Development of the Concrete Technology for a Precast Prestressed Concrete Segmental Bridge

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A comprehensive study to establish the concrete technology and quality requirements for the Linn Cove Viaduct in Linville, North Carolina, was undertaken. The study was planned to conform to the project specifications and other special requirements desired by the contractor.

Of particular concern was the development of early-age strengths of 3000 and 4000 psi (20.7 and 27.6 MPa) at nominal ages of 1 and 2 days, respectively, and a minimum 28-day strength of 6000 psi (41.4 MPa). In addition, the concrete had to be pigmented to match the color of the surrounding area. Since the specification contained costly penalties for deficient 28-day strengths, the compressive strength target was established at 25 percent above the specification requirements following statistical studies in ASTM C685.[1]

Other areas of concern were the workability characteristics and the maximum coarse aggregate size, since the job-site precast segments would be congested with reinforcing bars and post-tensioning ductwork as shown in Fig. 1. In addition, the concrete would be mixed at the site in a volumetric mixer (see Fig. 2), instead of at a conventional batching and mixing facility.

NOTE: This paper is based on a presentation given at the Segmental Concrete Bridge Conference in Kansas City, Missouri, March 9-10, 1982. The Conference was sponsored by the Associated Reinforcing Bar Producers—CRSI, Federal Highway Administration, Portland Cement Association, Post-Tensioning Institute, and Prestressed Concrete Institute.

Synopsis

A laboratory study to establish the concrete requirements for the Linn Cove Viaduct in North Carolina was undertaken for the contractor. This multispan precast prestressed segmental bridge is being built by the progressive placing method. The investigations conformed to the project specifications and to special requirements desired by the contractor.

The laboratory work included petrographic studies and physical tests on different aggregates, concrete mix proportioning studies using conventional and high-range water reducers, accelerated heat-curing studies, creep and drying shrinkage tests, the development of field mix proportions, and preparation of a quality control procedural manual.

A unique aspect of the project was the use of a volumetric mixing mobile at the site instead of a conventional batching and mixing facility.

STUDY OBJECTIVES

The following tasks were undertaken:

- Aggregate selection.
- Admixture selection.
- Pigment selection.
- Concrete proportioning tests.
- Concrete strength versus age tests.
- Concrete accelerated heat-curing tests.
- Selection of recommended field mix proportions.
- Creep and drying shrinkage studies.
- Development of quality control procedure manual.

This paper will briefly report on these various tasks.

Aggregate Selection

A study of two different sands and crushed stones (having two sizes) was conducted to determine which aggregates would best produce a high strength concrete. Physical tests and petrographic tests, as listed in Table 1, were made.

Note that all submitted aggregates

Linn Cove Viaduct
Courtesy: Figg & Muller Engineers

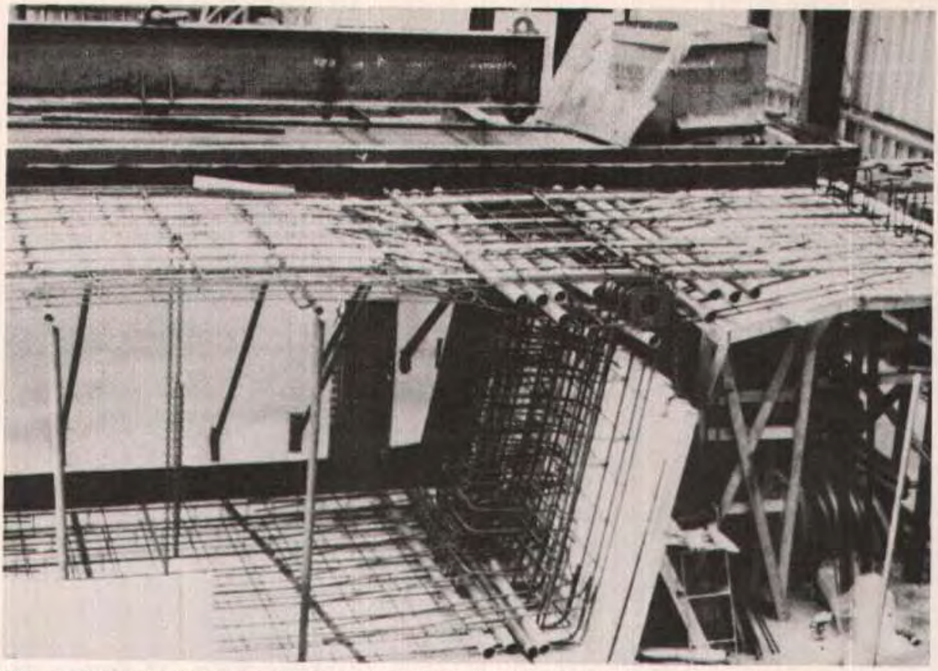

Fig. 1. Typical reinforcing bars and post-tensioning ductwork in precast form.

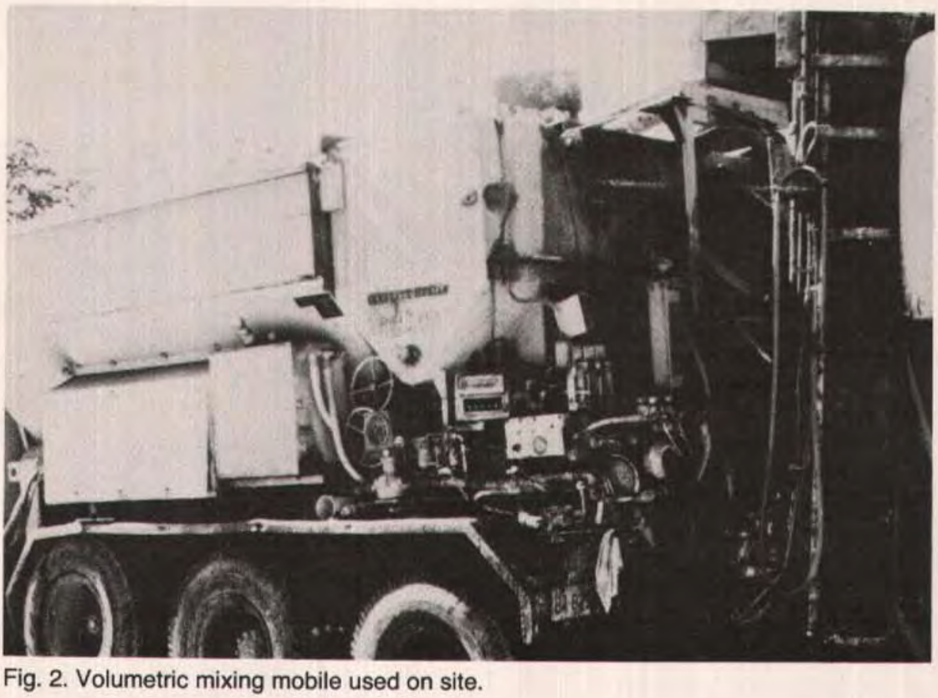

Fig. 2. Volumetric mixing mobile used on site.

Table 1. Aggregate Tests.

Test description	Test procedure
Petrographic examination of aggregates	ASTM C295
Test for clay lumps and friable particles	AASHTO T112 ASTM C142
Test for coal and lignite	AASHTO T113 ASTM C123
Test for material finer than No. 200 sieve	AASHTO T11 ASTM C117
Resistance to abrasion of coarse aggregates	AASHTO T96 ASTM C131
Test for organic impurities	AASHTO T21 ASTM C40
Aggregate gradation test	AASHTO T27 ASTM C136
Scratch hardness test	AASHTO T189 ASTM C235

met the tested ASTM and AASHTO requirements. However, due to the 7500 psi (51.7 MPa) concrete strength requirement, one sand and one coarse aggregate were not recommended. The rejected sand contained 13 percent mica, which would create an unnecessary water demand. The rejected coarse aggregate was granitic schist containing numerous elongated and splintery particles, which would create workability and water demand problems.

