MONITORING OF A HIGH PERFORMANCE PRESTRESSED CONCRETE BRIDGE WITH EMBEDDED OPTICAL FIBER SENSORS DURING FABRICATION, CONSTRUCTION AND SERVICE.

Rola L. Idriss Ph.D., P.E.
Professor, Civil Engineering Dept.
New Mexico State University
Las Cruces, New Mexico 88003-0001. USA
e-mail: ridriss@nmsu.edu

ABSTRACT
The Rio Puerco Bridge is located 15 miles west of Albuquerque, New Mexico. The bridge has 3 spans with length of 29 to 30 m. It is designed to be simply supported for dead load and continuous for live load. High Performance Concrete (HPC) was used for the cast-in-place concrete deck and the prestressed concrete beams. HPC can offer benefits such as shallower girders for a given span, longer spans for a given girder size or fewer girders for a bridge of a given size.

The prestress force in a prestressed concrete girder under service conditions can be significantly lower than the initial jacking force because of prestress losses due to elastic shortening, shrinkage, creep and relaxation. Accurate prediction of the losses is a very important step in the design of a highly stressed HPC girder. Current methods for calculating prestress losses according to the American Association for Highway and Transportation Officials (AASHTO, 1996), and the Prestressed Concrete Institute (PCI, 1975) were developed for conventional concrete with strength up to 6,000 psi. Actual prestress losses in HPC girders need to be measured and compared to predicted losses using these equations.

To detect the prestress losses, strain was monitored at several locations in the concrete. Long-gage (2m long) deformation sensors, along with thermocouples, were embedded in parallel pairs along the beam length. A total of 40 fiber optic sensors were installed in the bridge, measuring deformations in the flanges at supports, ¼ spans, and mid-span.

Measurements were collected during:
- Beam Fabrication
  - Casting of the beams
  - Steam curing
  - Strand release
- Bridge Construction
- Service

The data collected was analyzed to calculate the prestress losses in the girders, compare the losses to the predicted losses using available code methods, and get a better understanding of the properties and behavior of high performance concrete.

BRIDGE DESCRIPTION
The Rio Puerco Bridge on Route 66 is located 15 miles west of Albuquerque, NM. The bridge is a 3 span, prestressed concrete bridge as seen in Figures 1 & 2. It is designed to be simply supported for dead load and continuous for live load. High Performance Concrete (HPC) is used for the cast-in-place concrete deck and the prestressed concrete beams. Normal strength concrete is used for the substructure portion of the bridge.

Figure 1. View of the Rio Puerco Bridge
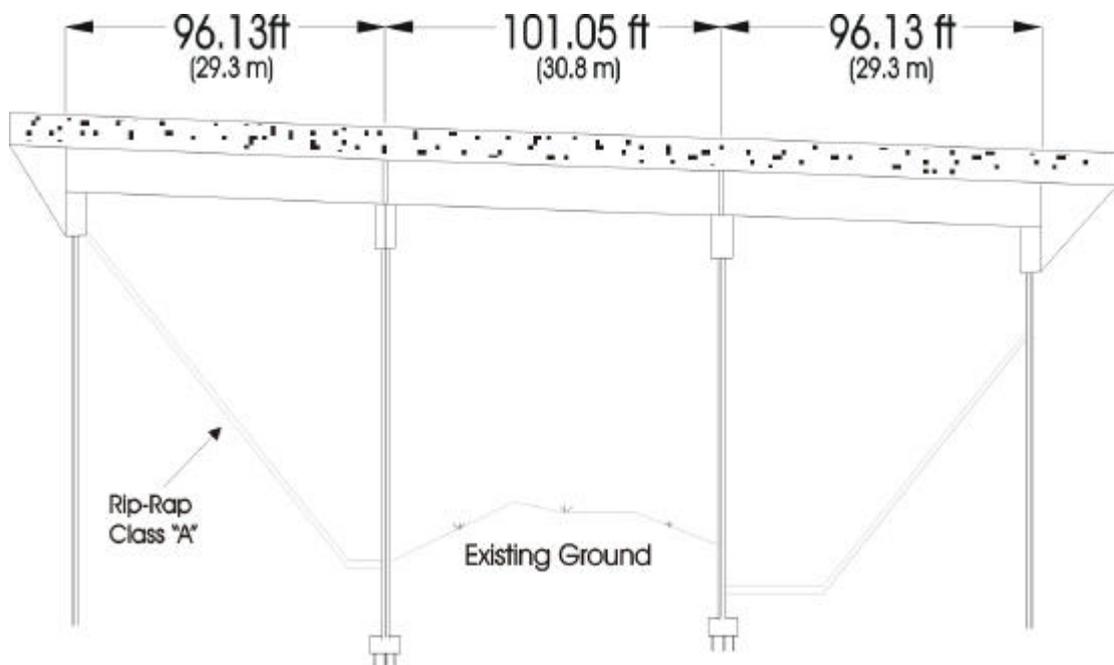
Figure 2. Bridge Profile Along Centerline

The primary members of the bridge consist of four I-beam type BT-1600 high performance concrete beams spaced at 12.63 ft (3.85 m) (Figure 3). The beams are prestressed by 42, Grade 270 steel tendons: 26 straight and 16 draped. The 0.5 in (12.7 mm) diameter tendons are 7-wire, low-relaxation strands and are designed for an initial prestress force of 30.98 kips per strand (137.8

kN/strand), slightly overstressed to 33 kips per strand (146.8 kN/strand) to compensate for anchorage losses. The beam cross-sections can be seen in Figure 4.
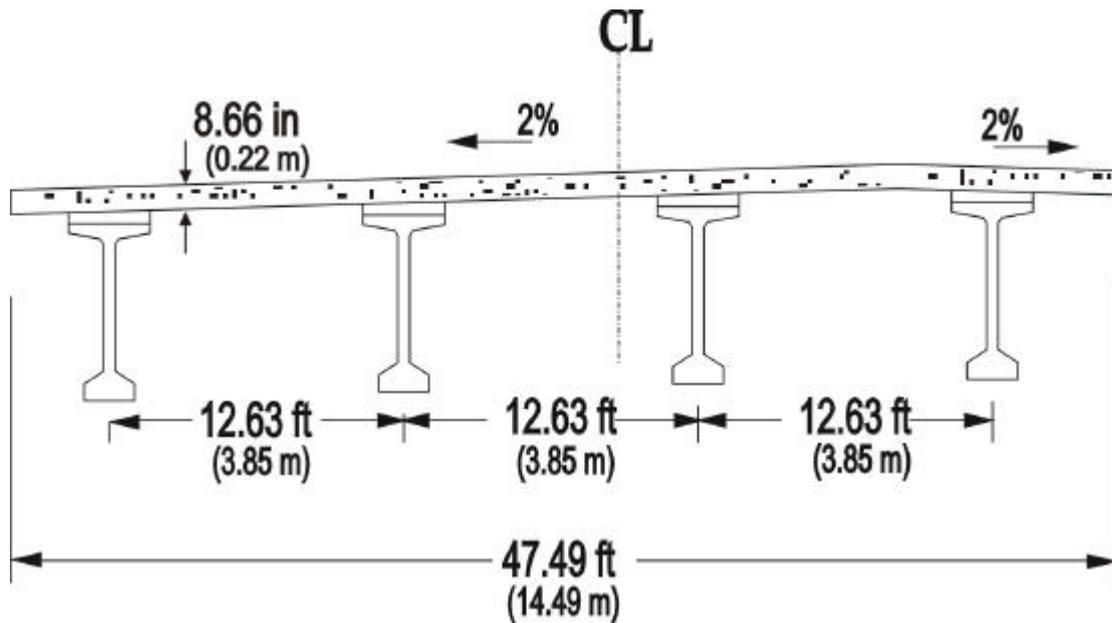

