Implementing nonproprietary, ultra-high-performance concrete in a precasting plant

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- By taking advantage of ultra-high-performance concrete's (UHPC's) compressive strength, durability, tensile strength, and postcracking capacity from fiber reinforcement, bridges may be designed with longer spans, slimmer members, and increased design lives.

- Trial batches were conducted to evaluate the plant and production capabilities for the effective batching of locally produced UHPC.

- Successful completion of the project demonstrates that UHPC can be produced by adapting laboratory methods for plant production with no changes to plant facilities.

Ultra-high-performance concrete (UHPC) is an advanced construction material that offers enhanced mechanical and durability properties. UHPC offers several advantages over normal-strength concrete and high-performance concrete. These advantages are achieved through optimized mixture proportions, a low water–cementitious material ratio *w/cm*, an optimized particle packing density, and curing in high-humidity and high-heat environments. UHPC also can exhibit improved tensile strength and ductility due to the addition of high-strength steel fibers, allowing the concrete to resist stresses imposed after initial cracking.[1] The dense nature of the UHPC matrix decreases the porosity of concrete, resulting in improved durability properties and increasing the expected service life of a structure.[2] The use of UHPC can also result in reduced detailing (for example, reduced mild steel reinforcement) leading to shorter construction times, smaller substructures, and reduced maintenance costs.[3] These benefits allow for lower transportation costs, longer design lives, and less impact on travelers (user costs); therefore, incorporating UHPC into prestressed concrete bridge design could significantly benefit transportation infrastructure.

UHPC production and testing

The mixing, casting, and curing methods that are used in the production of UHPC can have a significant effect on the properties of the concrete. Over the past several years, mixture proportions using materials local to New Mexico have been developed for a UHPC that has compressive strengths exceeding 20,000 psi (140 MPa), has a minimum durability factor of 95 (to ensure adequate resistance against freezing and thawing), and is resistant to alkali-silica reaction. The development of the mixture proportions and the strength and durability studies were conducted in laboratory facilities on small batches with a maximum volume of 1.50 ft^3 (0.0425 m^3). In the laboratory, material preparation was conducted to ensure precise mixture proportions, proper moisture content, sand gradation, and quality of ingredients. In addition, the mixing process was closely monitored and could easily be adjusted if changes were necessary. Following the completion of the small-scale laboratory study, the task to implement the production of the UHPC on a large scale was undertaken. As the production of the concrete on a large scale began to be considered, a variety of concerns arose as to how the UHPC could be reliably and consistently produced. Four batches of UHPC were cast in a trial program to address these concerns and investigate the feasibility of the production, casting, curing, and use of this locally made UHPC for precast and prestressed concrete applications.

The four trial batches of UHPC were cast at a precast concrete plant in Albuquerque, N.Mex., from November 2013 to January 2014. Due to the significant variations in conditions between the plant setting and the laboratory setting, separate mixing procedures and curing regimens were established. Although the environmental conditions and equipment were drastically different between the two locations (that is, laboratory versus precaster batch plant), every effort was made to ensure consistent and reliable methods regardless of the setting.

The constituents of the UHPC studied came primarily from regionally available materials. The mixture proportions were developed in the laboratory through optimization studies by Lyell[4] and Weldon et al.[5] The UHPC in this research has a *w/cm* of 0.145, with a target compressive strength of 20,000 psi (140 MPa). **Table 1** provides the mixture design for the typical UHPC that was used throughout the research using a 1.5% fiber addition by volume. The fiber used was a monofilament fiber with a diameter of 0.0080 in. (0.20 mm) and a length of 0.50 in. (13 mm), therefore having a length-to-depth aspect ratio of 65. The minimum tensile strength of the fibers was 285 ksi (1900 MPa) with a modulus of elasticity of 29,400 ksi (203 GPa). Fine angular sand was used with a sieve top size of 0.187 in. (4.75 mm) and minimum particle size of 0.0029 in. (0.075 mm). The high-range water-reducing admixture (HRWRA) used was polycarboxylate based.

Compression testing was conducted on all of the concrete batches following British standards (BS).[6] For all UHPC batches, 2.0 and 4.0 in. (51 and 102 mm) cubes were cast to eliminate the need for end preparation and grinding. Steel plates were placed on the tops and bottoms of the UHPC cubes during testing, with a thin layer of oil applied to minimize lateral confinement. The loading rate for the UHPC cubes was set to 9000 psi/min (62 MPa/min), which has been proved to be a reliable, efficient loading rate for UHPC in compression.[7]

Table 1. Ultra-high-performance concrete mixture proportions

Constituent	Quantity, lb/yd^3
Angular sand	1812
Type I/II cement	1296
Silica fume	203.0
Class F fly ash	122.0
Water	258.0
High-range water-reducing admixture	82.10
Steel fibers	198.0
Note: 1 lb/yd^3 = 0.593 kg/m^3.	

