Session:

Title: **Sustainable UHPC Bridges for the 22nd Century**

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Abstract:

The paper explores the problems, vision, definition and design parameters for sustainability, then uses a case study to demonstrate and compare current bridge design with a more sustainable solution using Ultra-High Performance Concrete (UHPC).

Bridges that are designed to optimize the mechanical properties of UHPC have different initial costs, maintenance and operation costs and environmental footprints. UHPC is still a relatively new material; however its durability properties, which include extremely low permeability, are typically an order of magnitude superior to High Performance Concrete (HPC). Using this material in an optimized design which minimizes initial material consumption and provides a very long design life can create a paradigm shift in how sustainable infrastructure may be viewed. An order of magnitude increase in design life will approach the current usage life of European cathedrals or Roman coliseums.

The paper not only explores the embodied CO_2 and energy consumption during initial bridge construction but also over the life cycle, which includes issues such as the environmental impact of traffic disruption and rehabilitation equipment.

"It is our attitude at the beginning of a difficult task which, more than anything else, will affect its successful outcome."
--William James,
American philosopher

Introduction:

Today there is much debate and discussion on CO_2 emissions and global warming by the public, government, academia, intellects, business professionals and environmentalists, without a consensus or clear resolution to the problems or solutions. However, one thing is clear; the "status quo" is unacceptable. We must change and sooner than later.

Many current strategies which address the challenges of sustainability focus on: (i) adding more capacity; (ii) reducing waste through improved efficiencies; (iii) technology or innovation or; (iv) reducing consumption [4]. While each of these strategies is important and necessary, by themselves they may not be sufficient. Furthermore, there are additional actions that engineers and builders can take to improve the sustainability of infrastructure in general; specifically, bridges.

Building a bridge once and having it function over a long period, with minimal maintenance or operational costs, could be considered one important aspect of approaching sustainability. If we can describe the parameters that make infrastructure sustainable or approach sustainability, then engineers would have a clearer vision, goal or guidelines for designing their projects.

This paper presents a different view towards sustainability and possible solutions for improving the sustainability of infrastructure, in particular bridges.

Today, there are many new materials and approaches which promise or endeavour to reduce global environmental impact and improve the sustainability of infrastructure. Ultra-High Performance Concrete (UHPC) is one such example.

Framing the Global Challenge:

Challenge I: Each day more than a quarter of a million babies are born, with a net effect of increasing the earth's population to 7 billion by 2020, even if birth rates continue to decline at current rates. That is the equivalent of adding the population of another China by 2020 [1,2]. The current population, as well as all those new babies, deserves to have clean water, food and shelter – a standard of living we take for granted in North America. This standard of living or quality of life is only made possible through our infrastructure – the networks that allow the movement of goods and people. Increasing population requires expansion and/or improvements in the infrastructure.

Challenge II: "North Americans' ecological footprint, for example, is huge. If everyone on earth consumed as many resources and generated as much waste as we do, we'd need the equivalent of nearly five more planets!"[2]. There is only one planet that is reasonably accessible today, so it is imperative that we use it wisely and sparingly, unlike we currently do. The 'big box' movement which drives down prices and feeds consumerism creates over consumption of large quantities of global resources. While lower prices help less privileged, it also facilitates over consumption by enabling the purchase 'wants' rather than 'needs' [3,4].

Challenge III: Our current infrastructure is deteriorating faster than we are repairing it [5]. In North America today, there are more than 150,000 bridges that are structurally deficient or functionally obsolete and more than 3000 new bridges are added each year [6]. The American Society of Civil Engineers' "2009 Report for America's Infrastructure" gave an overall D rating to America infrastructure, with an estimated $2.2 trillion investment need to bring it to an acceptable level.

Challenge IV: Today, municipal, state, provincial and federal governments globally, with few exceptions, do not have the money to upgrade and expand the infrastructure to meets the current or future needs of society. Raising taxes or reallocating current tax dollars does not appear to be on the government's agenda nor is it the political will.

