Sustainable Development, Global Change and Ecosystems

Sustainable Surface Transport

Strategic Targeted Research Project

ARCHES

Assessment and Rehabilitation of Central European Highway Structures

Deliverable D14

RECOMMENDATIONS FOR THE USE OF UHPFRC IN COMPOSITE STRUCTURAL MEMBERS

REHABILITATION LOG ČEZSOŠKI BRIDGE

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ABSTRACT

The increasing volume of European transport urgently requires an effective road and rail system in Central European and Eastern Countries (CEEC) with a major investment in building new and assessing and rehabilitating old structures.

Following 5 successful applications of rehabilitation with Ultra High Performance Fibre Reinforced Concretes in Switzerland, since 2004, the same concept was applied to a bridge in Slovenia in July 2009 with new UHPFRC mixes from local products.

An innovative concept of cement replacement by high dosages of limestone filler, developed at EPFL, helped break the workability barrier and produce a Slovenian UHPFRC with local cement (SALONIT), and superplasticiser (TKK), The material has excellent rheological properties and was tailored to be applied on slopes up to 5 %, without sacrificing the protective function and mechanical properties.

The full section of the deck and footpaths of the 65 m span Log Čezsoški bridge over Soča river in Slovenia was cast in one step, over two days for the full length. An original combination of UHPFRC with Controlled Permeability Formwork (CPF) membrane (ZEMDRAIN®) developed at ZAG helped produce finished footpath surfaces ready to walk barefoot which was one of the challenges set by the owner. The specially tailored thixotropic mix held the 5 % slope without difficulties.

The newly designed ECO-UHPFRC recipes have a dramatically reduced cement content which makes them more economical and particularly attractive from an environmental point of view. Over the whole life cycle, rehabilitations with ECO-UHPFRC have a much lower impact than traditional methods.

This successful example of transfer of technology opens up very promising perspectives for the dissemination of this new concept of rehabilitation of civil infrastructures not only in New Member States (which was the goal of the project ARCHES) but also in virtually any country.

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FOREWORD AND ACKNOWLEDGEMENTS

The goal of ARCHES WP 5 – "Harden Structures to last with UHPFRC" was to demonstrate on the basis of applications in Slovenia and Poland, *with products available locally to the largest extend,* that Ultra High Performance Fibre Reinforced Concretes (UHPFRC) can be successfully and price-efficiently implemented for rehabilitation in those countries, *which would be a major step forward the dissemination of this technique in New Member States (NMS).* This work is a direct continuation of WP 14 – SAMARIS (Sustainable and Advanced MAterials for Road InfraStructure) project, see http://samaris.zag.si/, based on the original concept of application of UHPFRC for the rehabilitation of reinforced concrete structures proposed at MCS by Prof. Dr. Eugen Brühwiler, in 1999.

This report is the second of two, resulting from R&D works performed within ARCHES WP 5:

- *ARCHES D06:* Recommendations for the tailoring of UHPFRC recipes for rehabilitation
- *ARCHES D14*: Recommendations for the use of UHPFRC in composite structural members – rehabilitation Log Čezsoški bridge.

Four research centres (MCS/EPFL - Switzerland, ZAG - Slovenia, LCPC - France, IBDIM – Poland) and two industrial partners (Salonit Anhovo – Slovenia – cement producer, and TKK Srpenica – Slovenia – producer of concrete admixtures) were directly involved into the research and application works in the workpackage.

The researchers and technicians who contributed to these works under the lead of Dr. Emmanuel Denarié from MCS/EPFL (WP 5 leader) are:

For MCS/EPFL: scientists and engineers: Dr. Hamid Sadouki, Dr. John Wuest, Dr. Aicha Kamen, Mrs Agnieszka Switek, Mrs Talayeh Noshiravani, Mr Cornelius Oesterlee, Dr. Yves Houst (LTP-EPFL), Mr Philippe Simonin (LMC-EPFL); technicians: MM. Roland Gysler, Gerald Rouge, Gilles Guignet, Sylvain Demierre, Lionel Sofia-Gabrion (LMC-EPFL).

For ZAG: scientists and engineers; Dr Aljoša Šajna (head of R&D works for WP 5 at ZAG), Mrs Jerneja Šuput; technicians: Mr. Vladimir Bras, Mr. Rafael Kajzer, Mr. Irfan Pašagič, Mr. Anton Kranjc; media and dissemination: Mrs. Polonca Štritof, Mr Matjaž Zupanc.

For SALONIT: Mrs Lojzka Reščič, Engineer

For IBDIM: MM Tomasz Wierzbicki, Artur Sakowski, Prof. Marek Lagoda

For LCPC: Dr. Pierre Rossi, Dr. Guillaume Habert

The support from TKK Slovenia - Mrs Lidija Cernilogar for supplying the superplasticiser used in the research works and for the full scale bridge application is gratefully acknowledged.

