Ultra-High Performance Concrete for Highway Bridges

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Summary

The U.S. Department of Transportation's Federal Highway Administration is investigating the use of Ultra-High Performance Concrete in highway bridges. The advanced properties of UHPC allow for a rethinking of the basic mechanisms normally used by concrete girders to carry loads. Structural testing has shown that UHPC girders exhibit high flexural and shear capacities due to the tensile load-carrying capabilities of the material without the aid of mild steel reinforcing bar. Analytical optimization of highway bridge girders for more efficient use of UHPC has led to the construction of an experimental highway bridge at the Turner-Fairbank Highway Research Center.

Keywords: ultra-high performance concrete; highway bridge; material characterization; strength; shrinkage; creep; large scale destructive testing; flexure; shear.

1. Introduction

The U.S. Department of Transportation's Federal Highway Administration has an ongoing research program investigating the use of Ultra-High Performance Concrete in highway bridges. Ultra-High Performance Concrete (UHPC) is a concrete characterized by its high strength, its superior durability, and its internal passive fiber reinforcement. The Federal Highway Administration (FHWA) is investigating whether UHPC's advanced properties can effectively and economically be used in new highway bridge construction.

2. FHWA UHPC Research Program

The ongoing research at FHWA is focusing on the characterization of the properties and the determination of optimal structural uses of UHPC. Research to date has focused on a UHPC produced by Lafarge, Inc. and marketed under the name Ductal®. The first phase of the research program focused on determining whether it was feasible to create prestressed bridge girders from UHPC and how those girders would behave structurally under flexural and shear loadings. Following these tests, a material characterization study was undertaken to determine the full range of UHPC properties relevant to its use in bridge structures. The next phase included analytical work to determine the optimal design of a bridge girder/deck combination for a medium span highway bridge (21.4 m). The FHWA then built three optimized full-scale bridge girders based on the analytical results. Finally, the FHWA is actively working with a number of U.S. state departments of transportation to begin using UHPC in the highway bridge construction.

3. Material Characterization

The material characterization of UHPC has focused on a full range of properties important to the use of UHPC in highway bridge girders [1,2]. Strength and long-term stability are two of these properties. Due to the varying nature of the curing procedures that can be applied to UHPC, the material characterization testing was performed on specimens treated to four different regimes. These regimes included steam treatment (90°C, 95% RH) for 48 hours starting at one day after cast, air treatment (laboratory ambient conditions), tempered steam treatment (60°C, 95%RH) for 48 hours starting at one day after cast, and delayed steam treatment (90°C, 95% RH) starting 15 days after casting.

3.1. Compressive Behaviour

Compression testing of cylinders was the primary means used to determine the compressive strength of the UHPC. The standard size cylinder had a diameter of 76 mm and a pre-end preparation length of 152 mm. All the cylinders discussed in this paper had their ends prepared with an end grinder, and their final lengths were approximately 1.95 times their diameter. The cylinders were all tested according to ASTM C39 except that the load rate was changed to 1 MPa/sec.

Table 1. Compressive Strength of UHPC.

Post-Cure Treatment	Compressive Strength	Standard Deviation
Steam	193 MPa	14 MPa
Ambient Air	124	12
Tempered Steam	174	9
Delayed Steam	172	10

The curing method applied to the UHPC has a significant effect on the compressive strength. Table 1 provides the 28 day strength results for the control cylinders. The strength of the Steam treated UHPC is approximately 193 MPa. The Tempered Steam and Delayed Steam treated specimens exhibited strengths approximately 10% lower. The Ambient Air treated specimens only achieved 65% of the Steam treated specimen strength.

The rate of strength and stiffness gain of UHPC is also an important factor in the design of bridges. Cylinders were loaded in compression according to the same procedure discussed above while their compressive stress-strain behaviour was continuously monitored. The results from these tests show that this UHPC mix design begins to gain its strength around 20 hours after casting. The strength gain is relatively rapid, and by 72 hours after casting non-steam treated UHPC exhibited compressive strengths over 80 MPa. Figure 1 shows the stress-strain behaviour of the delayed steam treated UHPC at various ages after casting. Recall that the steam treatment for these specimens occurred from days 15 through 17.

