Development of Non-Proprietary UHPC for Florida Precast Applications

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Abstract:

The development of non-proprietary ultra-high performance concrete (UHPC) mixtures based on locally available materials is of key importance in the deployment of the UHPC technology in the United States. With the development of lower cost, non-proprietary mixtures, larger-scale applications of UHPC are possible. This paper discusses a joint endeavor to develop precast bridge elements for Florida made from a non-proprietary, locally-based UHPC mixture. The paper discusses development of the non-proprietary mixture; evaluation of the mechanical properties and workability of the locally-based UHPC; considerations related to implementing the mixture at a plant-production scale; limited structural testing of a UHPC pile; and lessons learned from the trial placements to date.

Keywords: Non-proprietary UHPC, local materials, mix development, production, precast concrete

1. Introduction

Ultra-high performance concrete (UHPC) offers a number of potential benefits to the structural precast concrete industry. Because UHPC possesses high compressive and tensile strengths and an enhanced post-cracking ductility, precast UHPC elements may be designed with smaller cross sections and reduced amounts of prestressing strand and reinforcing steel relative to conventional precast elements. The lighter cross-sections can be used to produce longer span elements with fewer intermediate supports, providing more usable space between bridge piers, for example, and accelerating the construction process and reducing overall cost.

Although the use of UHPC in the United States has increased in recent years, most structural applications have been limited to joints between precast bridge panels and a few larger-scale bridge demonstration projects. One of the primary reasons that UHPC has not been more widely used in structural precast applications is the perception by many precasters that UHPC is an expensive, proprietary material that is simply too complicated and costly to produce. The purpose of this project was to challenge that perception by producing precast UHPC elements from a mixture based entirely on materials currently used by or locally available to a structural precaster in Tampa, Florida, and using equipment already employed by the plant for conventional precast production.

2. Background

The mechanical performance and long-term durability of UHPC are largely derived from its highly refined microstructure, which is created through a dense packing of fine and ultra-fine constituent materials and an ultra-low water-to-binder ratio (w/b). The constituent materials in UHPC typically include cement, silica fume, sand, and a fine supplemental material such as limestone powder, fly ash, slag cement, or ground silica. Steel fibers are used to provide additional tensile capacity and post-cracking ductility, and a high-range water reducer (HRWR) based on polycarboxylate technology is typically used to provide the UHPC with a self-consolidating, flowable consistency.

With the objective of making the UHPC more accessible to producers and designers, a number of researchers, producers, and transportation agencies have pursued development of non-proprietary UHPC mixtures. Wille (Wille, et al. 2011; Wille and Boisvert-Cotulio 2013) developed non-proprietary UHPC mixtures based on commercially available - but not necessarily local - constituent materials, with compressive strengths of up to 30 ksi (206 MPa) and a direct tensile strength of up to 5.4 ksi (37 MPa). Researchers at Montana State University - Bozeman (Berry, et al. 2017) developed a non-proprietary mixture based on locally available materials with compressive strengths between 18 and 20 ksi (124 and 138 MPa) and a post-cracking ultimate flexural strength of 3.4 ksi (23 MPa). In addition, an ongoing research effort through the Precast/Prestressed Concrete Institute (PCI), led by co-authors of this paper, is also seeking to develop and provide design guidance for the implementation of UHPC mixtures based on local materials at multiple precast facilities across the United States.

As efforts to develop UHPC mixtures based on locally available materials continue, it is anticipated that the technology will be more widely implemented in the structural precast industry. The purpose of this paper is to discuss the development of a non-proprietary UHPC mixture for a structural precaster in Tampa, Florida and the lessons learned from implementing the mixture at a plant-production scale. Although work to further refine the mixture and production methods are still ongoing, it is intended that the experiences of the project team to date will provide guidance to others seeking to develop UHPC mixtures based on locally available materials and to implement a laboratory-developed UHPC mixture at the plant scale.

