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Study on Field Thermal Curing of Ultra-High-Performance Concrete Employing Heat of Hydration

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A pilot-scale field investigation was conducted through which: 1) a refined ultra-high-performance concrete (UHPC) mixture was prepared in a ready mixed concrete plant; 2) a large reinforced UHPC block was constructed through placement, consolidation, and finishing of UHPC; and 3) a commonly available concrete curing (insulating) blanket was applied for field thermal curing of the UHPC block using the exothermic heat of hydration of the cementitious binder in UHPC. Monitoring of the reinforced UHPC block temperature over time confirmed the development of a reasonably uniform temperature and a viable temperature time history, which suited thermal curing of UHPC without any heat input. In-place nondestructive inspection of the reinforced UHPC structure pointed at timely setting and strength development, leading to achievement of ultra-high-performance status. Specimens were cored from the large reinforced concrete block and subjected to laboratory testing. The experimental results indicated that the field thermal curing was more effective than the laboratory thermal curing considered in the project, and that the pilot-scale production of the UHPC mixture produced compressive strengths approaching 170 MPa (24.7 ksi).

Keywords: heat of hydration; pilot-scale field production; thermal curing; ultra-high-performance concrete (UHPC).

INTRODUCTION

Ultra-high-performance concrete (UHPC) is an active area of research and development; some major topics of interest include assessment and management of the heat of hydration, autogenous/plastic shrinkage and creep,[1,2] restrained shrinkage crack control,[3-5] optimization of fiber reinforcement for realizing improved toughness and impact resistance,[6,7] use of nanomaterials toward further improvement of the packing density and toughness,[8-12] development of self-consolidating UHPC,[13,14] structural performance and failure modes of steel (or polymer composite) reinforced UHPC structures under quasi-static and dynamic (earthquake/blast) loading,[15-26] and repair applications of UHPC.[27,28] Field applications of UHPC have largely emphasized production of precast/prestressed concrete elements[13,29-35] and repair/rehabilitation of concrete structures.[28] Production of UHPC materials at reduced cost using ordinary raw materials and production methods has been subject of an investigation conducted by Wang et al.[36] The binder used in this investigation comprised normal portland cement:ground-granulated blast-furnace slag:silica fume:limestone powder (with twice the specific surface area of cement) at different weight ratios (ranging from 0.9 cement:0.1 slag:0 silica fume:0 limestone powder to 0.3 cement:0.1 slag:0.2 silica fume:0.4 limestone powder). Successful investigations have been reported on production and experimental evaluation of (self-consolidating) UHPC using materials that are locally available.[33] Few low-heat-of-hydration cements, different silica sands that are commonly used for sandblasting, various locally available silica fumes, different readily available polycarboxylate-based high-range water-reducing admixtures (HRWRAs), and commonly available straight steel fibers were used in these investigations.[33,37]

Because UHPCs have distinctly high cementitious binder contents, the amount of heat of hydration can be relatively large.[38] In mass concrete construction, heat of hydration together with relatively low thermal conductivity and surface cooling effects can generate high peak temperatures and temperature gradients that disrupt the hydration process and cause thermal stress cracking of concrete. Hence, it is important to assure a uniform buildup of temperature up to moderate peak levels, which suit thermal curing of concrete, followed by a low rate of cooldown to extend the thermal curing period. Some other issues involved in the transition of UHPC to mainstream consumption projects are: 1) the low water-binder ratio (w/b), high binder content, and high packing density of cementitious materials and fillers influence the kinetics and the extent of hydration as well as the moisture movements in UHPC, yielding relatively high rates and magnitudes of autogenous/plastic shrinkage, and minimal bleeding,[1,2,39-41] which are influenced by temperature rise and proximity to the surface, producing a tendency toward early-age cracking[41,42]; and 2) the need for curing at elevated temperatures (for example, 90°C [194°F] over 48 hours) to promote pozzolanic reactions (due to the relatively high contents of silica fume, other pozzolans, and less reactive fillers) challenges large-scale field production of UHPC structures.[40,43,44]

The main thrust of this study is to enable production of UHPC in a ready mixed concrete plant and to employ the heat of hydration for curing of UHPC. For this purpose, based on the investigations performed by authors, an appropriate UHPC mixture design (using locally available materials) was selected with targeted compressive strength of 200 MPa (29 ksi) at 7 days of age, with suitable fresh mixture workability. Experiments were performed on insulated, medium-sized UHPC blocks to investigate the poten-

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Table 1—UHPC mixture designs, kg/m³ (lb/ft³)

Mixture constituent	Mixture 1	Mixture 2
No. 7 crushed granite	715.80 (44.7)	487.00 (30.4)
No. 9 natural sand	565.90 (35.3)	512.70 (32)
Binder-to-aggregate ratio	0.75	0.75
Cementitious materials	961.30 (60)	961.30 (60)
Cement Type I	480.60 (30)	480.60 (30)
Silica fume	192.30 (12)	211.50 (13.2)
Slag	96.10 (6)	96.10 (6)
Quartz powder	192.30 (12)	0.00
Limestone powder	0.00	173.00 (10.8)
w/c	0.167	0.165
Water	144.20 (9)	132.70 (8.3)
HRWRA	36.00 (2.3)	37.10 (2.3)
Set retarder	0.00	4.60 (0.3)
Steel fiber, straight (0.175/13 mm)	119.70 (7.5)	119.10 (7.5)
Silica sand	0.00	282.00 (17.6)
Compressive strength (MPa), 7 days	177.0	203.0

tial for field thermal curing of UHPC structures using insulated blankets without any heat input.

A nondestructive test method was evaluated for in-place monitoring of the setting and strength development of UHPC. The specifics and variations of field thermal curing conditions differ from those in standard laboratory curing. It is therefore important to monitor development of actual UHPC strength in field conditions. Nondestructive test techniques enable field monitoring of UHPC quality, which may not be represented well by specimens cured and tested in laboratory. Ultrasonic pulse velocity (UPV) measurements offer reliable, convenient, and cost-effective means of nondestructive field monitoring of concrete elastic modulus. In this study, UPV measurements were performed on UHPC (cylindrical) compression test specimens to monitor the setting and strength development of UHPC.

