Cost and Ecological Feasibility of Using UHPC in Bridge Piers

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Abstract: There is a growing interest in expanding the use of Ultra-High Performance Concrete (UHPC) from highway bridge deck joints for accelerated bridge construction to architectural facades cast in unique and slender profiles. The high costs associated with the proprietary UHPC mixes, besides the environmental concerns resulting from its high cement content and massive energy consumption during its production, might limit the widespread use of UHPC in the built environment. On the other hand, the higher strength and durability of UHPC should result in more compact cross-sections, safer structures, and a longer service life compared to conventional concrete. This study investigates several UHPC mix designs to design a multi-column bridge pier and analyze its cost and ecological feasibility. The objective is to identify what would be the optimal UHPC mix from an economic and eco-friendly perspective. Ultimately, the study lays the foundation for future work to find the break-even costs of UHPC at which it would become economically and environmentally feasible to design substantial bridge substructures entirely with UHPC in lieu of regular concrete.

Keywords: UHPC, bridge piers, cost study, environmental impact

1. Introduction

Over the past few decades, ultra-high performance concrete (UHPC) has made major advances in structural applications throughout highway and pedestrian bridges. UHPC has garnered increased interests for its high strength, ductile behavior, long-term stability, and compactness. Its particularly low porosity increases the uniformity of its mix and allows the concrete to attain its extreme properties with a more uniform stress distribution (NPCA, 2014). Another advantage to its low porosity is UHPC's superior freeze-thaw durability. When water freezes, it experiences an approximate 9% increase in volume. When water penetrates the voids of normal strength concrete and freezes, the sudden increase in volume of water, once frozen, can rupture the voids causing the concrete to crack. Water penetrating concrete can also become problematic as it can corrode the reinforcing steel. This makes UHPC a very practical material for highway and pedestrian bridge designs.

Quality control is a significant factor when it comes to mixing and curing UHPC. Unless a qualified UHPC specialist is on site to inspect any field casts, most UHPC components (structural or architectural) are cast under controlled environments by a qualified precast concrete plant. Curing methods for UHPC vary for different circumstances and relies on two components, temperature and moisture (FHWA, 2013). Curing UHPC in its early stages in room temperature water leads to stronger formations of silicate hydrates. To continue this process, a high temperature cure either through steam or another heat source is applied to accelerate the silicate hydrate formation (Neville, 1995). Various methods of curing include steam curing at

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140°F (60°C) or 194°F (90°C) for 48 hours, 24 hours post-casting, steam curing at 194°F (90°C) 15 days post-casting, and curing at standard, controlled temperatures in a laboratory until satisfactory results are achieved. A study by Heinz et al. (2012) revealed that storage periods have an additional contributing factor on top of temperature and time of curing methods. Specimens immediately cured after setting for eight hours at 194°F (90°C), achieved compressive strengths greater than 29 ksi (200 MPa) when tested 30 hours post-cure. Other specimens that were 24 hours old were heat treated for eight hours in an autoclave at 300°F (148.9°C), cooled down to room temperature within 11 hours, and stored at 68°F (90°C) and 65% relative humidity until tested. These specimens achieved compressive strengths up to 38 ksi (262 MPa) (Heinz et al. 2012). The reason for elaborating on various curing methods is to emphasize how UHPC may not be as practical for field casting for highway bridges if a higher compressive strength is desired. Thus, this study utilizes UHPC mixes with respective mechanical properties that can be achieved in normal curing conditions, i.e. up to 25 ksi compressive strength rather than that 38 ksi so that it will be more suitable for field casting. However, it is worth noting that controlled curing can be beneficial to consider for precast concrete members with increased quality control and assurance.