3. Mix Development

The non-proprietary UHPC mixture was developed using a three-stage process modeled after Wille and Boisvert-Cotulio (2013), as outlined in Figure 1 below.

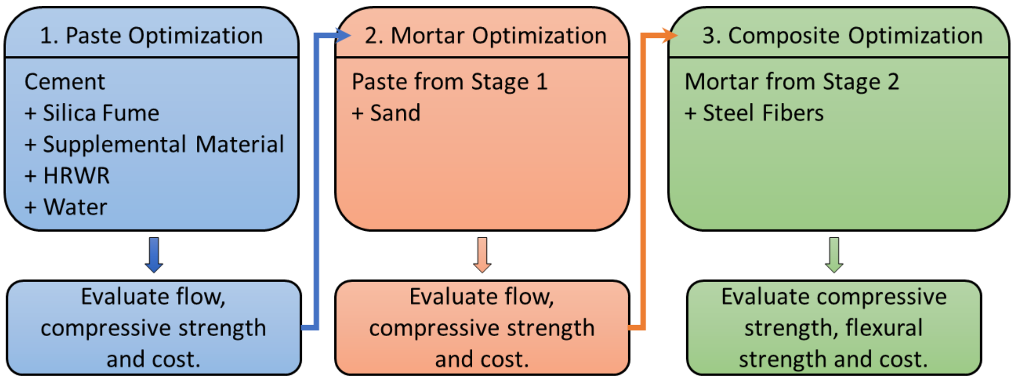

Figure 1. Three-Stage Mix Development Process

3.1. Paste Optimization

The first stage of the process consisted of paste optimization to identify the combination of cement, silica fume, supplemental material, and high-range water reducer (HRWR) that provided the most desirable combination of compressive strength, initial workability (flow), and cost. The materials considered consisted primarily of the materials currently used by the plant for production of structural precast, prestressed elements: a Type I/II (MH) cement; a dry, densified silica fume; Class F fly ash; fine concrete sand; and a polycarboxylate-based high-range water reducer (HRWR). Additional materials considered for mix development included a limestone powder and silica flour available through regional materials suppliers, and a finer mason sand provided from the same aggregate quarry as the plant's other concrete aggregates.

The paste optimization procedure used the orthogonal experimental design principles and statistical analyses described by Lawler, et al. (2007) to determine a "best predicted concrete" (BPC) based on a limited subset of mixtures tested. In this case, a total of 81 possible material combinations (represented by the factor-levels presented in Table 1) was reduced to a subset of 9 mixtures, from which the BPC mixture was selected based on consideration of the mixtures' compressive strength, initial workability, and cost.

Table 1. Variables Considered in Paste Optimization Stage

Factor	Silica Fume Dosage	Supplemental Material Type	Supplemental Material Dosage	Water-cement ratio (w/c)
Level 1	15%	Fly ash (Class F)	15%	0.23
Level 2	20%	Limestone powder	20%	0.25
Level 3	25%	Silica flour	25%	0.27

Small batches of each experimentally designed paste mixture were prepared in a 5-quart (4.7 liter) benchtop planetary mixer using the procedures illustrated in Figure 2. A nominal amount of sand (at a sand-cement ratio of 0.68) was included to facilitate dispersion of the densified silica fume during mixing. Initial workability was evaluated using the flow spread test defined in ASTM C1856, and compressive strength was evaluated on 2-inch (50-mm) cubes according to ASTM C109, using a modified loading rate of 145 psi per second (1 MPa per second). The BPC mixture for the materials considered was found to consist of the Type I/II cement, silica fume, and Class F fly ash, at a water-cement ratio (w/c) of 0.23 (w/b of 0.17).

