"INTRODUCTION OF HPC AND THE PRODUCTION OF HPC BRIDGE GIRDERS AT THE LOCAL LEVEL"

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ABSTRACT

The use of high performance concrete (HPC) is becoming more common in today's construction. Many HPC mixtures take advantage of pozzolans to increase strength and improve durability. However, some ready mix concrete plants and precast/prestressed facilities are not equipped to take advantage of pozzolans due to the limited numbers of silos or the layout of facilities does not allow for the addition of new materials. For this research program, HPC mixtures without pozzolans were developed in the laboratory and then trial batching was conducted at a precast/prestressed facility to optimize the concrete mixture based on strength and workability. From these trial batches, four bridge girders were cast with HPC at a w/cm of 0.26. The research demonstrates the efficacy for the local ready mix and precast/prestressed concrete industries to employ HPC mixtures using only materials and equipment in current use.

Keywords: High Performance Concrete, Bridge Girders, Mixture Proportions, Production

INTRODUCTION

The use of high performance concrete (HPC) in exterior structures has increased in recent years[1]. Its increased strength and durability make HPC very appealing to the prestressed concrete industry, particularly in bridge girders. Due to its increased strength and durability, HPC can reduce the number of girders, increase bridge spans, decrease bridge depth, and improve bridge durability[2]. To improve concrete strength and durability, most HPC mixtures incorporate supplementary cementitious materials such as fly ash, silica fume, or blast furnace slag. However, some ready mix plants and precast/prestressed facilities are not equipped to take advantage of pozzolans due to the limited number of silos, or the layout of the facilities does not allow for the addition of new materials. The research demonstrates the efficacy for the local ready mix and precast/prestressed concrete industries to employ HPC mixtures using materials and equipment in current use.

BACKGROUND

The definition of HPC has changed throughout the years. In 1979 the American Concrete Institute (ACI) Committee 363 on High Strength Concrete defined HPC as any concrete having a compressive strength of over 6000 psi[3]. In 1997, A.M. Neville in his book *Properties of Concrete*[4] defined HPC as any concrete with a compressive strength of over 12,000 psi. The Strategic Highway Research Program (SHRP) defined HPC by three requirements. The requirements were a maximum w/cm of 0.35, a minimum durability factor of 80, and a minimum compressive strength of either 3000-psi within four hours of placement, 5000 psi at one day, or 10,000 psi at 28 days[5]. In 1999, ACI redefined HPC as "concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices." As one can see, the definition of HPC has changed over the years, and it will continue to change as our knowledge of concrete increases.

High Performance Concrete is not necessarily different from normal strength concrete (NSC). Both HPC and NSC contain the same basic constituent materials. Those materials are cement, fine aggregate (sand), coarse aggregate (rock), and water. The differences are in the quantities of those materials. HPC may contain as much as or more than 900 lb/yd^3 of cement, whereas NSC may contain approximately 500 lb/yd^3 of cement. Also, HPC may have a w/cm as low as 0.20[4] where NSC may have a w/cm of 0.60. However, it should be noted that HPC can contain as little as 600 lb/yd^3 of cement.

Another difference between the two types of concretes is the addition of chemical and mineral admixtures in HPC that further enhance the fresh and hardened properties of concrete. Chemical admixtures are soluble chemicals that are added to concrete to improve its properties[6]. Chemical admixtures can reduce the water demand, increase or decrease the set time, entrain air, waterproof, and inhibit corrosion[7]. The advent of the superplasticizer or High Range Water Reducers (HRWR) had a dramatic impact on the future of HPC[3]. HRWR can reduce the amount of water in a given mixture by as much as 35 percent[4]. With HRWR a mixture with a w/cm of about 0.25 can have the same slump as a mixture with a w/cm of about 0.50. The reduction in water content increases the strength and also increases the density of the concrete, which results in concrete with lower permeability.

The use of HPC also has indirect benefits on the environment. The use of HPC can increase the life of concrete structures, reduce maintenance costs, and for bridges reduce the required number of girders. These examples either involve extending the life of a concrete structure or reducing the quantity and sizes of necessary members, thus promoting resource conservation by furthering the supply of cement.

EXPERIMENTAL PROGRAM

SCOPE

A goal of the research was to introduce HPC to the local prestressed/precast concrete industry. Four prestressed girders were cast. Two girders had a targeted total air content of two percent, and two had a targeted total air content of six percent. The girders were cast using concrete mixtures developed in the laboratory and refined through trial batching at the facility. The testing matrix is shown Table 1.

