"An Innovative Technology for Accelerated Bridge Construction – The Owner Designer Dilemma"

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Abstract: In the early 90's a breakthrough technology called Ultra-High Performance Concrete was being introduced to the bridge community as a new technology that could revolutionize bridge design and construction. The new material technology offered very durable new solutions, but required, new shapes, new design codes & standards, new precast fabrication methods and formworks. The new technology immediately met enthusiasm for use; however there were several barriers to entry as mentioned above. Bridge owners saw the value and so did bridge consultants; however the lack of design standards created increased risk to both owners and designers - a dilemma. This paper explains briefly the technology, applications, the risks of the owners and designers in using it, and how these risks were mitigated to develop innovative solutions.

Key words: Ultra-High Performance Concrete, Ductility, Durability, Bridges, Innovation.

1. Introduction

"Ultra-High Performance Concrete (UHPC) is a cementitious, concrete material that has a minimum specified compressive strength of 150 MPa (21.6 ksi) with specified durability, tensile ductility and toughness requirements; fibres are generally included to achieve specified requirements" (ACI-239, 2012). The material matrix is typically manufactured from fine materials such as sand (< 400 microns [0.002 in]), ground quartz, Portland cement and silica fume or other pozzolans. The matrix typically contains small fibres (12 mm x 0.2 mm diameter [0.5 in x 0.008 in]) in a very high dosage rate of 2% by total volume (types can be high carbon steel, PVA or Glass,…). The high compressive and tensile properties of UHPC also facilitate a high bond stress and hence, a short bond development length for rebar embedment. The matrix provides a very dense and low permeability (Chloride ion diffusion <0.02 x 10^{-12} m^2/s [0.07 x 10^{-12} ft^2/s]) to prevent the ingress of chlorides or other aggressive agents (Lafarge Website, 2013). UHPC is a family of products with different formulations that are used for different applications.

The improved properties of UHPC provide benefits of simplified construction techniques, speed of construction, improved durability, reduced maintenance, reduced out-of-service, minimum interruption, reduced element size and complexity, extended usage life and improved resiliency.

In the overall history of concrete, UHPC is still a very young material, although it has been researched for over 30 years and in development for approximately 20 years. Acceptance for UHPC has been growing at a moderate pace, with recent trends showing accelerated popularity among architects and bridge engineers, mainly for its aesthetic and durability properties.

2. Early Applications of UHPC

Early introduction and testing of UHPC for use in North American bridge structures and marine environments began in 1994, over 20 years ago (Perry, 2013). Raw material sourcing and formulating resulted in the preparation and placement of UHPC test prisms at the US Army Corps of Engineers (USACE) Long-Term Marine Exposure Station at Treat Island, Maine (Thomas et al., 2012). In 1996, three UHPC prisms were cast and placed on the exposure site to monitor long-term weathering (Figure 1). Subsequently, several additional sets of UHPC prisms have been cast and placed on the dock (elevation at mean tide) and are subject to twice daily tides of wet/dry and winter freeze/thaw cycles.

Figure 1: UHPC Prisms (left) at the US Army Corps of Engineers Treat Island Marine exposure station (right), Maine, U.S.A.

Each year, the Civil Engineering Department at the University of New Brunswick, Fredericton, NB, Canada visits the Treat Island site to collect data on the performance of concrete samples on the dock. To date, all of the UHPC specimens show no evidence of surface scaling, mass loss, cracking or strength regression. Visual inspections determined that, after nearly 20 years, the prism corners are still sharp and crisp. Additionally, chloride ion penetration tests have revealed that the permeability of the UHPC samples is significantly lower (or an order of magnitude better) than High Performance Concrete (HPC) (Thomas et al., 2012).

The first use of UHPC in a North American bridge was in 1997, for construction of the Sherbrooke Pedestrian Bridge (Figure 2a) in Quebec, Canada (Perry & Seibert, 2013). This 60 m (197 ft) clear span bridge was constructed from six precast 3-D Space Truss UHPC elements, post-tensioned together on site. Although not a highway bridge, it has been exposed to light vehicle loadings for winter snow removal and severe freeze/thaw conditions as well as deicing salts for almost 20 years.

