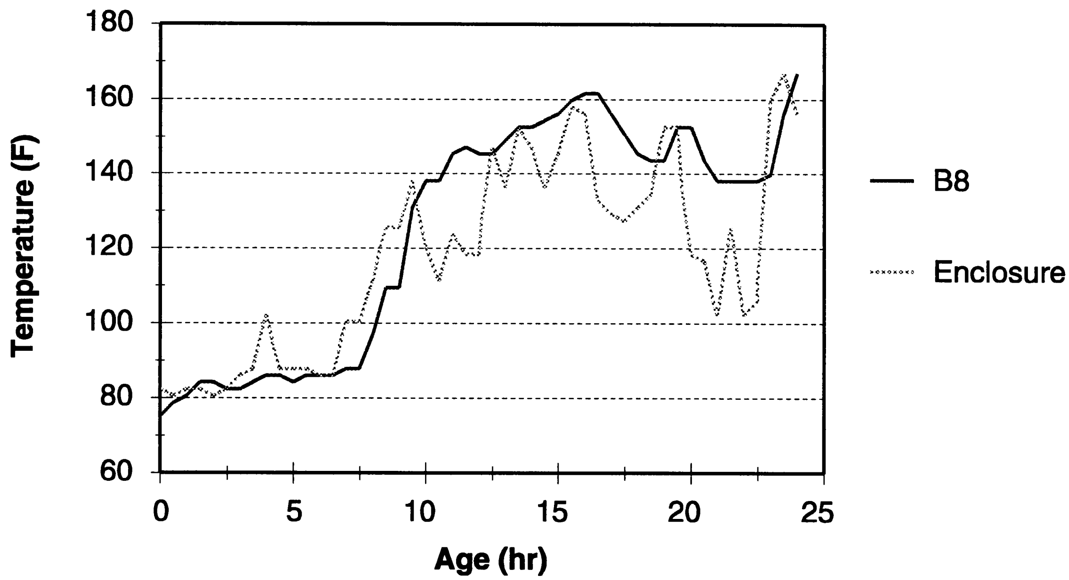
Mix Design of Test Beams

The beams were cast using materials locally available at the plant. The cementitious material was a combination of Type II modified cement with a C_3A content of less than 8% and slag. The coarse aggregate was a crushed granite with a maximum size of 13 mm (½ in). The fine aggregate was siliceous sand. The coarse aggregate had elongated pieces and a large amount of stone dust. The particle shape of the sand was angular, leading to a high void content (50.2%) and resulting in a high water demand. The concretes contained a commercially available air-entraining, water-reducing and retarding naphtalene-based HRWRA. At the dosage used, which was based only on the quantity of portland cement, the water-reducing and retarding admixture was not expected to delay the setting time or inhibit early strength development.

Production of Test Beams

A batch of concrete measuring 2.3 m^3 (3 yd^3) was prepared for each beam (Table A-7). Two of the 4 batches had 445 kg/m^3 (750 lb/yd^3) of cement and 178 kg/m^3 (300 lb/yd^3) of slag to achieve a strength of at least 57.0 MPa (8,400 psi) after steam curing and 83 MPa (12,000 psi) at 28 days. The other 2 batches had 386 kg/m^3 (650 lb/yd^3) of cement and 178 kg/m^3 (300 lb/yd^3) of slag to achieve a strength of 48 MPa (7,000 psi) after steam curing and 69 MPa (10,000 psi) at 28

A



B

Figure 13. Temperature Profiles for Batches B8 and B11

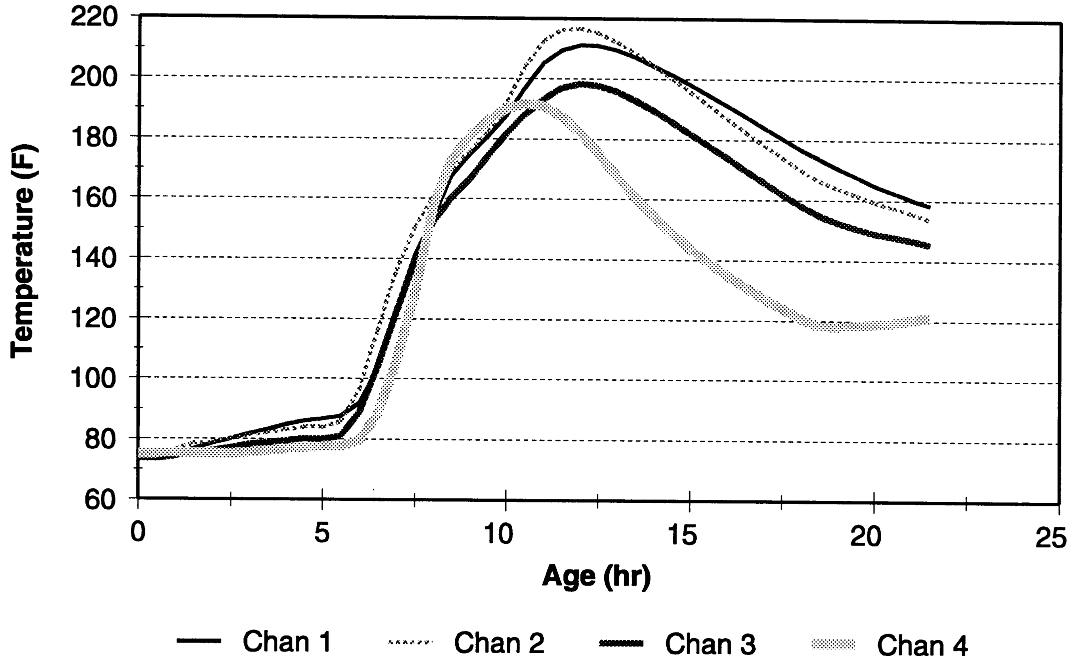
days. The normal mixing time was doubled to ensure thorough mixing. The concretes were transported from the batch plant to the nearby bed in vehicles with augers to facilitate the discharge. Even though the concrete reached the site within 15 min after the addition of water, there were slump loss problems, mainly attributable to the cement used. One batch was rejected because of the slump loss.

