PRELIMINARY INVESTIGATION INTO THE USE OF UHPC IN PRESTRESSED MEMBERS

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is a recent advancement in the concrete industry. UHPC is a type of concrete that possesses superior properties when compared to those of high performance concrete (HPC). UHPC can have compressive strengths of up to 30,000 psi when mixed and cured properly. This research program documents the mixing, casting, curing, and testing of 7 UHPC prestressed beams. The beam specimens were 6.5 in. by 12 in. and were 18 feet in length. The beams were cast with a commercially available UHPC mixture. Each beam contained two 0.60 inch diameter prestressing strands and no traditional shear reinforcement. The compressive strength of the beams ranged from 12,000 psi to 22,500 psi at release (4 days of age) and 26,920 psi to 28,830 psi when the heat treatment was completed. The average measured transfer length for the UHPC beams was approximately 14 inches at 28 days of age. Identical testing is also being conducted on control beam specimens cast with conventional high strength concrete (HSC) with an average compressive strength of approximately 12,000 psi at 28 days. Preliminary results show that the UHPC beams have approximately 50 percent shorter transfer lengths than the control, HSC beams. When compared to values calculated using the ACI/AASHTO equations, the measured transfer lengths of the UHPC specimens were approximately 60 percent shorter than the predicted values.

Keywords: UHPC, Transfer Length, Prestress Losses, Prestressed Bridge Girders

INTRODUCTION

In recent years the technology of concrete has changed greatly. As a result, concretes such as Self Consolidating Concrete (SCC) and High Strength Concrete (HSC) have been developed and their use has grown in the United States and internationally. More recently, a new concrete, that exhibits extraordinary strength (compressive and tensile), ductility, and durability has been developed. This new concrete, known as Ultra High Performance Concrete (UHPC), can attain compressive strengths exceeding 30 ksi and flexural tensile strengths of 7 ksi. UHPC is being considered as a material for use in prestressed concrete beams. Current concrete design specifications in the ACI 318 Building Code and AASHTO Bridge Design Specification were developed based on test data from conventional or high strength concrete. The ACI Building Code and AASHTO Specifications do not contain provisions for concretes with compressive strengths up to 30 ksi, and therefore design guidelines for using UHPC do not exist.

Researchers are now examining the development length and prestressed losses of beams cast with SCC and HSC. Research has shown differences in development lengths and prestressed losses of beams cast with SCC and HSC when calculated using current specifications, as compared to beams made with normal strength concrete (NSC). Similar results are expected to occur with UHPC. The main objective of this paper is to compare the transfer lengths of prestressed concrete beams constructed with UHPC to similar beams constructed with high strength concrete (HSC). This research program will also be one of the first research programs to provide data on the transfer lengths of UHPC prestressed beams.

BACKGROUND

Ultra-High Performance Concrete (UHPC) is an innovative material that has been developed in the last decade[1]. This new material exhibits extraordinary compressive and tensile strength, ductility, and durability that make it well suited for use in prestressed concrete bridges. UHPC is considered the next generation of high performance concretes (HPC)[2]. Compressive strengths can exceed 30 ksi, which can be more than twice that of a HPC mixture, and flexural strengths can exceed 7 ksi. Also known as reactive powder concrete, UHPC was first developed in the 1990's in France. Currently, several companies in France produce UHPC. In the United States it is available under the trademark Ductal®, a product of Lafarge North America Inc. Table 1 presents relevant material characteristics of Ductal®.

Table 1 Material Characteristics of Ductal®

Material Characteristic	Range
Compressive Strength (ksi)	23-33
Flexural Strength (ksi)	4-7.2
Modulus of Elasticity (ksi)	8000-8500
Chloride Ion Diffusion (ft^2/s)	0.02×10^{-11}
Carbonation Penetration Depth (in)	<0.02
Freeze-Thaw Resistance (%)	100
Salt-Scaling Resistance (lb/ft^2)	<0.0025
Density (lb/ft^3)	153-159
Entrapped Air Contend (%)	2-4
Post Cure Shrinkage (microstrain)	0
Creep Coefficient ($x10^{-6}$ in/in/^{o}C)	0.2-0.5

Reference: Lafarge North America Inc.

As with normal strength concrete (NSC) and HPC, UHPC does not have a unique mixture formulation. UHPC represents a group of similar concretes with a range of performance characteristics[3]. UHPC performance characteristics are superior to typical concretes of the NSC and HPC groups. Comparison of some material characteristics of HPC and UHPC is showed in Table 2.

Table 2 Comparison of UHPC and HPC

Material Characteristic	UHPC compared to HPC
Compressive Strength	2-3 times greater
Flexural Strength	2-6 times greater
Elastic Modulus	1.5 times greater
Total Porosity	4-6 times lower
Permeability	50 times lower
Water Absorption	7 times lower
Chlorine Ion Diffusion	25 times lower

Reference: Steinberg, E. and Lubbers, A. 2003

UHPC is a special combination of materials including portland cement, silica fume, quartz flour, sand, superplasticizer, water, and steel or organic fibers. The steel fibers are used in the composition to increase ductility and flexural strength. Since UHPC has no coarse aggregate, its constituent materials can produce a highly compacted concrete with a low and disconnected pore structure. A typical composition of UHPC is provided in Table 3.

