Effect of Curing Temperatures on High Strength Concrete Bridge Girders

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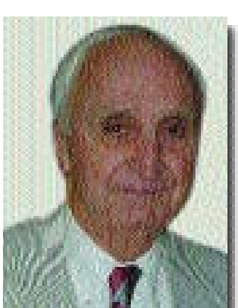

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The effects of high strength concrete curing temperatures on compressive strength development and force levels in straight, bonded pretensioned strands were investigated. Concrete temperatures and prestressing strand forces were monitored during the fabrication of five AASHTO Type III bridge girders with a specified design concrete compressive strength of 10,000 psi (69.0 MPa). After casting, hydration-induced concrete temperature increases resulted in an 11 percent reduction in the average prestressing strand force level due to thermal expansion. Measured concrete temperatures within the instrumented girders varied by as much as 30°F (17°C). Peak concrete temperatures measured in standard field-cured 6 x 12 in. (152 x 305 mm) cylinders cured alongside the girders were as much as 26°F (14°C) less than the peak temperature within the girder. Measured compressive strengths of the standard field-cured cylinders were consistently less than the strength of cylinders that were match-cured using a reference thermocouple installed in the girders. Based on the measured strength data, it was concluded that field-cured cylinders may underestimate the compressive strength of the girder concrete by as much as 10 percent.

Since high strength, high performance concrete (HPC) contains greater quantities of cementitious materials than conventional concrete, the heat generated during initial curing/hydration is also usually greater. This heat generation tends to accelerate the development of concrete compressive strength and other material properties. Therefore, in precast applications, steam curing of high strength concrete is often not necessary to achieve specified early-age concrete strength requirements.

In precast/prestressed concrete applications, the heat generated during initial concrete curing/hydration can affect force levels in bonded and unbonded pretensioned strands due to thermal expansion. In addition, heat loss through formwork and insulated covers can result in significant concrete temperature variations within the components being fabricated. Therefore, when the HPC girders were being fabricated for the Charenton Canal Bridge, a decision was made to study the effects of initial curing temperatures on concrete compressive strength and prestressing strand force levels.

The Louisiana Department of Transportation and Development (LADOTD) completed building their first HPC bridge in 1999.[1] The Charenton Canal Bridge is a 365 ft (111.3 m) long structure made up of five 73 ft (22.3 m) spans, each incorporating five AASHTO Type III girders at 10 ft (3.1 m) spacing. The specified minimum concrete compressive strengths for the bridge girders were 7000 psi (48.3 MPa) at release and 10,000 psi (69.0 MPa) at 56 days.

The middle span of the bridge was instrumented to monitor both early-age and long-term performance of the superstructure as part of a research program focusing on implementation of HPC in highway bridge structures sponsored by the Louisiana Transportation Research Center (LTRC).[2] The research program was conducted jointly by Tulane University, Construction Technology Laboratories, Inc. (CTL), and Henry G. Russell, Inc.

During fabrication of the girders for the middle span, load cells were installed on selected prestressing strands to monitor force levels beginning at the time of initial tensioning and continuing until release. In addition, thermocouples were installed to monitor concrete temperatures during initial curing of the girders. This paper presents girder fabrication details, along with results from instrumentation measurements and concrete material property tests.

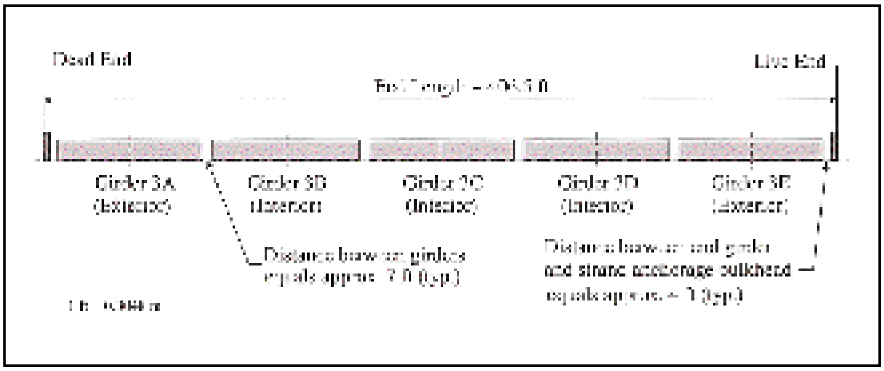

Fig. 1. Fabrication bed configuration.