Table 1. Testing Matrix.

Beam	Targeted Total Air Content (%)	
	2	6
1	X	-
2	-	X
3	-	X
4	X	-

MATERIALS

Type III cement was used in all mixtures. The coarse aggregate was 3/8 inch, crushed limestone from Oklahoma. The fine aggregate was washed river sand also from Oklahoma. To provide adequate workability, a water reducer (WR) and/or a high range water reducer (HRWR) was used. An air entraining agent (AEA) was used to attain the required target total air contents. The girders contained 0.60 in. diameter, low relaxation prestressing strand and Grade 60 mild reinforcement.

MIXTURES

The mixtures used to cast the girders were developed in the earlier phases of the research program. The mixtures were chosen based on workability and strength. The chosen mixtures are shown in Table 2. Girders 1 and 4 were cast with the same mixture, and girders 2 and 3 contained the same mixture. The only difference in the two mixtures was the targeted total air content and quantity of sand. Girders 1 and 4 had a targeted total air content of two percent, and girders 2 and 3 had a targeted total air content of six percent.

Table 2. Mixture Designs.

	Girder 1	Girder 2	Girder 3	Girder 4
Cement (lb/yd^3)	900	900	900	900
Coarse Aggregate	1790	1790	1790	1790
Fine Aggregate	1217	1040	1040	1217
Water	254	254	254	254
w/cm	0.26	0.26	0.26	0.26
Targeted Total Air Content (%)	2.0	6.0	6.0	2.0
Calculated Unit Weight (lb/ft^3)	153.4	146.8	146.8	153.4

GIRDER DESIGN

Four prestressed girders were cast. The girders were cast at Coreslab Structures, Inc, of Oklahoma City. All four girders had the same cross-sectional properties. The girders had a depth of 24 inches and a length of 24 feet. The moment of inertia and area of the girders were 12,370 in^4 and 163.25 in^2, respectively. The dimensions and cross-sections of the girders are shown in Figure 1.

All four girders contained 10 prestressing strands, however some of girders contained debonded strands. Girders 1 and 4 had a targeted air content of two percent (entrapped air only), while Girders 2 and 3 were targeted to have a total air content of six percent.

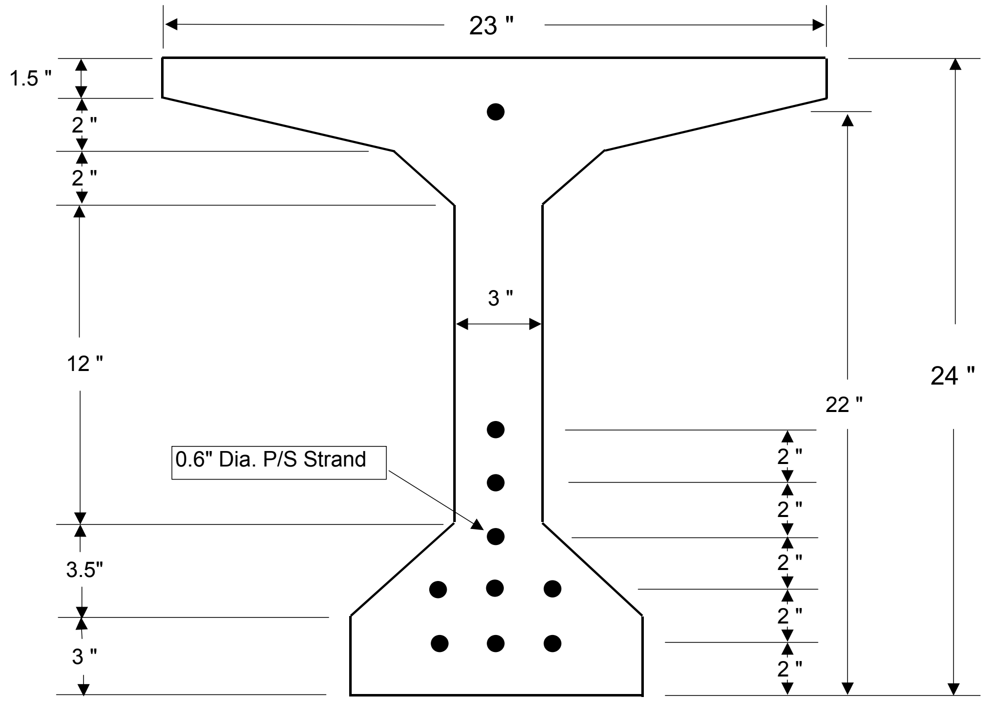

Figure 1. Cross-section of girders.

