Development of Ultra-High Performance Concrete as a Closure Strip Filling Material in Prefabricated Bridge Applications

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Abstract: There is a growing need for durable and resilient prefabricated bridge systems which facilitate rapid completion of on-site activities in order to minimize the impact on the travelling public. Prefabricated bridges can provide higher quality, accelerated, and safer construction. However, greater offsite prefabrications of bridge components necessitates an increased reliance on the long-term performance of field-installed connections between these components. Of particular interest here, ultra-high performance concrete (UHPC) can exhibit exceptional bond when cast against previously cast concrete and can significantly shorten the development length of embedded discrete glass fiber reinforced polymer (GFRP) bars. With the recent innovations in bridge infrastructure replacement, the use of UHPC in closure strips between precast concrete bridge segments became the main focus of bridge owners for its superior strength and durability. To increase competitiveness in supplying UHPC to bridge owners in Canada, this collaborative research with the industry is looking into an innovative UHPC design that combines both high concrete compressive strength, and enhanced durability and rheology. It is essential to produce design standards and performance-based specifications of UHPC through experimental trial and errors due to lack of reliable information in this subject in the related standards and literature. This research investigates different UHPC mixes designed to reach the desired strength and rheology. While UHPC materials clearly outperform conventional concrete in mechanical and durability performance, their production is proprietary and the development of economically competitive alternatives is warranted. Throughout this research, the desired fresh and hardened concrete properties as well as practical mixing procedure were achieved and reported herein.

1 Introduction.

The term UHPC refers to a class of advanced cementitious composite materials. Although the general concepts which lead to the advanced performance characteristics of UHPC are well known, the commercial availability of UHPC and the development of locally-sources UHPC mixes has been limited in North America. The availability of UHPC has developed differently in other parts of world, most notably Europe, where multiple pre-bagged and locally-sources UHPCs are available. Up to the knowledge of the applicant, Ductal, supplied by Lafarge, is currently considered the only commercial product widely available in North America in the quantities necessary for large scale infrastructure applications and remains a proprietary product with considerable cost premium. Typical UHPC composition and material properties can be found elsewhere (Graybeal, 2010 and 2006).

The concept of using the advanced properties of UHPC to significantly modify the design of connections between precast concrete components is not new. In fact, research and deployments in this area date back to at least 1995. At that time, a commercially available UHPC was used as a closure pour material in the connection of slab elements in a building being constructed at Aalborg University. A few years later, a second project at the same university resulted in the use of field-cast UHPC connections both between slab elements and between slabs and columns. In support and association with these two projects, a series of research projects were completed to assess the bonding performance between the UHPC and straight lengths of mild steel reinforcement (Aarup et al., 2000; Hansen and Jensen, 1999; Nielsen et al., 1996; Aarup and Jensen, 1998). Additional research, focused specifically on field-cast UHPC connections for precast bridge deck panels, was completed at Chalmers University of Sweden (Broo and Broo, 1997; Harryson, 1999; Harryson, 2000). Saleem et al. (2012) conducted tested on cube and beam samples to determine the developed length of steel bars in UHPC, while Ametrano (2011) conducted similar bond tests but for glass fiber polymer bars.

Research on the materials between precast bridge components has emerged in the last decade, including non-shrink cementitous grouts, ultra-high performance concrete, epoxy grout, magnesium ammonium phosphate grout and post-tensioning cable grout (among them: Badie and Tadros, 2008; Li et al., 2010a, 2010b). More recently, the concept of using the properties of UHPC to redesign the connections between prefabricated bridge components has been recognized in North America (among them: Graybeal, 2010). Field-cast UHPC connections between prefabricated bridge components have now been implemented in few bridges in Canada and U.S. However, research is need to develop guidelines for the design of transverse joints between precast deck panels for bridges.

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC), is the latest generation of concrete having an outstanding fresh and hard concrete properties, this includes the ease of placement and consolidation without affecting strength, early high strength, long term mechanical properties, toughness volume stability durability higher flexural and tensile strength and ductility.To achieve these properties, coarse aggregates should be completely eliminated and only fines should be considered; the grain size distribution should be optimized to densify the mix and improve rheology. Also, a superplasticizer or high range water reducer should be used to improve rheology while maintaining the water/cement (W/C) as low as 0.2. Moreover, steel or synthetic fibers should be added as a volumetric ratio up to 2% to improve ductility and achieve higher tensile and flexural strength (Kosmatka et al., 2003). This research program is intended to produce an UHPFRC that is applicable to be used mainly within the construction of bridges in Canada as an integral part of the accelerated bridge construction stream.