Table 1. Concrete mixture proportions.

Material	Quantity per cubic yard
Portland cement (Type III)	691 lb
Fly ash (Class C)	296 lb
Fine aggregate	1135 lb
Coarse aggregate (limestone)	1803 lb
Water	247 lb
Water reducer (ASTM C 494, Type D)	60 fl oz
Superplasticizer (ASTM C 494, Type F)	150 fl oz
Water-cementitious materials ratio	0.25

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 fl oz/yd^3 = 38.7 ml/m^3.

GIRDER FABRICATION

All girders for the Charenton Canal Bridge were fabricated by Gulf Coast Pre-Stress in Pass Christian, Mississippi. The five girders for the middle bridge span (Span 3) were fabricated at the same time on a single casting bed, as shown in Fig. 1.

Each girder incorporated 34 straight strands. All of these were uncoated $^1/_2$ in. (13 mm) diameter, Grade 270, low-relaxation, seven-wire strands conforming to ASTM A 416.[3] Eight of the 34 strands were debonded for various distances from the girder ends. The specified initial tensile force for each strand was 30.98 kips (137.8 kN), which corresponded to 75 percent of the guaranteed ultimate tensile strength (GUTS).

Tensioning was executed by pulling each strand to a predetermined target elongation. The target elongation corresponding to the specified initial strand force level was calculated using an assumed strand modulus of elasticity equal to 28,800 ksi (198.6 GPa), a nominal strand area equal to 0.153 sq in. (98.7 mm^2), and an overall length of the bed between strand anchor points equal to 406.5 ft (123.9 m).

The calculated target elongation also included allowances for seating losses and bulkhead movement. Shear and anchorage zone reinforcement was installed after stressing the strands. Grade 60 deformed reinforcing bars incorporated in the girders conformed to ASTM A 615.[4]

The concrete mixture proportions for the girders are shown in Table 1. Each girder required approximately 10.5 cu yd (8.0 m^3) of concrete. During casting, cylinders were made by the project team for the purpose of measuring compressive strength and modulus of elasticity at various specified concrete ages. The cylinders were made from concrete poured in the midspan region of each girder.

Test cylinders for the instrumented girders were made using two different methods of initial curing, namely, field- and match-curing. The field-cured cylinders were standard 6 x 12 in. (152 x 305 mm) specimens that were stored underneath the insulated tarpaulin that covered the girders immediately after casting. The match-cured cylinders were 4 x 8 in. (102 x 203 mm) specimens produced using the "Sure Cure Cylinder Mould System."

Using the Sure Cure System, the curing temperatures for the cylinders were controlled to match the concrete temperature at a specific location in the girder. Temperature sensors for

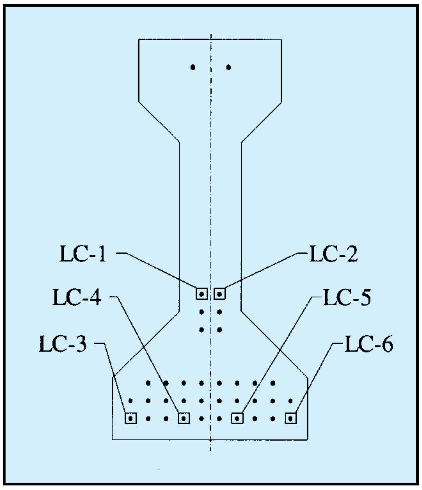

Fig. 2. Load cell instrumentation.

the system were installed in the center of the bottom flange of each instrumented girder near midspan. These sensors were connected to control units that automatically adjusted the temperature of the cylinders to match the girder concrete temperature at the sensor location during the initial curing interval.

After casting, the girders and field-cured cylinders were covered with an insulated tarpaulin, and the control units for the match-cured cylinders were activated. The project specifications allowed a maximum concrete temperature of 160°F (71°C) and required that the strands be released before the concrete temperature dropped 20°F (11°C) from the maximum value. Approximately 24 hours after casting, the required release strength had not yet been achieved, and the concrete temperature began to decrease.