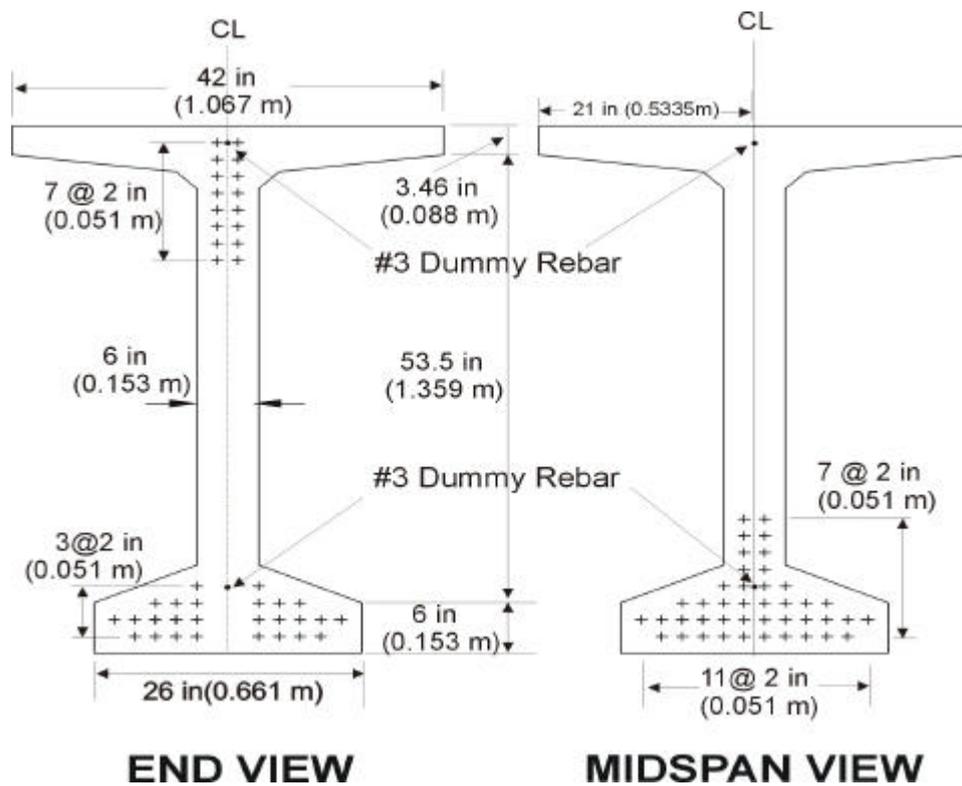**Figure 3. Bridge cross-section**

Figure 4. Cross-sectional view of BT-1600 I-beam

HPC can offer benefits such as shallower girders for a given span, longer spans for a given girder size or fewer girders for a bridge of a given size.

The prestress force in a prestressed concrete girder under service conditions can be significantly lower than the initial jacking force because of prestress losses due to elastic shortening, shrinkage, creep and relaxation. Accurate prediction of the losses is a very important step in the design of a highly stressed HPC girder. Current methods for calculating prestress losses according to the

American Association for Highway and Transportation Officials, and the Prestressed Concrete Institute were developed for conventional concrete with strength up to 6,000 psi. Actual prestress losses in HPC girders need to be measured and compared to predicted losses using these equations. The AASHTO LRFD method (AASHTO, 1996) and the PCI methods (PCI, 1975) need to be revaluated when used with HPC.

The main objective of monitoring the Rio Puerco Bridge is to determine the prestress losses in the tendons over time. The data collected from the time of casting of the girders is being analyzed to calculate the prestress losses in the girders, compare the losses to the predicted losses using available code methods, and get a better understanding of the properties and behavior of high performance concrete. The bridge will be monitored for one year.

MONITORING SYSTEM

Fiberoptic data acquisition system and sensors manufactured by SMARTEC co. were used to monitor the bridge. To measure the prestress losses, strain was monitored at several locations in the concrete. Long-gage (2m long) deformation sensors, were installed in parallel pairs along the beam length, one at the center of the top flange and one at the center of the bottom flange as shown in Figure 5.
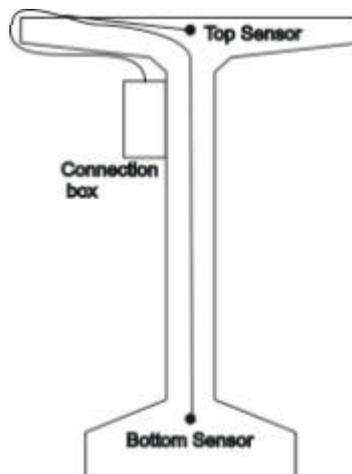
Figure 5. Cross-sectional view of the sensor location

Four beams were monitored in the west and center spans as shown in Figure 6. Five pairs of sensors were installed in each beam, measuring deformations at supports, at ¼ spans, and at mid-span for a total of 40 fiber optic sensors.
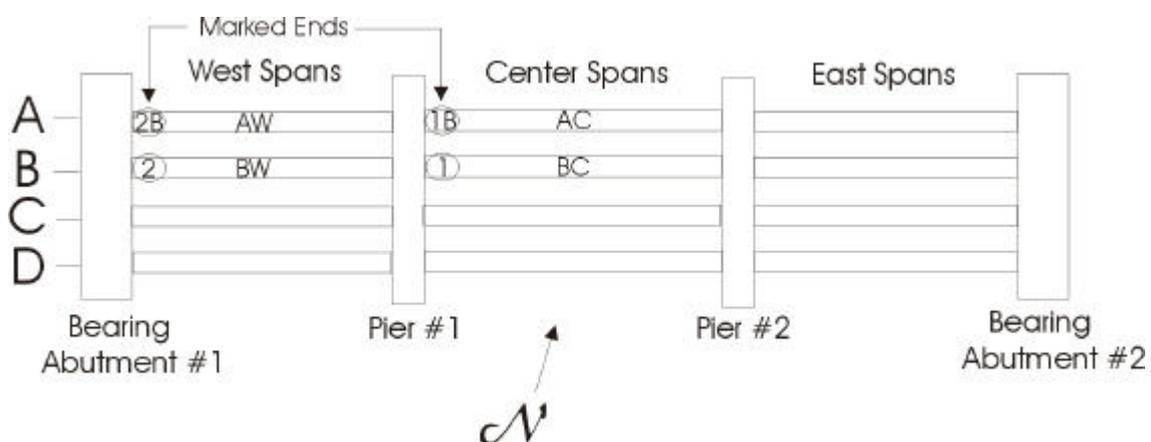
Figure 6.   Plan View of the bridge showing the beams to be monitored

To account for temperature strain, conventional thermocouples were installed at the supports and mid-span of each beam at the same location as the other sensors.