Today there is much debate and discussion on CO_2 emissions and global warming by the public, government, academia, intellects, business professionals and environmentalists without a consensus or clear resolution to the problems or solutions. However, one thing is clear; the "status quo" is unacceptable. We must change and sooner than later.

The 2020 Option:

While all of society has to share responsibility for the problems and solutions, this paper will focus on several aspects whereby the construction and civil engineering communities can have direct impact between now and the year 2020; more specifically in identifying opportunities to provide solutions for more sustainable bridge infrastructure.

Many current strategies to address the *Challenges (I-IV)* focus on: (i) adding more capacity; (ii) reducing waste through improved efficiencies; (iii) technology or innovation or; (iv) reducing consumption[4]. While each of these strategies is important and necessary, by themselves they may not be sufficient. Furthermore, there are additional actions that engineers and builders can take to improve the sustainability of infrastructure in general and specifically, bridges. One very important aspect of sustainability (often not given sufficient importance) is a bridge's life cycle or longevity. Building a bridge once and having it provide its function over a long period with minimal maintenance or operational costs could be considered one important way to approach sustainability. The USA Federal HighWay Administration's (FHWA) "Highways for Life" program is a good example of one organization trying to accomplish this goal.

By studying history we can learn a lot about the future. If we look back to examples of infrastructure that was built prior to the year 1000, and still exist today, we can learn about certain aspects of the design and construction that made it survive time.

Many European cathedrals built before year 1000, today still provide a place of worship (Figure 1). Many are unheated and/or don't have hot/cold running water, which means they are almost energy self-sufficient or have a minimal impact on our valuable water resources. The same could be said for the Roman coliseums or aqueducts.

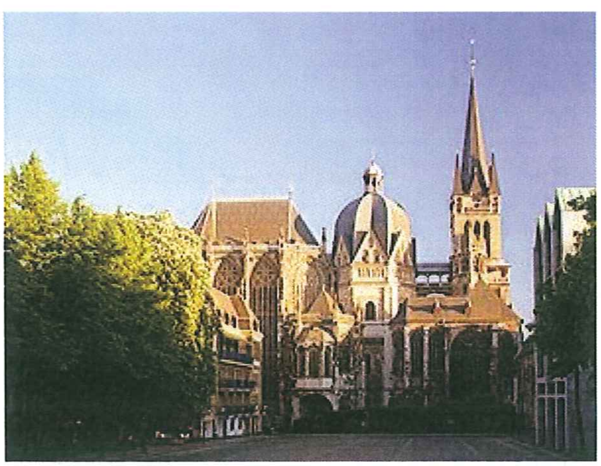


Figure 1: Aachen Cathedral, Aachen, Germany; consecrated in 805 by Pope Leo III.

If we can describe the parameters that make infrastructure sustainable or approach sustainability, then engineers would have a clearer vision or goal for designing their projects. Using the lessons learned from historical infrastructure that approaches sustainability could be described as follows:

- 1,000 year design life;
- Minimal embodied energy;
- Self-sufficiency for energy over usage life;
- Self-sufficiency for water over usage life;
- Minimal usage disruption or "out-of-use"
- Near zero maintenance & operations, and;
- Net zero impact on flora and fauna.

While this list is not exhaustive, it is a start to help create a strategic vision for more sustainable infrastructure. Other parameters that could be included are: how well the infrastructure meets the current and future needs of the users; how well it integrates with its macro-environment, etc.

Of course there will always be individuals who claim that (since we can't predict future capacity requirements or increasing loads) we will have to upgrade regardless or provide a number of excuses, only to justify that we continue to build using the same old approach. This is counter intuitive to sustainability and a cavalier approach which ignores that, as civil engineers, we are ethically and morally responsible as keepers of the infrastructure.

Technologies that permit us to expand infrastructure capacity will continue to evolve. Furthermore, sustainability is about the 3R's and not throwing away items that can be upgraded, recycled, reused or rehabilitated. History repeatedly shows that, in reality, once infrastructure is built, we keep using and upgrading it – an approach that is normally more cost effective, reduces the environmental footprint and more sustainable. For example, the Brooklyn Bridge, constructed in 1883, stills handles 145,000 vehicles per day and, with proper maintenance and care, will continue to do so for many more years to come (Figure 2).

