Title: **MONITORING OF A SMART BRIDGE WITH EMBEDDED SENSORS DURING MANUFACTURING, CONSTRUCTION AND SERVICE.**

Author: **Rola L. Idriss**

ABSTRACT

An optical fiber monitoring system was designed and built into a 3 span high performance prestressed concrete (HPC) highway bridge in Albuquerque, NM.

A total of 40 long-gage (2m long) deformation sensors, along with thermocouples were installed in parallel pairs in the top and bottom flanges of the girders. The embedded sensors measured temperature and deformations at the supports, at quarter spans and at mid-span. The sensors were embedded in the bridge beams during fabrication at the prestressing plant. The embedded sensors collected data during all phases of the project:

- Beam fabrication: Casting and steam curing of the concrete
- Bridge construction
- Service

The data collected was analyzed to determine the prestress losses in the tendons over time, and get a better understanding of the properties and behavior of HPC.

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BRIDGE DESCRIPTION

The Rio Puerco Bridge is located 15 miles west of Albuquerque, NM. The bridge is a 3 span, prestressed concrete bridge as seen in Figure 1. High Performance Concrete (HPC) is used for the cast-in-place concrete deck and the prestressed concrete beams.

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

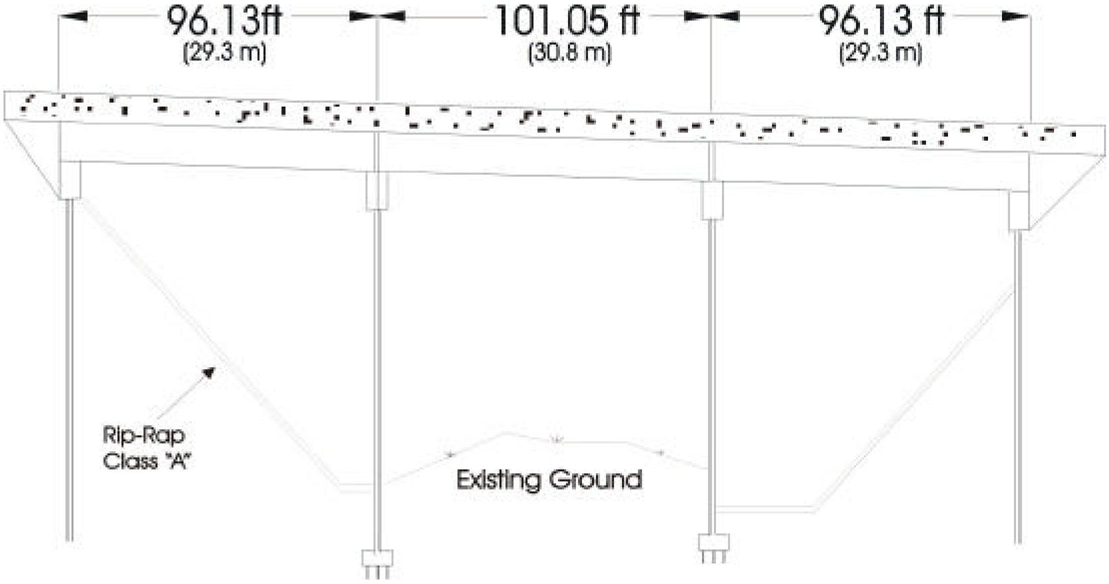

Figure 1. Bridge Profile Along Centerline

The primary members of the bridge consist of four I-beam type BT-1600 high performance concrete beams (Figure 2).