MEASUREMENTS

Measurements from the deformation and temperature sensors are read by a 40 channel reading unit. The reading unit contains an internal 10-channel multiplexer supplemented by an external 30-channel multiplexer. The sensors and data acquisition system were manufactured by Smartec Inc. The system is able to take measurements with a resolution of 2 microns over a 2m measurement.

Measurements were collected during:
- Casting of the beams
- Steam curing
- Strand release
- Storage of the beams, up to transport
- Casting of the slab

Currently, measurements are collected daily. The equipment is programmed to automatically collect data four times a day: at 4:00 am, 10:00 am, 4:00 pm and 10:00 pm. The bridge will be monitored for a full year, and the data collected will be analyzed to evaluate the prestress losses.

THE FIBER OPTIC SENSORS

The fiber optic sensors are manufactured by the Smartec co. The measuring system is based on the principle of low-coherence interferometry. Infrared radiation of light is sent into a single mode fiber and directed towards two fibers through a coupler. The fibers are installed inside the structure to be monitored. The "measurement" fiber is mechanically affixed to the structure and will follow its deformations in both elongation and shortening. The "reference" fiber is installed freely within the same tube. The difference in the length between the measurement fiber and the reference fiber can be measured to give the actual deformation in the structure. Figure 7 illustrates the fibers within a typical fiber optic sensor. When subjected to temperature changes, both fibers expand or contract; therefore, the sensor itself does not need to be temperature compensated.

Figure 7. SOFO Fiber optic sensor

The long gage (2m) SOFO fiber optic sensors were selected because of the following specified properties:
- High resolution: 2μm (2/1000 mm)
- Embeddable or surface mountable
- Insensitive to corrosion and vibrations
- Immune to electromagnetic fields
- No calibration required
- Waterproof
- 2 m length which provides an average strain measurement in the concrete

SENSOR INSTALLATION

The beams were prefabricated at CSR Prestressed in Albuquerque, NM. The installation of the sensors in the four beams took place on July 17-25, 2000. The four beams were fabricated simultaneously on one long fabrication bed. The bed layout is shown in Figure 8. The sensors and thermocouples were attached to dummy rebars in the beams (Figure 9).

Figure 8. Photograph of bed layout
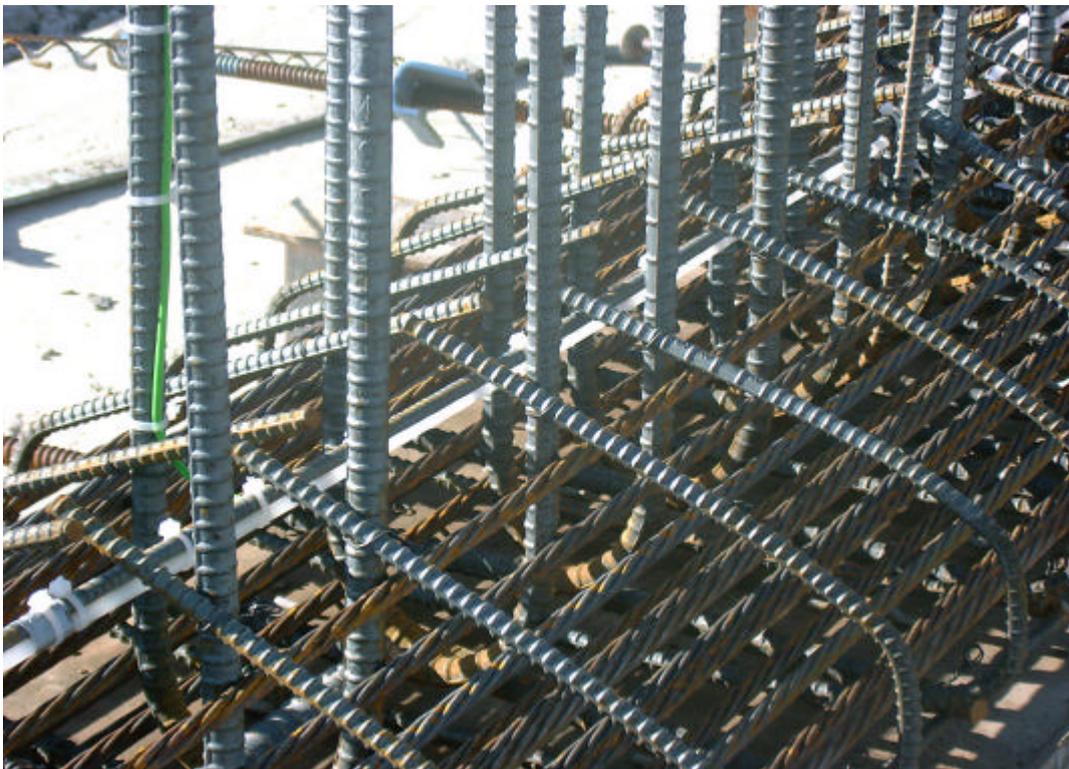
**Figure 9. Close up of sensor in bottom flange**

The connection boxes were then permanently installed on the beam webs (Figure 10).

