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Lowering the global warming impact of bridge rehabilitations by using Ultra High Performance Fibre Reinforced Concretes

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ABSTRACT

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is characterized by a unique combination of extremely low permeability, high strength and deformability. Extensive R&D works and applications over the last 10 years have demonstrated that cast on site UHPFRC is a fast, efficient and price competitive method for the repair/rehabilitation of existing structures. More recently, an original concept of ECO-UHPFRC with a high dosage of mineral addition, a low clinker content, and a majority of local components has been applied successfully for the rehabilitation of a bridge in Slovenia. The objective of the present study is to evaluate the global warming impact of bridge rehabilitations with different types of UHPFRC and to compare them to more standard solutions, both on the basis of the bridge rehabilitation performed in Slovenia. Life Cycle Assessment (LCA) methodology is used. The analysis shows that rehabilitations with UHPFRC, and even more ECO-UHPFRC, have a lower impact than traditional methods over the life cycle.

1. Introduction

The sector of building materials is the third-largest CO_2 emitting industrial sector world-wide, as well as in the European Union. Within this sector cement, iron and steel industries are the main contributors. Actually cement production is said to represent 7% of the total anthropogenic CO_2 emissions [1–3]. Furthermore, over the past decades, the demand for natural resources has increased so much that it is now widely considered as a serious threat to our economical and social equilibrium. Associated environmental problems such as climate change, biodiversity loss, ecosystem degradation [4,5] and their impacts on economy, which could absorb up to 20% of the world Gross Domestic Product in 2050 [6], are now clearly identified. One of the key sustainability challenges for the next decades is thus to improve the management of natural resources in order to reduce current levels of anthropogenic environmental pressures.

The increasing volume of European transport urgently requires an effective road and rail system in Central and Eastern European Countries (CEEC) with a major investment need in building new structures and assessing and rehabilitating existing structures, while keeping the associated CO_2 emissions at sustainable levels. With this aim in view, advanced rehabilitation systems consuming less natural raw materials and inducing less CO_2 emissions than traditional ones while providing the same reliability, with a much longer durability, are critically needed. Following the successful achievement of R&D works in Switzerland since 1999 on application of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) for rehabilitation of bridges [7,8], a further step was achieved in EU project ARCHES to make this concept portable in every country. An original Ultra High Performance matrix formulation with a high dosage of mineral addition has been developed that makes the application of UHPFRC technology feasible with a wide range of cements and superplasticisers in various countries while minimizing transport costs of components [9]. This new material has been applied successfully to the rehabilitation of a bridge in Slovenia.

The objective of the present study is to evaluate the Global Warming Potential of bridge rehabilitations based on different types of UHPFRC and to compare them to standard solutions based on reinforced concrete and waterproofing membranes. Life Cycle Assessment (LCA) methodology based on international standards of series ISO 14040 [10] was applied for the environmental evaluation of two rehabilitation systems: (1) traditional concrete replacement (deck and curbs) and waterproofing membrane on the deck, and (2) minimized concrete removal and application of

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a thin UHPFRC layer on the full bridge surface (without any waterproofing membrane), considering two types of UHPFRC. Finally, a sensitivity analysis of the most critical parameters was performed.

2. Concept of rehabilitation with UHPFRC

Ultra-High Performance Fibre Reinforced Concretes (UHPFRCs), are characterized by a very low water/binder ratio, high powders content and an optimized fibrous reinforcement, with an extremely low permeability [11] and outstanding mechanical properties. The concept of application of UHPFRC for the rehabilitation of structural members has been proposed by Brühwiler in 1999, as an "everlasting winter coat" provided by a thin UHPFRC overlay on the bridge superstructure in zones of severe environmental and mechanical loads (exposure classes XD2, XD3) and only where worth using it. Critical steps of the construction process such as application of waterproofing membranes or compaction by vibration can be avoided, as well as the associated sources of errors. The construction process becomes simpler, faster, and more robust.

In cast-on site rehabilitation applications with thin UHPFRC overlays, a tensile strain hardening UHPFRC is required. The CEMTEC$_{\text{multiscale}}^{\circledR}$ fibrous mix based on the patented multilevel fibrous reinforcement (material level with short fibres and structural level with long fibres) developed by Rossi at LCPC [11–13] is an excellent solution to meet these needs. The optimised fibrous reinforcement of CEMTEC$_{\text{multiscale}}^{\circledR}$ provides the structural engineer with a unique combination of extremely low permeability, high strength and tensile strain hardening. Extensive R&D works performed during EU project SAMARIS [8,14] and various full scale applications in Switzerland on bridges and also on industrial floors [7,15] have demonstrated the efficiency and simplicity of cast in situ UHPFRC technology for applications of rehabilitation, using standard construction site equipment.

3. Log Čezsoški bridge rehabilitation

The Log Čezsoški bridge is located in a mountain region in the very northwest of Slovenia, close to the city of Bovec, and crosses the Soča river (Fig. 1). The bridge has only one lane and a daily traffic as it is the only link between the two sides of the river within 15 km. It is 4.5 m wide, 65 m long, over 3 spans. It has a continuous longitudinal slope of 5% (Fig. 2). The rehabilitation concept was first to remove the existing asphalt pavement, the waterproofing membrane and 3 cm of deteriorated porous mortar to reach the level of exposure of a good quality concrete. The upper surface of the bridge was then covered with a continuous UHPFRC overlay with no dry joints in order to protect the full upper face of the bridge deck, footpath and external faces of the curbs (Fig. 3a). The thickness of the UHPFRC layer maximises the efficiency of the fibrous mix and it is varied according to the challenges of the geometry to cast. The deck has a 2.5 cm UHPFRC overlay whereas the inner faces of the kerbs, the footpaths, as well as the external faces of the kerbs are covered by a 3 cm thick UHPFRC overlay.

The new ECO-UHPFRC mixes developed in the context of the ARCHES project from a majority of Slovenian components, with massive use of limestone filler as cement replacement were used for the first time for this application that took place in July 2009 [9].

The fibre mix is based on the CEMTEC$_{\text{multiscale}}^{\circledR}$ family [13] and is similar to the one used for the rehabilitation of the bridge over river La Morge in Switzerland in 2004 [8], with two types of fibres: steel wool (1 mm length) and steel macrofibres (l_f = 10 mm, aspect ratio: 50) with a total dosage of 706 kg/m^3 (9 %vol.).