RESEARCH SIGNIFICANCE

Given the relatively high content of pozzolans (for example, silica fume and slag) and powder (quartz or limestone) used as partial replacement for cement in UHPC, the hydration kinetics of UHPC tend to be different from those of normal concrete. The distinctly high cementitious binder content of UHPC mixtures provides them with the potential to generate relatively large quantities of heat of hydration. In this study, the use of heat of hydration of UHPC towards field thermal curing was investigated.

MATERIALS

This study used readily available natural sand from mid-Michigan as fine aggregates, and silica sand was used occasionally to improve the packing density of the particulate matter. Fineness moduli ranging from 2.5 to 3.2 are recommended for the fine aggregates used in high-strength concrete to realize desired fresh mixture workability.[45] Existing UHPC mixtures do not generally use coarse aggregates. This study used locally available crushed granite and limestone from mid-Michigan as coarse aggregate in UHPC. Crushed granite (MAS 9.5 mm [3/8 in.]—ASTM C33 gradation) was the coarse aggregate supplied. Natural sands (MAS 4.75 mm [3/16 in.] No. 4 sieve—ASTM C33 gradation) and limestone powder (3 μm [0.000118 in.] average particle size) were also supplied. The cement used in the study is ordinary Type I portland cement, as well as silica fume and ground-granulated blast-furnace slag (GGBFS). Quartz powder with an average particle size of 3.9 μm (0.000153 in.) was additionally provided.

A high-range water reducer (HRWR) was used and a set retarder was also obtained from the same manufacturer. The steel fibers used in the UHPC mixtures were straight, brass-coated with 13 mm (0.5 in.) length and 0.175 mm (0.007 in.) diameter. Table 1 shows the two UHPC mixture designs used in this study. The mixture design used herein is based on the comprehensive experimental program performed by the authors to develop UHPC mixture designs using locally available materials.

METHODS

UHPC mixtures were prepared in a drum mixer. The fresh mixture workability was assessed using the flow table test per ASTM C124 and slump test per ASTM C143. Compression tests were performed on 76 mm (3 in.) diameter and 152 mm (6 in.) height cylinders consolidated on a vibrating table following standard procedures. The cylinders were held under a wet cloth at room temperature for 24 hours, after which they were demolded and subjected to two alternative thermal (steam) curing methods: 1) 90°C (194°F) over 48 hours; and 2) 70°C (158°F) over 72 hours. After thermal curing and cooldown to room temperature, the specimens were stored at room temperature and 50% relative humidity to equilibrate their moisture content. Initial tests for tailoring of material selections and mixture proportions were performed at 7 and 28 days of age. Both ends of compression test specimens were ground to produce flat loading surfaces. Length, diameter, and density of each specimen were measured prior to the performance of compression tests.

While thermal curing of UHPC can be implemented conveniently in a laboratory, its field implementation is a challenge. A preliminary investigation was conducted to assess the potential for using the heat of hydration of UHPC mixtures toward field thermal curing. This "semi-adiabatic" cuing process employs insulated formwork[46] and blankets[47] for effective use of the heat of hydration toward generating a uniform temperature rise within large UHPC structures over adequately long time periods for the purpose of thermal curing.

To make an experimental assessment of the temperature time-history that can be feasibly generated using the heat of hydration of the UHPC "Mixture 1" (refer to Table 1), an insulated 0.3 x 0.3 x 0.3 m (1 x 1 x 1 ft) block of UHPC was poured inside an insulated (polystyrene) foam with *R* value of 4.0/in. (with total thickness of 20 cm [8 in.]), as shown in Fig. 1.

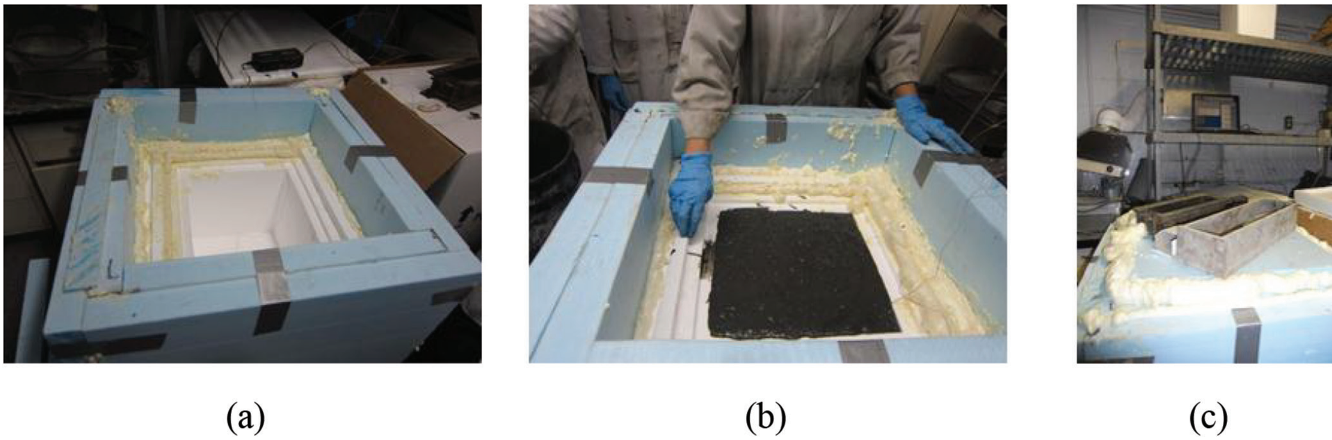


Fig. 1—(a) Insulated formwork; (b) UHPC placed inside insulated formwork; and (c) setup for measurement of temperature time history.

