Innovative Field Cast UHPC Joints for Precast Bridge Systems
– 3-span Live Load Continuous

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At the
Bridges – Adjusting to New Realities (A) Session

of the 2010 Annual Conference of the
Transportation Association of Canada
Halifax, Nova Scota

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Abstract:

Bridge owners are frequently faced with the need to replace critical bridge components during strictly limited or overnight road closure periods. This paper presents the development, testing and installation of precast, High Performance Concrete (HPC) bridge elements with field cast Ultra-High Performance Concrete (UHPC) Joint Fill, specifically designed for the Ministry of Transportation of Ontario, to repair deteriorated bridge decks.

As this new technology and method of construction moves into main stream, designers and owners need to expand its use into larger and more complex bridge geometries, such as multiple spans with live-load continuity and others.

The fundamentals of the technology, material properties, design details, manufacturing, prototyping, load testing, erection and an application utilizing live-load continuity are included.

By utilizing the UHPC material's unique combination of superior properties in conjunction with Glass Fiber Reinforced Polymer (GFRP), precast bridge deck panel design is advanced. Benefits include: reduced joint size and complexity, improved durability, improved continuity, speed of construction, elimination of post-tensioning and extended usage life. This paper further advances the use of this technology through demonstrating the use in developing live load continuity in multiple span bridges.

Keywords**:** abrasion; composite; ductile; durability; fiber-reinforced; impermeability; UHPC; GFRP; usage-life; rapid repair; precast

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Introduction:

In North America today, there are more than 150,000 bridges that are structurally deficient or obsolete and more than 3,000 new bridges are added each year [1]. State, provincial and municipal bridge engineers are seeking new ways to build better bridges, improve travel times, reduce construction times and improve repair techniques; thereby reducing maintenance costs which are diverted from capital budgets required for building much needed new highways and bridges. Bridge owners are frequently faced with the need to replace critical bridge components during strictly limited or overnight road closure periods.

One of the largest challenges facing bridge authorities is the long-term durability of bridge decks which receive continuous impact loading from trucks and changing environmental conditions. The years of continuous flexural and thermal stresses create long-term deterioration and maintenance issues for bridge decks. While Cast-In-Place (CIP) concrete decks with High-Performance Concrete (HPC) and corrosion resistant reinforcing can significantly extend the deck life, it creates high user inconvenience and is problematic for bridge deck replacement in high traffic areas. The use of HPC precast deck panels is a common method to speed construction and address the user inconvenience however; the jointing of the precast system is a source of potential maintenance.

The use of Post-Tensioning (P/T) across the joints has been utilized as a method to ensure the deck effectively remains structurally monolithic while performing under the constant pounding of truck wheel loads and seasonal conditions; more specifically, to ensure the joint does not deteriorate or leak. While post-tensioning can resolve most of the performance issues, it is not without potential problems. It is expensive, it has potential for corrosion and is not practical for slabs with a cross fall. Furthermore, the analysis is complex in terms of the correct post-tensioning forces (# of strands and forces longitudinal vs. transverse), creep losses, grout properties, potential long-term corrosion of the strands and sequencing of P/T vs. anchoring of the panels to the sub-structure.

The introduction of new methodologies and innovative material technologies facilitates the implementation of new solutions. One new technology helping to solve the problem with deteriorating bridges is an ultra-high performance, fiber reinforced cement composite material ("Ductal®") by Lafarge North America [2, 3] which offers superior technical characteristics including ductility, strength and durability while providing highly moldable products, with a high quality surface aspect and a short bond development length. Ultra-High Performance Concrete (UHPC), when used as a jointing material in conjunction with reinforced HPC panels, provides a synergistic, new approach for reconstruction of bridge superstructures.