Placement started from the south end of the bed. The concrete was consolidated using immersion-type vibrators and hand finished. Afterward, the beams were covered with insulating blankets. The time delay between finishing and covering caused plastic shrinkage cracks in Beams 1 and 2, which had a large amount of portland cement and a low W/CM. The bed was kept between 27 and 32 C (80 to 90 F) for about 6 hr, and then steam was applied to increase the temperature by about 22 C (40 F) per hour (Figure 14A-D). It was intended to increase the bed temperature to a maximum of 71 C (160 F) to enable curing temperatures in the beams to be between 71 and 88 C (160 and 190 F). However, about 10 hr after mixing, the temperature in the bed had reached almost 85 C (185 F). Beams 1 and 3 were instrumented with thermocouples, and the temperature in the beams was found to be approaching 88 C (190 F). The steam was turned off, and the bed was vented by raising the insulating blanket to enable exposure to the outside air. However, the temperature continued to rise. In Beam 1, temperatures in some locations exceeded the boiling point, and in Beam 3 they closely approached it (Figures 14 A-D and 15A-C).

Specimens from each batch were placed in the mold recesses of each beam. About 20 hr after batching, the specimens were unmolded. Horizontal cracks were noticed, especially in B1, attributed to the high curing temperatures. Heat-related cracking diagonal to the edge was observed on the top surface of Beam 1. In Beams 1 and 2, plastic shrinkage cracks were found perpendicular to the edge on top, and they penetrated 25 to 38 mm (1 to 1½ in) into the concrete. Surface blemishes (holes) were seen on the sides of the beams, which may be prevented by more internal vibration, some surface vibration, and placement in layers.

The first day after steam curing, specimens were tested for compressive strength. The specimens from Beam 1 had the lowest strength of 41.7 MPa (6,048 psi) and from Beam 2 the highest strength of 66.9 MPa (9,710 psi). The specimens from Beam 1 had more thermal cracking than the others. The specimens from Beams 1 and 3 were subjected to temperature-matched curing where the specimens in molds with heaters follow the temperature rise occurring in the structure. The 1-day results were similar to those for the steam-cured specimens. At 28 days, Beam 1 had the lowest compressive strength of 45.4 MPa (6,580 psi) and Beam 2 the highest strength of 80.8 MPa (11,720 psi) when tested using 150 x 300 mm (6 x 12 in) cylinders. The results from the 100 x 200 mm (4 x 8 in) cylinders were more variable, which may be related to the temperature effects. Splitting tensile strengths ranged from 3.2 to 4.4 MPa (460 to 640 psi).

A



B

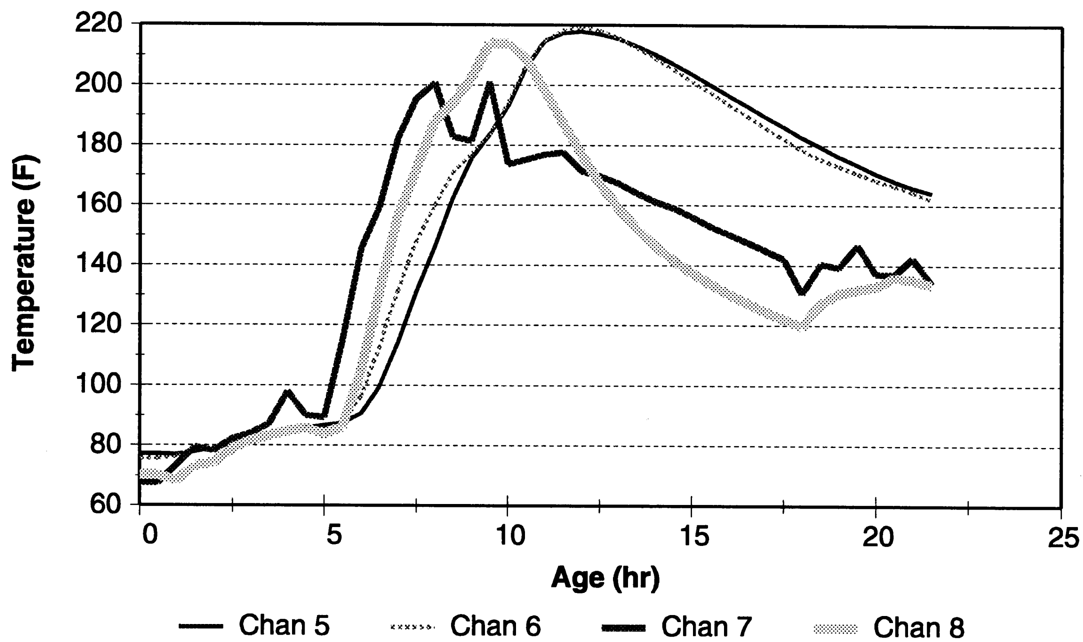
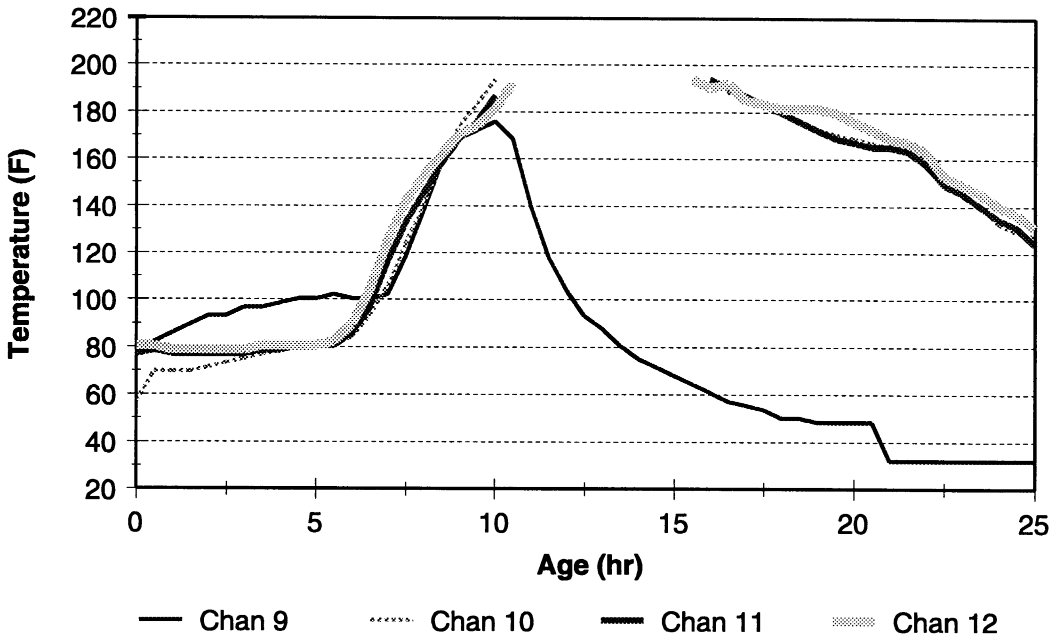