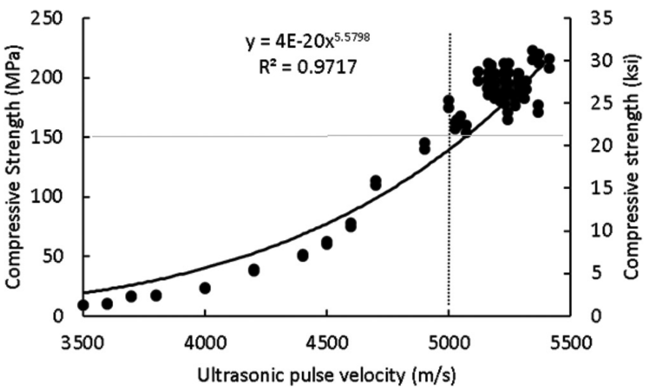


Fig. 2—Relationship between compressive strength and UPV for strengths covering normal, high, and ultra-high levels. (Note: 1 m = 3.28 ft.)

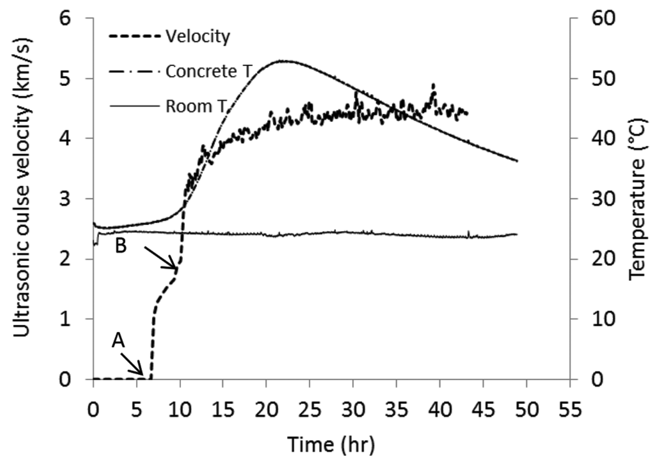


Fig. 3—Evolution of UPV and temperature in semi-adiabatic curing of UHPC. (Note: 1 km = 0.62 miles; °F = 1.8°C + 32.)

Ultrasonic pulse velocity (UPV) measurements offer convenient and cost-effective nondestructive means of monitoring the dynamic elastic modulus of concrete.[48] UPV can also be used to identify and map voids, cracks, delaminations, and other defects in concrete.[48] The relationship between UPV and compressive strength depends on a number of factors, including water-cementitious materials ratio (*w/cm*), aggregate type, and density. Some studies have attempted to draw correlations between UPV and the compressive strength of concrete materials with high volumes of mineral additives (supplementary cementitious materials).[49]

The UPV method uses a detector to measure the time of flight it takes for an ultrasonic pulse to pass through a known thickness of a solid material. For normal concrete made with ordinary portland cement and compressive strengths of 5 to 60 MPa (0.7 to 8.7 ksi), UPV varies from <2 km/s (1.2 miles/s) up to >4.7 km/s (2.9 miles/s); the empirical correlation of compressive strength with UPV has been found to be in the form of an exponential[50]: $f_c' = a.e^{h.V_c}$, where f_c' is the concrete compressive strength. In the case of high-strength concrete, an investigation conducted by Uysal and Yilmaz[51] concluded that UPV values range from 4.2 to 5 km/s (2.6 to 3.1 miles/s) within the compressive strength range of 55 to 105 MPa (8 to 16.2 ksi) for concrete containing limestone, basalt, and marble powder; the correlation between strength and UPV slightly deviated from the exponential relationship.

In this study, UPV measurements were initially performed using equipment on UHPC (cylindrical) compression test specimens just prior to the performance of compression tests. The UPV values for UHPC were found to range from 5 to 5.4 km/s (3.1 to 3.4 miles/s) for compressive strengths ranging from 160 to 200 MPa (23 to 29 ksi). Figure 2 shows the relationship between compressive strength and UPV for UHPC, combined with data from literature on normal- and high-strength concrete (on the left side of the dashed line).[49] All test results are shown as dark circles. The empirical relationship (shown as the curve) between compressive strength and UPV follows a power relationship with R^2 = 0.97. For the limited test data used herein, however, the correlation between UPV and compressive strength exhibits greater variability at higher strength values; a UPV ≥5 km/s (3.1 miles/s) seems to be a good indicator of achieving the UHPC status marked by compressive strengths exceeding 150 MPa (22 ksi).

UPV measurements were also used in this study for monitoring the early-age formation of the UHPC structure. The ultrasonic transducers were in direct contact with the fresh UHPC mixture; they were fixed using sprayed foam and the specimens were insulated with sprayed foam to achieve semi-adiabatic conditions. Figure 3 shows the evolution of UPV and temperature for a UHPC block

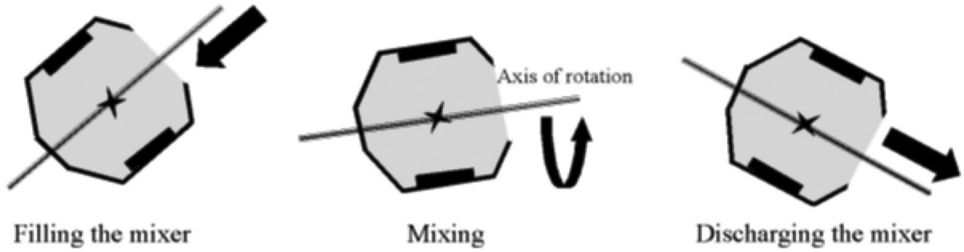


Fig. 4—Orientation of laboratory drum mixer at different stages of operation:

subjected to semi-adiabatic curing. A peak temperature of 52.6°C (127°F) was reached 20.8 hours after casting. The UPV barely changed during the first 7 hours, and then experienced a sudden rise at Point A, and rapidly climbed up to a bend at Point B after which the rate of UPV increase rose again to very high levels, and finally slowed down and reached a plateau of approximately 4.2 km/s (2.6 miles/s). The sharp rise in UPV between Points A and B indicates rapid formation of hydration products, yielding a percolated solid phase. Past investigations have shown that the transition Point A corresponds reasonably well with the initial setting of concrete.[52] Therefore, UPV can be used for field determination of the set time of UHPC, which adds to its value as a nondestructive tool for in-place quality control of UHPC. This finding confirms similar results obtained in nondestructive testing of UHPC.

