STRENGTH AND DURABILITY OF ULTRA-HIGH PERFORMANCE CONCRETE

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ABSTRACT

A new class of concrete that exhibits greatly improved strength and durability properties has recently been developed. The Ultra-High Performance Concrete (UHPC) tested in this research is a steel fiber reinforced concrete consisting of an optimized gradation of fine powders and a very low water to cementitious materials ratio. The research discussed herein provides a thorough characterization of the UHPC material properties examined at the Federal Highway Administration's Turner-Fairbank Highway Research Center.

Strength testing has produced results significantly greater than those established for conventional concretes. Compressive strengths range from 18 ksi for ambient air cured UHPC to 28 ksi for steam cured UHPC. Tensile strength tests have been completed using both direct tests such as the mortar briquette and an indirect test, namely the split cylinder. Tensile strengths range from 0.9 to 1.7 ksi depending on the curing procedure and the test method employed.

Durability testing has also demonstrated the enhanced characteristics of UHPC. Rapid chloride penetration results have ranged from extremely low to very low, and the freeze-thaw and scaling results indicate that UHPC exhibits a high resistance to this form of environmental attack.

Keywords: Ultra-High Performance Concrete**,** UHPC, Steel fiber, Compressive strength, Tensile strength, Chloride penetrability, Abrasion resistance, Freeze-thaw resistance, Scaling resistance

INTRODUCTION

A new class of concrete that exhibits greatly improved strength and durability properties has recently been developed. The Federal Highway Administration (FHWA) at its Turner-Fairbank Highway Research Center (TFHRC) is currently evaluating Ultra-High Performance Concrete (UHPC) for use in the transportation industry[1-2]. The research discussed herein aims to provide a thorough characterization of the material properties exhibited by UHPC.

The UHPC tested in this research is a steel fiber reinforced concrete consisting of an optimized gradation of fine powders and a very low water to cementitious materials ratio. As a class, UHPC's tend to exhibit enhanced strength, ductility, and durability properties when compared to high-performance concretes[3-6]. Two of the primary sources for these enhancements are the finely graded and tightly packed nature of the concrete constituent materials and the steel fibers which knit the material together after cracking has occurred[7-10].

The UHPC used in this research was originally developed by Bouygues SA and is currently being marketed by Lafarge, Inc. under the name Ductal®. This particular UHPC is the only one currently widely available in the United States; however, other companies have similar materials available in other markets.

OBJECTIVE

The objective of this research is to fully characterize the material properties of UHPC so that it can be utilized effectively and efficiently in the transportation industry and in particular, for bridge construction. The results of this research will be readily transferable to other structure types and industries.

BATCHING, CASTING, AND CURING

UHPC contains many of the same constituent materials as other concretes but in altered proportions. Table 1 provides the composition of the UHPC studied in this research. The manufacturer recommended superplasticizer for this mix was Glenium 3000 NS and the recommended accelerator was Rheocrete CNI, both products of Master Builders, Inc. The 0.2 mm diameter by 13 mm long steel fibers were added at a ratio of 2% by volume.

Table 1. UHPC Composition.

Material	Amount (lb/yd^3)	Percent by Weight
Portland Cement	1200	28.5
Fine Sand	1720	40.8
Silica Fume	390	9.3
Ground Quartz	355	8.4
Superplasticizer	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2
Water	184	4.4

This concrete contains a large amount of cement and cementitious materials, a large amount of superplasticizer, and a very small amount of water. The water to cementitious materials (i.e., cement and silica fume) ratio is 0.16.

The specimens tested in the research program were cast in approximately 1.0 cubic foot batches using a 2 cubic foot pan mixer. The mixing of the concrete generally took approximately 18 minutes from the first addition of water to de-airing the mix after the fiber addition. The flow of each mix was measured on a flow table according to ASTM C230. In the 40+ mixes completed in this study, the initial flow tended to be within 1 in. of 6.5 in. After twenty shocks, the final flow was measured to be within 1 in. of 7.5 in. The casting of all specimens was completed on a vibrating table. Demolding of specimens was performed at approximately 24 hours.

The curing of UHPC can have a significant impact on its final properties. The current research program is focusing on this variable by curing UHPC with four different regimes. The first regime is a manufacturer recommended procedure of Steam curing (194°F, 95%RH) for 48 hours beginning soon after stripping of the molds. The second curing regime, denoted Ambient Air curing, allows the specimens to remain in an ambient laboratory environment from casting until testing. The third curing regime is a lower temperature ‘steam’ cure (140°F, 95%RH) lasting 48 hours after stripping that will be denoted as Tempered Steam. The final curing regime is the Delayed Steam cure, in which the specimens received the same steam curing as in the first regime, except that the process is delayed until 15 days after casting. Establishing the effect of these four curing regimes on UHPC material properties will provide a basis from which the consequences of the inevitable curing variabilities that occur in non-laboratory environments can be quantified.

PHYSICAL PROPERTIES OF UHPC

COMPRESSIVE STRENGTH

Compression testing of cylinders was the primary means used to determine the compressive strength of the UHPC. This test method was also used as the control parameter to ensure consistency between batches. The standard size cylinder had a diameter of 3 in. and a pre-end preparation length of 6 in. 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 150 psi/sec. Preliminary testing has indicated that this increase in rate does not affect the strength or the modulus of the UHPC significantly enough to influence the test results. The rate change was necessary to ensure that test specimens would reach the level of load required for failure in a reasonable timeframe.