Large quantities of the selected aggregates along with the selected Type I cement (Type III cement was not available in the region) and a black iron oxide pigment were shipped to the WJE laboratories. The aggregates were tested to determine their gradation, specific gravity and absorption values. The results are shown in Table 2; note that all materials met the specifications.

Admixture Selection

Since the precast segments were to be heat cured to accelerate early-age strengths, it was necessary to make trial mixtures with various water-reducing and water-reducing, set-retarding admixtures to determine setting times. Trial mixtures with cement contents of 760 lbs per cu yd (450.9 kg/m^3) were evaluated with the following three ASTM C494 admixture types: Type A—Water reducing; Type D—Water reducing and set retarding; and Type F—High-range water reducing (naphthalene sulfonate type).

The initial set time for mixtures containing different admixtures and different admixture dosages was determined in accordance with ASTM C403, "Time of Setting of Concrete Mixtures by Penetration Resistance,"[2] as specified in AASHTO.[3] The results are shown in Table 3.

These tests show the following conclusions for 3 to 5-in. (76.2 to 127 mm) slump, air-entrained concrete:

1. When a water-reducing admixture was not used, the water demand was 42 gallons per cu yd (208 l/m^3).

2. Water demand with Type A or D admixtures was 38 gallons per cu yd (188 l/m^3).

3. When the Type F high-range

Table 2. Aggregate Properties.

Type of aggregate	Sieve size	Cumulative percent passing		
			Specification limits	
		Actual	AASHTO	ASTM
ASTM C33 Coarse Aggregate Size No. 67	1 in.	100	100	100
	¾ in.	99.9	90-100	90-100
	⅜ in.	32.0	20-55	20-55
	No. 4	6.0	0-10	0-10
	No. 8	0.7	0-5	0-5
Fine Aggregate	⅜ in.	100	100	100
	No. 4	99.3	95-100	95-100
	No. 8	92.2	—	80-100
	No. 16	78.2	45-80	50-85
	No. 30	45.8	—	25-60
	No. 50	11.0	5-30*	5-30*
	No. 100	1.2	0-10*	0-10*
Fineness Modulus = 2.72				
*AASHTO M6 allowable limits for concrete pavement or bases and ASTM C33 allowable limits for air-entrained concrete				

Specific Gravity and Absorption Values

Aggregate	Specific gravity (SSD)	Absorption (SSD) percent
No. 67 stone	2.83	0.38
Sand	2.62	0.50

Table 3. Mixture Characteristics and Initial Setting Times.

Mix No.	Cement content (lb/yd³)	SSD water content (lb/yd³)	SSD Water-cement ratio	Slump (in.)	Air content (percent)	AEA* content (fl oz/yd³)	Type A WR content (fl oz/yd³)	Type D WRSR content (fl oz/yd³)	Type F HRWR content (fl oz/yd³)	Initial† set time hrs-min.	
1	758	353	0.466	3¼	4.1	4.1	—	—	—	5	50
2	774	322	0.416	4	4.8	3.7	—	23.3	—	8	0
3	767	313	0.408	3	5.0	3.2	23.1	—	—	5	30
4	769	305	0.397	3¼‡	4.2	2.3	—	—	85.0	6	15
5	761	286	0.376	4‡	5.8	2.3	—	—	115.0	6	10
6	781	273	0.350	4½‡	5.5	1.9	—	23.0	80.0	10	25
7	771	276	0.358	3‡	5.2	1.4	—	9.3	79.0	7	10
8	754	269	0.357	6½‡	7.0	1.6	22.7	—	113.4	7	25

Note: 1 lb/yd³ = 0.5933 kg/m³; 1 in. = 25.4 mm; 1 fl oz/yd³ = 0.0386 l/m³.

* AE = Neutralized vinsol resin (ASTM C260).
† At temperatures of 70 F (ASTM C403).
‡ Slump at age of about 5 minutes.

water reducer was used by itself at a dose of 115 fl oz. per cu yd (4.4 l/m³), the water demand was 34 gallons per cu yd (168 l/m³).

4. When the Type F high-range water reducer was used in combination with either Type A or D admixtures, the water demand was 32 to 33 gallons per cu yd (158 to 163 l/m³). This combination provided a water reduction of about 24 percent.

5. Initial set times were 5½ to 6 hours for plain concrete, for concrete with a Type A water reducer, and for concrete with a Type F high-range water reducer.

6. Initial set times were longer with a Type D admixture, and when Type A or D admixtures were used in combination with the Type F admixture.

It was then decided to investigate two different mixture series. The first would use a Type A water reducer at a normal dose of 3 fl oz. per 100 lbs (7.4 ml/kg) of cement. This first series would study a conventional concrete that would incorporate a 10 percent water reduction.

The second series would use the Type F high-range water reducer at a dose of 120 fl oz. per cu yd (4.6 l/m³). Both series were anticipated to provide equal initial set times of 5 to 6 hours, which would provide reasonable initial set times for the overnight production of the precast segments.

Pigment Selection

Different concrete mixtures were cast to determine the black iron oxide pigment content to match the natural rock colors at the site. Concretes with pigment contents from 0 to 7 percent by weight of cement were produced. These concretes contained 775 lbs of cement per cu yd (460 kg/m³), the slump was maintained at 4 to 5 in. (102 to 127 mm), and the air contents ranged from 6 to 7 percent.

Concrete slabs and cylinders were heat-cured overnight at 135 F (57 C). Following overnight curing, the slabs were washed with water, brushed to remove the surface laitance, and then shipped to the site for examination. The selected concrete contained approximately 0.50 percent black iron oxide pigment by weight of cement.

Concrete Proportioning Tests

Two series of mixtures using ACI procedures[4] were made using air-entrained, pigmented concretes. One series used a Type A water-reducer with nominal 600, 700, and 800 lbs of cement per cu yd (356, 415, and 475 kg/m³). These concretes are referred to as H6, H7 and H8, respectively. The second series used a Type F high-range water reducer with nominal 600, 700, and 800 lbs of cement per cu yd (356, 415, and 475 kg/m³). These concretes are referred to as S6, S7, and S8, respectively.

The mixing was done in a 3.0 cu ft (0.085 m³) horizontal turbine-type pan mixer. The slump was measured 5 minutes after the mixing was completed. The plastic unit weight, air content and temperature of the fresh concrete were measured. Twelve cylinders were fabricated using the procedures of ASTM C192. Six were subjected to an 18-hour overnight heat-curing cycle and six were initially moist-cured in their molds in 70 F (21 C) air.

The six heat-cured cylinders received a 5-hour preset at 70 F (21 C). Following the preset, they were subjected to overnight radiant heat curing with a maximum air temperature of 140 F (60 C). A thermocouple was embedded in the cylinder at mid-depth and another was placed in the air in the curing box. Average time-temperature curves are given in Fig. 3. The typical rate of temperature rise of the air in the curing box was 25 to 30 deg F (14 to 17 deg C) per hour.

