



Med stöd från:



<i>Project title</i>	UHPC as maintenance and repair material for enhanced durability of transport infrastructures
<i>Project number</i>	2016-03301
<i>Duration</i>	2017-10-01 to 2019-09-30
<i>Deliverable no.</i>	D5.1
<i>Deliverable title</i>	Life Cycle Assessment and Life Cycle Cost report
<i>Date of delivery</i>	2020-09-30
<i>Responsible</i>	CBI
<i>Involved partners</i>	CBI, LTU
<i>Level of Dissem.</i>	Confidential

Contents

1	Introduction	4
2	Method	5
2.1	Compared materials and methods.....	5
2.1.1	Mix proportions and case study.....	5
2.1.2	Method for comparison.....	6
2.2	Life cycle assessment	6
2.3	Life cycle cost assessment.....	7
3	Life cycle assessment	9
3.1	Goal and scope	9
3.1.1	Functional unit.....	9
3.1.2	System boundary	9
3.1.3	Data quality	9
3.1.4	Allocation	9
3.1.5	Assumptions and limitations	9
3.2	Inventory	10
3.2.1	Production and transport to building site	10
3.2.2	Repair	10
3.3	Impact assessment	11
3.3.1	GWP of production and transport of 1 m ³ of concrete.....	11
3.3.2	GWP of production and transport of 1 m ² of concrete.....	13
3.3.3	GWP of repair	14
4	Life cycle cost assessment.....	15
4.1	System boundary	15
4.1.1	Limitations.....	15
4.2	Cost inventory	15
4.2.1	Raw materials	15
4.2.2	Production costs.....	15
4.2.3	Transport costs	16
4.2.4	Repair costs	16
4.3	Life cycle costs.....	16
4.3.1	Costs during production	16
4.3.2	Costs for concrete cover	17
4.3.3	Considering repair costs.....	18
6	Discussion.....	20

7	Conclusion	21
8	References.....	22

1 INTRODUCTION

The majority of the bridges in Sweden are made of concrete and have an average age of 47 years. This means that there are many bridges with a need for repair. Usually the normal concrete for bridges is based on CEM I cement and has a water-to-cement ratio of 0.45 and a compressive strength at 50 MPa. When the concrete deteriorates the normal repair procedure is to remove the old concrete, remediate the reinforcement and add a new concrete layer with the same type of properties and in some cases also a hydrophobic layer. It's a costly procedure with an inadequate long-term effect (Hassanzadeh 20014, ACI Committee 546 2006 and Krauss et al. 2009).

To reduce the environmental impact of bridges during the use stage there are different approaches to apply. One way is an efficient use of resources by reducing the total clinker content in the concrete mix. This can be achieved for example by replacing part of the CEM I with supplementary cementitious materials (SCM) from industrial waste products such as fly ash (FA) and ground-granulated blast furnace slag (GGBS). Another way is by increasing the durability of the structure and thereby extending the service life and reducing the need for repair and replacement. In Müller et al. (2014)] it is proposed that the sustainability potential of a concrete structure should be defined as the relationship between the lifetime performance and the environmental impact. According to this definition the authors suggest three approaches to enhance the sustainability: 1) lowering the environmental impact of the concrete mix; 2) improving the concrete performance, i.e. reduction of cross-section of members through high load bearing capacity and 3) by extending the life span of the material and the structure. By reducing the need for repair and replacement there can be a significant reduction in environmental impact over the life span of a construction.

Ultra-high performance concrete (UHPC) is an alternative solution which is rapidly spreading around the world to repair and strengthen concrete structures [8-10]. It has a high compressive strength and durability. In order to achieve these preferred properties a large amount of cement is needed. This in turn might not seem like a sustainable solution since CEM I cement has an approximate climate impact of 800-900 kg CO₂-eq/kg cement. However, if the amount of concrete needed for the structure could be reduced and the durability increased then there is a good possibility to reduce the climate impact. A reduced need for repair is also in line with the EU waste hierarchy where avoided waste is the top solution.

There are few studies on the climate impact of UHPC as a repair material. Most of the studies are based on constructing a new bridge. In a study by Habert et al. (2012) the environmental consequence by increasing the strength of concrete was analyzed. The authors used UHPC to construct a whole bridge, hypothetically. The bridge could be made slimmer and the authors concluded that that choosing a high-performance bridge construction solution to cross a four lane divided highway with a two-lane road is always more environmentally friendly than a traditional concrete bridge solution. A 50% reduction in greenhouse gas emissions for production of the building materials used in the bridge was obtained and a significant decrease could also be made when considering the service life.

The aim of WP5, Life Cycle Assessment (LCA) and Life Cycle Cost (LCC), is to evaluate the climate impact and cost efficiency associated to the newly developed method within the project. A cradle-to-gate perspective is used to reflect the repair/strengthening material as an individual material but also to assess its impact on the life of an existing structure.

2 METHOD

2.1 Compared materials and methods

2.1.1 Mix proportions and case study

The concrete mixes chosen for this study are described in Table 1. Two climate optimized UHPC mixes developed within this projects, CBI FA (here called UHPC 1) and LTU 8 (here called UHPC 2), are compared with a traditional UHPC mix and a conventional concrete for bridges (here called traditional concrete). The two developed UHPC formulas contain a lower amount of cement clinker and more cementitious waste materials such as fly ash and silica fuel but also limestone filler compared to the reference UHPC. In addition, steel fibers are added to reduce autogenous shrinkage. The traditional concrete contains only CEM I as a binder and it also contains air entraining agent for frost resistance. The concrete mix for the traditional concrete is based on an Environmental product declaration (EPD) of Betongindustri's infrastructure concrete called FrostBI (EPD no. NEPD-1711-695-SE). There might be a slight difference between a repair concrete and a concrete for new construction as the former might contain more polymers and thus be more expensive and less environmentally friendly. By choosing a concrete for new structures the comparative cost and environmental impacts for UHPC are not underestimated.