Figure 2: Brooklyn Bridge, NY; built in 1883 (already passed its 125th anniversary).

In order to visualize the practicalities of such design parameters, this paper will use an example of a bridge designed with UHPC, utilizing the cross section shape of a pi-girder (named because the shape resembles the Greek character, "Pi" (π)[7].

The Concrete Solution:

Concrete is one of the most durable building materials on the earth and, in North America, it is usually available locally. Durability means longevity and local availability means a reduction in transportation of resources. Furthermore, the cement, concrete and construction industries provide employment for people in local communities, also relating to reduced transportation impacts. Durable, long lasting and local products are fundamental elements to approaching sustainability.

The Material - UHPC:

The UHPC technology utilized for the pi-girders in this paper 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. The product utilized for this application, "Ductal® BS1000", is covered by one of many patents in a range of ultra-high performance concretes, all under trademark (Ductal®). Compressive strengths for bridge applications can range from 140 to 200 MPa (21,300 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 fibre geometry of 12 mm x 0.2 mm (½″ x 0.08″). The ratio of maximum coarse aggregate size to fibre is important to facilitate random orientation of fibres 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 fibre.

The following is an example of the range of material characteristics for Ductal® BS1000. [8]

Strength		**Durability**	
Compressive (28 days)	160 MPa (23,200 psi)	Freeze/thaw (after 300 cycles)	100%
Compressive (48 hours)	100 MPa (14,500 psi)	Salt-scaling (loss of residue)	<0.10 g/m^2
Flexural	30 MPa (4,300 psi)	Carbonation depth	<0.5 mm
Young's Modulus (E)	50 GPa (7,200 ksi)		

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.

Additional detailed material properties for UHPC may be found in the FHWA report, "Material Property Characterization of Ultra-High Performance Concrete"[9].

To better understand the material's long-term durability, a series of prisms (152 mm x 152 mm x 533 mm) were placed in 1996 and 2004, at the long-term exposure test site of the US Army Corp of Engineers, in Treat Island, Maine, USA[10] (Figures 3 & 4).

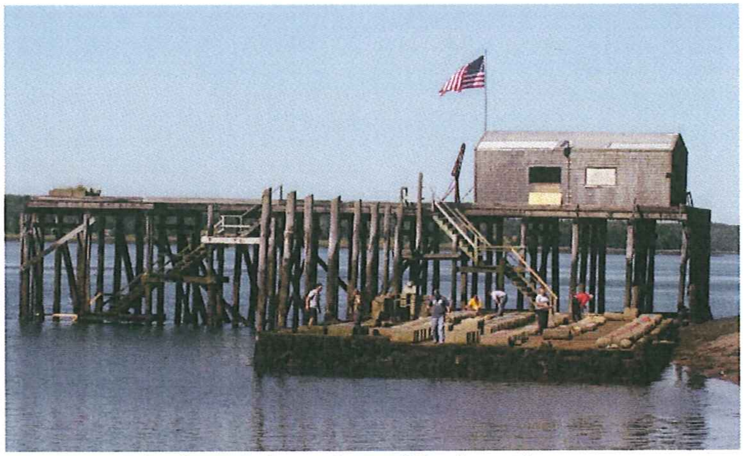


Figure 3: Wharf at US Army Corp of Engineers long-term exposure site, Treat Island, Maine, USA[11]

Figure 4: Prisms on the wharf at exposure site[11]

The prisms are placed on the wharf deck which is located at mean tide in the Bay of Fundy, Maine. The samples are subjected two tide cycles of wet/dry in sea water each day and, during winter at low tide, are subject to freeze/thaw. Following 13 years of exposure, the samples were removed and measurements taken for the depth of chloride penetration (Figure 5). The dashed line in Figure 3 represents a chloride mass of 0.05%, considered to be below the level in which corrosion would be initiated.

