IOP Conf. Series: Materials Science and Engineering **245** (2017) 052096 doi:10.1088/1757-899X/245/5/052096

Determining the Environmental Benefits of Ultra High Performance Concrete as a Bridge Construction Material

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Abstract. Ultra High Performance Concrete (UHPC) is a material that is attracting attention in the construction industry due to the high mechanical strength and durability, leading to structures having low maintenance requirements. The production of UHPC, however, has generally higher environmental impact than normal strength concrete due to the increased demand of cement required in the concrete mix. What is still not sufficiently investigated, is if the longer lifetime, slimmer construction and lower maintenance requirements lead to a net environmental benefit compared to standard concrete bridge design. This study utilizes life cycle assessment (LCA) to determine the lifetime impacts of two comparable highway crossing footbridges spanning 40 meters, designed respectively with UHPC and normal strength concrete. The results of the study show that UHPC is an effective material for reducing lifetime emissions from construction and maintenance of long lasting infrastructure, as the UHPC design outperforms the normal strength concrete bridge in most impact categories.

1. Introduction

Concrete is the most commonly used building material in the world with an annual production of approximately 10 billion m^3 [1, 2]. Reinforced concrete allows for flexible and cost-effective design with excellent bearing capacity and mechanical properties, it is highly available – made of mostly local constituents, and it allows a flexible construction process. Although concrete is a durable material compared to other types of building materials, it is exposed to degrading mechanisms such as carbonation and chloride penetration, leading the reinforcement bars to corrode which thus reduces service-life. This requires special attention, especially in chloride-rich environment like coastal areas and where salt is used during winter, to remove ice.

The concrete industry, account for approximately 8 % of total anthropogenic CO_2 emissions on a global scale, approximately 90 % attributable to production of Portland cement [1, 3, 4]. The world moves constantly forward on climate reduction goals. Reducing emission from the use of concrete, has potential for contributing significantly. The Paris Climate Agreement established global CO_2 emissions reduction goals for all nations. Norway has committed to cut the national emissions to a level 40% below 1990 levels, within 2030 [5]. Additionally, emissions from transport infrastructure are to be reduced by 50% of 2005 levels by the year 2050 [6]. This will require innovations in material production, construction design and maintenance. Given the emissions intensity of concrete, the construction industry has a vital role to play in reducing these emissions. Climactic challenges such as harsh weather and cyclic cold periods, cause excessive damage to existing infrastructure. A recent "State of the Nation"-report concludes that the maintenance backlog of infrastructure has reached a critical level [7].

The Norwegian government has decided to invest in several critical national highways, to bring these roads up to today's standards [8]. Developing this new infrastructure will require novel and innovative solutions to meet the challenging Norwegian weather, while also meeting the ambitious climate targets set out in the Paris Agreement.

One approach might be to lower the amount of concrete needed in a construction, by using UHPC. This type of concrete is characterized by its outstanding strength, durability and ductility [9, 10]. The bearing capacity of concrete constructions is often limited by its dead load, especially in structures with large spans. The increased mechanical strength of UHPC, makes it possible to design slender and lighter structures [2, 11]. Furthermore, UHPC is especially suitable for bridge constructions in challenging environments, as the material is extremely durable and the demand for rehabilitation during service-life is neglectable [12, 13]. Some early studies have shown environmental benefits of bridge design using UHPC instead of normal strength concrete. Bouhaya et al. [14] found the life cycle environmental impacts and energy demand of an innovative bridge design that utilized both UHPC and timber. The UHPC portion of the bridge deck was found to be maintenance free for 100 years (or more), leading to very low average CO_2 emissions per year and an overall slimmer design. Stengel & Schießl [15] looked at the construction of three different UHPC bridges in different locations. They found that the high load bearing capacity of UHPC makes it possible to build more slender constructions, and that cement, steel fibers and superplasticizer were the largest contributors regarding environmental impacts of the production. Habert et al. [12] compared the greenhouse gas emissions from a road bridge in high strength concrete with one in traditional concrete. 50 % reduction was obtained when only emissions from concrete was considered. Habert et al. [16] modelled the rehabilitation process of a road bridge by three different systems; traditional concrete with waterproofing membrane, UHPC and a new type of Eco-UHPC. They found that the CO_2 emission of UHPC was 5-7 times higher than that of Normal Strength Concrete (NSC), when comparing the same amount of material. However, by also considering the reduced concrete consumption and the improved service-life, the environmental impact of the Eco-UHPC and UHPC solutions were less than 60% and 72%, respectively, of the environmental impact from the traditional solution.

