Leadership in Sustainable Infrastructure

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THE NEXT GENERATION OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) BRIDGES IN CANADA: SUSTAINABLE MATERIAL FOR BRIDGE INFRASTRUCTURE

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1. Introduction

Sustainable infrastructure considers the following three factors: economic, social and environmental. This paper presents an investigation of using Ultra-High Performance Concrete (UHPC) as a sustainable environmental material for bridge infrastructure. Habert et al. (2012) in their paper has shown it is possible to reduce environment impact by increasing the strength of concrete. Examples of the environmental impact calculations of UHPC structures compared to that of concrete box girder design and also of steel box girder design are presented. The comparison studies show that many structures constructed from UHPC are in general more environmentally sustainable than using conventional structural materials with respect to the reduction of CO_2 emissions, embodied energy (EE) and global warming potential (GWP).

Through a technology transfer agreement, a proprietary UHPC design, which has been used in more than 100 bridges in Malaysia, will be produced in Canada using local raw material where available. The trial mixes of the Canadian UHPC are currently underway to be followed by full scale bridge girder load testing. This paper will provide application examples of this product.

2. Background

The technology of UHPC is considered as one of the biggest breakthroughs in the 21st century in the building material and construction industry. With 4 to 6 times stronger in compressive strength, remarkable in ductility and fracture mechanics, and at least 100 times more durable than conventional concrete, this has led to the production of high quality UHPC bridge components that has superior durability and prolonged service and design lives.

To-date, there are three (3) UHPC bridges constructed in Canada: Sherbrooke Footbridge in Sherbrooke, Quebec constructed in 1997; Glenmore/Legsby Pedestrian Bridge and Sanderling Drive Pedestrian Overpass in Calgary, Alberta constructed in 2007 and 2008 respectively. There are also over 50 bridges in Canada which have utilized UHPC in the closure strips between precast bridge elements similar to the project as presented by Perry and Royce (2010).

3. Evaluation Criteria of Sustainable Structural Design: EIC, EE and GWP

The undertaking of a full Environmental Impact Calculation (EIC) is a complex exercise. The EIC values used in this study is based on a research paper by Voo and Foster (2010).The values of EE and CO_2 emission in the production of the concrete and steel adopted for this study are extracted from the work of Struble and Godfrey (2004). According to Struble and Godfrey (2004), the energy consumed in the production of Portland cement is estimated to be 4.88 MJ/kg and the total energy in the production of steel is estimated to be 23.7 MJ/kg (i.e. 185.8 GJ/m^3). Elrod (1999) defines GWP as a measure of how a given mass of greenhouse gas is estimated to contribute to global warming over a given time interval. It is a relative scale that compares the gas in question to that of the same mass of CO2 and a 100-year of time horizon is most commonly adopted, as per the Kyoto Protocol (Forster et al. 2007).

3.1. Example 1 – Huron County Road 83 over Ausable River Bridge (single span 30 m)

Figure 1 presents the elevation view of County Road 83 over Ausable River Bridge, a 30 m span by 13.5 m wide integral abutment bridge, in Huron County, Ontario. The as-tendered design is based on using conventional side-by-side precast prestressed concrete box girders, and as shown in Figure 2, a total of 11 girders are required. The alternative design, shown in Figure 3, consists of five (5) precast NU-shaped UHPC post-tensioned girders. Unlike conventional precast concrete girders, the UHPC girders do not contain any steel reinforcement bars for transverse shear forces; instead embedded steel fibres are responsible for carrying the tensile component of the internal forces generated by shear (Voo et al. 2010, Voo and Foster 2009). The only conventional reinforcing steel required for the UHPC alternative is the interface shear steel between the cast-in-place concrete deck and the girders to achieve composite action.