In 2004, the Ministry of Transportation of Ontario (MTO) implemented a new solution for replacement of deteriorating highway bridge decks. The solution was to use a precast concrete deck and approach slab panels with Glass Fiber Reinforced Polymer (GFRP) bars in the top mat and curbs. It was the objective of the MTO to expand on the Harryson joint in order to eliminate field formwork and simplify the reinforcing details [4]. Field cast UHPC was used in the infill portions to develop the continuity in the deck panels. The project selected to introduce this new solution was a highway bridge over the Canadian National Railway (CNR) at Rainy Lake, near Fort Frances, Ontario [5, 6]. Since 2005, the MTO (Northwestern Region ["NWR"]) has used a similar solution for 6 completed bridge deck projects and more than 10 more are currently in various phases of design or construction.

Utilizing the superior characteristics of the material technology enabled the designer to greatly simplify the precast panel fabrication and installation processes. This simplified design provided the owner with improved tolerances, reduced risk, increased speed of construction, an overall cost savings in construction and a more durable, longer lasting bridge deck solution.

Investigating and Implementing the Use of UHPC for Joint Fill in Precast Girders

The use of precast bridge decks by the MTO is not a new idea, nor is the use of UHPC Joint Fill. MTO have used these technologies and methods of construction for several years, on many projects. The issues and problems associated with the joints in these systems as well as the advantages of a precast deck system manufactured in a plant environment are well understood.

MTO recognized that the properties of UHPC as a joint-fill material combined with precast decks holds great potential to address many concerns that bridge engineers have with respect to precast deck systems, such as the maintenance of joints in the precast system due to constant impact and flexing from truck traffic.

For these reasons the MTO commenced a program in 2004, to test, prototype and methodically introduce the use of UHPC Joint Fill in conjunction with a precast deck. Although the use of UHPC in North America was established in 1997 with the Sherbrooke Pedestrian Bridge in Quebec, it has been slow to gain acceptance due to the necessarily conservative and code restrictive nature of the bridge market. The first time that UHPC was used to produce girders for a highway bridge in North America was in 2004, for Iowa DOT, and several others have been completed since then.

Since 2004 the MTO (NWR) has been methodically implementing the use of UHPC Joint Fill with precast bridge decks in different configurations to continuously build on the previous learnings and expand the use of this system [7]. To date, the MTO has used this system in 5 different types/elements of bridge construction, including: side-by-side box girder bridges, full-depth deck panels, approach slabs for new and re-constructed bridges. To this point, the UHPC Joint Fill has only been used on single span bridges. This paper covers the first use of these construction methods on a multiple span bridge where the UHPC Joint Fill supports full live load continuity (LLC) over the intermediate piers.

The Concept and Design Parameters for Joints (LLC)

Previous papers published in Canada [6], France [7] and the USA [8] and the use of UHPC Joint Fill by the MTO and the New York State Department of Transportation (NYSDOT) have explained the design methodology utilized with these systems (full-depth deck panels, side-by-side deck tees and side-by-side box girders).

This paper will only cover the aspects of the design and construction of LLC joints for precast side-by-side box girders. The challenge facing designers, regardless of joint type, is the constant flexing from truck loads, thermal movements and corrosion from salt of the reinforcing crossing the joints. For intermediate joints on multiple span bridges, the elimination of this joint through the use of LLC joints can eliminate many of the problems associated with expansion joints, while improving the load distribution of the bridge superstructure, hence improving the bridge long term performance. The design of the joints focused on balancing a joint detail that provided deck continuity for loads, minimized traffic disruption during installation, speed of construction and long-term performance [9].

Precast side-by-side box girders are manufactured in a controlled environment, which facilitates the consistent batching vs. time of placement, curing, temperature, release of forms and handling, all which help to provide a product that is of superior strength, durability and geometry, with dimensional stability.

The precast production method enhances controlled handling to eliminate accidental cracking due to early or improper loading while proper curing and demoulding practices reduce the potential for cracking from moisture loss or external restraint. Precast side-by-side box girders not only have improved quality, low permeable concrete materials and mixes, they have reduced cracking due to the compressive forces of the pretensioning, the elimination of field shrinkage coupled with the restraint from the supporting structure.

The precast/pretensioned side-by-side box girders specified by MTO are designed with HPC and use Carbon Fiber Reinforced Polymer (CFRP) and GFRP bars to provide an extended usage life. The MTO standard specification for this type of girder is a minimum of 60 MPa (8,700 psi) compressive strength, maximum water-cement ratio of 0.40, for durability. The girder reinforcement design was based on live load continuity through the joints over the intermediate support piers. The dead load of the superstructure and construction live load was designed to be entirely carried by the girders.