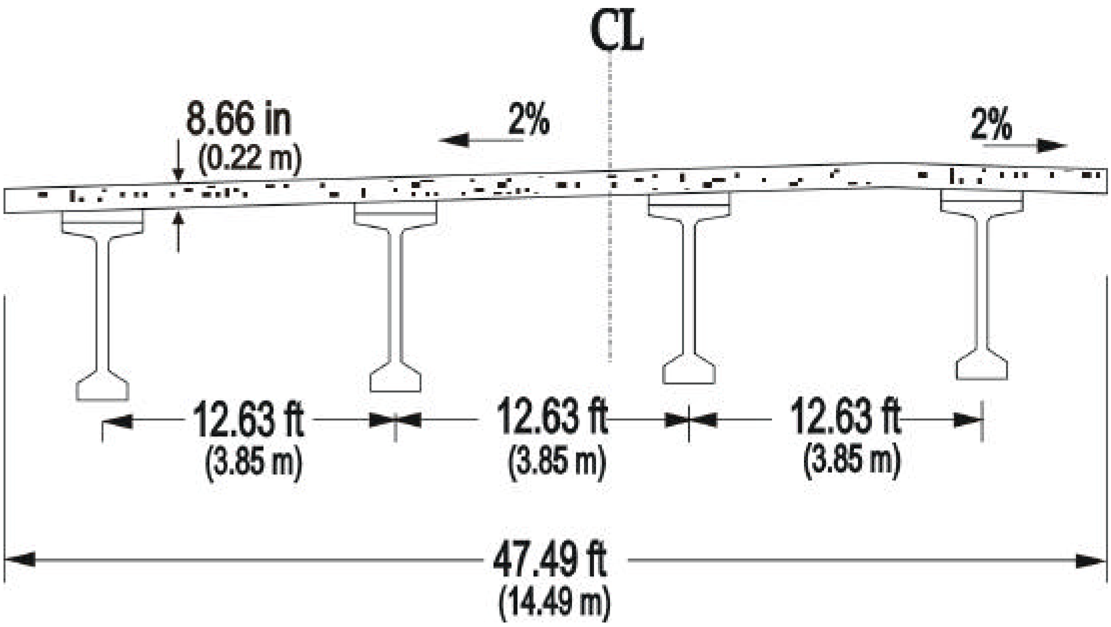

Figure 2. Bridge cross-section

The main objective of monitoring the Rio Puerco Bridge is to determine the prestress losses in the tendons over time, and get a better understanding of the properties and behavior of high performance concrete.

MONITORING SYSTEM

A fiberoptic data acquisition system and sensors manufactured by the SMARTEC co. were used to monitor the bridge. Four beams were monitored in the west and center spans as shown in Figure 3. 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.

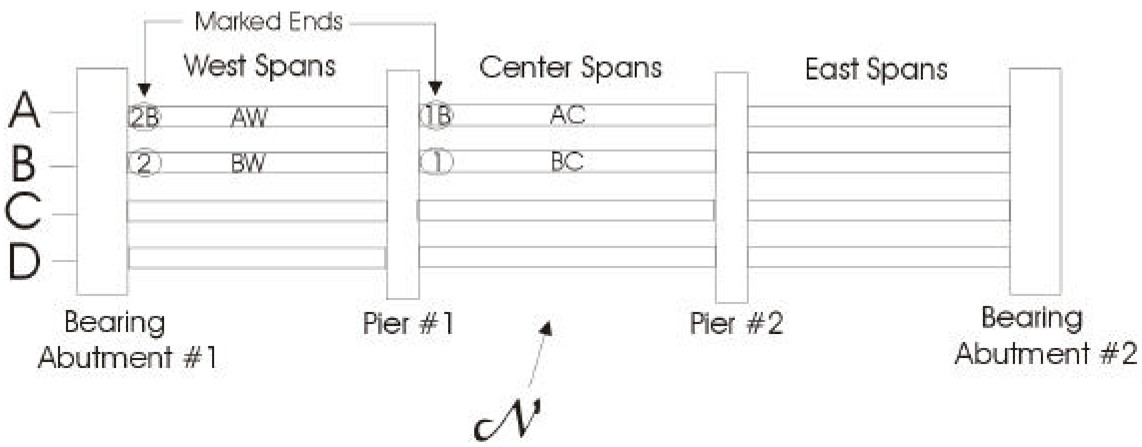

Figure 3. Plan View of the bridge showing the beams to be monitored

The sensors were installed in parallel pairs along the beam length, in the top and bottom flanges as shown in Figure 4.