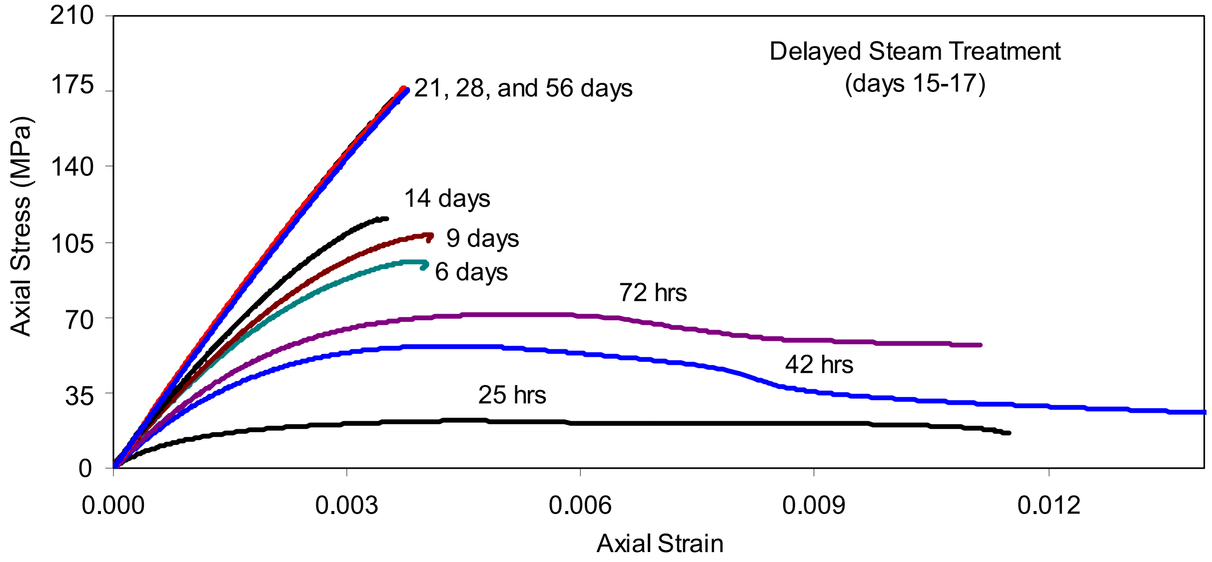

Figure 1. Stress-Strain Behaviour of UHPC.

3.2. Tensile Behaviour

Material characterization of the tensile behaviour of UHPC was determined through the use of the ASTM C496 split cylinder tension test. 100 mm diameter cylinders of approximately 195 mm length were tested for all four curing regimes previously discussed. Figure 2 shows the tensile cracking results from these tests, including the age of the UHPC at testing and an error bar indicating one standard deviation of the average results. The tensile cracking strength of the steam treated UHPC, regardless of the type or time of steaming, was approximately 11 MPa. Non-steam treated UHPC reached 9 MPa cracking strength at 28 days.

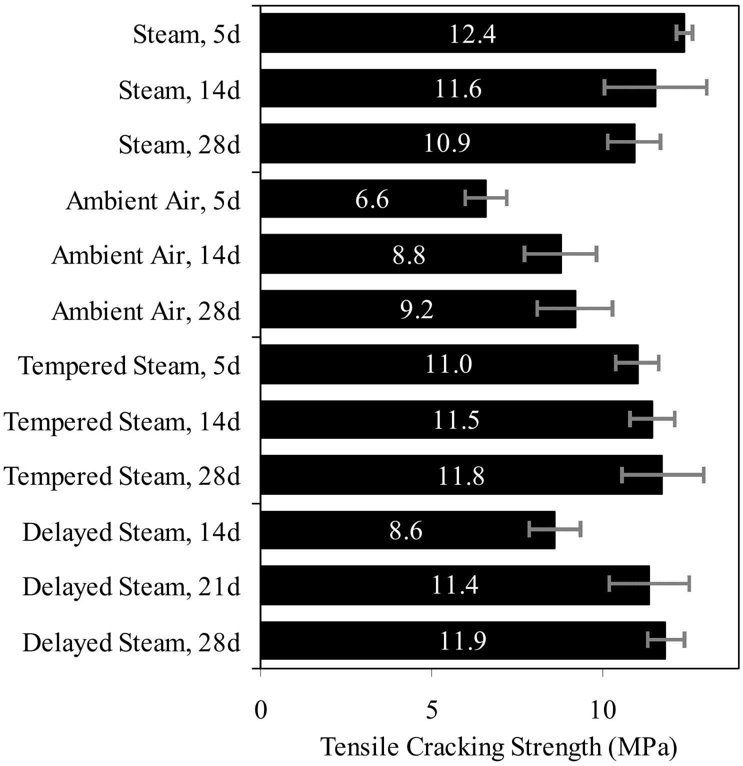

Figure 2. Tensile Cracking Strength of UHPC.