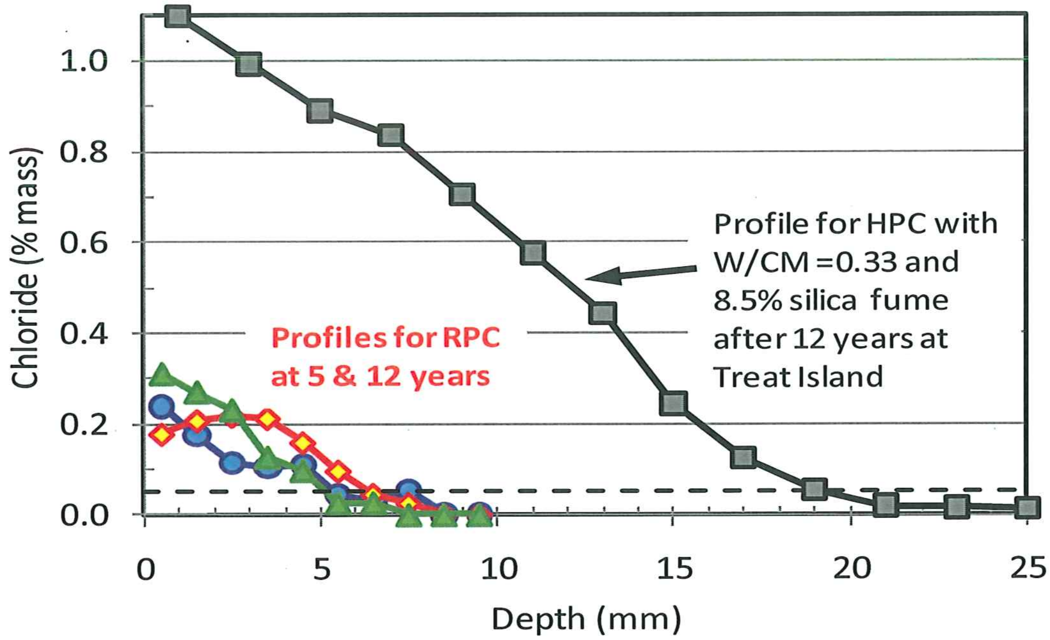


Figure 5: Depth of chloride vs chloride content for UHPC vs HPC [11]

Following 13 years of similar exposure, HPC has more than five times the chloride content and 2.5 times the depth of penetration compared to UHPC. In accordance with Fick's Law for Chloride Ion Diffusion, the rate of penetration depth of chlorides in concrete is proportional to the square of time. It takes four times as long to double the depth of penetration. Figure 6 below shows the predicted rate of penetration of UHPC vs HPC:

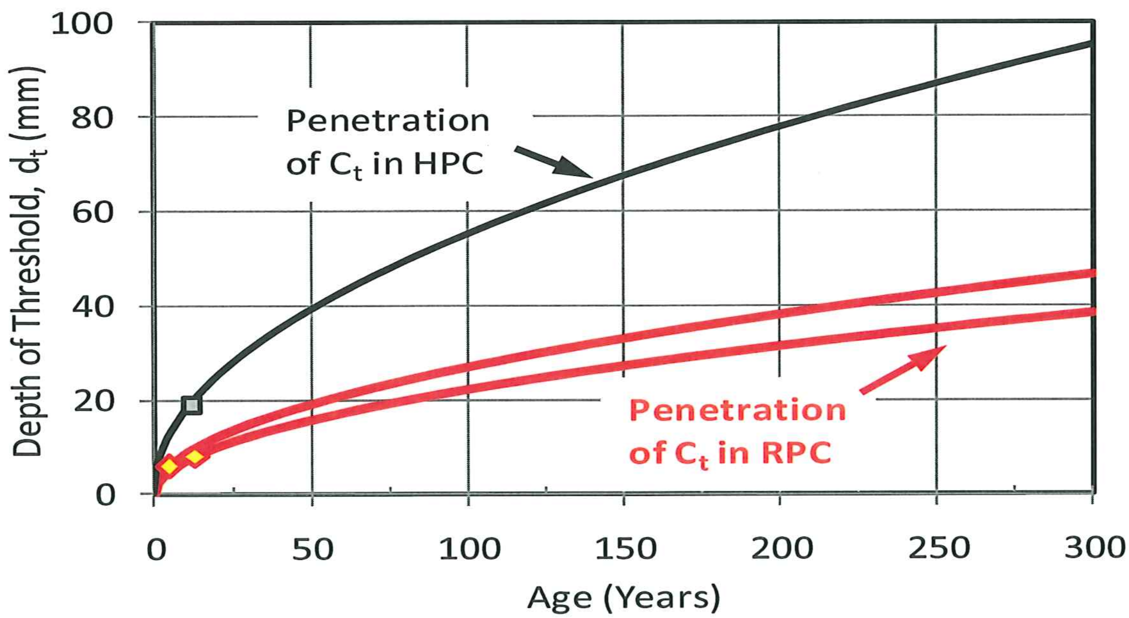


Figure 6: Predicted Rate of Penetration of $C_t = 0.05\%$ [11]

Extrapolating the data would suggest that UHPC requires 1,000 years to have the same level of chloride penetration that HPC would have in less than 100 years.

One additional observation is that after 13 years, the UHPC prisms at the exposure site still have corners that are as clean and sharp as the original samples. Most other concrete samples, after one season, show rounding of the corners due to freeze/thaw durability.

The Pi-Girder Bridge:

When research on UHPC began in the early '90's, it quickly became evident that this new break-through technology material with a unique combination of superior technical characteristics would require a long period of development, implementation and optimization. Current construction practices, engineering design methodologies, codes and standards would require changes in order to permit the full implementation of this technology. In the late '90's the FHWA quickly understood the potential of the technology and undertook a program to develop optimized shapes for the use of UHPC. It was understood that, just like steel and concrete bridges use their respective material in a manner that optimizes the material consumption, UHPC bridges would require different shapes. In 2002, the FHWA engaged MIT to conduct a shape optimization study for the use of UHPC in highway bridges, which resulted in a pi-girder configuration [12].

In 2005, Buchanan County and the Iowa State Department of Transportation (IADOT) were granted funding through the TEA-21, "Innovative Bridge Construction Program" (IBRC) for the purpose of constructing a bridge utilizing UHPC in a pi-girder configuration. Figure 7 shows the installation of precast UHPC pi-girders for a bridge installation in Buchanan County, IA in 2006[7].

The site selected was to replace an old existing bridge over a river. The new bridge (7.55m x 35.15m) would be a 3-span bridge with 3 pi-girders (15.24 m long) in the central span only.