It was decided that steam should be applied to the girders for a brief period of time so that the release strength could be achieved before the concrete temperature decreased beyond the specified 20°F (11°C) limit. Steam was applied approximately $30^1/_2$ hours after casting, for a period of approximately $2^1/_2$ hours. After the required minimum concrete strength was reached, the side forms were removed, the prestressing strands were released, and the girders were placed in storage at the precast yard until they would be transported to the bridge site.

GIRDER INSTRUMENTATION

The girders for the middle span (Span 3) were instrumented to monitor early-age and long-term performance. This instrumentation included load cells to measure pretressing strand forces and thermocouples to measure concrete temperatures during fabrication.

Transfer of force from the stressing jack to the strand anchorage, and subsequent changes due to temperature variations and steel relaxation, tend to cause reductions in strand force. Six of the 34 strands incorporated in the girders for the middle span were instrumented with load cells to monitor prestressing forces beginning at the time of initial tensioning and continuing until release.

The six strands selected for load cell instrumentation are shown in Fig. 2. Load cells were installed at the dead end of the bed (opposite from the jacking end) between the anchorage bulkhead and the strand chuck.

Type "T" thermocouples were installed in four of the five girders to measure concrete temperature variations during initial curing. The girders selected for thermocouple instrumentation included the three interior girders (Girders 3B, 3C, and 3D), plus one of the two exterior girders (Girder 3A).

Locations for thermocouple instrumentation are identified in Fig. 3. Girder 3A incorporated thermocouple instrumentation at three sections along the length (near midspan, one quarter-point, and one end). Girders 3B, 3C, and 3D had three thermocouples installed at midspan only.

Thermocouples were also used to monitor the following: concrete temperatures in three standard 6 x 12 in. (152 x 305 mm) cylinders that were field-cured alongside each of the four instrumented bridge girders, air temperatures beneath the insulated tarpaulin used to cover the girders after casting, and ambient air temperature. The cylinders containing thermocouples were made from the same concrete batch that was placed in the midspan region of each instrumented girder.

The load cells and thermocouples were connected to a data acquisition system that took automated readings at 15-minute intervals. The strand load cell readings began at the time of initial tensioning and continued until release. The thermocouple readings began immediately after casting the concrete and continued until release.

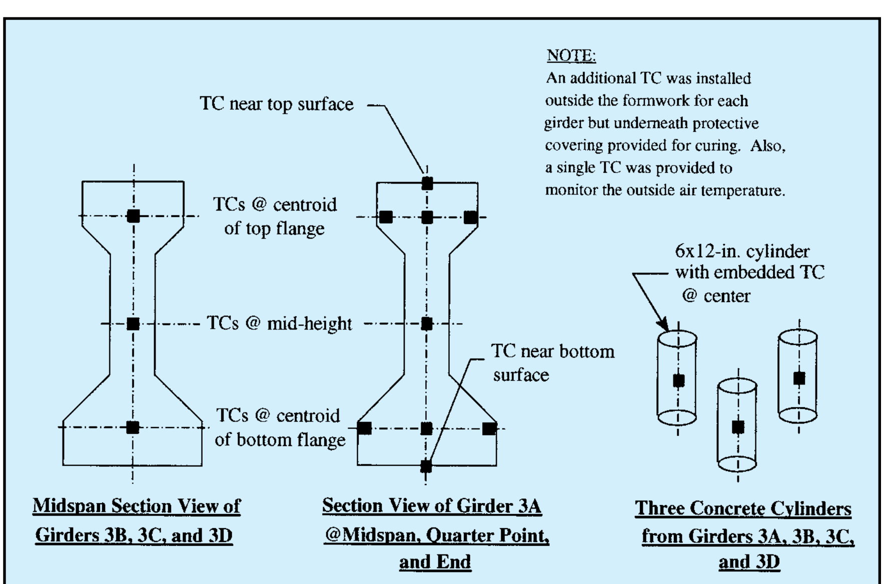

Fig. 3. Thermocouple instrumentation.