In 2013, Graybeal et al. [9] made a comprehensive report for the US Federal Highway Administration (FHWA), reviewing the most influential research on UHPC up to then. This report conclusively calls for more research on technical aspects, design practice and effectiveness on cost and environmental impact in a life-time view. This is claimed to be necessary to demonstrate the potential of UHPC, and widespread the use. More recently, a study on the environmental impacts of UHPC production has been done by Randl et al. [10]. In their study, they looked at the substitution of cement by other cementitious binders in the mixture. The study showed a significant reduction in environmental impact, and compared to a standard UHPC mixture the reduction of GWP was 42%. Thorstensen et al. [17] studied the effectiveness on cost and carbon footprint of two alternative bridge designs, made with UHPC and Normal Strength Concrete (NSC) respectively. It is concluded that both the carbon footprint and the cost (Net Present Value) are in favour of the UHPC alternative, in a life-time view.

All of these studies indicate, that well-planned designs utilizing UHPC can significantly reduce lifetime emissions from bridges. As the Norwegian road network is to be improved and expanded in the coming years, there is a potential for increased use of UHPC in bridge structures. The desire to construct UHPC bridges should consider the environmental impacts over the lifetime of the planned infrastructure in comparison to a conventional concrete alternative. Thus, this study is a comparative life cycle analysis of a T-beam bridge structure, designed with UHPC and NSC respectively, to determine which alternative has the lowest emissions profile. The goal of this study is to demonstrate impact of design, and determine whether UHPC would be an effective material for reducing lifetime emissions of bearing structures.

2. Methods and materials

2.1 Case study

A comparative study of a pedestrian bridge is carried out, using in-situ poured normal strength concrete (NSC) and UHPC as building materials.

2.1.1 Description of the bridge. The pedestrian bridge is designed to cross a 4-lane highway, has a total length of 40 m and a width of 3 m. The bearing structure is divided into two spans of 20 m, and consists of two simply supported T-beams, see Figure 1. The location is hypothetically in the south of Norway, associated with the new 4-lane highway (E18) from Tvedestrand to Arendal. This location is near representative for an average Scandinavian climate.

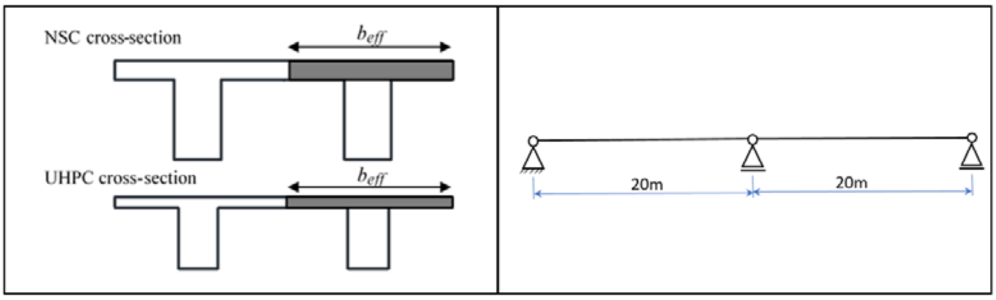


Figure 1. Cross-sections for normal strength concrete and ultra high performance concrete bridges (left side) and the longitudinal structural model (right side).

2.1.2 Materials. Concrete is the main building material used in footbridges in Norway. Concrete class C30/37 is chosen for the NSC alternative. Material properties for NSC used in this study are given in Table 1.

According to the definition of FHWA, UHPC is a cementitious based composite material with discontinuous fiber reinforcement, a compressive strength above 150 MPa and more than 5 MPa pre- and post-cracking tensile strength. Another important requirement for UHPC is the increased durability, due to discontinuous pore structure [9]. Material properties for UHPC are preliminary values from the Association Française de Génie Civil (AFGC) recommendation [19].

Table 1. Material properties for normal strength concrete and ultra high performance concrete.

Property	f_{ck}	f_{ctm}	f_{cd}	ε_{cu}	ε_{c1}	φ	E_{cm}	$E_{c,eff}$
	MPa			‰		-	GPa	
NSC	30	2.9	17	3.5	2.2	1.5	33	13.6
UHPC	150	9.0	85	3.5	2.2	0.8	50	27.8

The material model for both concrete types is the rectangular stress-strain curve given in Eurocode 2 [18], see Figure 2.