Figure 10. Connection box installation

SAMPLE DATA

The values read from the data acquisition system were transferred into an Excel program where the data could be processed and graphed. Figure 11 is a plot of deformation versus time for the deformation sensor in beams AC. Figure 12 is a plot of temperature versus time for the thermocouples in beams AC.
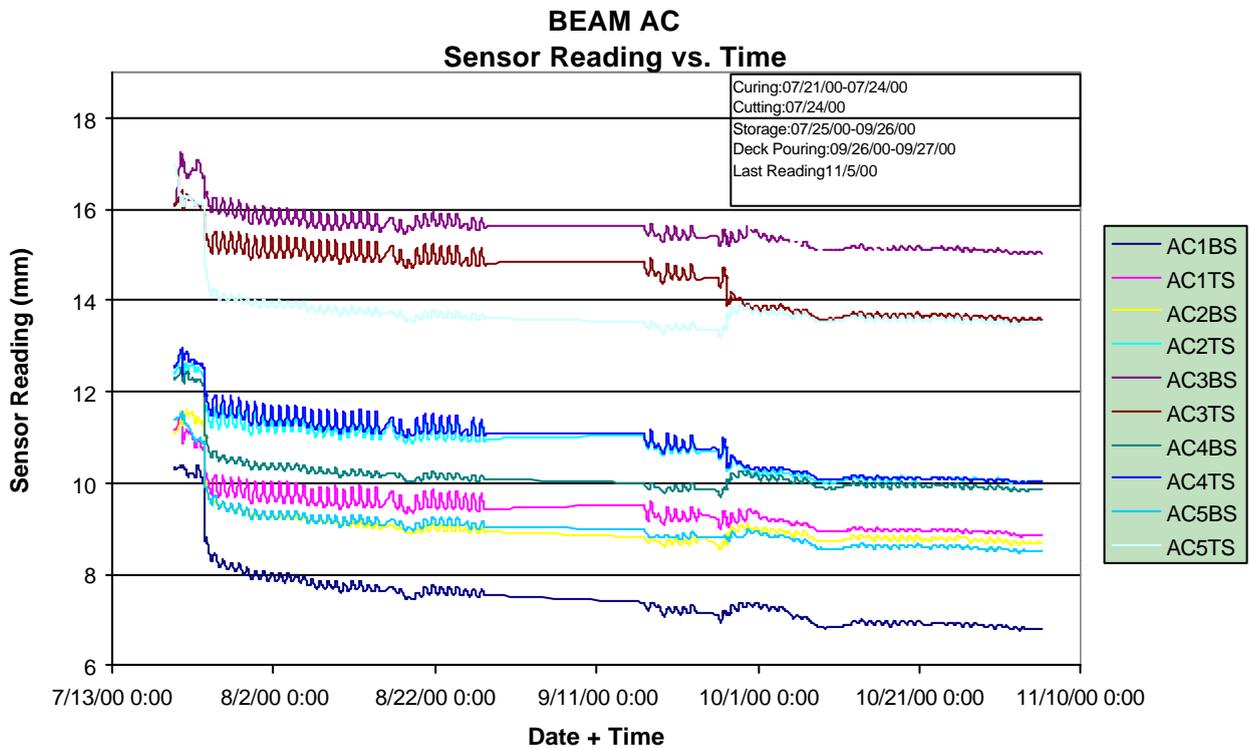
Figure 11. Sensor reading vs. time for beam AC

BEAM AC
Temp. Reading vs. Time
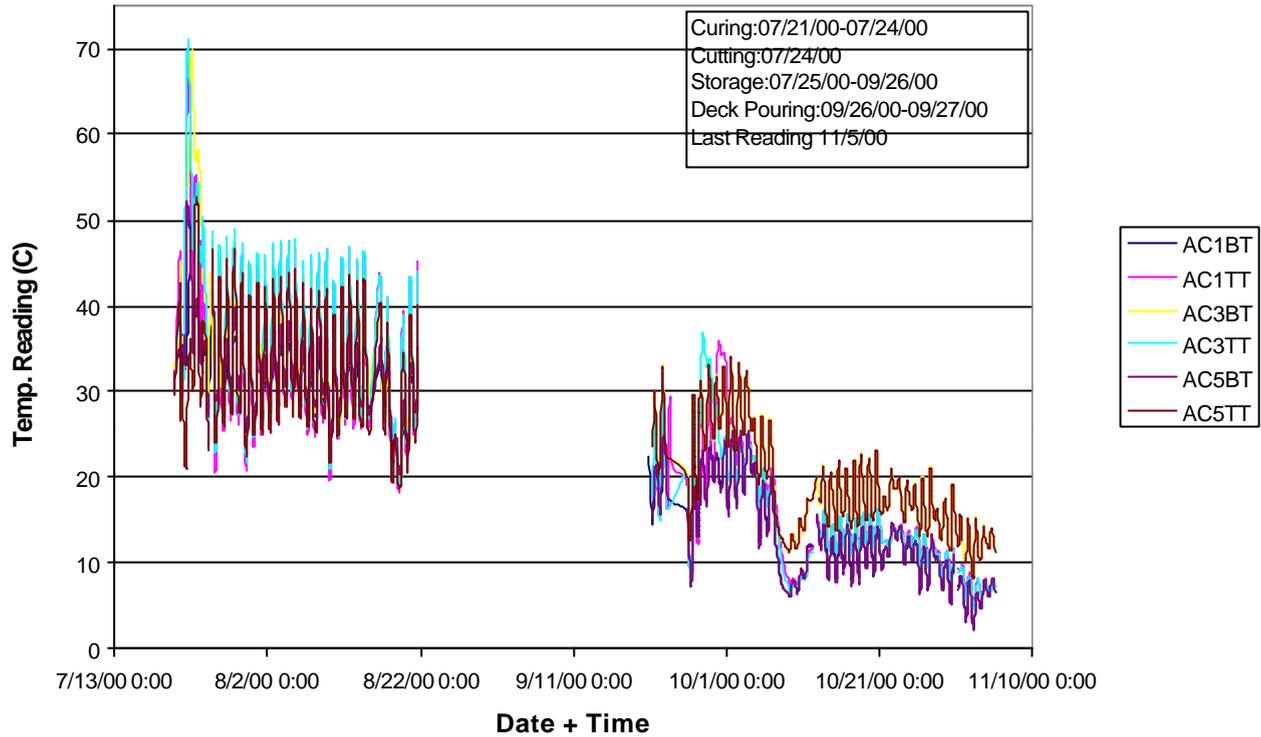
Figure 12. Temperature reading vs. time for beam AC

MATERIAL PROPERTIES

Concrete Strength
Cylinders were taken during the pouring of the girders and tested in the lab. Table 1 gives the compressive strength at 3 days, 28 days, and 56 days.

Table 1. Compressive strength data

	Compressive strength
Date of pour – 7/21	Psi (MPa)
3 days – 7/24	7325 (50.5)
28 days – 8/18	9076 (62.6)
56 days – 9/15	10151 (70.0)

Coefficient of Thermal Expansion
To account for thermal strain, thermocouples were installed to measure the changes in temperature over time. The change in length due to a change in temperature can be found by the following equation:

$$\Delta L = \alpha L(T - T_0) \qquad (1)$$

where   L = original length
        $T - T_0$ = Temperature change
        α = Coefficient of thermal expansion