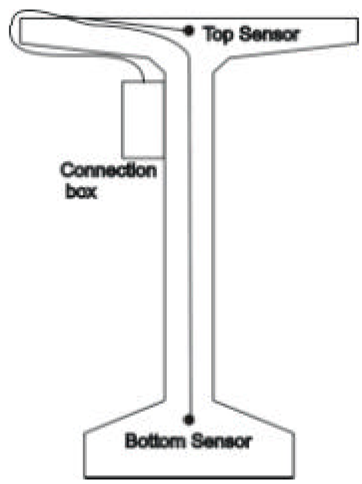

Figure 4. Cross-sectional view of the sensor location

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

Long-gage (2m) SOFO deformation sensors and a 40 channel reading unit manufactured by Smartec co. are used to acquire the data. 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 year.

THE FIBER OPTIC SENSORS

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 5 shows a sensor in a beam bottom flange.

Figure 5. Close up of sensor in bottom flange

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 6 is a plot of deformation versus time for beam AC.

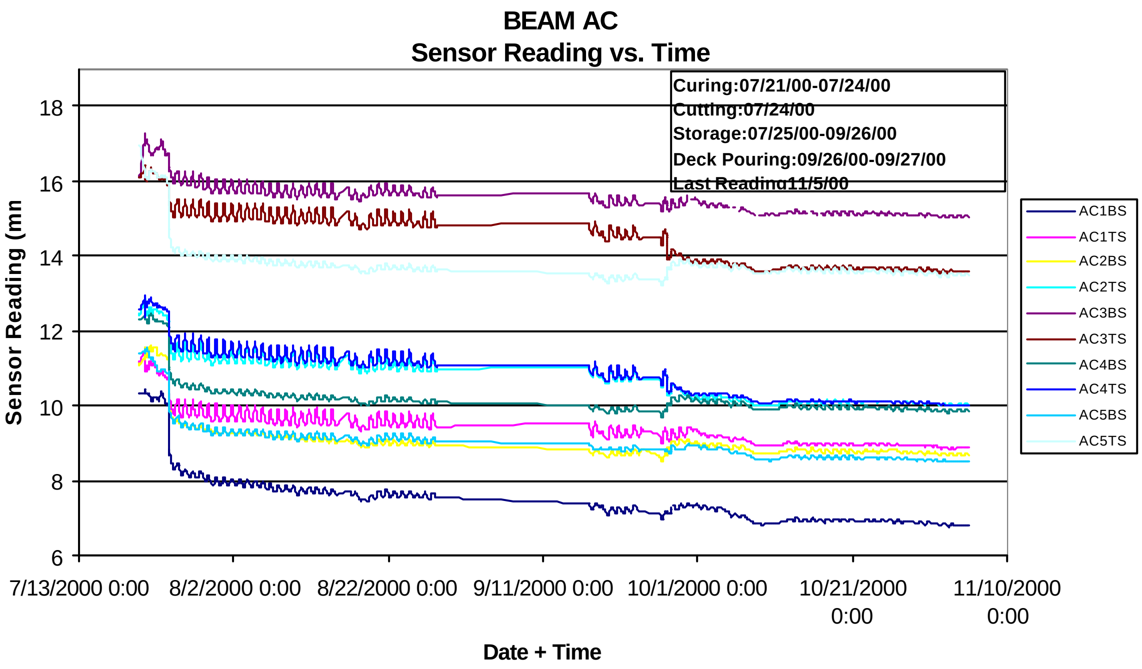

Figure 6. Sensor reading vs. time for beam AC

MATERIAL PROPERTIES

Concrete Strength

Cylinders were taken during pouring of the concrete and tested in the lab. Table I gives the compressive strength of the concrete.