Table 3 Typical Composition of UHPC

Material	Amount(Kg/m^3)	Amount(lb/yd^3)	% by Weight
Portland Cement	746	1259	28.8
Fine Sand	1066	1799	41.2
Silica Fume	242	408	9.3
Quartz Flour	224	378	8.6
Superplasticizer	9	15	0.3
Steel Fiber	161	272	6.2
Water	142	240	5.5

Reference: Vernet, C. P. 2003[4]

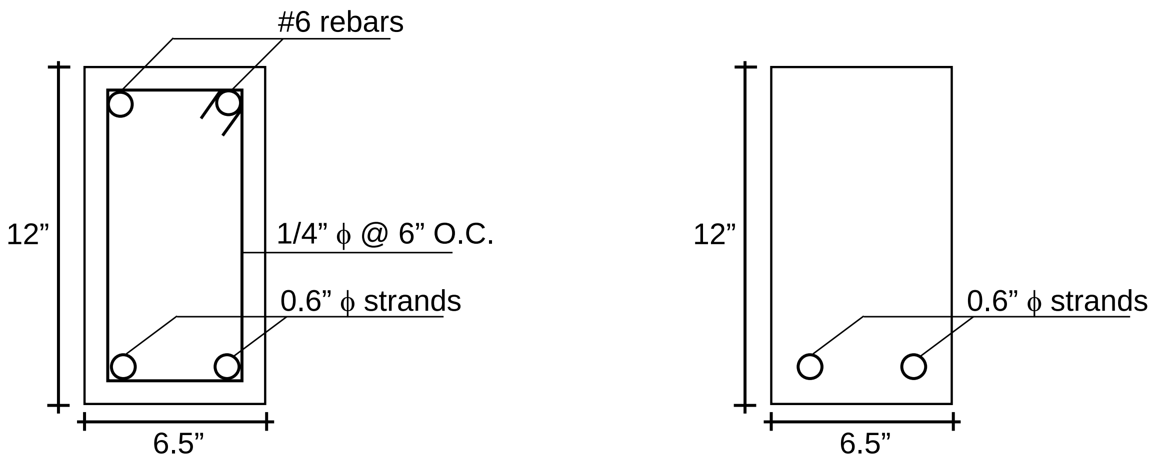
Each of the components in UHPC is responsible for its enhanced characteristics. Silica fume increases density due to its particle size and spherical shape which fills voids between larger particles. The average diameter of silica fume, the smallest particle in the mix, is 0.1-0.3 µm. The fine sand has the largest particle size among the constituents of UHPC. It is usually between 150 and 600 µm. Quartz flour, which has an average diameter similar to cement, 10-15 µm, is an exceptional paste and extremely hard. The combinations of these selected materials having similar size ensure homogeneity of the mix. The steel fibers used in the mix contribute to the superior ductility of UHPC. They add tensile strength and toughness to the material. The post-cracking strength capacity of UHPC increases because the steel fibers reinforce the mix on a microscopic level.

Heat treatment is applied in order to enhance its durability and mechanical properties. As a consequence, the material has almost no shrinkage and very low creep. The heat treatment usually consists of subjecting the material to a vapor bath at 195 ^{o}F for 48 hours.

Since the development of UHPC, much research has been focused on its application in bridges. Research has been conducted in numerous universities in order to determine and understand UHPC properties, but this program is one of the first to examine the transfer length of prestressed members cast with UHPC[5]. Additionally, federal funding has been granted to some states, such as Iowa and Virginia, for the construction of UHPC bridges[6]. More recently, the Federal Highway Administration (FHWA) has released two state of the art reports about the material property characterization and structural behavior of UHPC[7]. These reports, which present results from a first phase of an ongoing FHWA research program, reflect the interest level of using UHPC in the highway bridge industry in the United States.

EXPERIMENTAL PROGRAM

Thirteen beam specimens were fabricated and tested at the concrete laboratory located in the Engineering Research Center (ERC) at the University of Arkansas. Of the 13 beams, 6 were cast with a conventional HSC mixture, and the remaining 7 were cast with UHPC. The beams were 18 feet long having a cross section of 6.5 by 12 inches. Each cross section was furnished with 2 Grade 270 prestressing strands of 0.6 inches diameter. The HSC beams additionally had two number 6 Grade 60 rebars placed within the compression block of each beam. Stirrups of ¼-inch diameter were also provided at 6 in. centers along the entire length of the HSC beams. Note that the UHPC specimens contained only prestressing strands and no stirrups. Covers of 2 inch were used in all the beams. Figure 1 shows the typical cross section of the HSC and UHPC beams.



(a) HSC **(b)** UHPC

Fig. 1 Typical Beam Cross Section

Upon arrival from the manufacturer, the strand was kept inside to preserve the surface condition provided by the manufacturer. The strand was received with a clean, rust free surface. Prior to casting, the strand was unspooled and cut indoors, then transported less than 50 feet across clean plastic to the prestressing bed were it was tensioned. The strands for each beam were tensioned simultaneously to 75% of f_{pu}, or 202.5 ksi. This was achieved by using two hydraulic rams in parallel to push a steel block to which the strands were anchored. The strands were tensioned until a predetermined elongation that accounted for 4.5 inches of strand elongation, as well as 3/8 of an inch to account for chuck seating at each end of the strand. A hydraulic pressure gauge was also used to verify the tensioning procedure. At 1 day for the HSC beams and at 4 days for the UHPC beams, the strands were gradually released by slowly relieving the pressure simultaneously in each of the hydraulic rams used during the tensioning process.