To determine the coefficient of thermal expansion, the change in temperature versus the strain in the concrete are measured and plotted at 7 days and at 31 days (Figures 13 & 14). In each graph a trend-line is fitted to the data. The slope of the lines is the coefficient of thermal expansion.
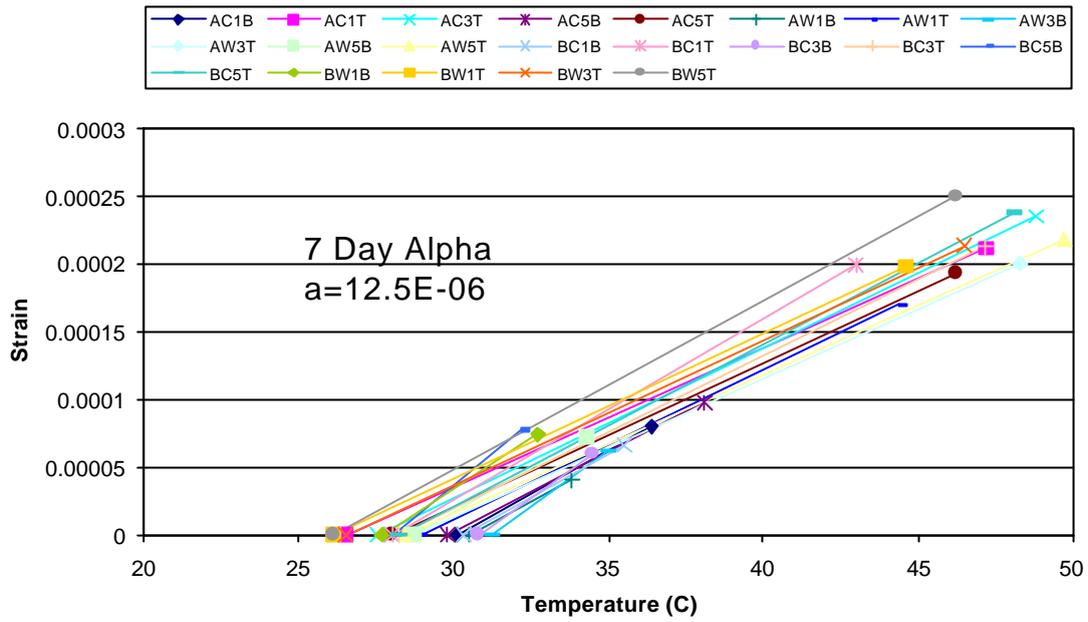
7 Day Alpha

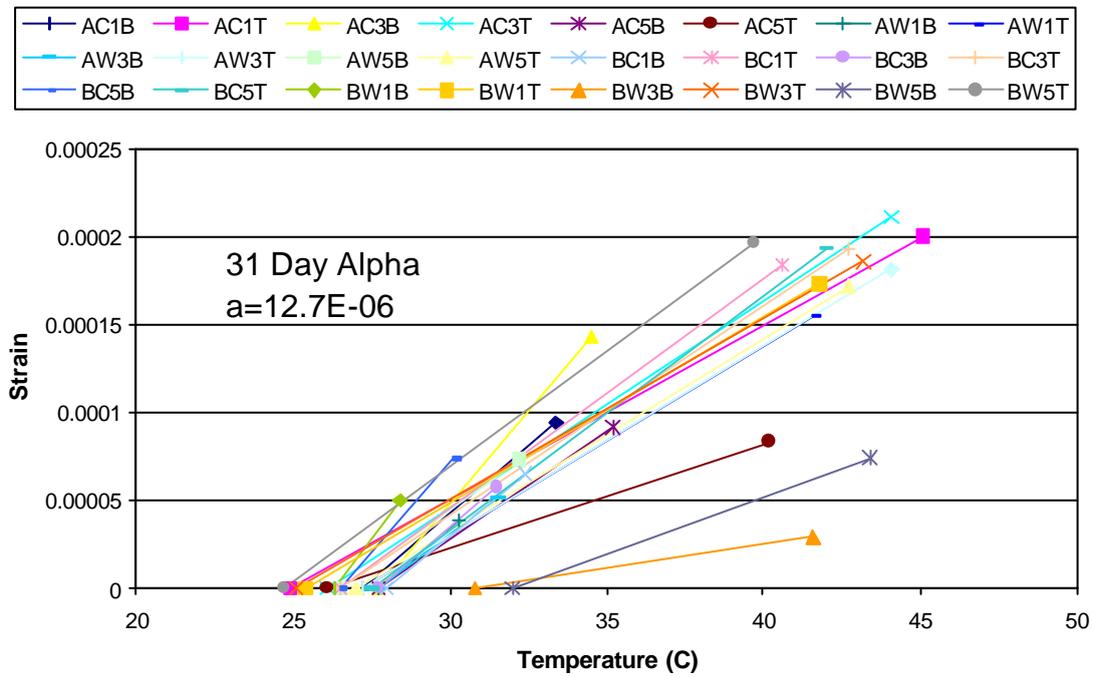**Figure 13. Average coefficient of thermal expansion at 7 days**

31 Day Alpha

Figure 14. Average coefficient of thermal expansion at 31 days

Table 2. Average Coefficient of Thermal Expansion

Time	Average a
days	microstrain/°C
7	12.5
31	12.7
Average	12.6

Modulus of Elasticity

The modulus of elasticity (E) of concrete varies with strength, concrete age, loading type, and the characteristics of the cement and aggregates. E can be determined by the following relationship:

$$E = \sigma/\varepsilon \qquad (2)$$

where σ = stress in the concrete
ε = strain in the concrete

E is calculated at two times: at 3 days when the prestressing force is transferred from the steel tendons to the concrete, and at 60 days when the deck is poured. At transfer, the only stress in the concrete is that caused by the prestressed tendons, and can be determined by the following equation:

$$\sigma = -P/A \pm Mc/I \qquad (3)$$

where P = Jacking force
A = Transformed cross-sectional area
M = Moment caused by prestress = P * e
e = Distance from steel centroid to transformed section centroid
c = Distance from the transformed section centroid to the location of the sensor (varies per sensor)
I = Moment of inertia of the transformed section

The strains are calculated for the bottom sensors at midspan of each beam and compensated for temperature using the following equation:

$$\varepsilon_{non\text{-}thermal} = \varepsilon_{raw} - \alpha_{concrete}\,\Delta T \qquad (4)$$

where ε_{raw} = raw strain
$\alpha_{concrete}$ = coefficient determined as 12.6×10^{-6} microstrain/°C
ΔT = change in temperature measured form by thermocouples

The modulus of elasticity at 60 days is calculated using the stresses and strains that occur in the concrete when the deck is poured. When the deck is poured, the change in stress is caused by the addition of the weight of the slab:

$$\sigma = M_{slab}\, c\, / \,I \qquad (5)$$

where M_{slab} = Moment at midspan due to weight of the slab
c = Distance from the transformed section centroid to the location of the sensor
I = Moment of inertia of the transformed section

The change in strain in the concrete is determined from the change in the sensor measurements when the slab was poured. The strains are calculated and compensated for temperature.

Section 8.5 of the ACI Code (ACI, 1998) states that the modulus of elasticity for normal weight concrete can be taken as:

$$E = 57{,}000\,(f'c)^{1/2}\ psi \qquad (6)$$

This equation has been modified for high-strength concrete (Mehta & Monteiro, 1993) and is given as:

$$E = 40{,}000\,(f'c)^{1/2} + (1\times10^{6})\ psi \qquad (7)$$

As seen in Table 3, the ACI code equation (Eq.6) gives a good estimate of the modulus of elasticity for HPC.

