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Errata

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The following changes were made to the document after publication on the Federal Highway Administration Web site:

Location
Page 4, Equation in Figure 3.

Incorrect Values

$$f'_{c,t} = f'_{c,28d}\left(1 - e^{-\frac{(t - t_{start})^{b}}{a}}\right)$$

Corrected Values

$$f'_{c,t} = f'_{c,28d}\left(1 - e^{-\left(\frac{t - t_{start}}{a}\right)^{b}}\right)$$

TECH**BRIEF**

Compression Response of a Rapid-Strengthening Ultra-High Performance Concrete Formulation

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This document is a technical summary of the unpublished Federal Highway Administration (FHWA) report, *Compression Response of a Rapid-Strengthening Ultra-High Performance Concrete Formulation*, available through the National Technical Information Service at www.ntis.gov.

Objective

Ultra-high performance concrete (UHPC) has garnered interest from the highway infrastructure community for its ability to create strong, robust, field-cast connections between prefabricated structural components. The objective of this research was to evaluate the compressive mechanical response of a rapid-strengthening UHPC formulation exposed to a range of curing conditions. The results of the research effort are provided herein.

Introduction

There is a growing need for durable and resilient highway bridge construction/reconstruction systems that facilitate rapid completion of onsite activities, thus minimizing the intrusion forced on the traveling public. Modular components can provide high-quality, accelerated, and safe construction; however, offsite prefabrication of bridge components necessitates an increased reliance on the performance of field-installed connections between these components. The mechanical and durability responses of the grouts used in these connections are critical to the overall performance of the infrastructure system.

UHPC is an advanced construction material that provides new opportunities for the future of highway infrastructures. Since 2001, the Federal Highway Administration has been researching the optimal uses of UHPC in highway bridge infrastructures through its Bridge of the Future initiative. Recently, the highway sector has focused on UHPC's use as a

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field-cast grout that can simultaneously afford simplified construction practices and enhanced long-term performance. One concern with UHPC-class materials has been their tendency to exhibit a dormant period after mixing and prior to the initiation of mechanical property development. The accelerated achievement of particular mechanical response benchmarks is of particular interest, as it could enable the broader use of UHPC-class materials in accelerated bridge construction projects.

UHPC

Advances in concrete materials have led to the development of a new generation of cementitious materials, namely UHPC. As a class, these concretes tend to contain high cementitious materials contents, low water-cementitious materials ratios, compressive strengths above 22 ksi (150 MPa), and sustained tensile strength resulting from internal fiber reinforcement. Table 1 presents a set of material properties for a UHPC formulation similar to that investigated in this study. Further details on the mechanical and durability properties of this UHPC can be found in *Material Property Characterization of Ultra-High Performance Concrete.*(1) An introduction to UHPC can be found in *Ultra-High Performance Concrete*, and assistance with the construction of field-cast UHPC connections is provided in *Construction of Field-Cast Ultra-High Performance Concrete Connections.*(2,3)

The exceptional durability of UHPC has been well documented. Of particular importance, UHPC does not exhibit early-age microcracking that commonly occurs with conventional concrete. This feature, combined with the discontinuous pore structure in the homogeneous cementitious matrix, results in concrete with an extremely low permeability.

Table 1. Field-cast UHPC material properties.

Property	Value
Unit weight	158 lb/ft^3 (2,535 kg/m^3)
Modulus of elasticity	7,500–8,500 ksi (52–59 GPa)
Compressive strength	25–32 ksi (170–220 MPa)
Post-cracking tensile strength	1.0–1.5 ksi (7.0–10.3 MPa)
Chloride ion penetrability (ASTM C1202-12)(4)	Very low to negligible

The tensile mechanical response of UHPC also surpasses that of conventional concrete. The discrete steel fiber reinforcement included in UHPC components allows the concrete to maintain tensile capacity beyond cracking of the cementitious matrix. The inelastic straining of the component is resisted by fiber reinforcement that bridges the tight, closely spaced cracks.

The durability and sustained tensile capacity of UHPC present opportunities to rethink common concepts in reinforced concrete structural design. For example, the tensile capacity of UHPC could eliminate the need for discrete mild steel reinforcement in some structural members, and the durability could reduce the cover required for any remaining reinforcement. Of particular interest, UHPC can significantly shorten the development length of embedded discrete steel reinforcement, can exhibit exceptional bond when cast against previously cast concrete, and can display both high and sustained levels of tensile resistance. These properties facilitate the redesign of the modular component connection, leading to simplified construction and enhanced long-term system performance.