At age 18 hours, two cylinders each

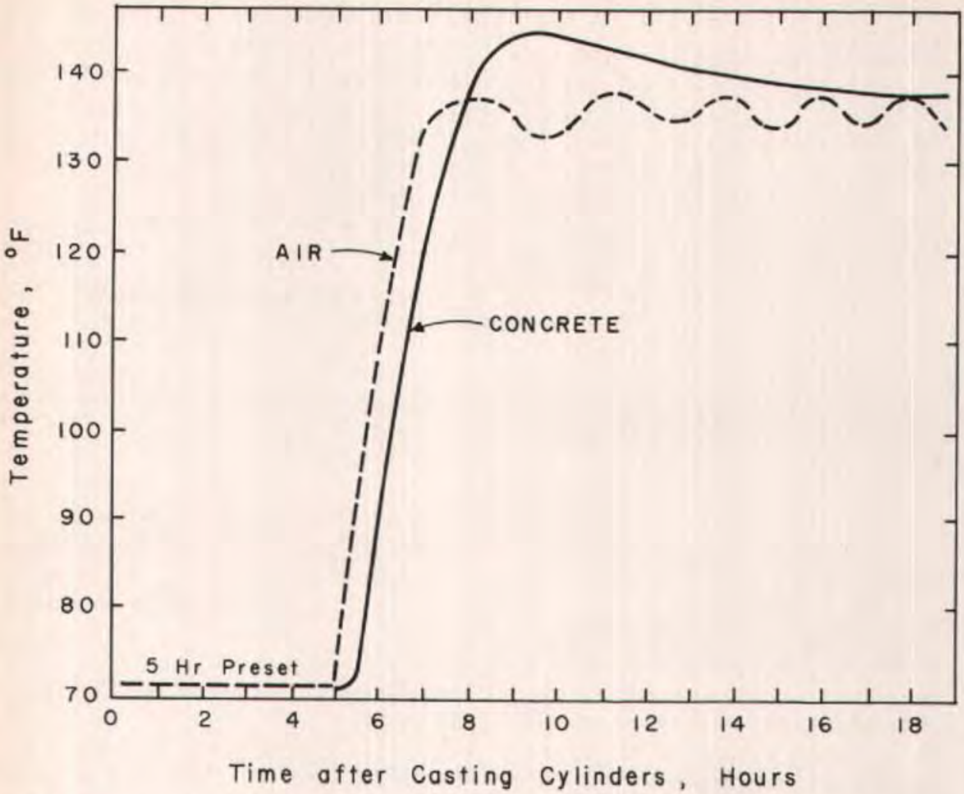

Fig. 3. Average concrete and air temperatures during overnight heat-curing cycle.

were tested for strength from the curing box and from the laboratory 70 F (21 C) moist-curing condition. The remainder of the cylinders were transferred into lime-saturated water at 73 F (23 C) until their 28 and 90-day test ages.

The mixture design data, water-cement ratios, fresh unit weight, slump and air content are given in Table 4. The compressive strength data are given in Table 5.

The compressive strength versus water-cement ratio data have been plotted in Fig. 4. These data exhibit a linear relationship between strength and water-cement ratio. Both mixture series had the same compressive strength at all tested ages when compared on the basis of the same water-cement ratio. These data show that the 28-day heat-cured strengths are somewhat lower than the 28-day continuously moist-cured strengths. This difference was about 10 percent with the concrete containing the Type A admixture, and about 6 percent for the concretes containing the Type F admixture. This magnitude of strength reduction due to heat curing is typical for concretes which have received a proper preset period prior to applying the heat curing. Much higher strength losses can occur if an inadequate preset period is used.[5,6,7]

One series of nonpigmented, air-entrained concrete was also investigated. This series was limited to the use of the Type A water-reducing ad-

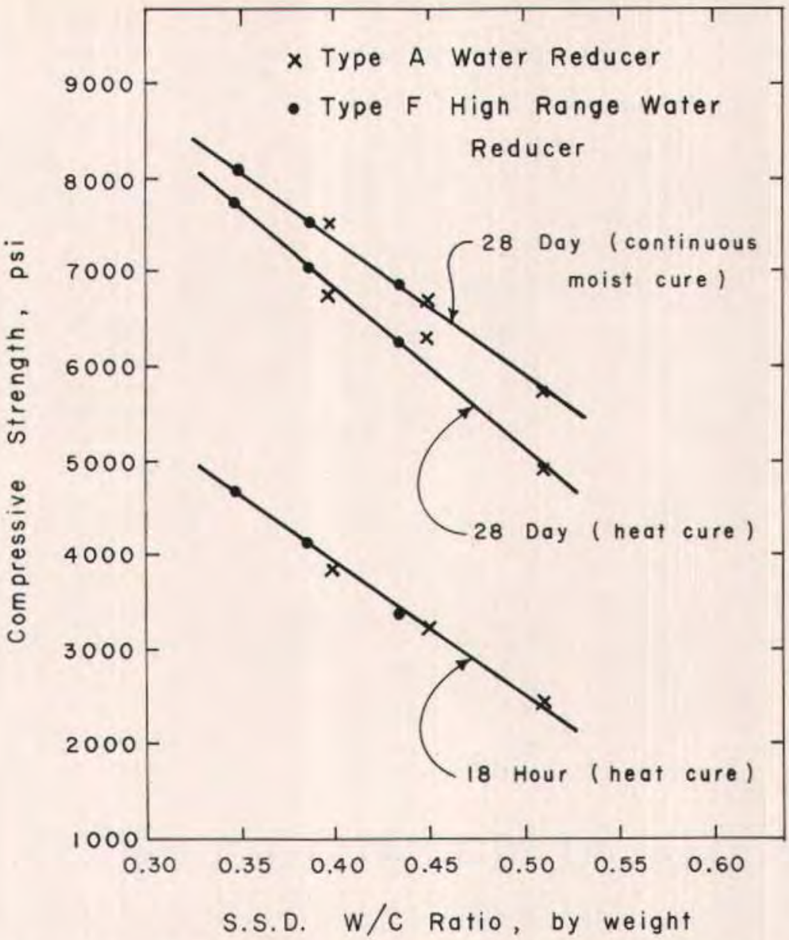

Fig. 4. Compressive strength versus water-cement ratio for pigmented concrete using Type A and F water reducers.

mixture, and nominal cement contents of 600 and 700 lbs cu yd (356 and 415 kg/m^3). The casting and curing procedures were identical to those previously described. These concretes were referred to as H6-NP and H7-NP, respectively. The data for these two mixes were given in Tables 4 and 5. The data from these nonpigmented concretes justify the following conclusions when compared with essentially identical pigmented concretes:

1. There was no apparent difference in water demand.

2. There was no difference in the amount of air-entraining agent (AEA) required to entrain 5½ to 6 percent air.

3. The 18-hour and 28-day heat-cured compressive strengths were essentially the same.

Concrete Strength Versus Age Tests

Since the precast segments required minimum strengths of 3000 psi (20.7 MPa) prior to moving the segment to

Table 4. Concrete Materials — Quantities and Properties.

Mix No.	Admixture type	SSD Quantities per cu yd						Properties			
		Cement (lb)	Water (lb)	Sand (lb)	Stone (lb)	AEA (fl oz)	Water reducer (fl oz)	Water-cement ratio (SSD)	Slump (in.)	Air content (percent)	Fresh unit weight (pcf)
H6	A	594	303	1413	1584	2.00	17.8	0.510	2.75	6.0	144.4
H7	A	689	310	1336	1575	2.70	20.7	0.450	2.75	5.5	145.0
H8	A	800	320	1249	1600	3.65	24.0	0.400	3	5.2	147.2
S6	F	592	257	1511	1579	1.13	120.0	0.434	5	6.5	146.4
S7	F	691	267	1404	1580	1.50	104.0	0.386	4	6.0	146.4
S8	F	797	279	1308	1594	2.27	120.0	0.350	6.5	6.0	147.8
H6-NP†	A	593	313	1399	1582	2.0	17.8	0.528	3.0	6.0	144.1
H7-NP†	A	695	313	1308	1589	2.7	20.9	0.450	3.25	6.0	144.8

Note: 1 lb = 0.4536 kg; 1 fl oz = 29.573 ml; 1 in. = 25.4 in.; 1 lb per cu yd = 0.5933 kg/m^3.