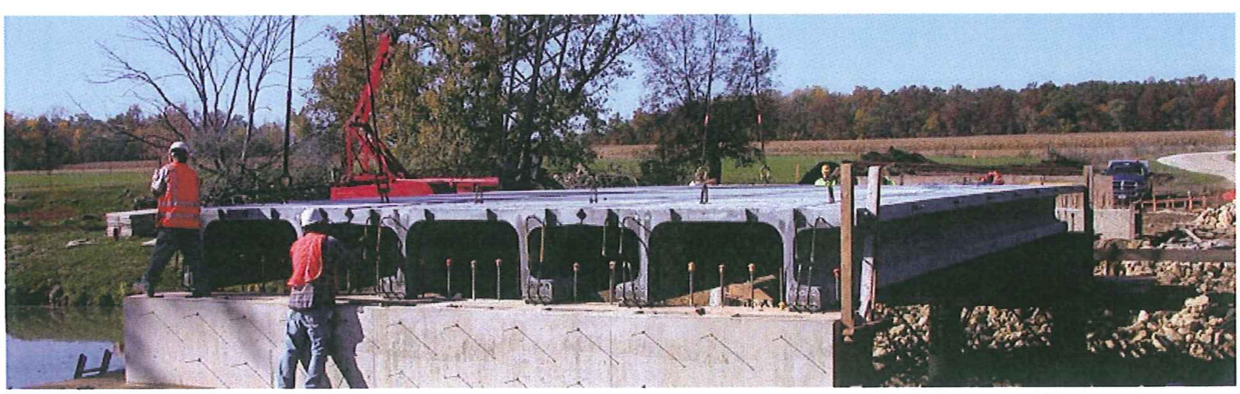


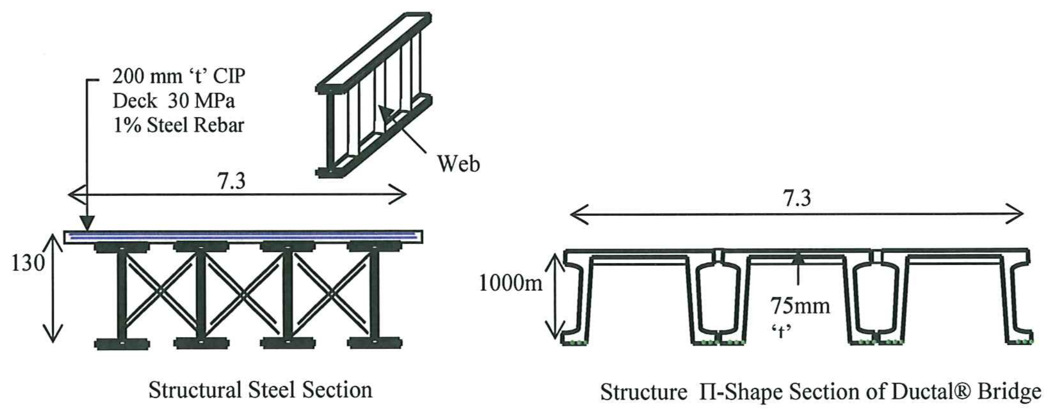
Figure 7: Installing the UHPC pi-girders at Buchanan County, IA [7]

The use of UHPC pi-girders for this project validated a solution that provides rapid construction (lightweight, single unit precast deck-beam) and durable (low permeability). Unlike conventional bridge decks, the low permeability also permitted the deck to remain exposed to the elements rather than adding a surface membrane for protection. This was an added savings in time, cost and material consumption.

In addition to the 3 pi-girders for the bridge, two more pi-girders were manufactured and shipped to the FHWA's Turner-Fairbanks Research Center (Maclean, VA) for full scale load testing. The results of the full scale load testing will be used for further optimization work and in the development of new codes for engineers to use in designing bridges with UHPC.

Environmental Comparison of Steel Girder Bridge vs UHPC Bridge:

UHPC not only provides more durable long lasting solutions, it results in a significant reduction in the quantity of concrete materials and hence, the environmental impact both initially and over the life cycle[13]. In order to understand the potential environmental impact of utilizing UHPC, in bridges, a study was conducted to compare a conventional steel girder bridge with a cast-in-place concrete deck to a UHPC pi-girder bridge (Figure 8).



Steel girders (x4) –	WWF 1100x291 30 m length Girder mass 291 kg/m Grade 310MPa	UHPC Structure -	Based on MIT[11] 30 m length X-Sect = 0.418m^2 UHPC = 160MPa
X- Bracing - (Diaphragms)	10 tons Grade 310MPa	Steel in UHPC -	156 kg /m^3 of fibre 30 strands / pi-girder

Figure 8: Equivalent cross-section of a structural steel bridge with cast-in-place concrete deck vs UHPC pi-girder bridge.

The study of the two equivalent bridges in Figure 6, compares the volume of each material in each bridge and calculates the embodied material energy and CO2 emissions for all materials, including delivery to the site.

Both bridges were designed to carry a typical HS20 Highway Truck loading for a 30 m span. The bridge section comparison in Figure 8 shows only those elements of the bridge that are uniquely different for the specific solution. All other aspects of the bridge are considered similar and do not impact the relative comparison between the bridges.

The Athena Sustainable Materials Institute (ASMI) [14] provides factors for embodied energy, and CO_2 emissions (Materials Environmental Data) for each construction material. The materials environmental data factors cover the total for each material from raw material extraction, through manufacturing, delivery and site construction. Table 1 provides the individual material environmental data extracted from an ASMI Report for materials for a bridge located in Vancouver, Canada.