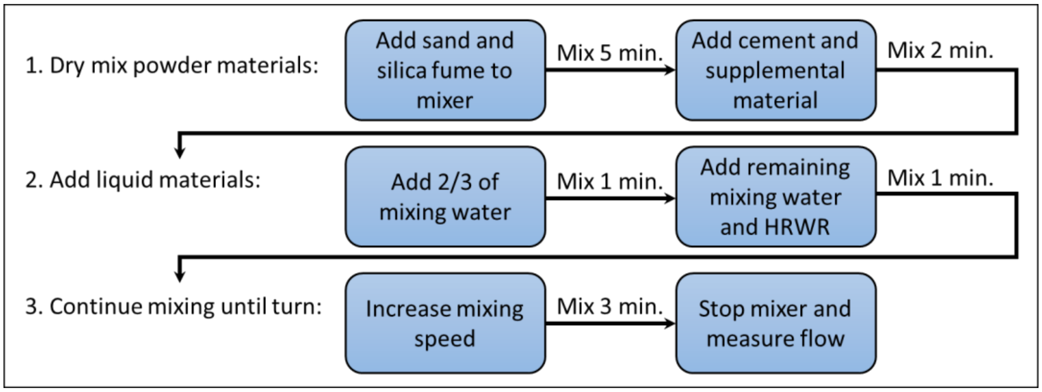

Figure 2. Laboratory Mixing Protocol

3.2. Mortar Optimization

The second stage of the mix development process consisted of mortar optimization, which considered the effect of sand gradation and proportions on the initial workability, compressive strength, and overall cost of the UHPC mixture. The materials were prepared following the same sequence as in the paste optimization stage, and the flow spread, compressive strength, and overall cost were evaluated for each combination.

The mortar optimization considered two sands: the conventional concrete sand currently used by the plant, and a finer mason sand supplied from the same quarry. The sands were added to the BPC paste mixture at three different sand-cement ratios (s/c) ranging from 1.0 to 2.0. It was observed that the mixtures containing the concrete sand had better workability at higher sand dosages, but mixtures containing the fine mason sand generally had higher compressive strengths as a result of the denser particle packing possible with the finer sand. The mixture selected for further development contained mason sand at a s/c of 1.0.

3.3. Composite Optimization

The final stage of the mix development process consisted of optimization of the UHPC composite, which considered the effect of fiber type and dosage on the compressive and flexural performance and overall cost of the UHPC mixture. The optimization considered two types of steel fiber, at dosages of either 1.5 or 2.0 percent by volume. The two fibers considered were a straight steel fiber with an aspect ratio of 100, and a 50/50 blend of straight and hooked-end steel fibers with aspect ratios of 100 and 83, respectively. All fibers had ultimate tensile strengths of 400 ksi (2,750 MPa).

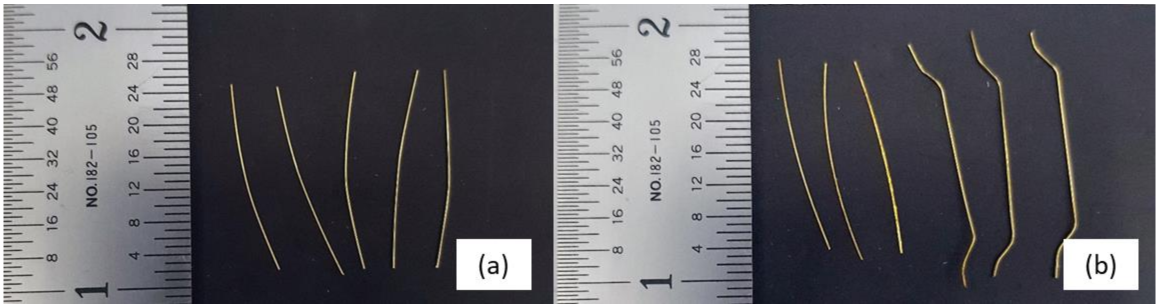

Figure 3. Steel fibers for composite optimization. (a) Straight fibers. (b) 50/50 blend of straight and hooked-end fibers.