Curing Effect

The curing method applied to the UHPC has a significant effect on the compressive strength. Table 2 provides the 28 day strength results for the 3 in. diameter control cylinders that were cast from each batch of concrete. The strength of the Steam cured UHPC is approximately 28 ksi. The Tempered Steam and Delayed Steam cured specimens exhibited strengths approximately 10% lower. The Ambient Air cured specimens only achieved 65% of the Steam cured specimen strength.

Table 2. Compressive Strength of 3x6 in. Cylinders.

Curing Method	Samples	Compressive Strength (ksi)	Standard Deviation (ksi)
Steam	96	28.0	2.1
Ambient Air	44	18.0	1.8
Tempered Steam	18	25.2	1.3
Delayed Steam	18	24.9	1.5

Cylinders and Cubes

As mentioned above, 3 in. diameter by 6 in. long cylinders were used as the control specimen throughout this research program. However, the laboratory equipment requirements to complete compression tests on this size cylinder may be beyond the capabilities of some labs. The two primary concerns are the end preparation requirements and the compression test machine load capacity. With regard to the end preparation, end grinding is the recommend technique for concrete of this strength level, but few testing laboratories have ready access to such a grinder. With regard to the test machine load capacity, a 3 in. diameter specimen with a strength of 31 ksi would require 220 kips of force to be tested to failure, while a 4 in. diameter specimen would require 390 kips.

For these reasons, the use of smaller cylinder specimens and cube shaped specimens were investigated for compression testing. The cubes in particular, by eliminating the need for end preparation, will simplify and expedite the compression testing process.

In addition to the control specimens, three other cylinder and two cube geometries were investigated. The cylinders included 2 and 4 in. diameter standard length cylinders as well as 3 in. overlength cylinders. The cubes included both 2 in. and 100 mm geometries. This series of tests was completed for Steam cured specimens from two batches of UHPC.

The results from one of the test series are presented in Table 3. Notice that the overlength 3 in. diameter cylinders have a 7.5% lower strength than the control cylinders. Also the 2 in. cubes have a 5.8% higher strength than the control cylinders. Otherwise, the strength results are very similar to the control. The second series results were similar with the overlength cylinders again having a lower strength by 7.5% and all other specimen geometries exhibiting strengths within 5% of the control cylinders.

Table 3. Compressive Strength Comparison of Various Specimen Geometries.

Sample Geometry	Height	Samples	Compressive Strength (ksi)	Standard Deviation (ksi)
3 in. Dia. Cylinder	5.8 in.	6	29.4	0.6
3 in. Dia. Cylinder	6.3 in.	3	27.2	1.3
4 in. Dia. Cylinder	7.9 in.	5	29.3	0.9
2 in. Dia. Cylinder	3.8 in.	6	29.5	1.0
100 mm Cube	100 mm	5	29.1	1.8
2 in. Cube	2.0 in.	6	31.1	1.7

TENSILE STRENGTH

Concrete tensile strength is a property that is often disregarded due to the inherently brittle nature of the material and its low overall tensile capacity. UHPC exhibits significantly improved tensile strength, both before and after cracking. In structural applications, this tension capacity permits higher precracking tensile loads, elevates post cracking section stiffnesses, and provides a greater ability to withstand environmental attacks which utilize cracks to provide rapid ingress to interior concrete regions.

In order to use the tensile strength of UHPC, it must first be quantified. Many test methods have been developed to directly or indirectly measure the tensile strength of concrete. A number of these methods have been used in this research program, as each test provides different information on this material behavior characteristic. The two direct tensile behavior test methods discussed below are the mortar briquette tension test and the direct cylinder tension test. The split cylinder tension test is an indirect method that will also be discussed.

Mortar Briquette

The mortar briquette tension testing was conducted according to AASHTO T132. This test method normally involves casting a small briquette of cement mortar, with a 1 sq. in. cross-section neck in the middle and enlarged ends. The enlarged ends allow for passive gripping of the specimen. The self-aligning grips that are used for this test ensure a uniform tensile stress on the specimen cross-section.

Two modifications of the standard T132 test method were necessary for this program. First, the test method specifies a constant load rate of 600 lbs. per minute. However, the UHPC testing was completed using a constant displacement rate from test initiation to conclusion that was derived from applying the specified load rate over the initial linear elastic portion of the materials load-displacement curve. Second, and more importantly, the T132 specification is intended for cement mortar. However, in this case the UHPC with all constituent materials as described in Table 1 was used. This is not an issue with regard to aggregate size, as UHPC is very similar to a mortar. However, due to the small cross-section of the mortar briquette specimens, a fraction of the 0.5 in. long fibers will not have the preferred random alignment potentially biasing the test results.

Figure 1 provides the tensile cracking results from this series of tests. The labels on the figure indicate the type of curing applied and the number of days after casting that the testing was completed. Note that each test condition listed (i.e., Steam, 28d) is the average of tests on six briquettes. Also, error bars denoting plus and minus one standard deviation are shown for each test condition. Finally and most importantly, the compression tests on the control specimens that were cast along with these briquettes indicated that some of these specimens might be understrength. The Steam and Ambient Air cured specimens exhibited strengths approximately 15% below the overall test program average. The Delayed Steam cured specimens were 8% below the overall test program average.

The results indicate that the tensile strength of UHPC varies depending on the curing applied. The Steam, Tempered Steam, and Delayed Steam cured specimens tend to have tensile cracking strengths of 1.2 ksi, 1.45 ksi, and 1.0 ksi, respectively. The Ambient Air cured specimens have the lowest strength at 0.9 ksi at 28 days; however, their strength tends to continue to increase up to 1.1 ksi at 84 days. Again, as the compressive strength values for some of these batches were somewhat understrength, these tensile strength values may also be somewhat understrength.