Table 1. Mix proportions of chosen concrete types.

Mix design (kg/m ³)	UHPC ref	UHPC 1 (CBI FA)	UHPC 2 (LTU 8)	Traditional concrete (C34/45)
CEM I 42,5 N - SR 3 MH/LA	960	550	664	420
Fly ash		400		
Silica fume	190	100	133	
Limestone filler			664	
Quartz filler	285		66	
Steel fibers		179	166	
Aggregates	670	1150	465	1780
Superplasticizer	30	25	34	3
Air entrainment				1,5
Water	210	140	184	170
Properties				
w/c (-)	0,238	0,282	0,308	0,400
w/b (-)	0,198	0,148	0,257	0,400
Density (kg/m ³)	2345	2544	2377	2369
Compressive strenght (MPa)	138	135	130	45

The structure which the cover thickness is applied on is a circular bridge pier with a diameter of 1 m and a length of 6 m. The pier is supporting a bridge over a highway and is therefore subjected to frost and deicing salt which comes from the moving cars. The corresponding exposure class is therefore XD3/XF4 and the exposure class is chosen accordingly.

The cover thickness used in this study are described in Table 2. The tolerances have been included in a sensitivity analysis.

Table 2. Cover thickness for a design service life of 100 years (corresponding 120 years according to Swedish Transport Administration).

	UHPC	Traditional concrete
Cover thickness (mm)	20	50
Cover thickness with tolerance (mm)	30	70

2.1.2 Method for comparison

The chosen mix designs in Table 1 are evaluated by comparing the GWP and costs based on the following:

- Production of one cubic meter of fresh concrete.
- Replacement of cover thickness based on regulations and recommendations in order to achieve the same design service life.

This will be done through an LCA and LCC as described in the next sections (2.2 and 2.3).

2.2 Life cycle assessment

LCA is a systematic approach to assess the inputs and outputs of a product system throughout the whole life cycle. LCA can be prepared in several methods. The one chosen in this project is an attributional LCA focusing on global warming potential, which is expressed as kg CO₂-eq. The method follows ISO 14040 and EN 15804, but with one chosen indicator. The ISO standard describes the LCA in the following 4 steps (Figure 1). The two direction arrows indicate that the assessment is an iterative process where the LCA is updated when new information has been received.

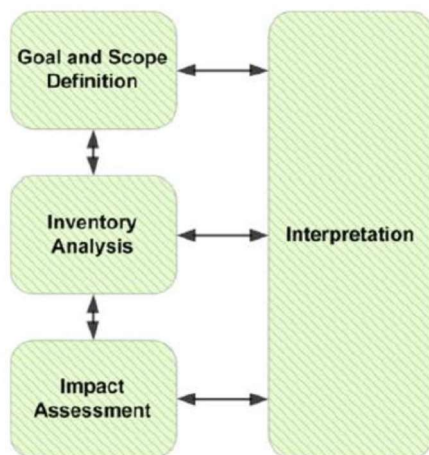


Figure 1. Steps in an LCA according to ISO 14040:2006.

EN 15804 in turn describes an attributional method for developing environmental product declarations (EPD) for construction works. It contains core LCA rules and a modular division of life-cycle stages together with chosen environmental indicators. Table 3 shows the modules in EN 15804.

Table 3. Life-cycle stages divided into modules according to EN 15804.

LIFE-CYCLE INFORMATION															
Production stage			Construction process stage		Use stage							End-of-life stage			
Raw materials	Transport	Manufacturing	Transport to construction site	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational water use	Demolition	Transport	Waste processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4

The core rules of EN 15804 enables for a comparison between building products and can be used to put together EPDs for evaluating the environmental impact of a new product. This is what has been done in this deliverable. EPDs published through an EPD system have always been verified by a third-party expert and can be considered as reliable data.

2.3 Life cycle cost assessment

The cost analysis has been carried out by calculating the costs for producing one cubic meter of concrete and the net present cost, NPC, in accordance with SS-ISO 15686-5:2008. NPC is a sum of future costs discounted to the present value. It can be calculated using equation (1):

$$NPC = \sum_{n=1}^p \frac{c_n}{(1+d)^n} \quad (1)$$

Where,

C is the cost in year n;

d is the expected real discount rate per annum;

n is the number of years between the base date and the occurrence of the cost;

p is the period of analysis.

The NPC is used when time becomes a parameter in the analysis, which is the case when future repair is taken into consideration.

The discount rate chosen for this study is 3,5 % which is based on the guidelines of the Swedish transport administration (STA). To include the influence of different discount rates a sensitivity analysis has been performed for a discount rate varying from 1% to 5%.

Material prices are based on Swedish market prices for the last 5 years and on information from industry. All prices are expressed in Swedish Krona (SEK). On 23 September 2020 EUR 1 corresponded SEK 10.4388 (European central bank 2020).

3 LIFE CYCLE ASSESSMENT

3.1 Goal and scope

3.1.1 Functional unit

Two units are used for comparison between the concrete alternatives:

- 1 m³ of fresh concrete which can be used for the exposure classes XD3 and XF4.
- 1 m² of concrete cover on a bridge pier with exposure classes XD3 and XF4 and a design service life of 100 years.

3.1.2 System boundary

The analysis covers the production stage, transport to building site and the repair which could also be called as a replacement of concrete cover. In EN 15804 this can be translated to the modules A1-A4 and B3. The LCA is based on Swedish conditions unless no other data can be found. In that case data is chosen based on the same technology and similar conditions as in Sweden. A service life of 100 years is chosen based on requirements from STA. According to STA a 100-year design service life can be assumed to last for 120 years.

3.1.3 Data quality

In first-hand, specific data from EPDs are used which are valid and third party verified. When no specific data can be found the ecoinvent version 3.1 (Wernet et al. 2016) database is used where the datasets are modified for Swedish conditions. This is the case for the aggregates and tap water, where ecoinvent data was modified in order to fit the Swedish conditions with electricity and energy use. For the district heating, the mix was based on information from Svensk Fjärrvärme and put together using ecoinvent data.