RESULTS AND DISCUSSION

Mixing

Conventional UHPC mixtures generally require intense mixing efforts rendered by special mixers over relatively long time periods to ensure thorough dispersion of the mixture ingredients.[53] The transition of UHPC to mainstream construction markets would benefit from refinements in mixture design and mixing procedures that enable use of commonly available mixers and reduce the mixing duration. A brief survey of large-scale mixing capabilities confirmed that the most readily available option for production and shipment of UHPC would be transit mixers of tilt drum type used by ready mixed concrete plants, noting that approximately 20% of plants have central mixers of tilt drum or pan type offering more intense mixing actions than transit mixers. Most plants are equipped with automated batching systems. Truck (transit) mixing and transport (in lieu of central mixing) is still prevalent in ready mixed concrete production. The drum mixing action employed by transit and central mixers cannot render the intensity and the versatile mixing action of planetary and paddle mixers used traditionally for production of UHPC mixtures. Successful production of UHPC in a laboratory drum mixer was the key step toward scaled-up production of UHPC in a ready mixed concrete plant. Selected UHPC mixtures were successfully produced at 100 kg loads in a relatively large laboratory drum mixer. This drum mixer has a constant (moderate) rotation speed. The variable speed of industrial (for example, transit) mixers would render more intense mixing action in scaled-up production of UHPC.

Figure 4 shows the orientations of a laboratory drum mixer at different stages of operation. There are blades attached to the insider of the drum; these blades help lift the fresh concrete during rotation of the drum. In each rotation, the lifted material drops down to the bottom of the drum, and the cycle starts again. This mixing action is very different from that of the planetary mixer, which produces high shear forces during mixing. The operation parameters of drum mixer that can be controlled in typical transit and central mixing setups are the rotation speed of the drum and, in certain mixers, the inclination angle of the rotation axis, as shown in Fig. 4.[54] When the drum is almost horizontal (0-degree inclination), more energy is provided to the fresh concrete because more concrete is lifted the full diameter of the drum before dropping, noting that the fresh concrete is knitted and mixed during the drop. Therefore, the higher the drop, the greater the mixing energy imparted to concrete. If the axis of rotation is almost vertical, the blades cannot lift the fresh concrete, minimizing the mixing action rendered to concrete. The drum axis commonly stays at an angle of approximately 15 degrees from horizontal during mixing.

Three UHPC mixing sequences were tried in a drum mixer:

1. Dry cementitious materials and aggregates were first blended, and then water mixed with HRWRA was added as mixing was continued until a stable, homogeneous mixture was formed.
2. Half of the cementitious materials were mixed with aggregates and fibers, followed by the addition of water mixed with HRWRA, with mixing continued until a stable, homogeneous mixture was formed; the remainder of the cementitious materials was then added as mixing was continued to produce a homogenous mixture.
3. Half of the cementitious materials were mixed with aggregates, followed by the addition of water mixed with HRWRA, with mixing continued until a stable, homogeneous mixture was formed; the remainder of the cementitious materials was then added, followed by the addition of steel fibers as mixing was continued until a homogeneous mixture was produced.

The total duration of each of the three mixing sequences was close to 25 minutes. It should be noted that the mixing sequence could influence the potential for fiber balling. The laboratory drum mixer used is shown in Fig. 5. The J-ring (ASTM C1621) test on a typical fresh UHPC mixture is shown in Fig. 5(b). The experimental results produced with a laboratory drum mixer indicated that the mixing sequences introduced previously produce marked differences in the dispersion levels of mixture ingredients and thus the slump flow of fresh mixture. With a typical UHPC mixture developed in the study, the slump flows obtained with the first, second, and third mixing sequences introduced previ-

(a) Mixing of UHPC in laboratory drum mixer

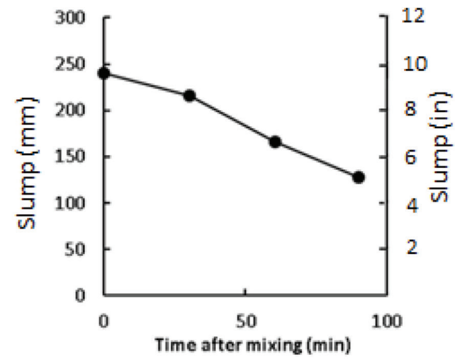
(b) Slump flow behavior of UHPC

Fig. 5—UHPC mixing in laboratory drum mixer, and slump flow behavior of fresh UHPC mixture: (a) mixing of UHPC in laboratory drum mixer; and (b) slump flow behavior of UHPC.

ously were 250, 420, and 560 mm (10, 16.5, and 22 in.), respectively. The third mixing sequence, which yielded improved fresh mixture workability that is comparable with that achieved using a planetary mixer, was thus selected for use in the study.

The preliminary experimental results presented previously point at the potential merits of a laboratory drum mixer, which simulates the mixing action of commonly available transit and central mixers in ready mixed concrete plants for production of the UHPC mixtures developed in the study. Steps involved in a refined variation of the third mixing sequence presented previously, which is recommended for mixing of UHPC in a drum mixer, are presented as follows:

1. Dry blend half of cementitious materials with aggregates in drum mixer.
2. Add a fraction of water mixed with HRWRA to the rotating mixer until a homogeneous, flowable mixture is formed.
3. Add the remainder of cementitious materials to the rotating mixer.
4. Add the remainder of water mixed with HRWRA to the rotating mixer over a period of approximately 1 minute.
5. Continue mixing until a homogeneous, flowable mixture is produced (approximately 15 minutes).
6. Add steel fibers to the rotating mixer.



(a) Slump loss over time

(b) Fresh mix slump at 0 (left) and 90 (right) minutes after mixing

Fig. 6—Loss of fresh UHPC mixture workability over time at 22°C (72°F).