1.1 Scope of work

This stage of the research program is concerned mainly with developing UHPC that satisfies a 28 days strength of 120 MPa with a minimum flow on a flow table of 180 mm, achieving the best mix formulation that produces the desired properties, and determining a practical mixing procedure that would produce a mix with the desired properties.

2 Experimental work

The Preliminary research plan was set such that to collect data from literature regarding UHPFRC mixes, create a database of different mixes and their properties, study the effects of different constituents of the mix on the materials strength, select the best formulation based on strength and finally, optimize this mix for greater enhancement. The plan was then modified to reproduce some of these mixes to determine their properties experimentally and decide on the best mix. When these mixes were reproduced, none of them worked as stated due to the fact that local materials being used in this study must be different from the materials used in each of the mixes in literature. Moreover, it was clear that mixes in literature were incomplete and the proportions presented were not the actual proportions used to produce the mix with the properties presented. At that point, it was decided to start formulating a new mix and study the effect of each ingredient separately, and from this point the project passed through two stages to reach the final formulation for the future work. A number of mixes were formulated and modified by trial and error such that the main aim was to reach ultra-high strength first, then modify the mix and optimize it to achieve the desired rheology while maintaining the ultra-high strength achieved. In total, nearly 50 trial mixes were performed till the mix presented herein was reached.

2.1 Tests and standards

Basically, conventional testing procedures for conventional concrete and cement mortar are applicable into UHPFRC. However, slight modifications could be made to the procedures in some cases to examine the behavior of UHPFRC.

2.1.1 Flowability Test

The flow ability of the self-consolidating concrete is a sign of good mix quality and is examined through the slump cone test or the flow table. In case of UHPC, the ASTM C1437 test method is common as it basically measures the flow of cement mortar. The test is performed right after mixing to ensure that it is consistent and suitable for casting. In this research, the minimum target flow was 180 mm and the test was carried out using a standard flow table machine according to the ASTM C230 test method.

2.1.2 Compressive strength test

The commonly considered to be the most significant property of concrete is its compressive capacity. Several research projects have assured that the standard compression testing methods are applicable to UHPCexcept that high compressive strength may require smaller specimen sizes in addition to testing equipment of higher capacity (Russell and Graybeal 2013) .Yet these methods might require very fine adjustments to give better accuracy. A loading rate of 0.5 MPa/sec has been used per ASTM standard. Specimens used in this test were small cylinders of 50 mm diameter and 100 mm length.

3 Constituent Materials

The materials used in the development of UHPFRC mix were Portland Cement and supplementary cementations materials (SCM) mainly densified Silica fume (Micro Silica) and Ground Granulated Blast Furnace Slag (GGBFS), fine aggregate of a grain size less than 0.6 mm, and ground quartz, water, chemical admixture; Polycarboxylate based HRWRA and straight steel fibers with aspect ratio of 13/0.2. Table1 lists the materials used in this research.

Table 1. Constituent materials used in this research

	Binder			Fines and Fillers		Chemical Admixture	Fibers
Material	Cement	Silica Fume	GGBFS	Sand	Quartz	HRWRA	Steel fibers

4 UHPFRC Mix

The final mix developed at this stage of the project meeting the target strength as well as the target rheology was mix XSFSLWR1-06. Two versions of this mix were made using different types of HRWRA, namely: WR1 and WR5, at the same dosage for the sake of comparison and learning that the rheology of UHPFRC relies strongly on the type of HRWRA being used. WR5 type showed better flow and a longer slump life, however an acceptable flow could still be achieved using the WR1 type but at a lower slump life.

4.1 Mix formulation

The Formulation of the mix developed is presented in Table 2 as a percent of cement weight.

Table 2. Formulation of the developed UHPFRC mix

Material	**Cement**	**Silica Fume**	**GGBFS**	**Sand**	**Quartz**	**W/C**	**HRWR**	**Fibres ***
% of cement	1.00	0.20	0.25	0.80	0.35	0.25	0.100	2% **

* Volumetric ratio, ** from 1.5% to 2%

4.2 Mixing Procedures

The differences between the productions of UHPFRC to the conventional concrete in terms of mixing and mixing procedures is that the UHPFRC would require more energy intake than that needed in the conventional concrete. Thus, it will demand an increased mixing time. The use of low water content as well as the elimination of the coarse aggregate might require modifications in the mixing procedures so as to create the best mixing conditions for the UHPFRC mix to be homogenous and to avoid overheating of the mix. The major concern of overheating the mixture during mixing can be solved through a series of precautions; first of which could be maintaining the constituents at low temperatures. Another way could be through replacing the mixing water with ice. Such precautions might facilitate the production of UHPFRC in the conventional concrete mixing plants with no dramatic change in machinery.