The UHPC Joint Fill material was assumed to provide sufficient bond development to allow full continuity of the longitudinal joint reinforcing, as if it were continuous through the joint (Figures 1 & 2). Previous testing has shown that the bond development length of a 13 mm (1/2″) bar in UHPC is less than 75 mm (3″). (See subsequent section: “Prototype and Test Panels with UHPC Joint Fill in a Laboratory”).

UHPC Joint Fill has excellent bond development length, superior freeze/ thaw resistance, extremely low porosity, high flexural strength and superior toughness, which provides improved resistance to climatic conditions and continuous flexing from truck loadings across the joints. With previous projects, field-casting of monolithic UHPC joints in excess of 25 m (82′) showed no signs of shrinkage, cracking or leaking [6]. For more information on the material properties, see page 8 (“*Characteristics of UHPC Jointing Material Technology”)*.

To minimize this corrosion potential, a non-corrosive rebar (GFRP & CFRP) was used. Additionally, the joint size is minimized to provide the least possible total shrinkage across the joint. Minimizing the joint size also reduced the quantity of jointing material to be cast on-site and simplified the girder manufacturing. To enhance the bond between the precast girder and the joint fill, the surface of each HPC precast girder had an exposed aggregate surface in the joint fill contact area (Figure 3). A water proof membrane and asphaltic overlay (90 mm thick) was provided to assure durability and provide a smooth riding surface.

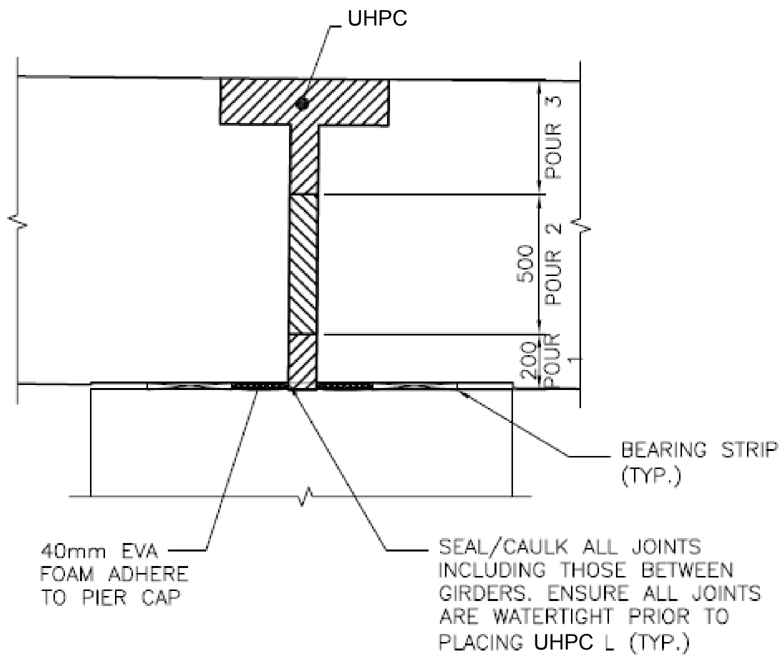

Fig. 1: Section Detail
- Live-load continuous joint, showing the area of UHPC Joint Fill.