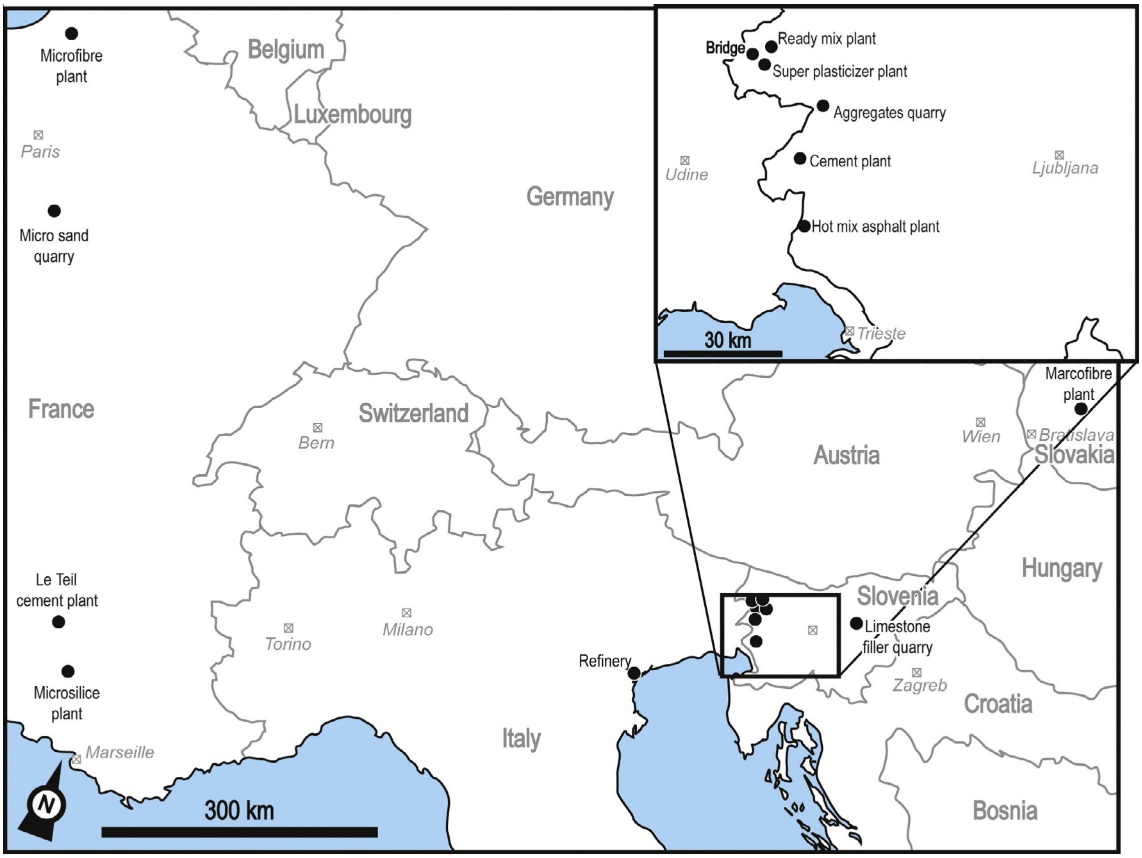

Fig. 1. Geographic overview of the study. Bridge and production plants locations of the different materials used for the rehabilitation.

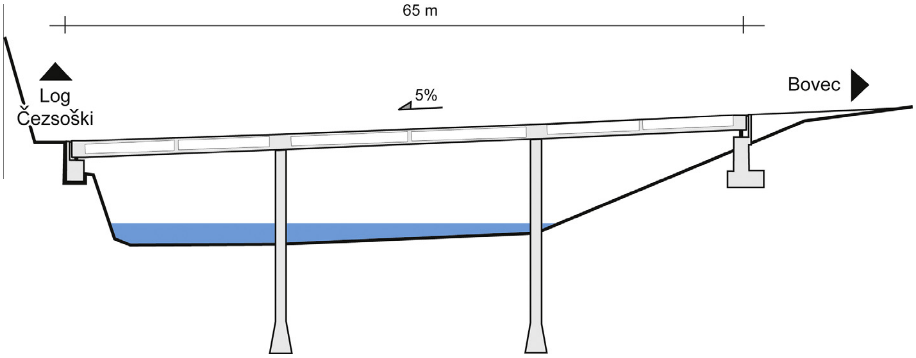

Fig. 2. Longitudinal cross section of the Log Čezsoški bridge. The rehabilitation with UHPFRC is shown in dark on the upper surface.

The innovative UHPC matrix uses half of the cement dosage of previous UHPFRC recipes [8], but with an equivalent workability and without losses in the mechanical or protective performances [9,16]. The massive cement replacement by limestone filler helps break the workability barrier [17] and minimise cement–superplasticiser incompatibility most often problematic when a very low water/binder ratio is sought such as in UHPFRC mixes [18]. Note that Bornemann and Schmidt [19] had already shown that it is possible to replace significant amounts of the cement in UHPC mixes by fine quartz sand of close size and distribution, while keeping the absolute water added constant, without significantly decreasing the compressive strength. The workability was even improved as demonstrated by the lower superplasticisers dosage required to achieve equivalent consistency.

The ECO-UHPFRC recipe consisted then of 763 kg/m^3 of cement CEM I 52.5 N from Salonit cement plant (Deskle, Slovenia), 763 kg/m^3 of limestone filler (IGM, Trbovlje, Slovenia), Microsilica from zirconia production (SEPR, France) with a mass ratio Microsilica/Cement of 20%, 55 kg/m^3 Superplasticiser Zementol Zeta Super S® from TKK concrete admixtures producer (Srpenica, Slovenia) and no fine sand. The Water/(Cement + Limestone Filler) ratio was 0.175.

Despite the very challenging temperature conditions during the day (around 30 °C) the works were accomplished in two days, as foreseen. The bituminous pavement was applied on the UHPFRC surfaces of the road after 7 days of moist curing. The bridge was reopened to traffic just one month after the start of the works, which is a dramatic decrease with respect to the 3 months needed with a traditional technique (concrete replacement + waterproofing membrane).

4. Environmental evaluation method

4.1. Functional unit and system boundaries

To perform the environmental evaluation, the Life Cycle Assessment (LCA) method was used. It is a methodology for evaluating the environmental load of processes and products during their life cycle, from cradle to grave [10]. LCA has been used in the building sector since 1990 [20], and it is now a widely used methodology [21–23]. The principle is to compare different solutions that will provide the same function. In this study the *functional unit* is the rehabilitation of a specific bridge in Slovenia (Log Čezsoški, nearby Bovec). Three systems are compared.