**Table 3. Modulus of Elasticity: Empirically determined
compared to calculations from field data**

Modulus of Elasticity	Expected in design	Calculated from field data	Empirically determined (Eq.6)	Empirically determined (Eq.7)
	ksi (MPa)	ksi (MPa)	ksi (Mpa)	ksi (MPa)
3 days	5076 (35,000)	4890 (34,159)	4878 (33636)	4423 (30,499)
60 days	6092 (42000)	5692 (39,247)	5742(39594)	5030 (34,683)

PRESTRESS LOSSES

Current methods used to estimate prestress losses are the PCI (Prestressed Concrete Institute) General Method (PCI, 1975), the ACI-ASCE (American Concrete Institute – American Society for Civil Engineers) Method (ACI, 1994), the LRFD (Load and Resistance Factor Design) Method (AASHTO, 1996), and the LRFD Lump Sum Method (AASHTO, 1996). The PCI Method is a time-step method, and therefore permits calculation of prestress losses at specific time intervals. Using the PCI General Method, the incremental prestress losses can be calculated and compared to the stresses measured by the sensors during that same time interval. The ACI-ASCE, LRFD, and the LRFD Lump Sum methods only give an estimate of the total prestress losses.

None of these methods are developed specifically for High Performance Concrete. Prestress losses measured in the field will be compared to losses predicted by these methods. This will give an insight into how well these methods can estimate prestress losses for High Performance Concrete.

The actual material properties determined in the field were used to calculate the prestress losses.

PCI method vs. field measurements

The PCI General method was used to calculate the early prestress losses that occurred at:
- Transfer
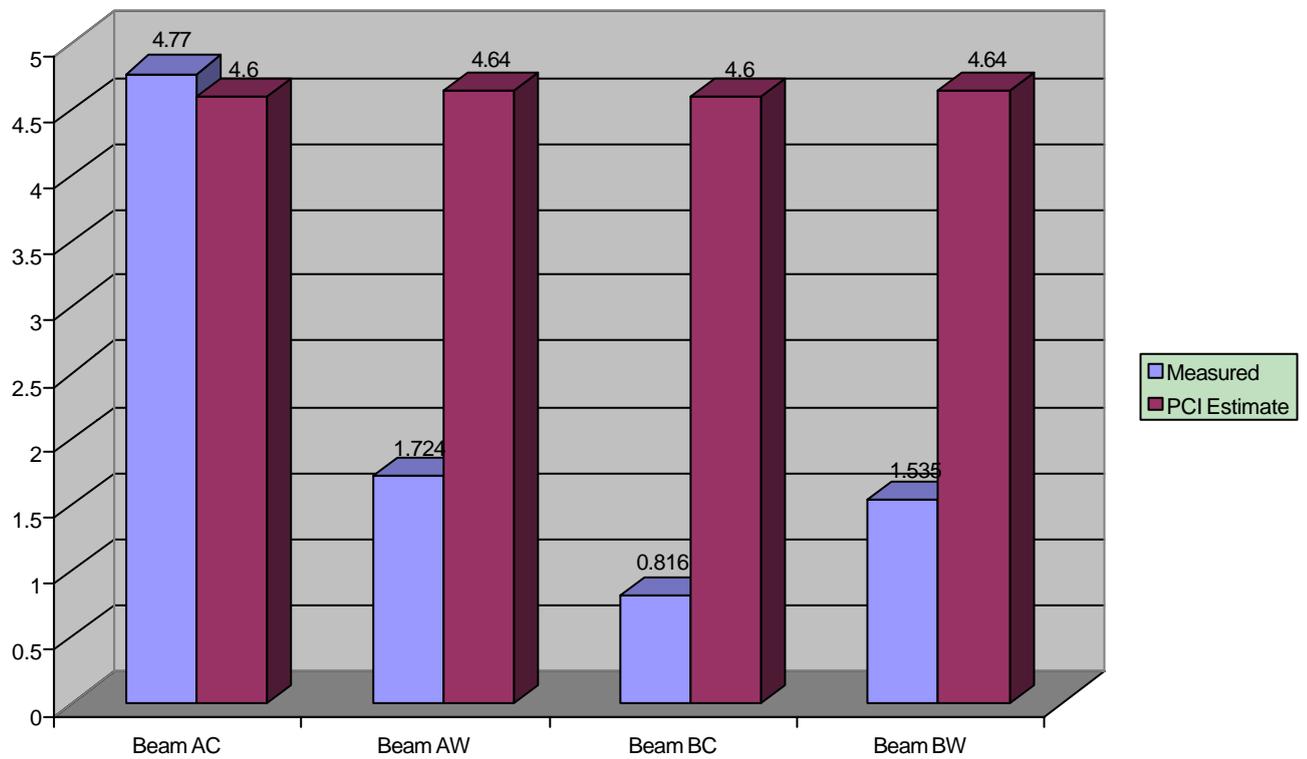- One day after transfer
- One month after transfer

It was also used to calculate the cumulative losses up to 5 months. The bridge will be monitored up to a year.

- The PCI method over predicted the prestress loss in the steel at transfer. Predicted losses at transfer were 8% larger than the measured losses (Figure 15)

- The PCI method over predicted the prestress loss in the steel one day after transfer. The predicted loss was twice as measured (Figure 16).

- The PCI method over predicted the prestress loss during storage. The predicted losses were 3.5 times the measured ones. The PCI method predicted large losses from creep during that first month. The high performance concrete showed much less creep than factored in the PCI equation (Figure 17).