Laboratory UHPC production

This concrete was first produced in small batches in a 0.25 ft^3 (0.007 m^3) pan mixer or a 2.0 ft^3 (0.057 m^3) portable drum mixer in the laboratory. Based on variations in mixing energy and ambient conditions, slight variations in the mixing procedure were used between the two mixers; however, the mixture proportions and curing process remained the same. Due to the lower mixing energy of the drum mixer, the total mixing time required for the UHPC to reach an adequate workability for casting was significantly increased, from approximately 25 minutes using the pan mixer to nearly an hour. Although a long mixing time has the potential to dry out fresh concrete prior to casting, a plastic sheet was placed over the mouth of the drum mixer to reduce moisture and material loss prior to the final concrete cast, and no negative effects were observed.

Prior to mixing, all fine aggregates were graded through a no. 4 sieve (0.187 in. [4.75 mm]) to ensure the proper maximum aggregate size and were then washed over a no. 200 sieve (0.0029 in. [0.075 mm]) to remove the finer particles. After washing, the sand was oven dried for 24 hours to a moisture content of 0%.

The laboratory mixing process consisted of a dry mixing stage to ensure total homogeneity of sand, cement, fly ash, and silica fume. After this dry mix, half of the total water was added while the concrete continued to mix. After this stage, the remaining water and the HRWRA were added and the concrete continued to be mixed until the proper consistency was reached.

Once the concrete was cast, the molds were covered with plastic and stored at ambient temperature for approximately 24 hours. Upon demolding, the specimens were placed in a heated water bath at a constant temperature of 203°F (95.0°C) for four days and were then removed from the water bath and cured in a dry heat phase for an additional two days at 203°F. After the curing process, compressive strengths were measured (7-day strengths). **Figure 1** provides the core temperatures of 4.0 in. (100 mm) UHPC cubes throughout the laboratory curing regimen as measured by embedded thermocouples in the center of the cube specimen. Temperatures were recorded every 5 minutes throughout the entire curing regimen. Although this mixing process is quite effective and has shown that it can produce UHPC with adequate strengths, it is not practical on an industrial scale. Therefore, alterations to the mixing and curing regimens were investigated during the trial batches conducted at the precasting facility.

Batch plant UHPC production

Due to a variety of mixing, curing, and casting requirements, UHPC is a structural material that is ideally suited for casting and manufacturing in a precast concrete setting. However, prior to the implementation of UHPC into structural design, it was first necessary to ensure that this material's unique batching requirements were possible on a large scale. Before proceeding with production, an in-depth analysis of the current capabilities of the precast concrete plant was conducted to determine what changes to the laboratory procedure were necessary to ensure that the UHPC could be reliably and confidently produced in an industrial setting. It was desired that the implementation of UHPC would require minimal changes to current production facilities.

Prior to starting the trial batches, a variety of concerns needed to be addressed:

Figure 1. Typical core temperatures of a 4.0 in. ultra-high-performance concrete cube during the laboratory curing regimen. Note: 1 in. = 25.4 mm; °C = (°F – 32)/1.8.

- batch plant mixing times
- delivery method from batch plant to casting location
- workability of the fresh concrete during mixing and casting
- duration of the curing regimen
- temperatures required during the steam- and dry-curing process
- capacity for testing specimen compressive strengths

Over a period of several months, steps were taken to address these concerns and to ensure that the mixing of UHPC could be accomplished with existing equipment. The process was to begin with the mixing of two small initial trial batches in a typical drum-style portable mixer with a volume of 9.0 ft^3 (0.25 m^3). By doing so, the precaster would be able to get a hands-on feel for the workability of the mixture and would also be able to assess its capability for steam curing the UHPC at the high temperatures required. The next stage in the trial batching process would be two large 1.0 yd^3 (0.77 m^3) batches in the batch plant. This would be the final test to evaluate whether mixing UHPC would be possible on an industrial scale with its current equipment.

Trial batch 1

The first UHPC trial batch took place on November 11, 2013. The mixture was 3.0 ft^3 (0.085 m^3) in volume and contained no steel fibers. Steel fibers contribute to a large portion of the cost of UHPC and were therefore left out of the small trial batches. The mixer was a gas-powered, 9.0 ft^3 (0.25 m^3) portable drum mixer. Mixing started at approximately 1:00 p.m., with an average ambient temperature of 45°F (7.2°C). The concrete was used to cast two 6.0 × 6.0 × 40 in. (150 × 150 × 1020 mm) beams and two 6.0 × 6.0 × 36.0 in. (914 mm) beams as well as several 2.0 and 4.0 in. (51 and 100 mm) cube specimens.