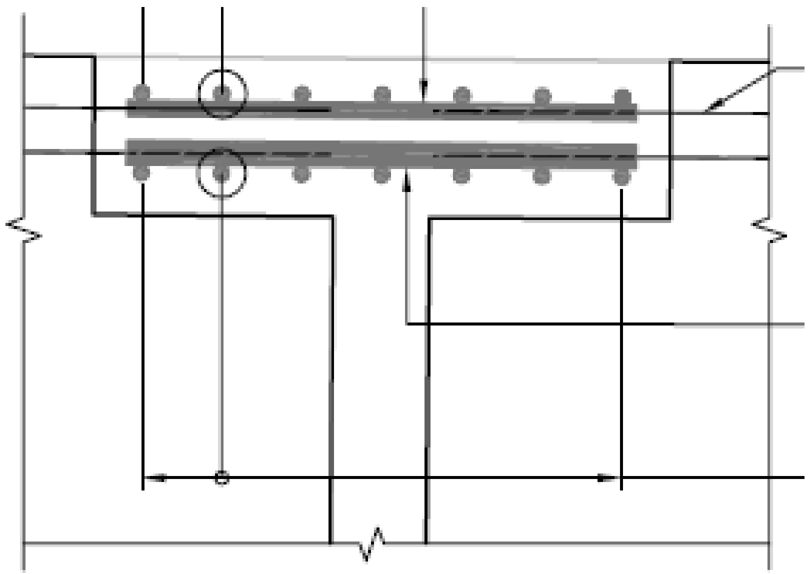

Fig. 2: Section Detail - Live-load continuous joint showing GFRP reinforcing.

Fig. 3: End of box girders showing GFRP reinforcing
and exposed aggregate roughening to enhance bond.

The improved durability of GFRP concrete bridge decks has also been shown in a recent study by ISIS Canada [13]. The ISIS study of cores taken from bridge decks, wharf decks and parapets constructed of GFRP in concrete during the periods of 1997 to 2000, showed no signs of deterioration.

Characteristics of UHPC Jointing Material Technology

UHPC is defined as a Portland Cement fiber composite, having minimum characteristic design values of 140 MPa (20,000 psi) compressive strength and 3 MPa (430 psi) direct tensile strength, in order to achieve a ductile behavior (non-brittle failure) under compression and tension, thereby dispensing with passive (non-prestressed) reinforcement.

The UHPC technology utilized for the joints in this project is an ultra-high-strength, ductile material formulation made with constituent ingredients such as: Portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water and steel fibers. Compressive strengths for bridge applications can range from 120 to 200 MPa (17,400 to 29,000 psi) and flexural strengths range from 15 to 40 MPa (2,200 psi to 5,800 psi).

The material's high mechanical properties are a result of proportioning the constituent ingredients to produce a modified compact grading with a nominal maximum coarse aggregate size of 400 μm, and a fiber geometry of 12 mm x 0.2 mm (½" x 0.008). The ratio of maximum coarse aggregate size to fiber is important to facilitate random orientation of fibers and a ductile behavior. These performance characteristics result in improved micro-structural properties of the mineral matrix, especially toughness and control of the bond between the matrix and fiber.

With a carbonation depth penetration of 0.5 mm (0.02″), there is almost no carbonation or penetration of chlorides or sulphides and a high resistance to acid attack. The superior durability characteristics are due to low porosity from a combination of fine powders, selected for their relative grain size (maximum 0.5 mm [0.02″]) and chemical reactivity. The net effect is a maximum compactness and a small, disconnected pore structure.

The material's ultra-high strength properties and low permeability also provide excellent protection of the rebar against corrosion and improved bond with the rebar, thereby providing short bond development lengths.

The following is an example of the range of material characteristics for UHPC Joint Fill [10]:

Strength		**Durability**	
Compressive (28 days)	140 MPa (20000 psi)	Freeze/thaw (after 300 cycles)	100%
Compressive (48 hours)	100 MPa (14500 psi)	Salt-scaling (loss of residue)	<0.10 g/m^2
Flexural	30 MPa (4300 psi)	Carbonation penetration	<0.5 mm
Young's Modulus (E)	50 GPa (7200 ksi)	Chloride$^-$ penetration	< 4 mm @ 13 yrs

The materials are supplied to the site in a three-component premix (pre-blended powders in 35 kg [80 lb] bags plus superplasticizer and fibers), along with a mixer and technical support from the supplier.

Testing

Previous work and various tests have been conducted to demonstrate the pullout capacity of steel strands in UHPC [11], which has shown that significantly shorter bond development lengths are required to fully develop the bars. Also, in 2004, testing was conducted to determine bond development lengths for GFRP in UHPC. The test program was undertaken in the labs of EBA Engineering Consultants Ltd. (Calgary), in order to develop a design recommendation.