On another note, cement production accounted for 9.5% of global carbon dioxide (CO_2) emissions in 2013 (Olivier and Muntean, 2014). These high emissions are caused by a combination of carbonate oxidation during the cement clinker production process and fuel combustion during the general cement production within the kiln. Limestone, a primary component of cement production, is made up of calcium carbonate. When heated to approximately 2,700°F (1,482 °C), the limestone breaks down into calcium oxide and CO_2 contributing to roughly 50% of all CO_2 emissions from cement production (Rubenstein, 2012). Concrete is still the second most consumed substance on Earth next to water and will continually contribute to the global CO_2 emissions. In order to produce a ton of concrete, nearly 400 lb (181 kg) of coal (4.7 million BTU of energy) is required producing nearly one ton of CO_2 (UNEP, 2010). According to a survey performed by the Portland Cement Association, nearly 2,044 lb (927 kg) of CO_2 is produced for every 2,205 lb (1,000 kg) of portland cement produced in the United States (Marceau et al. 2006). This translates to 1 lb (0.45 kg) of CO_2 produced for every 1.08 lb (0.49 kg) of portland cement produced. The easiest and simplest way to make an impact on CO_2 emissions within cement production is to follow the golden rule of global warming; decrease the use of cement. By utilizing UHPC, smaller sections can be designed relative to conventional concrete, which might require overall less cement, and furthermore decrease cement demand and production.

The objective of this study is to investigate the monetary and ecological costs of using UHPC in highway bridge piers in lieu of conventional concrete. Building bridge components entirely using UHPC can significantly enhance the durability and service life of bridges. However, the high costs might be a drawback. To help make a better engineering judgment, three different UHPC mixes are used to redesign a typical California highway bridge pier. The required concrete and associated cement along with reinforcing steel quantities are calculated and compared to the conventional concrete case. These quantities are interpreted in terms of costs and CO_2 emissions to assess the feasibility of using UHPC. More details about the prototype bridge, selected mix designs from literature, analysis, and results are presented in the following sections.

2. Prototype Bridge

This study focuses on redesigning a substructure of a three span highway bridge using UHPC. The prototype bridge is a typical California reinforced concrete box-girder bridge that is used by the Caltrans Bridge Academy. The substructure considered for this study is the bridge pier (bent) that consists of two columns and integral bent cap beam. The UHPC bridge pier is designed in accordance to the Caltrans Seismic Design Criteria (SDC, 2014) and AASHTO LRFD Bridge Design Specifications (2012). A typical CA bridge was chosen for this study to involve both vertical (gravity) and lateral (seismic) design, where UHPC can be beneficial for its exceptional performance. A summary of the Caltrans Academy bridge specifications is shown in Table 1. Note that this study considers only redesigning the bents and not the superstructure, i.e. values such as the width and depth of the concrete box girder are the same, and the only changes are the bent cap width, column diameter, and reinforcing steel. Thus, the column and bent cap demands dictated by the superstructure dead and live loads are same as in original design. For the sake of a simplified study, the analysis is performed on one of the bridge bents only, which is designated as Bent 2.

To set the stage for the analytical framework adopted in this study, one of the two columns of the original bent design is presented here as an example to calculate the concrete, cement, and steel quantities and associated monetary and ecological costs. These quantities are summarized in Table 2 based on conventional concrete use [f'c = 4.0 ksi (27.6 MPa)]. Note that only CO_2 emissions associated with total amount of cement used is considered as environmental impact (ecological) metric. For quantifying CO_2 emissions, one pound of portland cement produces 0.926 lb (0.42 kg) of CO_2, which is deduced from statistics by Marceau et al. (2006). There are other metrics that can be used to assess environmental impact such as the energy consumed during concrete production and pouring, but these are not included in this study. For the monetary costs, A rate of $441 per metric ton of reinforcing steel (SteelBenchmarker, 2016) was used to estimate the steel total cost. For estimating concrete costs, approximate rates reported by the FHWA (2013) were used for both conventional and UHPC. A rate of $\$100/yd^3$ for conventional concrete was used for estimating the original Caltrans design cost. A rate of $\$2000/yd^3$, which is almost 20 times the cost of conventional concrete, is used for UHPC costs for the later part of the study.