BATCHING

As mentioned earlier, the mixture designs for the girders were chosen from earlier phases of the research program. The mixtures were chosen based on workability and strength. Prior to the casting of the girders, several trial batches were cast at Coreslab Structures in Oklahoma City. The selected mixtures were developed at Fears Structural Engineering Laboratory (FSEL) using a 6-ft^3 rotary concrete mixer, but at Coreslab a much larger mixer (4 yd^3) was used to batch the concrete. The trial batches were necessary to determine appropriate dosages of water reducers and air entraining agents. Shown in Table 3 is a comparison of mixture proportions (particularly admixture dosages) between the mixtures cast at FSEL and the mixtures cast at Coreslab. The main difference between the mixtures cast at FSEL and at Coreslab was the dosage of AEA. At FSEL, a dosage of 15 fl oz/cwt was required to attain approximately six percent air, but at Coreslab only 0.65 fl oz/cwt was necessary. Higher dosages of AEA were required at FSEL because the smaller mixer was not as efficient in agitating the fresh concrete as well as the larger mixer used by Coreslab.

Table 3. Comparison of FSEL and Coreslab Mixtures.

	FSEL	Coreslab	FSEL	Coreslab
Cement (lb/yd^3)	900	900	900	900
Coarse Aggregate	1790	1790	1790	1790
Fine Aggregate	1217	1217	1040	1040
Water	254	254	254	254
w/cm	0.26	0.26	0.26	0.26
Targeted Total Air Content (%)	2.0	2.0	6.0	6.0
Calculated Unit Weight (lb/ft^3)	153.4	153.4	146.8	146.8
WR (fl oz/cwt)	3	3	3	3
HRWR (fl oz/cwt)	15	18	15	18
AEA (fl oz/cwt)	0	0	15	0.65

TESTS

The two mixtures were subjected to several tests. The fresh concrete properties tested were slump (ASTM C 143), unit weight (ASTM C 138), and air content (ASTM C 231). The hardened properties tested were compressive strength (ASTM C 39), length change (ASTM C 157), and modulus of elasticity (ASTM C 469).

PRESENTATION OF RESULTS

CONCRETE AND GIRDER PROPERTIES

The results from the fresh concrete tests are shown in Table 4. Also shown in the table are the fresh concrete properties of identical mixtures cast at FSEL. The compressive strength and modulus of elasticity of the girders are shown in Table 5. A comparison of the compressive strength between the FSEL mixtures and the Coreslab mixtures is shown in Table 6. The compressive strength, modulus of elasticity, and shrinkage reported are the averages of at least three individual tests.

Table 4. Fresh Concrete Properties.

Fresh Concrete Properties	Girders 1 & 4	9-26-2.4	Girders 2 & 3	9-26-5.6
Batch Location	Coreslab	FSEL	Coreslab	FSEL
Fresh Concrete Temp. (F)	68	74	60	75
Slump (in.)	10.0	6.50	9.75	4.25
Air Content (%)	2.3	2.4	6.2	5.6
Unit Weight (lb/ft^3)	151.1	152.3	146.9	147.2
Air Temperature (F)	36	91	35	91

Table 5. Hardened Concrete Properties of the Girders.

	Girder 1	Girder 2	Girder 3	Girder 4
Average Compressive Strength (psi)[1]				
1 day	8700	6130	6130	8700
14 days	10,190	7110	7110	10,190
28 days	11,060	8390	8390	11,060
56 days	12,440	9200	9200	12,440
180 days	14,460	10,850	10,850	14,460
360 days	15,610	11,460	11,460	15,610
Average Modulus of Elasticity (ksi)[1]				
1 day	5600	4700	4700	5600
14 days	5800	4900	4900	5800
28 days	6000	5500	5500	6000
56 days	6300	5400	5400	6300
180 days	6800	5500	5500	6800
360 days	6900	6000	6000	6900

1. Reported values are the average of three tests.

Table 6. Compressive Strength of FSEL and Coreslab Mixtures.