7. Continue mixing until a homogeneous, flowable fresh mixture is produced.

With these refinements, UHPC mixtures prepared in a drum mixer exhibited desired fresh mixture workability complemented with mechanical properties, which were comparable with those obtained with planetary and pan mixers. The refined UHPC mixture Mixture 2 was successfully prepared in a drum mixer using the aforementioned mixing sequence. The compressive strength of the UHPC prepared in the drum mixer reached 183.8 ± 4.8 MPa (26.7 ± 0.7 ksi), and 193.7 ± 5.7 MPa (28.1 ± 0.8 ksi) at 7 and 28 days of age, respectively. Again, it is worth emphasizing that many conventional UHPC mixtures cannot be mixed satisfactorily in a drum mixer; the UHPC mixtures developed in this investigation, however, were successfully mixed in a drum mixer, which simulates (at a lower intensity) the mixing action of commonly available transit and central mixers used in ready mixed concrete plants.

Improved slump retention over time

The high binder content and heat of hydration of UHPC together with its low water-cement ratio (*w/c*) can challenge the retention of adequate slump over the time required for transportation, field placement, and consolidation of UHPC. These challenges would be more pronounced at higher ambient temperatures. Because the UHPC mixtures were, immediately after mixing, moderately flowable, their

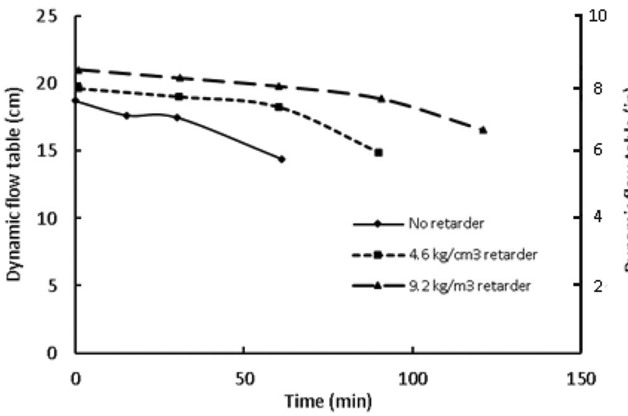


Fig. 7—Loss of flowability over time for UHPC mixtures with different set retarder contents.

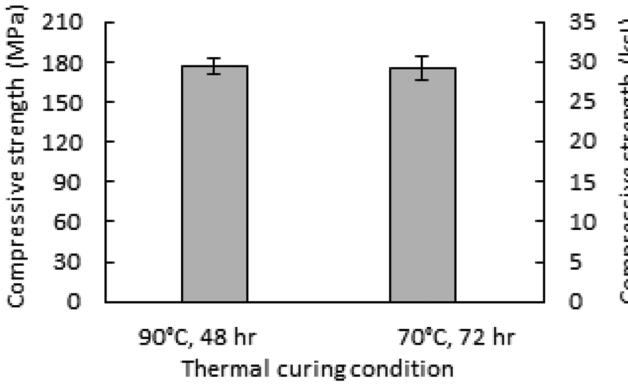


Fig. 8—Compressive strength test results (means and standard deviations) for "Mixture 1" UHPC subjected to different thermal curing procedures and tested at 7 days of age.

slump values could be measured over time. The test results presented in Fig. 6 show the trends in slump loss of a UHPC mixture design (Mixture 2) developed in this investigation over a period of 90 minutes at room temperature. Set retarders, which are commonly used for hot weather concrete construction, can help extend the period over which a desired slump is retained. An investigation conducted by Wang et al.[36] concluded that citric acid is effective in preserving the slump of a UHPC mixture; citric acid, however, did not work well with the UHPC mixture design developed in the study. Another set retarder from the same manufacturer that supplies the HRWRA used in the study was evaluated. This set retarder was evaluated in dosages ranging from 4.6 to 9.2 kg/m^3 (0.29 to 0.57 lb/ft^3). As shown in Fig. 7, the fresh UHPC mixture without set retarder lost close to 30% of its initial dynamic flow within 60 minutes. At a 4.6 kg/m^3 (0.29 lb/ft^3) dosage of set retarder, the fresh mixture flowability was largely retained over a period of 60 minutes and dropped to 75% of initial value after 90 minutes. Doubling the dosage of set retarder to 9.2 kg/m^3 (0.57 lb/ft^3) enabled retention of the fresh mixture flowability over a period of 90 minutes; after 120 minutes, 80% of the initial flowability was preserved. Compressive strength of the UHPC with 9.2 kg/m^3 of retarder, however, experienced a significant (approximately 30%) drop. The UHPC mixture with 4.6 kg/m^3 (0.29 lb/ft^3) set retarder, on the other hand,

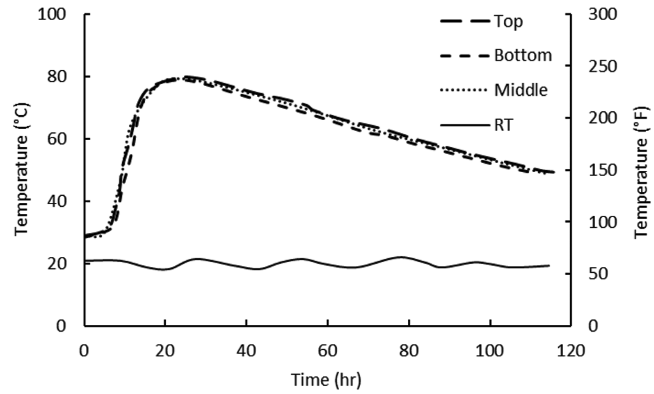


Fig. 9—Measured temperature time histories within UHPC block in insulated form (and measured values of room temperature).