MIXTURE PROPORTIONS

The HSC mixture used in this research was developed in a larger research program undertaken at University of Arkansas to develop high strength SCC mixtures for use in the precast/prestressed industry[8]. The research program included the development of HSC mixtures which were used to compare properties of both types of concretes, SCC and HSC. Table 4 presents the proportions of the HSC mixture.

Table 4 Mixture Proportions for HSC

Materials	HSC
Cement (lb/yd^3)	900
Coarse aggregate (lb/yd^3)	1800
Fine aggregate (lb/yd^3)	1207
Water (lb/yd^3)	234
W:b	0.26
ADVA 170 (fl oz/cwt)	9-10

The UHPC mixture was obtained from Lafarge North America Inc. which is produced under the brand name of Ductal®. Its components were delivered to the laboratory in different parts: premix, steel fibers, and a high range water reducing admixture (HRWR). The premix, which consists of cementitious material, aggregate, and filler materials, was delivered in bags of 80 pound. The steel fibers, 0.5 in. long and 0.008 in. diameter, were delivered in boxes of 44 pound and 66 pound. The HRWR was delivered in containers of 5 gallons. All these materials were stored inside in the original containers in order to ensure its quality. The Ductal® mix proportion used throughout this research was based on recommendations suggested by Lafarge North America Inc. and is shown below in Table 5.

Table 5 Mix Proportions of Ductal® BS 1000

Material	UHPC
Ductal® Premix (lb/yd^3)	3698
HRWR (lb/yd^3)	51
Water (lb/yd^3)	219
Steel fibers (lb/yd^3)	263

MIXING PROCEDURE

The mixing procedure for the HSC beams followed a modified version of ASTM C 192, in which the main difference was the mixing time. The HSC beams were cast using a rotating drum mixer with a capacity of 13.5 ft^3. The materials were added to the mixer as described in ASTM C 192, however, the HSC mixture required a much longer mixing time. Each HSC mixture required approximately 25 minutes of mixing before it could be placed. Additionally, due to the dense consistency of the HSC mixture, the maximum amount of HSC that could be batched in the mixer was 10 ft^3 which was not enough concrete to cast the beam and make test cylinders. Therefore, the HSC beams were divided into two batches of 8 ft^3, and the total time to batch the concrete for the HSC beams was 50 minutes.

The mixing procedure for Ductal® is different to that of conventional concrete. Ductal® is very thick and dense with a very low w:b, and because of that, a high shear mixer is recommended for batching. This type of mixer imparts high energy into the mix to ensure adequate rheology and to avoid extended mix times. The only available high shear mixer at the University of Arkansas was a Hobart Mixer with a mixing capacity of approximately 0.5 ft^3. A photograph of the Hobart Mixer containing the Ductal® premix is shown in Figure 2. The total mixing time for Ductal® using the Hobart Mixer was approximately 15 minutes.

Fig. 2 Hobart Mixer

Each of the prestressed beams required approximately 11.75 ft^3 of concrete. This 11.75 ft^3 also included a sufficient amount of concrete for casting cylinders for testing. If the Hobart Mixer had been used, each beam would have required 24 Hobart mixtures. Only accounting for mixing time, the total time to batch the 24 Hobart mixtures would have been 360 minutes (6 hrs). Additionally, Ductal® contains steel fibers which require that it be placed in one lift or pour. This would necessitate the use of a rotating drum mixer to keep the Ductal® fluid while each of the remaining Hobart batches were being mixed. The 6 hrs does not include additional time for removing the Ductal® from the Hobart and placing it into the rotating drum mixer. Therefore, to cast the two beams, the total time would have been in excess of 12 hrs.

Due to these estimated mixing times, several trial mixtures of Ductal® were batched using a standard rotating drum mixer with a capacity of 13.5 ft^3. The consistencies and flows of these mixtures were measured and compared to those mixed in the Hobart Mixer, and the results were identical for both mixers. However, the Ductal® required 45 minutes of mixing to become fluid compared to 15 minutes in the Hobart Mixer. Even though the rotating drum mixer required longer mixing times than the Hobart, the rotating drum mixer had a much larger capacity than the Hobart (13.5 ft^3 vs. 0.5 ft^3) and would require a significantly shorter time to cast the beams.

A photograph of the Ductal® being batched in the rotating drum mixer is shown in Figure 3. The evolution of the Ductal® is shown in photographs A through D. The time interval between photographs A and C was approximately 45 minutes. At photograph C, the steel fibers were added to the mixer and mixing continued for an additional 5 to 6 minutes.