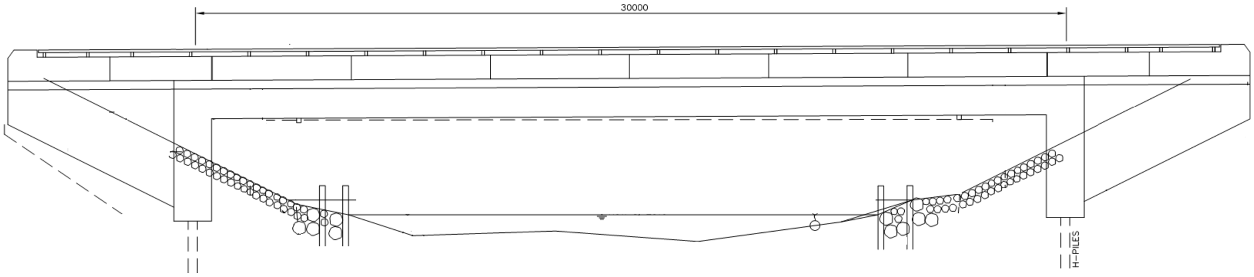

Figure 1: Elevation View of Huron County Road 83 Bridge over Ausable River

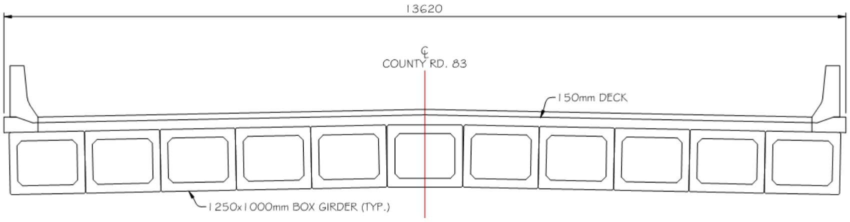

Figure 2: Cross-section of Huron County Road 38 Bridge: As-Tendered design

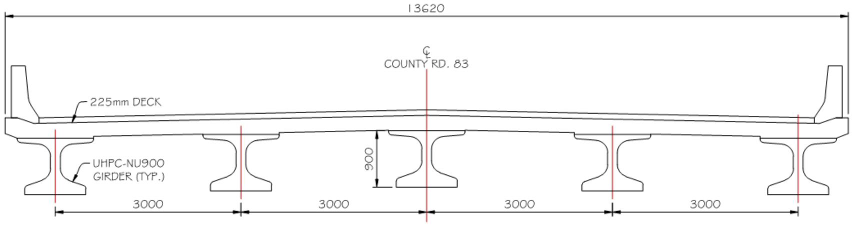

Figure 3: Cross-section of Huron County Road 38 Bridge: UHPC Alternative

Table 1 summarizes the material quantities and EIC of the two above-mentioned bridge superstructure designs. The amount of EE, CO_2 emissions and 100-year GWP are obtained from multiplying the amount of materials by the environmental data which are tabulated in Table 1

Table 1: Summary of Environmental Data of the Structure Alternatives (based on Huron County Road 38 Bridge over Ausable River)

	Concrete (m3)	Steel (kg)	Mass (ton)	Embodied Energy (GJ)	CO_2 (ton)	GWP (ton CO2 eq.)
Concrete Girders (As-Tendered)						
150 mm Concrete Deck	64	13368	164	427	48	110
B1000 Concrete Girders	179	-	421	310	53	142
Prestressing Strands	-	13673	14	324	29	60
Reinforcing Steel	-	30789	31	730	67	135
		Σ =	629	1791	199	447
UHPC Girders (Alternative)						
225 mm Concrete Deck	96	15471	241	533	62	144
NU900 Girders	64	-	153	497	68	162
Post-Tensioning Strands	-	6215	6	147	14	27
Reinforcing Steel	-	5014	5	119	11	22
		Σ =	406	1296	155	355

Comparisons of the EIC results are presented in Figure 4. In terms of material consumption, the UHPC solution consumed 36% less material than the conventional solution. In terms of environmental impact, the UHPC solution has 28% less embodied energy and 22% less CO_2 emissions. In terms of the 100-year GWP, the UHPC solution provides for a reduction of 21% over that of the conventional solution. It also needs recognition that in this example, only the savings at the level of the superstructure are considered. Further possible savings will result from the lighter weight of the UHPC solution giving a smaller substructure, foundations and lower transport costs.