Most of the environmental product declarations (EPD) that are gathered are not older than 5 years. Generic datasets are not older than 10 years.

In case of data gaps, an allowable limit for exclusion of inputs and outputs is maximum 5 % of the total energy use and mass.

3.1.4 Allocation

The by-products fly ash and silica fume have a revenue which is less than 1 % of the total revenue compared to the main products as of first half year of 2020. This means that no environmental burdens are allocated to fly ash and silica fume in accordance to EN 15804.

3.1.5 Assumptions and limitations

It is assumed that the reinforcement does not need to be replaced during a concrete repair. It will only need to be cleaned. The concrete cover is repaired by removal and adding a new cover. It can be assumed that the work and preparations which is needed to repair the cover is the same for both UHPC and traditional concrete. In that case it will not be necessary for comparison.

3.2 Inventory

3.2.1 Production and transport to building site

Due to lack of information, it is assumed that the energy use at the concrete factory is the same for both UHPC and traditional normal concrete. The energy use is based on Al-Ayish et al. (2018) where the electricity use is 18 kWh/m³ and the heating, which comes from district heating, is 15 kWh/m³. The factory is assumed to be located in the Stockholm area. Aggregates for traditional concrete have a short transport distance and is in this study set at 40 km. For the UHPC special types of aggregates are used which have a longer transport distance. All other transport distances are based on actual plants from the used products. Table 4 presents the resources which are used in this study.

As previously mentioned in section 3.1.4, Fly ash and silica fume are low-revenue by-products and will therefore have no burden allocated to them from the production of the primary product.

Table 4. Environmental data for different materials, energy and transport types.

Resources	Reference	Gate
CEM I 42,5 N - SR 3 MH/LA	EPD-HCG-20190047-CAA1-EN	Slite, Sweden
Aggregates	Ecoinvent 3.1	40 km
Aggregates for UHPC (Baskarpsand)	Ecoinvent 3.1	Baskarp, Sweden
Tap water	Ecoinvent 3.1	
Superplasticizer	EPD-EFC-20150091-IAG1-EN	Spånga, Sweden
Air entrainer	EPD-EFC-20150086-IAG1-EN	Spånga, Sweden
Fly ash	Waste product with low revenue	Rotterdam, Netherlands
Silica fume	Waste product with low revenue	Kristiansand, Norway
Limestone filler	RISE internal	Köping, Sweden
Steel fibers	NEPD-1383-447-NO	Zwevegem, Belgium
Electricity, Swedish mix	Ecoinvent 3.1	
District heating	Svensk fjärrvärme (2014)	
Truck, 40 tonne	NTM	
Concrete truck, 6m ³	RISE internal	

3.2.2 Repair

The energy use for concrete repair processes has been chosen from Årskog, Fossdal and Gjørnv (2004) [11]. Table 5 shows the energy use and associated climate impact per square meter of surface of the different steps in patch repair. In the study, the energy supply at the construction site is based on diesel engines. The study describes briefly the assumptions and the method and in order to have reliable data more research is needed.

Table 5 Energy use and climate impact of repair processes (Årskog, Fossdal and Gjørnv, 2004).

Process	Energy use [MJ/m ²]	GWP [kg CO ₂ -eq/m ²]
Hydro jetting	677	84
Cleaning of reinforcement	296	22
Protective coating of reinforcement	35	1,4
Application of shotcrete	59	4,4
Transportation	127	10
Total	1194	122

3.3 Impact assessment

3.3.1 GWP of production and transport of 1 m³ of concrete

When considering only the raw material production and transport of raw materials to concrete plants the climate impact is, as expected, higher for the UHPC concrete due to the larger amount of cement clinker used. Since the cement replacing materials have a low embodied climate impact the reduction will be noticeable. Figure 2 shows the GWP in kg CO₂-eq per cubic meter of fresh concrete. It can be noted that the UHPC 1 and UHPC 2 have a significantly lower impact than the reference UHPC, for the same performance. However, steel fibers, which are used for reducing shrinkage, have a remarkable contribution and without those the GWP could be reduced by 40 % of the UHPC reference, coming closer to the impact of the reference concrete.

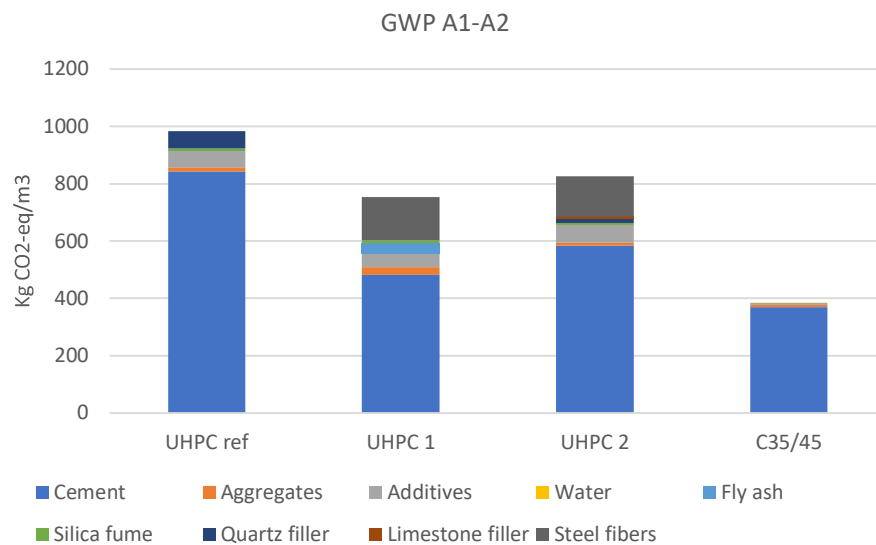


Figure 2 Climate impact of the concrete mixes during raw material production and transport to concrete plant.