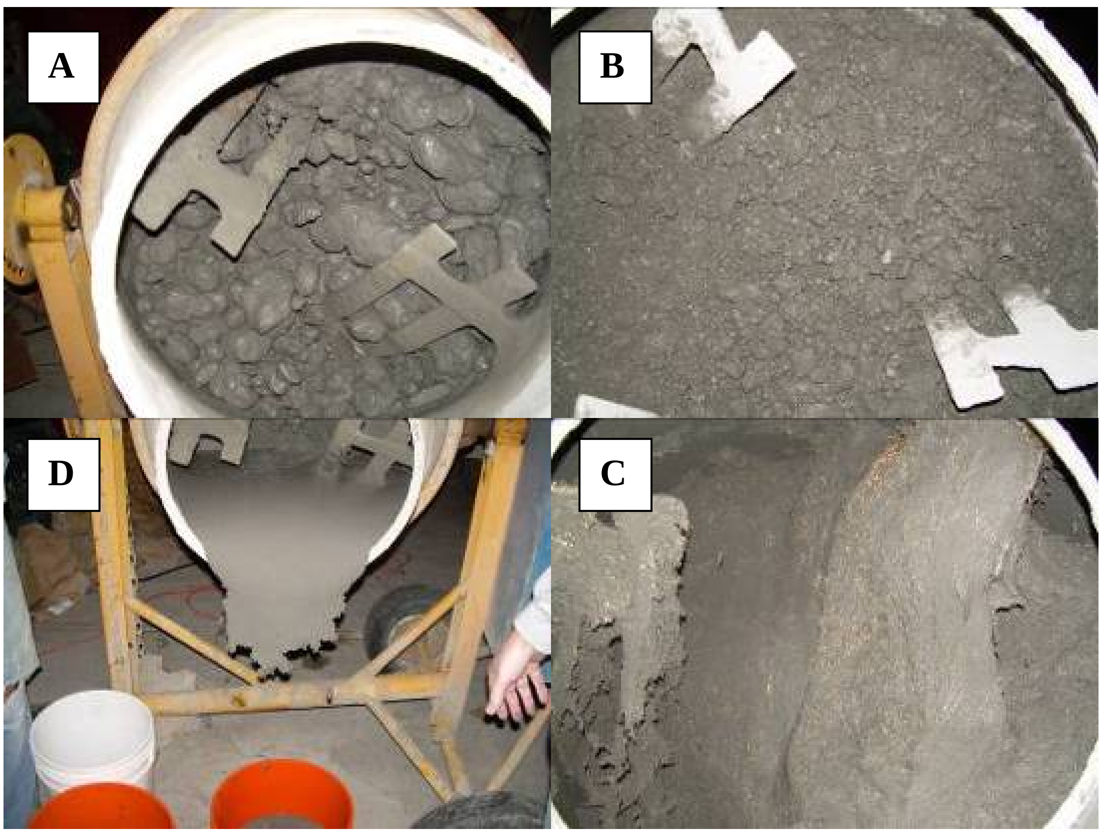


Fig. 3 Batching Ductal® in a Rotating Drum Mixer.

As previously stated, each beam required 11.75 ft^3 of Ductal® (plus cylinders for testing). Even though the capacity of the rotating drum mixer was 13.5 ft^3, 9.35 ft^3 of Ductal® was the largest batch of the Ductal® that could be mixed in the mixer, and this quantity was batched in two stages. A second rotating drum mixer with a capacity of 6 ft^3 was used to batch the remaining 2.4 ft^3. The total mixing time was 105 minutes for the 9.35 ft^3 batch, and the smaller batch (2.4 ft^3) required 50 minutes of mixing time.

CASTING

As stated earlier, the 6 HSC beams were cast using two 8 ft^3 batches. Initially, the first mixture batched would be transported in wheelbarrows from the mixer and placed into the formwork after the strands were tensioned. This mix would on average fill the formwork from end to end to a depth of 7 inches. Immediately after the first batch was emptied out of the mixer, the second batch would be mixed and again transported in wheelbarrows to be placed in the form. The time between the final pouring of the first mix to the initial pouring of the second mix was within 45 minutes for all specimens. To sufficiently place and consolidate the concrete, all HSC beams utilized extensive internal and external vibration.

Each Ductal® beam was cast in one pour or placement using the two previously described batches (9.35 ft^3 and 2.4 ft^3 batches). Before casting, the formwork for the Ductal® beams was internally lined with plastic sheets to prevent moisture loss (Figure 4). The Ductal® was transported from the mixer to the formwork in wheelbarrows. The concrete was placed at one end of the form and was allowed to flow in one direction. Because of the presence of the steel fibers, this procedure kept the fibers' orientation as unaltered as possible. The Ductal® mixtures were completely self-consolidating and therefore required no vibration. Because of the self-consolidating nature of the Ductal®, the plastic sheeting also prevented the material from flowing out of the formwork through any joints. Once casting was complete, the beams were sealed with the plastic sheets, as shown in Figure 5.

Fig. 4 Formwork before Casting

Fig. 5 Beam Sealed after Casting

CURING

The 6 HSC beams were cured outdoors and left uncovered in their forms. Typically the beams were cast by noon and the strands were released 24 hrs later. The HSC beams were not subjected to any curing regimen other than the ambient conditions. The daily temperatures during the time that the HSC beams were cast ranged from a low of 70 ^{o}F to a high of 95 ^{o}F.