Single GFRP bars were embedded into UHPC blocks at lengths of 100 mm (4″) and 150 mm (6″) (Figure 4). The bars were loaded to failure, in accordance with Annex B of CAN/CAS-S806-02 [12]. Test results (Table 1) show that the mode of failure for the 150 mm (6″) embedment was a tensile force induced fracture of the GFRP rod, with no discernible slippage or detectable UHPC fracturing. For the 100 mm (4″) embedment, the failure was a delamination of the epoxy sand layer to the bar. Both embedment lengths failed in the bond of the epoxy sand coating. The force applied was in excess of the ultimate capacity of an equivalent steel bar.

Table 1 Pullout test data – 15 mm GFRP in UHPC

Sample #	**Embedment Length**	**Failure Load (N)**	**Failure Method**
1	100 mm (4″)	67,110	GFRP Rod Rupture
2	150 mm (6″)	95,684	GFRP Rod Rupture

This test result validated the design, which allowed for a precast bridge deck with a 210 mm (8″) wide joint compared to a conventional design of a 600 mm (24″) wide joint. This also permitted the use of the CHBDC simplified method of analysis [12].

Fig. 4: Test set-up for pullout capacity of GFRP in UHPC block.

Additional testing recently completed by the NYDOT [8] shows pullout test specimens (Figure 5) manufactured with 13mm, 16mm and 19mm (1/2″, 5/8″ and 3/4″) bar sizes in epoxy coated and black steel bars. Embedment lengths were 75mm (3″) for the 13mm (1/2″) Ø bar; 100mm (4″) for the 16mm (5/8″) Ø bar; and 125 mm (5″) for the 19mm (3/4″) Ø bar. Failure behavior of the pullout tests conducted on all samples was rebar failure (Figure 5).

Fig. 5: Pullout test set-up (epoxy coated rebar) showing failure behavior.

Another concern for bridge owners with respect to joints is the ability of the joint to remain water tight during the life of the bridge. In order to simulate wheel impact loading under environmental conditions, test panels were tested at the US Federal Highway Administration's (FHWA) Turner-Fairbanks laboratory for fatigue testing in a field simulated, wet condition [8].

Fig. 6: Bridge deck panels with water ponding under fatigue loading (courtesy of FHWA).

The HPC precast deck panels (Figure 6) with the UHPC Joint Fill showed no signs of leakage or degradation at 9 million cycles of a simulated wheel loading (cycling from 1 ton to 8 tons).

Use of UHPC Joint Fill in Side-by-Side Box Girders for LLC

The first demonstration project selected for the use of UHPC Joint Fill for live-load continuity was a 3-span side-by-side box girder bridge on Highway 17, over Eagle River, in the northwestern region of MTO, between Vermillion Bay and Dryden, ON, (Figures 7, 8). MTO selected this project (designed by Hatch Mott MacDonald) in order to validate the use of UHPC Joint Fill for developing live-load continuity. The project was an existing 3-span (26.213m - 34.138m - 26.213m) post-tensioned concrete deck on steel girder bridge in need of superstructure rehabilitation .

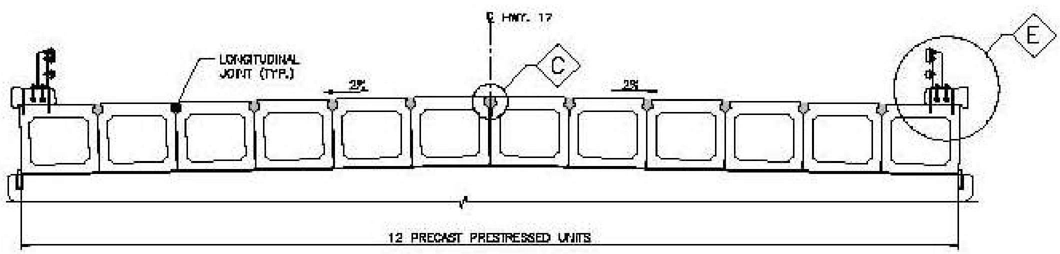

Fig. 7: New bridge cross section for Eagle River Bridge [9].