Figure 3 shows the climate impact when considering also the energy use at concrete plant and transport to construction site. It can be noted that the raw materials have the highest contribution, although transport to factory cannot be neglected. The other life cycle stages, factory activities and transport to building site, have a much lower contribution in comparison.

Regarding the transport distances for UHPC, the biggest influences on the GWP are the distances of the special aggregates, fly ash, silica fume and steel fibers. The contribution of the transport of fly ash is notable in UHPC 1.

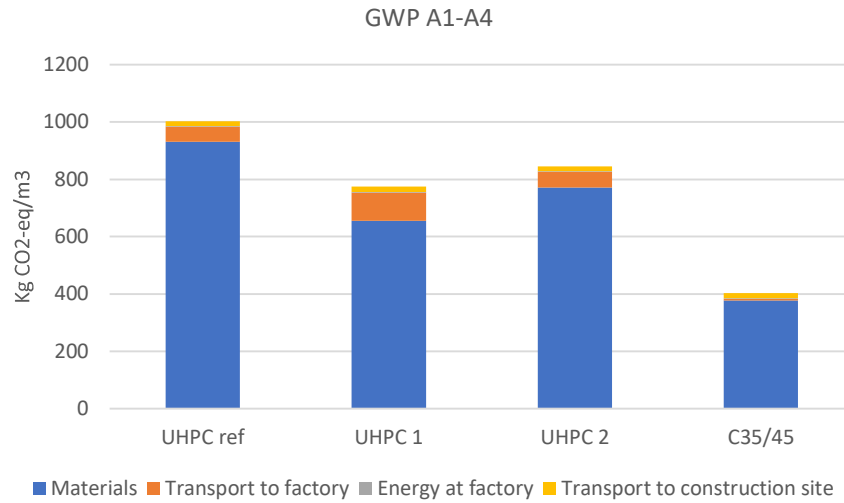


Figure 3. Climate impact of chosen concrete mixes from production and transport to building site.

3.3.1.1 ANALYSIS WITHOUT FIBERS

The previous LCA of the production stage highlighted the significance of the steel fibers. An additional analysis was therefore performed in order to investigate the potential of the concrete types without fibers where the shrinkage is dealt with through an alternative approach. Figure 4 a) shows the material related climate impact of the concrete types without fibers while Figure 4 b) shows the climate impact during production and transport to factory. It shows that the UHPC 1 has a 50 % higher GWP than C 35/45 compared to the previous 94 % when A1-A4 is considered.

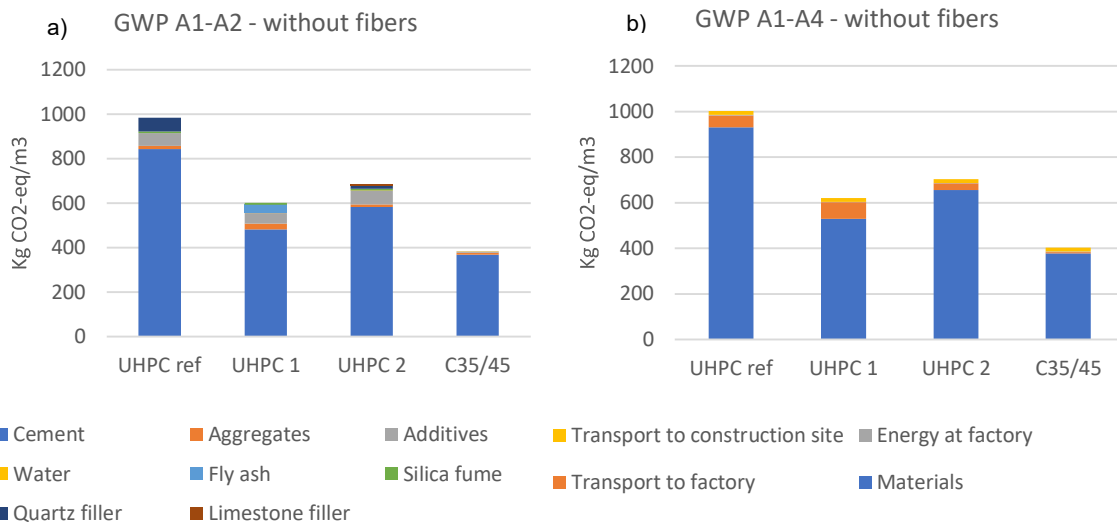


Figure 4. Climate impact of concrete mixes without fibers during a) A1-A2 raw materials and transport and b) A1-A4 production and transport to construction site.

3.3.2 GWP of production and transport of 1 m² of concrete

The first step of the analysis was to investigate whether the concrete mix of UHPC was climate optimised and how it could be further optimised. In this step the application of the concrete is considered in order to understand if the amounts used are enough to compensate for the higher climate impact of 1 m³ of concrete. In Table 2 the cover thicknesses for XD3/XF4 in order to get a service life of 100 years was shown. When applying those cover thicknesses in the analysis it can be noted that the UHPC alternatives have a lower impact than the traditional C 35/45 concrete (Figure 5). Especially the UHPC 1 which has a 32 % lower impact.