- The PCI method also over-predicted the measured losses one month after the slab placement. Predicted losses were 34% greater than the measured losses (Figure 18).
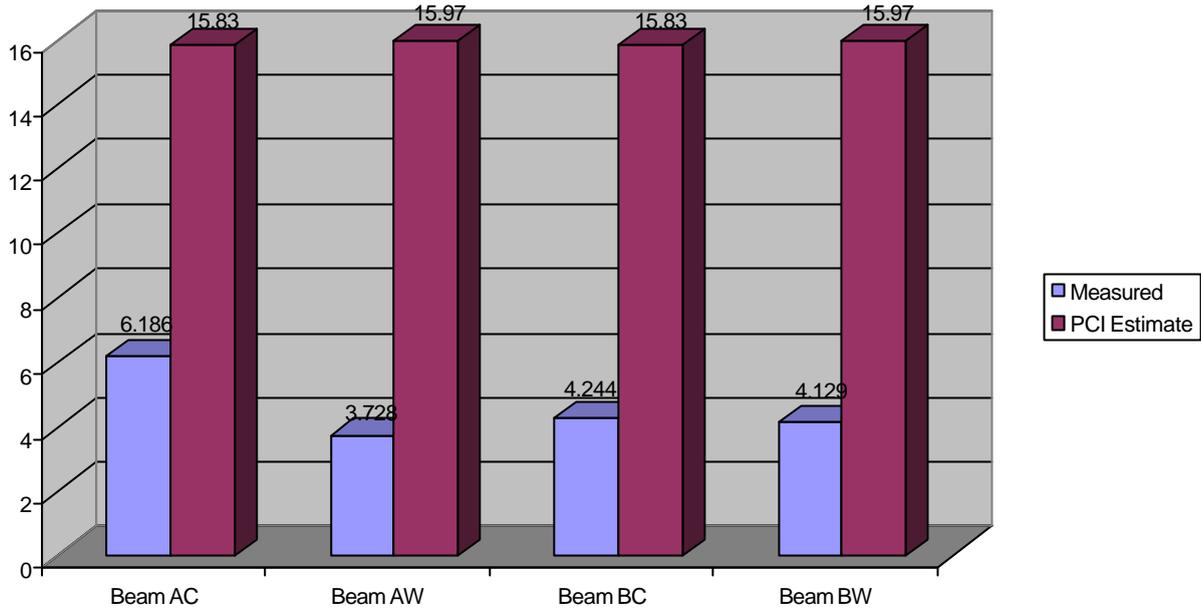
In summary, the PCI General method over predicted the prestress losses at every stage (Figure 19).
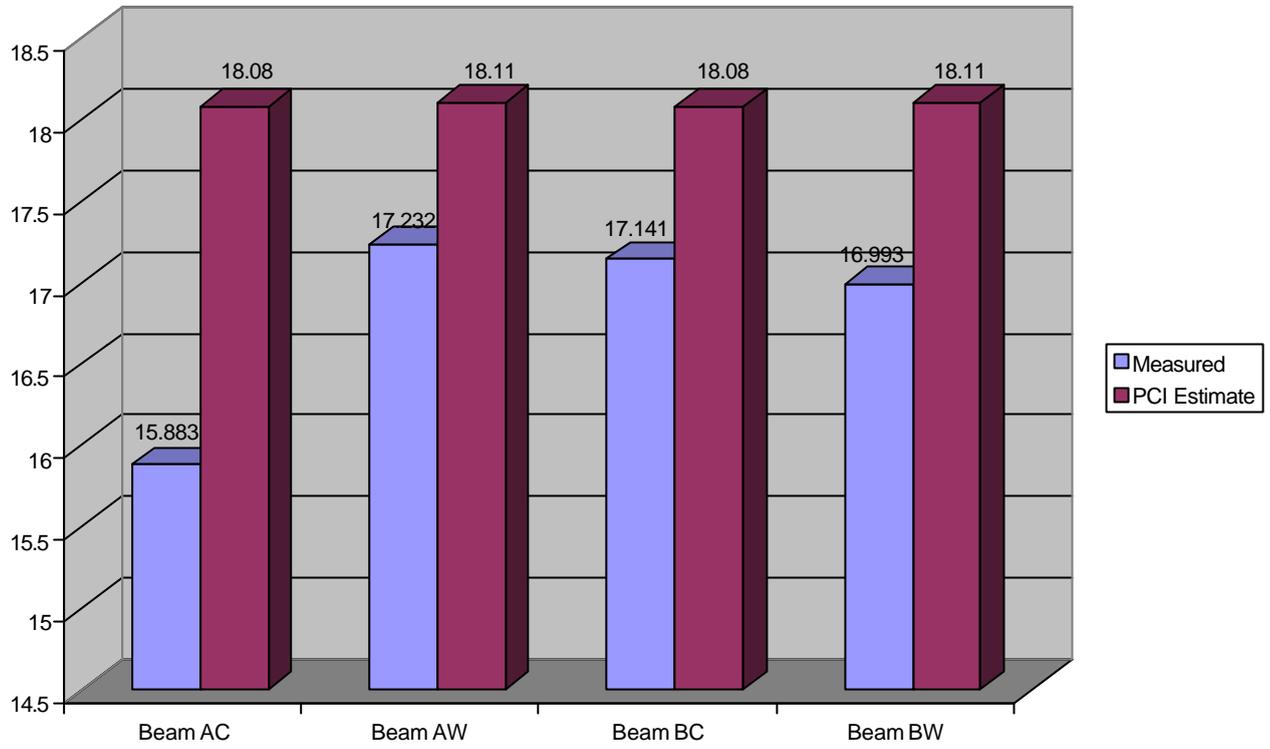
Figure 15. Prestress losses at transfer (ksi)
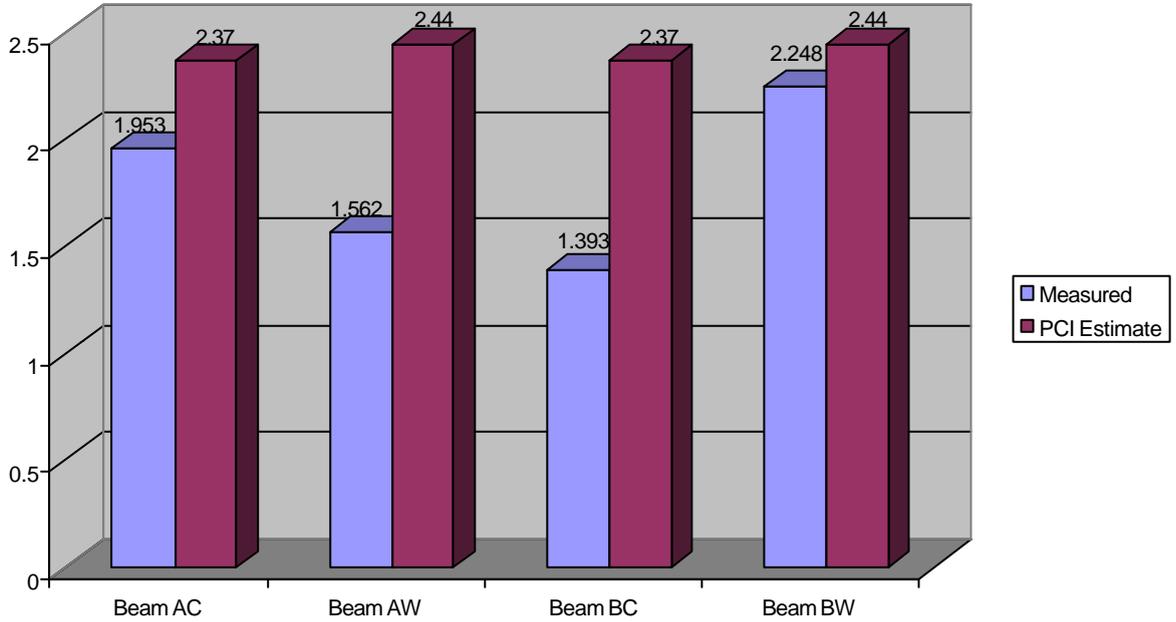

