UHPC IN THE U.S. HIGHWAY INFRASTRUCTURE: EXPERIENCE AND OUTLOOK

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Abstract

The U.S. highway transportation infrastructure is currently facing many challenges. One emerging solution is the use of ultra-high performance concrete (UHPC) to create resilient structures through enhanced mechanical and durability properties. The Federal Highway Administration (FHWA) has been investigating the use of UHPC in the transportation infrastructure since 2001 and has made major strides in introducing the concrete and transportation industries to this next generation of concrete technology.

The decade of progress in the U.S. has provided a strong foundation on which to build. States around the country are beginning to consider UHPC solutions, with great interest being focused on the use of field-cast UHPC as a connecting element between prefabricated bridge elements. Design procedures are being developed and test methods are being devised. Twenty bridges with UHPC components are currently in service in the U.S. highway transportation system. The future promise of UHPC-class materials is beginning to be realized today.

Résumé

Les infrastructures routières de transport aux Etats-Unis sont actuellement confrontées à de nombreux défis. Une solution émergente consiste à utiliser les propriétés mécaniques et de durabilité améliorées des bétons fibrés à ultra-hautes performances (BFUP) pour produire des ouvrages résilients. L'administration fédérale des routes (FHWA) étudie l'utilisation des BFUP dans les ouvrages routiers depuis 2001 et a franchi des étapes majeures pour mettre à niveau la profession du béton et des travaux publics vis-à-vis de cette nouvelle génération technique pour le béton.

Cette décennie de progrès a constitué aux Etats-Unis une base solide pour la suite. Plusieurs Etats à travers le pays commencent à étudier des solutions en BFUP, avec un fort intérêt concentré sur les joints en BFUP coulés en place permettant de connecter les éléments préfabriqués des ponts. Les procédures de calcul et les méthodes d'essais sont en cours de conception et de mise au point. Vingt ouvrages comprenant des composants en BFUP sont actuellement en service sur le réseau routier américain. On commence aujourd'hui à réaliser l'avenir prometteur des matériaux de la gamme des BFUP.

1. INTRODUCTION

Ultra-high performance concrete (UHPC) continues to be an emerging construction material that shows great potential for addressing vexing problems in the highway infrastructure sector [1]. Twenty bridges that engage UHPC as a key structural component have been constructed in the U.S., and owners around the country are beginning to consider the advantages that can come from this class of materials. The application with the least barriers to entry, and thus the greatest immediate promise, is the use of UHPC as a field-cast grout to connect prefabricated bridge elements [2]**.** Many opportunities for continued advancement of UHPC technology currently exist, including a need for test methods, updated construction practices, competing UHPC-class materials, and demonstration of full-scale structural performance. Focusing efforts towards addressing these needs while developing infrastructure construction solutions will enable continued advancement in this sector.

2. ENGINEERING COMMUNITY RECOGNITION OF UHPC

The opportunities afforded by UHPC in terms of construction and reconstruction of the country's physical infrastructure continue to be recognized by the engineering profession. There is a significant demand for knowledge dissemination and a recognition that significant additional knowledge generation is going to be necessary if UHPC-class materials are to be mainstreamed into the group of commonly designed and deployed construction materials. The American Concrete Institute facilitated the formation of Committee 239 in 2011, thus granting a higher profile to the topic area and encouraging broader inclusion of concrete experts from across the knowledge spectrum. Many research funding agencies are also recognizing the opportunities afforded by UHPC and are soliciting proposals in this topic area.

3. DEPLOYMENT STATUS IN THE U.S.

There continues to be significant interest in engaging UHPC as a solution to address long-standing issues with the construction and performance of the U.S. highway bridge infrastructure. As of the end of 2012, twenty bridges had been constructed in the U.S. by using UHPC as a critical structural element. Table 1 provides a listing of the bridges completed to date with UHPC components. While only four of the bridges use prefabricated UHPC components, 17 use UHPC as a field-cast material to complete connections between prefabricated components. This concept is gaining momentum as a deployable solution that reduces fabrication costs, simplifies construction, and affords long-term durability. Owners around the country are considering the use of field-cast UHPC as a key component of their efforts to accelerate construction through the use of prefabrication.

