TRANSFER AND DEVELOPMENT LENGTHS OF PRESTRESSED BEAMS CAST WITH ULTRA-HIGH PERFORMANCE CONCRETE

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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 achieve compressive strengths of up to 30,000 psi when mixed and cured properly. For this research program, 7 UHPC prestressed beams were cast. The beams measured 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 approximately 28,000 psi to 29,000 psi when the heat treatment was completed (excluding one beam which was overdosed with high range water reducer). The average measured transfer length for the UHPC beams was approximately 14 inches at 28 days of age. The measured development lengths were less than 35 inches for the UHPC beams tested.

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. This paper presents the measured transfer and development lengths of prestressed beams cast with UHPC.

BACKGROUND

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. 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.

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 1[1].

Table 1 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

Within the last few years, there has been some research conducted on the material properties of UHPC and its application to prestressed members. In 2006, Graybeal conducted a thorough study on the material properties of UHPC. In his study, he measured compressive strengths as high as 28 ksi at 4 days of age along with a modulus of elasticity of 7,650 ksi. Graybeal determined that curing conditions immediately during setting significantly affects the properties of UHPC[2]. Graybeal also examined the performance of two, AASHTO Type II prestressed girders. These two beams were tested in shear and in flexure. The two girders measured 30 ft and 90 ft in length. The beams were reinforced with 0.50 in. diameter prestressing strands, but both girders did not contain any mild reinforcement. The results from the shear tests indicated that the development length was less than 37 inches[3].

Related work on the bond of prestressing strand in UHPC was conducted by Steinberg and Lubbers. Strands measuring 0.50 in. in diameter (and 0.50 in. oversized) were cast (untensioned) into pull-out blocks. For standard 0.50 in. strands, they determined that an embedment length greater than 18 in. in UHPC was necessary to achieve the same bond performance as an embedment length of 24 in. in conventional concrete[4]. They also determined that an embedment of only 12 in. was necessary to fracture the strands[5].

Federal funding was granted for the construction of the first UHPC bridge in the U.S. The bridge is located in Wapello County, Iowa. The bridge consists of three, 110 ft. long girders. For the girders, a modified version of a standard Iowa bulb tee section was used. Additionally, the girders contained only 0.60 in. diameter prestressing strands, and the only mild reinforcement used in the beams was there to provide composite action between the slab and the beams. The bridge was open to traffic in February 2006. To verify the flexural and shear capacities of the beam, a 71 ft UHPC girder was cast and tested by Iowa State University (ISU). There were concerns that the “reduced transfer lengths (possibly less than 12 inches) may cause a concentration of release forces at the interface between the bottom flange and web”. Because of this, some strands were debonded and some were draped. After casting, the researchers found no cracking in the flange/web interface due to the shortened transfer lengths[6].

As previously shown, there has been some research that indirectly measured the transfer and development lengths of prestressing strands cast in UHPC. The goal of this research program is to directly measure those lengths for 0.60 in. diameter strands cast in UHPC beams.

EXPERIMENTAL PROGRAM

Seven UHPC beams were cast and tested at the concrete laboratory located in the Engineering Research Center (ERC) at the University of Arkansas (UA). The beams were 18 feet long and contained two 0.60 diameter prestressing strands. The cross-section of the UHPC beams is shown below in Figure 1.

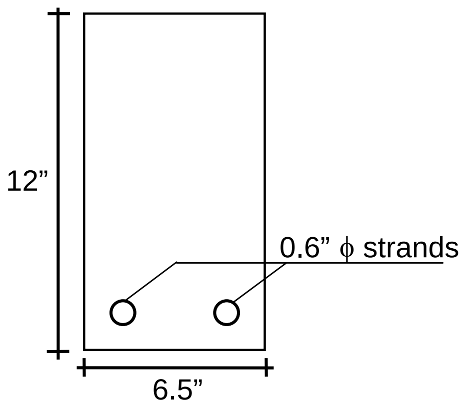

Fig. 1 Typical Beam Cross Section

MIXTURE PROPORTIONS

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 80 pound bags. The Ductal® mix proportion used throughout this research was based on recommendations suggested by Lafarge North America Inc. and is shown below in Table 2.

Table 2 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 Ductal® is different to that of conventional concrete. Ductal® is very thick and dense with a very low water to binder ratio, 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. Because of the limited mixing capacity of the UA's high shear mixer, the UHPC was cast in a rotating drum mixer. The mixing procedure was described in greater detail in an earlier paper by the authors[7].

A photograph of the Ductal® being batched in the rotating drum mixer is shown in Figure 2. 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.