Material	Density (Kg/m^3)	Production Direct energy (GJ/m^3)	Electricity Share (GJ/m^3)	Primary Energy (GJ/m^3)	CO_2 Total (Kg/m^3)	NOx Total (Kg/m^3)	CH4 Total (Kg/m^3)	GWP (100 years) Kg CO_2EQU/m^3
Concrete 30 MPa	2324	1.999	0.233	2.039	370.8	2.07	0.15	690.8
Concrete 60 MPa	2386	2.387	0.251	2.442	393.4	2.27	0.17	744.6
Prestressed Steel	7800	-	-	84.94	17 123	55.38	30.65	27 361
Steel Framework	7800	-	-	84.94	17 123	55.38	30.65	27 361
Structural Steel	7800	-	-	84.94	17 123	55.38	30.65	27 361
Ductal® (UHPC)	2500	-	-	6.62	1 138	5.68	0.97	2 051

Table 1: Material Environmental Data, for Vancouver, Canada [14]

The following assumptions were used when completing the above material environmental data:

- All steel was considered to be from 100% recycled materials, produced in an electric arc furnace and manufactured in central USA. (This provides values that are closest to the national average.)
- The UHPC was calculated based on a Ductal® BS1000 formula (approximately double the cement content to 30 MPa concrete), which includes 156 Kg/m^3 of steel fibers.
- The Global Warming Potential (GWP) is calculated based on the ASMI method, where GWP (Kg) = CO_2 (Kg) + 150 * NOx (Kg) + 63 * CH_4 (Kg).
- Primary Energy is defined as the energy need for production and transportation (includes both electrical and fuel oil).

Table 2 shows the environmental out-based on the quantities of materials in the steel bridge solution and using the factors in Table 1. The bottom line (l"Total") in Table 2, shows the total Primary Energy, Emissions and GWP for the steel bridge. The bottom line in Table 3, shows the Primary Energy, Emissions and GWP for the UHPC Bridge.

		Quantities (m^3)	Quantities (t)	Primary Energy (GJ)	Emissions (CO_2 (Kg)	GWP (Kgequ. CO_2)
	B30	43.92	102.07	89.55	16 286	30 340
Slab	Steel framework	0.44	3.43	37.37	7 534	12 039
Structure	Steel	5.76	44.93	489.25	98 628	157 599
Total		50.12	150.43	616.17	122 448	199 978

Table 2: Steel Bridge Solution: Quantity of Material, Embodied Energy and Emissions.

		Quantities (m^3)	Quantities (t)	Primary Energy (GJ)	Emissions CO_2 (Kg)	GWP (Kg equ. CO_2)
	-	-	-	-	-	-
Slab	-	-	-	-	-	-
Structure	Ductal®	37.62	94.05	249.04	42 812	77 159
	Prestressed	0.41	3.20	34.83	7 020	11 218
Total		38.10	97.25	283.87	49 832	88 377

Table 3: UHPC Bridge Solution: Quantity of Material, Embodied Energy and Emissions.

The relative comparison of the total materials environmental data for the two bridge solutions is shown in Figure 9. For the initial construction, the UHPC Bridge solution uses 65% of the materials, consumes 46% of the Primary Energy, produces 41% as much CO2 and has 44% of the Global Warming Potential compared to the steel bridge.