Mixing the commercially available UHPFRC in various mixer types was examined by few researchers as stated in the literature. However, optimum results were achieved when a shear mixer is used. Casting of UHPFRC would require special measures as any conventional fiber-reinforced concrete would. In terms of rheology, the UHPFRC would show similar behavior of the self-consolidating concrete which shall be taken into consideration while casting. Vibration of UHPFRC is not required nor recommended due to the presence fibers whose orientation will be altered. On the other hand, external form vibration might be helpful in releasing trapped air bubbles. The casting procedure has a strong influence on the long term characteristics and durability of the UHPFRC. Therefore, all useful measures should be made use of to ensure the most appropriate casting environment and procedure for a well performing UHPC mix.

In this research, a practical mixing procedure was developed as shown in Figures 1 through 5. This mixing procedure showed good and consistent results with the type of mixer used in this research, and is assumed to work well for a shear mixer. However, it is highly recommended that this procedure is to be tested for applicability of use with truck mixer if the use of a truck mixer is demanded.

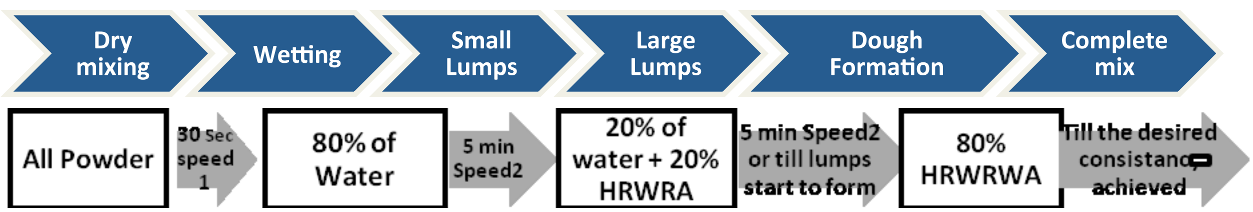

Figure 1. Flow diagram of the developed mixing procedure


Figure 2. Small hard shiny lumps


Figure 3. Larger lumps


Figure 4. Dough formation


Figure 5. Complete Mix with the desired consistency

5 Test results

5.1 Flow table test

The flow table test was conducted as per ASTM Standards for the developed mix and its derivatives and a comparison is presented in Table 3.

Table 3. Flow table test results

Mix		XSFSLWR1-06	XSFSLWR1-06-fib1.5%	XSFSLWR1-06-fib 2%	XSFSLWR5-06	XSFSLWR5-06-fib 2%
Fiber %		0	1.5	2	0	2
Flow (mm)	Immediately after mixing	171	165	154	225	221
	After 25 min from mixing	Not measured but the mix sets quickly			---	180

It is clear that the flowability of the mix using HRWRA type 1 was significantly reduced as the fiber dosage increased as shown in Table 3 and Figure 13. Views of the Flow table test for mix XSFSLWR1-06 after the mix reached a steady state are shown in Figure 6 through 9.On the other hand, using HRWRA type 2, the effect of addition of fibers on the flowability is almost negligible. Views of the Flow table test for mix XSFSLWR2-06 after the mix reached a steady state are shown in Figure 10 through 12. It was clear that HRWRA type 2 has produced a mix with better flow and better slump life than type 1 as shown in Table 3.

Figure 6.View of the flow of XSFSLWR1-06 without fibers

Figure 7.View of the 171 mm flow of XSFSLWR1-06 without fibers and without impacts

Figure 8.View of the 165 mm flow of XSFSLWR1-06-fib2% without impacts

Figure 9.View of the 154mm flow of XSFSLWR1-06-fib1.5% without impacts

Figure 10.View of the 225 mm flow of XSFSLWR5-06 without fibers and without impacts

Figure 11.View of the 221 mm flow of XSFSLWR5-06-fib2% without impacts

Figure 12.View of the 180 mm flow of mix XSFSLWR5-06- fib2% without impacts and after 25 minutes from mixing