Figure 14A and B. Temperature Profile for Beam 1

C



D

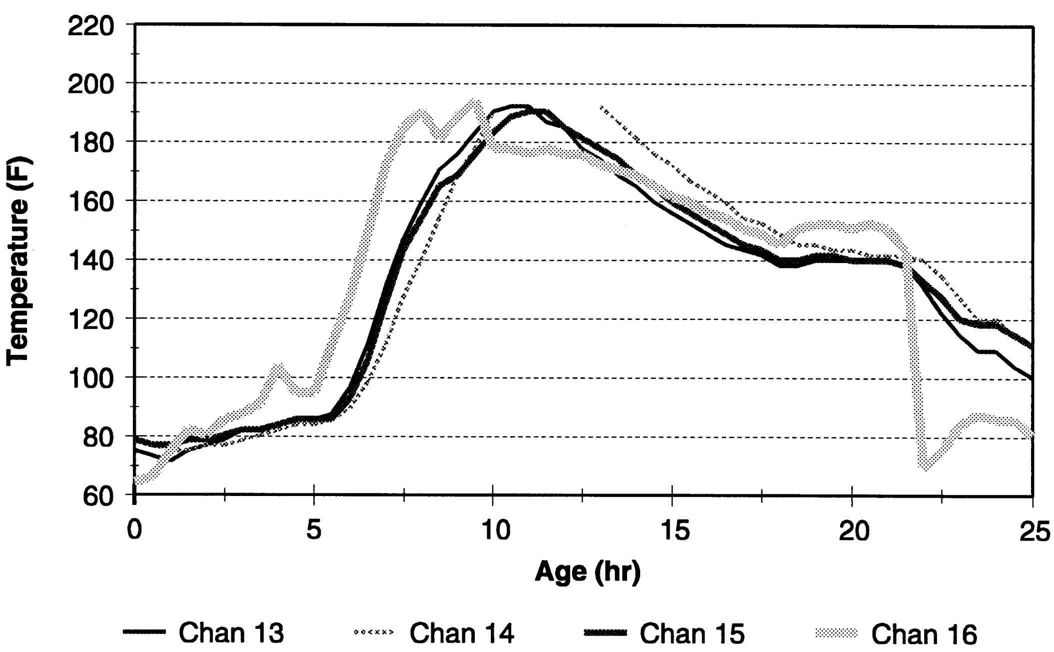
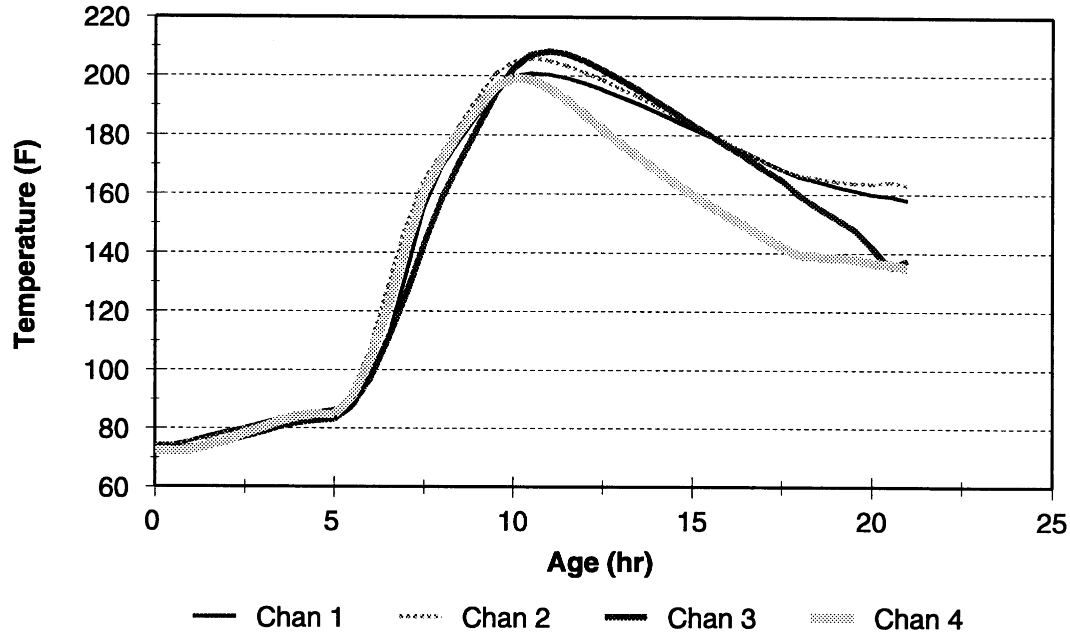