*Pigment content of 3.9 lb per cu yd in all mixes except NP mixes
† NP = No pigment used in concrete.

Table 5. Measured Compressive Strength Data.*

Mix No.	Moist-cured strength (psi)			Heat-cured strength (psi)		
	18 hr	28 day	90 day	18 hr	28 day	90 day
H6	1060	5750	6360	2450	4930	5860
H7	1220	6760	7200	3300	6370	6540
H8	1850	7550	7930	3900	6790	7420
S6	980	6810	7860	3350	6250	7170
S7	1630	7470	8580	4190	7050	8460
S8	1450	8010	9380	4680	7750	8920
H6-NP	1170	5530	6180	2460	4900	5700
H7-NP	1310	6350	7000	3200	5940	6600

Note: 1 psi = 0.006895 MPa.
*All test results are the average of two tests.

the match-casting position, then 4000 psi (27.6 MPa) prior to moving to yard storage as shown in Fig. 5, and eventually 6000 psi (41.4 MPa) at 28 days, it was necessary to make tests to determine strength versus age characteristics.

Three high strength potential mixes were made with Type A and F admixtures. Since the specified maximum water-cement ratio for the segment concrete was 0.44, three different concretes were proportioned with water-cement ratios of 0.40 and 0.35. As shown in Fig. 4, these water-cement ratios were anticipated to provide 28-day heat-cured strengths of about 6700 and 7700 psi (46.2 and 53.1 MPa), respectively.

With water requirements of 310 and 270 lbs per cu yd (184 and 160 kg/m^3) for the Type A and F admixtures, respectively, the necessary cement contents for these two water-cement ratios would be as shown in Table 7. Three mixtures were then proportioned,

Fig. 5. Typical yard storage along road leading to bridge site.

Table 6. Cement Content, Preset Time, Actual SSD, and Admixture Type for Various Mixtures.

Mix No.	Actual cement content (lb per cu yd)	Preset time (hours)	Actual SSD Water-cement ratio	Admixture
F-675	624	5	0.410	Type F
A-775	779	5	0.402	Type A
F-771	780	5	0.352	Type F
F-771	780	3	0.352	Type F

Note: 1 lb per cu yd = 0.5933 kg/m³.

mixed, cast, heat-cured and tested as previously described and as listed in Table 6. The F-675 and the A-775 mix had the same water-cement ratio of 0.40 to 0.41. The A-775 and F-771 mixes contained the same amount of cement but had different water-cement ratios of 0.41 and 0.35.

All cylinders were heat cured for 20

Table 7. Cement Content for Type A and F Admixtures.

Admixture	Water-cement ratio	
	0.40	0.35
Type A	775	885
Type F	675	771

Note: 1 lb per cu yd = 0.5933 kg/m³.

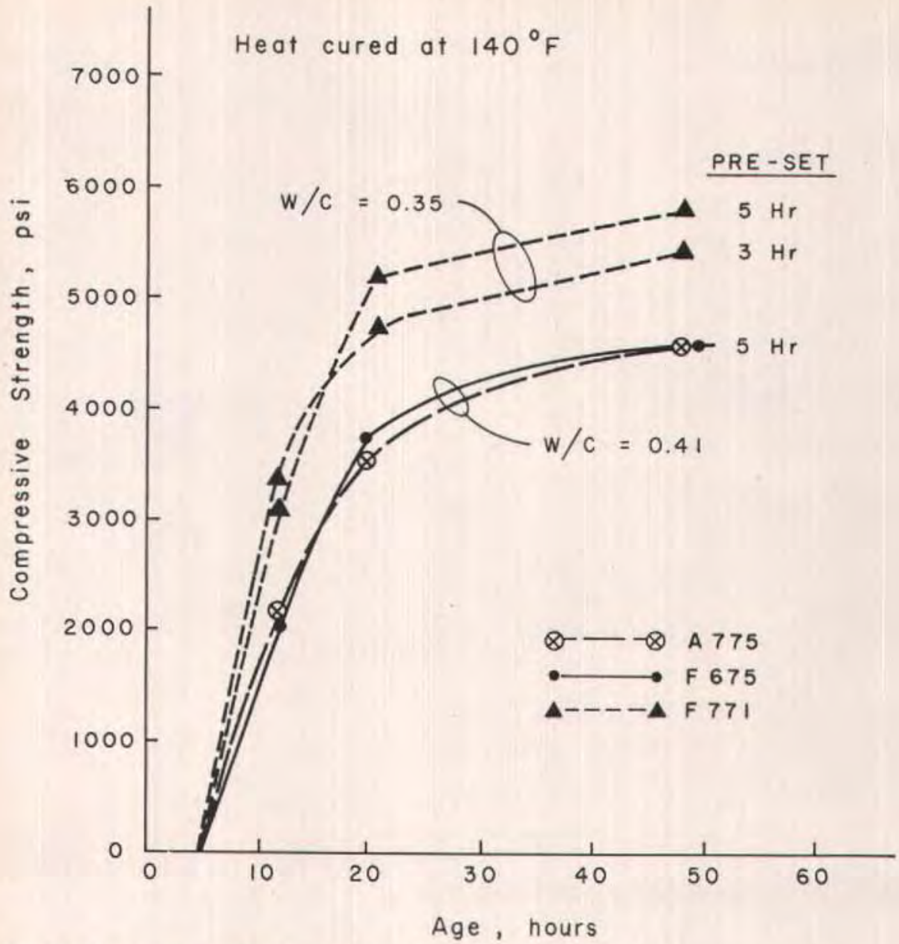

Fig. 6. Strength versus early age for selected high strength potential concretes.

Table 8. High Strength Potential Mix Design Data and Compressive Strength Data.*

Mix No.	Cement content (lb/yd³)	Air content (percent)	Slump (in.)	Water reducer content (fl oz/yd³)	Water-cement ratio	Compressive strength (psi)					
						12 hr	20 hr	48 hr	7 day	14 day	28 day
F-675	624	6.0	6	118	0.410	2050	3740	4590	5440	6000	6710
A-775	779	5.5	3.5	23	0.402	2180	3530	4580	5460	5970	6460
F-771	780	5.3	4.5	117	0.352	3080	5170	5790	6670	7220	8140
F-771†	780	5.3	4.5	117	0.352	3360	4730	5430	6320	7300	7810

Note: 1 lb per cu yd = 0.5933 kg/m³; 1 in. = 25.4 mm; 1 fl oz = 29.573 ml; 1 psi = 0.006895 MPa.
* All strength results are an average of two tests.
† 3-hour preset