- The first one follows the solution presented on Fig. 3a, using the ECO-UHPFRC applied on the Log Čezsoški bridge in July 2009.
- The second one follows the solution presented on Fig. 3a, but using the UHPFRC applied on the bridge over river La Morge in 2004 in Switzerland [8], with 1434 kg/m^{3}pure CEM I, optimum for UHPFRC mixes but imported from the “Le Teil” Plant in France for cement/plasticizer incompatibility problems, 373 kg/m^3 of microsilica from SEPR (France), 80 kg/m^3 of fine sand from Fontainebleau (France) and the same fibrous mix as the ECO-UHPFRC.
- The third one is a traditional rehabilitation system using conventional concrete (C30/37) and a waterproofing membrane (Fig. 3b). In a first step, the existing Reinforced Concrete curbs and 8 cm concrete is removed from the bridge deck. Then 8 cm of new C30/37 concrete with a steel reinforcement mesh is cast on the deck. This thickness is needed even if a smaller

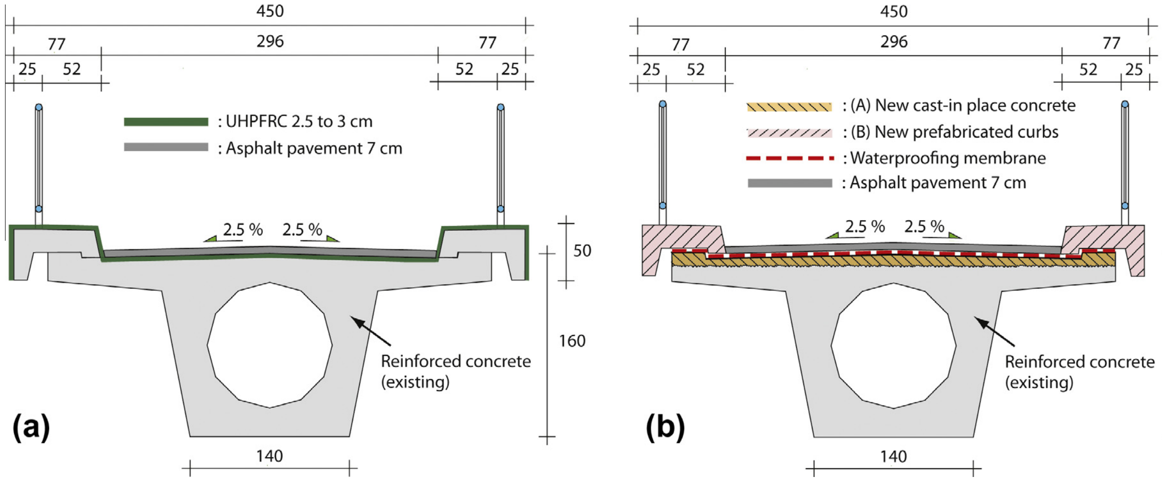

Fig. 3. Rehabilitation systems. (a) Concept of application of the local “hardening” of bridge superstructures with UHPFRC; (b) traditional rehabilitation systems using conventional concrete (C30/37) and a waterproofing membrane.

Table 1
Rehabilitation procedure (a) with UHPFRC rehabilitation system; (b) with traditional rehabilitation system.

Description *Demolition work*	Environmental evaluation	Quantity
Panel A		
Removal of existent asphalt and waterproofing membrane on bridge and access ramp + permanent disposal	Demolition and disposal, building, bitumen sheet, to final disposal [24]	1250 kg
	Demolition and disposal, asphalt, 0.1% water, to sanitary landfill [24]	35,175 kg
Removal of deteriorated concrete on upper surface (3 cm)	Demolition and disposal, building, concrete, not reinforced, to final disposal [24]	18,720 kg
Cleaning of upper surface of concrete with high pressure water jetting or sandblasting	Hydraulic cleaner [25]	4 h
Repair works		
Delivery and casting UHPFRC concrete	Ready mix concrete production [26]	11 m^3
Delivery and laying asphalt pavement	Asphalt hot mix, at plant [27]	35,175 kg
Panel B		
Removal of existent asphalt and waterproofing membrane on bridge and access ramp + permanent disposal	Demolition and disposal, building, bitumen sheet, to final disposal [24]	1250 kg
	Demolition and disposal, asphalt, 0.1% water, to sanitary landfill [24]	35,175 kg
Demolition and permanent disposal of concrete curb, thickness 25 cm, width 75 cm.	Demolition and disposal, building, concrete, not reinforced, to final disposal [24]	88,800 kg
Removal of deteriorated concrete on upper surface (8 cm)	Demolition and disposal, building, concrete, not reinforced, to final disposal [24]	37,440 kg
Cleaning of upper surface of concrete with high pressure water jetting or sandblasting	Hydraulic cleaner [25]	4 h
Repair works		
Delivery and mounting of reinforcement steel	European steel production [28]	4240 kg
Delivery and casting C30/37 concrete	Ready mix concrete production [26]	53 m^3
Delivery and laying of waterproofing membrane	Bitumen sealing, at plant [27]	1466 kg
Delivery and laying asphalt pavement	Asphalt hot mix, at plant [27]	35,175 kg

amount of concrete is effectively deteriorated because of shrinkage and spalling of the new concrete. Actually, contrarily to UHPFRC, standard concrete cannot be cast in small layers as shrinkage will cause adhesion problems between the old and the new concrete. After concrete curing and sufficient drying, a waterproofing membrane is applied on the new concrete and new precast reinforced concrete curbs are attached to the bridge sides.

The different steps of the rehabilitation system with the two studied UHPFRC are presented in Table 1a. In comparison to traditional rehabilitation systems, a waterproofing membrane is not needed in UHPFRC systems and less concrete is removed during maintenance works. Table 1b shows the procedure with traditional rehabilitation system. Mix designs for the different repair materials are shown in Table 2. It can be noted that UHPFRC always imply a high dosage of paste. Furthermore, for this specific case the amount of paste is even higher as the fibre dosage reaches a very high value. In the ECO-UHPFRC, as the very high content of limestone filler which is substituted to the cement needs also to be deflocculated, the percentage of superplasticiser is referred to the amount of cement + limestone filler (Table 2).

Fig. 4 shows the *boundaries of the studied system*. It can be seen that attention is paid to the production and transport of materials. Transport distances of the different component to the ready mix plant which is located at 5 km from the site work are gathered in Table 2. The asphalt comes from a hot mix asphalt plant located at 77 km from the site work. Distances and mass ratio of the asphalt components are shown in Table 3. Disposal is located at 30 km from the site work and all transports are made by trucks. The traffic on the bridge during service life has not been taken into account because it will hide the difference between the three repairing solutions. Actually it has been shown that the impact of the traffic during the use of a bridge is largely dominant on the environmental impact [30,31], therefore as the objective of the study is to study the difference between three repairing solutions it is necessary to avoid the impact of this traffic. However, the consequences of traffic deviations caused by the reparation works will be discussed in the discussion section. Finally the further maintenance of the bridge is studied because the extent of maintenance

Table 2
Materials mix design. Mix design for traditional concrete were calculated using BetonlabPro software [29].