4. PROMISING APPLICATIONS

As a concrete with enhanced material properties, UHPC can reasonably be considered for use in any application where conventional cementitious composites are appropriate. Beyond this, the higher strengths and enhanced durability can facilitate deployment in applications wherein conventional cementitious composites may have previously been deemed less than ideal. Three promising application topic areas that are particularly relevant to UHPC are discussed below.

Table 1: Bridges with UHPC components in the U.S. bridge inventory.

Name	Year	Application
Mars Hill Bridge, Wapello County, Iowa	2006	Three 45-in.-deep bulb-tee beams
Route 624 over Cat Point Creek, Richmond County, Virginia	2008	Five 45-in.-deep bulb-tee girders
Jakway Park Bridge, Buchanan County, Iowa	2008	Three 33-in.-deep pi-shaped girders
State Route 31 over Canandaigua Outlet, Lyons, New York	2009	Joints between deck bulb tees
State Route 23 over Otego Creek, Oneonta, New York	2009	Joints between full-depth deck panels
Little Cedar Creek, Wapello County, Iowa	2011	Fourteen 8-in.-deep waffle deck panels with UHPC connections
Fingerboard Road Bridge over Staten Island Expressway, New York	2011-2012	Joints between deck bulb tees
State Route 248 over Bennett Creek, New York	2011	Joints between deck bulb tees
U.S. Route 30 over Burnt River and UPRR bridge, Oregon	2011	Haunch and shear connectors and transverse joints
U.S. Route 6 over Keg Creek, Pottawatomie County, Iowa	2011	Longitudinal and transverse joints between beams
Ramapo River Bridge, Sloatsburg, New York	2011	Joints between full-depth deck panels
State Route 42 Bridges (2) near Lexington, New York	2012	Joints between full-depth deck panels
State Route 31 over Putnam Brook near Weedsport, New York	2012	Joints between full-depth deck panels
I-690 Bridges (2) over Peat Street near Syracuse, New York	2012	Joints between full-depth deck panels
I-690 Bridges (2) over Crouse Ave. near Syracuse, New York	2012	Joints between full-depth deck panels
I-481 Bridge over Kirkville Road near Syracuse, New York	2012	Joints between full-depth deck panels
Windham Bridge over BNSF Railroad on U.S. Route 87 near Moccasin, Montana	2012	Joints between full-depth deck panels and shear connections to beams

4.1 Field-Cast Connections between Prefabricated Components

From the U.S. highway infrastructure perspective, the most promising UHPC application is the use of field-cast UHPC to connect prefabricated elements, thus affording resiliency to the connections and affording the opportunity to modify construction schedules and engage advanced prefabrication technology. There are two primary factors behind the growing acceptance of UHPC in this application. First, UHPC allows for simplified prefabrication activities and for simplified construction activities due to its ability to engage discrete embedded reinforcements in very short distances. Second, UHPC is in many ways similar to the grouts traditionally used in these types of connections. Specifically, both types of field-cast connection fill material are normally proprietary products that cost more than \$1300/m^3 (\$1000/yd^3) and must be mixed and placed onsite using somewhat specialized equipment. From an owner's standpoint, selecting UHPC for the connection fill material can be a low risk decision that provides significant benefits.

The U.S. Federal Highway Administration has been actively investigating this use of UHPC since 2008. Studies completed and ongoing have demonstrated that UHPC offers significantly advanced structural performance as compared to conventional concrete or conventional cementitious grouts. Many concerns have been addressed through this research, including the structural design of common lap splice connections for plate-type elements, the simplified design of shear connections between bridge girders and decks, the splice length of non-tensioned prestressing strand, and the potential rate of strength gain under varying field conditions.