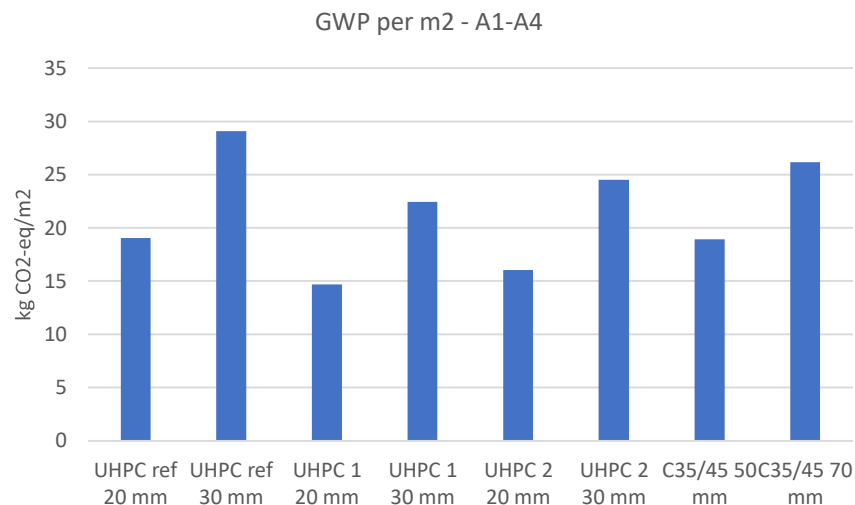


Figure 5. Climate impact of concrete cover with the chosen mixes during production and transport to construction site.

3.3.2.1 ANALYSIS WITHOUT FIBERS

Without fibers the environmental gain is higher where UHPC 1 shows a decrease by 38 % compared to C35/45 (Figure 6).

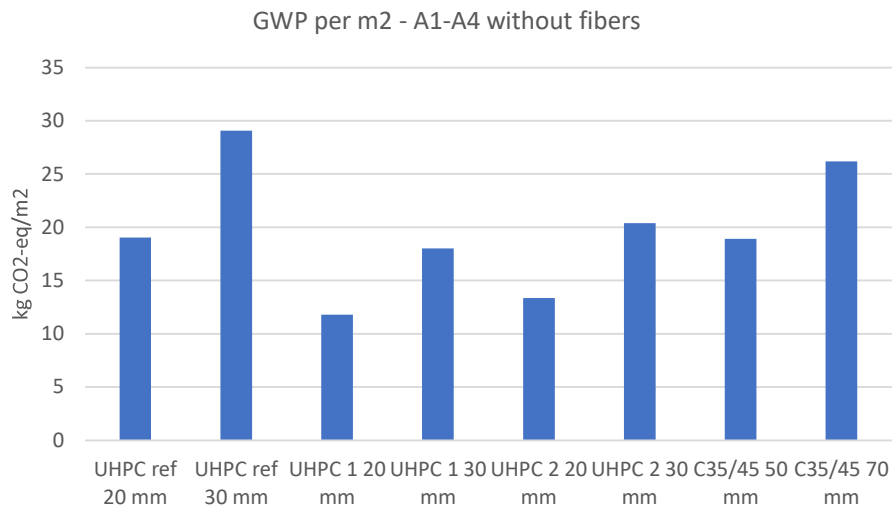


Figure 6. Climate impact of for concrete cover without fibers.

3.3.3 GWP of repair

When considering the repair, it can be noticed that the material itself does not have the highest climate impact (

Figure 7). Most of the energy consumption is due to hydro jetting which is run on diesel. In this case, based on the study by Årskog, Fossdal and Gjørsv (2004), the reduction in climate impact for avoiding a repair by using UHPC has a greater benefit than the direct emissions from the concrete itself. This indicates that the durability of the concrete cannot be neglected in an LCA analysis. The figures are valid for an average repair depth of 50 mm which is in line with the current study.

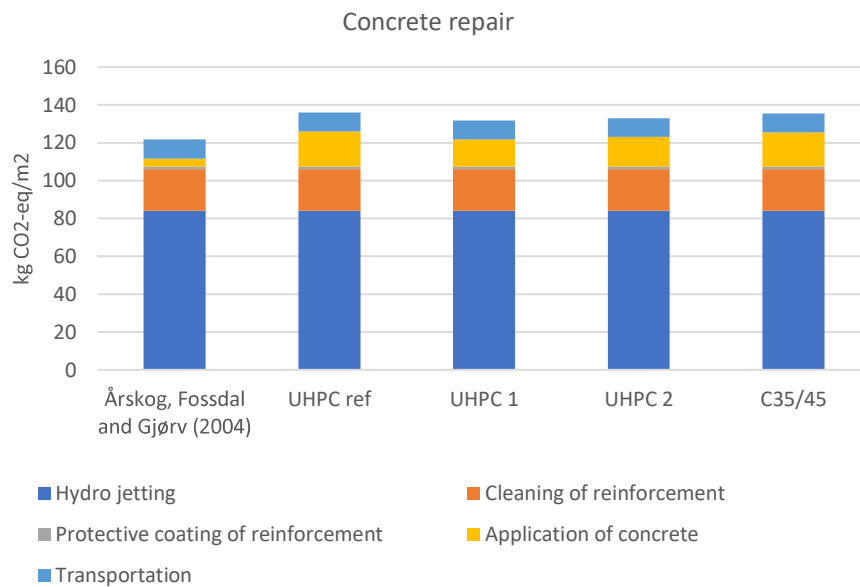


Figure 7. Climate impact of repairing a 50 mm cover.

4 LIFE CYCLE COST ASSESSMENT

4.1 System boundary

The cost analysis is based on Swedish conditions and includes material and repair costs. As this is a comparative analysis the exact figures of all life cycle stages might not be necessary if the costs are equal for all concrete types. This is for example the case for “other costs” during production.

4.1.1 Limitations

This study is limited to Swedish geographical boundary and to the estimated average repair costs by STA. It does not include user and societal costs due to traffic disturbance and accidents indirectly caused by the repair activities. Additionally, the analysis is made on 1 m² of repair area. The total area which needs a repair might vary and is therefore not included in this study.

4.2 Cost inventory

A cost inventory has been performed for raw materials, production and repair.

4.2.1 Raw materials

The costs for raw materials have been gathered through RISE contacts which are confidential. The data for steel fibers however is based on price information from Bekaert and Wikells (2016).

The costs in Table 6 are valid for the Swedish market and are a “purchasing price”.

Table 6. Costs for materials for concrete.