Testing Program

This research project focused on the assessment of compressive mechanical response of rapid-strengthening UHPC. Eight batches of this UHPC formulation were mixed and used to cast sets of cylinders that were 3 inches (76.2 mm) in diameter and 6 inches (152.4 mm) in nominal length. The mix design included the manufacturer-supplied premix, superplasticizer, and steel fiber reinforcement, along with potable water. The steel fiber reinforcement was 0.5 inches (12.7 mm) long and 0.008 inches (0.2 mm) in diameter and was composed of straight fibers included at 2 percent by volume. The primary mix design was used for six of the batches, while the remaining two batches also included a chemical accelerator to assess its ability to accelerate the attainment of compressive mechanical response benchmarks.

Approximately 33 cylinders were cast from each batch and then cured using 1 of 3 curing regimes until testing. The curing regimes included an ambient room temperature cure, an elevated temperature cure, and a reduced temperature cure. The associated temperatures were 73, 105, and 50 °F (23, 41, and 10 °C), respectively. The test specimens were subjected to the curing condition continuously from casting until approximately 1 h before compression testing.

The tests were completed through a modified version of ASTM C39-11, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," and ASTM C469-10, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression."(5,6) According to the ASTM C39-11 test method, the two modifications were that the load rate increased and that the axial strain was captured during the test. The specified loading rate of 35 psi/s (0.24 MPa/s) was changed to 150 psi/s (1.0 MPa/s) due to the high compressive strength of UHPC and the duration of the test, which resulted from the slower load rate. The axial strain was measured through the use of a parallel ring compressometer. This device is similar to the traditional compressometer described in ASTM C469-10, except that it holds three measurement transducers and does not use a hinge to multiply the deformations. Aside from the increased load rate, the tests completed in this study followed the alternative given in section 6.5 of ASTM C469-10, which allows for the simultaneous collection of both compressive strength and modulus of elasticity.(6)

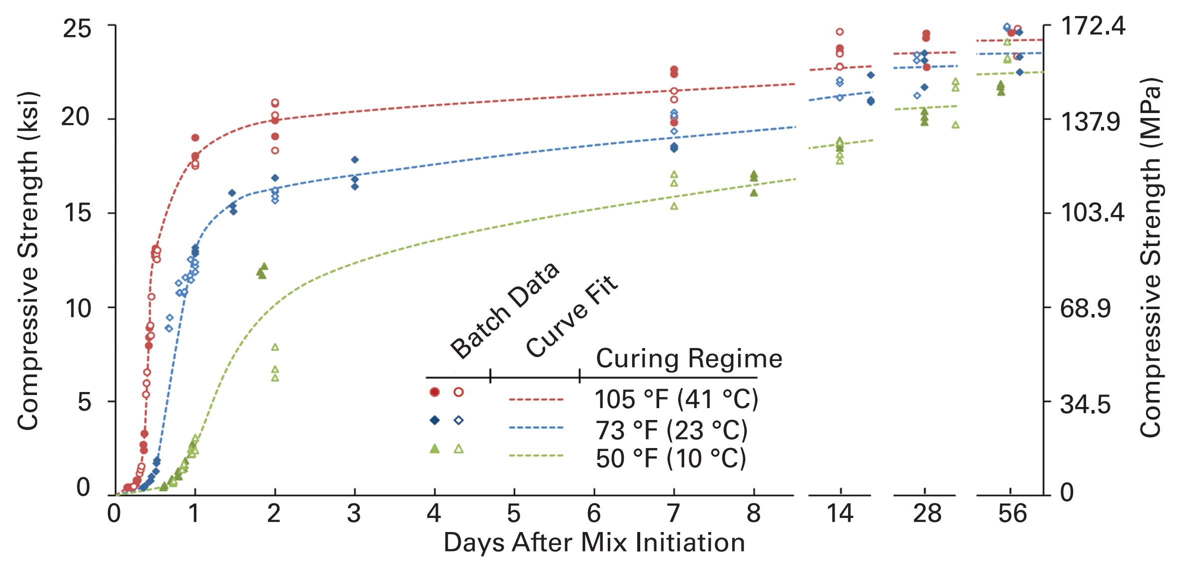
The variables considered within this study included the effect of using a chemical accelerator and the effect of curing temperature on the compressive mechanical response. Additionally, specimens were cast from two different premix deliveries, thus allowing for assessment of the effect of premix age after blending. Batches were mixed with premix ages ranging from 2.5 to 6 months.