Table 1. Caltrans Highway Bridge Design Specifications

Superstructure Type	Continuous prestressed reinforced concrete box girder
Substructure Type	Two UHPC columns per bent
Span Lengths	126 ft. (38.4 m.) – 168 ft. (51.2 m.) – 118 ft. (36.0 m.)
Foundation	Piles
Seismic Design Category	D
Seismic Design Strategy	Type 1
Soil Profile	Type C
Magnitude	8.0 ± 0.25
Peak Rock Acceleration	0.5g
Design Spectral Acceleration (S_{D1})	0.97g
Latitude and Longitude	37.8800º, -122.522000 º

Table 2. Summary of design, monetary and ecological costs of one bridge pier column

Column Diameter	6.0 ft. (1.83 m.)
Column Height	44.0 ft. (13.41 m.)
Compressive Strength (f'$_c$)	4.0 ksi (27.6 MPa)
Modulus of Elasticity of Concrete (E_c)	4,372 ksi (30.0 GPa)
Longitudinal Reinforcement	26 #14 bars
Transverse Reinforcement	#8 hoop at 5 in. (12.7 cm.) c-c
Volume of Concrete	1,244 ft^3 (35.2 m^3)
Weight of Cement Consumed	12.53 tons (11,371 kg)
Weight of Steel Consumed	4.76 tons (4,323 kg)
Total Cost of Concrete	$4,607
Total Cost of Steel	$2,099
CO_2 Produced	11.61 tons (10,529 kg)

3. UHPC Mix Design

Several previous studies developed and tested proprietary and non-proprietary UHPC mixes. Many of the published mix designs with its respective mechanical properties, such as compressive strength f'c, vary drastically based on different curing methods, admixtures, types of silica fume, and steel fibers used. The goal of this study is to choose different UHPC mixes and utilize them for redesigning the bridge pier based on their respective mechanical properties. The optimization of the structural design along with the variation in the mix design and constituents can be a first step towards identifying the most economical and eco-friendly mix design to create the most efficient multi-column bridge pier. Three mix designs were considered for this analysis with variable f'c and E [Graybeal 2006, Graybeal 2007, Yu et al. 2014, Ritter and Curbach 2015]. Based on each mix design, the total amount of concrete, cement, and reinforcing steel utilized in each pier design will be used to calculate total cost per bent and total CO_2 produced. Tables 3 and 4 summarize the three mix designs in detail and their corresponding mechanical properties, respectively.

Table 3. UHPC Mix Design Summary lb/yd^3 (kg/m^3)

	Mix #1	Mix #2	Mix #3
Cement	1,200 (712)	1,180 (700)	1,402 (832)
Fine Sand	1,720 (1020)	1,778 (1055)	-
Microsand	-	369 (219)	-
Ground Quartz	355 (211)	295 (175)	349 (207)
Quartz Sand	-	-	1,643 (975)
Silica Fume	390 (231)	74 (44)	228 (135)
High Range Water Reducer	51.8 (31)	77.4 (46)	50 (30)
Accelerator	50.5 (30)	-	-
Steel Fibers	263 (156)	82 (49)	324 (192)
Water	184 (109)	341 (202)	280 (166)
W/C	0.15	0.29	0.20
Source	Graybeal, 2006	Yu et al. 2014	Ritter & Curbach, 2015

Table 4. UHPC Mechanical Properties Summary

	Mix #1	Mix #2	Mix #3
Compressive Strength (f'_c), psi (MPa)	17,200 (119)	21,611 (149)	25,240 (174)
Modulus of Elasticity (E), psi (MPa)	6.07E+6 (41851)	6.79E+6 (46815)	7.33E+06 (50,539)
Source	Graybeal, 2007	Yu et al. 2014	Ritter & Curbach, 2015

4. Pier Design

The analytical study presented in this paper involved design the Caltrans Academy bridge pier (bent cap and 2 columns) using three different UHPC mixes. The new design considered the actual mechanical properties (compressive strength, tensile strength, and modulus of elasticity) of the selected UHPC mixes as discussed in previous section. The exceptional mechanical properties of UHPC are expected to result in more compact cross-sections for the pier columns and bent cap. Thus, the overall reduction in the required concrete volume can still result in a substantial reduction in the associated cement and, in turns, CO_2 content. The design procedure is based on the bridge demands calculated and used in Caltrans LRFD Bridge Design (2006) from the Caltrans Bridge Design Academy. The demands form the superstructure dead and live loads along with the demands from seismic scenario were used to perform the column checks. These checks included a demand analysis, displacement capacity using pushover analysis, shear capacity design, and P-Δ checks. While there are no set design specifications for UHPC columns in highway bridge design, this study assumed that current design equations are still valid for UPHC. This exercise aims at demonstrating UHPC's potential to reduce column cross-sectional areas, cement consumption, and CO_2 production.