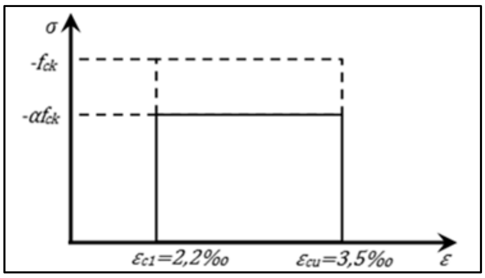


Figure 2. Material model for both concrete types.

Steel type B500C is applied in the reinforcing steel, with f_{yk}=500 N/mm2. Material factors for concrete and steel are γ_c=1.5 and γ_s=1.15, respectively, as given in Eurocode 2 [18]. For both NSC and UHPC α_{cc}=0.85 is used, corresponding to the Norwegian National Annex of Eurocode 2 and the AFGC recommendation for UHPFRC structures [18, 19].

UHPC contains two to three times the cement content of NSC. Hence, to be efficient in terms of environmental impact, it is highly important to decrease the total amount of concrete in the bridge construction.

2.1.3 Design calculations. The verification of the girders has been carried out according to the Eurocode series [18, 20, 21]. The bridge is calculated considering the following loads: i) uniformly distributed traffic load of 5· kN/m^2; ii) railing load of 1.5 kN/m [21] and iii) dead load of 25 kN/m^3 for the reinforced concrete. Partial factors used in the calculations are taken from Eurocode 0: in ULS 1.2 is used for dead load and 1.5 for variable load, and in SLS partial factors are set to 1.0 [20]. ULS and SLS are verified in both alternatives according to Eurocode 2 [18]. Necessary exceptions are made for the shear resistance, concrete cover and rebar spacing, which are done according to the recommendations for UHP(FR)C structures by AFGC [19]. To be able to compare the two solutions, the utilization was set to the same value of 95% in both cases. The bridge decks have not been designed; the thickness of the slabs are assumptions and are considered to be representative for the applied concrete types (t_{NSC}=20cm, t_{UHPC}=11cm).

2.2 LCA methodology

This study utilizes life cycle assessment (LCA) to determine the environmental impacts of each alternative. Life cycle assessment determines these impacts by comprehensively analysing resource and energy use, and outputs along an entire process chain of products and systems. The LCA framework, specified in ISO14040, is composed of four main parts described in the following sections [22].

2.2.1 Goal and scope. Goal and scope determines the specific aim (goal) of the study and determines how the study will be accomplished (scope). The goal is in relation to the functional unit of the study, which is a quantitative measure of the product or system's function. The scope determines the size and boundaries of the studied system and what is not included in the study.

2.2.2 Inventory analysis. Inventory analysis collects and organizes data from all processes in a system and relates them in terms of the functional unit. Data collected in the inventory analysis includes process inputs, material requirements, energy inputs, product output, emissions output and waste scenarios. This information, when compiled, is usually called a life cycle inventory (LCI).

2.2.3 Impact assessment. Impact assessment takes the information in the life cycle inventory and converts the information into environmental impact categories through a process called characterization. Characterization organizes emissions according to the environmental compartment in which they cause damage (aquatic, land, air, and health) and to the type of damages they cause in the form of a set of environmental indicators, or impact categories. Impact categories allow a simplified and effective way of presenting comprehensive environmental impacts so that useful decisions can be made.

2.2.4 Interpretation. Interpretation uses the results to determine which options are acceptable and is related to the goal of the study. As LCA is an iterative process, revisiting assumptions and adjusting for new information is common in order to provide the best results.

2.3 Data collection

The design calculations of the two alternative solutions are used as basis for the LCI, considering concrete and steel consumption. Longitudinal steel reinforcement, steel fibers and concrete in beams, decks and columns are evaluated. The foundations and railings are assumed to be the same for both solutions, hence not included in the comparative analysis. Data for the different processes are collected from Ecoinvent version 3.1 [23] as contained in SimaPro version 8.1. However, some processes are not given in SimaPro and therefore Environmental Product Declarations (EPD) are considered to be sufficient as input in the model. For this study, a European EPD for the accelerator in the UHPC mix had to be used [24]. Due to lack of concrete classes in SimaPro, 32 MPa concrete is used for the C30/37. The UHPC is built up in SimaPro based on the different components in the mixture. The steel fibers in the UHPC premix are taken as normal reinforcing steel in SimaPro. The impact assessment is carried out according the the ReCiPe 2008 methodology, based on the European Hierarchical definition method [25]. The impact assessment calculations are carried out using SimaPro version 8.1.