MEASURED PRESTRESS FORCES

Plots of force versus time for the six prestressing strands instrumented with load cells are shown in Fig. 4. After stressing all 34 strands, the average force in the six strands monitored with load cells was 30.19 kips (134.3 kN). Although the average measured initial force was approximately 0.79 kips (3.5 kN) less than the specified initial force, it was still well within the 5 percent tolerance allowed in the PCI Quality Control Manual.[5]

The force level in each strand remained somewhat uniform for the first 30 hours after stressing, until the completion of concrete casting. After casting, the force in each strand gradually decreased as the concrete temperature increased. At 20 hours after casting and 50 hours after initial stressing, the increase in concrete temperature due to hydration resulted in a reduction in the average strand force of 3.4 kips (15.1 kN), or 11 percent from the specified initial value.

About $30^{1}/_{2}$ hours after casting and 58 hours after initial stressing, steam was applied to the girders for a period of approximately $2^{1}/_{2}$ hours. The application of steam resulted in a reduction in the average strand force of approximately 5.8 kips (25.8 kN), or 19 percent from the specified initial value. After the steam curing was terminated, the concrete temperature began to decrease and strand force began to increase.

Prior to release, the average force in the six strands monitored by the load cells was 28.70 kips (127.7 kN) or approximately 7 percent less than the specified initial force of 30.98 kips (137.8 kN). The design prestress loss due to steel relaxation for the bridge girders, calculated by AASHTO formulas,[6] was approximately 1 percent.

Bonding between the strand and concrete most likely occurred within the first 6 hours after casting. Therefore, the decrease in strand force from the specified initial value prior to bonding was probably 6 percent at most. Nonetheless, based on our measured data, it is apparent that the reductions in strand force caused by the combined effects of steel relaxation and thermal expansion can be somewhat greater than expected.

MEASURED CONCRETE TEMPERATURES

Plots of concrete temperature versus time at various elevations along the midspan centerline of Girder 3A are shown in Fig. 5. The average concrete

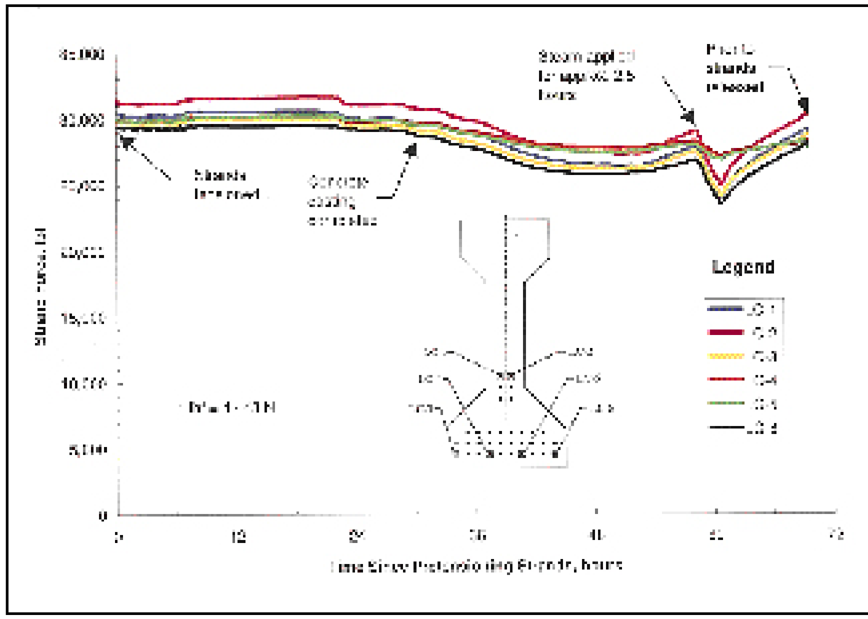

Fig. 4. Plot of strand force versus time.

temperature at the time of placement was approximately 85°F (29°C). Concrete temperatures gradually increased during the first 24 hours and then began to decrease.

Twenty-four hours after casting, the required release strength had not yet been achieved and the concrete temperature began to decrease. Approximately $30^{1}/_{2}$ hours after casting, steam curing was applied for a period of about $2^{1}/_{2}$ hours to prevent the concrete temperature from dropping 20°F (11°C) from the maximum value of 134°F (57°C) before achieving the required release strength.

The brief interval of steam curing proved sufficient to increase the concrete strength up to the required release strength. During the steam curing period, the maximum concrete temperature measured in the instrumented girders increased to 150°F (66°C). This maximum concrete temperature was still well below the 160°F (71°C) limit stipulated in the project specifications.