The curing regimen and heat treatment are important components that significantly impact the properties of Ductal®. The curing regimen occurs from the time of placement and continues until the Ductal® achieves approximately 11.6 ksi which is typically 48 hrs after batching. The heat treatment is post-curing and is applied for 48 or 72 hrs. In this research program, the applied curing regimen and heat treatment was based on recommendations by Lafarge North America Inc. Lafarge North America Inc. suggested two regimens. The first regimen had two stages: curing at 40 ^{o}C (104 ^{o}F) and 95% relative humidity (RH) for 48 hours and followed by the heat treatment at 60 ^{o}C (140 ^{o}F) and 95% RH for 72 hours. The second option consisted of 48 hrs at 40 ^{o}C followed by 48 hrs of 90 ^{o}C (194 ^{o}F) and 95% RH. Lafarge North America Inc. also recommends detensioning when the Ductal® achieves a compressive strength of 11.6 ksi (80 MPa) and this generally occurs when the beams are two days old.

Although the second option at higher temperatures would result in greater compressive strengths (when compared to the first regimen), the researchers chose the lower temperatures because of the difficulties encountered while trying to attain and maintain 90 ^{o}C. However, due to a variety of unforeseen circumstances, the beams (excluding UHPC 2 and 3) were cured at 40 ^{o}C for 96 hrs instead of 48 hrs. The beams were also detensioned at 4 days of age. Shown below in Table 6 are the curing regimens and heat treatments for each beam and the rationale or justification for the extended times.

Table 6 Curing Regimens and Heat Treatments for UHPC Beams

UHPC Beams	**Curing Regimen**	**Heat Treatment**	**Rationale**
1	4 days at 40 ^{o}C	3 days at 60 ^{o}C	13.91 ksi was achieved by 3 days of age, but it was too late in the day to glue DEMEC points and take measurements so the strands were released on day 4.
2 & 3	4 days at 40 ^{o}C	4 days at 40 to 60 ^{o}C	Both beams were overdosed with HRWR and the cylinders did not set up until day 6. Once the cylinders set up, the temperature was gradually ramped up to 60 ^{o}C on day 5.
4 & 5	4 days at 40 ^{o}C	3 days at 60 ^{o}C	Beams achieved release strength at 3 days, but rain postponed release until 4 days of age because the DEMEC targets could not be glued on during the rain.
6 & 7	4 days at 40 ^{o}C	3 days at 60 ^{o}C	To be consistent with UHPC Beams 1, 4, and 5, these beams were also cured for 4 days at 40 ^{o}C.

A curing chamber having a cross section of 2 by 2 feet was fabricated from Styrofoam panels and was built on the prestressing bed (Figure 6). In the center of the prestressing bed, a wood box containing a metal splitter was used to receive and distribute heat from a kerosene heater. The joints between the Styrofoam panels as well as between the panels and the wood box were sealed with 2 to 3 layers of duct tape. Because the chamber had to be assembled immediately after casting, then disassembled for release, and again assembled to complete the curing process, taping was the fastest way to accomplish those tasks. A 35,000 BTU power heater maintained the required temperatures inside the curing chamber (Figure 7).


Fig. 6 Curing Chamber

Fig. 7 Heater

A temperature controller was used to regulate the temperature inside the chamber. The controller would turn the heater on when the temperature inside the chamber fell 2 ^{o}C (3.6 ^{o}F) below the targeted temperature. Additionally, temperature loggers were located inside the chamber to monitor the average of temperature during curing. Once the curing was complete, the beams were then moved from the prestressing bed to the laboratory yard. The recommended curing and thermal treatment RH of 95% was not obtained. The beams were cast during the winter months which typically have low humidity, plus the use of the kerosene heater further reduced the humidity.

INSTRUMENTATION

Instrumentation of the beams consisted of Detachable Mechanical Strain Gauge (DEMEC) targets glued onto the beams. These DEMEC targets were placed along both sides of the beam at the center of gravity of the prestressing steel. The DEMEC targets were placed at four inch increments for the first 44 inches on both sides and both ends of all beams. The DEMEC targets were used in conjunction with a DEMEC gauge to measure the change in length between the target locations. Readings using the DEMEC system were taken before the prestressing strands were cut, immediately after release (within one to two hours), and periodically up to 28 days of age. By evaluating the changes in length between DEMEC targets, the concrete strains were calculated. Additionally, using Hooke's law and the modulus of elasticity of the prestressing steel, the change in stress was computed. Shown in Figures 8 and 9 are the DEMEC targets and DEMEC gauge.

Fig. 8 DEMEC Target Locations

Fig. 9 DEMEC Gauge Reading

HARDENED CONCRETE PROPERTIES

The compressive strengths for all mix designs were determined by ASTM C39. Cylinders of 4 in. diameter and 8 in. length were used to measure the compressive strengths of the HSC mixtures. Immediately after batching, all cylinders were prepared and allowed to cure adjacent to each beam to expose them to identical states of humidity and temperature. Compressive strengths were measured at 1 (release), 7, and 28 days of age for the HSC mixtures. Release was usually at 24 to 30 hours after casting. Compressive strength averages are presented in Table 7 for the HSC mixtures.

Table 7 Compressive Strengths of HSC mixtures

Mix	**Average Compressive Strengths (ksi)**		
	1 day (f'_{ci})	**7 day**	**28 day (f'_c)**
HSC-1	8.83	10.09	12.63
HSC-2	8.84	11.07	12.69
HSC-3	9.92	13.03	12.52
HSC-4	9.85	10.28	12.67
HSC-5	8.92	11.22	10.70
HSC-6	9.58	11.95	13.10

For the Ductal® mixtures, 3 in. by 6 in. cylinders were cast. The concrete was placed into the cylinders without rodding. The random orientations of the steel fibers in the mixtures can be affected by rodding. Once the cylinders were filled, their top surfaces were partially screeded and then covered in plastic to prevent moisture loss. Complete screeding is not recommended for Ductal® because it produces voids due to the displacement of the steel fibers that may occur. After the cylinders were cast, they were cured along side each beam.