Figure 14C and D

A



B

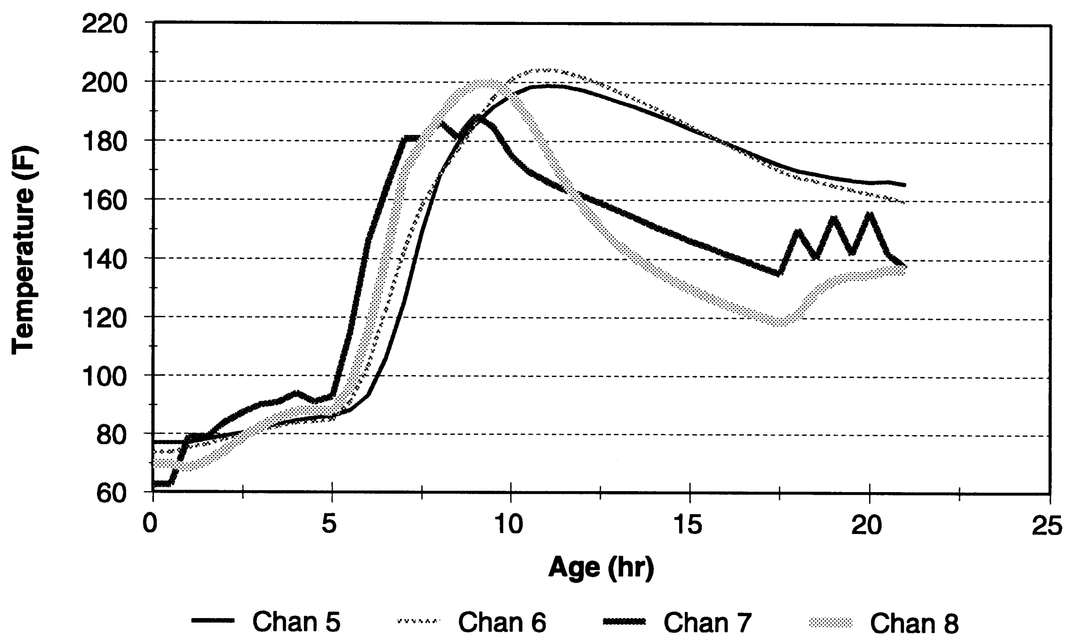


Figure 15A and B. Temperature Profiles for Beam 3

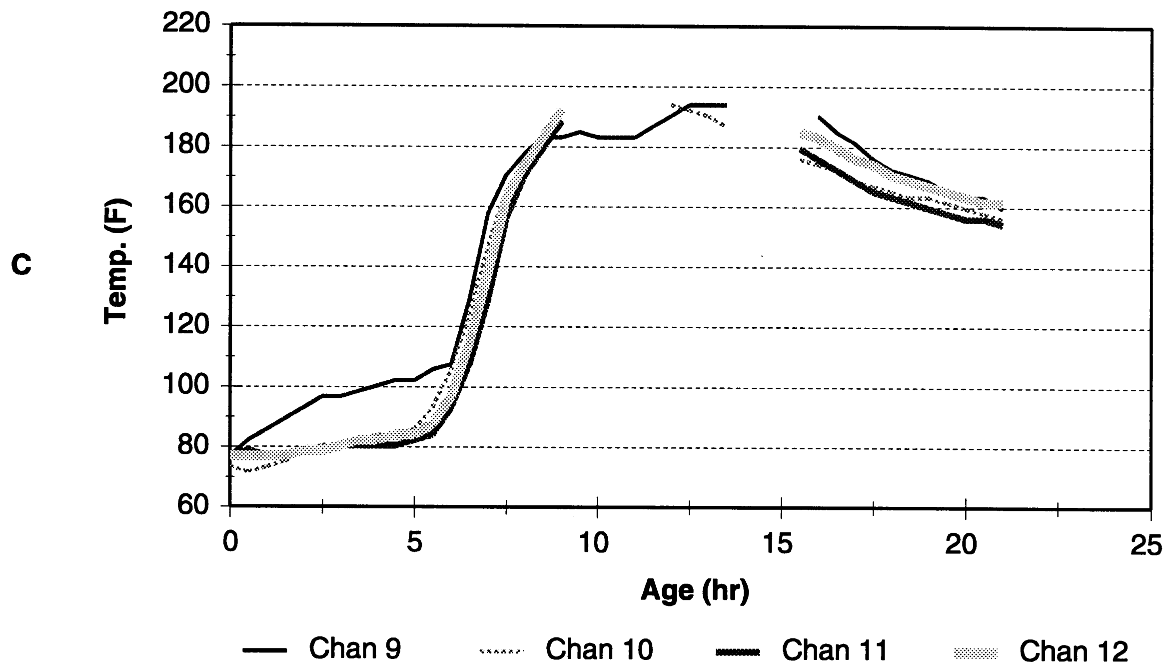


Figure 15C

Elastic modulus values ranged from 32.9 to 43.7 GPa (4.77 x 10^6 to 6.34 x 10^6 psi). The values calculated from the formula given in ACI 318 using a unit weight of 89 kg/m^3 (150 lb/yd^3) ranged from 33.9 to 45.4 GPa (4.91 x 10^6 to 6.58 x 10^6 psi). The experimental values compared closely with the theoretical values even though they were slightly higher for the 83 MPa (12,000 psi) and lower for the 69 MPa (10,000 psi) concretes, some of which were damaged by heat.