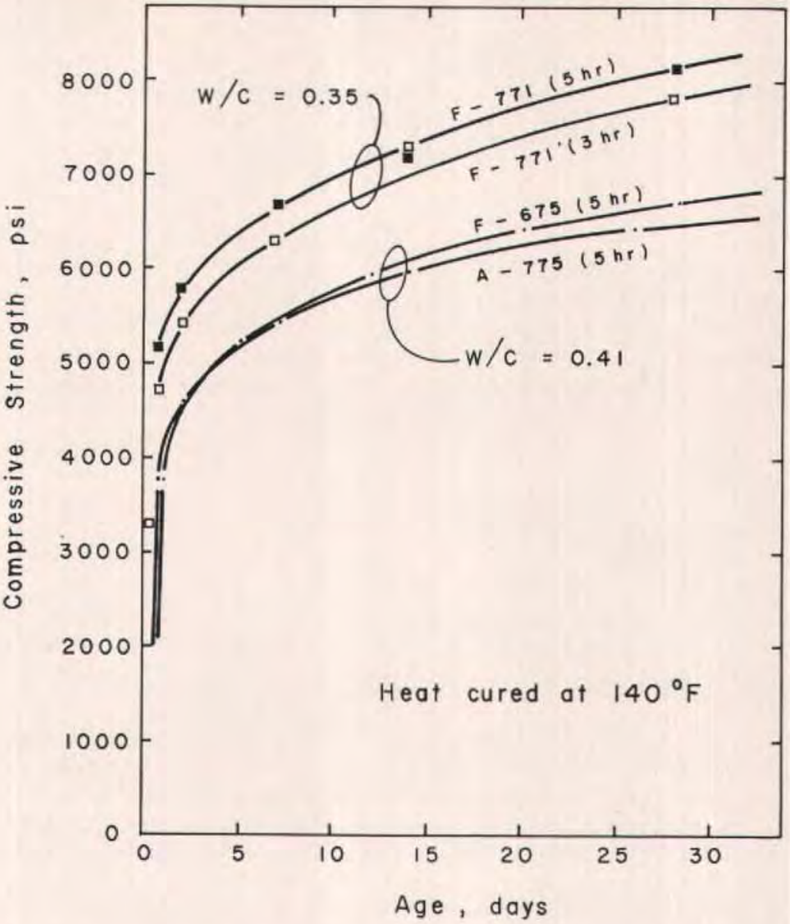

Fig. 7. Strength versus age for selected high strength potential concretes.

hours followed by continuous moist curing in lime-saturated water at 73 F (23 C) until test age. A preset time of 3 and 5 hours was used during the two F-771 tests. Compressive strength test ages were 12 hours, 20 hours, 48 hours, 7 days, 14 days, and 28 days. Mix proportioning data and compressive strength data are given in Table 8.

The compressive strength versus age characteristics for these mixes during the first 48-hour period are given in Fig. 6. Conclusions drawn from these early-age strength data are as follows:

1. Mixes A-775 and F-675, which had the same water-cement ratio of 0.41, had the same strength vs. age curves even though Mix A-775 contained an additional 155 lbs of portland cement per cu yd (92 kg/m^3).

2. With a water-cement ratio of 0.41, the average rate of strength gain from 20 to 48 hours was 35 psi (0.24 MPa) per hour.

3. The use of the 0.35 water-cement ratio increased the 12 or 20-hour strengths by 40 to 45 percent over the 0.41 water-cement ratio concretes. The

2-day strengths of the 0.35 water-cement ratio concrete was about 5500 psi (37.9 MPa), well above the 4000-psi (27.6 MPa) requirement. The 0.41 water-cement ratio concrete 2-day strength was only 4600 psi (31.7 MPa), a value which was too close to the 2-day 4000-psi (27.6 MPa) strength requirement.

4. With a water-cement ratio of 0.35, the average rate of strength gain from 20 to 48 hours was 25 psi (0.17 MPa) per hour.

5. The use of a 3-hour preset versus a 5-hour preset with the 0.35 water-cement ratio concrete increased the 12-hour strength by 9 percent, but the strengths at 20 and 48 hours were about 8 percent lower than the concretes allowed at 5-hour preset.

The strength versus age characteristics for these same concretes during the entire 28-day period are given in Fig. 7. Conclusions drawn from these data are as follows:

1. The F-675 and A-775 heat-cured concretes, which had the same water-cement ratio of 0.41, had the same strength at all ages and had a 28-day strength potential of about 6500 psi (44.8 MPa). This compares with the anticipated 6700 psi (46.2 MPa) as shown on Fig. 4.

2. The F-771 heat-cured concrete, which had a water-cement ratio of 0.35, had a 28-day strength potential of 7800 to 8100 psi (53.8 to 55.8 MPa). This compares with the anticipated 7700 psi (53.1 MPa) as shown on Fig. 4.

3. The use of a 3-hour preset reduced the 28-day strength potential by 5 percent in comparison with a 5-hour preset condition.

This particular investigation measured the 90-day compressive strength for concretes tested during the mix proportioning investigation. These various concretes were continuously moist cured following initial overnight curing in their molds at 70 F (21 C). The subsequent moist curing is as specified in ASTM and AASHTO.

The strength data for concrete containing Type A water-reducing admixture showed that the 90-day strengths were 7 to 10 percent greater than the 28-day strengths, with increases amounting to 400 to 700 psi (2.8 to 4.8 MPa).

The data from concrete containing Type F high-range water-reducing admixture showed that the 90-day strengths were 15 to 20 percent greater than the 28-day strengths, with increases amounting to 1100 to 1300 psi (7.6 to 9.0 MPa).

Since accelerated heat-cured concretes normally have a lower ultimate strength potential when compared with continuously moist-cured concrete, an analysis of the strength data was made. Data comparing the ratio of heat-cured strength divided by continuously moist-cured strength for 28 and 90-day old concretes are presented in Table 9.

These comparisons show that heat-cured concrete containing a Type A water reducer had an average strength reduction of 10 percent at 28 days and 8 percent at 90 days. The concrete containing the Type F high-range water reducer had a much lower average

Table 9. Relative Concrete Strengths at 28 and 90 Days for Various Mixes.

	Ratio of heat-cured to moist-cured strength at 28 and 90 days	
Mix No.	28-day ratio	90-day ratio
H6	0.86	0.92
H7	0.94	0.91
H8	0.90	0.94
S6	0.92	0.91
S7	0.94	0.99
S8	0.97	0.95
H (Avg)	0.90	0.92
S (Avg)	0.94	0.95

strength reduction of 6 percent at 28 days and 5 percent at 90 days (see Table 9).

Selection of Recommended Field Mix Proportions

Concrete proportions were required for four different mixtures having 28-day design strengths of 3000, 4000, 5000, and 6000 psi (20.7, 27.6, 34.5, and 41.4 MPa). The actual proportions for field usage included a 25 percent over-design factor for statistical variations which established the target 28-day compressive strengths at 3750, 5000, 6250, and 7500 psi (25.9, 34.5, 43.1, and 51.7 MPa), respectively. Proportions were selected for these four different strength levels while incorporating a Type A water reducer and also for the 7500-psi (51.7 MPa) strength level while incorporating a Type F high-range water reducer.

3000 and 4000 psi (20.7 and 27.6 MPa) Cast-in-Place Concretes. The project specification established maximum water-cement ratios of 0.49 and 0.44 for the cast-in-place 3000 and 4000 psi (20.69 and 27.58 MPa) moist-cured concretes, respectively. The recommended proportions for both concretes were controlled by these water-cement ratio limits. As a result, these recommended proportions resulted in concretes having anticipated 28-day moist-cured compressive strengths as listed in Table 10.