The cylinders were tested in a Forney 400 kip capacity compression testing machine. The Ductal® cylinders were tested using neoprene bearing pads for compressive strengths up to approximately 14 ksi. At strengths in excess of 14 ksi, the cylinders were tested with lead bearing pads. Compressive strengths were measured at 2 days of age and continued until the concrete had attained a compressive strength of 11.6 ksi (80 MPa). This is the strength at which Lafarge North America Inc. recommends releasing the strands. Table 8 reports the average compressive strength at release and at 28 days for the Ductal® mixtures. The strengths reported in Table 8 are the average of 3 cylinder tests.

As shown in Table 8, UHPC Beams 1, 4, 5, 6, and 7 were released at 4 days of age. For UHPC – 1, the compressive strength was measured at two days of age, but the strength was below the recommended release strength of 11.6 ksi. The strength was measured again at 3 days of age and at this time the compressive strength was 13.91 ksi. The strands could have been released at this time, but it was too late in the day to glue DEMEC targets onto the beam, take measurements before and after release, and reassemble the curing chamber. Therefore, it was decided to release the strands on day 4. When compared to UHPC Beams 4, 5, 6, and 7, the release strength of UHPC-1 was significantly lower (approximately 6 ksi), and this lower than expected release strength can be attributed to two factors. UHPC-1 was cast at 8:00 PM on November 28, 2006. Not only did this beam not benefit from the warmer day temperatures, the curing regimen did not begin until the following morning. This 12 hr delay in curing slowed the strength gain of the beam when compared to UHPC Beams 4, 5, 6, and 7 and is evident in the 4 day strength of only 14.37 ksi. Once the final treatment was completed, the compressive strength of UHPC – 1 was very similar to UHPC Beams 4, 5, 6, and 7.

The compressive strength at release for UHPC Beams 2 and 3 are also significantly lower and were measured at a later age than were UHPC Beams 4, 5, 6, and 7. Beams UHPC 2 and 3 accidentally received a double dose of HRWR which increased the w:b and reduced early and late age strength. While the strength of UHPC – 2 attained similar strengths as the other beams after the heat treatment, UHPC – 3 never recovered from the over dosage of HRWR.

Also reported in Table 8 are the results of compressive strength tests conducted by Lafarge North America Inc. at their Kansas City Performance Center (KCPC). The cylinders tested at KCPC were ground and surfaced on both ends and were then tested in a compression machine without any caps or neoprene pads. As shown in Table 8, the compressive strength after heat treatment for cylinders tested at KCPC ranged from 26.92 ksi to 28.83 ksi (excluding UHPC – 3). These results are significantly higher than the cylinders tested at the University of Arkansas which used neoprene and lead caps for compression testing. The neoprene and lead caps were approximately 5 ksi less than the strengths of the cylinders which were ground and surfaced at KCPC.

Table 8 Compressive Strengths of UHPC Mixtures Batched in a Drum Mixer

Mix	Release at:	Average Compressive Strengths (ksi)		
		Tested at U of A Using Neoprene and Lead Caps		Tested at KCPC with End Grinding
		f'_{ci} At Release	f'_c After Heat Treatment[b]	f'_c After Heat Treatment[b]
UHPC-1	4-day	14.37	26.51	27.94
UHPC-2[a]	8-day	12.77	23.00	28.83
UHPC-3[a]	8-day	12.85	15.69	17.19
UHPC-4	4-day	21.11	21.47	26.92
UHPC-5	4-day	20.88	23.78	28.30
UHPC-6	4-day	21.17	22.37	27.66
UHPC-7	4-day	22.54	22.37	27.91

[a] These beams accidentally had an increase of HRWR
[b] Modified heat treatment as per Table 6

TRANSFER LENGTH RESULTS

Transfer lengths were determined by using the 95% average maximum strain (95% AMS) method reported by Russell and Burns[9]. This method states that the transfer length is determined by the distance from the end of the beam to the point where 95 percent of the average maximum concrete strain is measured. Before applying the method, the strain profile was smoothed by averaging the data over three consecutive strain points. Figure 10 depicts the profiles of the average data obtained from DEMEC targets and the smoothed data for the live end of specimen UHPC-5. The major advantage of the 95%AMS method is that it eliminates arbitrary interpretation of test data. The method is illustrated in Figure 11 for specimen UHPC-5.

The measured transfer lengths for the HSC and UHPC beam specimens are presented in Tables 9 and 10, respectively. All measured transfer lengths were determined by using the previously described 95% AMS method. The values for transfer lengths reported in these tables are for data collected at release, 14, and 28 days at each end of each beam specimen.