To mimic the laboratory procedure, the sand used in the first trial batch was washed prior to casting. However, due to the increased quantity, oven drying was not an option, and thus, the sand remained saturated until the time of mixing. On the day of mixing, a sample of sand was oven dried, and the moisture content was approximately 11.11%. This moisture was taken into account in the mixture proportions.

The mixing procedure followed a procedure similar to what is currently practiced in the laboratory. **Figure 2** illustrates the schedule for the laboratory mixing procedure, which was duplicated for the first two small-scale trial batches. The figure also provides the altered mixing

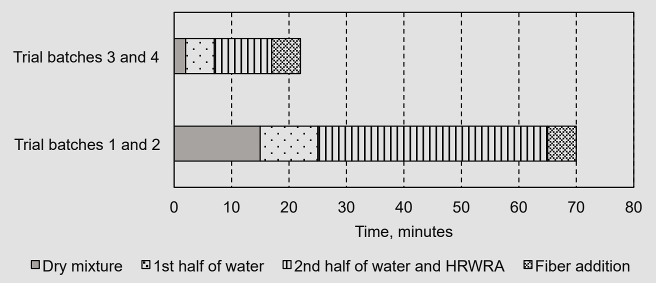

Figure 2. Average mixing times and procedures for the trial batches at the precast concrete plant.

procedure for the 3.0 yd^3 (2.3 m^3) batch plant that was used in trial batches 3 and 4. Due to the high moisture content of the washed aggregate, the dry mix stage was significantly less effective. Once the dry mix stage finished, half of the water was added. The consistency of the mixture was similar to that experienced in the laboratory, and no problems were noted.

After 10 minutes of mixing with half of the water, the rest of the water and HRWRA were added. However, the concrete immediately became fluid, a significantly different result from what was observed in the laboratory at the same stage. Upon closer inspection of calculations and material properties, it was discovered that an error had been made involving the aggregate absorption rate. A value of 8% was input into the programmed mixture design, but the absorption rate was actually 0.8%. This led to a significantly larger amount of water addition than required. Although this trial batch was not likely to reach the required strengths, the curing process was still performed to evaluate the plant's curing capabilities.

The curing process of trial batch 1 differed from that currently practiced in the laboratory. One large concern of the precaster was the long curing regimen for UHPC, which required monitoring the curing process over the weekend, resulting in excessive costs. To eliminate these costs, a new curing schedule was adopted. **Figure 3** shows the typical curing procedure for the laboratory and the precast concrete plant. The new curing regimen takes into account the precaster's five- to six-day workweek. The decision was made to cast the UHPC on a Friday evening and allow it to cure at ambient conditions (with propane heat to prevent freezing) until steam could be initiated and continuously monitored throughout its duration. Steam treatment would be conducted for four days, similar to the laboratory regimen; however, the dry heat stage would be reduced to one and a half days in order to end the curing regimen by midday the following Saturday.

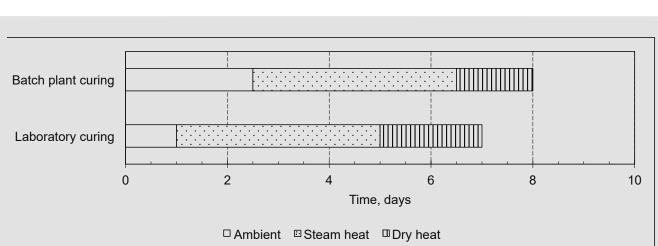

Figure 3. Comparison of batch plant and laboratory curing regimens.

During the curing process, there was a power outage during which the steam-generation equipment was shut down for several hours. This resulted in issues getting the specimens to the required temperatures during curing, with an average steam temperature of approximately 126°F (52.2°C), much lower than the desired 203°F (95.0°C). Large ambient temperature fluctuations were seen, which also contributed to the lower average curing temperatures. In addition, the data logger that was used to record the core concrete temperatures ran out of available memory just prior to the dry heat curing stage, so no temperature data is available for this time period. **Figure 4** provides the core temperature of a 6.0 × 6.0 × 40 in. (150 × 150 × 1020 mm) beam during the curing regimen compared with the expected core temperature. The large fluctuations in the concrete temperature are due to the problems with the steam-generation system shutting off.

Trial batch 2

Trial batch 2 was cast on December 6, 2013, with the goal of replicating trial batch 1 while eliminating the errors that occurred. Again, no steel fibers were used, and the batch had a slightly larger volume of 3.5 ft^3 (0.10 m^3) mixed in the portable 9.0 ft^3 (0.25 m^3) drum mixer. The average ambient temperature on this day was approximately 30°F (-1.1°C), which was much colder than the temperature during trial batch 1.