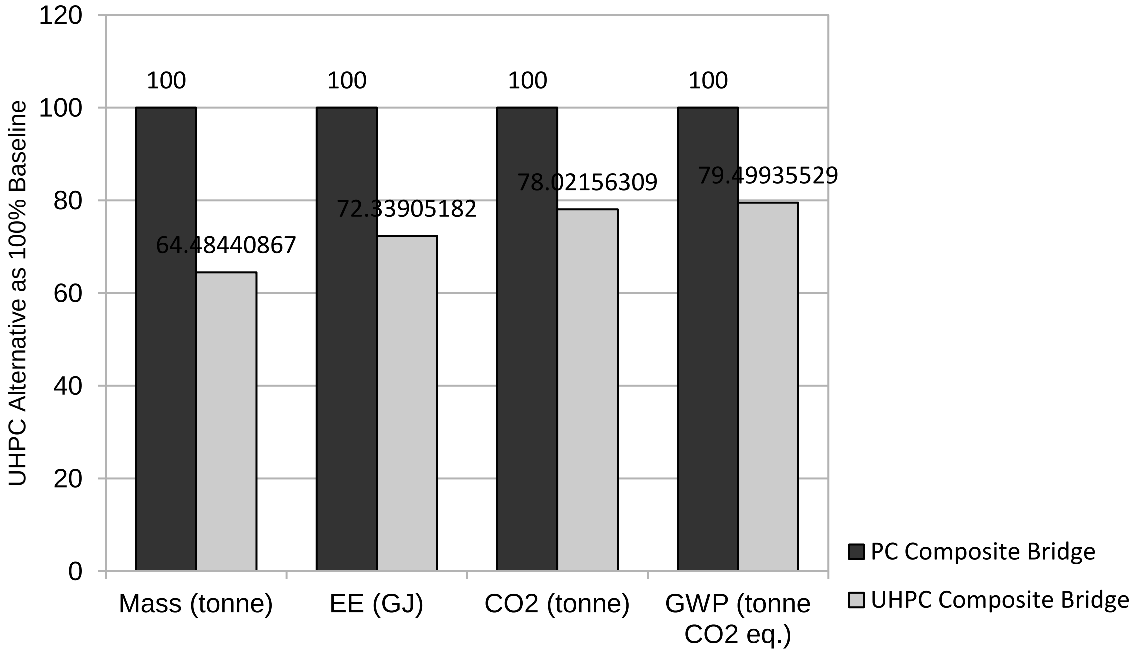

Figure 4: Comparison of the EIC Results for Huron County Bridge 38 over Ausable River

3.2. Example 2 – MacKenzie River Bridge (single span 42 m)

Figure 5 presents the layout of MacKenzie River Bridge, a 42 m span by 10.5 m wide integral abutment bridge, in Cape Breton Highlands National Park, Nova Scotia. The as-tendered design is based on slab-on-steel box girders as shown in Figure 6. The alternative design, shown in Figure 7, consists of two (2) precast UHPC box girders (UBG 1750) with post-tensioning. Similar in Example 1, the UHPC alternative does not have any reinforcing steel bars for vertical shear, except for the interface shear steel between the cast-in-place concrete deck and UHPC girders for composite action.