Field-cast non-contact lap splice connections using UHPC have been deployed in bridges across the U.S. The supporting research demonstrated the #5 (i.e., 15 mm diameter) reinforcing bars can be fully developed within less than 152 mm (6 inches) [3]. These tests were conducted on connections between precast concrete bridge deck elements, thus indicating that shear key connections for typical bridge deck top and bottom mat reinforcement can be completed with straight reinforcing bars within a 152 mm (6 inch) wide shear key. Figure 1 provides an illustration of the basic concept as tested. The testing included high cycle fatigue testing of the system in flexure and shear, with significant overloads and high stress ranges in the reinforcing steel. The most severely loaded specimen resisted over 10 million load cycles before experiencing a series of reinforcing bar metal fatigue failures in the precast components outside of the connection. No evidence of reinforcing bar slippage within the connection was observed.

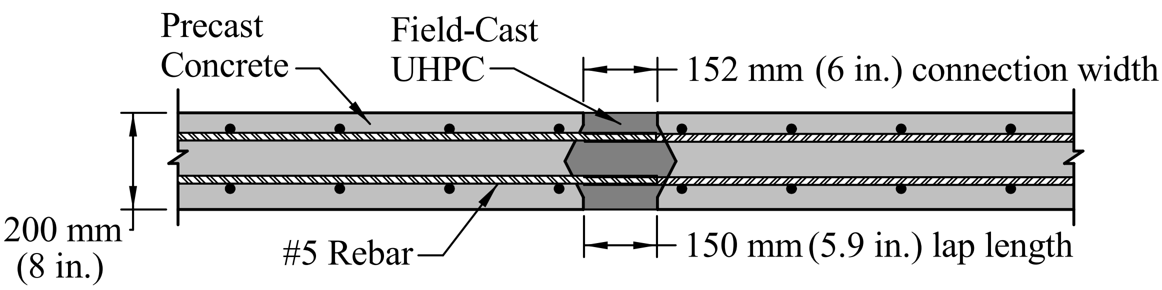

Figure 1: Field-Cast UHPC Lap Splice Connection Detail

The use of UHPC to facilitate the broader use of precast bridge deck systems has also been investigated [4]. The composite connection between precast concrete panels and the supporting bridge girders has traditionally been completed by interlacing connectors extending from the girders into pockets in the panels. These pockets tend to be congested with reinforcement, thus creating issues during field assembly of the bridge components. The mechanical and rheological properties of UHPC are particularly well suited to facilitating a redesign of this type of connection. Figure 2 illustrates the concept, wherein the discrete connectors on each component are physically separated, thus eliminating the interference issues that occur with conventional details. The enclosed space of this hidden connection necessitates the use of a very fluid material. The lack of interlacing reinforcement necessitates the use of a field-cast material with inherent tensile and shear strength. The two connections shown in the figure were subjected to more than 11 million structural cycles that exceeded the design horizontal fatigue loading calculated for a particular 63.6-m (209-ft) span bridge with 2-m (79-inch) deep steel plate girders. The connections resisted all loads applied, with eventual static failure of the system occurring within the precast components at a shear load of 2215 kN (498 kips).

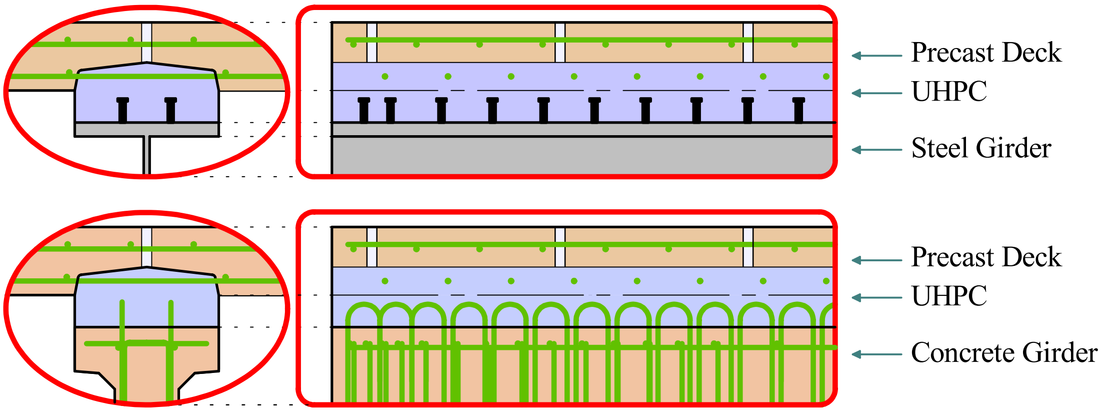

Figure 2: Field-Cast UHPC Composite Connection Detail for Precast Bridge Deck Panels