Material	Price (SEK/unit)	Unit	Reference
CEM I (anläggning)	1100	tonne	RISE internal
Fly ash, incl transport	1300	tonne	RISE internal
Silica fume	4000	tonne	RISE internal
Limestone filler	325	tonne	RISE internal
Quartz filler	4300	tonne	RISE internal
Steel fibers, default	30	kg	Bekaert
Steel fibers, alternative	19	kg	Wikells 2016
Aggregates	100	tonne	RISE internal
Admixtures	25000-30000	tonne	RISE internal

4.2.2 Production costs

The cost estimation in this study was based on material costs only. For the purpose of comparing concrete types it can be assumed that all types have the same additional costs such as energy, labor and profit. Based on the market price of concrete (1500 SEK/m³ for C35/45) from sektionsfakta (Wikells 2016) and material prices listed above, the other costs could be estimated at around 750 SEK/m³.

4.2.3 Transport costs

Transport costs have not been considered.

4.2.4 Repair costs

According to a STA calculation, the average repair cost for a pier with a repair depth at 30 to 70 mm is 10300 SEK/m². This cost does not include traffic disturbance and societal costs. This cost is valid for traditional concrete. If UHPC would be used, then the additional cost for materials needs to be added.

It is quite complicated to estimate the repair cost of a bridge pier as more information would be needed such as how big area which needs to be repaired and the extent of the damage. Additionally, it is the owner who decides when a repair needs to be made and what type of repair. The choice could for example be between more frequent small repairs or larger repairs or replacements further in the future.

Except for the repair cost the traffic and societal costs have a big impact on the total life cycle costs. This is, however, not included in this study.

4.3 Life cycle costs

4.3.1 Costs during production

The costs for 1 m³ of the chosen concrete types is shown in Figure 8. The steel fibers are very costly and stands for the biggest cost impact. Other large contributions are due to the additives, quartz fibers, silica fume and fly ash. Here the transport distance plays a big role.

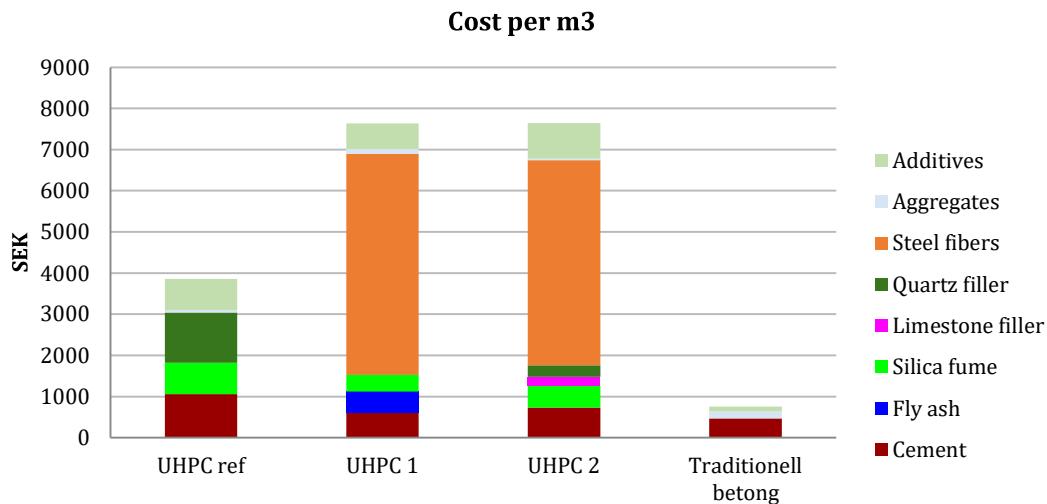


Figure 8. Material costs for producing 1 m³ of concrete.

Due to the large contribution of the steel fibers, a sensitivity analysis has been made. The costs for the steel fibers was varied from 30 SEK/kg to 19 SEK/kg (according to a reference).

In addition, a scenario where steel fibers were not used was included. The results show that UHPC 1 and UHPC 2 have the potential to be more cost efficient than a traditional UHPC if the need of steel fibers is considered (Figure 9). However, the UHPC is still more costly than traditional C35/45 concrete.

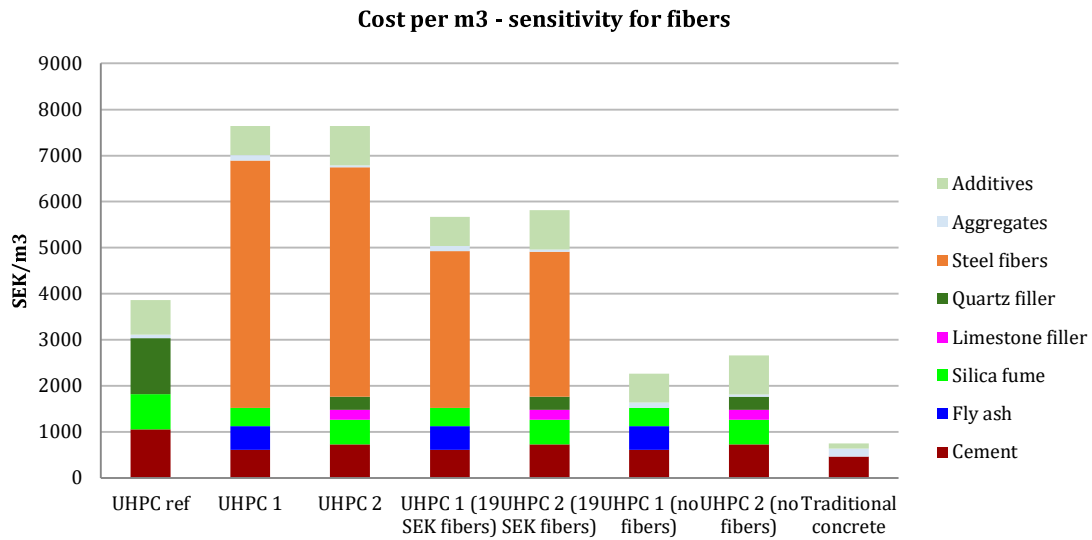


Figure 9. Material costs of 1 m³ of concrete, including a price sensitivity of steel fibers.