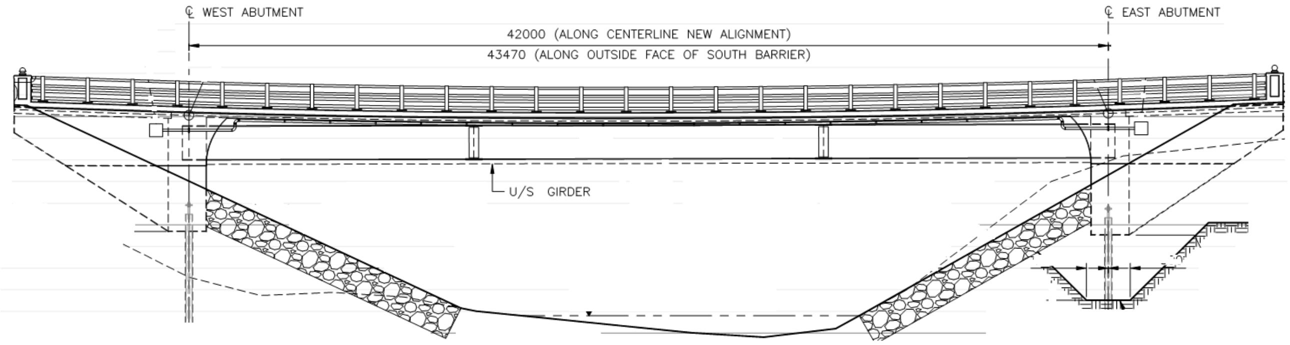

Figure 5: Elevation View of MacKenzie River Bridge

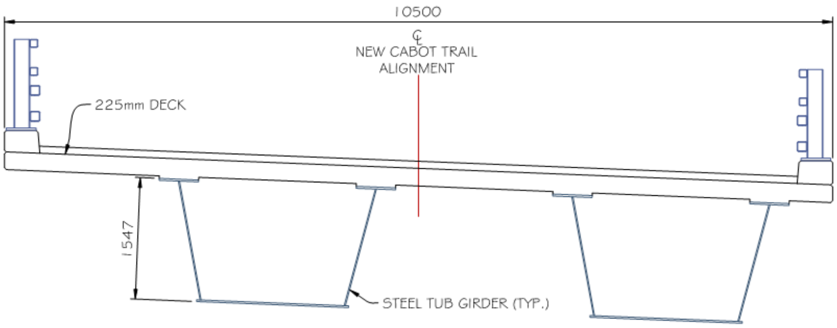

Figure 6: Cross-section of MacKenzie River Bridge: As-Tendered design using Steel Box Girders

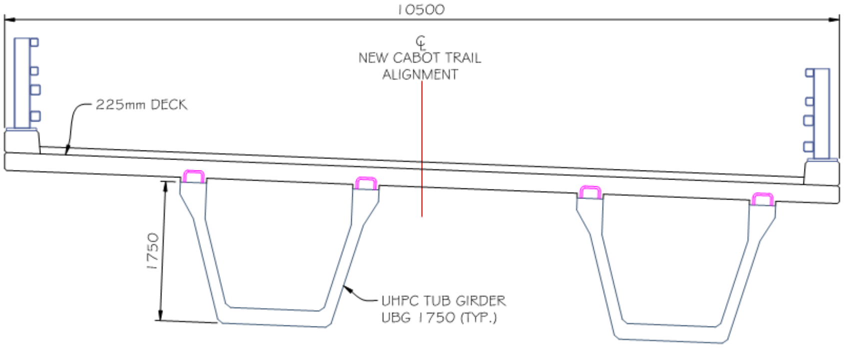

Figure 7: Cross-section of MacKenzie River Bridge: Alternative Design using UBG 1750 girders (UHPC)

Table 2 summarizes the material quantities and EIC of the two bridge superstructure designs. The amount of EE, CO_2 emissions and 100-year GWP are obtained from multiplying the amount of materials by the environmental data given in Table 2.

Table 2: Summary of Environmental Data of the Structure Alternatives (based on McKenzie River Bridge)

	Concrete (m3)	Steel (kg)	Mass (ton)	Embodied Energy (GJ)	CO_2 (ton)	GWP (ton CO2 eq.)
Steel Box Girders (As-Tendered)						
225 mm Concrete Deck	99	20005	253	646	73	167
Steel Box Girders	-	85525	86	2027	187	375
Steel Bracing & Misc.	-	10103	10	239	22	44
		Σ =	349	2912	282	586
UHPC Girders (Alternative)						
225 mm Concrete Deck	99	20005	253	646	73	167
UHPC Girders	80	-	192	622	85	203
Strands	-	83	8	196	18	36
Reinforcing Steel	-	40	4	95	9	18
		Σ =	458	1558	185	423

A comparison of the EIC results is presented in Figure 8. In terms of material consumption, the UHPC solution consumed more materials than the conventional solution; however, in terms of environmental impact, the UHPC solution has 46% less embodied energy and 34% less CO_2 emissions. In terms of the 100-year GWP, the UHPC solution provides for a reduction of 28% over that of the original solution.