Use of UHPC as a field-cast grout places the setting and strength gain of the material on the critical path of the construction project. Concerns about the comparatively slow rate of strength gain for the most commonly available UHPC in the U.S. led FHWA to investigate this parameter for a variety of curing conditions [5]. Three constant curing temperatures were investigated, with compression tests completed periodically on cylinders through 56 days after casting. Figure 3 presents the strength gain results. Compressive strengths above 124 MPa (18 ksi) can be achieved within 24 hours with curing at 40 °C (105 °F). This study also investigated the overall compressive response of this UHPC formulation. Equation (1) was proposed as an appropriate relationship for the modulus of elasticity as a function of the compressive strength for the compressive strength range from 97 to 179 MPa (14 to 26 ksi).

$E_c = 49000\sqrt{f_c'}$ in psi (U.S. customary) units, or $E_c = 4069\sqrt{f_c'}$ in MPa (SI) units (1)

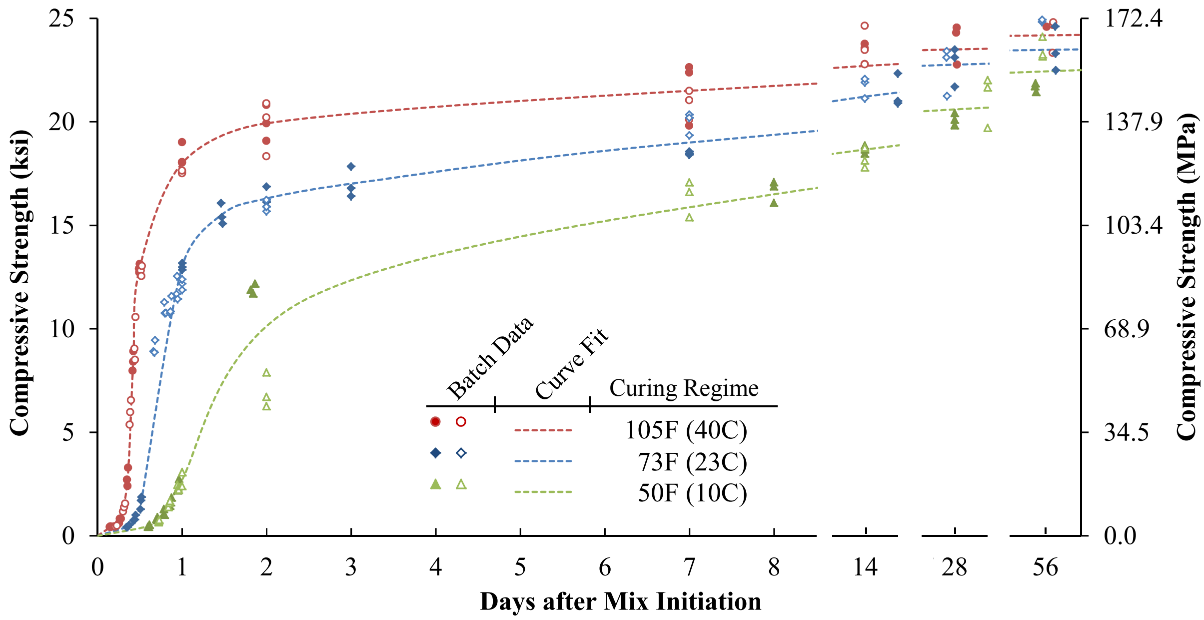

Figure 3: Field-Cast UHPC Compressive Strengths under Various Curing Regimes

An ongoing body of research is investigating the lap splice length of un-tensioned prestressing strands in field-cast UHPC. This topic is relevant to the potential application wherein strands emanating from adjacent precast components are engaged within a field-cast connection to provide resistance to applied loads on the structure. For example, the ability to fully develop a strand within a short distance could allow for a reconsideration of design methodologies for spliced girder bridge superstructures, potentially facilitating the reduction or elimination of post-tensioning. The tests completed to date have focused on the pullout behavior of one strand embedded between two others within a 76 x 127 mm (3x5 inch) prism. These tension-tension tests were completed on a commercially available steel-fiber reinforced UHPC product. Full development of the strand can be achieved in 0.46 m (18 inches) for 12.7 mm (0.5 inch) strand and in 0.66 m (26 inches) for a 15.2 mm (0.6 inch) strand.