Batches of UHPC, 1 ft^3 (0.03 m^3) in volume, were prepared in a 2-ft^3 (0.06-m^3) planetary pan mixer using the same general procedures outlined in Figure 2. After the mixture achieved a workable consistency, the fibers were added manually to the mixer. Compressive strength was evaluated using 3-inch by 6-inch (75 mm by 150 mm) cylinders (ASTM C39, as modified by ASTM C1856) and flexural performance was evaluated using 4-inch by 4-inch by 14-inch (100 mm by 100 mm by 350 mm) beams (ASTM C1609, as modified by ASTM C1856). All four mixtures evaluated had similar performance in terms of initial workability, compressive strength, and flexural performance; therefore, the mix containing 1.5 percent straight steel fibers by volume was selected for the final mix design based on consideration of material cost.

4. Field Trials

Two in-plant field trials were conducted with the developed UHPC mixture at Standard Concrete Products' (SCP's) precast facility in Tampa, Florida. The first trial, conducted in May 2017, was performed with the objective of developing a process for batching UHPC at the plant and for transporting and placing UHPC into standard forms. The second trial, conducted in February 2018, was performed with the objective of demonstrating the production of an octagonal pile element designed for Florida bridge structures based on the unique mechanical properties of the UHPC mixture.

The first field trial with the newly-developed UHPC mixture was conducted May 2, 2017. Ambient temperatures on the day of the field trial ranged from a low of 75 °F (24 °C) to a high of 91 °F (33 °C). The high temperatures, combined with a light breeze, meant that the UHPC mixture would be particularly susceptible to workability loss and finishing challenges as a consequence of early-age drying. In consideration of this possibility, every attempt was made to control the concrete temperatures during batching and at the time of placement, including using chilled mixing water (approximately 40 °F [4 °C]) and pre-cooled aggregates.

The second field trial was conducted February 7, 2018. Ambient temperatures on the day of the field trial ranged from a low of 72 °F (22 °C) to a high of 79 °F (26 °C). Although the temperatures were milder than for the first field trial, the high temperatures of the cement recently received by the plant still prompted concern over workability loss and early-age drying. Chilled mixing water was again used to reduce the concrete placement temperatures.

4.1. In-Plant Batching and Materials Testing

The UHPC mixtures used for both field trials were based on the mixture developed during laboratory trial batching. The mixtures consisted of Type I/II (MH) cement, silica fume, Class F fly ash, chilled water, mason sand, straight steel fibers, and a polycarboxylate-based high-range water reducer. All materials, with the exception of the mason sand and steel fibers, were already used by the plant for production of conventional precast elements and required no additional integration into the plant's materials storage system or batching operations. The mason sand was obtained from the aggregate supplier in one-ton (900 kg) super sacks, which were stored in a cool, shaded location, and the steel fibers were obtained from the fiber producer in 44-pound (20 kg) bags, which were stored in an enclosed storage space away from rain and direct sunlight.

The UHPC was mixed using the plant's horizontal twin-shaft mixer with a 5.5 yd^3 (4.2 m^3) output capacity. The individual material quantities for each batch were adjusted based on the moisture content of the aggregates, which was measured immediately prior to batching, and admixture dosage, which was adjusted between batches to achieve a target flow spread between 8 and 10 inches (200 and 250 mm).

For each batch, the mason sand, cement, silica fume, and fly ash were added to the mixer, in order, and dry-mixed for a total of 5 minutes, after which approximately two-thirds of the mixing water was added to the mixture. After 1 minute, the remaining mixing water and all of the HRWR were added to the mixer, and the materials were mixed until "turnover" was achieved. This was indicated by a peak current draw from the mixer and the transformation of the UHPC into a paste-like flowable mixture. On average, "turnover" was achieved approximately 10 minutes after all of the dry materials had been added to the mixer.