At both levels, the anticipated 28-day strengths were well above the target design strengths of 3750 and 5000 psi (25.9 and 34.5 MPa), respectively. The data in Fig. 4 show that the water-cement ratio for 28-day moist-cured 3000-psi (20.7 MPa) concrete could easily be increased from 0.49 to 0.55 while maintaining an anticipated 28-day strength of 5100 psi (35.2 MPa), which was still 70 percent over the 3000-psi (20.7 MPa) design level. With this change, the cement content could be reduced from 305/0.49 = 622 lbs (282 kg) to 305/0.55 = 554 lbs (251 kg), or by 68 lbs (31 kg). This savings in portland cement represents a savings of about \$2.00 per cu yd (\$2.62 per m^3) for Type I cement at \$60.00 per ton (\$66.14 per tonne).

The data in Fig. 4 show that the water-cement ratio for 28-day moist-cured 4000-psi (27.6 MPa) concrete could be easily increased from 0.44 to 0.49 while maintaining an anticipated 28-day strength of 6000 psi (41.4 MPa), which was still 50 percent over the 4000-psi (27.6 MPa) design level. With this change, the 4000-psi (27.6 MPa) concrete cement content could be reduced from 310/0.44 = 705 lbs (320 kg) to 310/0.49 = 633 lbs (287 kg) or by 72 lbs (33 kg). A similar \$2.00 per cu yd (\$2.62 per m^3) saving would result.

5000 psi (34.5 MPa) Cast-in-Place Concrete. The recommended proportions for the cast-in-place 5000-psi (34.5 MPa) concrete to be used for the closure sections of the bridge were the same as the 4000-psi (27.6 MPa) concrete since the water-cement ratio limitation of 0.44 controlled the proportioning. The anticipated strength at 28 days for this moist-cured concrete was 6900 psi (47.6 MPa). This provided an over-design factor of 38 percent.

6000 psi (41.4 MPa) Precast Concrete. Two recommended mix proportions for 6000-psi (41.4 MPa) concrete which could be used for casting the precast segments were developed; these are

Table 10. Overdesign Factor for Two Mixes.

Mix No.	Anticipated 28-day strength*	Overdesign factor
3000 psi	6100 psi	103
4000 psi	6900 psi	73

Note: 1 psi = 0.006895 MPa.
* Continuous moist cure

Table 11. Recommended Field Mix Proportions for Precast Segment Concrete.

Material and property	Recommended SSD quantities per cu yd	
	Type A	Type F
Cement, lb (Type I)	910	756
Pigment, lb	4	4
Coarse aggregate, lb	1600	1600
Sand, lb	1097	1349
Water, lb	328	272
AEA, fl oz	4.6	2.0
Water reducing admixture, fl oz	27.3	120.0
Water-cement ratio, SSD	0.36	0.36
f_c, psi	7500	7500
Slump, in.	3 to 4	6 to 7
Air content, percent	5.0 to 6.0	5.0 to 6.0

Note: 1 lb = 0.4536 kg; 1 fl oz = 29.573 ml;
1 psi = 0.006895 MPa; 1 in. = 25.4 mm.

shown in Table 11. The recommended proportions for conventional 3 to 4-in. (76.2 to 101.6 mm) slump concrete using a Type A admixture required a water-cement ratio of 0.36. This concrete mixture resulted in an extremely high cement content of 910 lbs or 9.7 bags per cu yd (540 kg/m^3).

The alternative recommended proportions used the Type F high-range water reducer and an initial slump of 6 to 7 in. (152 to 178 mm). The water-cement ratio was the same 0.36, and the 28-day target strength was also 7500 psi (51.7 MPa). This alternative required only 756 lbs of cement per cu yd (448 kg/m^3) or about 150 lbs of cement per cu yd (89 kg/m^3) less. With average 1982 prices of Type I portland cement, and Type A and F admixtures, the average price of these ingredients per cu yd would be as shown in Table 12.

Thus, the use of the Type F high-range water reducer resulted in a cost savings of $2.00 per cu yd ($2.62 per m^3) a higher initial slump, the same water-cement ratio, and a 7500-psi (51.7 MPa) 28-day strength potential.

It is imperative that it is understood that the 6 to 7-in. (152 to 178 mm) slump achieved by adding the Type F admixture to the concrete is only a temporary increase in slump. This temporary fluidity was available in the laboratory for a total of about 20 minutes. At 30 minutes, the concrete had essentially reverted to a no-slump concrete. The no-slump concrete could still be internally vibrated for a long period of time after this slump loss process since the initial set time was in excess of 5 hours.

The Type F high-range water-reduced concrete was selected for use in the precast segments. As shown in Fig. 2, all concrete was proportioned and mixed in a continuous volumetric mixing mobile. A statistical analysis of 253 pairs of 28-day job-site cylinder tests has been made. This analysis covers the precasting period from February 1980 to October 1981 and the production of essentially all the precast segments. The results are listed in Table 13.

These data show that the use of the volumetric mixer in combination with a Type F high-range water reducer was

Table 12. Costs of Cement and Admixtures.

Admixture type	Costs of cement and admixtures per cu yd		
	Cement	Admixture	Total
A	\$27.30	\$0.85	\$28.15
F	22.68	3.50	26.18

Table 13. Summary of Job Site Precast Concrete Compressive Strength Data.

Property	Strength
Mean 28-day strength	6960 psi
Lowest 28-day strength	5380 psi
Highest 28-day strength	8840+ psi
Standard deviation	478 psi
Coefficient of variation	6.9 percent

Note: 1 psi = 0.006895 MPa.

successful and that the average job-site strengths were about 7 percent less than the 7500-psi (51.7 MPa) 28-day laboratory strengths.

Creep and Drying Shrinkage Studies

An investigation to establish the elastic, creep, and drying shrinkage properties of the concrete for the precast segments was required in the specifications. Some of the test procedures specified in ASTM C512, "Creep of Concrete in Compression," were modified so as to reflect more accurately the curing and segment storage conditions used at the site.

Since the original proportioning investigation used two different concretes, the creep and drying shrinkage study also used this dual approach. One series used a Type A water-reducing admixture, while the second series incorporated a Type F high-range water reducer. Both series were proportioned to have a 28-day heated-cured compressive strength of 6600 psi (45.5 MPa). This selected strength level required a water-cement ratio of 0.41. The in-place proportions are given in Table 14.

The 6 in. (152 mm) diameter by 20 in. (508 mm) long creep cylinders and the 6 x 12 in. (152 x 305 mm) drying shrinkage cylinders were allowed a 5-hour preset at 70 F (21 C). They were then heat cured as previously described.

After the 18-hour heat curing cycle, all specimens were stored in air at 73 F (23 C) and 50 percent relative humidity. Thus, no additional moist or water curing was used. This procedure was specified only for the creep and shrinkage study.

At 18 hours of age, all cylinders were instrumented with Whittemore strain gage plugs. The initial gage lengths were taken at age 24 hours when the specimens had cooled down to room temperature. During this 6-hour cooling period, all specimens were tightly

Table 14. Mix Proportions for Creep and Shrinkage Test Series

SSD quantities per cu yd		
	Mix Series No.	
Material	Type A	Type F
Cement (Type I)	779 lb	643 lb
Water	320 lb	264 lb
Coarse aggregate	1624 lb	1623 lb
Sand	1243 lb	1501 lb
Pigment	4 lb	4 lb
AEA	3.2 fl oz	0.83 fl oz
Type A WR	22.8 fl oz	—
Type F HRWR	—	122 fl oz
Water-cement ratio (SSD)	0.411	0.411
Slump, in.	2¾	6.0
Air content, percent	4.8	4.2
Fresh unit weight, pcf	147.16	149.8

Note: 1 lb = 0.453 kg; 1 fl oz. = 29.573 ml; 1 in. = 25.4 mm; 1 lb per cu ft = 16.02 kg/m³.

wrapped in plastic bags to eliminate weight loss and drying shrinkage.