UHPFRC rehabilitation system					Traditional rehabilitation system		
Material	UHPFRC		Eco UHPFRC		Material	Concrete C30/37	
Components	Quantity ($kg.m^{-3}$)	Distance (km)	Quantity ($kg.m^{-3}$)	Distance (km)	Components	Quantity ($kg.m^{-3}$)	Distance (km)
Cement	1434	950	763	55	Cement	385	55
Limestone filler			763	188	Sand	690	35
Micro sand	80	1100			Gravel	1060	35
Microsilica	373	1000	153	1000	Water	185	
Steel fibers[a]	707	760	707	760	Super plasticiser	4.9	10
Water	189		224		Steel rebars	80	150
Superplasticiser[a]	47.5	10	55	10	Bitumen sealing	27.6	250
For comparison					For comparison		
Superplaticiser[a] (wt.% of cement + limestone filler)	3.3%		3.6%		Superplaticiser* (wt.% of cement + limestone filler)	1.3%	

[a] Total = liquid + dry extract.

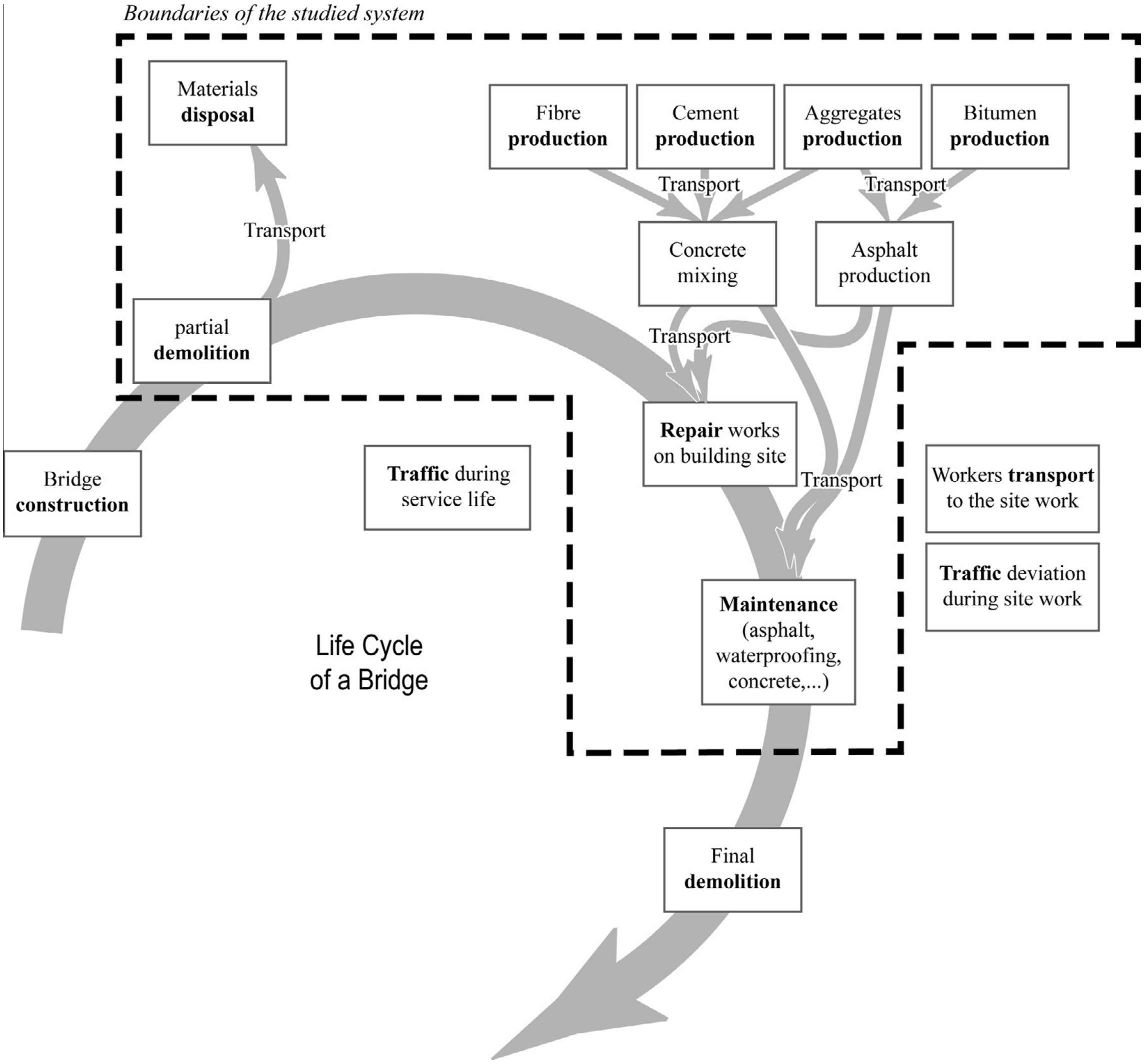

Fig. 4. System boundaries for the Log Čezsoški bridge rehabilitation.

is linked to the chosen reparation system. For an additional service life of 60 years after the bridge rehabilitation, it is expected that the asphalt pavement will have to be changed every 15 years for all solutions. Concerning rehabilitation system with C30/37 concrete, it is assumed that the waterproofing membrane will have to be replaced once after 30 years as well as deteriorated concrete underneath and the whole curbs (a procedure very often used in practice is to consider curbs as "consumables" although this way of doing is very questionable). These service life values for asphalt and waterproofing membrane are coming from common practice and have been gathered and confirmed by different experts working on infrastructure maintenance in Slovenia (Šajna, personnal communication). The amount of concrete replacement comes also from common observation in Slovenia. Concerning the UHPFRC solutions, field observations that enable estimation of service life are rare, since this new technology is uncommon. It has been applied over the last 15 years, which is much shorter than the expected service life. However, other studies provide insight on the durability of this material. The first one was conducted in a nuclear power plant, where UHPFRC beams submitted to an aggressive environment (hot water, high chloride content, low pH) have been evaluated after 10 years of exposure [32]. In this study, it has been shown that chloride ingress was still less than 0.1 g Cl^- per 100 g of cement, which is actually the precision limit of the measurement and can therefore be considered as insignificant [32]. Similarly the porosity accessible to water as well as the capillarity where equal to one tenth of what is normally measured for high performance concrete and carbonation death was hardly measurable and often reduced to 1 mm, which is insignificant considering the aggressive environment (dripping water, intense air flow and mild temperature). In comparison, measurements have been performed on the Log Čezsoški bridge after 2 years of exposure [33]. Air permeability was close to 0.004×10^{-16} m^2, which is similar to the original value and can be classified as very low according to quality class made by Torrent [34]. Capillary absorption tests gave a value around 60 g m^{-2} $t^{-0.5}$ which is similar to UHPFRC evaluated in the nuclear power plant [32] as well as on the Samaris project [8] and to the measurements performed in the laboratory before the execution on the Log Čezsoški bridge [9]. This value is

Table 3
Asphalt mix design. Mix design for asphalt pavement were calculated using Eurobitume values [30].