2.4 System description

This study evaluates the material production and construction phases for the two alternatives. The material production phase takes into account the extraction of raw materials and distribution. Only production of the different concrete types and its constituents and steel are considered as they are the dominant contributors in this phase. Prebagged UHPC is transported from France to Norway, as it is not produced in Norway for commercial use. At the concrete mixing plant, high-range water-reducing admixture (HRWR), accelerator, steel fibers and water are added in the UHPC dry-mix and mixed together. Due to the low water-binder ratio of UHPC the mixing process is longer. According to Habert et al. [16], the mixing time is 20 times longer than for normal concrete. This has been taken into account by adding a factor of 20. UHPC is often steam-cured at high temperatures (90°C) over 48 hours to achieve improved properties such as higher strength, lower creep and higher resistance to chloride ion penetration. For in-situ production of UHPC, steam curing is not relevant. It is taken into account that creep is larger with no curing treatment according to AFGC recommendations [19]. All types of steel reinforcement, including steel fibers, are assumed to be transported from China to location in Norway, which is a common practice. Transportation in this phase is considered to be the distance from extracting of raw materials to ready-mix plant nearby Arendal. The construction phase in this study only includes transportation of materials from the different production locations to the construction site: transport of concrete from the mixing plant to construction site, in addition to transportation of steel from production facility in China. As a simplification, earthworks and formworks are estimated to be equal for both alternatives. Although construction machinery and electricity used in construction process may be different for UHPC compared to normal concrete, it is not included in this study. The maintenance phase is not directly taken into account. In order to be able to determine environmental impact during the life cycle of the bridges, the lifetime of UHPC is considered to be at least two times longer than for normal strength concrete [10]. The Norwegian Public Road Authority sets the service-life for bridges to 100 years [26]. Consequently, we assume that the lifetime of an UHPC bridge is 200 years, i.e. to attain the same function – which is to cross a 4-lane highway – for one UHPC bridge it requires two NSC bridges. End-of-life phase is not evaluated, as a result of large uncertainties associated with demolition, recycling rate, energy use etc. after 200 years.

3. Results

3.1 Design calculation results

SLS is governing for both alternatives. The high Young's modulus and low creep properties of the UHPC have positive effects on the deformation, which is the governing reason why a considerably smaller cross-section is obtained for UHPC than for NSC. Several mechanisms contribute to this; the reduced requirements for concrete cover allowed by the high degrading resistance, the negligible need of shear reinforcement, and reduced spacing between reinforcement bars due to the absence of large particles in UHPC. Consequently, the total amount of concrete used in the UHPC alternative is reduced by 36.7% compared to the NSC alternative. The designs of these cross-sections are shown in Figure 3.

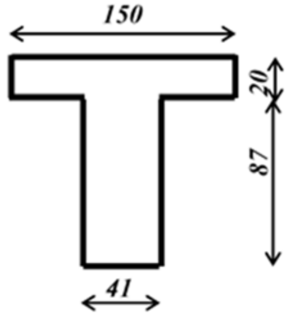
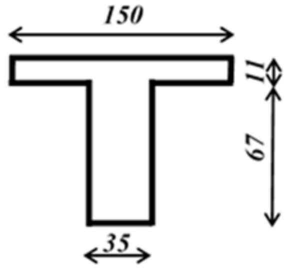
NSC cross-section	UHPC cross-section
	
$A_c = 1.25\ m^2$ $A_s = 15{,}39\ mm^2$	$A_c = 0.80\ m^2$ $A_s = 15{,}39\ mm^2$

Figure 3. Cross-sectional data for normal strength concrete alternative and ultra high performance concrete alternative.

3.2 Life cycle inventory analysis
The material inventory for each alternative is shown in Table 2 below. It is important to note that the NSC alternative inventory is for one bridge only, not two NSC bridges as required by the defined functional unit.

Table 2. Material consumption and transport per bridge.