After experiencing issues with the saturated sand during trial batch 1, the washing process for the fine aggregates was eliminated. Based on previous results from a compressive strength study on the effect of washing aggregates

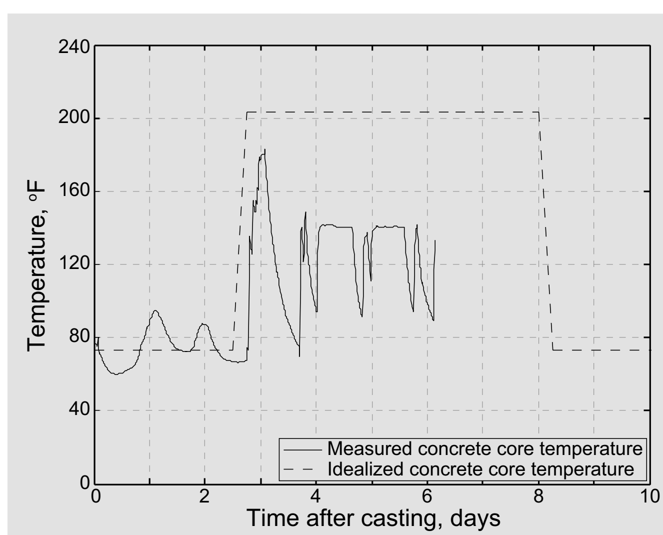

Figure 4. Core temperature of a 6.0 × 6.0 × 40 in. ultra-high-performance concrete beam during the curing of trial batch 1. Note: 1 in. = 25.4 mm; °C = (°F – 32)/1.8.

over a no. 200 sieve (0.0030 in. [0.076 mm]), it was shown that there is minimal effect on the compressive strength of this UHPC when mixed with washed or unwashed sand.[4] These results were confirmed when casting at the precasting facility because no adverse effects were observed regarding the compressive strength of the cube specimens. The moisture content of the aggregate was measured at 5.5%, and the error with the absorption from the first trial batch was corrected to 0.8%.

To reduce mixing times and due to the sand not being oven dry, the dry mixing stage was reduced to 1 minute with only cement, fly ash, and silica fume being dry mixed. The dry mix was performed with a plastic sheet over the mixer opening to avoid loss of material. The dry constituents were allowed to settle in the mixer for approximately 4 minutes prior to uncovering to help reduce material loss.

The sand was then added, and mixing continued for 2 minutes. The cover was removed without shutting down the mixer, and half of the add water was slowly poured into the mixer over a period of 2 minutes. The cover was replaced, and mixing continued for 10 minutes, at which time the cover was again removed and the remaining water and the HRWRA were added. The cover was replaced, and the mixer continued for another 10 minutes until the concrete was at the proper consistency for casting. During all stages of mixing, the concrete showed similar consistency and mixing characteristics to those seen in the laboratory.

The concrete from trial batch 2 was used to cast two 6.0 × 6.0 × 40.0 in. (150 × 150 × 1020 mm) beams and two 6.0 × 6.0 × 36.0 in. (914 mm) beams as well as several 2.0 in. (51 mm) and 4.0 in. (100 mm) cube specimens. Due to the low ambient temperatures, and therefore the low temperature of the steel drum mixer, the final consistency of the concrete was significantly less workable than that observed at the laboratory. A laser temperature scanner showed that the concrete surface temperature at casting was approximately 40°F (4.4°C). To prevent freezing of the fresh concrete over the weekend, electric heaters with thermostats were set to 81°F (27°C) and kept on continuously for approximately 60 hours. Despite the use of these heaters, internal concrete temperatures reached temperatures as low as 40°F and evidence of frosting on the outer faces of several of the 2.0 in. cube specimens was visible. The steam-curing temperatures were slightly better than those seen in trial batch 1, with smaller fluctuations in temperature throughout the week. The average steam-curing temperature was approximately 160°F (71°C). Due to memory restrictions, no data were recorded after approximately seven days after casting. **Figure 5** shows the core temperatures of a 6.0 × 6.0 × 40.0 in. (100 mm) UHPC beam compared with the idealized curing temperatures.

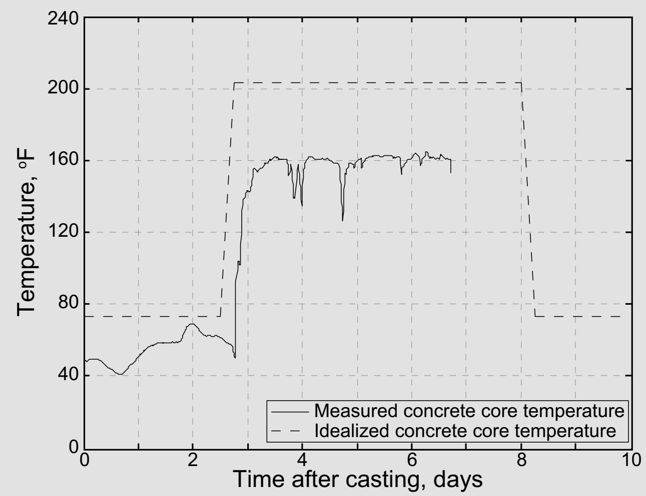

Figure 5. Core temperature of a 6.0 × 6.0 × 40 in. ultra-high-performance concrete beam during the curing of trial batch 2. Note: 1 in. = 25.4 mm; °C = (°F – 32)/1.8.