The support of SIKA Switzerland (Mr Heinz Bänziger) for the choice of suitable admixtures for the development of slope tolerant recipes and Sika Austria (Mr Michael Jernei) and Sika Slovenia (Mr Samo Križaj) for providing materials is gratefully acknowledged.

The support of the Municipality of Bovec, Slovenia and of its Mayor, Mr Danijel Krivec for the first application of UHPFRC in Slovenia on the Log Čezsoški bridge is gratefully acknowledged.

Mr Bogomir Ipavec, engineer from Primorje – Slovenia was kind enough to accept to discover the technology of UHPFRC and apply it to the rehabilitation of the Log Čezsoški bridge.

Finally, Dr. Pierre Rossi of LCPC-France, inventor of CEMTEC$_{multiscale}$® and worldwide known expert of Fibre Reinforced Concretes, proposed the original fibrous mixes for the UHPFRC recipes used in this study and the concepts for their tailoring to the specific applications of rehabilitation.

Lausanne, November 27, 2009 Dr. Emmanuel Denarié

EXECUTIVE SUMMARY

Introduction

The increasing volume of European transport urgently requires an effective road and rail system in Central European and Eastern Countries (CEEC) with a major investment in building new and assessing and rehabilitating old structures.

Ultra-High Performance Fibre Reinforced Concretes (UHPFRC), characterized by a very low water/binder ratio, high binder content and an optimized fibrous reinforcement, provide the structural engineer with a unique combination of extremely low permeability, high strength and tensile strain hardening. UHPFRC are perfectly suited to the rehabilitation of reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses, to provide a long-term durability and thus avoid multiple interventions on structures during their service life. Extensive R&D works performed during EU project SAMARIS and various full scale applications in Switzerland on bridges have demonstrated that UHPFRC technology is mature for cast in-situ applications of rehabilitation, using standard equipments.

EU Project ARCHES dedicates a significant effort to demonstrate the applicability of this innovative rehabilitation technique in CEEC, with cheaper UHPFRC based on locally available components, and with improved rheological properties (tolerance to inclined substrates at fresh state).

Achievement of tensile strain hardening, extremely low permeability and self-compacting character is indeed a challenge that few current UHPFRC recipes can satisfy. An original concept of Ultra High Performance matrix 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 a further step, the rheology of those mixes has been adapted to enable them to accommodate challenging 5 % slopes of the substrates at fresh state. Finally, these new materials have been applied to the rehabilitation of a bridge in Slovenia.

The following document analyses this new application with innovative UHPFRC in the perspective of a sustainable use of construction materials. It also gives practical recommendations based on the experiences gathered during the site.

Rehabilitation of the Log Čezsoški bridge – Slovenia

The bridge is located in the very northwest of Slovenia, close to the city of Bovec, and crosses the Soča river, in a mountain region. It has only one lane and a frequent traffic as it is the only link between the two sides of the river within 15 km. The cross section of the bridge, with the concept of rehabilitation is shown on Figure 1.

- A continuous UHPFRC overlay with no dry joints is applied to protect the full upper face of the bridge deck, footpath and external faces of the kerbs.
- The thickness of the UHPFRC layer is varied according to the more or less difficult geometry to cast, and also in order to maximize the efficiency of the fibrous mix. The deck (A) has an overlay of 2.5 cm, the inner faces of the kerbs (B), 3 cm, the footpaths (C) 3 cm, as well as the external faces of the kerbs (D).