Process	Unit	NSC bridge	UHPC bridge
Concrete, C30/37	m^3	51.00	-
Concrete, UHPC	m^3	-	32.30
Accelerator	t	-	0.97
Cement, Portland	t	17.52	23.00
Gravel, round	t	48.97	-
Plasticizer	t	-	0.99
Sand	t	43.81	32.95
Silica fume, recycled	t	-	7.46
Silica sand	t	-	6.82
Tap water	t	10.55	4.32
Reinforcing steel	t	9.81	9.72
Steel fiber	t	-	5.04
Transport, lorry 16-32 t	k-tkm	1.28	38.82
Transport, tr.oc. tanker	k-tkm	-	54.01

The NSC alternative is shown to consume more concrete per bridge but less cement per bridge than the UHPC alternative. The lifetime consumption of cement for the NSC bridge, however, is 52% greater than the UHPC bridge. The UHPC bridge requires slightly less reinforcing steel than an NSC bridge, but 33% less steel in the lifetime (when including steel fibers in the UHPC bridge) of two NSC bridges due to the greater bearing capacity of UHPC. The NSC bridge has higher lifetime material consumption for all materials that are used in both bridges. The UHPC bridge utilizes some materials that are not used in the NSC bridge, such as accelerators, plasticizers, silica sand and fume, and steel fiber. Transport for the UHPC materials, however, is much greater than the NSC bridge due to the transportation of UHPC from France.

3.3 Impact assessment
In the impact assessment of the study, the UHPC alternative is found to have lower emissions in all impact categories studied, as shown in Figure 4.

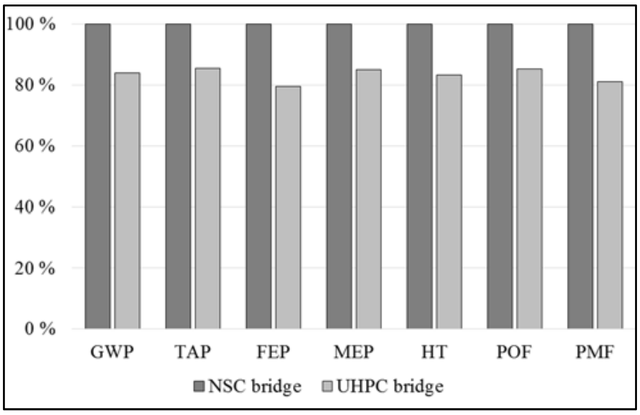


Figure 4. Normalized impact assessment results for all impact categories studied. (Global warming potential (GWP), Terrestrial acidification potential (TAP), Freshwater eutrophication (FEP), Marine eutrophication (MEP), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF).

Figure 4 shows the normalized impact assessment results for both alternatives. Impacts of the UHPC alternative are lowest in all categories over the 200-year lifetime of the study. Global warming potential (GWP) results show that the UHPC alternative has 84% of the emissions. UHPC alternative ranged from 79-86% of the total emissions compared to the NSC alternative.

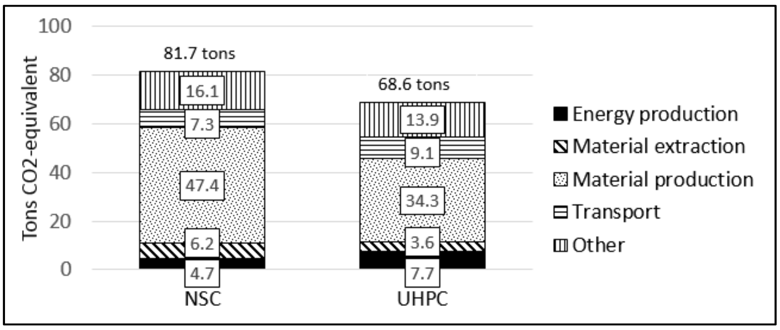


Figure 5. Contribution analysis to overall global warming potential (GWP), expressed in tons CO_2 equivalents.

Figure 5 shows the contribution of the main life cycle phases to the overall GWP, expressed in tons CO_2 equivalent over the lifetime of each alternative. The total lifetime CO_2 equivalent emissions of the NSC alternative are 81.7 tons, while the UHPC alternative is 68.6 tons. Material production is the largest contributor to CO_2 equivalent emissions for both alternatives, at 58% of total emissions for the NSC alternative versus 50% of total emissions for the UHPC alternative. The largest contributor to material production for the NSC alternative is the production of cement at 26.7 tons followed by steel components at 12.4 tons. The largest contributor to material production for the UHPC **alternative** is also cement, at 17.7 tons while steel components at 9.4 tons.

4. Discussion

The main results of the research show some possible environmental and design viability of utilizing UHPC in pedestrian bridges. The overall lower impacts of the UHPC alternative over the 200-year time period proved to be much lower than for the NSC alternative. This indicates that the best option from an environmental perspective is to choose the UHPC alternative. The results of this study, however, must be critically assessed in terms of methodological choices related to functional unit choice and life cycle phases, the uncertainty regarding future material production emissions, and the limitations of the standard T-beam bridge design in a comparative analysis.