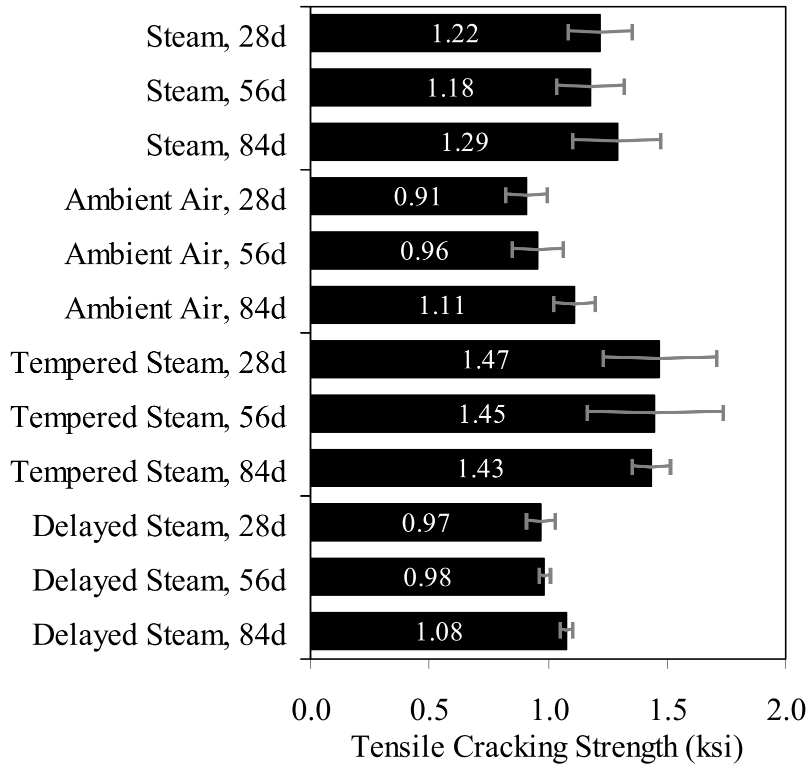

Figure 1. Mortar Briquette Tensile Cracking Strength.

Relative to normal concrete, steel fiber reinforced UHPC's are unique in that they continue to carry significant tensile loads after cracking. This behavior is a result of their randomly distributed network of discontinuous steel fibers. From a structural standpoint, this post-cracking tensile strength permits a reduction in other post-crack tensile force carrying mechanisms (i.e., rebar), provides an increase in ductility or energy dissipation capacity, and preserves a larger portion of the initial section stiffness.

The mortar briquette test can also be used to focus on this characteristic of UHPC behavior. Figure 2 shows the load-displacement relationship recorded during the testing of a Steam cured briquette. It was observed that the stiffness of the specimen changes at initial cracking, but the specimen continues to carry significant tensile forces through a large subsequent displacement. As the fibers pull out of the UHPC matrix along the fracture surface, the load capacity decreases until eventually the section is severed.

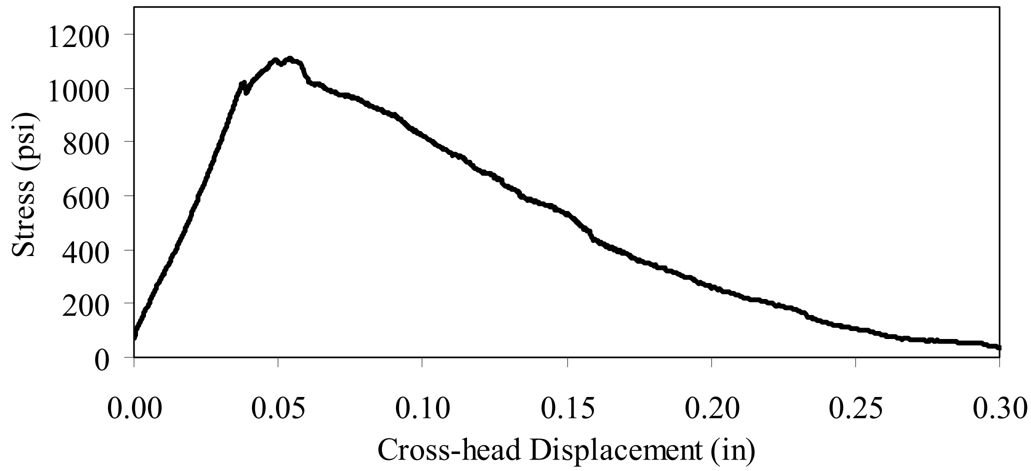

Figure 2. Load-Displacement Response for a Steam Cured Mortar Briquette.

The area under the load-displacement curve after the specimen cracks is a measure of the toughness of the UHPC. Figure 3 provides a measure of this toughness from cracking until the load decreased to 200 pounds. The values have not been normalized so that direct comparison between different specimen groups can be made, without regard to their pre-cracking strength. The Steam cured specimens exhibit the best post-cracking behavior, with almost twice the toughness of the Ambient Air cured specimens. The Tempered Steam and the Delayed Steam cured specimens both exhibit approximately 75% of the toughness of the Steam cured specimens.