	Asphalt	
	Quantity (kg m^{-3})	Distance (km)
Bitumen	125	150
Aggregates	2375	35

one order of magnitude lower than high performance concrete (around 400 $\text{g m}^{-2}\,\text{t}^{-0.5}$) and two orders of magnitude lower than standard concrete (6000 $\text{g m}^{-2}\,\text{t}^{-0.5}$). With these measurements and considering the consequence of an extremely low permeability as a protection to aggressive environment, it can be assumed that the UHPFRC solution will last much longer than the traditional solution. However, to be conservative in the hypothesis presented in this study, it has been assumed that UHPFRC will only last twice as long as the traditional solution (60 years) without further maintenance due to the very low permeability of the matrix. Similar hypotheses are considered for common UHPFRC and ECO-UHPFRC as capillary absorption and air measurements show similar trends for both UHPFRC [9,16]. Consequences of these life cycle hypotheses are discussed later in the paper.

4.2. Inventory data and impact assessment

The only impact category that is shown in the study is the Global Warming Potential for one hundred year of time horizon (GWP_{100}) expressed in kg CO_2 equivalent and calculated by the CML01 methodology [35]. This reduction can be justified as the main impact of concrete industry is CO_2 emission caused by both the fuel combustion and the limestone decarbonation in the clinker kiln [36,37]. In the following, the paper will refer to this environmental impact as Global Warming Potential (GWP). To calculate the life cycle inventory, the all-inclusive components are calculated with the original system boundary of the ecoinvent database [38]. The details of the used processes during the different step of the life cycle are presented in Table 1. No environmental load has been included for site work and the only burdens come from the production of the materials. For asphalt work, studies have shown that site work is negligible compared to production phase and represent 2% of GWP for the whole life cycle [39]. Note that it is different for other indicators such as toxicity or ecotoxicity that can be more important on the site work. Similar results for concrete [25] and steel [40] structures show that on the environmental impacts for the site work are negligible compared to production and transport phases. Therefore, it seems justified to avoid environmental loads for the casting and curing of concrete and steel on site work. Concrete mixing has been calculated differently for the two rehabilitation systems because there is an important difference between the traditional and Ultra High Performance Fibre Reinforced concretes. Mixing time is much longer (10 min compared to 30 s) for UHPFRC. Therefore it has been decided to affect 20 times the impact of traditional concrete mixing for UHPFRC. The environmental impact of concrete ready mix plant has been taken from Chen [26]. Microsilica has been considered as a waste and therefore the only processes that have been considered are the storage on the production site and the transport to the ready mix plant. The storage has been considered as similar to the one for fly ash already calculated in a previous study [41]. As this assumption of considering microsilica as a waste and not a by-product from zirconia industry could induces a significant environmental impact difference [42], it has been chosen evaluate this potential allocation question in the discussion section of this paper. Finally concerning the global warming impact of the fibres, the study of Stengel and Schießl [43] was used. In this study the fibre production is modelled by the following process: electric steel production, hot rolling, descaling, dry wire drawing, wet wire drawing, tempering, steel cord wire strand fabrication and cutting fibres [43]. The result is an environmental impact of 2.68 kg CO_2 eq. per kg of fibres produced. However as the electricity mix used to calculate this data is not explicitly given by the authors, a study on the sensitivity of the result to the choice of the electricity mix will be done with different cases, for different countries, in the discussion section of this paper.

4.3. Sensitivity analysis

An environmental evaluation is always based on many hypotheses that are difficult to fully constrain. Uncertainties are present all along the process of environmental evaluation [44]. These can be due to a poor knowledge of processes included in the environmental database [45] or to uncertainties on the way pollutants are transferred and act into the different ecosystems [46]. For building materials, the evaluation has also to deal with specific concerns of civil engineering compared to other industrial sectors [47]. Building structures have actually a long living period (50–100 years). Over such a long period of time, the energy basket and even the climate are expected to change which raises concerns about the applicability of standard LCA method [48–50]. Kellenberger and Althaus [51] also deplored the lack of reliable data on life span of building components.

In this study, we focused on four main points and evaluate the sensitivity of these hypotheses. The first one is about temporal considerations. Actually it is important to fix a common service life between the different studied solutions and it is known that UHPFRC have a longer durability than standard concrete. However, as what will happen in 50 or 60 years to this bridge is unpredictable, it is necessary to evaluate the consequences of different scenarios.

The second point is the fact to take into consideration the traffic deviation due to site work on the bridge. Its environmental consequences are actually difficult to consider as it depends on many different individual actors that may change their comportments during the bridge interruption.

The third one is the fact that if microsilica is considered as a by-product rather than a waste, a certain amount of the environmental impact related to production process has to be allocated to the microsilica even if the main product produced by this industry is zirconia. This allocation question has been raised by many authors [42] and no method seems to be the correct one [52,53].

Finally, the last point considers the uncertainty on the fibre mix environmental data. Actually the environmental impact of the steel fibres that has been used in this study comes from Stengel and Schießl [43] who did a detailed evaluation of the different processes involved in the production of steel fibres for UHPFRC, without explaining which type of electricity mix they used. This imprecision can have considerable impact as the impact of the electricity strongly depends on the country where the electricity is produced. Therefore it has been chosen to recalculate the environmental impact of the fibre production for different countries, i.e. electricity mix. A synthesis of all data used to calculate the environmental impact of the different bridge rehabilitation solutions are presented with the results of the evaluation in Table 4.

5. Results

The global warming impact of the different rehabilitation solutions is presented in Table 4. Our study shows that the rehabilitation system with ECO-UHPFRC has a slightly higher impact than the traditional rehabilitation system, if the further maintenance of the bridge after the rehabilitation is not taken into account. It, means that the first rehabilitation is the only operation evaluated. The production of constituent contributes then for more than 70% of the environmental impacts for all the rehabilitation systems. The demolition phase induces more impact for the traditional rehabilitation system as more concrete has to be removed. On the contrary the transport of the constituent for the UHPFRC solution represents around 10% of the global warming impact compared to only 6% in both other studied systems. This is due to the fact that local cement cannot be used because of plasticiser incompatibility.

Table 4
Global Warming Potential for Log Čezsoški rehabilitation (in kg CO_2 equivalent). Only one rehabilitation operation is considered and no maintenance for the concrete WPM system is included.