4.1 The lifetime aspect

The functional unit of this study uses a 200-year time period and assumes that the UHPC alternative will remain standing over the entire period. This is due to the mechanical strength and durability of UHPC allowing for a far longer lifetime than standard NSC bridges. Implementing a shorter time period for the functional unit would affect the outcome for which alternative should be chosen and challenge the assumptions of this study. The UHPC alternative has higher emissions compared to a single NSC bridge given today's production technology and that this study has assumed two NSC bridges are required to produce the same function as one UHPC bridge. This methodological choice does not attempt to predict future production technologies and does not address the uncertainty of a 200-year use period for the UHPC bridge.

In a study from 2016, Thorstensen et al. [17] investigated CO_2 emissions from corresponding considerations between two foot-bridge alternatives (NSC and UHPC respectively). Effects from local production of UHPC and also necessary maintenance measures were included. The life-time was set to 100 years, and hence only one construction was included in each alternative. This investigation concluded that CO_2 emissions from the UHPC alternative would be approximately 90% of that of the NSC alternative.

4.2 System boundaries

The system boundaries defined in the study did not include some processes that have impacts. Most prominently, maintenance for the bridges were not included. The Norwegian Public Road Administration assumes that a bridge design will last for a 100-year time period before being demolished [27]. The uncertainty of future maintenance 100 or even 200 years into the future is difficult to model and the methods for maintenance are varied depending on climate, use and construction materials used. As the UHPC alternative is considered to be maintenance free, the effect of not including maintenance in this study is not predicted to influence the conclusions from this study as maintenance emissions for the UHPC alternative would be lower regardless. Other processes not included are concrete formwork and other temporary structures in construction, which would be very similar between the two alternatives thereby not providing useful information to decision makers. Additionally, shear reinforcement was not taken into consideration in this study, although it assumed that the UHPC alternative will use less shear reinforcement than the NSC alternative, with lower emissions in the UHPC alternative as a result.

4.3 Material production and use

Both the UHPC and NSC used in this project, assumes production under French conditions. The assumption of French production is based on the lack of Norwegian UHPC production. This leads to high transportation emissions. The highest emissions in both alternatives came from the material production phase, while the highest emitting material was cement used in both NSC and UHPC. NSC is assumed to be mixed in Norway. Comparing **our** results to other studies show that the UHPC production is relatively similar [14, 15] with the exception of Habert et al. [16], who implemented a UHPC mixture with 5 times as much steel fiber and double amount of cement, compared to the UHPC used in this study. There is a trend towards developing UHPC with less cement, hence lowering the CO_2 consequences [2]. Future production technologies that are less emission intensive, particularly with respect to cement and steel production will most certainly influence results for both alternatives.

4.4 Structural design

The structural design of the two alternatives resulted in two highly efficient cross-section designs and the utilization was the same for both alternatives. It is possible to construct a very large bridge span with UHPC due to the potential weight reduction, and because of the potential for use of pretensioned reinforcement, allowed by the high compressive strength of UHPC.

4.5 Further work
Currently, there are no bridges in Norway built in UHPC. This highlight both a lack of research and a lack of implementation from authorities. Further research should both expand on elemental knowledge of useful UHPC designs while also accounting for the environmental impacts of these designs as they may not yield the same comparative results. Additional designs should be considered for their viability and to showcase the versatility of UHPC. Designs that implement pretension and designs that have even longer spans utilizing UHPC are possible. Research on additional bridge designs in UHPC should be prioritized. Additional design improvements from the implementation of prefabricated elements and heat treatment will also allow for more control in the production process further highlighting the advantages of UHPC. Heat treatment allows for less creep and higher strength, thus should be included in future studies. To what extent local factors and local systems processes can influence the environmental profile of UHPC is unknown as UHPC is not currently produced in Norway. Research that promotes the development of commercial viability of UHPC production under Norwegian conditions should be undertaken. LCA studies that are based on potential production of UHPC under Norwegian conditions should also be done to determine if there are environmental benefits to domestic production. Development of design codes for UHPC, development of new UHPC compositions with reduced environmental footprints, and erection of industrial showcases demonstrating economic benefits, are necessary preconditions for widespread use.

5. Conclusion
This study shows some possible viability of UHPC footbridge designs. The environmental advantages of implementing UHPC as a construction material for bearing structures which are designed for long service life are shown to be large enough to call for further research on additional structure types, production methods, and to find further uses of UHPC.

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