Performance indicators focused on the axial compressive stress and strain response of the UHPC. Compressive strength, modulus of elasticity, strain at compressive strength, and overall stress-strain response were captured and analyzed.

Results

This study provided a clear indication of the compressive mechanical response of this UHPC formulation as influenced by a range of curing temperatures. The compressive strength gain as a function of time and curing temperature is of greatest practical interest to the everyday use of this UHPC. Figure 1 shows the compressive strength gain from 0 to 56 days after casting for the three curing conditions. Two independent

Figure 1. Compressive strength gain results.



batches were tested for each curing condition. An approximate response curve is shown for each curing condition. Note the clear impact that the curing temperature had on the time to strength gain initiation and on the rate of strength gain. In all cases, the strength surpassed 21.7 ksi (150 MPa) by 56 days after mixing.

A relationship between the constant curing temperature and the time to start of rapid strength gain was developed. This simple relationship is provided in figure 2.

Figure 2. Relationship between curing temperature and initiation of rapid compressive strength gain from 50 to 105 °F (10 to 41 °C).

$$t_{start} = \frac{2.8}{\sqrt{T}}$$

Where:

t_{start} = Time of initiation of rapid strength gain in days.
T = Curing temperature in degrees Celsius.

A curve fitting analysis was conducted on the strength gain results. The result of this analysis is shown in figure 3. The strength of the UHPC can be determined based on the 28-day strength and the time after the start of mixing. Table 2 provides the appropriate curve-fitting parameters for the three curing regimes.

Figure 3. Relationship between time after mix initiation and compressive strength as a function of curing temperature.

$$f'_{c,t} = f'_{c,28d}\left(1 - e^{-\left(\frac{t - t_{start}}{a}\right)^{b}}\right)^{*}$$

Where:

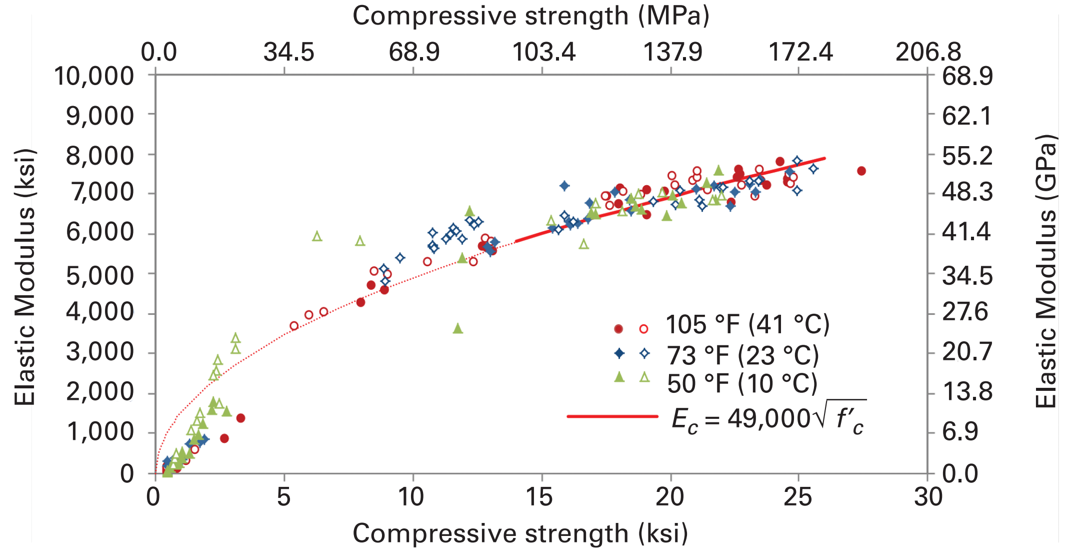
$f'_{c,28d}$ = Compressive strength at 28 days (ksi).
$f'_{c,t}$ = Compressive strength at time t in days after mix initiation (ksi).
a = Fitting parameter in days.
b = Dimensionless fitting parameter.

Table 2. Parameters relevant to function presented in figure 3.

Curing Regime	T (°C)	$f'_{c,28d}$ (ksi)	a (days)	b
105 °F (41 °C)	41	24.5	0.25	0.25
73 °F (23 °C)	23	24	1.0	0.30
50 °F (10 °C)	10	22.5	4.0	0.50

The relationship between the compressive strength and the modulus of elasticity was also evaluated. Figure 4 provides the results from the six batches of UHPC at three curing temperatures. A best-fit analysis of the compressive strength results between 14 and 26 ksi (97 and 179 MPa) indicates that the equation in figure 5 provides an appropriate fit over this strength range.