In 2001, the US Federal Highway Administration (FHWA) initiated a research program to evaluate and introduce UHPC into the US Highway program (Graybeal, 2008). The first UHPC highway bridge completed in North America was the Mars Hill Bridge in Wapello County, Iowa (Bierwagen, Moore & Perry, 2006). This single span, two-lane rural bridge (subject to frequent "farm-to-market" heavy loads [Figure 2b]) has three 34 m (111 ft) long UHPC I-girders with a conventional cast-in-place, reinforced concrete deck. The most significant aspect of this first UHPC highway bridge was the use of the three UHPC I-girders without any stirrups for shear reinforcing. This was a major milestone and a significant step towards the introduction of UHPC into the North American highway system.

Figure 2: a) (Left) Sherbrooke Pedestrian Bridge, Quebec, Canada (1997); b) (Right) Placing UHPC I-girders at Mars Hill Bridge, Wapello County, Iowa, USA (2006).

During this same period of time, the FHWA was working on an "optimized" precast bridge profile, named the "Pi-Girder" (π). The first generation of this girder was prototyped and installed at a test track in the FHWA's Turner-Fairbank Research Center near Washington, DC (Perry, Ghoneim & Carson, 2010). In 2008, Buchanan County, Iowa completed the Jakway Park Bridge using the second generation precast UHPC Pi-girder (Graybeal, 2004).

3. Overview of Field-Cast Applications Constructed with UHPC in North America

As of the end of 2016, over 200 bridges with UHPC elements would been completed in North America. These include either precast bridge elements or field-cast connections (for precast bridge elements) or, in some cases, both precast and field-cast UHPC solutions. The material has also been implemented for a range of other precast architectural and structural applications, such as cladding systems, high security products, wastewater treatment troughs, urban furnishings, underground utility products and canopies, struts and columns (for a light rail transit station), plus others.

3.1 Field-Cast UHPC Connections for Precast Bridge Element

While it is recognized that precast bridge components can provide high durability, conventional joints are often the weakest link in a bridge deck system. UHPC offers superior technical characteristics including ductility, strength and durability while providing extremely moldable products with a high quality surface aspect. It also has a very short bond development length and, when used as a jointing material in conjunction with reinforced HPC precast bridge components, UHPC provides a synergistic, new approach for the reconstruction of resilient bridge superstructures.

During the period of 2006 and 2016, more than 200 precast bridges have been completed utilizing UHPC field-cast connections. In 2006 an initial bridge (Rainy Lake, ON) was constructed using this technology for the deck level connections (Figure 4) and each subsequent year, the number has grown significantly. In 2012, 13 bridges were completed using this technology and in 2013, more than 30 bridges with UHPC elements were completed in multiple state and provincial jurisdictions in the USA and Canada.

UHPC field-cast connections have been used to connect bridge precast elements such as: full depth precast deck panels (shown in figure 3), side-by-side box girders, side-by-side Deck Bulb-Tees, live-load continuity connections, precast approach slabs to abutments, curbs to decks, piles to abutments and in the haunches (to provide horizontal shear for composite construction) (Perry & Seibert, 2013).

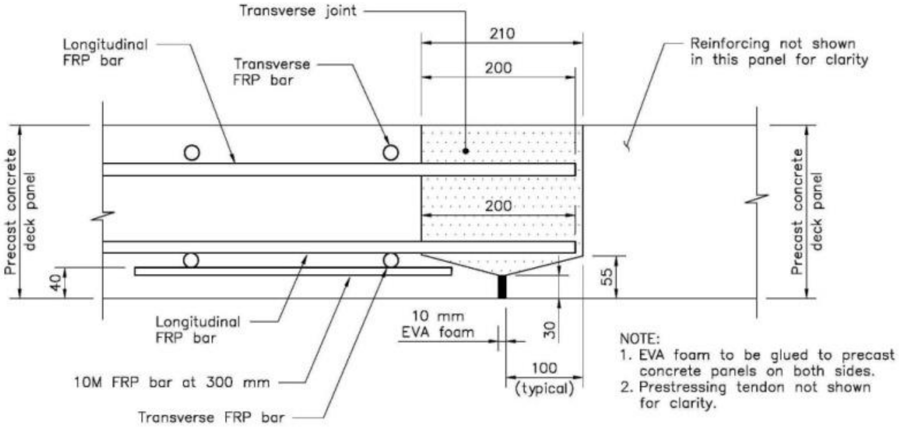

Figure 3: Typical section through a transverse, full-depth precast panel joint

3.2 Supply of UHPC Premix, Equipment, On-Site Batching and Casting Methods

Materials are typically delivered to the job site or precast facility in a three-part premix (bag of powders [sand, silica flour, Portland Cement and silica fume]; admixtures and fibers) on pallets and shrink wrapped. The premix is ready to add to the mixer with water. For large projects, sand can be delivered separately to a partial premix to optimize logistics. A high shear mixer is usually used for optimum results; however other mixers have been used successfully by adjusting the mixing process.