These tests were made using the procedures specified in ASTM C157. The creep specimens were loaded at ages of 28 and 90 days to a constant 2000-psi (13.8 MPa) stress. The procedures used follow those in ASTM C512. The tests were continued over a 2.32-year period.

Compressive Strength Results. The original mix proportioning study utilized standard ACI, ASTM and AASHTO procedures for curing which involved a heat-curing cycle followed by continuous moist storage at 73 F (23 C).

This creep and shrinkage study utilized an 18-hour heat-curing cycle but the following storage was in air at 73 F (23 C) and 50 percent relative humidity. As a result, companion compressive strength tests were made on cylinders which were cured using both curing techniques for both series. The test results are shown in Table 15.

The target 28-day heat-cured strength was 6600 psi (45.5 MPa). The AASHTO or ASTM moist-cured specimens had strengths of 6860 and 7150 psi (47.3 and 49.3 MPa). The strengths for companion concretes cured in air with no additional moist curing were identical at 6110 psi (42.1 MPa). Thus, the loaded creep specimens had a strength of 6110 psi (42.1 MPa) at 28 days.

Modulus of Elasticity Data. The modulus of elasticity was measured at ages 19 hours and 28 days. The 28-day tests were made on both AASHTO or ASTM moist-cured concrete and on 50 percent relative humidity air-cured concrete. These data are given in Table 16.

The measured modulus values were greater than those calculated when using the ACI equation as shown in Table 16. The elastic modulus at 19 hours varied from 3.7 to 4.1 x 10^6 psi (25,500 to 28,300 MPa) for the two series. The equal-strength concrete containing the Type F high-range water reducer had the higher 19-hour modulus.

This higher value may be due to the

Table 15. Concrete Compressive Strengths Using Various Water Reducers.

Curing after heat curing	Average 28-day compressive strength, psi	
	Type F Water reducer	Type A Water reducer
Moist—73 F (23 C) and 100 percent relative humidity (AASHTO and ASTM)	7150	6860
In Air—73 F (23 C) and 50 percent relative humidity (as specified)	6110	6110

Note: 1 psi = 0.006895 MPa.

Table 16. Modulus of Elasticity Data*

Mix No.	Age	Cure after heat cure	Measured avg. compressive strength (psi)	Measured avg. modulus of elasticity (10^6 psi)	Theoretical ACI E_c† (10^6 psi)	Measured E_c/ACI E_c
A	19 hr	—	3810 psi	3.72	3.64	1.02
A	28 day	In air	6110 psi	5.05	4.60	1.10
A	28 day	In water	6860 psi	5.99	4.88	1.23
F	19 hr	—	3690 psi	4.08	3.68	1.11
F	28 day	In air	6110 psi	5.47	4.73	1.16
F	28 day	In water	7150 psi	6.02	5.12	1.18

Note: 1 psi = 0.006895 MPa.
*All test results are an average of two tests
†ACI $E_c = 33\, w^{3/2} \sqrt{f'_c}$

fact that the Type F concrete contained 3124 lbs of sand and gravel per cu yd (1854 kg/m³) versus the 2867 lbs per cu yd (1700 kg/m³) that the Type A concrete contained. This represents an increase in aggregate weight of 9 percent. The elastic modulus at 28 days varied from 5.0 to 5.5 x 10^6 psi (34,000 to 38,000 MPa) for specimens cured in air, and was 6.0 x 10^6 psi (41,400 MPa) for ASTM or AASHTO subsequently moist-cured specimens.

Drying Shrinkage. The average shrinkage data are presented in Fig. 8. These measured shrinkage values are normal for high strength, low water-cement ratio concretes. The concrete containing the Type F high-range water reducer exhibited 15 percent less shrinkage than the concrete which contained the Type A water reducer. This is not unexpected since the water and cement contents of the Type F concrete were 17 percent lower than the concrete containing the Type A admixture.

Creep Data. The creep data are presented in Fig. 9. The initial elastic strain and the subsequent drying shrinkage strains have been removed mathematically from total measured strain to obtain net creep strain. Both concretes

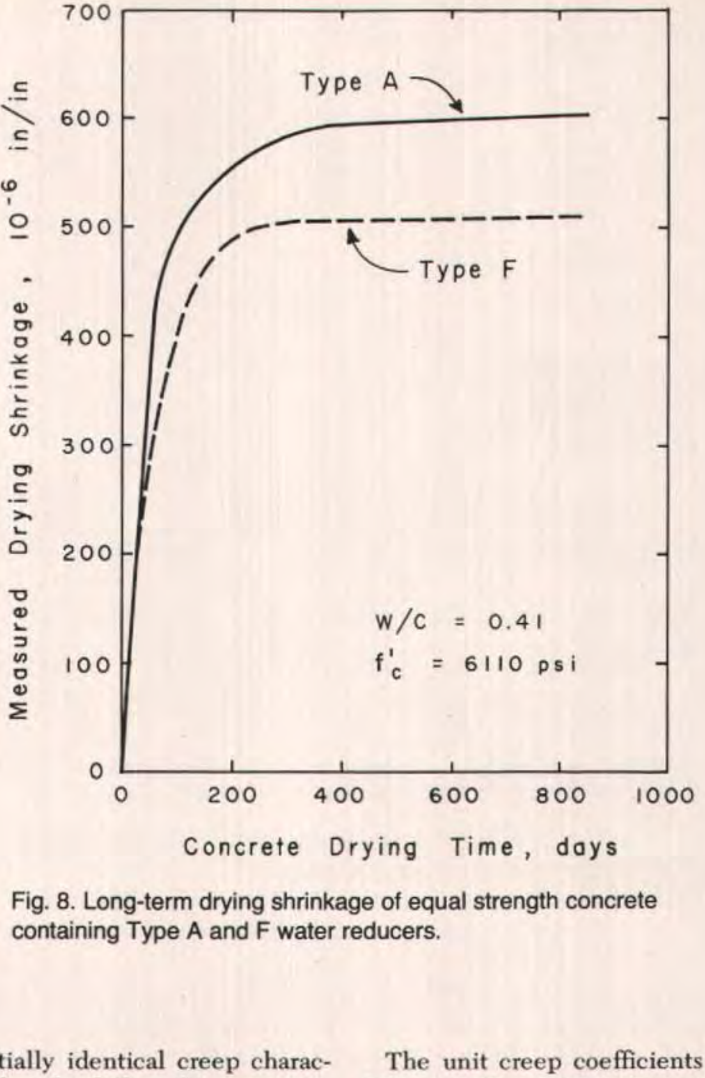

Fig. 8. Long-term drying shrinkage of equal strength concrete containing Type A and F water reducers.

had essentially identical creep characteristics when loaded at the same age. As anticipated, the 90-day old concrete had less creep after 760 days under load, i.e., about 530 x 10^{-6} in./in. when compared to the 28-day old concrete after being under load for 760 days, i.e., about 720 x 10^{-6} in./in.

At an age of 850 days, the concretes which were loaded at 28 and 90 days exhibited the following creep characteristics after 820 and 760 days of load, respectively, while under a constant stress of 2000 psi (13.8 MPa) (see Table 17).

The unit creep coefficients of about 0.26 to 0.36 x 10^{-6} in./in./psi are very low. These low values reflect the benefits of accelerated heat curing, low water-cement ratio, and high compressive strength of the concrete used for the precast segments. Even lower creep values would occur for concrete having a 0.36 water-cement ratio and a 28-day compressive strength of 7500 psi (51.7 MPa) as actually proportioned for the precast segments.