Figure 4. Modulus of elasticity as a function of compressive strength.



* Equation revised March 29, 2016

Figure 5. Modulus of elasticity as a function of compressive strength between 14 and 26 ksi (97 and 179 MPa).

$$E_c = 49{,}000\sqrt{f'_c}$$

Where:

E_c = Modulus of elasticity in psi.
f'_c = Compressive strength in psi.

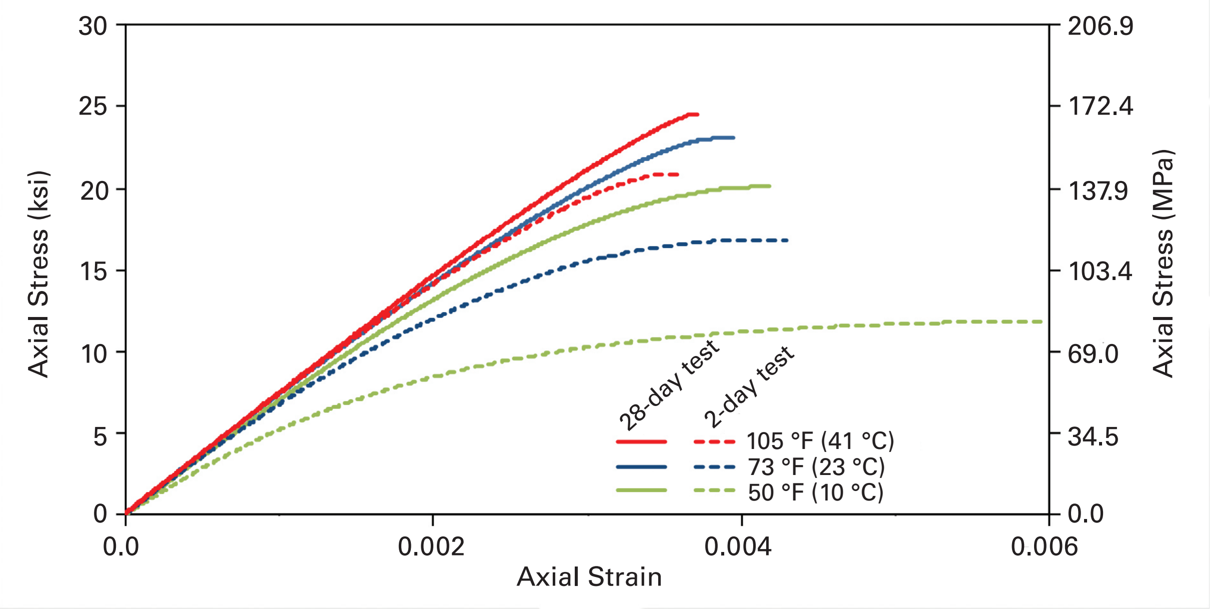
The overall stress-strain response of this UHPC was also captured through this test program. Both qualitative and quantitative assessments of the development of overall compressive mechanical response were completed. Figure 6 shows two stress-strain responses obtained at each of the three curing temperature. The development of the response between 2 and 28 days after mixing is clearly displayed.

Conclusions

This research project captured the compressive mechanical response of a rapid-strengthening UHPC. The conclusions of this research project are as follows:

- The early-age compressive strength gain of the rapid-strengthening UHPC formulation is directly proportional to the curing temperature to which the UHPC is subjected. Using ambient room temperature specimens as a baseline, the cool cure specimens required significantly longer curing time to reach comparable strength levels. Similarly, specimens subjected to elevated curing temperatures achieved higher strengths more quickly. All batches, regardless of curing condition, reached 56-day compressive strengths within approximately 2 ksi (13.8 MPa) of one another.
- The rate of compressive mechanical property attainment was not significantly impacted by the age of the premix at the time of mix initiation. Premix ages between 2.5 and 6 months after blending were investigated.
- The use of a chemical accelerator to promote rapid strength gain did not seem to accelerate the attainment of the desired mechanical properties at early ages. The use of accelerating admixtures should be investigated prior to deployment in order to ensure appropriate performance.
- The compressive strength was found to be predictable as a function of time based on the 28-day compressive strength and

Figure 6. Example compressive stress-strain results.



the constant temperature curing regime to which the concrete is subjected.

- The modulus of elasticity of this UHPC formulation was found to be predictable as a function of the compressive strength. The developed relationship is applicable for compressive strengths from 14 to 26 ksi (97 to 179 MPa).

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