As shown in Fig. 5, concrete temperatures in the center of the top flange, web, and bottom flange at

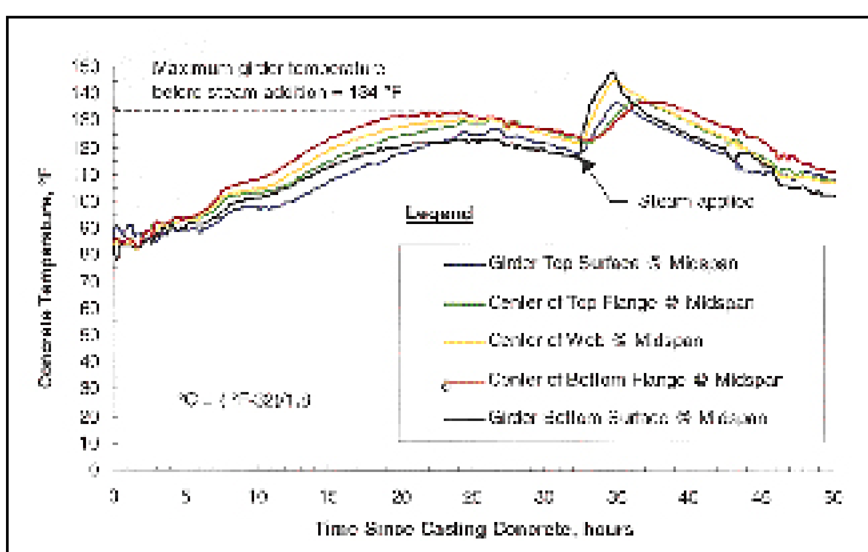

Fig. 5. Concrete temperature versus time at elevations along midspan centerline of Girder 3A.

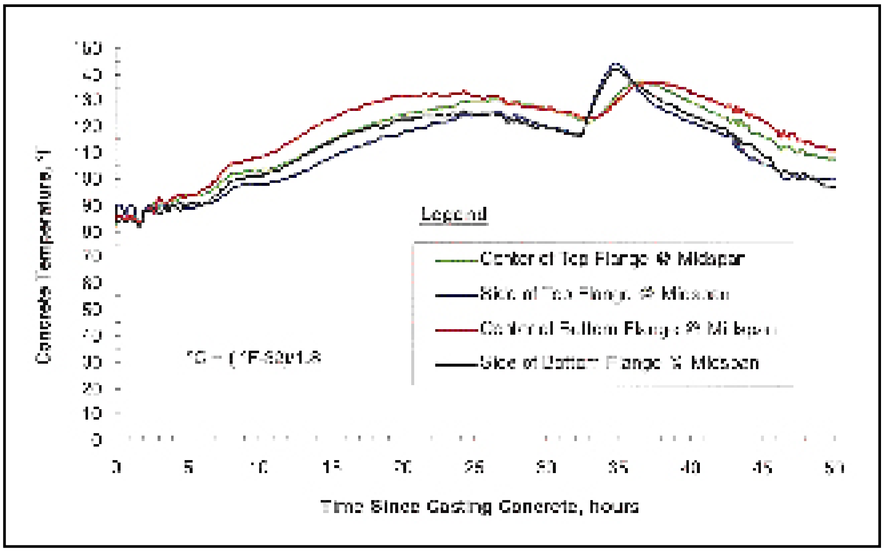

Fig. 6. Concrete temperature versus time for top and bottom flange at midspan of Girder 3A.