Other concepts being investigated within this topic area include the use of UHPC within grouted ducts to facilitate development of large diameter bars used in precast substructure elements for bridges, the use of UHPC as a field-cast grout to complete the connection of pre-manufactured metal bridge deck joints to the existing structure, and as a connecting/bedding material during the installation of precast bridge barrier rails.

4.2 Optimized Precast Components

Engaging the advanced mechanical properties of UHPC can allow for a reconsideration of the traditional design process for many common infrastructure components. Past work at FHWA has investigated optimal designs for UHPC superstructure elements, resulting in the development and construction of the first pi-girder bridge in the U.S. Work has also been completed on a precast bridge deck system that uses UHPC to lighten the deck along with field-cast UHPC connections to simplify construction, resulting in the first UHPC waffle slab bridge in the U.S. UHPC's advanced mechanical and durability properties can facilitate the redesign of nearly any structural component. However, the low cost of conventional precast concrete components commonly negates the potential advantages that could be experienced with UHPC components. Engaging precast UHPC components requires that the breadth of advantages outweighs the likely increased initial cost of the structural components.

4.3 Thin Shells and Overlays

UHPC is also being considered for semi-structural or non-structural applications in the highway infrastructure wherein the durability advantages of UHPC are at the forefront. Considered applications include thin overlays and cladding systems that can protect the underlying conventional concrete from premature degradation. For new structural components, the UHPC can be cast into the component as a thin layer on the critical exterior surface(s). For existing structures, both cast-in-place and precast cladding options are being considered. Cast-in-place overlays offer durability and abrasion resistance advantages, but must overcome surface finish and rideability concerns. Precast claddings can be particularly advantageous in the rehabilitation of deteriorated components. One example application is the rehabilitation of bridge barrier rails in freeze-thaw regions of the country through the use of precast UHPC claddings that can be bolted or glued into place. These claddings can protect the underlying concrete barrier from further deterioration caused by salt-laden snow piled against the barrier during winter months.

5. OPPORTUNITIES TO SPEED DEPLOYMENT OF UHPC

In order to fully realize the potential inherent in UHPC-class materials, a series of further advancements are needed. These advancements cover practical considerations that are necessary for any innovation to succeed in the infrastructure marketplace. Individuals in a position to conduct research, fund research, or otherwise facilitate advancements in this field are encouraged to carefully consider the following opportunities.

5.1 Availability

Widespread usage of any construction material requires that the material be widely available for purchase by both private and public sector organizations. Much of the initial development and commercialization of UHPCs occurred in private firms, thus leading to the development of proprietary products. These types of products are not uncommon in the infrastructure market, but they tend to be discouraged due to the lack of direct competition that can result. Concrete is generally a non-proprietary construction material and thus a proprietary UHPC's ability to compete with conventional concrete will be hindered until multiple proprietary competitors enter the marketplace. Competing in a market space where existing solutions are also proprietary products, such as prebagged grouts, can allow for easier initial acceptance and broader recognition of the benefits of UHPC.

Recent years have brought additional proprietary UHPC-class materials to market and have also afforded time for public sector owners and academics to begin developing and disseminating the knowledge necessary to facilitate the development of non-proprietary UHPC-class materials. These important steps coincide with the increased interest by infrastructure owners in UHPC usage. The three additional opportunities listed below necessarily coincide with the availability of a class of new infrastructure materials. Without readily available UHPC-class materials, the promising concepts will remain niche ideas.