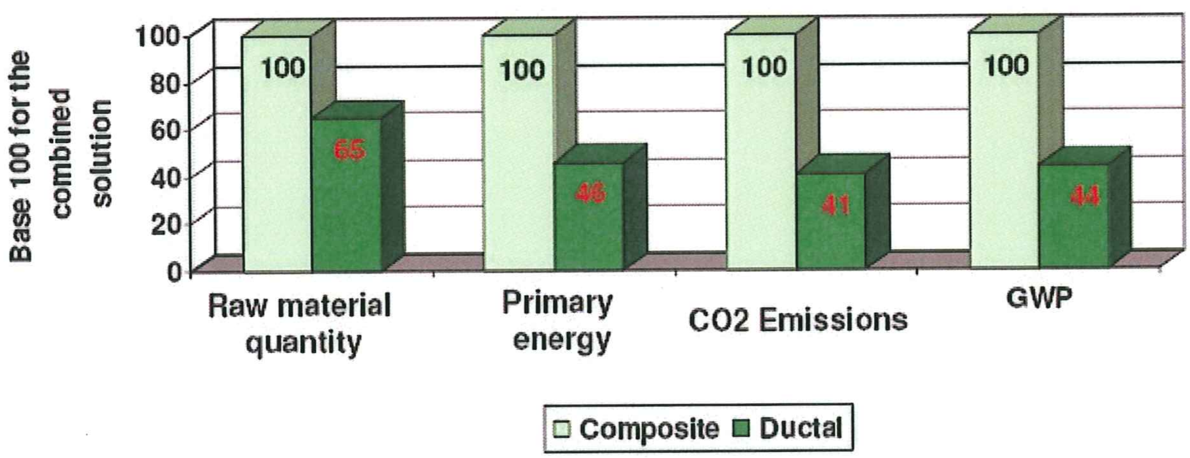


Figure 9: Relative Quantities of Embodied Energy and Emissions for the Steel vs UHPC Bridge

In order to fully understand the overall benefits and environmental impact (i.e., sustainability) of utilizing UHPC for bridges it is also necessary to include the effects of reduced construction schedule, lower maintenance and increased usage (both longer life expectancy and reduced loss of use for periods where the bridge has rehab construction detours). For example, a bridge is normally on the critical path to putting in service any piece of highway, which when open will improve traffic congestion and reduce CO_2 emissions from vehicles.

In the case of a pi-girder bridge vs a steel girder bridge with CIP deck, there is considerable time savings in the schedule due to not having to form, set rebar, cast, and cure the CIP deck before opening to traffic. The CIP deck can take 30 days extra compared to the precast integral beam-deck system of a pi-girder bridge. Assuming a new bridge could reduce travel by 2 km per day for five days (conservative reduction of construction schedule for a precast UHPC bridge) for 10,000 vehicles per day, would result in a reduction of 35,000 kg of CO_2, based on Environment Canada's estimate of 0.25 kg per vehicle kilometer. This would have an effect of further reducing the net CO_2 for the UHPC from 49,832 kg to 14,832 kg, which would be 8.26 times less than the steel bridge.

If, only once in the life of the steel bridge option, it is required to rehabilitate the CIP concrete deck or re-coat the steel girders for corrosion protection, then the impact of the material consumption for the repairs and the CO_2 emissions from the construction traffic delays will significantly increase the environmental impact of the steel bridge solution.

Conclusions / Recommendations:

Many current strategies to address the challenges of sustainability focus on: (i) adding more capacity; (ii) reducing waste through improved efficiencies; (iii) technology or innovation, or; (iv) reducing consumption. While each of these strategies is important and necessary, by themselves they may not be sufficient.

This paper presented a new approach to sustainability and possible solutions for improving the sustainability of infrastructure, in particular, bridges. The Civil engineering profession needs to create a new vision and set of General Engineering Design Parameters (GEDP) for infrastructure in terms of design life and Global Environmental Impact (GEI).

There are new materials and approaches to reducing the GEI and improving the sustainability of infrastructure. UHPC is one such example as shown. Through the use of ion transportation modeling, the life expectancy of UHPC could be predicted to be over 1,000 years, an order of magnitude better then HPC. Without considering the life cycle benefits, the use of UHPC for the construction of bridges has the potential to reduce the raw materials consumption by a factor of 1.3, Primary Energy usage by 2.1, CO_2 Emissions by 2.4 and the Global Warming potential by 2.1.

Engineers need to consider the following GEDP:

- 1,000 year design life
- Minimal embodied energy
- Self-sufficiency for energy over usage life
- Self-sufficiency for water over usage life
- Minimal usage disruption or "out-of-use"
- Near zero maintenance & operations, and;
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Today there is much debate and discussion on CO_2 emissions and global warming by the public, government, academia, intellects, business professionals and environmentalists without a consensus or clear resolution to the problems or solutions. However, one thing is clear; the 'status quo' is unacceptable. We must change and sooner than later.

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