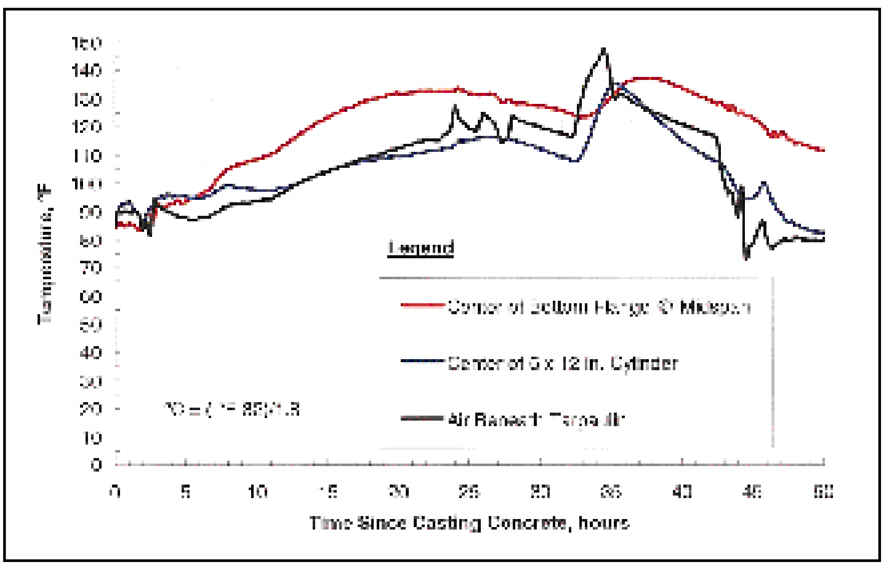

Fig. 7. Measured temperature versus time at various locations for Girder 3A.

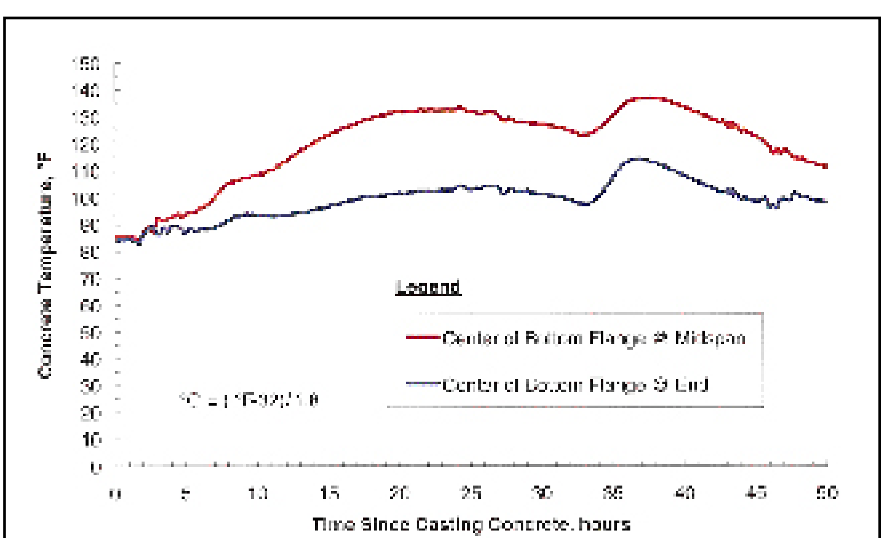

Fig. 8. Concrete temperature versus time for bottom flange of Girder 3A.

midspan of Girder 3A were comparable throughout the curing period. Similar observations were made for the three other girders (Girders 3B, 3C, and 3D) instrumented with thermocouples at midspan. Prior to applying the steam, measured concrete temperatures near the top and bottom surfaces of the girder were somewhat less than those measured in the center of the two flanges and web.

Plots of concrete temperature versus time for the top and bottom flange at midspan of Girder 3A are shown in Fig. 6. As indicated by the data in this figure, peak concrete temperatures near the side surfaces of the top flange and bottom flange were 7 to 12°F (4 to 7°C) less than those measured in the center prior to introducing steam curing. Temperature variations between center and exterior were caused by heat loss through the insulated tarpaulins used to cover the girders, and the steel forms conducting heat out of the concrete.

Match-cured cylinders were used to determine concrete compressive strength at various ages for the instrumented girders. The curing temperature for these cylinders matched the concrete temperature in the center of the bottom flange at midspan of the girder they represented. For the purpose of comparison, conventional field-cured cylinders instrumented with thermocouples were also fabricated during concrete placement. The concrete used to make both the match- and field-cured cylinders came from the batch placed in the midspan region of each girder.

Plots of measured temperature versus time for the concrete in the center of the bottom flange of Girder 3A at midspan and concrete placed in a 6 x 12 in. (152 x 305 mm) cylinder cured alongside the girder are shown in Fig. 7. Measured data from a thermocouple used to monitor air temperature beneath the insulated tarpaulin cover are also included in Fig. 7.