Trial batch 3: Reinforced concrete specimens

After assessing the issues seen in trial batches 1 and 2 and becoming more familiar with the UHPC and its mixing procedure, the team was ready to move to the batch plant facility. Several of the factors that would provide improvements compared with the mixing of trial batches 1 and 2 included the following:

- increased mixing energy
- the use of heated water to help mixture consistency
- faster mixing time
- a more regulated and automated process

Trial batch 3 was mixed on December 13, 2013, at approximately 4:30 p.m., one week after trial batch 2. The batch volume was 1.0 yd^3 (0.76 m^3) and was mixed in a 3.0 yd^3 (2.3 m^3) batching plant.

Due to the precise mixing procedure (Fig. 3), several ingredients required manual addition into the batch plant mixer. The dry mixing stage for trial batch 3 was similar to that of trial batch 2. The cement, fly ash, and silica fume were added to the mixture first and were dry mixed for approximately 1 minute. To prevent the chance of losing silica fume along a conveyor belt system that typically adds supplemental materials into the batch plant, all silica fume was added by hand. (This process has since been automated.) The sand was then added, as well as half of the water, which came from the batch plant itself. Mixing continued for exactly 10 minutes, until the remaining water was added. Due to the current formatting of the batch plant computer system, water cannot be added incrementally. To account for this, half of the water was added manu-

Dry mixing stage

After half water addition

After superplasticizer addition and second half of water

Desired consistency prior to fiber addition

Manual addition of fibers

Final mixing stage as fibers are distributed into the concrete

Figure 6. Batch plant mixing process.

ally. Also, the precaster currently uses an HRWRA that varies from the HRWRA used in the mixture proportions. Therefore, it was unable to add the HRWRA automatically. Because of this, all of the HRWRA was also added manually.

The consistency of the mixture seen in the batch plant at specific mixing stages varied significantly from what was observed in the laboratory's drum-style mixer. After the water from the batch plant was added, there was little observable difference in the mixture and it still appeared to

UHPC consolidation around reinforcement

Beam surface consistency immediately after casting

Figure 7. Ultra-high-performance concrete (UHPC) during casting as it consolidated around the mild steel reinforcement.

be dry. However, after adding the remaining water and the HRWRA, the mixture quickly turned over into a workable consistency. The final workability was reached after approximately 10 minutes, at which time the fibers were added. The fibers were added manually, one bag at a time. It was important that the fibers be added in a manner that provides adequate fiber dispersion. Once the fresh concrete with fibers was mixed for approximately 5 minutes, the batch was emptied into an auger-fed delivery truck for casting. **Figure 6** shows images of the concrete inside of the batch plant mixer during the mixing process.

The concrete from trial batch 3 was used to cast four 6.0 in. × 9.0 in. × 13 ft (150 mm × 230 mm × 4.0 m) beams. These beams were used to examine casting methods and workability and to determine whether the concrete would have any consolidation issues around mild steel reinforcement. Two 6.0 × 6.0 × 40.0 in. (150 × 150 × 1020 mm) beams and two 6.0 × 6.0 × 36.0 in. (914 mm) beams were also cast, as well as several 2.0 in. (51 mm) and 4.0 in. (100 mm) cube specimens for compressive strengths. Casting took approximately 15 minutes. It was important for the delivery process to be efficient to have the UHPC cast within 20 minutes of mixing to ensure proper workability. Bed vibrators were used to aid consolidation of the concrete, and the concrete showed good workability and flowed well around mild steel reinforcement. **Figure 7** provides images of the fresh UHPC during casting as it consolidated around the mild steel reinforcement. The top surface of a specimen immediately after casting can be seen as well.

A steel-framed canopy was erected around the concrete and covered with a thick plastic tarp. Two 125,000 to 170,000 BTU/hr propane heaters were used to provide adequate ambient curing temperatures over the weekend to prevent freezing. Ambient temperatures over the weekend had an average of 49°F (9.4°C). The average steam temperature was much steadier over this week, with an average temperature of approximately 175°F (79.4°C). Dry heat temperatures had an average of approximately 107°F (41.7°C), lower than those seen in the laboratory, but there were no issues with reaching the required compressive strengths. **Figure 8** provides the core temperatures of a 6.0 in. × 9.0 in. × 13 ft (150 mm × 230 mm × 4.0 m) beam compared with the expected temperatures throughout the curing regimen.