Structural Testing of Test Beams

Initial plans included the determination of the development length in the beams, which requires the transfer length. Workers released the metal strips holding the brass studs attached to the formwork too soon. The concrete was still in a plastic state; thus the strips sunk into the beams, resulting in the loss of a significant portion of gage points. This and operator error in the use of the Whittemore gage resulted in significant scatter in the concrete strain profiles, as shown in Figure 16. Ideally, the strain values should rise linearly to a plateau of constant value. Thus, transfer lengths could not be determined with the needed precision, and testing at the FHWA laboratory for the determination of development lengths was canceled. Also, plans for the use of 15 mm (0.6 in) strands for the Brookneal bridge were discontinued because of the lack of a thorough testing program needed for evaluation of these larger strands at a 51-mm (2-in) spacing. However, all four beams were tested to determine the maximum load-carrying capacity under a concentrated load at midspan. During stress transfer, the distance each strand had slipped into the concrete was measured by attaching end slip brackets at each end of the strands and using a

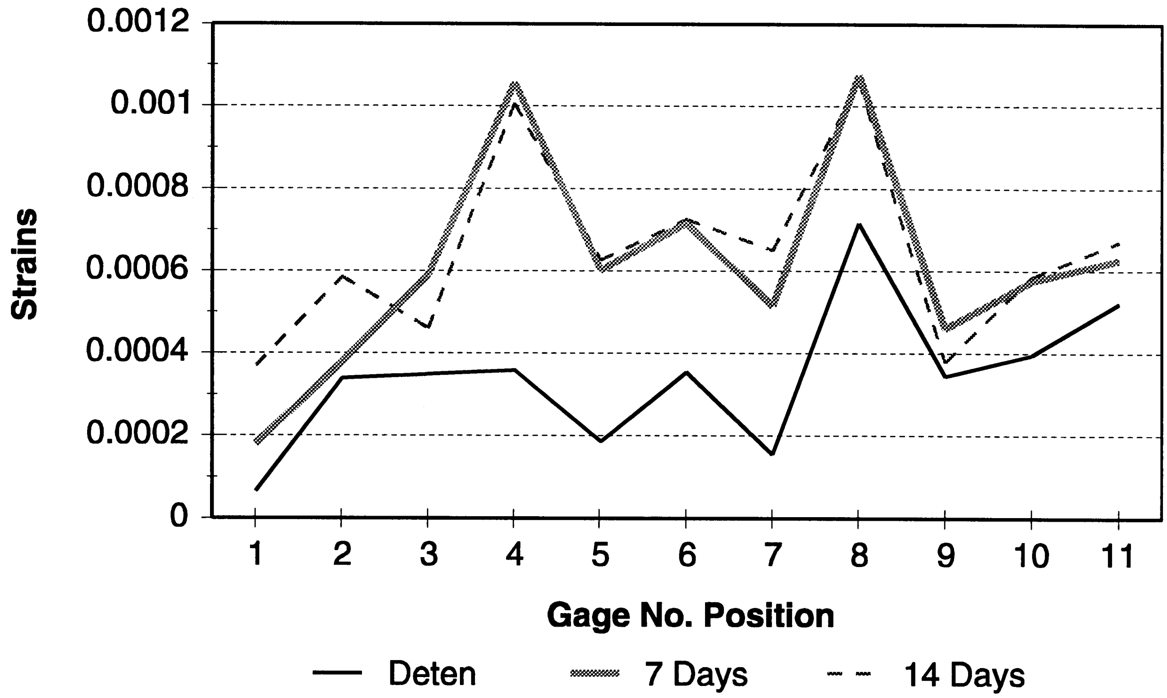


Figure 16. Strain Readings

depth micrometer to measure the amount of slip. The results indicated that very small amounts of slip had occurred, as shown for Beam 2 in Figure 17.

The load deflection data are given in Figure 18 and Table 4. The calculated maximum design concentrated load at midspan was 641 kN (144 kips) for the 69 MPa (10,000 psi) mix and 659 kN (148 kips) for the 83 MPa (12,000 psi) mix. All four beams exceeded this value, as shown in Table 4. A typical flexural failure load is shown in Figure 19. Failure was caused by crushing of the top flange in compression.

The calculated maximum concentrated load at midspan to cause the first cracking was 369 kN (83 kips) for the 69 MPa (10,000 psi) beam design and 378 kN (85 kips) for the 83 MPa (12,000 psi) design. The lowest load to cause the first cracking was 400 kN (90 kips) in Beam 1. The loads to cause the first cracking in the other three beams ranged from 445 to 467 kN (100 to 105 kips). The variability in strengths in the cylinders subjected to high temperature was not reflected in the beams. The cylinders were damaged by high heat, and horizontal cracks were noticed before testing. However, the beams did not show such cracking, except for diagonal cracks on the top of Beam 1. Thus, the prestressed beams with strands 15 mm (0.6 in) in diameter had satisfactory concrete strengths (exceeding 69 MPa [10,000 psi]) and performed as intended under the loading condition.