	Elementary impact (kg CO_2)	Concrete C30/37 (kg CO_2)	UHPFRC (kg CO_2)	Eco UHPFRC (kg CO_2)
Demolition	per kg	5414	3829	3829
Concrete	1.47×10^{-2}	1861	276	276
Bitumen	2.34	2927	2927	2927
Asphalt	1.78×10^{-2}	625	625	625
Constituent production	per kg	26,253	34,944	28,988
Cement	8.4×10^{-1}	17,222	13,311	7079
Sand	2.4×10^{-3}	88	2	–
Gravel	4.3×10^{-3}	241	–	–
Water	1.5×10^{-4}	2	3×10^{-1}	4×10^{-1}
Plasticizer	7.5×10^{-1}	195	485	548
Microsilica	3.1×10^{-4}	–	1	1
Limestone filler	2.6×10^{-2}	–	–	216
Steel rebars	1.58	6700	–	–
Steel fibres	2.68	–	20,828	20,828
Bitumen sealing	1.01	1490	–	–
Asphalt	9.0×10^{-3}	317	317	317
Constituent transport	per kg.km	2162	6662	3019
Concrete	1.0×10^{-4}	134	28	28
Cement	1.7×10^{-4}	250	3341	103
Sand	1.7×10^{-4}	285	217	–
Gravel	1.7×10^{-4}	438	–	–
Water	1.7×10^{-4}	–	–	–
Plasticizer	1.7×10^{-4}	1	4	4
Microsilica	1.7×10^{-4}	–	914	374
Limestone filler	1.7×10^{-4}	–	–	352
Steel rebars	1.7×10^{-4}	142	–	–
Steel fibres	1.7×10^{-4}	–	1329	1329
Bitumen sealing	1.7×10^{-4}	82	–	–
Asphalt	1.7×10^{-4}	830	830	830
Fabrication		621	1059	1059
Ready mix plant	3.7 (per m^3)	198	821	821
Sand blasting	29.8 (per hour)	358	238	238
Anti corrosion painting	2 (per kg)	65	–	–
Total		34,449	46,494	36,895

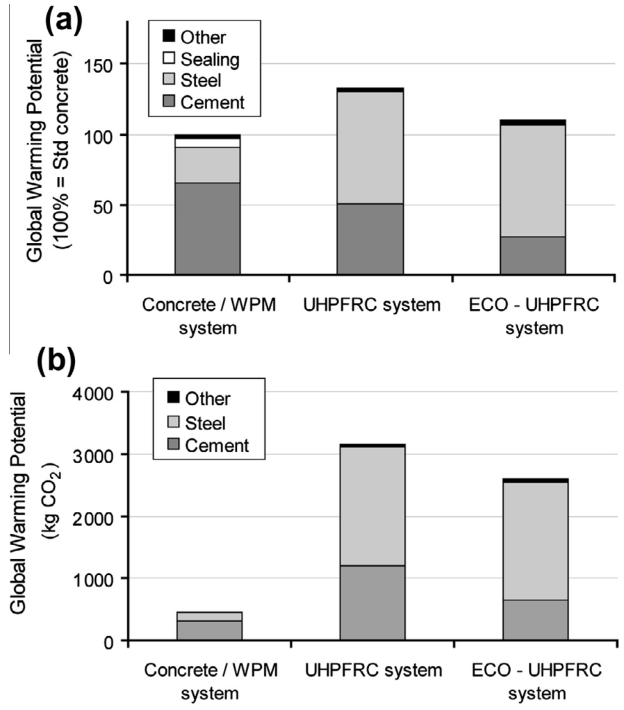

Fig. 5. Global Warming Potential induced by the different solutions for the Log Čezsoški rehabilitation: (a) materials effectively used during the rehabilitation. No maintenance for the standard concrete system is included. All solutions are compared to the traditional rehabilitation system with standard concrete taken as reference (100%); (b) a cubic metre of the concrete used for the different rehabilitation system. The results are presented in kg CO_2 equivalent.

The impact of the concrete production (fabrication phase, Table 4) is negligible compared to the production and transport of constituents from their production plants to the ready mix plant.

As on Table 4, the constituent production are responsible of most of the environmental impact, a detailed study of the production of the constituents for the rehabilitation phase (no further maintenance, no transport, no demolition) has been done. Fig. 5a shows the GWP for the different rehabilitation systems. For the traditional rehabilitation system, cement production induces the largest impact while steel and waterproofing membrane are sharing the 35% left (Fig. 5a). For UHPFRC systems the impact of steel production represents the major part of the GWP. For the ECO-UHPFRC system, the impact of cement is much lower than UHPFRC as 50% of cement is replaced by limestone filler that has a very low impact. Steel fibres are then the major contributor to material impact with 2/3 of the impact.

The impact of a cubic meter of concrete used for the different rehabilitation system is presented in Fig. 5b. The UHPFRC solutions release 5–7 time more CO_2 than a cubic meter used for the traditional rehabilitation system (3000 kg and 2500 kg compared to 450 kg CO_2 eq.). It is interesting to note that while there is a very large difference between the two solutions at the cubic meter scale, the fact that a much lower volume is needed with UHPFRC allows having only 0.1–0.3 times more CO_2 than for traditional rehabilitation system when the effective volume used is calculated (Fig. 5a). Finally Fig. 5b shows how the innovative concept of the cement substitution by limestone filler considerably reduces the impact of the ECO-UHPFRC compared to standard UHPFRC (from 3000 to 2500 kg CO_2 eq./m^3).

As the durability of UHPFRC is much higher than traditional concrete and waterproofing membranes, the rehabilitation

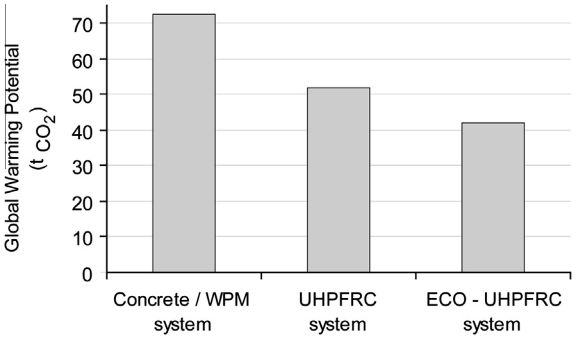

Fig. 6. Global Warming Potential induced by the different solutions for the Log Čezsoški rehabilitation. The rehabilitation system and its maintenance are considered over a common life cycle of 60 years. The results are presented in tons of CO_2 equivalent.

solution have to be compared over a similar life cycle, with a the same target service life of 60 years and not only considering the impact of one rehabilitation work. The results presented in Fig. 6 consider the further maintenance that will be needed with the traditional rehabilitation system, in particular the fact that the waterproofing membrane has to be changed every 30 years as well as deteriorated concrete underneath and the whole curbs, while no further maintenance is assumed to be needed for the UHPFRC except asphalt pavement. Actually, for all solution asphalt pavement has to be changed every 15 years. With these hypotheses the rehabilitation system with ECO-UHPFRC has a much lower impact than all the other rehabilitation systems. It represents less than 60% of the impact of a traditional rehabilitation with conventional C30/37 concrete. Classic UHPFRC solution has also a lower impact than C30/37 concrete solution (72%).