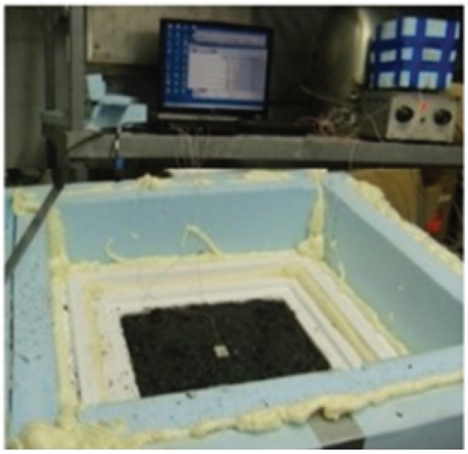
provided compressive strengths similar to those offered by the UHPC mixture prepared without any set retarder. Based on these results, a dosage of 4.6 kg/m^3 (0.29 lb/ft^3) of the set retarder was selected for use in the UHPC mixture developed in the study.

Use of heat of hydration toward practical and scalable field thermal curing of UHPC

In the experimental work reported so far, thermal curing was accomplished at 90°C (194°F) over 48 hours.[31,34,40,43] A comparative study of the UHPC Mixture 1 indicated that similar results can be obtained with thermal curing at 70°C (158°F) over 72 hours (Fig. 8). While some investigations emphasizing mechanical properties have concluded that room-temperature moist curing of UHPC is a viable option (with some loss of strength),[34] more comprehensive investigations have found excess creep deformations occurring in UHPC subjected to moist-curing at room temperature.[55] This finding points at the value of thermal curing toward development of the UHPC structure (especially at interfacial transition zones).

While thermal curing of UHPC can be implemented conveniently in laboratory, its field implementation is challenging. Relevant experience with high-strength concrete[1] implies that one can feasibly cure large UHPC structures at 70°C (158°F) over 72 hours through effective use of the heat of hydration of the cementitious binder. Control of moisture loss in such field thermal curing processes is also a concern, which is alleviated to a large extent by the distinct moisture barrier qualities of UHPC (even at early age).[2]

The measured temperature time histories at top, middle, and bottom layers of the UHPC block placed in an isolated formwork described earlier are presented (together with the measured values of room temperature) in Fig. 9. Temperatures were measured at equal distances from the four insulated walls of the formwork. Significant temperature rise initiated 3 hours after casting of UHPC, and a peak temperature of 78°C (172°F) was reached after 24 hours. The temperature gradient was negligible in this test, and the temperature time-history measured in this preliminary study seemed satisfactory for reproducing the effects of laboratory (external) thermal curing at 70°C (158°F) over 72 hours. The



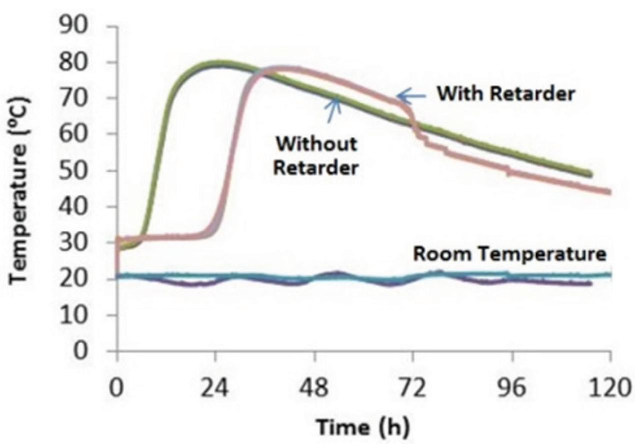


Fig. 10—Insulated block test setup, and measured temperature time histories within insulated blocks of UHPCs without and with set retarder (and measured values of room temperature).

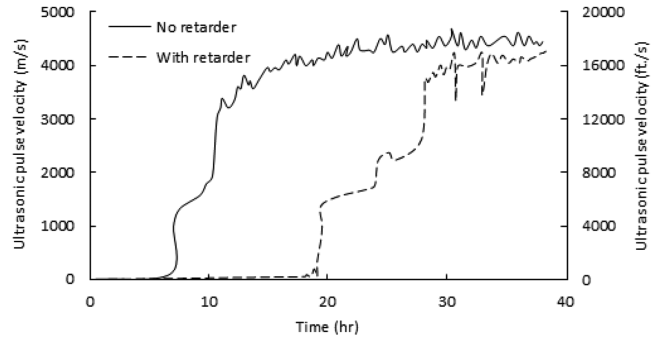


Fig. 11—Ultrasonic pulse velocity development over time for UHPC mixtures with and without set-retarding chemical admixtures.

distribution of temperature within the volume of insulated UHPC block was also found to be uniform, thus hindering development of thermal stresses (which are associated with temperature gradients).

The use of heat of hydration of UHPC toward field thermal curing was further demonstrated using the final UHPC mixture design (Mixture 2) refined with an optimized dosage of set retarder using the experimental setup shown in Fig. 10 (left). An insulated 0.3 x 0.3 x 0.3 m (1 x 1 x 1 ft) block of this UHPC mixture was prepared, with insulation placed on exterior surfaces. Figure 10 (right) presents the measured temperature time histories at top, middle, and bottom layers of this UHPC block; similar measurements for the UHPC mixture without set retarder are also shown together with the measured values of room temperature over time. Significant temperature rise initiated 2 hours after casting of the UHPC mixture without retarder, and a peak temperature of 79°C (174°F) was reached after 24 hours. With set retarder, initiation of temperature rise was significantly delayed (it started approximately 24 hours after casting), and a peak temperature of 77°C (171°F) was reached after approximately 35 hours. Temperature gradients were negligible with both UHPC mixtures, and the measured temperature time histories seemed to be satisfactory for reproducing the effects realized by laboratory (external) thermal curing at 70°C (158°F) over 72 hours.

The block specimen subjected to adiabatic curing was also subjected to nondestructive evaluation during the curing process by measurement of ultrasonic pulse velocity. Figure 11 compares the development of UPV over time for UHPC mixtures prepared without and with set retarder. Nondestructive measurements confirmed that the use of set retarder significantly delayed initial setting of UHPC in the insulated block from approximately 6 hours to approximately 18 hours. Cores obtained from the block after 28 days of semi-adiabatic curing produced compressive strengths that were slightly (approximately 10%) less than that obtained for specimens subjected to external thermal curing at 90°C (194°F) over 48 hours.