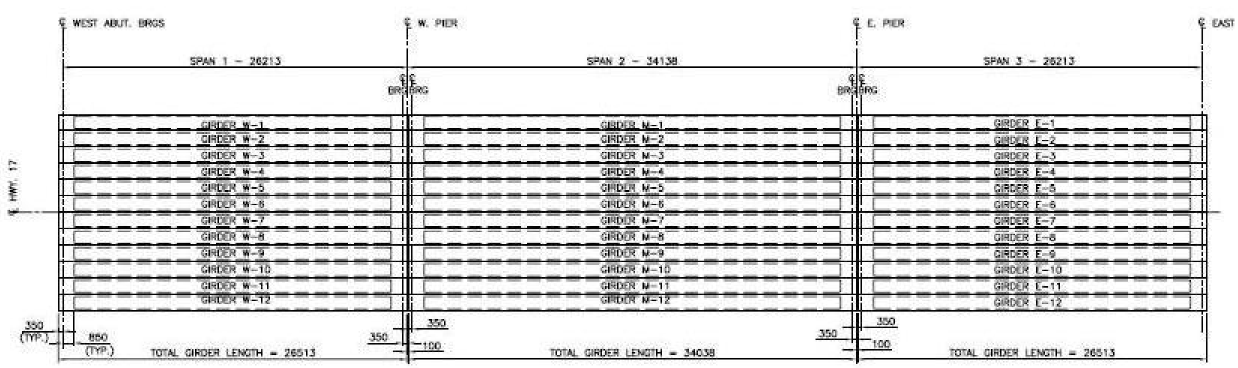

Fig. 8: Layout of side-by-side box girder Plan [9].

MTO called tenders for the project in the spring of 2009 and awarded the contract to Carillion Canada Inc. Carillion had completed previous bridge projects with UHPC Joint Fill and hence, familiar with the technology and methods for casting.

During the spring/summer of 2009, Carillion removed half of the existing bridge deck, while maintaining traffic on one-half of the bridge. Necessary repairs were made to existing abutments and the new side-by side box girders were installed on half of the bridge (Figure 9). In October 2009, the UHPC Joint Fill was installed in the longitudinal joints between the side-by-side box girders and in the transverse joints over the intermediate piers to provide live load continuity.

Fig. 9: Side-by-side box girders installed on one-half of the bridge.

Following installation of the girders, the joints were prepped to ensure water tightness, in order to minimize any potential for leakage of the UHPC Joint Fill material. Additional GFRP bars were added to the transverse LLC joints to assist in developing the load transverse (Figure 11).

The UHPC Joint Fill materials and portable mixers were delivered to the site by the material supplier and set up for batching (Figure 10). The mixers are set up in pairs to provide a continuous supply of material for the joint filling operation. (Mixers are normally set up at the end of the bridge to provide direct access to the bridge deck.)

The IMER Mortarman 750 mixers are capable of batching 0.23 m^3 (8 ft^3) per 20 minute batch cycle time for a volume of 1.36 m^3/hour (1.77 yd^3) per pair of mixers. The number of mixers delivered to the site is based on the contractor's schedule. For this project, 4 mixers were set up onsite, which provided a total hourly production capacity of 2.72m^3. However, due to the size of the crew available on site, only 3 mixers were required to provide a continuous supply of UHPC.

Fig. 10: Four - UHPC portable on-site mixers.

The UHPC Joint Fill material is transported to the joints by power buggy or wheel barrow then placed directly into the joints (Figure 11). The UHPC material was batched with a mini-slump of 200 mm (8 in) to 225 mm (9 in) (self-consolidating and self-leveling). The highly plastic rheology of material permitted the UHPC to be poured directly into the joints without any vibration.

Figure 11: Rebar congestion in the LLC joint over the Pier

Fig. 12: Filling the transverse (LLC) joints with UHPC.

The joints are covered with form grade plywood strips, and then allowed to cure until reaching 100 MPa (14,500 psi), before opening to traffic. The time to reach 100 MPa (14,500 psi) will vary. At ambient temperatures (20˚C [68˚F]) without any accelerators, this strength would be reached in approximately 3 days. This initial strength can be reached sooner with accelerator and higher heat levels.