The measured air temperature data were consistent with the cylinder temperature data, as expected. However, measured concrete temperatures in the girder bottom flange were substantially greater than the cylinder temperatures. There was a maximum temperature differential of 22°F (12°C) between the bottom flange concrete at midspan of Girder 3A and the field-cured 6 x 12 in. (152 x 305 mm) cylinder prior to steam curing.

The maximum temperature differential prior to steam curing between the bottom flange and field-cured cylinders for the other three girders instrumented with thermocouples ranged from 21°F (12°C) in Girder 3D to nearly 30°F (17°C) in Girders 3B and 3C. Based on these data, it is apparent that the common practice where cylinders are stored under the tarpaulins used to cover the girders may result in curing conditions that are somewhat different from those occurring at various locations within the girders.

Plots of measured temperature versus time for the concrete in the center of the bottom flange at midspan and concrete in the center of the bottom flange near one end of Girder 3A are shown in Fig. 8. Measured concrete temperatures in the bottom flange at midspan were substantially greater than those measured near the girder end. There was a maximum temperature differential of approximately 30°F (17°C) between the bottom flange concrete at midspan and near the girder end prior to steam application.

Based on the data presented in Fig. 8, it is evident that there was a considerable amount of heat loss at the girder end. This temperature difference was partially due to the prestressing strands conducting heat out of the concrete at the end of the girder. Also, since the thermocouples located near the end of Girder 3A were at the end of the casting bed, the insulation provided by the tarpaulin cover at this location may have been somewhat less effective in preventing heat to escape.

Table 2. Measured concrete material properties.

Concrete property	Curing method	Girder	Concrete age				
			Release	7 days	28 days	56 days	90 days
Compressive strength, psi	Match	A	9,110	8,910	10,620	11,350	12,040
		B	8,210	9,850	10,520	11,400	12,420
		C	8,510	9,100	11,160	12,180	11,570
		D	7,630	9,140	9,960	—	11,760
		Avg.	8,360	9,250	10,570	11,640	11,950
	Field	A	6,470	8,360	9,080	9,580	10,220
		B	6,840	8,590	10,490	10,600	11,600
		C	7,790	8,000	9,670	10,280	10,520
		D	7,000	8,140	9,210	9,930	10,320
		Avg.	7,020	8,270	9,610	10,100	10,670
Modulus of elasticity, ksi	Match	A	5,800	6,050	5,750	6,000	6,000
		B	5,750	5,550	5,600	5,750	5,750
		C	5,650	6,050	6,200	6,200	6,150
		D	5,400	6,000	5,600	—	6,150
		Avg.	5,650	5,900	5,800	6,000	6,000
	Field	A	5,000	5,850	6,050	6,050	6,300
		B	5,450	5,500	5,750	5,900	6,250
		C	5,450	6,000	5,950	5,850	5,800
		D	5,400	6,400	5,800	6,100	5,600
		Avg.	5,350	5,950	5,900	6,000	6,000

Note: 1 psi = 6.895 kPa; 1 ksi = 6.895 MPa.

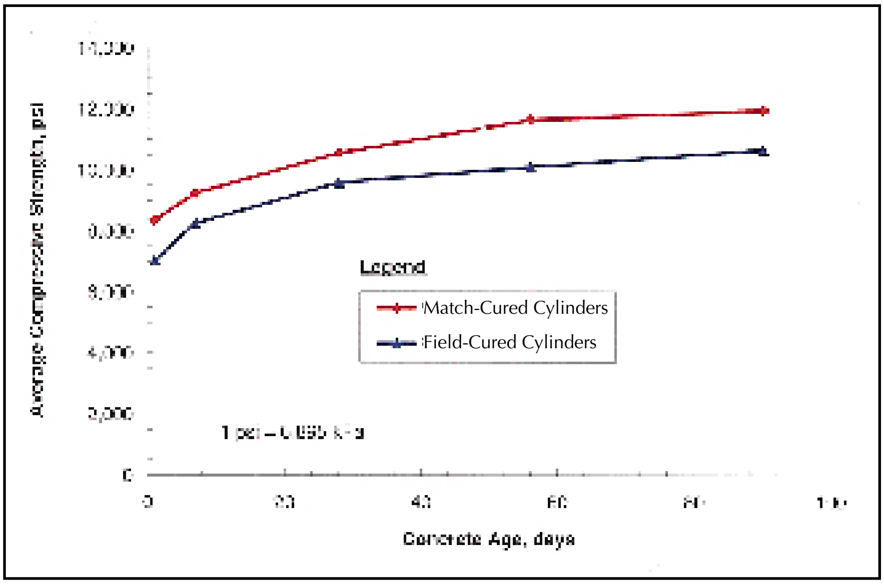

Fig. 9. Concrete compressive strength versus time for match- and field-cured cylinders.