TABLE I. 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 determine the coefficient of thermal expansion, the change in temperature versus strain in the concrete is plotted (Figure 7). A trend-line is fitted to the data. The slope of the lines is the coefficient of thermal expansion.

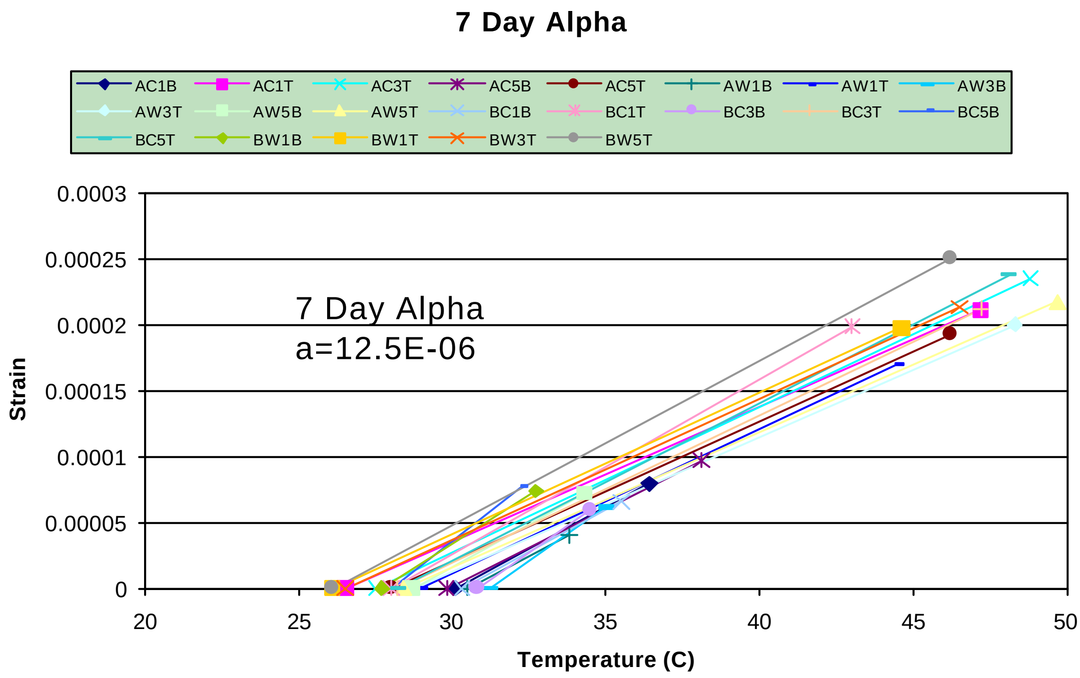

Figure 7. Average coefficient of thermal expansion at 7 days

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 using Hooke's law:

$$E = \sigma/\varepsilon \tag{1}$$

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 stress in the concrete is that caused by the release of the prestressed tendons. At 60 days the change in stress is due to the deck pouring.

Section 8.5 of the ACI Code [1] states that the modulus of elasticity for normal weight concrete can be taken as:

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

This equation has been modified for high-strength concrete [2] and is given as:

$$E = 40{,}000\ (f'c)^{1/2} + (1x10^{6})\ \text{psi} \tag{3}$$

As seen in Table II, the ACI code equation (Eq.2) gives a good estimate of the modulus of elasticity for HPC.

TABLE II. MODULUS OF ELASTICITY: EMPIRICALLY DETERMINED COMPARED TO CALCULATIONS FROM FIELD DATA

Modulus of Elasticity	Expected in design	Calculated from field data	Empirically determined (Eq.2)	Empirically determined (Eq.3)
	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 Prestressed Concrete Institute (PCI) General Method [3], the American Concrete Institute – American Society for Civil Engineers (ACI-ASCE) Method [4], the Load and Resistance Factor Design (LRFD) Method [5], and the LRFD Lump Sum Method [5]. None of these methods was developed specifically for High Performance Concrete.