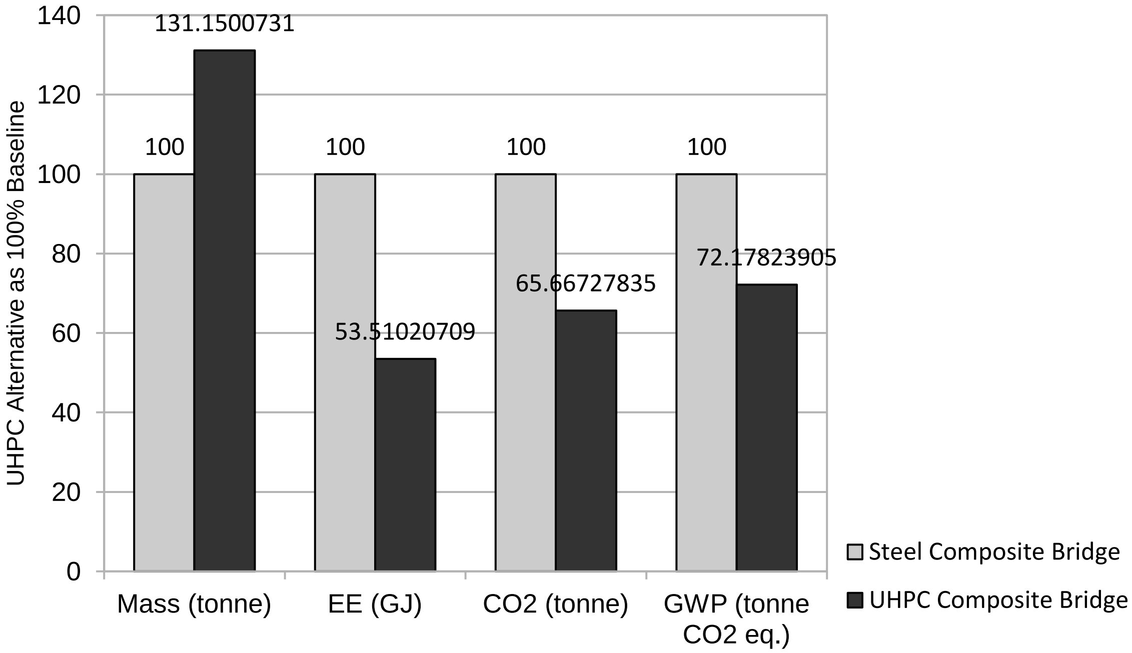

Figure 8: Comparison of the EIC Results: MacKenzie River Bridge

4. Other Discussions

The use of precast segmental UHPC bridge girders with post-tensioning allows UHPC girders to go beyond the typical short and medium span threshold. In 2014, a single span 100 m long integral-abutment bridge was completed in Perak, Malaysia (Figure 9). The superstructure of the Batu 6 Bridge girders was constructed using post-tensioned segmental UHPC boxes. The single 100 m span eliminates the need of erecting a pier in the middle of the river. This project was recognized by Precast/Prestressed Concrete Institute (PCI) and chosen as the 2016 Design Award Winner for Best International Transportation Structure.

Figure 9: UHPC Box-Girder Bridge – Batu 6 Bridge over the Perak River, Malaysia

Due to the lack of UHPC structural design code in Canada, to demonstrate the UHPC's strength, a performance load proof test on full-scale bridge girders is being prepared in Canada, and the test results will likely confirm that the precast UHPC girders can meet and exceed the CHBDC design requirements for conventional bridges. Locally sourced materials will be used to fabricate the UHPC girders which will reduce the material costs and the environmental footprint.

In the market today, there are several UHPC suppliers: Ductal®, Ceracem®, BSI®, and Densit®. Although there are differences among these commercial UHPC products, there are also similarities. Most UHPC products consist of a combination of portland cement, silica fume, fine sand, special small aggregates, chemical admixtures including high-range water reducing admixture, non-brittle steel fibres, and water (Graybeal, 2013). To optimize the locally sourced materials for compressive strength, packing density, flowability and workability, several UHPC mix proportions are currently being evaluated and UHPC samples tested. Although effect of curing temperature on UHPC was previously examined by Schachinger et al. 2008, an independent follow-up study will be conducted using multiple UHPC trial mixes with heat treatment during curing.