PILOT-SCALE PRODUCTION OF UHPC FOR EVALUATING POTENTIAL FOR FIELD THERMAL CURING

Materials and methods

The ready mixed concrete plant used its existing facilities and instruments to batch the mixture ingredients identified in Table 1 (Mixture 2) into a concrete truck (transit mixer) to produce a total UHPC volume of 1.33 m^3 (1.74 yd^3). The UHPC ingredients of Table 1 (Mixture 2) were either available in the ready mixed concrete plant or could be conveniently acquired from sources supplying materials to the construction industry and stored in the plant. Consultations were made with the technical personnel of the ready mixed concrete plant to devise a mixing sequence that reflects the experience in laboratory preparation of UHPC in a drum mixer, and also the experience of the ready mixed concrete plant with production of high-strength concrete. Based on these consultations, the following sequence of batching and mixing was selected:

1. Automated batching of 50% of granite coarse aggregate, all the natural sand fine aggregate, silica sand, cement, slag, silica fume, and 50% of water and HRWRA (with mixer rotating at 15 revolutions/minute);
2. Manual addition of limestone powder;
3. Automated batching of the remaining 50% of granite coarse aggregate, water, and HRWRA (with mixer rotating at 15 revolutions/minute); and

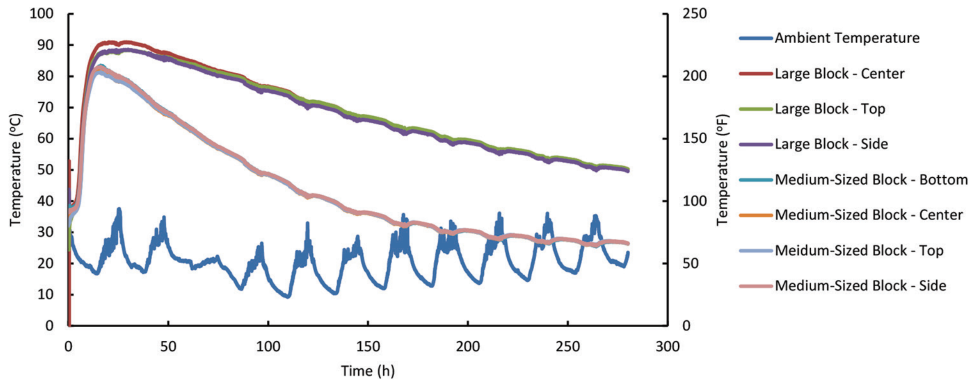


Fig. 12—Temperature time histories at different locations within large and medium-sized blocks made with UHPC prepared at pilot scale.

4. Manual addition of steel fiber and set retarder followed by thorough mixing, and final checking of fresh mixture prior to delivery.

The fresh UHPC mixture delivered to the jobsite was subjected to slump and slump flow tests (considering that the fresh UHPC mixtures exhibited moderately flowable rheologies). The UHPC mixture was then cast directly from the concrete truck into the formwork prepared for production of blocks. Following internal consolidation and surface finishing of the UHPC blocks, their exterior surfaces were covered with concrete curing (insulating) blanket. The readily available concrete curing (insulating) blanket used to facilitate effective use of the heat of hydration of the cementitious binder in UHPC towards field thermal curing of the block provided an insulation *R*-value of 7.0. A medium-sized 0.3 x 0.3 x 0.3 m (1 x 1 x 1 ft) concrete block was also prepared similar to the large block.

Four thermocouples were placed inside each UHPC block for monitoring of temperatures near bottom, center, and top (all central region), as well as side (midheight near wooden formwork) of the block over time. Ambient temperature was also monitored. In addition, UPV measurements were made to monitor the setting and strength development of UHPC in the field.

An important consideration in scaled-up production of UHPC is the precision in batching of different mixture ingredients. The relatively low water content of UHPC as well as the sensitivity of UHPC compressive strength to *w*/*cm* require careful control of the water content and also the cementitious binder content of the mixture. The precision of the instruments used for automated batching of the mixture ingredients in the ready mixed concrete plant together with the fact that a relatively small quantity of UHPC (accounting for only 15% of the truck capacity) was prepared produced up to 10% deviation from the targeted water and cementitious contents of UHPC. These deviations could be lowered to below 2% if approximately 70% of the truck capacity was batched (which is the common practice). An important lesson from the pilot-scale investigation was that the 10% deviation from the targeted water and cement contents when only 15% of the truck capacity was batched compromised the fresh mixture workability. The lack of precision in automated batching of this relatively small quantity of UHPC in ready mixed concrete plant required a rise in the HRWRA content by 10% of the originally targeted level to achieve an acceptable fresh mixture workability marked by 279 mm (11 in.) slump and 610 mm (24 in.) slump flow. This desired fresh mixture workability facilitated convenient casting, consolidation, and finishing of the relatively large UHPC blocks in a sunny day with measured site temperature of 30°C (86°F).

Construction of the larger 1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft) and the medium-sized 0.3 x 0.3 x 0.3 m (1 x 1 x 1 ft) UHPC block provided a basis for: 1) assessment of the potential for field placement, consolidation, and thermal curing of large UHPC structures; and 2) evaluation of the potential for nondestructive field monitoring of the setting and strength development of large UHPC structures.