PCI method vs. field measurements

The PCI Method is a time-step method, and therefore permits calculation of prestress losses at specific time intervals. The PCI General method was used to calculate the prestress losses up to 5 months. The results to date show that the PCI General method over predicted the prestress losses at every stage (Figure 8).

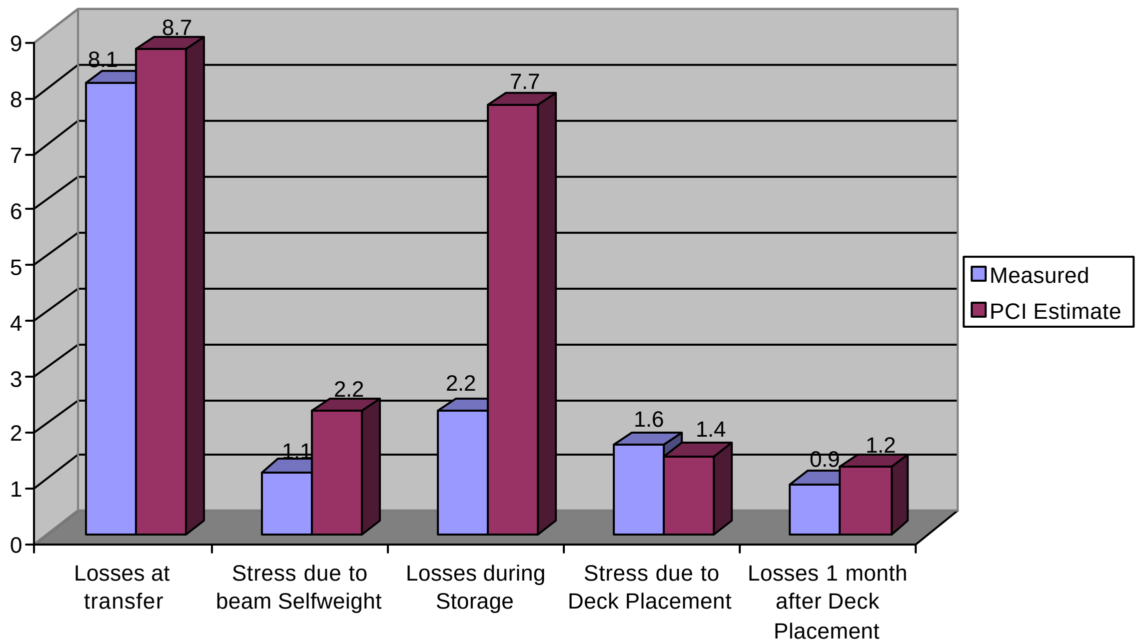

Figure 8. % Prestress Loss. Field measurements vs. the PCI Method

Comparing total losses

The measured prestress losses are compared to the total losses estimated by each method (figure 9). The losses are expected to taper off over the next few months. Overall, all methods are found to be very conservative.