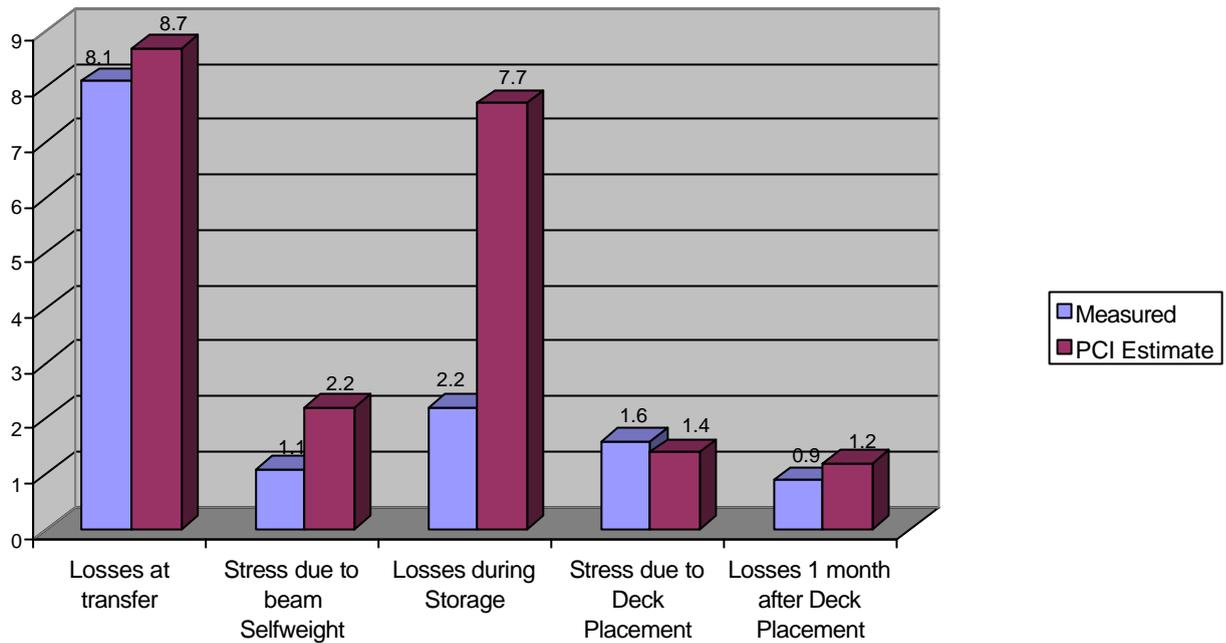**Figure 16. Prestress losses 1 day after transfer (ksi)**

Figure 17. Prestress losses during storage (ksi)

Prestress Losses One Month after the Slab Placement

Figure 18. Prestress losses during the 1 month period after the placement of the slab (ksi)
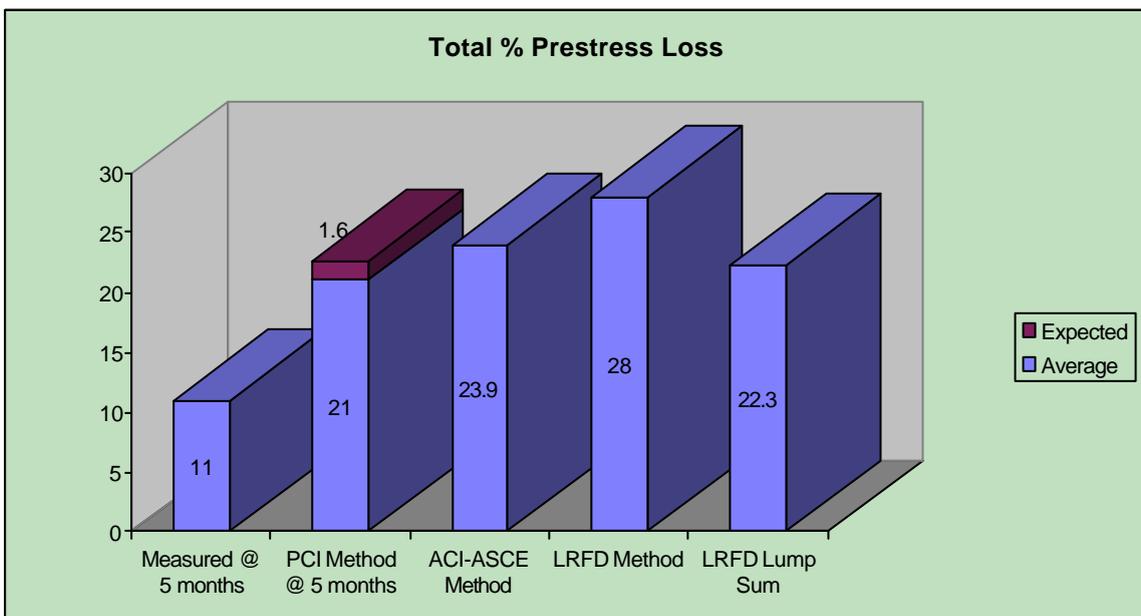
% Prestress Loss
Field Measurement vs. PCI Estimates

Figure 19. Field measurements vs. the PCI Method

COMPARING TOTAL LOSSES

In Figure 20, the measured prestress losses (up to 5 months from beam casting) are compared to the total losses estimated by each method. The losses are expected to taper off over the next few months. The predictions of the four methods are relatively similar. The PCI method is a complex, time-stepped method for predicting the prestress losses. On the other hand, the LRFD Lump Sum method is very simple to use, requiring no calculations. The LRFD Lump Sum predicted an average loss close to that of the PCI method. The LRFD method predicted the most losses, and the ACI-ASCE method predicted losses somewhere in the middle. The LRFD Lump Sum method offered a quick estimate that was quite close to the refined PCI General method estimate. Overall, all methods are found to be very conservative.

Figure 20. Measured losses vs. losses estimated by various methods.

RESEARCH RECOMMENDATIONS

The current empirical methods used to estimate the prestress losses were not developed for HPC. The results of this research project show these methods over predict the losses for HPC. There is a need to modify these methods or develop new methods to better predict prestress losses for HPC. Future research should include variations of mix designs, the curing process, and the age at loading.

REFERENCES

1.)   ACI Committee 304 1998, "Building Codes for Structural Concrete (318-95) and Commentary (318R-95)", American Concrete Institute, Farmington Hills, MI

2.)   American Association of State Highway and Transportation Officials, 1996 "AASHTO LRFD Bridge Design Specifications", 2nd Edition, Washington, D.C.

3.)   Mehta, Kumar P. and Monteiro, Paul J. M. 1993, Concrete: Structure, Properties, and Materials, 2nd Edition, Prentice Hall Inc., Englewood Cliffs, NJ

4.)   PCI Committee on Prestress Losses 1975, "Recommendation for Estimating Prestress Losses", PCI Journal, Vol. 20, No. 4, July-August 1975, pp. 44-75