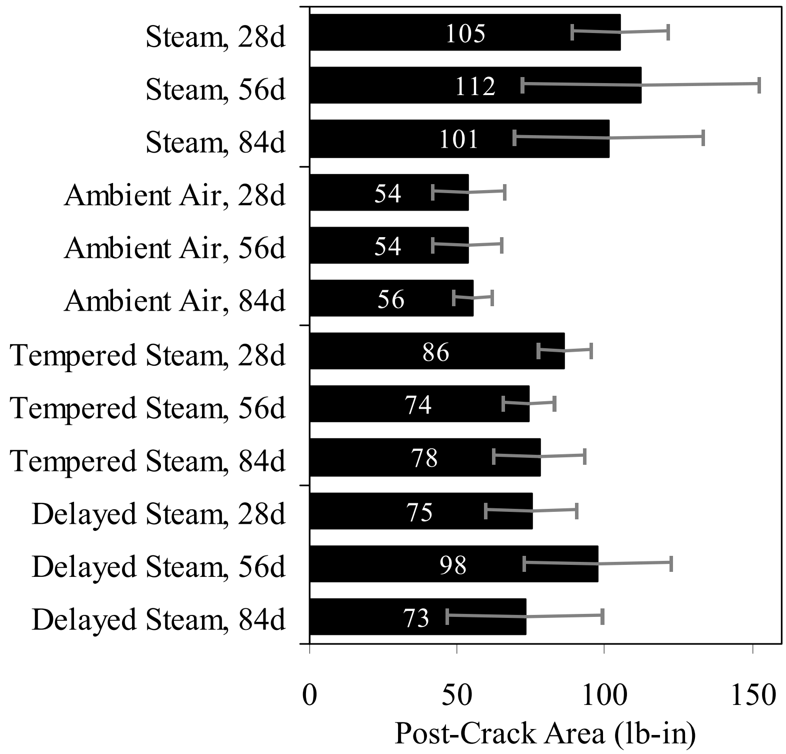

Figure 3. Area Under Mortar Briquette Load-Deflection Curve After Cracking.

Split Cylinder

Split cylinder tension tests were also conducted to determine the tensile properties of UHPC. This indirect tension test allows for determination of the tensile strength of concrete through the use of a standard compression testing machine. Four inch diameter cylinders of approximately eight inch length were tested for all four curing regimes previously discussed.

The ASTM C496 test procedure was followed except for two minor modifications. First, the load rate range specified in the procedure is 100 to 200 psi/min. In order to complete the tests in a reasonable timeframe, these tests were completed at a 500 psi/min load rate. As before, preliminary testing indicated that this rate change did not significantly influence the results. Second, the lateral diametrical expansion of the cylinder was measured during the test through the use of a spring-loaded apparatus that holds two displacement transducers, one at each end of the specimen. This displacement measurement system is similar to a system used by Nanni[11] in his work on fiber-reinforced concrete. This device applies approximately 50 lbs. (1.6 psi) of lateral confining force to the specimen throughout the test.

Figure 4 shows a load-displacement response recorded from one of the Steam cured cylinders. Note the stiffness change and lateral expansion that occurs at cracking. This recorded behavior was usually accompanied by a loud, brittle rupture sound. The displayed response is also typical for most of the Tempered Steam and Delayed Steam cured cylinders.

The Ambient Air cured specimens did not always behave in this manner. In approximately half of these cylinders the crack occurred gradually, and in all cases the cracking was quieter or inaudible.

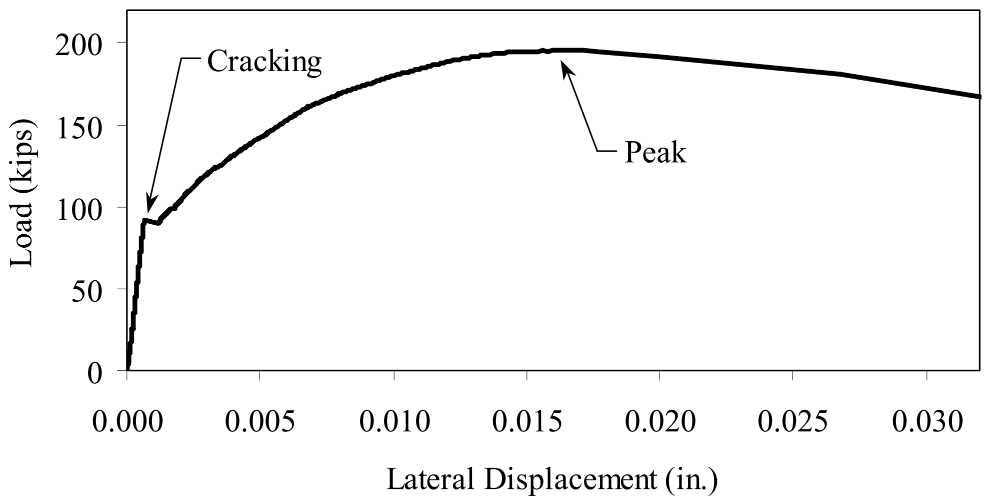

Figure 4. Split Cylinder Lateral Deflection Response for a Steam Cured Specimen.

The tensile cracking results from the split cylinder tests are presented in Figure 5. Cracking is defined as when an abrupt or semi-abrupt change in specimen lateral stiffness occurs. The Steam cured specimens exhibit the highest tensile cracking strength at 1.7 ksi. The Tempered Steam specimens show a slightly reduced strength at 1.6 ksi. In both of these cases, the strength results are consistent from 5 days to 28 days. The Delayed Steam specimens show a post-curing strength of 1.6 ksi and a pre-curing 14 day strength very similar to the Ambient Air cured specimens at that age. Finally, the Ambient Air cured cylinder results indicate that the tensile strength continues to grow throughout the first 14 days up to approximately of 1.3 ksi.