A sample of mortar was removed from the mixer and its total flow spread was measured in accordance with ASTM C1856. If the flow spread was within the target range of 8 to 10 inches (200 to 250 mm), pre-weighed fibers were manually added to the mixer. After all of the fibers had been added, the UHPC was mixed for an additional 3 minutes to ensure mixture homogeneity, then discharged. The total mixing time for each batch was approximately 35 minutes, with the manual addition of fibers consuming approximately 20 minutes of the total duration. Fibers were not added to the first batch for each field trial; instead, this batch served as a basis for adjusting the HRWR dosage to achieve the target workability for the subsequent batches produced each day.

Several properties of the UHPC mixture were evaluated during the trial batching efforts. These properties included:

- The temperature of the materials during mixing and immediately after discharge,
- The flow spread of each mixture before and after fiber addition (ASTM C1856),
- The funnel flow time of each mixture based on a modified grout flow test (ASTM C939),
- The unit weight and air content of the freshly discharged UHPC (ASTM C138 and C231, respectively),
- The working time of the material, i.e., how long the flow spread remained above 8 inches (200 mm),
- Fiber segregation according to a static segregation test based on ASTM C1610,
- The early-age (match-cured) and 28-day (standard-cured) compressive strengths of 3-inch by 6-inch (75 mm by 150 mm) cylinders (ASTM C39, as modified by ASTM C1856), and
- The flexural performance of 4-inch by 4-inch by 14-inch (100 mm by 100 mm by 350 mm) beams at an age of 28 days (ASTM C1609, as modified by ASTM C1856).

The average flow spread of each batch ranged between 9.5 and 10.5 inches (240 and 267 mm) at the time of fiber addition, and between 8.5 and 11.5 inches (216 and 292 mm) at the time of discharge from the mixer. Material temperatures ranged between 85 and 93 °F (29 to 34 °C) at the time of placement. The mechanical properties measured for field-cast specimens were generally consistent with those measured for laboratory-batched specimens for both field trials, with an average compressive strength of 18.3 ksi (126 MPa), an average first-cracking flexural strength of 2.3 ksi (16 MPa), and an average ultimate flexural strength of 3.1 ksi (21 MPa) at 28 days for standard moist-cured specimens. A 1-day compressive strength of 20.0 ksi (138 MPa) was achieved for match-cured specimens tested as part of the second field trial, so it is anticipated that the in-place compressive strength of the UHPC elements exceeded of 20 ksi (138 MPa) by 28 days.

4.2 Trial Placements

Mock-up elements cast between the two field trials included two panel elements measuring 10-feet by 10-feet by 4 inches (305 cm by 305 cm by 10 cm), two 5-foot (152 cm) sections of 12-inch (30 cm) square piles, and three 30-foot (914 cm) sections of 24-inch (61 cm) hollow octagonal piles. The cross-sectional dimensions of the octagonal piles were specially designed to take advantage of the increased compressive and flexural capacity of the UHPC material. Photographs of the finished octagonal piles are shown in Figure 4.

The concrete was transported from the batch plant mixer to the forms, located approximately one-half mile (0.8 km) away, using two different methods. For the panel and short pile elements, the UHPC was transported using a forklift-mounted bucket, which provided no agitation to the material during transit. This material flowed easily out of the bucket into the forms when placement first started, but quickly lost flow, resulting in difficult placement overall. Within minutes, a thick “elephant skin” formed on the surface of the UHPC, causing ripples and surface cracking as additional UHPC was placed. The skin significantly reduced the finishabilty of the UHPC surface, and the thixotropic behavior of the material limited its lateral flow distance.

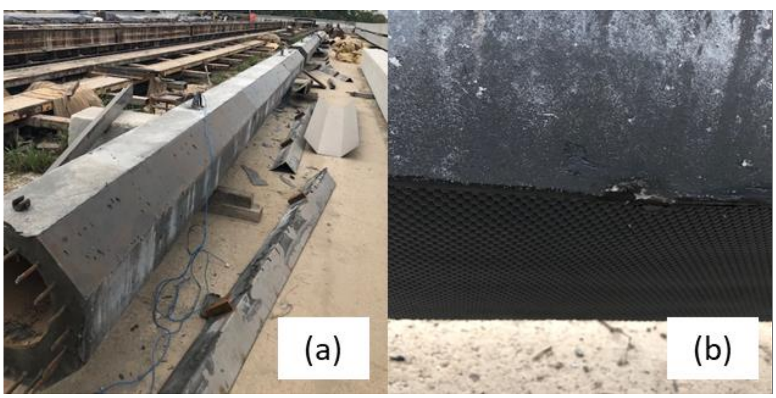

Figure 4. Photos of 24-inch Hollow Octagonal UHPC Piles. (a) Overall view of pile. (b) Transfer of pattern from textured formwork to pile surface.

For the octagonal pile elements, the UHPC was transported in a concrete mixing truck, which provided continuous, slow agitation of the material during transit, at a rate of approximately 6 revolutions per minute. Agitation helped maintain the workability of the material at the time of placement into the forms to near that when initially discharged from the mixer, but the material lost flow toward the end of the placements, which took 10 to 20 minutes to complete. For the final octagonal pile, the speed of the mixing truck was increased for 1 minute immediately prior to discharge into the forms, which improved the workability of the mixture at the time of placement such that the form could be completely filled within 3 minutes, with no loss of workability during that time.

While research has indicated that providing a 48-hour, 194 °F (90 °C) post-cure thermal treatment to UHPC imparts beneficial properties, this is an added operation in precast production. For these trials, no post-cure treatment was performed. Instead, the elements were covered with a tarp to limit evaporation from the surfaces, and only ambient heating, imparted by the warm Florida climate, was relied upon to cure the UHPC.

4.3 Structural Testing

Flexural testing of the pile was conducted at the laboratories of the Florida Department of Transportation Structures Research Center in Tallahassee, Florida (see Figure 5). The measured experimental moment was nearly 30 percent greater than the calculated theoretical moment. The theoretical moment was estimated using strain compatibility analysis with a standard rectangular stress block and a 0.003 ultimate strain at the compression face. No allowance was given in the flexural analysis for the tensile strength contribution of the fibers, only the prestressing strand contribution was considered. Despite these conservative assumptions and having less than half of the cross-sectional area of concrete, the flexural capacity of the UHPC octagonal pile matched that of a conventional baseline pile. Additionally, the axial strength of the UHPC pile far exceeded that of a baseline pile, indicating superior qualities during pile driving.

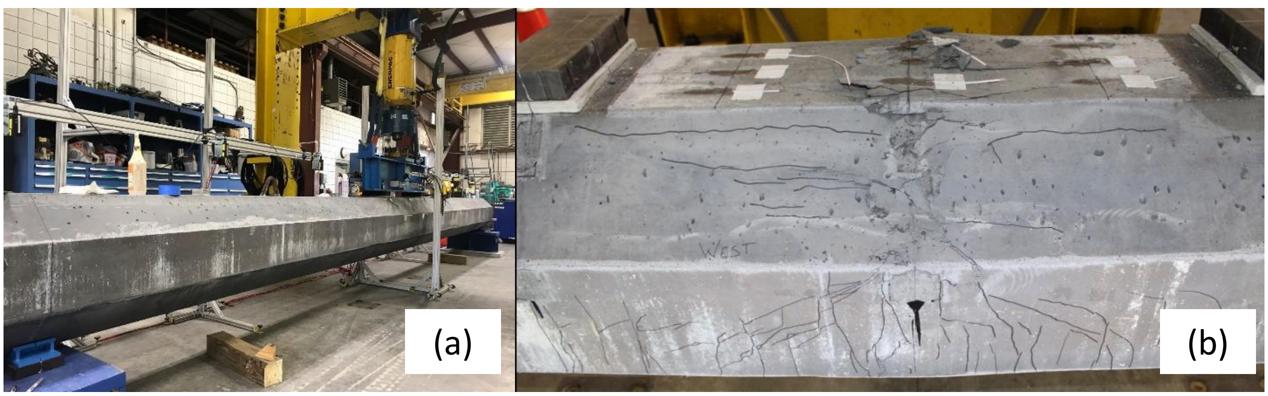

Figure 5. Flexural testing set up at FDOT Structures Research Center. Crack pattern at mid-span below point of loading.

5. Lessons Learned

A primary goal of the two trial batching efforts was to establish procedures by which UHPC can be batched and placed into forms by a structural precaster. Some lessons learned throughout the course of the two trial batching efforts are summarized below:

- When dry mixing the consistent materials, sand should be added to the mixer first to help minimize the potential for clumping of the powder materials. Clumping (i.e. accumulation of powder materials due to residual moisture present after cleaning the mixer) was observed when powder materials were added concurrent with the sand, but was not observed when powders were added after the sand.
- Accurate monitoring and measurement of sand moisture content is essential to maintaining control over the material properties and performance. Excessive flow and increased fiber segregation potential was observed for one batch where moisture content was underestimated.

- Fibers should be added in a manner that balances the desire to maximize production rates against the potential for fiber balling. Several fiber balls were observed in the discharged material from the first trial batching effort when fibers were added to the mixer directly from the pre-weighed bags at a single location. Fiber balls were not observed for any subsequent batches, when the fibers were gradually dispersed into the mixer at two locations. Optimization of the fiber addition process (not yet completed for this application) will be a key factor in determining production rates.
- Agitation of the UHPC during transit significantly improved the working time of the material. UHPC that was agitated in the mixing truck during Field Trial #2 remained workable over a significantly longer duration than UHPC that was transported under static conditions in the bucket during Field Trial #1.
- High material temperatures at the time of placement reduce the working time of the material and promote early drying of the concrete surfaces. Some of this workability loss may be counteracted by using additional chemical admixtures to improve the workability and/or finishability of the UHPC mixture; however, the most effective means to reduce workability challenges is to limit the placement temperature of the material.
- Due to its low water content, UHPC is significantly more susceptible to early drying and plastic shrinkage than conventional concrete. This manifests itself through the formation of “elephant skin” on the surfaces of freshly cast elements. Elements with large exposed surface areas (e.g., flat panels) are likely to exhibit this surface phenomenon, especially when the UHPC is placed at a relatively high temperature and the element is exposed to wind and direct sunlight. Rapid placement of the concrete followed by immediate protection of the exposed surfaces is helpful to limit the drying.
- Compressive strength test cylinders that were match-cured with piles reached a strength of 20.0 ksi (138 MPa) within 24 hours, driven by the high heat of hydration of the UHPC mixture. While further trials are needed to fully determine the reliable strength development of the mixture, the results suggest that ambient temperature curing may be viable for precast production in warm climates like Florida’s.

6. Conclusions

The purpose of this study was to develop a UHPC mixture based on materials local to and currently used by a structural precast concrete producer, and to implement that material at the plant for the production of structural precast UHPC elements. A UHPC mixture was developed using many of the plant’s current materials for conventional precast production, requiring the addition of only two additional materials that are available locally. The resulting UHPC mixture was demonstrated to achieve a compressive strength of 18.3 ksi (126 MPa) and an ultimate flexural strength of 3.1 ksi (21 MPa) after 28 days of standard ambient moist curing. Compressive strengths of over 20 ksi (138 MPa) were achieved when supplemental heat was provided during curing.

Three 24-inch (61 cm) hollow prestressed octagonal piles were successfully produced using the plant-batched UHPC material. The cross-section of these piles was designed based on consideration of the improved compressive and flexural performance of the UHPC relative to conventional and high-performance concretes. Although there are several differences between the production methods used to make conventional precast elements and UHPC precast elements, the two field trials have demonstrated that it is possible to produce precast pretensioned UHPC elements using materials and equipment used for conventional precast production.

7. References

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