6. Discussion

6.1. Impact of service life

The comparison between the three solutions should consider the durability differences between systems. UHPFRC exhibits an extremely low permeability to water and gases [54] and their strain hardening tensile response helps avoid any cracks. Consequently, UHPFRC alone applied on bridge decks as overlays are sufficient and much more durable than concrete + waterproofing membrane systems. To illustrate this, a very conservative lower estimate of a doubled durability for UHPFRC systems was assumed.

Furthermore, studies on the new ECO-UHPFRC with mineral addition have shown that the durability is the same as standard UHPFRC because the pore size distribution of ECO-UHPFRC and their protective properties are similar than UHPFRC [16] With these hypotheses it has been shown that both UHPFRC solutions have lower GWP impact than C30/37 concrete solution. However, when the rehabilitation system is chosen, it is hard to know how will the traffic on that bridge evolves over the next 60 years. Maybe an increase of the traffic will lead to the construction of a new larger bridge and to the early destruction of the previous structure. Therefore it is more correct or at least more transparent with the used hypothesis to write that, the proposed solution of ECO-UHPFRC has a slightly higher GWP than the C30/37 concrete solution for the rehabilitation work (107%, Table 4); and that as soon as the rehabilitation lasts more than 30 years, the environmental impact is much lower (58%, Fig. 6). It is then a significant improvement compared to UHPFRC solution which has a much higher GWP for the first rehabilitation work (135%, Table 4).

6.2. Impact of site work

In this study it has been shown that the use of ECO-UHPFRC has lower global warming impact compared to traditional rehabilitation systems when service life is considered. However, in this study the boundaries of the system have been reduced to the production and transport of materials for rehabilitation. The result might be even clearer if other aspects of the system are included. The impact of site work has not been accounted, as many studies have shown that it is negligible [25]. For our present study, taken site work into account would actually be beneficial for UHPFRC solutions as there are more site works with traditional rehabilitation systems than with UHPFRC. Another aspect that would be considerably different between the two rehabilitation systems is the impact of traffic deviation caused by the site work. Actually the log Čezsoški bridge is the only link between the two sides of the river within 15 km in order to connect the village of Log Čezsoški with the main road Žaga – Bovec. Then during site work every car, bus or truck would had to drive 30 more km. Taking a very low assumption of 50 cars a day, 22 days a month and CO_2 emission of 2.17×10^{-1} kg CO_2 eq.km^{-1} (Ecoinvent data), the reduction of the site work using UHPFRC is in fact very much impressive. A traditional rehabilitation work would last at least 3 months, whereas a rehabilitation

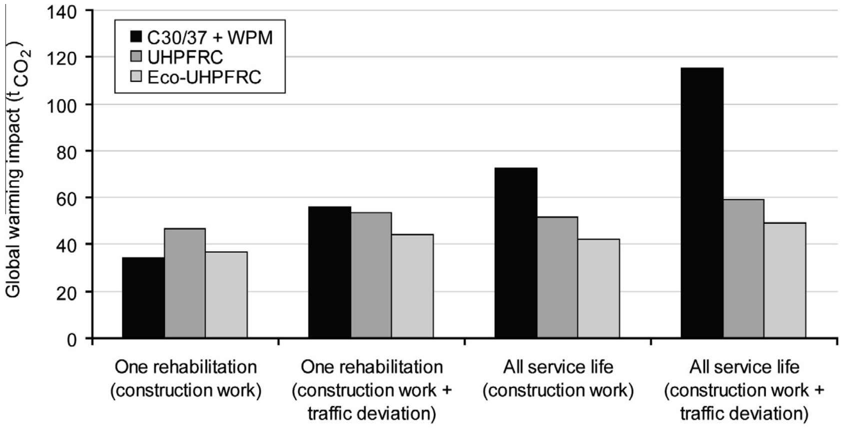

Fig. 7. Global Warming Potential induced by the different solutions for the Log Čezsoški rehabilitation depending on which hypothesis is considered. Comparison is made either for only one rehabilitation without the further maintenance of the bridge or for the rehabilitation and 60 years of service life after this rehabilitation. For each hypothesis, two evaluation solutions are considered: the construction works are the only impact considered or the impact of traffic deviation are included. All results are presented in tons of CO_2 equivalent.

with UPFRC lasted just 1 month. Therefore we can consider that at least 14 tons of CO_2 have been saved, which actually represents nearly half of the total impact of the rehabilitation work. This aspect is shown in Fig. 7 where the effects of different hypotheses on the environmental impacts of the three rehabilitation solutions are shown. It shows very clearly that taking into account further maintenance of the bridge and the impact of traffic deviation during site work drastically change the impact of the traditional solution with conventional C30/37 concrete and waterproofing membrane (C30/37 + WPM), whereas for UHPFRC solutions most of the impacts are induced by the construction works during the first rehabilitation of the bridge. Therefore, if traffic deviation is taken into account, Eco-UHPFRC solution has clearly a lower GWP than the traditional solution even without considering an extended service life (one rehabilitation: construction work + traffic deviation, Fig. 7). It is not the case for classic UHPFRC which has a similar (slightly lower) GWP than the traditional rehabilitation solution.

6.3. Allocation of microsilica production

In this study it has first been considered that microsilica was a waste and that no environmental impact due to its production needed to be allocated. However, a recent European Union directive [55] notes that “a waste may be regarded as by-product if the following conditions are met: (i) further use is certain, (ii) the substance is produced as an integral part of a production process; (iii) the substance can be used directly without any further processing other than normal industrial practice; and (iv) further use is lawful”. Microsilica fulfils all these criteria and should not therefore be considered as a waste anymore. The question rises whether it would not be more appropriate to allocate a part of the environmental load of zirconia production to the microsilica. This question is not often raised for the environmental evaluation of concrete made with mineral additions, such as microsilica as well as fly ash or blast furnace slag, as only a few studies can be found for allocation consideration for supplementary cementitious materials in concrete [41,42,56]. None of them found an appropriate method except than testing the sensitivity to different allocation methods.