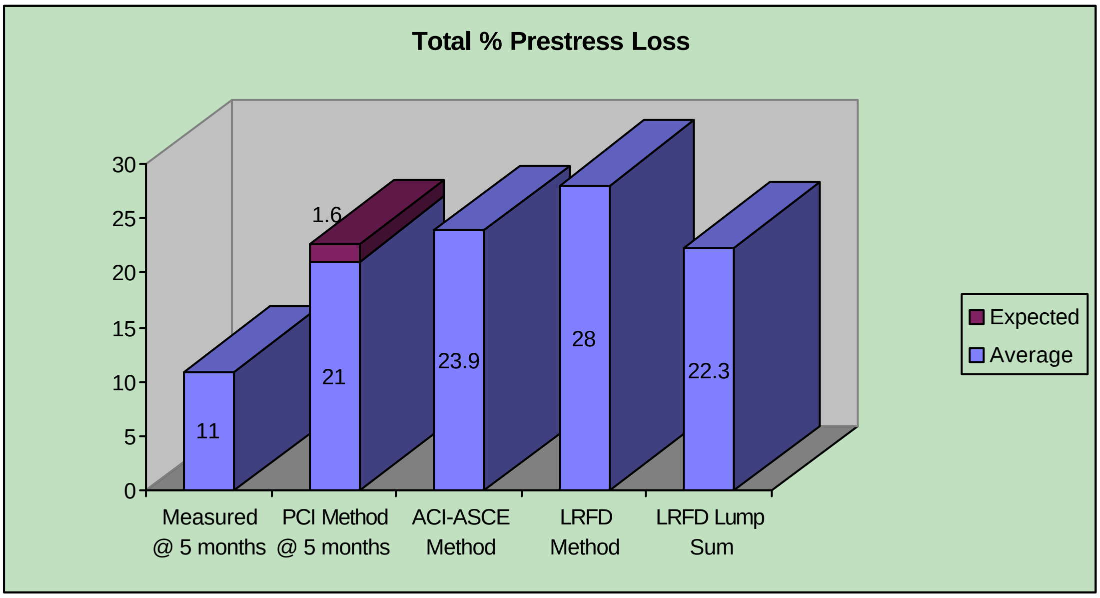

Figure 9. Measured losses vs. losses estimated by various methods.

EFFECTS OF CURING TEMPERATURE

Beam AC was accidentally uncovered during curing and had lower curing temperatures. The highest temperature measured for beam AC was about 70 vs. 90 degree Celsius for the other beams. Figures 10 & 11 show a plot of temperature vs. time for beams AC and BC. Beam AC exhibited much larger early prestress losses when compared to the other beams as shown in figures 12 & 13.