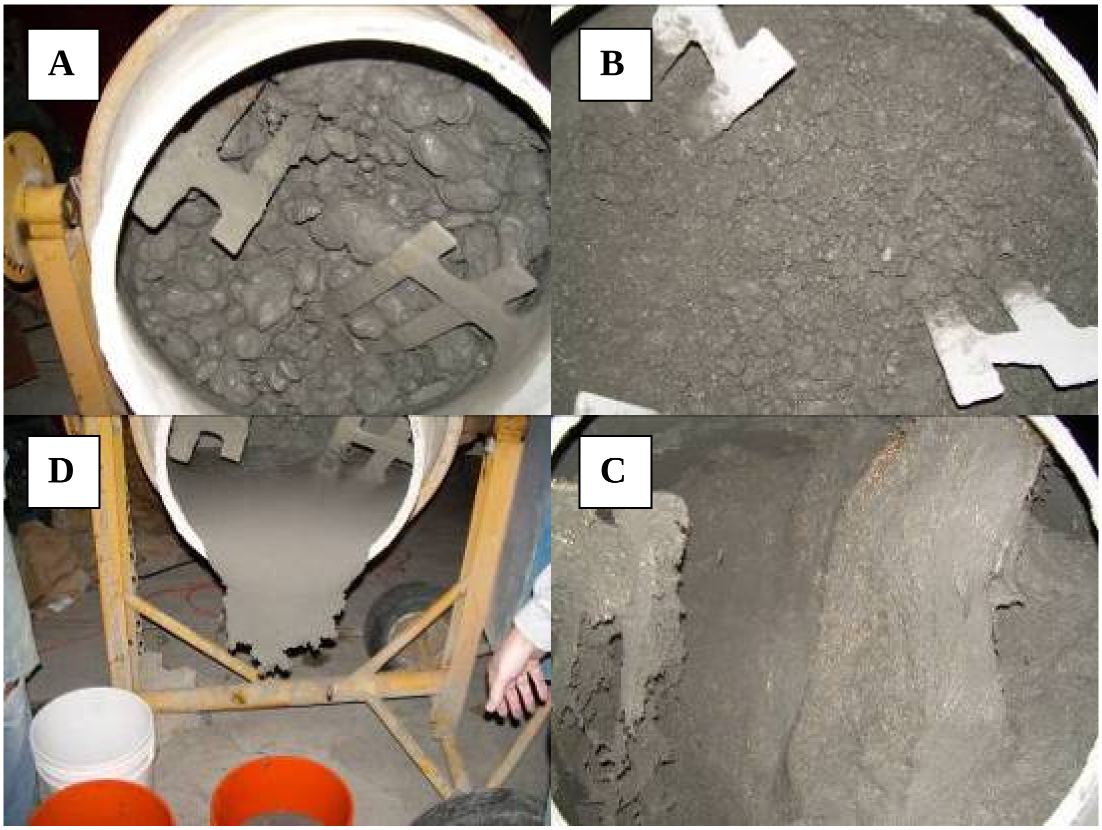

Fig. 2 Batching Ductal® in a Rotating Drum Mixer.

CASTING

The UHPC beams were cast in one pour or placement using two batches of 9.35 ft^3 and 2.4 ft^3. Before casting, the formwork for the Ductal® beams was internally lined with plastic sheets to prevent moisture loss. 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.

CURING

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. However, due to a variety of unforeseen circumstances, the beams (excluding UHPC 2 and 3 which were overdosed with HRWR) were cured at 40 ^{o}C for 96 hrs instead of 48 hrs. The beams were also gradually detensioned at 4 days of age. The heat treatment is described in greater detail in an earlier paper by the authors[7].

TRANSFER LENGTH 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. 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. Shown in Figures 3 and 4 are the DEMEC targets and DEMEC gauge.

Fig. 3 DEMEC Target Locations

Fig. 4 DEMEC Gauge Reading

DEVELOPMENT LENGTH

Evaluation of development length for the selected beams was performed using flexural load tests. A single point load was applied to the beam at a specified distance from the beam end, and the beam was loaded to failure. The location of the load was based on the embedment length, L_e. The embedment length is defined as the distance from the end of the beam to the section that can develop its full strength when the load is applied. This section is also known as the critical section. The location of the point was varied in order to establish bounds for the development length. The behavior of the strands at failure is used to determine whether the tested embedment length is longer or shorter than the development length. If strand slip occurs before the nominal moment is reached, then the embedment length is shorter than the development length and a longer embedment length is used for the next test. Conversely, if no strand slip is detected after the beam achieves the nominal moment, the embedment length is greater than the development length and a shorter embedment length is used for the next test. For the case where the embedment length is equal to the development length, failure by flexure occurs at the same time as strand slip after the nominal moment is reached.

The flexural tests used a setup consisting of a simple span beam loaded with a single concentrated load at a predetermined distance from the beam end being tested. The beam was placed within a testing frame and load was applied using a hydraulic jack. The load frame setup and a tested beam are shown in Figures 5 and 6.