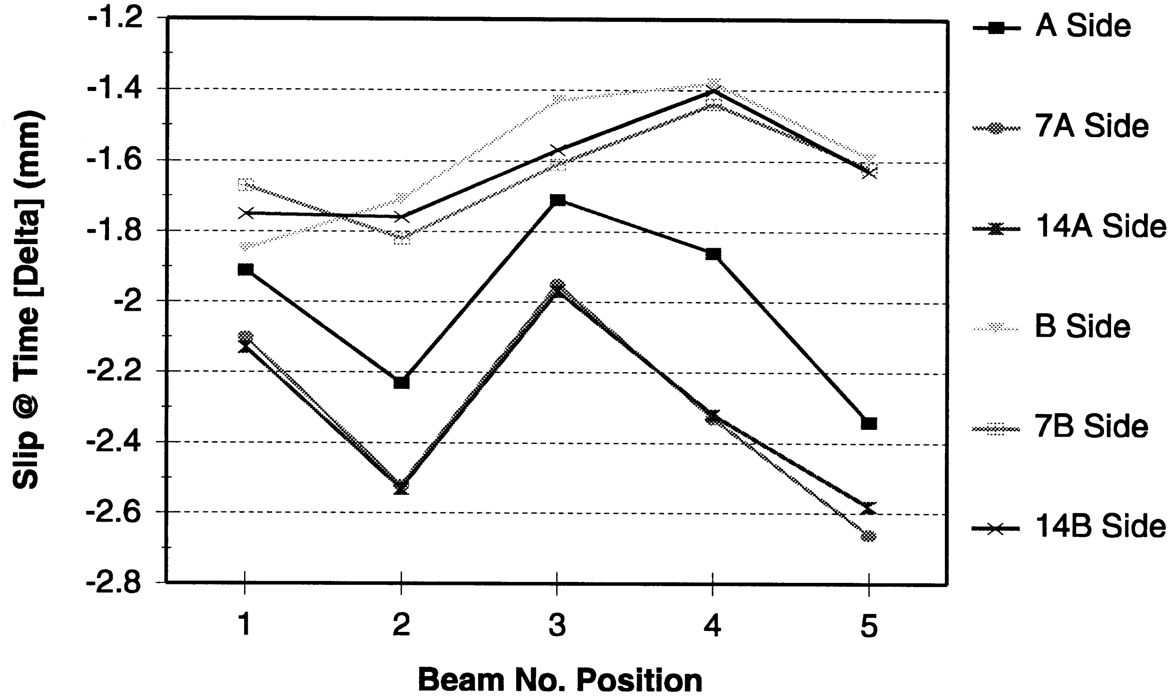


Figure 17. End Slip

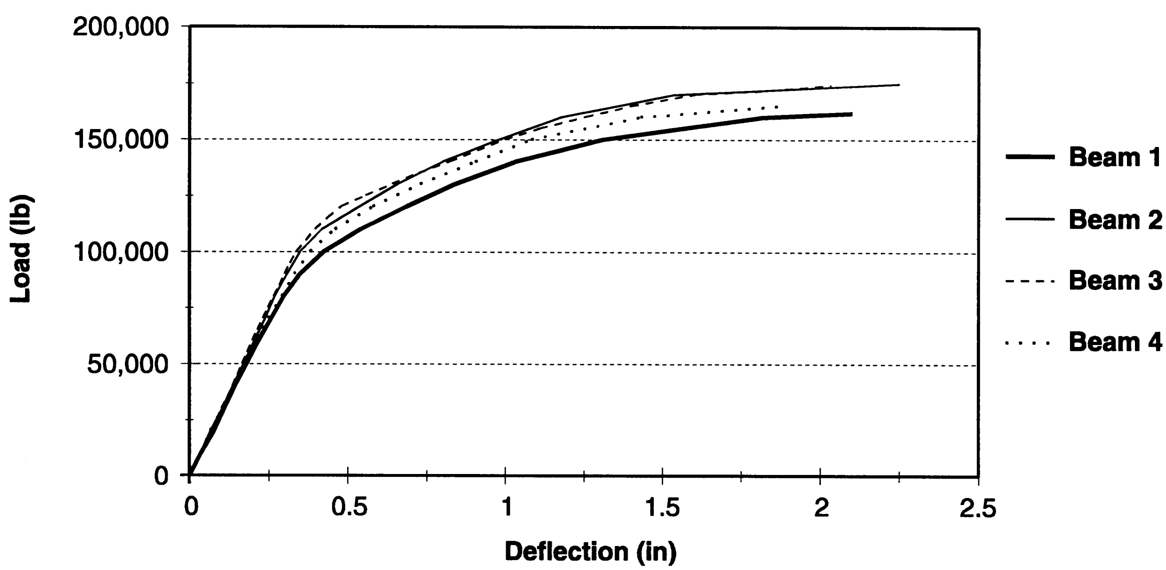


Figure 18. Load versus Deflection

Table 4. Load vs. Deflection Data

Load (lb)	Deflection (in)			
	Beam 1	Beam 2	Beam 3	Beam 4
0	0	0	0	0
10000	0.037	0.037	0.036	0.037
20000	0.077	0.069	0.068	0.067
30000	0.11	0.106	0.102	0.106
40000	0.144	0.139	0.136	0.142
50000	0.182	0.173	0.167	0.18
60000	0.218	0.206	0.2	0.215
70000	0.259	0.24	0.233	0.25
80000	0.298	0.27	0.267	0.292
90000	0.35	0.31	0.301	0.332
100000	0.424	0.352	0.338	0.382
110000	0.541	0.42	0.398	0.46
120000	0.686	0.539	0.482	0.579
130000	0.839	0.658	0.643	0.73
140000	1.031	0.803	0.824	0.906
150000	1.311	0.983	1	1.084
160000	1.818	1.181	1.257	1.43
162000	2.1			
165000			1.4	1.868
170000		1.537	1.603	
174000			2.035	
175000		2.25		

Figure 19. Typical Flexural Failure Load

CONCLUSIONS

- *High-performance air-entrained concretes with a 28-day strength exceeding 69 MPa (10,000 psi) and a minimum release strength of 70% of the 28-day strength can be produced with a W/CM close to or below 0.30.* Achieving such a low W/CM requires trial batching, large amounts of cementitious material, proper selection of aggregates, and high dosages of an HRWRA. The cementitious materials should be a combination of portland cement and pozzolans to produce concretes with low permeability, high ultimate strength, and high resistance to chemical attack. Thorough mixing is necessary, and good construction practices during placement, consolidation, and curing must be followed. Excessive retardation should be eliminated.

- *To achieve high early strengths (within 20 hr), proper temperature management is needed.* With low curing temperatures, achieving high early strengths is difficult, but higher ultimate strengths (28 days and later) are achieved. The optimum temperature for both early and ultimate strengths can be determined by trial batching and testing.

- *Achieving 83 MPa (12,000 psi) at 28 days with air-entrained concrete using locally available materials may be difficult.* More work with temperature management and the selection of materials is needed. Specifying the desired strengths would be helpful, normally specified at 28 days, to be achieved at 56 days, benefitting from the additional strength gain in concrete.

- *The chloride permeability test results for concretes containing pozzolans with a W/CM around 0.30 or less were below 1,500 coulombs.*

RECOMMENDATIONS

These recommendations are based on the authors' experience with producing HPC with 28 day strengths exceeding 69 MPa (10,000 psi) and coulomb values below 1,500 at 28 days and early strengths exceeding 48 MPa (7,000 psi) within 20 hr.

- *Use a low W/CM, about 0.30 or below.*

- *Use pozzolans or slag for low permeability, high ultimate strength, and high resistance to chemical attack. The content should be as follows: slag (minimum 35 % of the cementitious material), silica fume (minimum 7% of the cementitious material).*

- *Minimize retardation.* Delays in initial setting result in low early strengths. The compatibility of the cementitious material with the type and amount of chemical admixtures should be determined.