3.3 Field-Casting of Connections for Precast Element

The UHPC joint fill materials and portable mixers are delivered to the site by the material supplier and set up for batching. The mixers are set up in pairs to provide a continuous supply of material for the joint filling operation. The mixers are normally set up at the end of the bridge to provide direct access to the bridge deck. A typical mixer of the Ductal fleet (Figure 4) is capable of batching 0.50m^3(0.65 cy) per 15 minute batch cycle time for a volume of 4.0 m^3 (5.2 cy)per hour per pair of mixers. The size and number of mixers delivered to the site is determined based on the contractor's schedule, weather and project size.

Figure 4: UHPC Portable Mixers

Figure 5: Filling the joints with UHPC

The UHPC joint material is transported (from the mixer to the joints) by power buggy or wheel barrow and then poured directly into the joints (Figure 5). The self consolidating, self-leveling

UHPC material is batched with a mini-slump of 200 mm to 225 mm (8 in to 10 in). The rheology of material permits the UHPC to be poured directly into the joints without any vibration.

Prior to placing the UHPC material, a mini-slump test is conducted on each batch to ensure consistency of the mix. Once per day, a set of 75 mm x 150 mm (3 in x 6 in) cylinders are made in order to validate the hardened material properties (Figure 6).

Figure 6: (left) Mackenzie River Twin Bridges – precast concrete decks with UHPC joints (Perry, Krisciunas & Stofko, 2012); and (right) on-site QA/QC equipment.

The joints are covered with form grade plywood strips and allowed to cure until reaching 100 MPa (15 ksi) before opening to traffic. The time it takes to reach 100 MPa (15 ksi) will vary. At ambient temperatures (20°C [70F]) without any accelerators, this would take approximately 3 days. This time can be reduced with accelerator and heat to produce 80 MPa (12 ksi) in 12 hours.

4. Background / Setting

Considering the properties of UHPC and the potential benefits of a more resilient infrastructure, then why hasn’t UHPC been adopted more rapidly? Or, a more appropriate question could be, “Why don’t more bridge engineers use UHPC in their designs?”

In 1994, when UHPC was being introduced for infrastructure projects, the engineering community was not aware of the new technology and there were no existing codes or standards that permitted the use of a concrete with a compressive strength of 150+ MPa (21.6+ ksi), nor did any codes permit the use of concrete in tension. Furthermore, a bridge engineers job “one” is to protect the public, not encourage new technologies that don’t meet the codes and standards. The bridge engineering community, by training and responsibility, is to be conservative and not take unnecessary risks. Additionally, the first cost of a new solution utilizing UHPC would be more expensive than the current solutions, which further impaired the ability to get UHPC specified in projects.

However; bridges were deteriorating, governments (Department of Transportation’s) were short on budgets, population was growing and transportation was increasing both in volume and size. Additionally, the environment was becoming more important and the users of infrastructure (highways and bridges) were becoming more impatient with construction repairs and delays.

High performance concrete was just starting to be used and new solutions were being explored for bridges. The industry recognized that new solutions were required to build more resilient bridges and that a more long-term solution was required. This awareness was the opportunity for a break-through technology such as Ultra-high Performance Concrete.

5. The Early Approach to Development of UHPC

It was recognized from the launch of UHPC that even though this technology uses basically the same types of raw materials and equipment as normal concrete, there were several significant differences that required a new approach to implementing the technology. These significant differences, such as the selection and proportioning of the raw materials, the batching sequence and high batching energy demands, the cost of the raw materials and the need for superior QA/QC to reduce variations could only be met by a very tightly controlled and lengthy development plan. The developers recognized that the success of implementing this technology would require significant control, resources and patience.