Trial batch 4: Prestressed beam specimens

After the successful completion of trial batch 3, the last trial batch was used to cast prestressed UHPC beams. Trial batch 4 was used to check the repeatability of large-batch production (including mechanical and physical concrete properties), as well as the potential for large-scale prestressed UHPC casting. Three prestressed UHPC beams that measured 7.0 in. × 15 in. × 16.0 ft (180 mm × 380 mm × 4.88 m) were cast. Similar to the previous batches, two 6.0 × 6.0 × 40.0 in. (150 × 150 × 1020 mm) beams and two 6.0 × 6.0 × 36.0 in. (914 mm) beams were also cast, as well as several 2.0 and 4.0 in. (51 and 100 mm) cube specimens. The final batch was cast on January 10, 2014, and had a volume of 1.60 yd^3 (1.22 m^3). The concrete was mixed in a 3.0 yd^3 (2.3 m^3) batching facility following the procedure used for trial batch 3. No

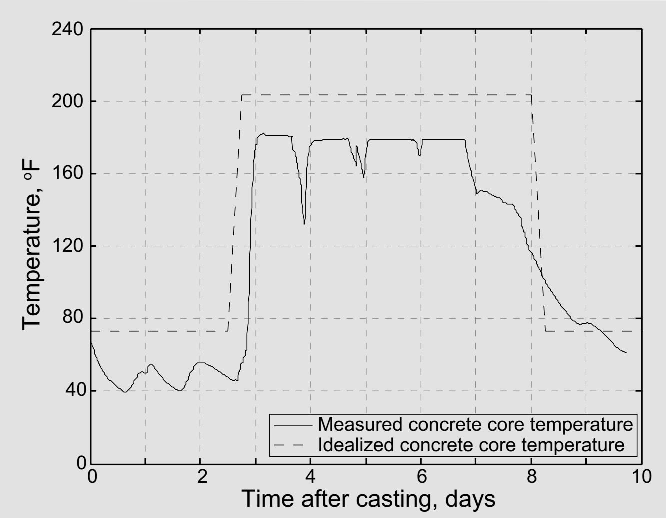

Figure 8. Core temperature of a 6.0 in. × 9.0 in. × 13 ft ultra-high-performance concrete beam during the curing of trial batch 3. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m; °C = (°F – 32)/1.8.

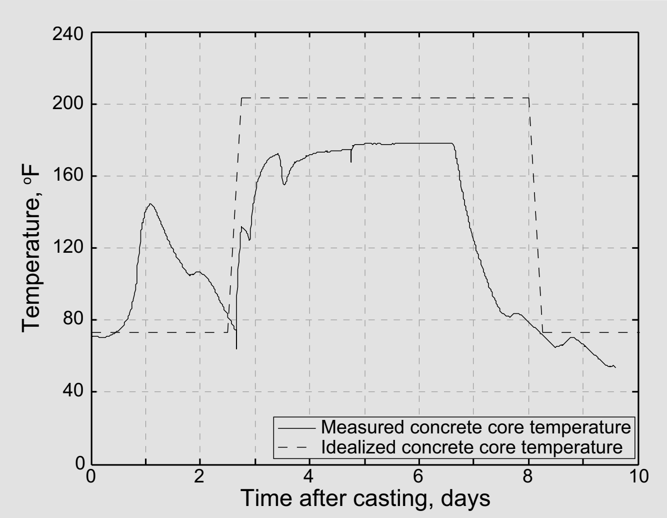

Figure 9. Core temperature of a 7.0 in. × 15 in. × 16.0 ft ultra-high-performance concrete beam during the curing of trial batch 4. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m; °C = (°F – 32)/1.8.

issues were encountered in the mixing process of the fourth UHPC batch, and the workability of the concrete was similar to that observed during the third trial. The larger volume of concrete did not hinder the batch plant's mixing capability. Once mixing was completed after approximately 25 minutes, the UHPC was transferred into an auger-fed delivery vehicle for casting.

The casting of the final batch was performed in approximately 12 minutes. The concrete was vibrated using external form vibrators throughout casting to ensure proper consolidation. Due to high winds on the day of casting, the top surface of the exposed concrete quickly began to dry, making it difficult to finish the top surface, but no adverse structural effects were noted. Compression specimens were cast from the same batch as the prestressed members. The compression samples were not externally or internally vibrated, but no consolidation issues were observed. The specimens were quickly covered with a plastic sheet in order to prevent moisture loss and shrinkage on the exposed surface, and were left under the same heavy insulated tarp as the prestressed concrete specimens for the duration of the curing regimen in order to ensure that the concrete was exposed to the same temperatures as the prestressed concrete beams.