A simplified design framework was adopted here which involved: (1) select the column diameter and reinforcement ratio; (2) perform design checks on column including sectional analysis to calculate accurate moment capacity and ductility using UHPC properties; (3) compare capacities versus the demands for the column to satisfy design checks; (4) optimize the design by reducing the column diameter and/or reinforcement ratio if needed; (5) finalize the bent cap beam dimensions by using same depth as original design but width equals to new column diameter plus two feet as required by Caltrans SDC (2013); and (6) perform a capacity design check for the bent cap beam using new dimensions to finalize required reinforcement if different from original. This framework was repeated three times for each of the three UHPC mixes. To perform the sectional analysis for capacity checks, the software XTRACT (Chadwell and Imbsen, 2004) was used. In addition, SAP2000 was also utilized to perform a simple frame analysis for the columns and the bent cap. The moment-curvature relationship obtained from sectional analysis were applied to the pushover analysis for each column section. A sample moment-curvature relationship as obtained from XTRACT for one of the columns designed using UHPC mix #3 is shown in Figure 2. The final design and associated monetary and ecological costs for one column is summarized in Table 5 for original and three UHPC cases. All calculations are based on the rates previously described in Section 2 for steel and concrete costs and CO_2 emissions.

5. Discussion of Results

By utilizing UHPC in this column design, higher shear capacities can be immediately observed along with much less axial load. By decreasing the column cross-sectional area, its own weight decreases and the required bent cap width can decrease resulting in lower dead loads. Increased elastic modulus values for concrete also improved lateral bending stiffness significantly. From the results summarized in Table 5, we can observe that UHPC can benefit in both cement and steel consumption and CO_2 emissions. Another way of interpreting the results is by estimating the percentage of change in design parameters and costs with respect to the original design as summarized in table 6. The designs demonstrate a reduction in cross-sectional area between 33.3% in Mix #1 up to 50% in Mix #3 along with a decrease of total reinforcing steel between 52.8% in Mix #1 up to 72.7% in Mix #3. Most importantly, between 3.5-36.6% of the cement content was eliminated, effectively decreasing CO_2 emissions as high as 36.6%. The main drawback, which can be expected before hand, is the tremendous increase in concrete monetary costs (up to 790% increase in cost/column in case of Mix #1 for instance). The objective of this study was to identify the most feasible mix design for cost and ecological benefits. Mix #1 immediately broke-even with the original design in terms of cement and CO_2 content. Mix #3 demonstrated the best properties with the lowest cement content, steel reinforcement, and CO_2 emissions. From concrete cost perspective, all UHPC mixes and not feasible. However, the reduction in the required concrete volume can be up to 75% as in case of Mix #3. Thus, hypothetically, if UHPC cost is 5 times cheaper than the current $2000/yd3 FHWA estimate, a cost-benefit can be observed as well. Further cost benefits can be observed if construction time saving and overall extended service life as considered.