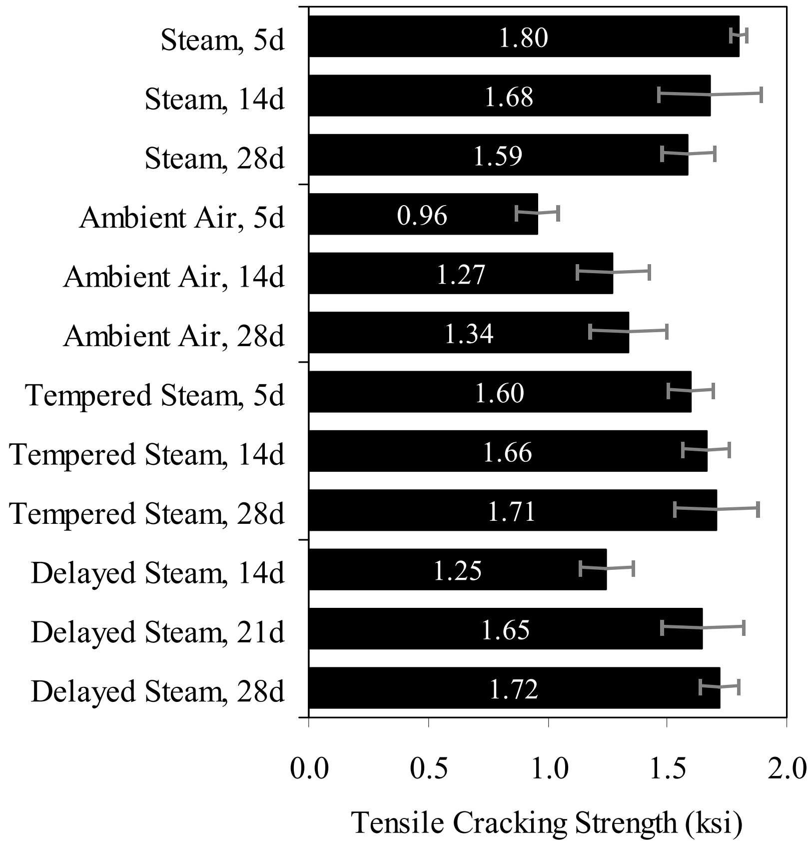

Figure 5. Split Cylinder Tensile Cracking Strength.

The peak split cylinder tensile strength values are presented in Figure 6. These results are not accurate representations of the actual tensile strength of the UHPC, either before or after cracking. The split cylinder loading configuration causes a biaxial state of stress, which produces significantly increased fiber pullout strengths. However, these results do indicate that there is a clear difference in the peak strength of specimens produced with different curing regimes. Therefore, it may be possible to use this test method to determine the extent and type of curing a UHPC specimen has experienced.

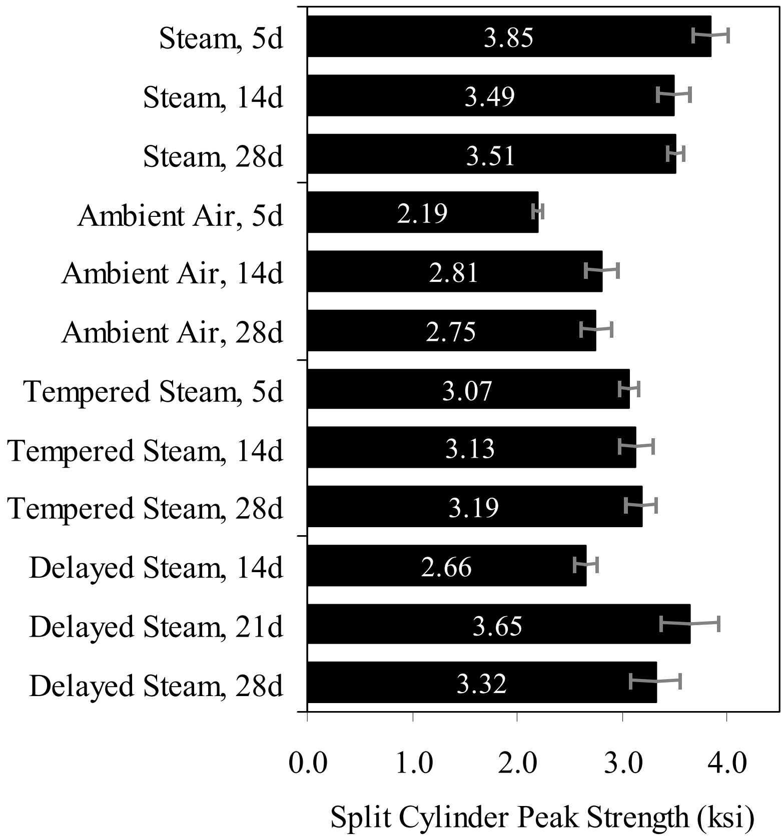

Figure 6. Split Cylinder Peak Strength.

Cylinder Direct Tension

Cylinder direct tension testing is another direct method of determining the tensile strength of concrete. This test method is analogous to the cylinder compression test, except that the cylinder's ground ends are adhered to the heads of the test machine. The test described herein is based on both the RILEM Uni-axial Tension Test for Steel Fibre Reinforced Concrete[12] and USBR 4914[13] test methods. Cylinders of 4 in. diameter were used for these tests and the load application was displacement controlled. All tests were completed at least 50 days after casting. Only partial test results are available at this time.

Table 4 provides some of the cracking strength results obtained from these tests. The Steam and Delayed Steam cured specimens both exhibit cracking strengths of 1.6 ksi while the Tempered Steam and Ambient Air cured specimens are significantly lower. However, these cylinders were cast alongside the mortar briquette specimens thus, as discussed previously, the compression tests on the control specimens indicate that some of these tension cylinders specimens might be understrength.

Table 4. Direct Tensile Cracking Strength of UHPC Under Different Curing Condition.