To prevent any freezing effects while the concrete achieved initial set, propane heaters similar to those used in trial batch 3 were used and maintained an average temperature inside the insulated tarp of 57.2°F (14.0°C). After a period of 60 hours, the steam treatment was initiated maintaining an average concrete core temperature of 170°F (76.5°C) for four days. After steam curing was completed, propane heaters were used to simulate the dry curing stage of the laboratory curing regimen; however, the heaters were again not able to reach the same temperatures as achieved in the laboratory setting. The dry heat stage showed rapidly declining temperatures as soon as the steam heat was turned off, with an average temperature over the course of 36 hours of 84.0°F (28.9°C). However, the lower temperatures during the final curing stage did not affect the compressive strength of the compression specimens. **Figure 9** plots the core temperature of a 7.0 in. × 15 in. × 16.0 ft (180 mm × 380 mm × 4.88 m) prestressed concrete beam cast from trial batch 4 against the expected core temperatures throughout the curing process.

Summary

The trial batching was a successful model for how this UHPC can be batched, cast, and cured on a large scale. In each progressive batch, the efficiency of the processes saw significant improvement. Once the precaster became familiar with the material during the first two trial batches, it was better prepared for how the material would behave in its batching facility, as well as for its delivery to the casting bed. The plant's curing efficiency improved as well once the requirements of the steam generation system and curing regimen were better understood. The average curing temperatures increased as the trial batching process was conducted, ultimately providing the necessary temperatures for this UHPC to reach its desired compressive strength.

Perhaps the most significant accomplishment from the trial batching phase was that the batching, casting, and curing of this unique material was able to be accomplished without any significant alterations or improvements to the existing equipment. Many of the production steps could clearly be made more efficient, yet it is clear that producing large-scale members from this UHPC is possible and can be done without adjustment to the precaster's batch plant, delivery vehicles, or steam generation system.

A precaster's view

The project offered several challenges, such as precise mixing procedures, longer mixing/curing times, and high curing temperatures. After addressing these topics with the research team, the trial batch process began. After the successful completion of the trial batches, a lot was learned:

- how to handle the working consistency of the mixture compared with a conventional or high-strength concrete
- how to incorporate the unique challenges of the curing regimen
- the importance of continuously monitoring temperatures

The batching of this UHPC was the first of its kind in New Mexico, and a lot of knowledge was gained through this study. The processes used in the trial batches will continue to improve and become more automated as the use of the material increases. For example, the manual addition of the HRWRA can be an automated process for the regular production of precast concrete members rather than the small batches used in this research project. As more experience is gained using UHPC, the mixing and curing will become more efficient (as shown by the improvements observed from trial batch 1 to trial batch 4). Furthermore, continued research and investigation into the use of UHPC for prestressed concrete design will be conducted, including the development of full-scale prestressed concrete beam specimens.

Concrete compressive strength results

Tables 2 and **3** provide information regarding *w/cm*, fiber dosage, number of samples tested, specimen geometry, and the final specimen age and compressive strength at the time of specimen testing. The compressive strength specimens were tested at the time that the beam specimens (for example, 40.0 in. [1020 mm] beams) were tested; thus, the time intervals are varied. All of the batches containing fiber reinforcement used the same fibers and fiber content.

Conclusion

The capability to batch, cast, and cure UHPC using the precaster's existing equipment was addressed by conducting four trial batches. This process consisted of the following stages:

1. Mix small (3.0 to 4.0 ft^3 [0.085 to 0.11 m^3]) batches of UHPC to evaluate mixture proportions, ambient (outdoor) mixing and curing conditions, and repeatability and to familiarize the precaster with the material.
2. Evaluate results from the small-scale batches and work with the precaster to address concerns and recommendations for effectively moving UHPC production to their large batch plant mixer. Issues addressed included mixing times, method for fiber addition, delivery method from batch plant to formwork, concrete workability, curing temperatures, curing durations, time of prestress transfer, and capacity for testing 4.0 in. (100 mm) cubes.
3. Batch, cast, and cure prestressed UHPC specimens with minimal alterations to the current procedures and equipment at the precasting facility.

The following conclusions were made about the future mixing, casting, and curing of UHPC in both laboratory and plant environments:

- When mixing the UHPC in a traditional drum mixer, the current laboratory mixing procedure for the UHPC should be used. Lower mixing energies can cause workability issues if the mixing procedure is not carefully followed. However, the desired workability and compressive strengths are achievable without requiring a high-energy pan mixer or batch plant.
- When a high-energy mixer is used to mix this UHPC, mixing times may be reduced considerably. Desired consistency was achieved in approximately 15 minutes, which may potentially be reduced even further by increased automation of the batching process.
- The delivery of this UHPC to the casting beds was successfully accomplished using the standard auger-fed delivery vehicles currently in use by the precaster.
- Form vibrators should be used when available to ensure adequate consolidation around reinforcement and strands. Care should be taken to make sure overvibrating does not occur because this can lead to settling of the fiber reinforcement, which can affect flexural behavior.
- A minimum of 24 hours should be allowed for the concrete to achieve an initial set prior to steam treatment. Delaying the steam treatment for up to 60 hours after casting did not reduce ultimate compressive strengths.
- Desired 7-day strengths were achieved despite the maximum recorded core temperature during curing reaching only 180°F (82°C). This was 55°F (13°C) below the recommended curing temperature of 203°F (95.0°C). Therefore, the required temperatures for both the laboratory and plant procedure may be reduced to this value. However, careful monitoring should be performed to ensure that the target tempera-