Conclusions

The UHPC material's combination of superior properties including strength, durability, fluidity and increased bond capacity, in conjunction with reinforced precast panels, provides engineers with the ability to create new, optimized solutions for bridge construction. By utilizing the combined material properties in this application, precast bridge deck panel design is advanced. Direct benefits may include: improved bridge deck performance through the reduction of joint size and complexity; improved continuity and speed of construction and; elimination of field post-tensioning while indirect benefits include: improved durability; lower maintenance and; extended usage life.

The highlighted project and testing presented are the preliminary findings of MTO's first use of precast bridge decks with UHPC for developing live-load continuity. This experience further contributes to the current state-of-the-art for this technology. The early testing to date indicates that rebar in UHPC has a much shorter bond development length. This significance of this experience provides opportunities for bridge engineers to design for fully developed rebar in shorter joint widths for precast deck systems without the use of post-tensioning. This project also demonstrates the potential benefits of expanding the use of UHPC Joint Fill to multiple span bridges.

The field batching of UHPC Joint Fill for the Eagle River Bridge project proves that this material can be successfully batched on site and provide adequate strengths during typical field curing conditions. This experience also shows that local contractors can easily adapt to using the material in bridge projects.

While there are still some challenges when implementing this solution on a wide scale basis, the real challenge ahead is to identify the optimized shapes for precast deck panels and joints for various deck arrangements. When optimized configurations are determined, precasters, manufacturers and contractors can invest in the formwork and equipment to economically produce these solutions. The heightened economics of these systems will bring even more value to highway users through standard mass production of optimized shapes and systems and ultimately, years of low maintenance usage.

References

[1] BHIDE, S., "*Material Usage and Condition of Existing Bridges in the US*", *PCA*, Skokie, Illinois USA, 2008.

[2] GRAYBEAL, B.A., "*Fabrication of an Optimized UHPC Bridge*", PCI National Bridge Conference, Atlanta, GA, USA, 2004.

[3] BIERWAGEN, D., MOORE, B. and PERRY, V., *"Revolutionary Concrete Solutions"*, *Construction Specifier,* USA, 2006.

[4] HARRYSON, PETER, *"High Performance Joints for Concrete Bridge Applications", Structural Engineering International,* Volume 13, Number 1, 2003.

[5] COOK ENGINEERING, *"Project Drawings for CN Overhead at Rainy Lake, ON",* Thunderbay, Ontario Canada, 2006.

[6] PERRY, V., SCALZO, P., WEISS, G., *"Innovative Field Cast UHPC Joints for Precast Deck Panel Bridge Superstructures – CN Overhead Bridge at Rainy Lake, Ontario"*, 2007 Concrete Bridge Conference, USA.

[7] PERRY, V., WEISS, G., *"Innovative Field Cast UHPC Joints for Precast Bridge Decks – Design, Prototype Testing and Projects"*, Designing and Building with UHPFRC: State of the Art and Development, fib Conference, France, 2009.

[8] PERRY, V., ROYCE, M., "*Innovative Field Cast UHPC Joints for Precast Bridge Decks (side-by-side deck-tees) Village of Lyons, NY",* 3rd fib International Congress,USA 2010.

[9] Drawings, *"Eagle River Bridge Rehabilitation" Ministry of Transportation, North Western Region, Structural Section (Hatch Mott MacDonald),* February 2009.

[10] LAFARGE NORTH AMERICA, *Product Data Sheet: Ductal® JS1000,* www.imagineductal.com, 2009.

[11] LUBBERS, A., and STEINBERG, E., *"Bond of Pre-stressing Strands in UHPC",* International Symposium on High Performance Concrete, USA, 2003.

[12] Canadian Highway Bridge Design Code, CAN/CSA – S6-06, Canada, 2006.

[13] MUFTI, A., et al, *"Field Study on Durability of GFRP Reinforcement"*, International Bridge Deck Workshop, Winnipeg, Manitoba, Canada, 2005.