3.3. Shrinkage Behavior

Given the high cement content and the lack of an aggregate skeleton, UHPC can exhibit a large amount of shrinkage. ASTM C157 test results from prisms cast and cured under the four different curing regimes are shown in Figure 3. All the prisms were stripped at approximately 24 hours after casting and their initial length reading was then recorded. The period of time during which a prism was being steamed is shown with a dotted line.

Early age shrinkage can be especially large in UHPC, and the highest rate of shrinkage tends to occur during the period of early age strength gain. Due to this fact, traditional shrinkage measurement techniques can miss shrinkage that is occurring as the UHPC is beginning to set. Tests using embedded vibrating wire gages were conducted to measure this early age shrinkage.

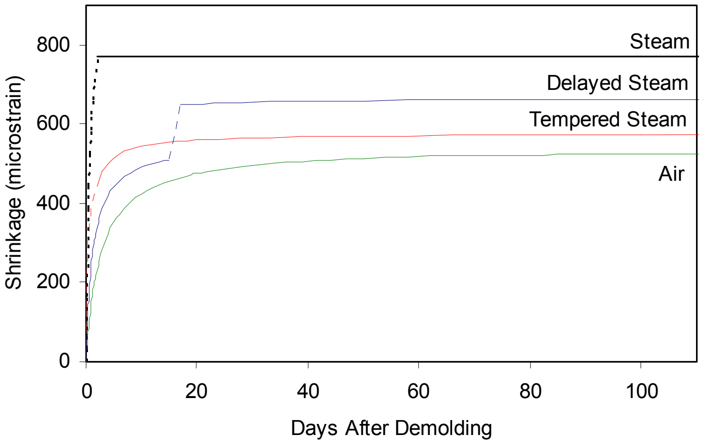

Figure 3. Shrinkage of UHPC.

Gages were embedded along the longitudinal axis of a shrinkage prism. These gages were monitored continuously under both the air and the steam treated regimes. These tests showed that the shrinkage began to occur at 20 hours after casting and by 30 hours after casting over 300 microstrain of shrinkage had already occurred. The air cured UHPC then tended to exhibit approximately 35 microstrain shrinkage per day from the second through the sixth day after casting while the steam treated UHPC exhibited over 400 microstrain of shrinkage during the treatment but was then effectively stabilized.

3.4. Creep Behavior

The creep behavior of UHPC has also been studied for the four curing regimes. Creep testing was conducted according to ASTM C512 with the load applied to specimens from all curing regimes being forty percent of the expected compressive strength of the steam cured cylinders (i.e. 77 MPa applied load). The cylinders were loaded 28 days after casting, regardless of the curing method.

The creep behavior of the UHPC is shown in Figure 4. The projected creep coefficients based on the first 100 days of testing are 0.13, 0.66, 0.50, and 0.24 for the steam, air, tempered steam, and delayed steam treatments, respectively.

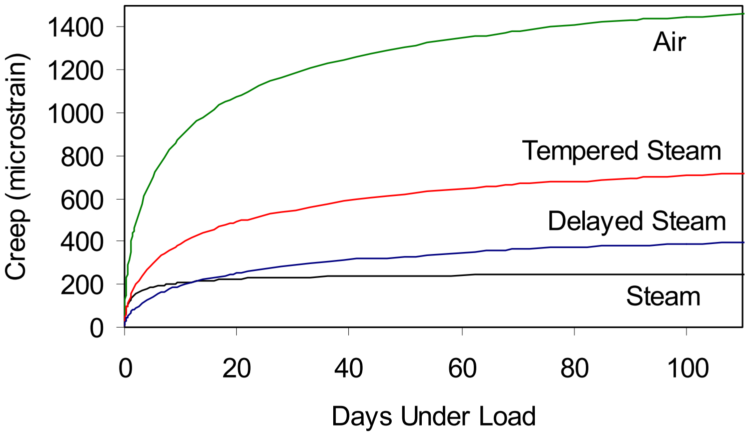

Figure 4. Creep of UHPC.

4. Bridge Girder Testing

The FHWA has conducted full-scale bridge girder testing of 0.91 m deep AASHTO Type II prestressed girders [3]. These UHPC prestressed girders contained no passive reinforcing steel, thus the steel fiber reinforcement was expected to carry significant tensile forces within the girders. The testing included one flexure test and three shear tests.