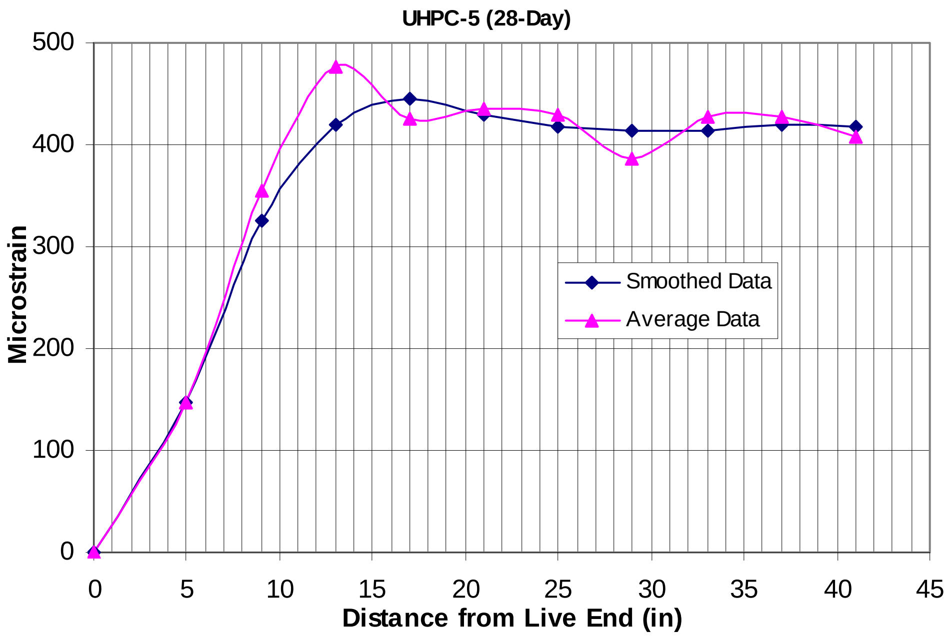


Fig. 10 Average and Smoothed Data for Specimen UHPC – 5

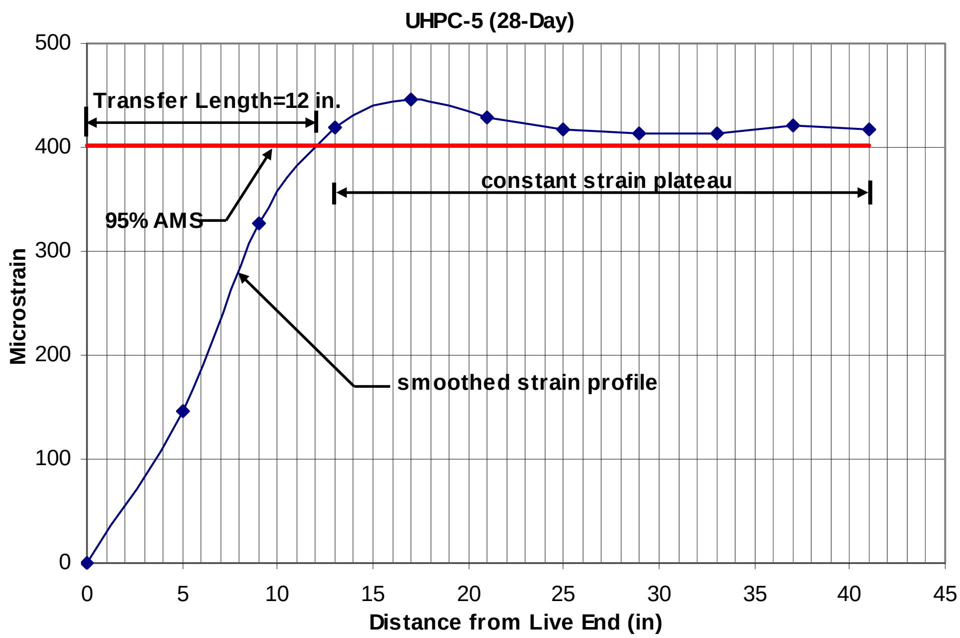


Fig. 11 95% Average Maximum Strain Method for Specimen UHPC – 5

Table 9 Measured Transfer Lengths for HSC Beam Specimens

Specimen	Measured Transfer Length Values (in.)[a]					
	Release		14 Days		28 Days	
	Live End	Dead End	Live End	Dead End	Live End	Dead End
HSC-1	16.0	18.5	17.0	19.0	21.0	19.5
HSC-2	20.5	16.0	21.0	19.0	18.0	17.0
HSC-3	15.5	22.5	22.0	25.0	21.5	25.0
HSC-4	19.0	21.0	22.0	21.0	23.0	26.5
HSC-5	21.0	25.0	22.5	27.5	25.5	28.5
HSC-6	25.0	19.0	25.0	21.5	25.5	22.5

[a] Determined using 95% AMS Method

Table 10 Measured Transfer Lengths for UHPC Beam Specimens

Specimen	Measured Transfer Length Values (in.) [a]					
	Release		14 Days		28 Days	
	Live End	Dead End	Live End	Dead End	Live End	Dead End
UHPC-1	14.5	10.5	14.5	7.5	16.0	10.5
UHPC-2	17.0	17.0	17.0	15.0	16.5	18.0
UHPC-3	15.5	14.0	17.5	10.5	16.0	14.5
UHPC-4	17.0	12.0	16.5	11.5	16.0	13.5
UHPC-5	12.0	13.0	13.0	12.0	12.0	12.0
UHPC-6	13.0	11.0	13.0	10.5	14.0	11.0
UHPC-7	16.0	15.0	16.0	12.5	14.0	13.0