	Beams 1 & 4	9-26-2.4	Beams 2 & 3	9-26-5.6
Batch Location	Coreslab	FSEL	Coreslab	FSEL
1 day (psi)	8700	6830	6130	4560
7 day	-	11,040	-	9270
14 day	10,190	-	7110	-
28 day	11,060	12,190	8390	10,560
56 day	12,440	12,960	9200	11,290

DISCUSSION OF RESULTS

FRESH CONCRETE PROPERTIES

The goal of the research was to develop a HPC mixture that could be easily used in the local prestressed industry. The slumps of the mixtures used in casting the girders were 9.75 and 10 inches. Both mixtures had sufficient workability to produce the girders. As can be seen in Figures 2 and 3, the girders had a smooth finish and there were no "honeycombed" areas.

Girders 1 and 4 had a targeted air content of two percent, and Girders 2 and 3 had a targeted air content of six percent. Both mixtures were within ± 0.50 percent of the targeted air contents. The first batch of concrete for Girders 2 and 3 had to be discarded due to an air content of 9.6 percent. The unit weights of the mixtures inversely correlated to the air contents of the mixtures. The mixture for Girders 1 and 4 had a higher unit weight than the concrete mixture for Girders 2 and 3, which was expected.

The unit weights of the mixtures cast at FSEL and at Coreslab are shown in Table 7. The calculated unit weights and the percent difference between the calculated and measured unit weights are also shown in Table 7. All mixtures were within 1.5 percent of the calculated unit weight. The difference between the measured and calculated unit weights was considered acceptable. This is a testament to the quality control procedures employed by Coreslab. The mixtures cast at FSEL were smaller mixtures (approximately 2.2 ft^3) and the materials were weighed using a digital scale. The materials were weighed to the nearest hundredth of a pound. At Coreslab, the mixtures were much larger (approximately 2.5 yd^3 or 67.5 ft^3) and the materials were weighed using a weight and balance system. The minimal differences between the measured and calculated unit weights (l.5 percent and less) and the use of a mixer that was built in 1926 confirms that HPC can be produced at most facilities that are currently casting concrete.

Table 7. Comparison of Unit Weights.

Location	9-26-2.4	Measured Calculated	9-26-5.6	Measured Calculated
Unit Weight - Coreslab (lb/ft^3)	151.1	98.5 %	146.9	100.1 %
Unit Weight – FSEL (lb/ft^3)	152.3	99.3 %	147.2	100.3 %
Unit Weight – Calculated (lb/ft^3)	153.4	100.0 %	146.8	100.0 %

Figure 2. Photograph of Girders.

Figure 3. Photograph of Girders.

HARDENED CONCRETE PROPERTIES

A comparison of the FSEL and Coreslab mixtures are shown in Figures 4 and 5. The difference between the mixtures was the curing regimen. The cylinders cast at Coreslab were steam cured for approximately 12 hours (overnight) with the girders and then cured with the girders outside in ambient temperatures. The FSEL cylinders were cured at 73ºF and 50 percent relative humidity for 24 hours and then cured at 73ºF and 100 percent relative humidity until tested. The use of heat curing increased the one-day compressive strengths of the Coreslab mixtures, but decreased their long term compressive strength, which is shown in Figures 4 and 5. Steam curing increases early age strength by increasing the initial hydration. This results in a "less uniform distribution of hydration products within the paste" which decreases the ultimate strength of concrete[6] . This is evident in Figure 4 and 5 where the compressive strength of the Coreslab mixtures was approximately 30 percent greater than the FSEL mixtures at one day of age, but by 28 days of age, the FSEL achieved compressive strengths that were greater than the steam cured Coreslab mixtures.