4.3.2 Costs for concrete cover

When considering the cover thickness needed to reach a 100-year service life the UHPC concrete is still more costly than conventional concrete. Figure 10 shows the cost per m² of concrete cover for the different concrete types.

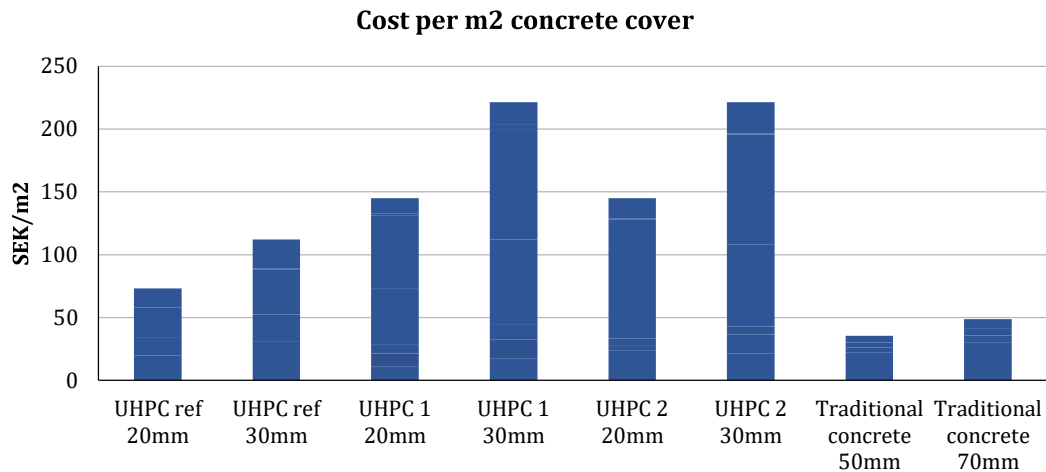


Figure 10. Costs per square meter of concrete cover for the chosen concrete types.

The hot-spots for the concrete costs are the steel fibers. An additional analysis was therefore performed to investigate the costs without fibers. Figure 11 shows the costs for each concrete for different cover depths per 1 m². It can be noted that without fibers, both developed UHPC alternatives have a lower cost than the traditional UHPC. Although the costs are still higher than for traditional concrete the figures are now quite close. This shows that there is an improvement potential for UHPC.

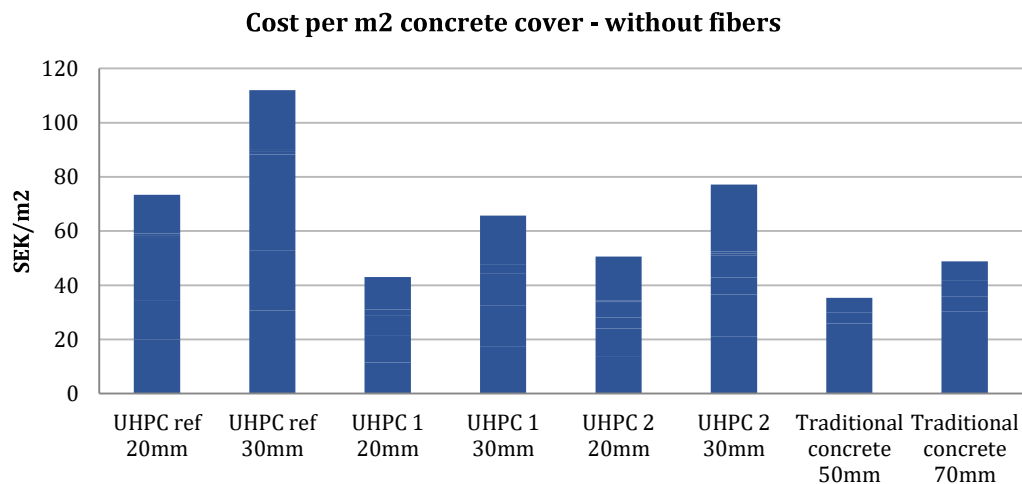


Figure 11. Costs per square meter of concrete cover without steel fibers for UHPC 1 and UHPC 2.

4.3.3 Considering repair costs

Since it is unknown when a repair might be needed the repair costs are shown in a graph which shows the NPV in relation to timing (Figure 12). The cost for repairing 1 m² of pier by using UHPC was estimated to cost an additional 110 SEK, which is equal to the difference in

material cost between UHPC and C35/45. In that case it would be beneficial to use UHPC on the following conditions:

- The UHPC cover protects the reinforcement for a longer time than the traditional concrete (preferable 100 years).
- The pier needs to be repaired within 100 years with traditional concrete.
- There are no substantial additional costs for using UHPC.

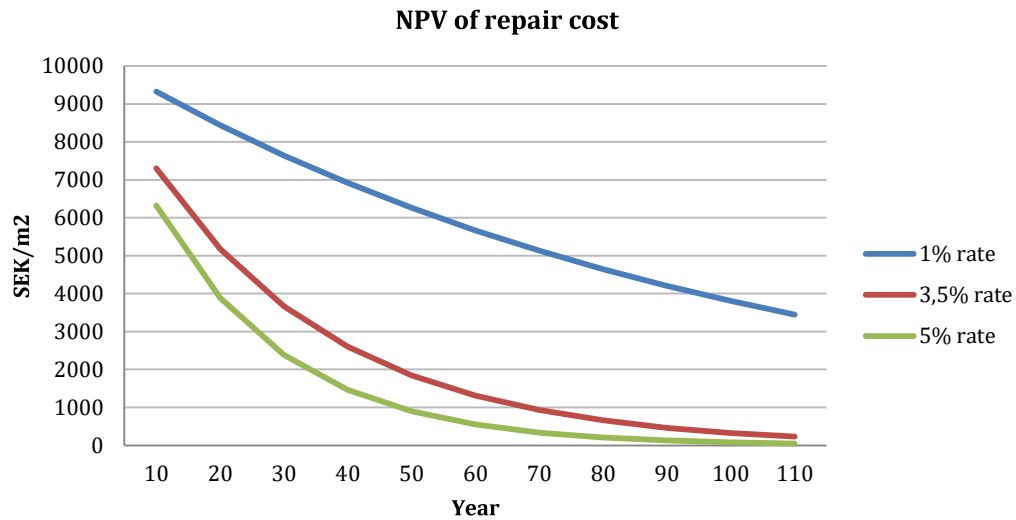


Figure 12. Net present value of a 50-70 mm concrete repair per square meter of bridge pier.