The developers of the technology used a “push-pull” strategy to have demonstration UHPC projects deployed. Development work was conducted with both the precasters on the manufacturing side and with the owners (Department of Transportation) on bridge side. Both a supply capability and a demand were developed in parallel.

Early projects as shown previously (FHWA Pi-girder, Mars Hill Bridge, Jackway Bridge, etc) were all demonstration projects developed under partnerships through the “push-pull” strategy. All of these projects demonstrated the benefits of the technology.

Since there were no North American codes or standards available, all of the early projects were designed with conservative approaches, then, fully prototyped and load tested to failure. Before any construction started, the full-scale load testing results were reviewed and any necessary design revisions could be made. In every case the load test proved the designs to be very conservative; however, the designs were not revised.

Following several years of successfully constructing demonstration projects, an acceleration of the adoption of this technology was expected. However, the lack of codes and standards created an interesting challenge. Discussions with bridge owners and consultants on accelerating the use of UHPC for bridges resulted in a dilemma for the industry. The bridge owners (Department of Transportation) wanted to use UHPC and their engineering consultants wanted to use UHPC; however, when a project was discussed the owners would say, “we will accept UHPC if our consultant recommends it” and their engineering consultant would say “we will design the bridge with UHPC is the owners tells us to do it” – hence the dilemma! Neither wanted the liability of using UHPC without a design code to follow.

6. Risks / Mitigation

In the early implementation of a break-through technology such as UHPC many risks exist for partners in the supply chain - from material supplier through to the owner. The owner has a new solution with unknowns about how the structure will perform over the long-term and the consulting engineer has to design a structure without codes or standards to follow, thereby increasing their liability and time cost to complete the design. The precaster has to manufacture with a new and unfamiliar expensive material, where any rejected elements become a high cost to the precaster to absorb on a fixed price contract. The general contractor is concerned that if they damage a precast element during installation that it will drive up costs and delay the schedule. The material supplier has to guarantee the hardened properties and material performance on an innovative material that doesn't comply with exiting standards nor have adopted testing standards. All of these risks or unknowns are normally covered by adding extra costs to the contract, further impairing the speed of adoption of UHPC.

In order to mitigate these increased risks to each partner in the supply chain, a set of standard operating procedures were adopted by the material supplier. Many of the mitigation methods simultaneously addressed the risks of several partners in the supply chain. These mitigation methods included the following:

- Design Assistance to the Engineer (shadow designs by independent engineers).
- Manufacturing small prototypes to validate casting techniques.
- Load testing of full-scale prototypes to validate the design load capacity.
- Joint Financial guarantees to precasters (rejected elements would be replaced on a cost share).
- Memorandum of Understanding (prior to contract awards to cover risks and mitigation plans).

7. Current Situation

Today numerous excellent examples exist showing how the technology can provide value to the owner and end-users. These projects, with up to more than 20 years of in-service validate the performance of the material. There exist today hundred's of competed projects that use UHPC and perform as expected. These completed projects demonstrate to the industry that the technology is working and meets the needs of the users. It also demonstrates that codes and standards are required.

Currently, structural design guides have been written in countries on every continent, except Africa and North America. In 2013, the American Concrete Institute (ACI) established committee ACI-239 'UHPC". In 2015, the American Association of Testing and Materials (ASTM) begin to write standards that recognize UHPC. In Canada, the Canadian Standards Association is writing standards on UHPC. All of these organizations are in the early stages of developing codes and standards for UHPC. The demand of the material is growing and precasters / contractors are learning how to work with the technology.

8. Conclusions

In the overall history of concrete, UHPC is a very young material, albeit has been researched for over 30 years and in development for approximately 20 years. Acceptance has been growing at a moderate pace, with recent trends showing an accelerated popularity among architects and bridge engineers, mainly for its aesthetic and durability properties.

The application of this technology is growing and the users /specifiers are demanding a better way to ensure that the properties specified are the properties delivered in the final project. This family of concretes requires new test methods that address the material's superior characteristics, where conventional concrete testing methods may not be sufficient. There is a need for standards organizations to more rapidly address the growing demand for standardized testing of new technologies. Introducing Innovative Break-through technologies requires a patient and persistent approach.

For the adoption of new technologies the owner, consultant and contractor need to all work with a common objective to successfully implement the new solution.

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