Curing Method	Samples	Cracking Strength (ksi)	Standard Deviation (ksi)
Steam	3	1.60	0.13
Air	1	0.82	N/A
Tempered Steam	3	1.14	0.13
Delayed Steam	2	1.62	0.07

SHRINKAGE

A limited shrinkage study has been completed on the early age shrinkage behavior of UHPC. This work was completed in conjunction with the alkali-silica reaction (ASR) study that is discussed later. Here, 1 in. by 1 in. UHPC bars with 11 in. length were cast and cured. The shrinkage testing was completed according to ASTM C157. The initial reading was acquired immediately after stripping of the molds. The final reading was taken after the curing procedure had been completed, or at 28 days for the Ambient Air cured specimens.

Table 5 provides the results of these tests. The Steam and Delayed Steam cured specimens exhibited similar shrinkage, while the Tempered Steam specimens shrank approximately half as much. The Ambient Air cured specimens exhibited the most shrinkage. Given the high cement content and the lack of coarse aggregate in the mix design, these large shrinkage values are to be expected. However, further research into the post-cure shrinkage of UHPC is needed.

Table 5. Shrinkage of UHPC Mortar Bars.

Curing Method	Bars Tested	Measurement Time (Days After Casting)		Shrinkage (%)	
		Initial	Final	Average	Standard Deviation
Steam	6	1.1	4.1	0.047	0.002
Ambient Air	6	1.1	28.1	0.062	0.004
Tempered Steam	6	1.2	4.1	0.025	0.001
Delayed Steam	6	1.1	18.0	0.050	0.002

HEAT OF HYDRATION

Considering the large amount of cement present in UHPC, the heat generated by this concrete during its initial curing was expected to be significant. Figure 7 provides temperature-time results for this UHPC formulation both with and without an accelerator. This plot shows that the temperature in the 6 in. diameter by 12 in. tall cylinder increased by approximately 15°F. Also, the accelerator has a significant effect, causing the large temperature rise to begin more than 30 hours sooner and causing the peak temperature to be higher. Figure 8 provides a similar plot for a Steam cured 6 in. diameter by 12 in. cylinder. Here, the accelerated UHPC is Steam cured beginning soon after the initiation of its temperature rise. Again, the temperature rise above the surrounding environment is approximately 15°F to a peak temperature of 210°F.

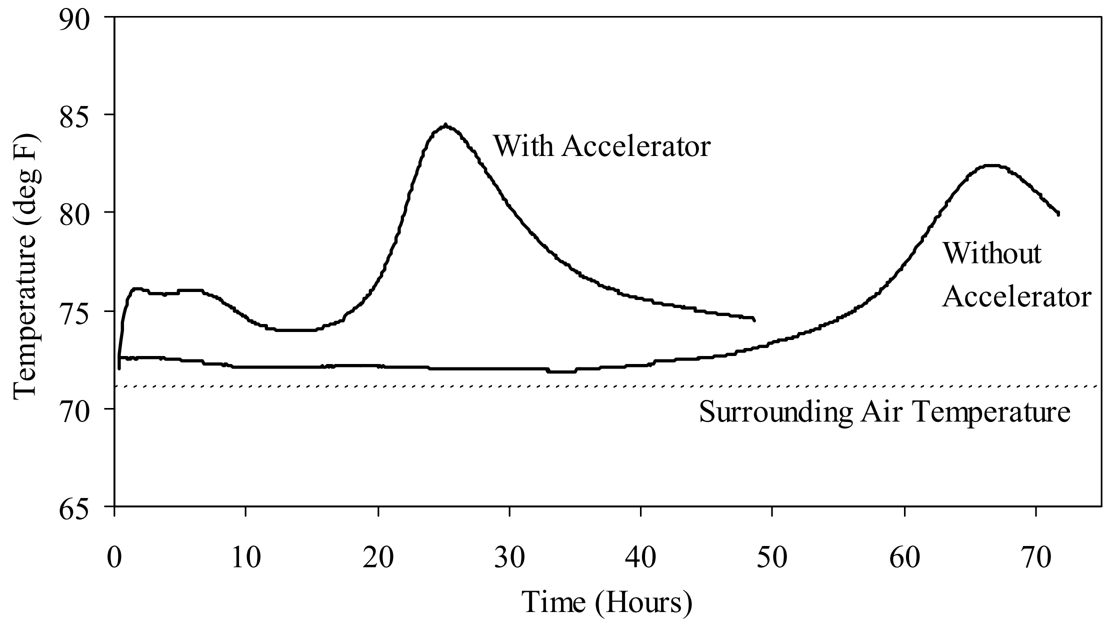

Figure 7. Temperature in a 6x12 in. Cylinder With and Without Accelerator in Mix.