- *Measure the temperatures within the concrete during steam curing to ensure the maximum internal concrete temperature of 190 F (88 C) is not exceeded.* Further evaluation of this upper limit for concretes with and without pozzolans or slag is recommended since high early temperatures provide high early strengths but result in reduced ultimate strengths.

- *Place concrete in layers to minimize entrapment of air under inclined surfaces. Use internal and external vibrators for better consolidation and elimination of surface blemishes.*

- *Take precautions as recommended in ACI 308, the standard practice for curing concrete, to minimize the surface evaporation rate to prevent plastic shrinkage cracking. Immediately after finishing, apply a curing compound unless another layer of concrete will be bonded or use fogging until the concrete is covered with wet burlap and plastic.*

- *Use the maturity method or use specimens subjected to temperature-matched curing for a representative determination of the compressive strength of the concrete in the member at an early age.*

ACKNOWLEDGMENTS

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APPENDIX

DATA ON TRIAL BATCHES

Table A-1. Set 1 at Plant (I1-I7)

Bayshore Plant Mixes	Dry Bag Silica Fume		Slurry Silica Fume				
	I1	I2	I3	I4	I5	I6	I7
Date	2/7/94	2/7/94	2/8/94	2/8/94	2/8/94	2/8/94	2/8/94
Cement Content (pcy)	735	835	800	800	800	800	850
Cement Type	Type II MF						
Slag (pcy)	0	0	0	0	0	0	0
Silica Fume (pcy)	51	58	40	80	120	120	0
WR (oz/cwt)	2.5	2.5	0.0	0.0	0.0	0.0	0.0
WR or R Type	WR+R(1)						
HRWR (oz/cwt)	25.0	30.1	25.0	29.5	33.7	33.7	30.0
HRWR Type	HRWRA(1)						
CA (pcy)	1873	1873	1873	1873	1873	1405	1873
CA Location	Garrisonville						
Max. Agg. Size (in)	0.75	0.75	0.75	0.75	0.75	0.50	0.75
FA (pcy)	1229	1171	984	913	835	1208	1224
FA Location	Rappahannock						
Slump (in)	1.5	1.2	2.0	1.75	2.5	2.0	1.0
Air (%)	4.4	5.6	3.0	3.6	3.8	3.4	4.0
Strength (1 D Stm) psi	4930	6250	7030	8080	7680	7400	7480
Strength (1 D) MC	4540	6010	5690	6010	5490	5250	6330
Strength (7 D) MC	5690	7320	6640	7280	6610	6490	7520
Strength (28 D) MC	8280	9790	8710	9430	9990	9870	9550
Strength (56 D) MC	8040	9750	10540	10150	10660	10380	9870
Water/Cementitious	0.39	0.33	0.34	0.34	0.34	0.39	0.3
Water (pcy)	304	297	288	301	315	318	259

Table A-2. Set 2 at Plant (B1-B4)

Bayshore Plant Mixes	B1	B2	B3	B4
Date	4/14/94	4/14/94	4/14/94	4/14/94
Cement Content (pcy)	700	700	600	600
Cement Type	II MF	II MF	II MF	II MF
Slag (pcy)	300	300	400	400
Silica Fume (pcy)	50			50
WR (oz/cwt)	4	4	4	4
WR or R Type	WR+R(1)			
HRWR (oz/cwt)	18	18	12	16
HRWR Type	HRWRA(1)			
CA (pcy)	1800	1800	1800	1800
CA Location	Garrisonville			
FA (pcy)	1035	1035	975	916
FA Location	Providence Forge			
Slump (in)	3	8.25	9	7
Air (%)	2.8	5.7	3.6	5.4
Unit Weight (lb/cft)	153.2	145.9	152	147.8
Strength (3 D Stm) psi	7240	3780	3020	4780
Strength (3 D)		6640		7960
Strength (7 D)		6760	5900	9390
Strength (28 D)	9660	9210	10970	10740
Permeability (28 D)	634	1423	1031	531
Water/Cementitious	0.30	0.30	.030	0.29
Water (pcy)	320	300	300	300

Table A-3. Set 3 in Laboratory (L1-L7)

Lab Mixes	L1	L2	L3	L4	L5	L6	L7
Date	4/19/94	4/21/94	4/26/94	4/26/94	4/26/94	4/26/94	4/26/94
Cement Content (pcy)	700	700	700	700	700	700	700
Cement Type	III						
Slag (pcy)	300	300	300	300	300	300	300
Silica Fume (pcy)	50	50	50	50	50		50
WR (oz/cwt)	15	10	5	3(pc)	3(pc)	5	3(pc)
WR or R Type	WR(2)	WR(2)	WR(2)	WR+R(1)	WR+R(1)	WR(2)	WR+R(1)
HRWR (oz/cwt)	9	16	19	15	17.5	19	18.5
HRWR Type	HRWRA (2)	HRWRA (2)	HRWRA (2)	HRWRA (1)	HRWRA (1)	HRWRA (2)	HRWRA (1)
CA Location	1800	1800	1900	1900	1800	1800	1800
CA Type	Red Hill	Red Hill	Petersburg				Garri-sonville
FA Location	782	847	653	653	724	748	932
FA Type	Peters-burg	Peters-burg	Kingsland Reach				Peters-burg
Slump (in)	7.5	7.25	7.5	6.0	7.5	7.5	7.75
Air (%)	10.5	8.4	3.6	2.4	3.6	5.5	4.5
Unit Weight (lb/cft)	132.4	139.2	145.6	147.2	145.2	142.4	150.0
Strength (1 D) psi	6810	8400	8870	8700	9480	7860	7970
Strength (2 D)	7340	10090	10200	9790	10560	9480	9310
Strength (28 D)	8230	10860	11150	10920	11110	11120	9660
Permeability (28 D)		374					
Initial Set	8.25	9.25	7	8	8.5	8.5	7
Water/Cementitious	0.29	0.28	0.28	0.28	0.28	0.28	0.28
Water (pcy)	300	290	290	290	290	280	290