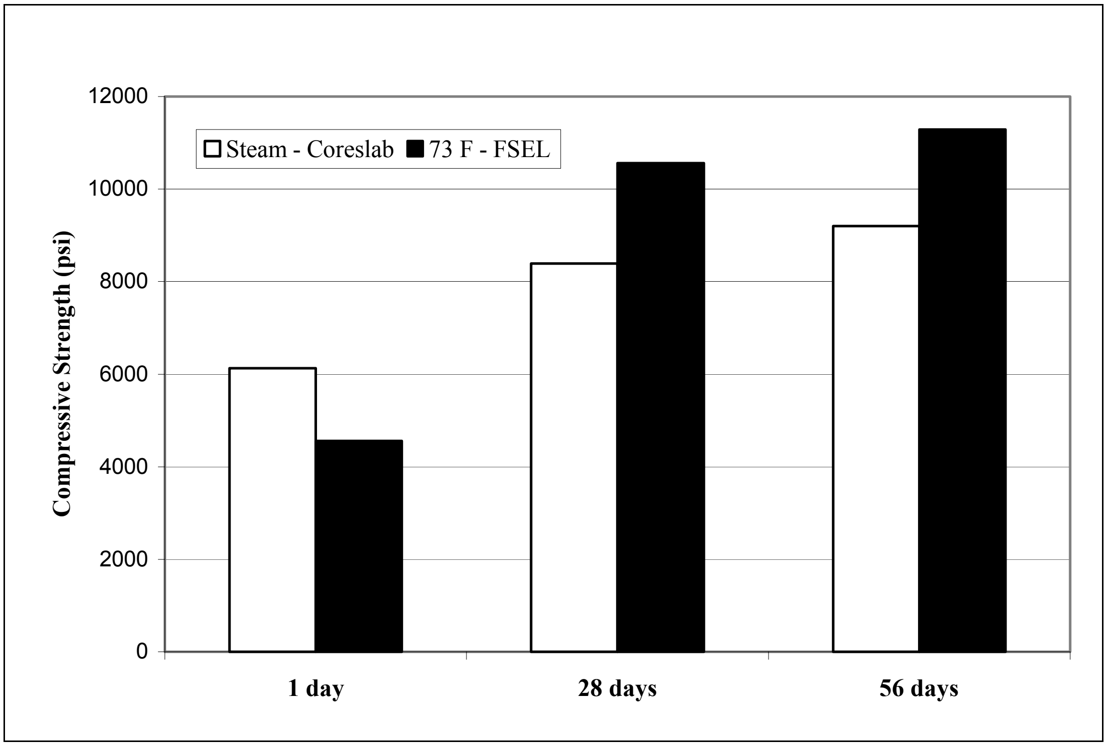

Figure 4. Comparison of One-day Compressive Strengths (psi).

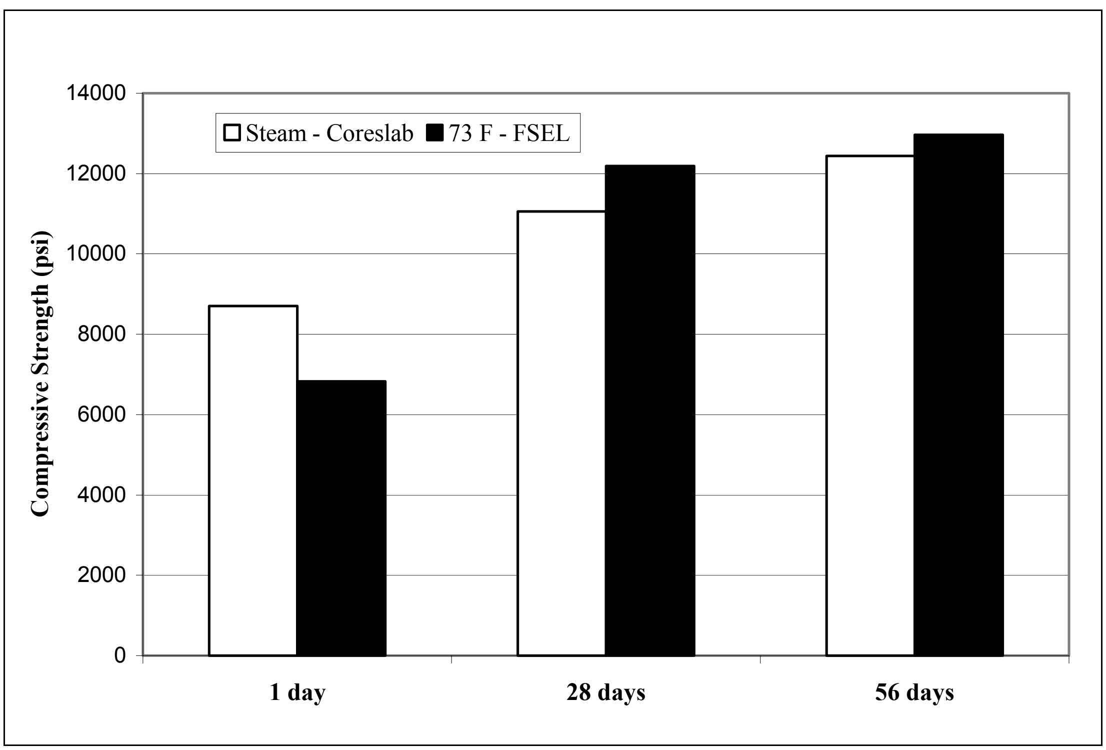

Figure 5. Comparison of 28-day Compressive Strengths (ksi).