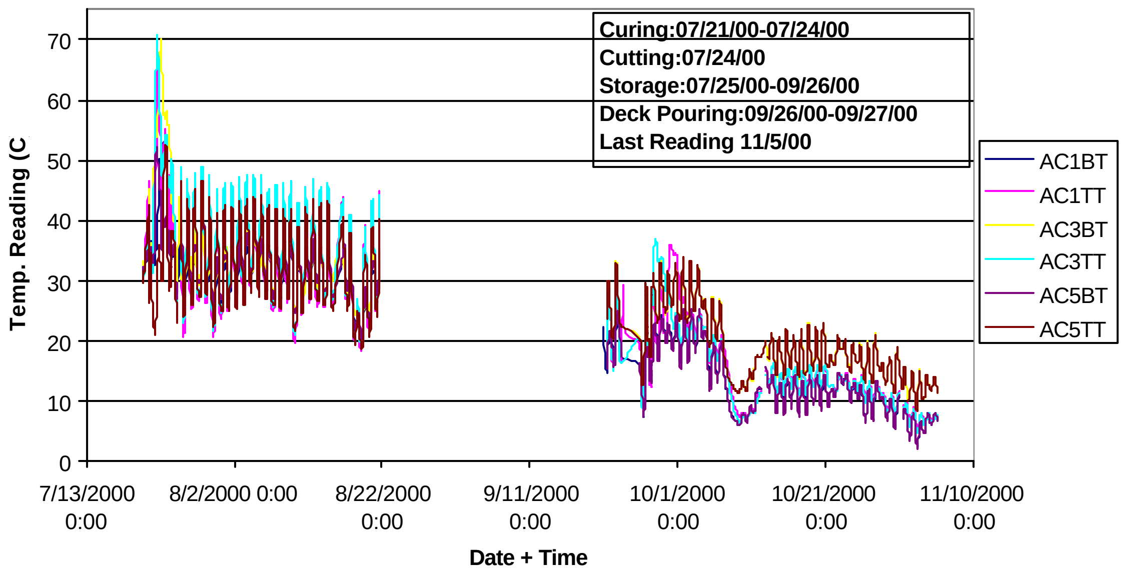

Figure 10. Temperature reading vs. time for beam AC

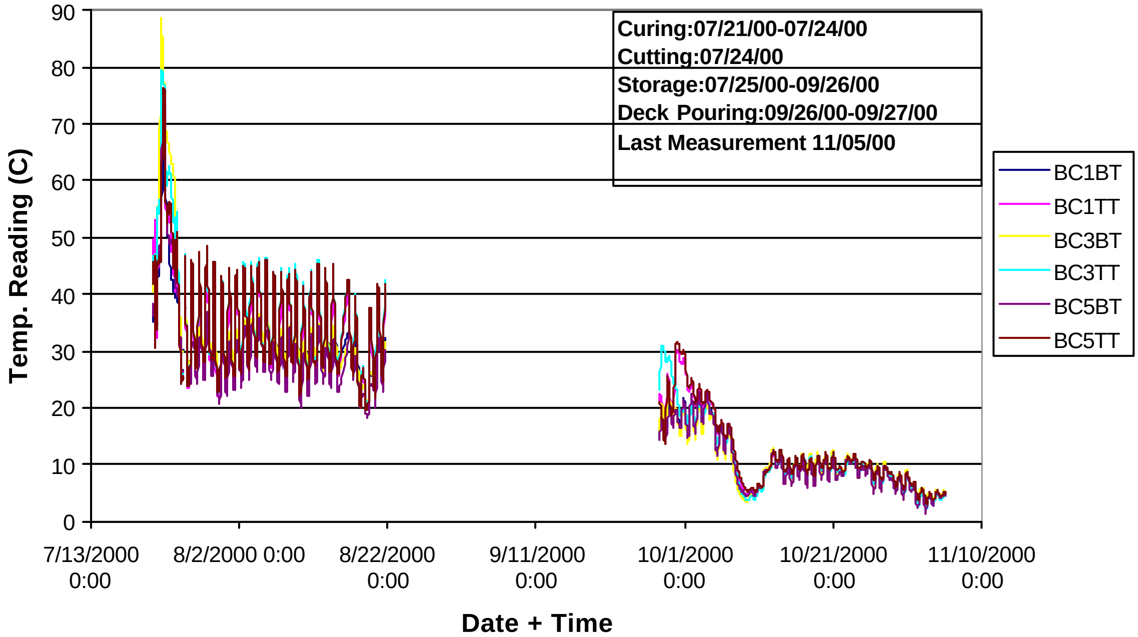

Figure 11. Temperature reading vs. time for beam BC

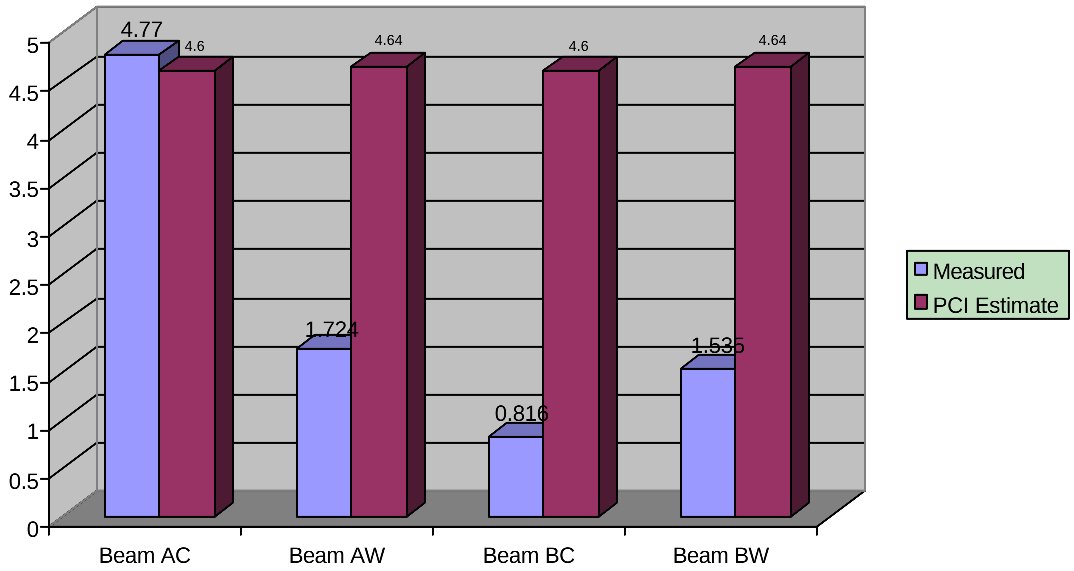

Figure 12. Prestress losses one day after transfer

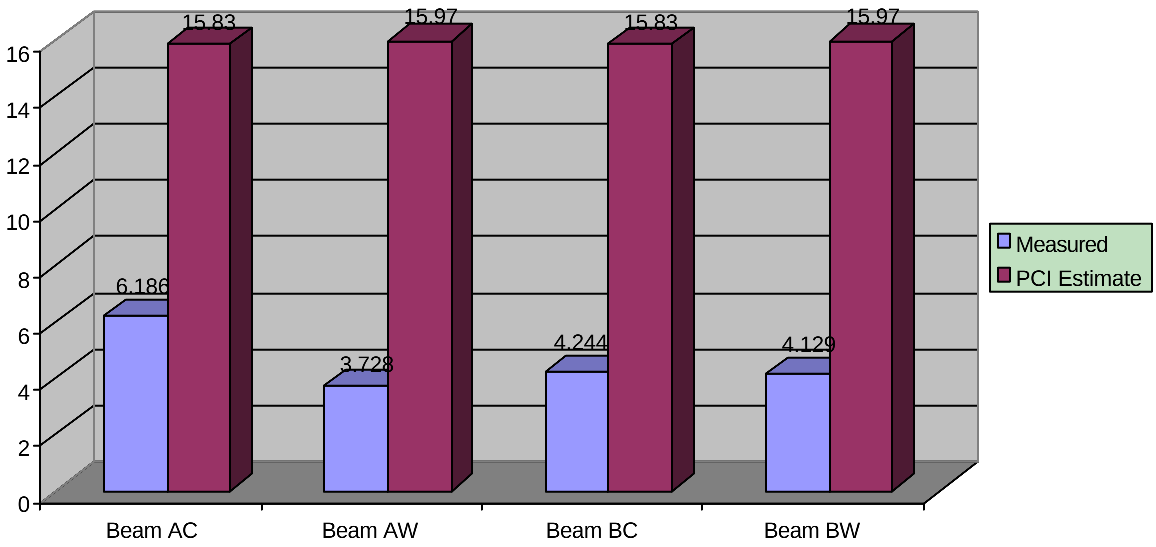

Figure 13. Prestress losses during storage for each beam (ksi)

CONCLUSIONS AND RECOMMENDATIONS

A built-in monitoring system was used successfully to monitor a bridge during fabrication and construction. Material properties and prestress losses were measured using the built-in sensor system.

Monitoring the beams during the fabrication process gave an insight into the effect of curing temperature. It showed that curing temperature can have a significant effect on the early prestress losses. The beam cured at lower temperatures exhibited much larger early prestress losses than the other beams.

The current 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 ones 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. Mehta, Kumar P. and Monteiro, Paul J. M. 1993, Concrete: Structure, Properties, and Materials, 2nd Edition, Prentice Hall Inc., Englewood Cliffs, NJ
3. PCI Committee on Prestress Losses 1975, "Recommendation for Estimating Prestress Losses", PCI Journal, Vol. 20, No. 4, July-August 1975, pp. 44-75
4. ACI Committee 363 1984, "State-of-the-Art Report on High Strength Concrete", ACI Journal, Vol. 81, No. 4. July-August 1984, pp. 364-404
5. American Association of State Highway and Transportation Officials, 1996 "AASHTO LRFD Bridge Design Specifications", 2nd Edition, Washington, D.C.