Two methods are tested herein. The first one is an allocation by mass. The silica fume (microsilica) used in this study is produced in the arc fusion process when silica is separated from zirconium silicate, which means that 1 mol of zirconium silicate ($ZrSiO_4$) will produce one mole of zirconia (ZrO_2) and one mole of silica fume (SiO_2). Silica fume represents then 33% of the final products’ mass and 33% of the environmental burden of the production of zirconia should then to be affected on the microsilica. The second method considers the relative benefit of the zirconia industry to sell both products. While 1 ton of zirconia, which is a very high value product is sold 2000 USD [57], the associated 500 kg of microsilica are sold 500 USD per ton. 11% of the plant’s benefit comes then from the microsilica. As a result 11% of the environmental impact should be affected to microsilica. Concerning the GWP, it has been considered that the destabilisation process of Zirconium silicate into zirconia and silica fume release 3.3 kg CO_2 eq. for each kg of silica fume produced [28,58,59]. The production of one kg of silica fume will then either contribute to 3.1×10^{-4} kg CO_2 eq. if it is considered as a waste or 3.64×10^{-1} kg CO_2 eq. if an economic allocation is used or 1.09 kg CO_2 eq. if a mass allocation is used. With these two allocation procedures a mass allocation modify the results and std UHPFRC and Eco-UHPFRC have an environmental impact equal to 148% and 112% respectively compared to a standard C30/37 solution. An economic allocation modify even less the results as environmental impacts are equal to 139% and 109% for the both UHPFRC compared to 135% and 107% when no allocation on by-product is considered. This sensitivity analysis shows us that an allocation procedure that considers silica fume as a by-product, and not a co-product from the zirconia industry such as an economic allocation, will not modify the environmental impact of the rehabilitation system. Therefore, even if in a medium term perspective silica fume will probably have to be loaded with a certain environmental burden, this will not modify the results of the present study as this load will be close to what can be calculated with an economic allocation more than with a mass allocation in order to keep providing an incitation for waste valorisation [41].

6.4. Sensitivity of the steel fibres production environmental impact to the electricity mix

The environmental impact of the steel fibres that has been used in this study comes from Stengel and Schießl [43] who did a detailed evaluation of the different processes involved in the production of steel fibres for UHPFRC. However they do not explain from which country the electricity come from. This imprecision has considerable impact as the impact of the electricity strongly depends on the process used to produce electricity and therefore strongly depends on the country where the electricity is produced. Therefore it has been chosen to recalculate the environmental impact of the fibre production with the same technical data as Stengel and Schießl, but with electricity coming from different countries. Table 5 indicates the global warming impact of one kg of steel fibres depending on the country where they are produced. As the microfibres are produced in France, the French electricity (Production + importation) can be used. The only European plants that are producing the macrofibres used in this type of UHPFRC are located in Belgium and in Slovakia. Table 6 shows the effect of the location of the production of the fibres on the GWP. The SK solution is the solution that has been effectively used for the log Čezsoški bridge rehabilitation, which means microfibres coming from France and macrofibres coming from Slovakia. The BE solution is a solution that could have been used as the macrofibres could come as well from the Belgian plant. The transport distance is increased from 525 km to 1200 km but the environmental impact of the fibre production is reduced (Table 5). Finally the last solution is not possible at the moment and represents a solution where all the fibres would come from France. Even if this solution does not exist now, it has been calculated as it could represent a potential improvement of the environmental impact of the fibre production using the French electricity country mix or whatever electricity type that has a low CO_2 footprint. The results presented in Table 6 shows that the choice of the electricity country mix effectively changes the impact of the UHPFRC solutions. In Table 6, all microfibres are considered to have been produced with French electricity except for the reference solution which has been calculated with Stengel and Schießl results. Then macrofibres produced with Slovakian electricity increase the impacts by 10% while the use of Belgian macrofibres (more transport impact, less production impact) has similar impact than the studied solution (Table 4). Finally, Table 6 shows that a fibre plant that would use a low-CO_2 electricity mix would allow for the production of very low-CO_2 rehabilitation solutions that would reduce by 20% the carbon dioxide emission compared to traditional rehabilitation system. In this simulation, no extended service life

Table 5
Global Warming Potential of the steel fibre production for different electricity country mix (production + importation). SK = Slovakia, BE = Belgium, FR = France.

Origin of electricity used	Stengel and Schießl [43]	Slovakia	Belgium	France
kg CO_2 eq. per kg of steel fibre	2.68	3.99	3.08	1.30

Table 6
Global Warming Potential of both UHPFRC solutions calculated in comparison to the C30/37 concrete solution, for different hypothesis on the electricity country mix used to produce steel fibres. For each hypothesis, the environmental impact of C30/37 concrete solution is set to 100% and UHPFRC impacts are compared to this impact. (REF): All steel fibres are calculated with Stengel and Schießl [39]. For (SK), (BE) and (FR), microfibers are produced in France and macrofibres are produced in Slovakia, Belgium and France respectively.

Hypothesis	UHPFRC (%)	Eco-UHPFRC (%)
One rehabilitation (REF)	135	107
One rehabilitation (SK)	155	127
One rehabilitation (BE)	145	117
One rehabilitation (FR)	118	91

has been considered as well as no traffic deviation. The only environmental impact considered is associated with the first rehabilitation. It means that this new Eco-UHPFRC would be able to provide a solution that has directly (without any further hypotheses) a lower GWP than the traditional rehabilitation solution as soon as steel fibres would be produced with a low-CO_2 electricity mix. This low-CO_2 electricity could be the French electricity or any other low-CO_2 electricity based on renewable electricity production system.

7. Conclusion

As a conclusion, life cycle impact assessment method allows to compare different solutions of bridge rehabilitation from an environmental point of view. It shows that the impact due to the production of materials is the major contribution to the environmental impact whatever the rehabilitation systems used. In this study, an innovative rehabilitation system has been evaluated. It has been shown that this system, which uses a new UHPFRC with a large amount of limestone filler, has similar impact to traditional rehabilitation systems without considering the service life of the rehabilitation. Furthermore, if this bridge is in use for more than 30 years, the rehabilitation which has been effectively done on the log Čezsoški bridge with Eco-UHPFRC would represent less than 60% of the impact of the C30/37 concrete solution that would have need for more maintenance (Fig. 6).

For the rehabilitation of Log Čezsoški bridge slovakian macrofibres were used. This study emphasised that using fibres from a Belgian plant would have reduced the global warming impact of the rehabilitation even if the transport distance is twice longer. But a steel fibre production plant that would use a low-CO_2 electricity mix would allow for the development of a highly efficient rehabilitation system, in terms of reducing Global Warming Potential, using ECO-UHPFRC. That system provides a reduction of 20% without considering service life rehabilitation and therefore yields a much larger reduction (by a factor 2) compared to the conventional C30/37 concrete solution if service life is considered.

Finally, the impact of traffic deviation due to bridge closure is not negligible. UHPFRC solution reduces the bridge interruption and thus drastically limits associated impacts due to traffic deviation. Actually, both UHPFRC solutions have twice lower impact than the traditional one when impact of traffic deviation is considered over the service life. The Eco-UHPFRC solution clearly has a lower GWP than the traditional solution even if only one rehabilitation is considered.

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