The strength gain of the two mixtures cast at Coreslab is shown in Figure 6. The difference between the two mixtures is the total air content. One mixture contained no entrained air (air content of 2.3 percent) and the other contained 6.2 percent air (approximately 4 percent entrained air). The effects of the entrained air are also shown in Figure 6. The rate of strength gain for the two mixtures is almost identical, but for each age tested the addition of entrained air reduced the compressive strength by roughly 30 percent.

The addition of one percent of entrained air normally decreases the compressive strength by two to five percent[6]. The decrease in compressive strength per increase in entrained air is shown in Table 8 for each age tested. The decrease in compressive strength per one percent increase in entrained air ranged from 6.2 to 7.8 percent. This is slightly more than the "2 to 5 percent decrease" suggested by many books, but still within an acceptable and expected range.

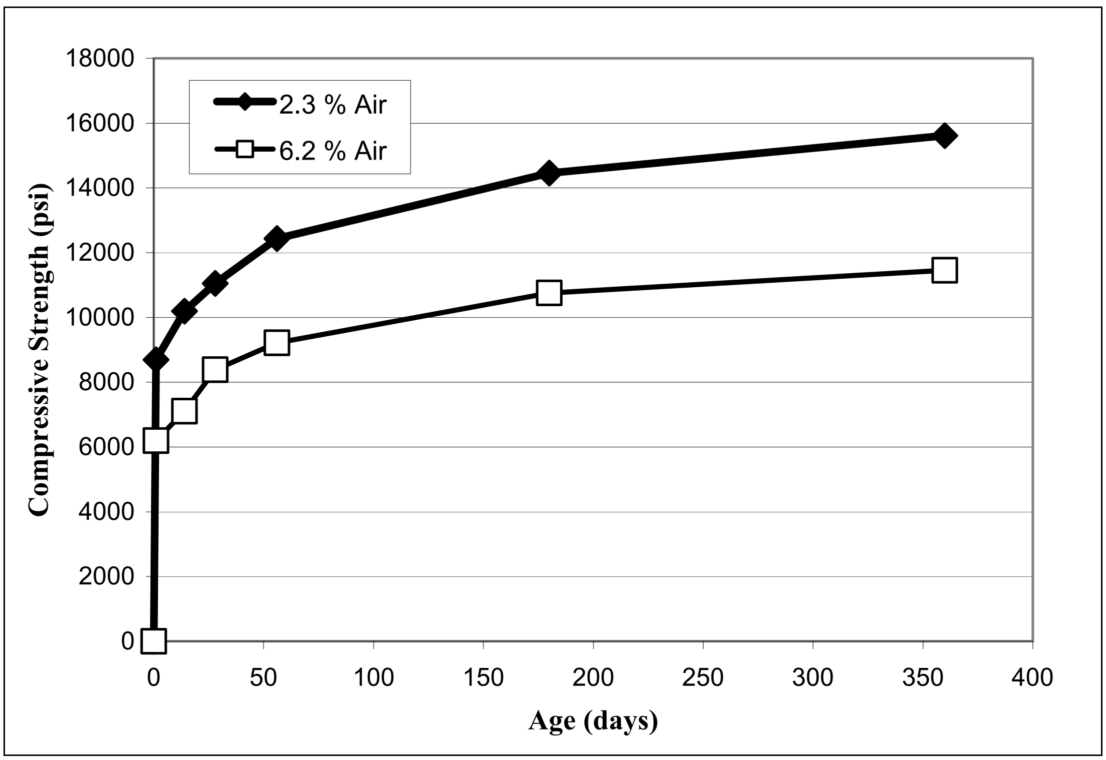

Figure 6. Strength Gain for the Coreslab Mixtures.

Table 8. Decrease in Compressive Strength due to Entrained Air.