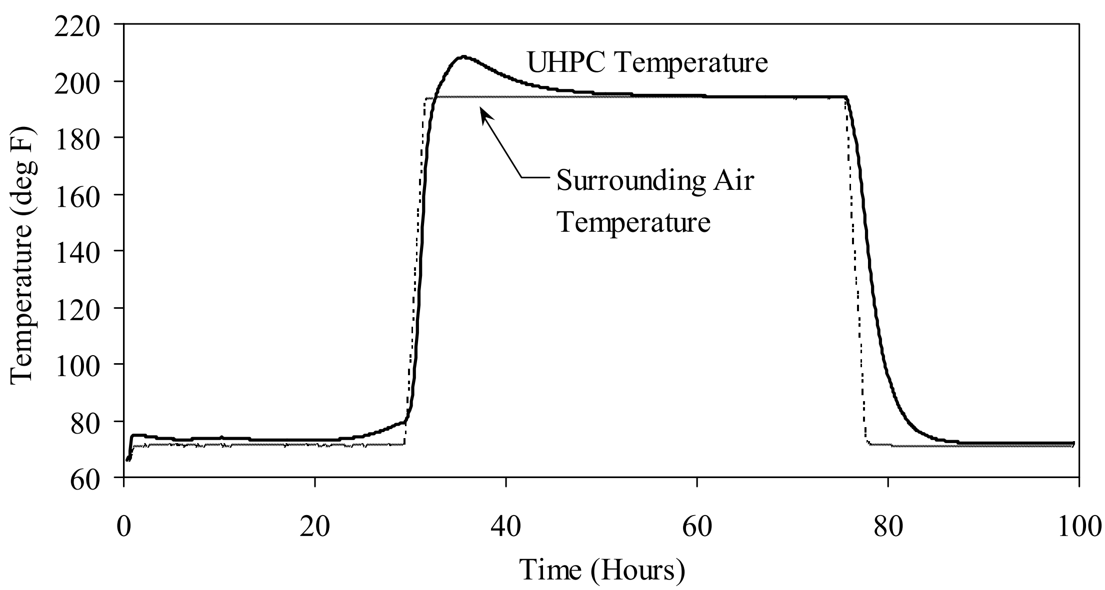

Figure 8. Temperature in a 6x12 in. Cylinder from Casting through Steam Curing.

DURABILITY OF UHPC

The durability of UHPC in terms of its resistance to internal and external environmental attack was also studied. These investigations included chloride ion penetration, abrasion, ASR, freeze-thaw, and scaling testing.

RAPID CHLORIDE ION PENETRABILITY

Rapid chloride ion penetrability tests were completed on UHPC specimens according to ASTM C1202. The electrical current was recorded at 1 minute intervals over the 6 hour timeframe, resulting in the total coulombs passed value shown in Table 6. Two or three specimens were completed for each condition and specimens were tested at both 28 and 56 days. The results show that the rapid chloride ion permeability is minimal, regardless of the curing regime applied. Also, it is of note that the penetrability decreased significantly between 28 and 56 days for specimens from the Ambient Air curing regime.

Table 6. ASTM C1202 Rapid Chloride Ion Penetrability Results.

Curing Method	Tests	Age (days)	Coulombs Passed		Chloride Ion Penetrability
			Average	Standard Deviation	
Steam	3	28	18	1	Negligible
Ambient Air	2	28	360	2	Very Low
Ambient Air	3	56	76	18	Negligible
Tempered Steam	3	28	39	1	Negligible
Tempered Steam	3	56	26	4	Negligible
Delayed Steam	3	28	18	5	Negligible

ABRASION RESISTANCE

Abrasion resistance can be an important parameter for any concrete that is exposed to contact with other materials. The abrasion resistance of UHPC was measured through testing according to ASTM C944 in which a rotating abrading wheel bears on and wears away the concrete surface for a period of two minutes. One modification to the standard test method was made in this program. The reported test results are the product of 10 total minutes of abrasion representing five two-minute cycles completed on each specimen.

The abrasion testing was performed on three specimens from each of the four curing regimes. However, as abrasion resistance is highly dependent on the surface condition of the concrete, each specimen was tested on three different surfaces. First, all specimens were tested on the surface formed by casting UHPC against the steel mold in which they were produced. Following these tests, the cast (and now abraded) surface was sandblasted until it displayed a uniform texture. The testing was then repeated for this sandblasted surface. Finally, the testing was again repeated for all the specimens subsequent to having the test surface ground plane using a cylinder end grinder.

The average weight loss per 2 minute abrading results are shown in Figure 9. The results clearly show that the Ambient Air cured specimens have significantly less abrasion resistance. Also, as would be expected, cast surfaces tend to show more abrasion resistance. This holds true until the surface is broken, after which all equally cured specimens behaved similarly.

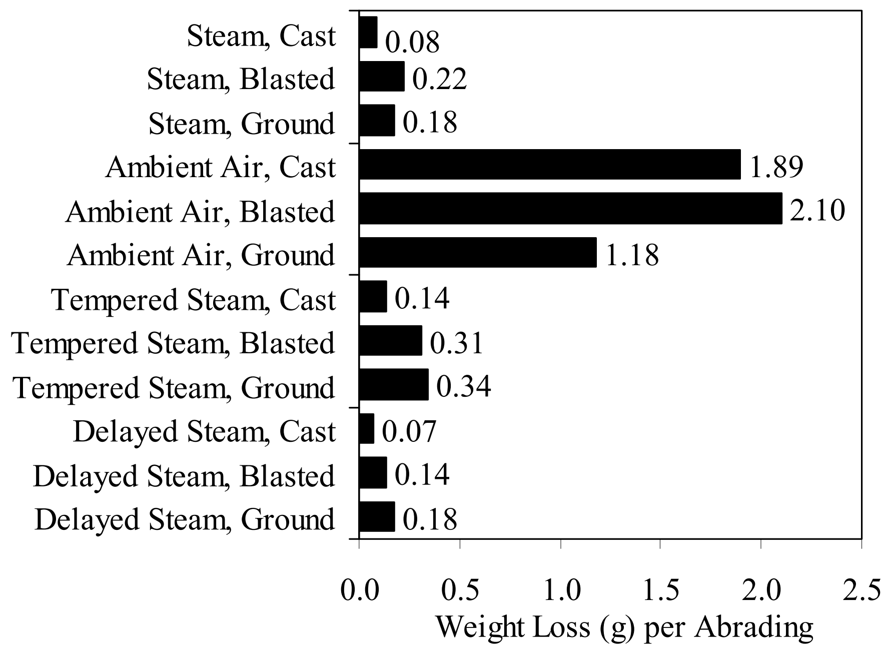

Figure 9. ASTM C944 Abrasion Resistance.