Table A-4. Set 4 at Plant (B5-B7)

Bayshore Plant Mixes	B5	B6	B7
Date	5/12/94	5/12/94	5/12/94
Cement Content (pcy)	700	700	700
Cement Type	II R	III R	III R
Slag (pcy)	250	250	250
Silica Fume (pcy)	50	50	50
WR (oz/cwt)	3 (pc)	3 (pc)	3 (pc)
WR or R Type	WR(1)		
HRWR (oz/cwt)	28	23	23
HRWR Type	HRWRA(1)		
CA (pcy)	1800	1800	1800
CA Location	Garrisonville		
FA (pcy)	1006	1006	1006
FA Location	Rappahannock		
Slump (in)	9.5	8	6
Air (%)	5.9	2.3	2.7
Unit Weight (lb/cft)	150	155.2	155.4
Strength (1 D Stm) psi	7560	7520	6840
Strength (1 D) Box	1590	5770	6170
Strength (7 D)	7640	9950	9550
Strength (28 D)	9030	11420	9110
Water/Cementitious	0.30	0.28	0.28
Water (pcy)	298	280	280

Table A-5. Set 5 in Laboratory (L8-L15)

Lab Mixes	L8	L9	L10	L11	L12	L13	L14	L15
Date	5/3/94	5/3/94	5/3/94	5/3/94	5/17/94	5/17/94	5/17/94	5/19/94
Cement Content (pcy)	800	800	800	800	700	700	700	585
Cement Type	III				III			
Slag (pcy)	200	200 FA	200	200	250	250	250	315
Silica Fume (pcy)	50	50	50	50	50	50	50	50
WR (oz/cwt)	2	2		2	3	3	3	3
WR or R Type	WR+R(1)	WR+R(1)		WR+R(1)	WR(1)			
HRWR (oz/cwt)	19	15.5	25	19	21	23	28	17
HRWR Type	WRDA 19	WRDA 19	HRWR A (2M)	WRDA 19	WRDA 19			
CA (pcy)	1800	1800	1800	1800	1800	1800	1800	1800
CA Location	Red Hill			Manassas	Garrisonville			Red Hill
FA (pcy)	862	813	888	943	954	1006	1011	1043
FA Location	Kingsland Reach			LaPlata	Rappahannock			K. Reach
Slump (in)	7.5	6.75	6	6	7.5	7.5	8.2	7.5
Air (%)	4.7	4.2	6.6	4.7	5.3	4.8	5.6	6.8
Unit Weight (lb/cft)	146.8	145.6	144.8	149.6	148.4	150.4	150.8	145.6
Strength (1 D) psi	9670	8760	8920	10300	8450	9010	6690	6990

Strength (1 D) Oven					8410	8580	8060	7980
Strength (2 D)	10710	10210	10330	11130	9170	10030	9930	
Strength (28 D)	11720	11380	10260	11740	9990	11560	11730	10580
Permea-bility (28 D)		520		505	764		932	1369
Initial Set	7.25	6.75	4.75	7.15	6.75	6.25		10+
Water/Ce-mentitious	0.28	0.28	0.27	0.27	0.3	0.28	0.28	0.3
Water (pcy)	290	290	280	280	300	280	290	270

Table A-6. Set 6 at Plant (B8-B11)

Bayshore Plant Mixes	B8	B9	B10	B11
Date	5/25/94	5/25/94	5/25/94	5/25/94
Cement Content	585	750	650	650
Cement Type	Type II MF			
Slag	315	250	350	300
Silica Fume		50		50
WR (oz/cwt)	3 (pc)	3 (pc)	3 (pc)	3 (pc)
WR or R Type	WR(1)			
HRWR (oz/cwt)	17	28	20	25
HRWR Type	HRWRA(1)			
CA (pcy)	1800	1800	1800	1800
CA Location	Garrisonville			
FA (pcy)	1126	1022	1042	1001
FA Location	Rappahannock			
Slump (in)	7.8	2.5	7.5	4.0
Air (%)	7.2	3.2	7.0	5.4
Strength (1 D Steam) psi	4530	8480	5180	5680
Strength (28 D)			8210	8290
Water/Cementitious	0.30	0.30	0.27	0.28
Water	270	317	270	280

Table A-7. Concrete Mixtures Used in Beams

Job Mixes	Beam 1	Beam 2	Beam 3	Beam 4
Date	5/27/94	5/27/94	5/27/94	5/27/94
Cement Content	750	750	650	650
Cement Type	Type II MF			
Slag	300	300	300	300
Silica Fume				
WR (oz/cwt)	3 (pc)	3 (pc)	3 (pc)	3 (pc)
WR or R Type	WR(1)			
HRWR (oz/cwt)	23.5	26	23	25
HRWR Type	HRWRA(1)			
CA (pcy)	1800	1800	1800	1800
CA Location	Garrisonville			
FA (pcy)	977	977	1086	1086
FA Location	Rappahannock			
Slump (in)	7.5	5	3	6
Air (%)	6.5	4.1	3.6	4.8
Strength (1 D Stm) psi	6050	9710	7600	6330
Strength (1 D) TMC	6600		8356	
Strength (7 D)	6230	10880	9360	7660
Strength (28 D) 6x12	6580	11720	9180	8970
Strength (28 D) 4x8	7050	10270	10160	7990
Strength (56 D) 4x8	7450	12510	10880	8400
Flexure (28 D) psi	1080	1390	1370	1345
Splitting (28 D) psi	460	640	600	585
Modulus (10^6 psi)	4.77	6.27	6.34	6.00
Modulus (10^6 psi) Theo.	4.91	6.56	5.81	5.74
Permeability (28 D)	2464	625	723	1448
Water/Cementitious	0.28	0.27	0.32	0.31
Water (pcy)	293	286	304	280