Age (days)	Girder 1	Girder 2	% Decrease in Compressive Strength per One % Increase in Entrained Air
1	8700	6130	7.60
14	10,190	7110	7.80
28	11,060	8390	6.20
56	12,440	9200	6.70
180	14,460	10,850	6.40
360	15,610	11,460	6.80

The modulus of elasticity (MOE) is a measure of the stiffness of the concrete. The MOE of concrete is seldom measured for design; instead ACI318-99 provides two prediction equations (Eqns. 1 and 2) that can be used to determine the MOE. As can be seen in the equations, the compressive strength and unit weight are the major factors that influence the MOE of concrete. Increases in both compressive strength and unit weight result in higher MOE. These trends exist in the results of the mixtures examined in this research. Increases in compressive strength resulted in increases in MOE.

The MOE of the mixtures are plotted in Figure 7 versus the square root of the compressive strength. Also plotted on the graph are equations 1 and 2. As shown in Figure 7, the MOE of the mixtures plot near the prediction equations, meaning the equations can be used when estimating the MOE based on their compressive strength.

$$E_c = 57{,}000 * \sqrt{f'_c} \qquad \text{Eqn. 1}$$

Where
f'_c = compressive strength (lb/in^2)

$$E_c = 33 w_c^{1.5} * \sqrt{f'_c} \qquad \text{Eqn. 2}$$

Where
f'_c = compressive strength (lb/in^2)
w_c = unit weight of the concrete (lb/ft^3)

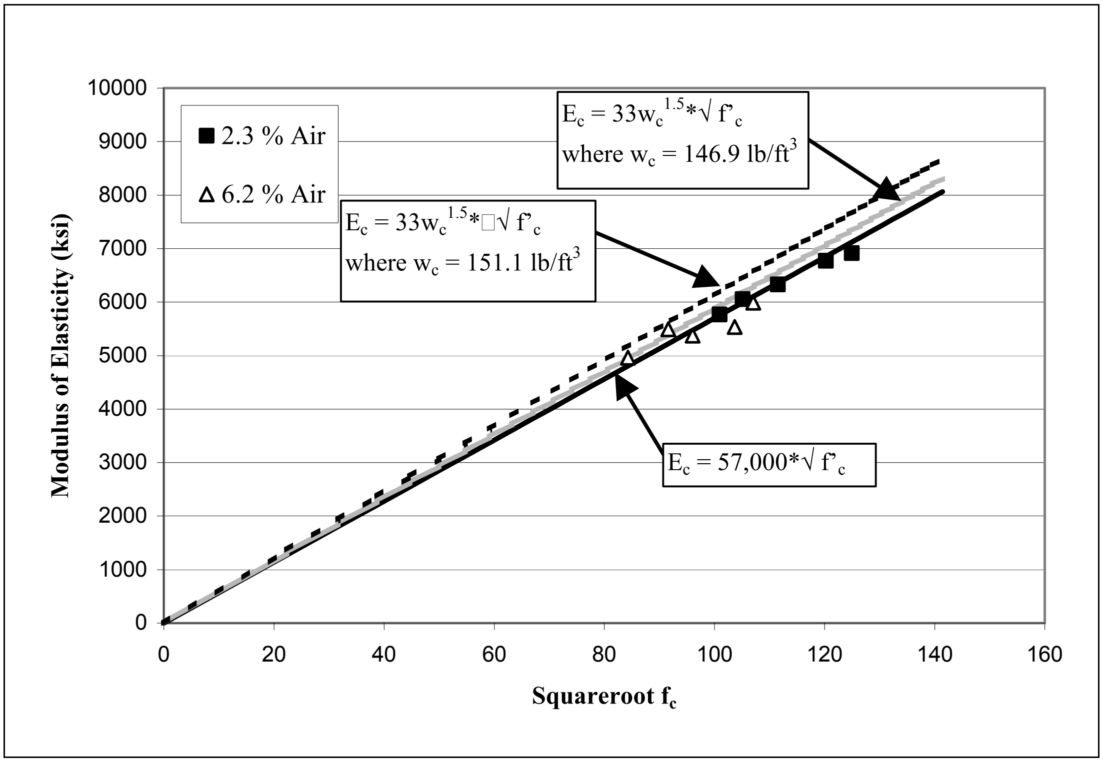

Figure 7. MOE and Prediction Equations.