4.1. Flexure Testing

AASHTO Type II girders are normally used for relatively short span bridges of around 16 m. The UHPC girder flexure test consisted of loading a 23.8 m prestressed girder by two point loads each located 0.9 m from midspan. Periodic unloadings throughout the testing allowed for determination of the residual stiffness of the girder at varying levels of sustained damage. The load-deflection response of the girder is shown in Figure 5. This testing confirmed that fiber reinforced UHPC can carry significant tensile forces after cracking of the concrete matrix. The moment capacity of this girder was over two times the moment capacity that would be expected from an identical girder composed of 55 MPa concrete. This test also showed that this UHPC could exhibit a very tightly spaced crack pattern and a high post-cracking tensile strain capacity in highly strained areas. Based on the strain in the compressive flange and the neutral axis location, the equivalent strain in the bottom flange of this girder at peak loading was

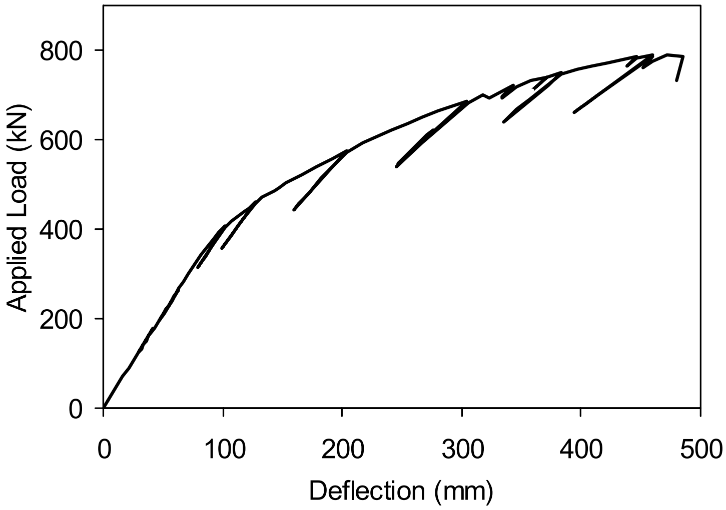

Figure 5. Load Deflection Response for a UHPC Flexural Girder Test.

approximately ten thousand microstrain. The crack spacing on the bottom flange near midspan was less than 3 mm.

4.2. Shear Testing

Three shear tests were conducted on AASHTO Type II prestressed girders containing no mild steel shear reinforcement. These single point loaded, simple span girders had shear spans ranging from 2.0 to 2.5. Additionally, two of the girders had their prestressing strands fully transferred prior to the shear span. Again, periodic unloadings were performed to determine the residual stiffness of the girders throughout the load history.

Two of these girders failed by traditional diagonal shear cracking followed by fiber pullout and failure. The third girder failed due to localized cracking at the base of the web in the shear region, likely due to damage that the girder sustained prior to the shear test. The shear capacity exhibited by these girders ranged from 2200 kN for the fully transferred girder to 1950 kN for the partially transferred girder to 1700 kN to the previously damaged girder. Shear capacity calculations based on the Setra/AFGC Interim Recommendations for Ultra High Performance Fiber-Reinforced Concretes [4] indicate that the ultimate limit state shear capacity of these girders is 810 kN.

5. Bridge Girder Optimization

The flexure and shear girder testing described above indicates that UHPC can effectively be used in highway bridge girders. However, the AASHTO Type II girder clearly does not make efficient use of the advanced properties of UHPC. Optimization of highway bridge girder shapes to take advantage of these advanced properties has been completed [5]. The optimized shape for a 21 to 31 m long bridge consists of a prestressed π-shaped girder/deck combination that is 0.84 m deep and has webs and a deck 76 mm that are thick. The FHWA is currently building a 21.3 m long optimized prestressed UHPC bridge at the Turner-Fairbank Highway Research Center.

6. Conclusion

The Federal Highway Administration's recent research into the use of UHPC in highway bridges indicates that this material is applicable and is a viable structural alternative compared to standard prestressed concrete designs. This material's structural properties are significantly advanced over currently used concretes. Structural testing indicates that UHPC can exhibit significant post-cracking tensile load-carrying capacity and can carry shear forces without the aid of passive mild steel reinforcement. These results have led the FHWA to construct an optimized UHPC bridge to demonstrate the capabilities of the material.

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This paper is intended as an academic discussion, not as engineering advice, and no reliance upon this paper is permitted. Independent advice by the professional of record as to the application of the concepts and opinions contained herein to any specific project should be sought.

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