ALKALI-SILICA REACTION

Alkali-silica reaction testing was performed primarily in accordance with ASTM C1260. The only modification made to the specification was that the test duration was extended from 14 to 28 days to provide more time for initiation of the ASR reaction. Table 7 provides the results from these tests. Two Ambient Air cured groups were examined, with testing initiating for one of them immediately after demolding of the prisms and the other initiating after 28 days of curing. In all cases, both the 14 day and the 28 day expansion results are approximately an order of magnitude below the specification defined innocuous ASR behavior cut-off limit of 0.10%. However, the test method requires immersion of the specimens in a water and sodium hydroxide bath with an elevated temperature. This treatment may have resulted in additional curing of the UHPC and an underestimation of the ASR reaction.

Table 7. ASTM C1260 Alkali-Silica Reactivity Expansion

Curing Regime	Bars Tested	14-day Expansion (%) Average	14-day Expansion (%) Standard Deviation	28-day Expansion (%) Average	28-day Expansion (%) Standard Deviation
Steam	6	+0.013	0.008	+0.009	0.005
Ambient Air†	6	+0.011	0.002	+0.012	0.002
Ambient Air‡	6	-0.004	0.002	+0.012	0.001
Tempered Steam	6	+0.005	0.002	+0.004	0.003
Delayed Steam	6	+0.001	0.002	+0.002	0.002

† ASR test initiated 28 days after casting
‡ ASR test initiated 1 day after casting

FREEZE-THAW RESISTANCE

The freeze-thaw resistance of UHPC was tested according to ASTM C666. This specification calls for repeated cycling of specimens between the temperatures of 0 and 40º Fahrenheit. Periodically, the cycling is stopped and the dynamic modulus of elasticity of the specimens is measured. The test is based on the premise that the repeated freezing and thawing will cause microscopic degradation of the concrete resulting in a decreased dynamic modulus of elasticity. Prisms measuring 3 in. by 4 in. by 16 in. were used as specimens in this series of tests. Prior to initiation of the testing, all specimens were at least 28 days old.

Figure 10 provides the results from 300 cycles of freeze-thaw testing. The results show that the Steam, Tempered Steam, and Delayed Steam cured specimens all retained dynamic modulus characteristics close to their original characteristics. The Ambient Air cured prisms displayed a continuous increase in dynamic modulus throughout the testing. As every cycle contains a period of time when the prisms are standing in water, it is likely that this water recharge continued the curing process during the months of freeze-thaw testing.

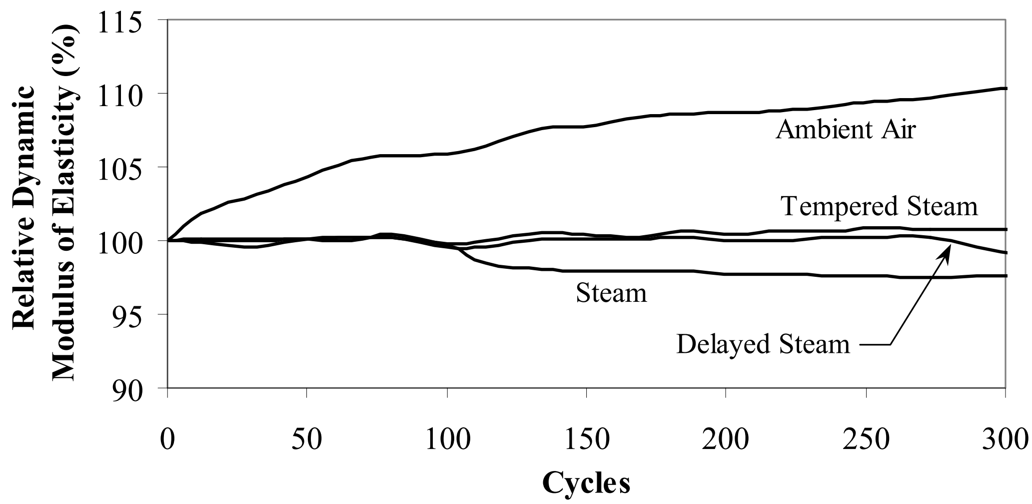

Figure 10. Freeze-Thaw Resistance of UHPC.

SCALING RESISTANCE

Scaling resistance was measured in accordance with ASTM C672. This specification calls for ponding a calcium chloride solution on the concrete surface, then freezing the specimen for 18 hours followed by 6 hours of thawing. Two UHPC specimens from each curing regime were tested, with the solution ponded on surfaces created by forming against a steel mold.

For the UHPC specimens discussed here, 50 cycles were completed. After 50 cycles, the texture of the test surfaces was visually altered; however, no scaling was measured or observed. Corrosion staining was evident near the exposed ends of some fibers.

CONCLUSIONS

The UHPC studied in this research program has displayed an impressive set of material properties. When steam cured as recommended by the manufacturer, the user can expect to achieve a compressive strength of 28 ksi and a tensile cracking strength of at least 1 ksi. As compared to normal concretes, a steam cured UHPC section should be effectively immune to freeze-thaw, scaling, and chloride ion penetration damage.

The results presented in this study also clearly show that the curing of UHPC can have a large impact on its properties. The properties of air cured UHPC, although still impressive relative to conventional concretes, are significantly different than steam cured UHPC.

The research program described herein is ongoing with much testing is still to be completed. Ongoing and future testing includes creep and shrinkage studies, prism flexure testing, and compressive and tensile modulus of elasticity testing.

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