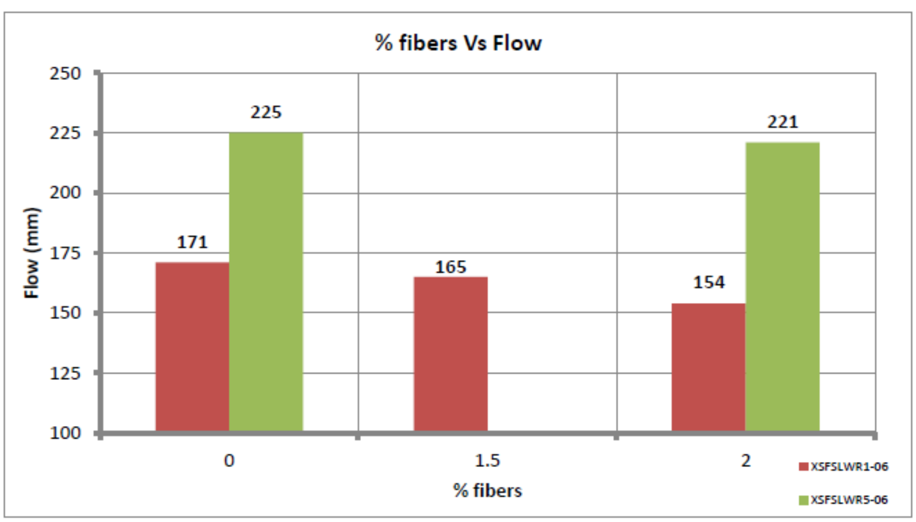

Figure 13Flow-fiberpercentage relationship for mixes XSFSLWR5-01 and XSFSLWR5-06

5.2 Compressive strength ASTM-C39

Compressive strength test was carried out according to the ASTM standards using the machine described early in this report. Strength development with time curves are presented in Table Figure 14.

Table 4. Strength development with time in selected mixes

	Compressive Strength (MPa)			
Mix	**24 hr**	**3 days**	**7 days**	**28 days**
XSFSLWR1-06	62.64	92.76	101.40	111.60
XSFSLWR1-06-fib 1.5%	71.44	88.61	95.12	117.70
XSFSLWR1-06-fib 2%	55.39	97.08	105.58	119.00
XSFSLWR5-06-fib 2%	25.00	95.44	106.50	122.60

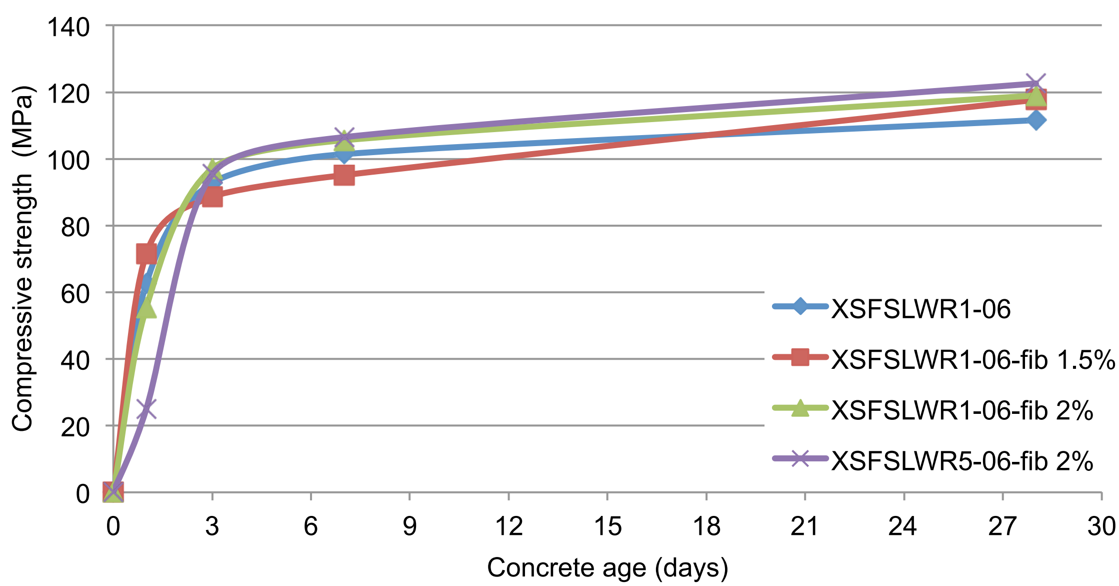

Figure 14. Compressive strength development with time for different mixes

6 Conclusion and Future Work

The developed mix is an initial mix from Phase I of this project to develop a comprehensive and integrated UHPFRC mix for use in prefabricated bridge application in addition to many other structural applications. The best mix XSFSLWR5-06- fib2%produced 180 mm flow of mix without impacts and after 25 minutes from mixing as well as 28-day compressive strength of 122.6 MPa. Future work will include modifications to the developed UHPFRC mix to achieve a strength of at least 160 MPa, while maintaining the workability of 180 mm, then modifying the workability by either adjusting chemical admixture dosage, investigating the effect of other types of HRWRA on improving the workability, or through the modifying particle size distribution of the mix.Moreover, future work will investigate the material behavior and characteristic structural properties through a series of ASTM standard tests to meet the material requirements for certification. From a structural application perspective, the structural behavior and response of the developed mix to different loads and straining actions acting on the closure strip between the prefabricated elements will be investigated.

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