The above observations can be seen graphically in Fig. 9. Table 17 summarizes some of the pertinent data.

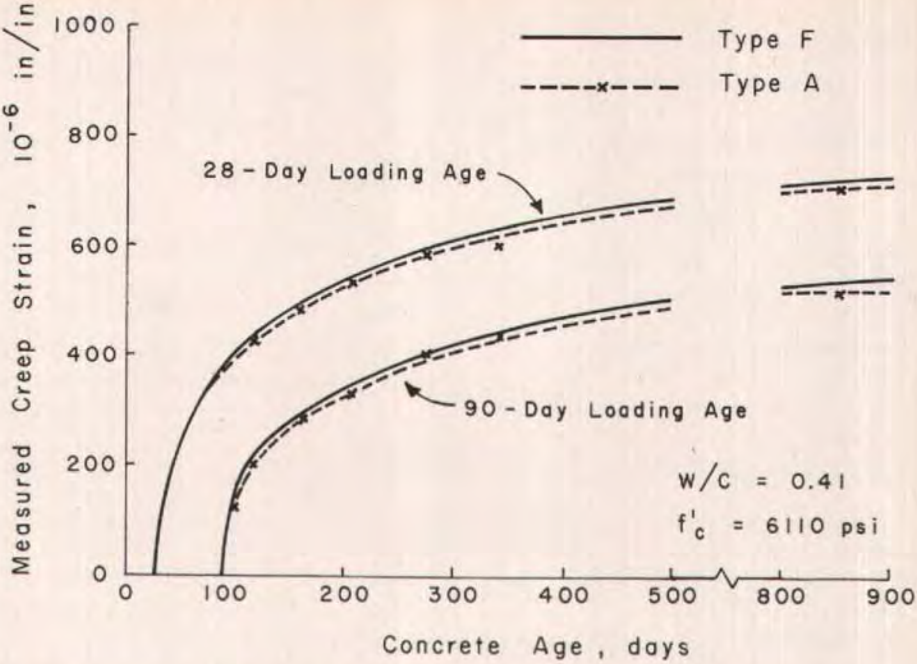

Fig. 9. Long-term creep of equal strength concrete containing Type A and F water reducers.

Table 17. Summary of Creep Data for Various Mixes.

Mix type	Loading age, days	Total Creep strain, 10^{-6} in./in.	Unit creep, 10^{-6} in./in. per psi	Creep strain/ Instantaneous strain
F	28	725	0.36	2.2
F	90	544	0.27	1.6
A	28	718	0.36	1.9
A	90	525	0.26	1.4

Quality Control Procedural Manual

Following the laboratory studies, a quality control procedures manual was prepared as required by the project specifications. The manual established acceptable guidelines to measure the concrete manufacturing and testing procedures. The manual was generally in compliance with the *PCI Manual for Quality Control for Plants and Production of Precast, Prestressed Concrete Products*,[8] the ACI 318-77 Code Requirements,[4] and the project specifications. Also included in the manual were the provisions of ASTM C685, "Concrete Made by Volumetric Batching and Continuous Mixing." A section dealing with geometry control during the erection was also included.

The outline of the quality control procedural manual is as follows:

Division I—Quality Control
- Section 1—Objectives and Methods
- Section 2—Personnel
- Section 3—Testing
- Section 4—Inspection and Records

Division II—Concrete
- Section 1—Concrete Mixtures
- Section 2—Batching and Mixing
- Section 3—Placing Concrete
- Section 4—Curing Concrete
- Section 5—Finishing
- Section 6—Concrete Material

Division III—Geometry Control
- Section 1—General Derivation
- Section 2—Use of the Geometry Sheets

Appendix A—ASTM C685-74, "Concrete Made by Volumetric Batching and Continuous Mixing"

Appendix B—WJE "Investigation of Aggregates for Use in Concrete"

Appendix C—Quality Control Charts, Laboratory Equipment and Forms

CONCLUSIONS

A comprehensive study to establish the concrete technology and quality requirements for a large precast prestressed, segmental concrete bridge has been completed. Petrographic studies on different aggregate sources were useful to identify aggregates which would have undesirable characteristics for producing consistent, high strength concrete even though the aggregates meet ASTM and AASHTO specifications.

The use of an ASTM C494 Type F high-range water reducer allowed water reductions of 15 to 25 percent when compared to a concrete that did not contain a water reducer. The initial setting time of concrete containing the Type F high-range water reducer was the same as that of a concrete without any water reducer. When the Type F admixture was used with a Type A or D admixture, the water reduction was increased but the initial setting time was also extended, sometimes significantly.

Concretes made with Type A or F admixtures to the same water-cement ratio had the same heat-cured strength at any age from 12 hours to 28 days, even though there was a very significant difference in cement content and slump. With the use of equal amounts of Type I cement, the use of the Type F admixture increased the early age heat-cured strength by 40 percent by producing a 0.35 water-cement ratio instead of a 0.41 water-cement ratio when a Type A admixture was used. For equal amounts of Type I cement, the use of the Type F admixture increased the 28-day strength potential by 1500 psi (10.3 MPa) when compared to the Type A admixture concrete.

For the 6000-psi (41.4 MPa) concrete to be used in the precast segments, the 7500-psi (51.7 MPa) strength level selected for the project required a water-cement ratio of 0.36. This was well below the 0.44 maximum water-cement ratio specified. The use of the Type F high-range water reducer allowed the achievement of this 0.36 water-cement ratio while producing a 6 to 7-in. (152 to 178 mm) initial slump.

This Type F concrete mix was less costly than a conventional 3 to 4-in. (76 to 102 mm) slump concrete which used a Type A water reducer and which required an additional 150 lbs of portland cement per cu yd (89 kg/m^3). The cost savings, while still producing a 6 to 7-in. (152 to 178 mm) slump, for 7500-psi (51.7 MPa) concrete was $2.00 per cu yd ($2.62/m^3).

A statistical analysis of over 500 28-day job-site cylinder tests on the Type F 6000-psi (41.4 MPa) concrete which was used in the precast segments was made. This analysis resulted in a mean 28-day strength of 6960 psi (48 MPa) and a coefficient of variation of 6.9 percent during the entire precasting operation. The mean field strength was 7 percent less than the anticipated 7500-psi (51.7 MPa) strength measured in the laboratory for the same concrete.

High strength concretes which are cured in 73 F (23 C), 50 percent relative humidity air for 27 days after the heat curing instead of being cured in moist air or water at 73 F (23 C), 100 percent relative humidity for 27 days develop less strength at age 28 days. During this series, this decrease in strength was 750 to 1050 psi (5.17 to 7.24 MPa).

The 2.3-year drying shrinkage of the concrete containing the Type F high-range water reducer was 15 percent less than the concrete which contained the Type A water reducer. Both concretes had the same water-cement ratio, and the same 28-day strength of 6100 psi (42.1 MPa). The shrinkage values of both concretes were relatively low, i.e., 500 to 600 x 10^{-6} in./in.

The creep of equal water-cement ratio, equal strength concretes containing Type F or A admixtures were identical after 2.3 years. The unit creep coefficients were very low at approximately 0.30 x 10^{-6} in./in./psi. These low values reflect the benefits of accelerated heat curing, low water-cement ratios and high compressive strength. Such low creep values contribute to lower prestress losses.

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NOTE: Discussion of this paper is invited. Please submit your discussion to PCI Headquarters by May 1, 1983.