The shrinkage or length change of the mixtures used to cast the girders was measured for one year. Shrinkage specimens were cast from the same concrete mixtures that were used in casting the girders (mixtures 9-26-2.3 for Girders 1 and 4, and 9-26-6.2 for Girders 2 and 3). The shrinkage curves for the mixtures are shown in Figure 8.

Since the paste content was approximately the same for both mixtures and the coarse aggregate was the same for both mixtures, the shrinkage would also have been expected to be approximately the same. As shown in Figure 8, the shrinkage curves for the two mixtures were similar. The shrinkage at one year of age was 680 and 740 microstrains for mixtures 9-26-2.3 and 9-26-6.2, respectively.

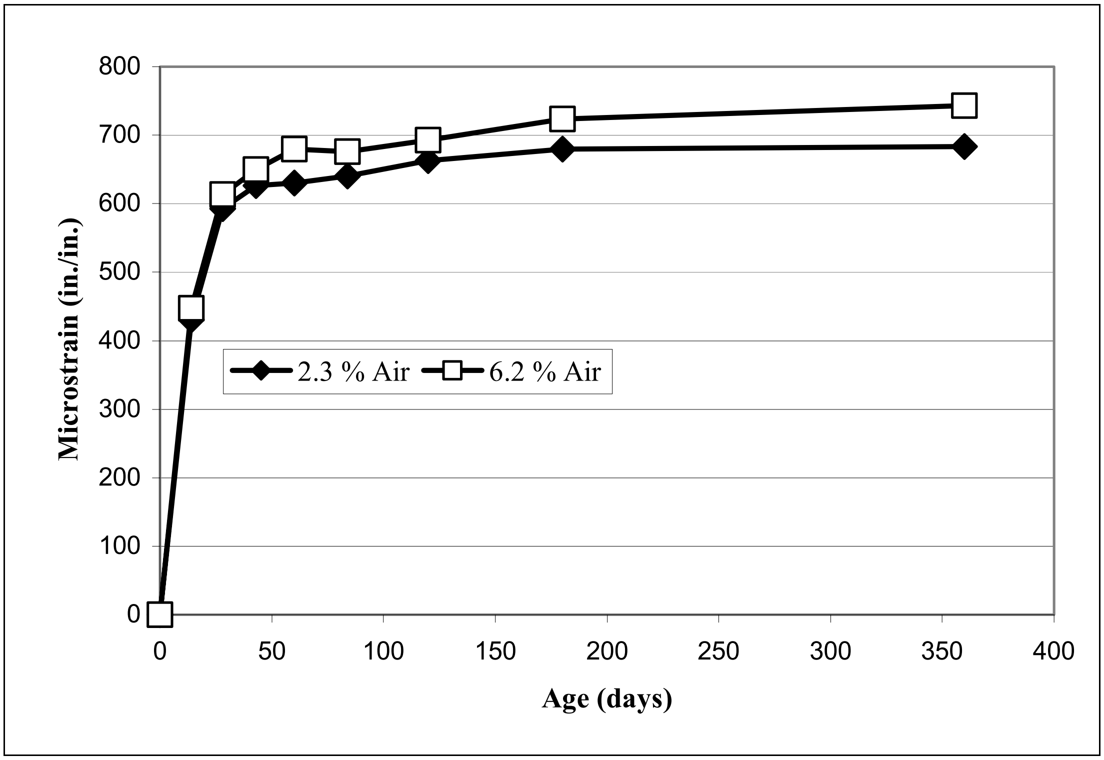

Figure 8. Shrinkage Curves.

CONCLUSIONS

One of main objects of the research program was to demonstrate that the use HPC is possible in the local prestressed concrete industry. Girders were cast with mixtures that had a w/cm of 0.26. The mixtures attained an early strength of 8700 psi (for Girders 1 and 4) and reached over 15,000 psi at one year (for Girders 1 and 4). It must be noted that these mixtures did not contain any special chemical or mineral admixtures. The girders were cast with materials that Coreslab uses in their normal day-to-day operations. The casting of the girders also reemphasized the detrimental effects that air entrainment has on the compressive strength of concrete. At one day of age, the difference between the two mixtures was over 2500 psi, and at later ages (14, 28, and 56 days of age) this difference was approximately 3000 psi. With good quality control measures, most precast/prestressed concrete facilities have the capabilities to produce to HPC. HPC was produced using locally available materials and produced using a concrete mixer that was manufactured in 1926.

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