5.2 Test Methods

Infrastructure materials require appropriate test methods to quantify the materials' performance in terms of commonly understandable engineering properties. As new materials are developed, promising materials must move through a stage wherein existing test methods are modified and new test methods are developed to accurately reflect the new materials' behavior to the non-expert engineering community. As a close relative of conventional concrete, many UHPC properties can be quantified through the use of existing concrete test methods. However, it must be recognized that many concrete test methods include arbitrary constraints that may not be appropriate for UHPC-class materials.

For example, the load rate specified in compression tests allows a conventional concrete specimen to relate a compressive strength with a few minutes of testing. However, for UHPC at its higher strength level, the completion of an individual set of compression test may prove to be time prohibitive. Accelerating the test may be an option, but this modification must be assessed for the impact it may have on the results.

Other conventional concrete test methods rely on subjective measures of performance. These tests, such as a scaling durability test, have been calibrated to conventional concrete and may not provide a useful quantification of UHPC performance. Another example is common freeze-thaw resistance tests that require saturation of specimens prior to and during testing. This saturation can facilitate additional curing reactions, thus noticeably enhancing the performance of a UHPC-class material containing unreacted cementitious particles. Although freezing and thawing does not enhance the performance of UHPC, the existing concrete test method might indicate that it does.

Test methods to assess the unique tensile mechanical performance of UHPC are also needed. One key aspect of efficiently using UHPC in structures is the engagement of the tensile response to allow for modifications to cross-section shapes and supplemental reinforcements. Existing concrete test methods are not capable of quantifying the strain-hardening tensile response of UHPC. Test methods for other common materials, such as metals, may be adaptable to UHPC but will need significant modifications to be relevant to brittle cementitious composites. Examples of recent advancements in this topic area can be found in [6] and [7].

5.3 Construction Practices

As an established industry, the construction sector tends to make incremental changes that build on past practice. Deployment of new materials and/or new construction practices is not uncommon, but it must be accompanied by a clear incentive for the contractor and owner to break from past practices. The type of changes required on a construction project engaging field-cast UHPC include items such as ensuring formwork will not leak, planning for an extended time prior to initial setting, and ensuring that the casting process considers the included fiber reinforcement. Although none of these items are particularly significant, together they introduce risk that must be dealt with by the affected parties. Advancements in construction processes that make it easier for contractors and owners to embrace UHPC are needed.

5.4 Structural Performance

Many decades of concentrated effort have allowed nations around the world to develop sophisticated structural design specifications geared to commonly available construction materials. It is not reasonable to expect that such specifications could inherently address the advanced performances of UHPC-class materials. However, for widespread use of UHPC to become a reality, codified provisions addressing structural performance must be developed in such a way that a non-expert in UHPC can confidently design a structure.

The largest hurdle facing UHPC in this topic area is the lack of design provisions relevant to the tensile mechanical performance of strain-hardening fiber reinforced concretes. Micro-reinforcement of the concrete can allow for ductility, sustained tensile capacity, and enhanced durability; however, structural design provisions generally do not consider fiber reinforcements. In order to quantify this tensile mechanical performance, a number of steps must be taken. These include an enhanced understanding of the efficiency of fiber reinforcement / UHPC paste combinations, a better understanding of the role casting processes play in the dispersion and orientation of fiber reinforcement, an investigation into the differences between performances at the material scale and at the structural scale, and a codification of the structural performance benefits provided by fiber reinforcement.

Given that codified structural design provisions for UHPC will likely grow from existing reinforced concrete design provisions, a number of additional topics are also of interest. It is widely expected that structural design with UHPC components will afford more slender, appealing concrete structures. Service load deflections and out-of-plane component deformations may be of increased importance. The opportunity to reduce concrete cover over discrete reinforcement may also need to be investigated given the enhanced durability characteristics of UHPC.

6. SUMMARY

UHPC-class materials are gaining increasing recognition as a solution to long-standing hurdles in the highway infrastructure construction/reconstruction sector. From use as a field-cast grout to use in precast components, UHPC can offer new solutions that afford benefits that cannot be captured by conventional construction materials. Individuals in a position to conduct research, fund research, or otherwise facilitate advancements in this field are encouraged to consider the opportunities UHPC presents.

ACKNOWLEDGEMENTS

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