MEASURED CONCRETE PROPERTIES

Compressive strength and modulus of elasticity tests were conducted on cylinders representing concrete used in the midspan region of each instrumented girder. The cylinder tests were conducted by Federal Highway Administration (FHWA) personnel in their mobile testing laboratory. Both 6 x 12 in. (152 x 305 mm) field-cured and 4 x 8 in. (102 x 203 mm) match-cured cylinders were tested.

Results from cylinder tests are reported in Table 2. Each value reported in Table 2 represents the result from one cylinder for each instrumented girder. A plot of average compressive strength versus concrete age for the field- and match-cured cylinders is shown in Fig. 9.

As indicated by the data in Table 2 and Fig. 9, compressive strengths of the match-cured cylinders were consistently greater than the field-cured cylinders. At a concrete age of 28 days, the difference between match-cured and field-cured cylinder compressive strength was approximately 1000 psi (6.9 MPa). The average compressive strength of the match-cured cylinders remained approximately 10 percent greater than the strength of the field-cured cylinders at concrete ages of 56 and 90 days.

The project specifications for the

Charenton Canal Bridge project required the use of 4 x 8-in. match-cured cylinders for compressive strength determination. To date, there has been no clear consensus among researchers on the correlation of compressive strength results for 4 x 8 in. (102 x 203 mm) and 6 x 12 in. (152 x 305 mm) test cylinders.[7,8] As a result, the current ASTM and AASHTO standard test methods do not recognize the need for cylinder size effect corrections as long as the length to diameter ratio is 2.

Considering the fact that the field- and match-cured cylinders for each girder were all made from the same batch of concrete, the difference between the measured compressive strengths was most likely the result of variations in the initial curing temperatures. It is concluded that the field-cured cylinders could underestimate the early- and later-age compressive strength of the girder concrete by as much as 10 percent. These results also demonstrate the importance of using match-cured cylinders for measuring the strength properties of high strength HPC.

The average concrete modulus of elasticity at release for the match-cured cylinders was about 6 percent greater than the field-cured value. At concrete ages of 7, 28, 56, and 90 days, the average modulus of elasticity was essentially equal for both match- and field-cured cylinders.

CONCLUSIONS

Based on the results from this study, the following conclusions are made:

1. Since high strength HPC contains higher quantities of cementitious material than conventional concrete, the heat generated during initial curing is usually greater. The heat generated by cement hydration can cause permanent reductions in prestressing strand force levels due to thermal expansion. The extent of force reduction will depend on the average maximum temperature of the concrete surrounding the strands at the time that bonding between the strand and concrete occurs. The combined effects of steel relaxation and thermal expansion could cause permanent strand force reductions that are somewhat greater than expected.

2. Initial curing temperatures in high strength HPC members can vary considerably from one location to another, both within the cross section and along the length of the girder. These variations can be due to conduction of heat out of the concrete through adjacent steel elements (such as the formwork and prestressing strand), and heat loss through insulated tarpaulins typically used to cover the casting bed. The heat generated during initial curing can have a significant effect on the development of concrete compressive strength. Therefore, an accurate measurement of concrete compressive strength requires test cylinders to be cured under conditions that are the same as those in the member they represent.

RECOMMENDATIONS

Based on results from this study, the following recommendations can be made:

1. The effects of thermal expansion of pretensioned strands before and after bonding with the concrete should be investigated further to determine whether the higher curing temperatures that typically occur with high strength concrete will consistently result in higher initial prestress loss. In addition, the effects of the potential thermal expansion loss in combination with other sources of initial loss (such as stressing tolerances and strand relaxation) should be examined to determine if these parameters are adequately accounted for in current design specifications.

2. Use of match-cured cylinders should be required for precast, prestressed concrete members with a specified concrete compressive strength exceeding 8000 psi (55 MPa).

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