To enhance UHPC as an sustainable infrastructure materials, glass powder made of recycled glass in UHPC, will be evaluated. Recycled glass powder could potentially substitute or reduce some non-renewal raw materials such as silica fume, fine sand and small aggregates. Tagnit-Hamou et al. (2016) are investigating using waste-glass materials in UHPC and the early results exhibited excellent workability and rheological properties due to the zero absorption of the glass particles as well as the material's optimized packing density.

In addition, a research and development project currently undertaken is the development and validation of a modular "waffle-slab" system using UHPC for accelerated bridge construction similar to the system designed and evaluated by Honarvar et al (2016). The proposed prefabricated waffle-slab system will have a thinner deck than the typical 225 mm conventional concrete deck, made possible by the material strength of UHPC ribs, resulting in potentially lower EE, CO_2 emissions and 100-year GWP.

5. Conclusions

Ultra High Performance Concrete (UHPC) has the potential to be a sustainable construction material for bridge infrastructure. Due to its high strength, UHPC can significantly reduce the cross sectional area of structural members when comparing with other similar conventional concrete structures. Even if the overall mass of the UHPC superstructure is higher than that of steel structures, the environmental significance of the UHPC cannot be overlooked. Such technology will soon be applied to Canadian bridges, eliminating corrosion-prone reinforcing steel bars in bridge while reducing the carbon footprint of bridge infrastructure.

References

Elrod, M., 1999. Greenhouse warming potential model. *Journal of Chemical Education*, 76: 1702–1705.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schultz, M., Van Dorland, R. 2007. Changes in atmospheric constituents and in radiative forcing. *In: S. Solomon et al. eds. Climate change 2007: The physical science basis. contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change.*

Graybeal, B.A. 2013. "Ultra-High Performance Concrete: A State-Of-The-Art Report for The Bridge Community." *Federal Highway Administration, FHWA-HRT-13-060: Ch. 2 - Materials and Production.*

Habert, G., Arribe, D., Dehove, T., Espinasse, L., and Le Roy, R. 2012. Reducing environmental impact by increasing the strength of concrete: Quantification of the improvement to concrete. *Journal of Cleaner Production*, **35**: 250-262.

Honarvar, E., Sritharan, S., Rouse, J.M. and Aaleti, S. 2016. Bridge Decks with Precast UHPC Waffle Panels: A Field Evaluation and Design Optimization. *Journal of Bridge Engineering:* **21**(1).

Perry, V.H., and Royce, M. 2010. Innovative Field-cast UHPC Joints for Precast Bridge Decks (Side-by-Side Deck Bulb-Tees), Village of Lyons, New York: Design, Prototyping, Testing and Construction. *3rd fib International Congress*.

Schachinger, I., Hilbig, H., and Stengel, T. 2008. Effect of Curing Temperature at an Early Age on the Long-term Strength Development of UHPC. *Second International Symposium on UHPC – 2008.*

Struble, L. and Godfrey, J. 2006. How Sustainable is Concrete?. *International Workshop on Sustainable Development and Concrete Technology. University of Illinois at Urbana-Champaign, 201-211.*

Tagnit-Hamou, A., Soliman, N., and Omran, A. 2016. Green Ultra-High-Performance Glass Concrete. *First International Interactive Symposium on UHPC – 2016.*

Voo, Y. L. and Foster, S.J. 2010. Characteristics of ultra-high performance “ductile” concrete and its impact on sustainable construction*, The IES Journal Part A: Civil & Structural Engineering,* **3**(3): 168-187*.*

Voo, Y.L., Poon, W.K., and Foster, S.J. 2010. Shear Strength of Steel Fiber-Reinforced Ultrahigh- Performance Concrete Beams without Stirrups. *Journal of Structural Engineering,* **136**(11): 1393–1400.