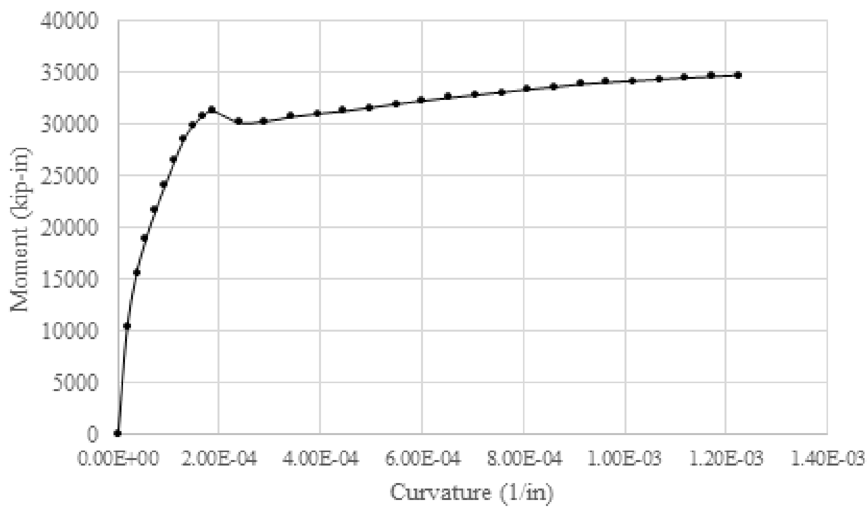

Figure 2. Moment Curvature for column design using UHPC Mix #3

Table 5. UHPC Column Design Summary

Design Per Column	**Original Design**	**Mix #1**	**Mix #2**	**Mix #3**
Column Diameter [ft (m)]	6.0 (1.83)	4.0 (1.22)	3.5 (1.07)	3.0 (0.91)
Longitudinal Reinforcement	26 #14 bars	22 #10 bars	18 #10 bars	16 #9 bars
Transverse Reinforcement	#8 hoop at 5 in.	#6 hoop at 5 in.	#5 hoop at 5 in.	#5 hoop at 5 in.
Volume of Concrete [ft^3 (m^3)]	1,244 (35.2)	552.9 (15.7)	423.3 (12.0)	311.0 (8.8)
Weight of Cement [ton (kg)]	12.53 (11,371)	12.09 (10,969)	9.09 (8,250)	7.94 (7,207)
Weight of Steel [ton (kg)]	4.76 (4,323)	2.24 (2,037)	1.82 (1,653)	1.30 (1,181)
Total Cost of Concrete	$4,607	$40,955	$31,355	$23,037
Total Cost of Steel	$1,003	$990	$803	$574
CO_2 Produced [ton (kg)]	11.61 (10,529)	11.20 (10,156)	8.42 (7,639)	7.36 (6,673)

Table 6. Percentage of change in UHPC design parameter and costs with respect to the original conventional concrete design

Design Per Column	Mix #1	Mix #2	Mix #3
Column Diameter	33.3%	41.7%	50%
Longitudinal Reinforcement	52.2%	60.9%	72.6%
Transverse Reinforcement	87.3%	92.3%	93.5%
Volume of Concrete	55.5%	65.9%	75%
Weight of Cement Consumed	3.5%	27.4%	36.6%
Weight of Steel Consumed	52.9%	61.8%	72.7%
Total Cost of Concrete	-790%*	-578%*	-400%*
Total Cost of Steel	52.9%	61.8%	72.7%
CO_2 Produced	3.5%	27.4%	36.6%

*minus sign indicates an increase not a reduction, i.e. unfavorable change with respect to original design

6. Conclusions

While UHPC is garnering much more interest across North America, advances in research and applications can accelerate UHPC deployment. Two aspects that are strongly tied to UHPC vast deployment are the costs, which stem from the use of steel fibers and stringent quality control on materials and production, and environmental impacts due to higher cement content and production energy consumption. This preliminary study focused on assessing the cost and environmental aspects of using UHPC in highway bridge piers. The benefit associated with introducing UHPC to bridge piers is reducing cross-sections, which in turns, result in overall less material and cement quantities, and reduced CO_2 emissions. Additional benefits include higher durability and longer service life. However, the high monetary costs remain the main drawback that slow the widespread use of UHPC.

This study showed that up to 75% less materials can be used in bridge piers if UHPC is used in lieu of conventional concrete. This translates to faster construction and smaller footprints for bridge columns which allow for better traffic flow. Moreover, the use of UHPC of compressive strength in the 25 ksi range can result in reducing bridge piers' carbon footprint by up to 35%. This means that the high cement content in typical UHPC mixes is outweighed by overall reduction in the required concrete quantities, i.e. utilize UHPC for more structural applications can be sough as one solution towards green construction.

Finally, cost benefit of using UHPC can be achieved if associated material costs are reduced by four to five times than the current $2000/yd^3 FHWA estimate. Cost benefits can be maximized with respect to inspection and maintenance costs given UHPC's durability and superior service life. Thus, it is recommended for future work to consider full life cycle assessment of using UHPC in bridges to accurately identify break-even UHPC costs. Developing non-proprietary UHPC with local materials and comparable quality to commercial proprietary ones should be the focus of more studies as well to alleviate UHPC costs.

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