Fig. 5 Development Length Test Set-Up

Fig. 6 Tested Beam

The applied load was measured using a pressure transducer connected to the hydraulic lines of the hydraulic jack. Applied loads were continually monitored using the data acquisition system while pressure was applied with a hand pump. Displacement was measured at the point of load. Linear voltage displacement transducers (LVDTs) were used to measure strand slip. One LVDT was attached to each strand at the end of the beam being tested. Readings from the LVDTs were continuously monitored using the data acquisition system in order to detect the beginning of any strand slip. Strand movements as small as 0.001 in. could be detected by the LVDTs.

HARDENED CONCRETE PROPERTIES

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 Ductal® cylinders were tested using neoprene bearing pads for compressive strengths up to approximately 14 ksi. 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 3 reports the average compressive strength at release and after the heat treatment for the Ductal® mixtures. The strengths reported in Table 3 are the average of 3 cylinder tests.

Table 3 Compressive Strengths of UHPC Mixtures Batched in a Drum Mixer

Mix	Release at:	Average Compressive Strengths (ksi)	
		f'_{ci} At Release	f'_{c} After Heat Treatment
UHPC-1	4-day	14.37	27.94
UHPC-2[a]	8-day	12.77	28.83
UHPC-3[a]	8-day	12.85	17.19
UHPC-4	4-day	21.11	26.92
UHPC-5	4-day	20.88	28.30
UHPC-6	4-day	21.17	27.66
UHPC-7	4-day	22.54	27.91

[a] These beams accidentally had an increase of HRWR

TRANSFER LENGTH RESULTS

Transfer lengths were determined by using the 95% average maximum strain (95% AMS) method reported by Russell and Burns[8]. 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.

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 Table 4. 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%.

Table 4 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**

DEVELOPMENT LENGTH RESULTS

As previously stated, the development length cannot be determined directly from a single test. To estimate a range where the development length exists, flexural load tests were performed by varying the embedment length (L_e). This trial and error process led to a range bounded by the longest and the shortest embedment length where the development length may be located. To date, three of the seven UHPC beams have been tested. The results of the three tests are shown below in Table 5. In addition to the nominal moment capacity (M_n), Table 5 also shows the maximum moment measured during testing (M_{max}) and the moment when strand slip occurred (M_{slip}).

Table 5 Summary of Flexural Tests

Specimen	L_E (in)	M_n (kip-in)	M_{slip} (kip-in)	M_{max} (kip-in)	M_{slip}/M_n	M_{max}/M_n
UHPC-5	35	1111	1686	1740	1.52	1.57
UHPC-6	45	1107	----	1538	----	1.39
UHPC-7	60	1107	----	1551	----	1.40

All UHPC specimens failed in flexure. Even with the short embedment length of 35 in., no shear failures were observed. The flexural failures occurred when the applied moment exceeded the corresponding calculated nominal moment for each beam. Strand slip was observed only in specimen UHPC-5 with an embedment length of 35 in. It should be noted that the first specimen tested was UHPC-7, then UHPC-6, and finally UHPC-5. This sequence of tests followed a criterion of testing a longer embedment length first and then reducing it on following tests until strand slip occurs. Since strand slip occurred in UHPC-5 at a moment that was approximately 50% greater than M_n, the development length of the UHPC specimens is less than 35 in.

Both the ACI Code and AASHTO Specification represent development length as $\left(\frac{f_{se}}{3}\right)d_b + \left(f_{ps} - f_{se}\right)d_b$ where f_{se} is the effective stress in the strands after all prestress losses (ksi), f_{ps} is the nominal stress in the strand (ksi), and d_b is the diameter of the strand (inches). The calculated values of development lengths using this equation and the embedment length values are compared in Table 6. From this table, it can be seen that the predicted development length using ACI/AASHTO equation is greater than that observed by testing. The overestimation of the development length for UHPC specimens is expected to be greater than 58%.

Table 6 Development Length Comparisons

Specimen	f_{se} (ksi)	f_{ps} (ksi)	L_e (in)	Development Length (in.)		$\frac{L_e}{\text{ACI/AASHTO}}$
				Observed	ACI/AASHTO	
UHPC-5	191.10	267.86	35.00	<35	84.28	0.42
UHPC-6	185.80	267.70	45.00		86.30	0.52
UHPC-7	186.30	267.70	60.00		86.10	0.70

CONCLUSIONS

The goal of the research program was to provide information on the transfer and development lengths of 0.60 in. prestressing strands cast in UHPC. For the seven beams examined in which transfer length was measured and the three beams tested in flexure, the results show that UHPC beams can achieve significantly lower transfer and development lengths than those obtained from ACI and AASHTO prediction equations. Detailed conclusions from the research program are presented below.

- 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 63% for UHPC beams.
- The development length of all tested beams was less than 35 inches.
- The ACI/AASHTO Equation overestimated the development length for all beams by approximately 60%.

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