Table 2. Compressive strength summary for trial batches 1 and 2

Trial batch	*w/cm*	v_f, %	Specimen cube size, in.	Specimen number	f_c', psi	Age at test, hr
1	0.247*	0	2.0	1	14,214	168
				2	13,256	168
				3	13,706	168
				4	7078.0	1008
				5	13,967	1008
				6	9573.0	2688
				7	9906.0	2688
				8	11,777	6408
				9	14,939	6408
				10	14,504	6408
				11	15,954	6408
				12	19,435	6408
			4.0	1	15,374	1008
				2	15,954	1008
				3	14,939	2688
				4	13,300	2688
				5	11,734	6408
				6	14,504	6408
2	0.145	0	2.0	1	9935.0	168
				2	7527.0	168
				3	11,284	168
				4	20,160	168
				5	10,530	168
				6	12,038	408
				7	12,038	408
				8	19,725	5808
				9	20,015	5808
				10	14,504	5808
				11	19,435	5808
				12	15,954	5808
				13	12,444	5808
			4.0	1	18,855	168
				2	20,015	168
				3	17,550	5808
				4	20,305	5808
				5	15,954	5808
				6	19,290	5808

Note f_c' = compressive strength; v_f = volume of fibers; *w/cm* = water–cementitious material ratio. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.
*High *w/cm* due to miscalculation of aggregate absorption

Table 3. Compressive strength summary for trial batches 3 and 4

Trial batch	*w/cm*	v_f, %	Specimen cube size, in.	Specimen number	f_c', psi	Age at test, hr
3	0.145	1.5	2.0	1	5279	60
				2	5250	60
				3	16,534	120
				4	22,771	120
				5	19,290	168
				6	22,336	168
				7	22,626	5640
				8	21,901	5640
				9	18,275	5640
			4.0	1	23,061	168
				2	22,336	168
				3	18,275	5640
				4	23,061	5640
				5	22,626	5640
4	0.145	1.5	2.0	1	27,557	168
				2	21,031	168
				3	20,450	1440
				4	18,420	4944
				5	22,626	4944
				6	21,321	5472
				7	23,496	5472
				8	24,076	5472
				9	23,786	5472
			4.0	1	23,641	168
				2	24,076	168
				3	20,740	1440
				4	23,206	1440
				5	22,916	4944
				6	21,756	4944
				7	23,641	5472
				8	21,466	5472
				9	23,496	5472
				10	23,931	5472

Note f_c' = compressive strength; v_f = volume of fibers; *w/cm* = water–cementitious material ratio. 1 in. = 25.4 mm; 1 psi = 6.895 kPa.

ture of 180°F is being reached. This core temperature was a result of trying to cure the concrete at 203°F, and lowering the target temperature could lower the observed temperature even further.

- The dry heat curing stage that consists of two additional days of curing at 203°F (95.0°C) was ineffective in the precasting setting due to the inability to trap the heat under the insulated sheets. However, desired strengths were still achieved; therefore, it is recommended that this stage be eliminated from the curing regimen of this UHPC.

- Any changes to the curing regimen could affect the durability of the concrete. Therefore, if changes are made, additional tests are required to ensure the durability properties of the concrete.

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Notation

f_c' = concrete compressive strength

v_f = volume of fibers

w/cm = water–cementitious material ratio

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Abstract

Ultra-high-performance concrete (UHPC) is a material with significantly different properties from conventional concrete. By taking advantage of this material's increased compressive strength, durability, tensile strength, and postcracking capacity from fiber reinforcement, bridges may be designed with longer spans, slimmer members, and increased design lives. UHPC mixture proportions were developed with materials available primarily within the state of New Mexico. To familiarize the local concrete industry with this concrete, the batching, casting, and curing of four trial batches were conducted with local precasters to evaluate production methods and develop recommendations and procedures for the batching of this UHPC. The trial batches were conducted to evaluate the plant and production capabilities for the effective batching of the locally produced concrete. Successful completion of the project demonstrates that this UHPC can be produced by adapting laboratory methods for plant production with no changes to plant facilities.

Keywords

Batching, bridge, casting, curing, design life, durability, local materials, postcracking capacity, span, tensile strength, UHPC, ultra-high-performance concrete.

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