6 DISCUSSION

An LCA and LCC analysis has been carried out on two types of UHPC formulas which were developed within the project. The purpose was to evaluate the influence of the concrete types, as a repair material for bridge piers, on the greenhouse gas emissions and to evaluate the cost effectiveness on a longer perspective.

The results show that the production of UHPC has, as expected, a high climate impact and cost. This can however be reduced substantially by cement clinker replacing materials and to use steel fibers to less extent. When applied as a repair material which replaces the old concrete cover, the UHPC has a lower climate impact than a traditional C35/45 concrete due to the thinner cover thickness needed for a 100-year design service life. On a longer perspective, if assuming that the UHPC is maintenance free during the service life, the benefit is even bigger, since according to the reference, the repair activities such as hydro jetting is more energy intense than the concrete production and raw materials. The climate impact at the construction site can be reduced by using energy with low greenhouse gas emissions such as electricity from renewable sources. However, this is still indicating that having to avoid a repair by increasing the durability of the repair concrete is as important as optimizing the mix design considering embodied emissions.

Regarding the costs the results show that the production of UHPC 1 and UHPC 2 is quite expensive compared to both the traditional UHPC and the C35/45 concrete. Most of the costs are due to the addition of steel fibers which are intended to reduce autogenous shrinkage. The analysis without steel fibers and with lower purchase costs shows that the costs can actually be reduced to a value closer to the one of C35/45 concrete.

When considering the cover thickness the UHPC with steel fibers is still more expensive than the alternatives. However, the net present cost analysis shows that if the UHPC is maintenance free within the chosen time frame and the traditional repair concrete would need more frequent repairs it would be more beneficial to choose the UHPC concrete. The costs for repairing a pier is based on the Swedish average figures derived from STA and does not include user and societal impacts. If this is included the benefit of a higher durability is even greater. However, this depends on how big the repair area is and type of road. There is a greater benefit if it's a heavy traffic road.

As the analysis showed lower impacts and costs when considering the downstream impacts with repair activities it is still very important to continue reducing the upstream impacts to avoid a build-up of greenhouse gases. For future research it is therefore recommended to investigate ways to reduce the hot-spots shown in this study and to compare different repair techniques with more precision. The chosen traditional concrete for repair has a slight difference to a real case repair concrete. In a real case the concrete contains more polymers which might lead to a more expensive concrete. However, this is included in the analysis when the average pier repair cost from STA is taken into account.

7 CONCLUSION

The developed UHPC mixes (UHPC 1 and UHPC 2) showed potential in lowering the greenhouse gas emissions in the following ways:

- During production of 1 m³ of concrete due to lower clinker content compared to traditional UHPC. Additionally, further increase could be made if steel fibers could be reduced.
- Through a thinner concrete cover compared to traditional C 35/45.
- During the service life due to less repair activities needed.

Regarding the cost impacts the UHPC mixes showed a higher cost compared to the traditional C 35/45 concrete for both the production and amount needed for the cover thickness. However, the repair activities are more costly than the concrete itself and there is a benefit of using UHPC if it proved to have less need for repair compared to traditional concrete.

There is a benefit of using UHPC, especially in the longer-term, however there still potential for improvement in the production stage. The study shows that the UHPC can be an alternative as a repair material to lower the climate impact and that further research is needed in the field.

8 REFERENCES

ACI Committee 546, Guide for the selection of materials for the repair of concrete, American Concrete Institute, 2006.

Al-Ayish, N., Daring, O., Malaga, K., Silva, N., & Gudmundsson, K. (2018). The influence of supplementary cementitious materials on climate impact of concrete bridges exposed to chlorides. *Construction and Building Materials*, 188, 391-398.

Arskog, V., Fossdal, S., & Gjør, O. E. (2004, May). Life-cycle assessment of repair and maintenance systems for concrete structures. In *Proc., Int. Workshop on Sustainable Development and Concrete Technology* (pp. 193-200). Ames, IA: Iowa State University.

European central bank, website accessed September 23, 2020, https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-sek.en.html

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

Hassanzadeh, M., Reparation av Betongkonstruktioner: Skador och reparationsmetoder från 1970-talet och framåt. Reparationsbehov, forskningsbehov, effektivitet. Bidrag till project Bygginnovationen. Rapport TVBM-3176, 2014.

ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework.

Krauss, P.D., Lawler, J.S., Steiner, K.A. and Janney, W., Guidelines for selection of bridge deck overlays, sealers and treatments, National Cooperative Highway Research Program (NCHRP) Transportation Research Board of The National Academies, 2009.

Müller, H. S., Haist, M., & Vogel, M. (2014). Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime. *Construction and Building Materials*, 67, 321-337.

SS-EN 15804:2012+A2:2019 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.

SS-ISO 15686-5:2008 Buildings and constructed assets - Service-life planning - Part 5: Life-cycle costing

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8>

Wikells, S. V. (2016). 16/17 Teknisk-Ekonomisk Sammanställning Av Byggdelar (Technical and Financial Compilation of Building Parts). *Wikells Byggbäräkningar AB, Växjö, Sweden*.