Field evaluation of large UHPC structure

The temperature time histories recorder at different locations of the large (1 x 1 x 1 m) and medium-sized (0.3 x 0.3 x 0.3 m) blocks are shown in Fig. 12 together with the measured values of ambient temperature, which varied from 10 to 35°C (50 to 95°F). The temperature timehistories obtained within the medium-sized block made with UHPC produced at pilot scale were comparable to those obtained for similar blocks made earlier using the UHPC produced in laboratory. Temperatures measured at different locations within the medium-sized UHPC block pointed at a reasonably uniform distribution of temperature within the volume; a peak temperature of 80°C (176°F) was reached after 12 hours; subsequently, temperature dropped gradually and it took 96 hours to drop to 50°C (122°F). This is a favorable temperature time history for thermal curing of UHPC. In the case of the large 1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft) UHPC block covered with concrete curing (insulating) blanket, temperature within the volume rose uniformly to 90°C (194°F) within 13.5 hours, and remained above 70°C (158°F) for more than 100 hours. This is a highly desirable temperature time history for thermal curing of UHPC. The higher peak temperature and slower temperature drop in the large UHPC block, when compared with the medium-sized block, points at the reduced rate of heat loss (per unit volume) from the larger block. This can be attributed to the smaller surface-to-volume ratio of the larger block.

Figure 13 presents results of in-place nondestructive UPV measurements. UPV is observed to start rising 2.5 hours

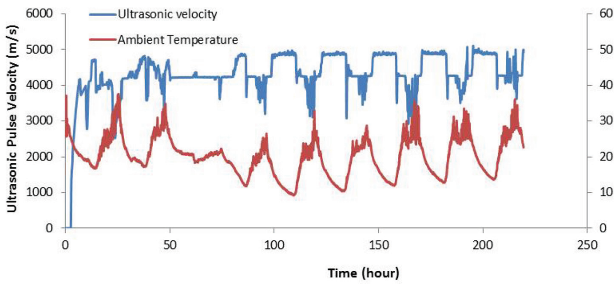


Fig. 13—Ultrasonic pulse velocity measurements versus time made in field on reinforced concrete block made with UHPC prepared at pilot scale.

after casting, and to reach 4 km/s (2.5 miles/s) at 6.25 hours. Beyond this point, UPV increased slowly, reaching 5 km/s (3.1 miles/s) at 84 hours after casting, which (based on the correlations established earlier) indicates that the mixture batched at pilot scale in the ready mixed concrete plant, and mixed and transported using a transit mixer could be categorized as ultra-high-performance concrete. Figure 13 also depicts measurements of ambient temperature over time, indicating that ambient temperature could influence the field UPV measurements. The temperature rise in large UHPC placements can influence the UPV test results, noting that an ambient temperature range of 0 to 40°C (0 to 104°F) has been specified during UPV measurements.

Due to the somewhat imprecise batching of the relatively small quantity (15% of truck capacity) of UHPC at the ready-mixed concrete plant, cylinders made directly from the UHPC truck and cured at 90°C (194°F) over 48 hours provided 7-day compressive strengths of 159 ± 4 MPa (23.0 ± 0.6 ksi), compared to >200 MPa (29 ksi) compressive strength obtained with the same UHPC mixture produced in laboratory. Cores extracted from the large concrete block, which experienced a particularly favorable temperature time history (using the heat of hydration of cementitious binder, without any external heating), produced compressive strengths of 167 ± 6 MPa (24.2 ± 0.9 ksi), which exceeded the strengths produced with controlled thermal curing in laboratory. This confirms the desired thermal curing condition within the large concrete block generated by the heat of hydration of the UHPC cementitious binder (in the presence of a set retarder). Still, the inaccurate batching of the relatively small volume of UHPC in the ready mixed concrete plant lowered the 7-day compressive strength of the pilot-scale UHPC below the 200 MPa (30 ksi) obtained in laboratory-scale production. An evaluation of the batching operation in the ready mixed concrete plant indicated that production of approximately 70% of truck capacity (7.6 m^3 [10 yd^3]) versus the 15% truck capacity prepared in the pilot-scale investigation alone could yield the precision needed to reproduce the success in laboratory-scale preparation of UHPC, which reached the 200 MPa (29 ksi) compressive strength. The favorable curing conditions within large UHPC structures produced core compressive strengths that exceeded that obtained with controlled thermal curing in laboratory. It should be noted that only one truck of UHPC, using 15% of truck capacity, was produced in this work. Therefore, the truck-to-truck variability was not investigated.

CONCLUSIONS

A pilot-scale field investigation was conducted where the heat of hydration of the cementitious matrix was used for curing of ultra-high-performance concrete (UHPC). A nondestructive test method based on measurement of the ultrasonic pulse velocity (UPV) was devised and calibrated for in-place monitoring of the development of the structure and strength of UHPC. Given the reliance on heat of hydration for field thermal curing of UHPC, in-place monitoring of UHPC is an important quality control tool because laboratory thermal curing may deviate from the actual thermal curing conditions experienced by UHPC in field. Selected UHPC mixture designs were used in pilot-scale production of a large 1 x 1 x 1 m (3.3 x 3.3 x 3.3 ft) reinforced concrete block with UHPC batched in a ready mixed concrete plant and mixed/transported using a conventional concrete truck (transit mixer). The mixing process was reasonably successful, and the fresh mixture provided desired workability characteristics. The temperature time histories monitored at different locations within the block covered with a readily available insulating blanket indicated a uniform temperature rise that suits thermal curing of UHPC. Nondestructive measurements pointed at satisfactory setting characterizations while provided adequate working time in a warm, sunny day. The strength development of UHPC in field within the large block was adequate to realize the ultra-high-performance status. Compression testing of specimens made from the UHPC produced under pilot-scale condition and also those cored from the large block indicated that the field thermal curing conditions generated by the heat of hydration of the consumption parts within the UHPC block produced core compressive strengths, which were higher than those obtained via laboratory thermal curing. This finding indicates that the heat of hydration of the cementitious binder in UHPC enables effective field thermal curing of large UHPC structures. The values of compressive strength obtained for cylindrical specimens via pilot-scale batching of UHPC in a ready mixed concrete plant and mixing in a transit (truck) mixer were, however, 15% below those obtained via laboratory mixing. The UHPC mixture developed in the study incorporated relatively high dosages of readily available aggregates and relatively low cementitious binder contents, and made optimum use of chemical admixtures and fibers; these features reduced the raw material costs of the new UHPC mixtures to approximately 60% of existing UHPC materials. The use of conventional mixers and construction practices further reduced the initial cost of the UHPC materials developed in the study.

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NOTES: