TECHNOTE

Ultra-High Performance Concrete

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Introduction

Advances in the science of concrete materials have led to the development of a new class of cementitious composites, namely ultra-high performance concrete (UHPC). The mechanical and durability properties of UHPC make it an ideal candidate for use in developing new solutions to pressing concerns about highway infrastructure deterioration, repair, and replacement.[(1)] Since 2000, when UHPC became commercially available in the United States, a series of research projects has demonstrated the capabilities of the material. Three State transportation departments have deployed UHPC components within their infrastructure, and many more are actively considering the use of UHPC. This TechNote provides an introduction to UHPC and discusses practical considerations associated with it.

Definition

UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained postcracking tensile strength greater than 0.72 ksi (5 MPa).[1] UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability as compared to conventional and high-performance concretes.

[1] The tensile behavior of UHPC may generally be defined as "strain-hardening," a broad term defining concretes wherein the sustained postcracking strength provided by the fiber reinforcement is greater than the cementitious matrix cracking strength. However, the definitional dependence on cementitious matrix cracking strength may inappropriately include or exclude some concretes that exhibit dissimilar precracking and postcracking strength levels. The postcracking tensile strength and strain capacity of UHPC is highly dependent on the type, quantity, dispersion, and orientation of the internal fiber reinforcement.

Applications

UHPC is being considered for use in a wide variety of highway infrastructure applications. The high compressive and tensile strengths allow for the redesign and optimization of structural elements. Concurrently, the enhanced durability properties facilitate a lengthening of design life and allow for potential use as thin overlays, claddings, or shells.

In the United States, UHPC has been used in three prestressed concrete girder simple-span bridges. The first two, located in Iowa and Virginia, used UHPC as a replacement for conventional concrete within I-girder shape members (see figure 1). In both cases, the tensile properties of UHPC were engaged to allow for the elimination of the mild steel reinforcement shear stirrups. The third bridge, located Iowa, used a prestressed deck-bulb-double-tee girder shape. This girder shape was optimized to engage the mechanical and durability properties of UHPC in a shape that facilitated accelerated construction.[(2–4)]

An optimized bridge redecking system has also been developed.[(5)] The two-way ribbed precast slab system, also known as a waffle slab, uses the mechanical and durability properties of UHPC to create a resilient, lightweight deck. This concept has been tested and is scheduled to be deployed by the Iowa Department of Transportation in 2011.[(6)]

UHPCs have demonstrated exceptional performance when used as a field-cast closure pour or grout material in applications requiring the onsite connection of multiple prefabricated elements.[(7)] This use of UHPC has gained significant momentum recently, with States around the country considering the application. In 2009, two bridges using field-cast UHPC to create deck-level connections between precast

Figure 1. This Wapello County, Iowa, structure was the first UHPC bridge constructed in the United States.

concrete elements were constructed in New York. In one case, the UHPC was used in transverse connections between precast deck panels. In the other case, the UHPC was used in longitudinal connections between the top flanges of deck-bulb-tee girders (see figure 2). Field-cast UHPC will also be used in the longitudinal and transverse deck-level connections of the UHPC waffle slab bridge.

UHPC is also being investigated for use in a variety of other applications. These applications include precast concrete piles, seismic retrofit of substandard bridge substructures, thin-bonded overlays on deteriorated bridge decks, and security and blast mitigation applications. (See references 8–13.) In a general sense, UHPC has proven to be particularly relevant in applications where conventional solutions are lacking. For example, conventional connection solutions have hindered the use of prefabricated elements; field-cast UHPC allows for a redesign and simplification of the system while simultaneously promoting long-term durability.[7]

Availability

The development of concretes within the UHPC class has progressed in recent years. The most readily available UHPC product in the United States is a proprietary product sold by a large multinational construction materials supplier. This product has undergone a significant body of testing in order to demonstrate its specific characteristics. Alternate UHPC products are available in other parts of the world. Most notably, there are approximately five commercialized products available in Europe. Some of these product manufactures appear to be monitoring the U.S. market in preparation for the launch of competing UHPC products. Additionally, various research programs

Figure 2. Longitudinal connections are cast between deck-bulb-tee girders on the Route 31 Bridge in Lyons, NY. Field-cast UHPC can simplify connection details and ease constructability.

Source: New York State Department of Transportation

in Europe are facilitating the development of non-proprietary UHPC products produced from locally available constituents. Research programs in the United States are also progressing along this path.[14]

Mixing and Casting

UHPC is sufficiently similar to conventional concrete that the large majority of conventional concreting operations remain relevant and applicable. Nearly any conventional concrete mixer will mix UHPC. However, it must be recognized that UHPC requires increased energy input compared to conventional concrete, so mixing time will be increased. This increased energy input, in combination with the reduced or eliminated coarse aggregate and low water content, necessitates the use of modified procedures to ensure that the

UHPC does not overheat during mixing. This concern can be addressed through the use of a high-energy mixer or by lowering the temperatures of the constituents and partially or fully replacing the mix water with ice. These procedures have allowed UHPC to be mixed in conventional pan and drum mixers, including ready-mix trucks (see figure 3).

The placement of UHPC may immediately follow mixing or be delayed while additional mixes are completed. Although the dwell time prior to the initiation of the cement hydration reactions can be influenced by factors such as temperature and chemical accelerators, it frequently requires multiple hours before UHPC will begin to set. During any extended dwell time, the UHPC should not be allowed to self-desiccate.

Casting of fiber-reinforced concretes requires special considerations in terms of placement operations. UHPCs tend to exhibit rheological behaviors similar to conventional self-consolidating concretes, thus possibly necessitating additional form preparation but also allowing for reduced during-cast efforts. Internal vibration of UHPC is not recommended due to the fiber reinforcement, but limited external form vibration can be engaged as a means to facilitate the release of entrapped air.

The long-term mechanical and durability properties of UHPC can be affected by casting procedures because the dispersion and orientation of the fiber reinforcement is influenced by the casting. First, fiber reinforcement tends to show a preference for aligning in the direction of flow during casting. This behavior must be recognized and considered when the casting sequence for a component is developed. Second, the ability of the fiber reinforcement to be maintained in suspension in the UHPC is dependent on the rheology of the concrete. Thus, any modification of the rheology or overreliance on form vibration must be carefully considered.

Curing Procedures

Applying appropriate curing methods is essential to the performance of any concrete, especially UHPC. Like all concretes, UHPCs require hydration water, but unlike other concretes, UHPCs have been engineered to require very little additional water, instead facilitating appropriate rheological behaviors through the use of an optimized gradation of granular materials. The reduced water content in a UHPC mix necessitates careful attention to curing practices so as not to allow the included water to escape prior to hydration.

Immediately after casting, any exposed UHPC surface needs to be sealed with an impermeable layer. Metal, plastic, or plastic-coated wood are appropriate materials with which to seal the surface. The seal must rest against the UHPC and should not allow for any space between the covering material and the fresh concrete. Sealing of the surface eliminates the possibility of surface dehydration, which can lead to cracking and significant degradation of final material properties.

Figure 3. UHPC is delivered via truck chute to a precast girder form. UHPC can be used in both precast and field-cast applications.

Supplemental heat may be applied to UHPC castings after placement in order to accelerate setting behaviors and attainment of final properties. It is important to ensure that any added heat serves to raise the temperature of the UHPC while not allowing material dehydration.

The UHPC should remain sealed in the formwork until it has attained sufficient properties to allow it to self-support and not self-desiccate. A compressive strength of 14 ksi (97 MPa) is frequently used as a surrogate value to indicate the attainment of an acceptable level of hydration.

It is possible to supplement the natural curing process of UHPC through the use of a steam treatment. This treatment can both enhance the final mechanical and durability properties of UHPC and accelerate the acquisition of said properties. A common steam treatment consists of subjecting the UHPC to a 194 °F (90 °C), 95 percent humidity environment for at least 2 days. If applied, this treatment frequently occurs at a precast concrete plant soon after form stripping. This treatment is not necessary and can be ignored if the properties of the as-cast UHPC are appropriate for the application being considered.

Testing Procedures

In general, well-established testing procedures for conventional concrete are applicable to UHPC. However, in some instances, procedures may need to be modified to appropriately capture the true behaviors of the UHPC.[15–17] Compression testing is a prime example. The conventional test method is generally appropriate, but compressive strengths as high as 35 ksi (240 MPa) may necessitate smaller specimen sizes, different specimen shapes, higher test machine capacities, or different specimen preparation techniques.

Flow Testing

Mix quality of self-consolidating concretes is frequently assessed through a slump cone flow test. With UHPC, it is more common to use the ASTM C1437 test, which measures flow of hydraulic cement mortars.[18] Both an initial flow reading and a dynamic flow reading are recorded. Frequently, this test is completed immediately after mixing to assess consistency between mixes and appropriateness for casting.

Compression Testing

Compressive strength is arguably the most readily captured and used property of concrete. Research has demonstrated that standard concrete compression testing methods (i.e., ASTM C39, ASTM C109) are applicable to UHPC.[19,20] However, these test methods may benefit from slight modification to facilitate efficient use. Most notably, a loading rate of 150 psi/s (1 MPa/s) has been demonstrated to be acceptable, thus allowing for individual tests to be completed in a reasonable timeframe.[15]

Figure 4. Either cylinders or cubes can be used for compression testing of UHPC.

Additional research has demonstrated that, at the high strength levels achieved with UHPC, cube compressive tests are an appropriate substitute for cylinder compression tests (see figure 4).[21,22] Companion cylinder and cube strength results tend to be within 5 percent of one another, thus allowing for direct substitution of results. If cylinder tests are used for specimens at strength levels above those appropriate for capping methods, both cylinder ends must be ground planar to within the ASTM C39 specification of 0.5 degrees. Also recognize that the high compressive strengths of UHPC may necessitate the use of higher capacity compression testing platens and machines.

Modulus of Elasticity Testing

UHPC does not present any specific challenges or require any specific modifications to the standard ASTM C469 test method for static modulus of elasticity.[23]

Tensile Testing

UHPC in particular and fiber-reinforced concrete in general present specific challenges in terms of quantifying tensile behaviors. Tensile cracking strength of UHPC can be measured through the same tests used for conventional concrete. However, special precautions must be taken to ensure that the true cracking strength, not a postcracking fiber reinforcement-enhanced strength, is recorded as the cracking strength. Prism flexure testing and split cylinder testing are both appropriate means of determining first cracking, but the specimen must be closely monitored to capture the load at first cracking, since the load may continue to increase thereafter without noticeable change in global specimen behavior. Monitoring of specimens can be done visually, audibly, or through the use of nondestructive testing equipment.[15,24]

The postcracking tensile behavior of UHPC is one of the unique properties that differentiate it from conventional concrete. UHPC generally falls into the category of strain-hardening fiber-reinforced concrete, which means that the postcracking strength provided by the fiber reinforcement bridging a crack is equal to or greater than the cracking strength of the cementitious matrix. This behavior is responsible for the multicracking response of UHPC components and allows for the potential inclusion of UHPC tensile strength and strain capacities in structural design calculations.

No standardized test for quantitative determination of the full range of UHPC tensile behaviors exists in the United States. Overseas, most notably in France, a set of standardized prism flexure tests is used to quantify the tensile response. Development of standardized tests is underway in the United States, with an emphasis on the development of a test to directly capture the tensile response by pulling cast or extracted UHPC prismatic specimens (see figure 5). Until such a test is available, the use of non-standardized tests or the derivation of tensile response from the testing of a full-scale structural component may be necessary.

Chloride Penetration Testing

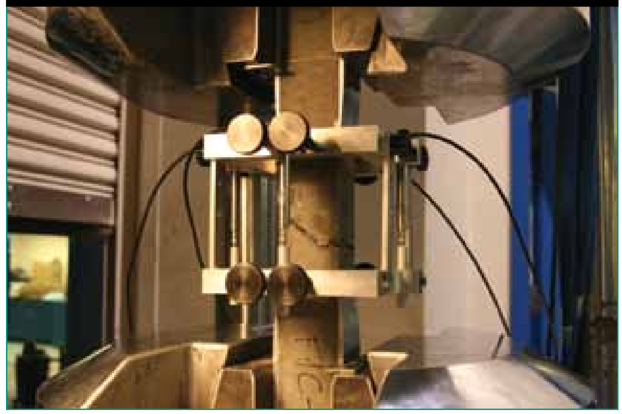
Conventional, ponding-type chloride penetration tests, such as AASHTO T259, can be completed on UHPC specimens.[25] Exposed steel fiber reinforcement may corrode during long-duration tests, but this should not impact the overall test results. When completing such a test, recognize that UHPC frequently contains unhydrated cementitious constituents. Thus, initial water penetration can lead to additional hydration and a further reduction in permeability. Also recognize that testing extracted powder samples for chloride concentration may require extra processing in order to remove included fiber pieces.

Rapid chloride penetrability testing can be completed on UHPC samples as well. Whether reinforced by steel or organic fibers, the reinforcement within the UHPC matrix is generally dispersed and discontinuous. Tests have shown that steel fiber reinforcement within UHPC does not provide a direct path to complete an electric circuit. As such, completing the ASTM C1202 test on a UHPC cylinder containing 0.5-inch (13-mm)-long steel fiber reinforcement can provide a comparative result indicative of chloride ion penetrability.[26]

Freeze-Thaw Durability Tests

Conventional freeze-thaw test methods, such as ASTM C512, can be applied to UHPC.[27] However, the unhydrated cementitious particles frequently present in UHPC can hydrate when contacted by water. Thus, any exposure of the UHPC to liquid water can result in surface penetration of the water, localized hydration, and increased dynamic modulus. In practice, freeze-thaw testing can indicate that the UHPC performance is bolstered through exposure to these conditions, while in actuality the thaw portion of the cycle is facilitating delayed hydration and a requisite dynamic modulus increase.

Figure 5. Testing procedures aimed at directly capturing the tensile behavior of UHPC are under development.



Scaling and Other Durability Tests

Other conventional concrete durability test methods can generally be applied to UHPC specimens. Many of these tests can provide comparative results indicating the relative durability of UHPC in terms of conventional concrete. However, many of these tests use subjective, qualitative measures to assess performance. Since these measures have been developed for use with conventional concrete, UHPC may exceed the anticipated performance range, thus making comparisons between individual UHPCs difficult.

Sample Preparation and Extraction

The creation and/or acquisition of UHPC samples for material testing does not differ significantly from methods used for conventional concrete. Cast specimens may be fabricated into any shape desired through the use of conventional concrete molds. However, it is important to recognize that UHPC flow during casting can cause preferential fiber orientation that may impact later test results.

Extraction of specimens from larger components may be completed through methods normally used for conventional concrete. In general, UHPC and conventional concrete are both composed of similar constituent materials. Not surprisingly, conventional cutting and grinding equipment has been found to be both applicable and effective.

Structural Design, Analysis, and Modeling

As with any structural material whose physical properties are outside the bounds of existing structural design specifications, the design of UHPC structural components presents challenges not normally present in the design of routine reinforced concrete components. However, it must be recognized that the properties of UHPC can be determined and that full-scale structural testing has demonstrated the fundamental structural performance of UHPC. (See references 2, 3, and 28–32.) The understanding and appropriate application of basic structural engineering principles such as flexure and shear are critical in the development of effective UHPC designs.

Analysis of UHPC structural components is not necessarily more complex than analysis of conventional reinforced concrete structures. However, it is imperative that the analysis be completed rationally without allowing preconceived notions of reinforced concrete behavior to cloud the computations. For example, the compressive stress-strain response of conventional concrete has a parabolic shape that is sometimes modeled through a rectangular stress block. Such a stress block would only be appropriate for UHPC if appropriate factors were applied to adjust the block to match the stiffer and more linear UHPC response. Moreover, it is frequently desirable to include the sustained tensile capacity of UHPC in an analysis. Although this extra stress block may increase the complexity of the calculation, it does not introduce new theory and should be able to be computed appropriately.

More complex analytical procedures for UHPC have been developed recently.[33] These procedures rely on commercially available finite element software to accurately model the structural response of UHPC components and structures (see figure 6).

Inspection

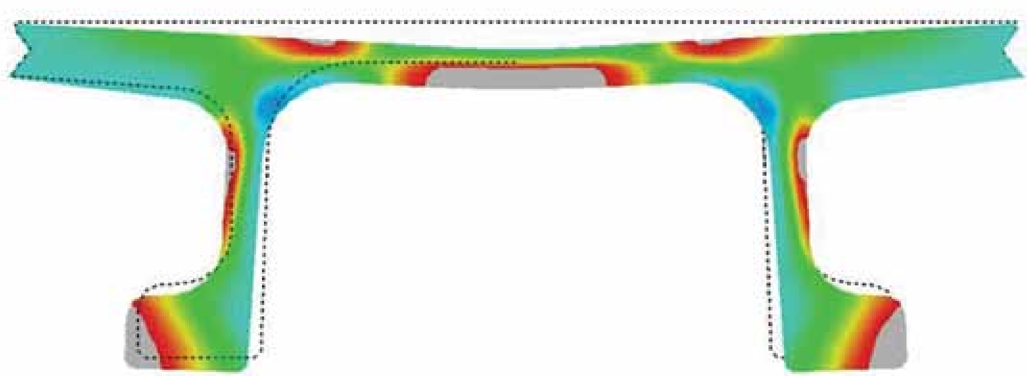
Inspection of structural concrete components in the deployed infrastructure involves a set of well-known processes and inspection tools. Inspection of UHPC is no different than that of conventional concrete, except that the years of experience associated with UHPC assessment has not yet been developed. In general, any inspection procedure associated with conventional concrete should be applicable to UHPC structures. The simplest inspection process, namely visual inspection, will differ primarily in that the scale of defects considered significant will be reduced. UHPC tends to exhibit tightly spaced, small-width cracks that are difficult to locate with the unaided eye.[34] The use of an evaporative, penetrating liquid, such as alcohol, can greatly simplify the identification of cracks.

Advanced inspection technologies, such as acoustic methodologies, can be simplified and expanded when used on UHPC structures. The comparatively homogenous composition of UHPC, in conjunction with its increased modulus of elasticity, expands the potential technologies applicable to this concrete to include some items previously reserved for metals.[35]

Conclusion

Whether used to facilitate accelerated construction, lengthen span ranges, or rehabilitate substandard infrastructure, UHPC can facilitate the development of unique solutions to existing challenges. As with any new material, utilization will grow as innovative applications are developed and market demand intensifies. A decade of research and deployment efforts by groups associated with the U.S. highway transportation sector has demonstrated that UHPC is a material both capable of and poised for future deployment in infrastructure-scale applications.

Figure 6. Finite element computer modeling techniques have been calibrated and demonstrated capable of modeling UHPC structural response.



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