[a] Determined using 95% AMS Method

TRANSFER LENGTH ANALYSIS

All measured transfer lengths for the specimens tested in this research program are shorter than those predicted using the ACI and AASHTO equations. Both ACI Code and AASHTO Specification represent transfer length as $\left(\frac{f_{se}}{3}\right)d_b$ where f_{se} is the effective stress in the prestressed reinforcement after all prestress losses (ksi) and d_b is the diameter of the strand (inches). Additionally, the ACI Code and AASHTO Specification allow for approximating transfer lengths to $50d_b$ and $60d_b$ respectively. The calculated transfer lengths using these equations and the measured transfer length values are compared in Tables 11 and 12 for the UHPC and HSC series. For the UHPC series (Table 11), the average of measured transfer lengths is 14 in., approximately $23d_b$, which is less than the suggested values of the ACI Code, $50d_b$, and the AASHTO Specification, $60d_b$. The average calculated transfer lengths using the ACI/AASHTO equation, $\left(\frac{f_{se}}{3}\right)d_b$, is also longer than the average measured transfer lengths by 63%.

A similar pattern is also observed in the HSC series. In the case of HSC series (Table 12), those values are 23 in. ($38d_b$) and 37%. It should be noted that the UHPC beams present the higher average of f_{se} and also the lower average of transfer lengths. This pattern is the opposite for the HSC beam specimens, which would suggest that the transfer length for UHPC beam specimens is not directly proportional to f_{se} as the ACI/AASHTO equation establishes.

Table 11 Transfer Length Data for UHPC Specimen Series

Specimen	f_{se}(ksi) at 28 Days	Transfer Lengths (in.)					Measured / $(f_{se}/3)d_b$	
		Measured		ACI & AASHTO $(f_{se}/3)d_b$	ACI $50d_b$	AASHTO $60d_b$	Live End	Dead End
		Live End	Dead End					
UHPC-1	188.9	16.0	10.5	37.8	30.0	36.0	0.42	0.28
UHPC-2	189.6	16.5	18.0	37.9	30.0	36.0	0.44	0.47
UHPC-3	193.8	16.0	14.5	38.8	30.0	36.0	0.41	0.37
UHPC-4	188.5	16.0	13.5	37.7	30.0	36.0	0.42	0.36
UHPC-5	191.1	12.0	12.0	38.2	30.0	36.0	0.31	0.31
UHPC-6	185.8	14.0	11.0	37.2	30.0	36.0	0.38	0.30
UHPC-7	186.3	14.0	13.0	37.3	30.0	36.0	0.38	0.35
Average	**189.1**	**14.9**	**13.2**	**37.8**			**0.39**	**0.35**

Table 12 Transfer Length Data for HSC Specimen Series

Specimen	f_{se}(ksi) at 28 Days	Transfer Lengths (in.)					Measured / $(f_{se}/3)d_b$	
		Measured		ACI & AASHTO $(f_{se}/3)d_b$	ACI $50d_b$	AASHTO $60d_b$	Live End	Dead End
		Live End	Dead End					
HSC-1	183.3	21.0	19.5	36.7	30.0	36.0	0.57	0.53
HSC-2	183.2	18.0	17.0	36.6	30.0	36.0	0.49	0.46
HSC-3	182.9	21.5	25.0	36.6	30.0	36.0	0.59	0.68
HSC-4	181.9	23.0	26.5	36.4	30.0	36.0	0.63	0.73
HSC-5	181.2	25.5	28.5	36.2	30.0	36.0	0.70	0.79
HSC-6	180.4	25.5	22.5	36.1	30.0	36.0	0.71	0.62
Average	**182.2**	**22.4**	**23.2**	**36.4**			**0.62**	**0.64**

CONCLUSIONS

The goal of the research program was to provide information on the behavior of prestressed beams constructed with UHPC. In general, results obtained from both measured and predicted values confirm that UHPC beams can achieve lower transfer lengths than HSC beams. Detailed conclusions for each of the parameters studied in this research are presented in the following sections.

- Depending on the required mechanical and durability requirements, a high shear mixer is not necessary for batching UHPC such as Ductal®. In this research program, Ductal® with compressive strengths up to 28 ksi was successfully batched in a rotating drum mixer. However, the mixing time for Ductal® was approximately twice as long as the mixing times for conventional high strength concrete mixtures.
- The results of this study also show that there may not be any adverse affect on the strengths of Ductal® mixtures when a rotating drum mixer is used. Ductal® with compressive strengths of 26.92 ksi to 28.83 ksi were produced using a rotating drum mixer while laboratory mixed Ductal® using a high shear mixer would typically achieve 34 ksi.
- For this research program, end grinding of the cylinders was necessary to achieve compressive strengths of 28 ksi. Preliminary testing using neoprene and lead caps on the cylinders were at best 6 ksi less than identical cylinders which had the ends ground and surfaced.
- To produce strengths in excess of 25 ksi, all parties involved in the batching and testing of the UHPC must pay close attention to all the details associated with batching, curing, and testing the UHPC.
- Measured transfer lengths of UHPC beams were shorter than those of the HSC beams by 40%. The average transfer length for the UHPC beams was $23d_b$.
- The ACI/AASHTO Equation overestimated the transfer lengths for all beams. The overestimation was of 63% for UHPC beams and 37% for HSC beams.

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