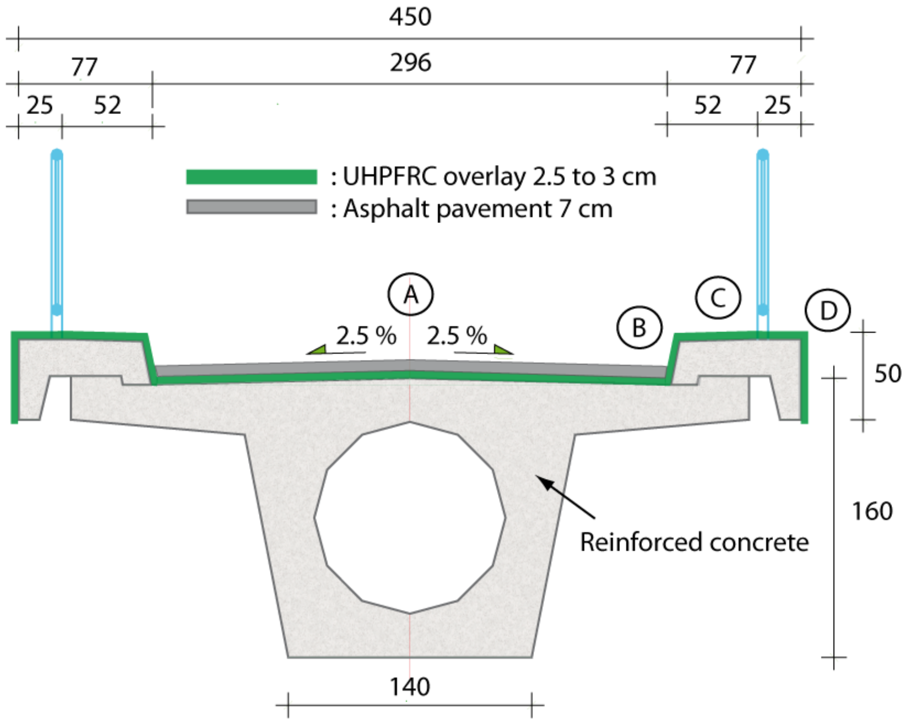


Figure 1: Cross section of the bridge with concept of rehabilitation, dimensions in cm.

The selected concept with no dry joints along the full cross section guarantees a continuous protection. However, it sets high requirements to the choice of the UHPFRC mixes:

- For parts (A), and (C): ability to hold the longitudinal and transversal slopes of 5 % and 2.5 %.
- For part (D), no slope tolerance needed but ability to fill properly the formwork over 50 cm height with a width of 3 cm.
- For part (B); most challenging, ability to hold the slopes and to penetrate in the narrow space of 3 cm of the formwork, without however completely flowing throughout it as the lower part of formwork has to remain open to guarantee the continuity of the overlay without any dry joint.

Following the requirements of the concept of rehabilitation, two new UHPFRC recipes of the CEMTEC$_{multiscale}$® family (LCPC, Rossi et al. (1997, 2005)), with new matrices developed within the ARCHES project from products available in Slovenia, with different rheological properties, were used to satisfy the challenges of the site. The first mix CM32_13, with a thixotropic behaviour was applied for parts (A), (B) and (C), and the second mix CM32_11, more fluid, was applied for the casting of the outer faces of the kerbs – (D), in the narrow space of the formwork.

New processing and surfacing techniques were also applied for the first time.

The materials were produced in a concrete plant, transported to the site by a truck, and poured directly from the truck into carts for the casting of the outer faces of the kerbs, or onto the bridge deck or open faces of the footpath. For each day of casting, the outer faces of the kerb were first realized with mix CM32_11. An inclined plate helped the workers fill the material in place. The material CM32_13 was then used to cover the footpath, fill the inner face of the footpath and finally cover the deck. A great care was taken to cover as fast as possible the fresh UHPFRC surfaces with a wet textile and a plastic foil, as external temperatures quickly reached 35 °C, Figure 2.

Figure 2: processing of the materials on the site.

From a general point of view, one can say that the casting progressed well, as planned on two days on July 16 and 17, 2009, despite minor problems, and that the workers very quickly took the UHPFRC technology into their hands, with standard tools. Dr. E. Denarié and Dr. Pierre Rossi were present for the application and together with Dr. Šajna advised the workers with the help of translators. The workability of the UHPFRC mixes over the full duration of the site was very satisfactory, despite some small incidents. The slope of 5 % was held without difficulties and the casting of footpath and outer faces of the kerbs went as expected.

The bituminous pavement was applied on the UHPFRC surfaces after 7 days of moist curing[1], and the bridge was reopened to traffic just one month after the start of the works.

Owing to the special processing technique used for footpaths (woods platens over ZEMDRAIN® foils), pedestrians and to some extend cyclists could use the bridge at the end of each casting day.

The overall surface appearance of the bridge after the rehabilitation is very satisfactory and barefoot walking is possible on the footpath. Only several parts of the inner faces of the footpath were not filled properly with the UHPFRC and had to be filled later. An unsuccessful attempt was done to do this with a special UHPFRC mix and the decision was finally taken to fill those gaps with a high quality repair mortar adapted for this purpose.

Figure 3: the bridge after the rehabilitation.

Finally, a global assessment of the environmental impact of this system of rehabilitation was done. Four levels of assessment were analysed: 1: One cubic meter materials, 2: Effective material volumes per system, 3: All rehabilitation work involved, 4: All rehabilitation work considering the whole life cycle. Four systems were compared: two traditional rehabilitation systems and two rehabilitation systems using UHPFRC. The difference between the two solutions in the same system was the nature of the binder used.

➔ The impact due to the production of materials is the major contribution to the environmental impact of the rehabilitation. The UHPFRC that use local components have a similar impact than traditional rehabilitation systems using waterproofing membranes. Furthermore, if the durability of the rehabilitation is considered, this study shows that the impact of this innovative system is much lower than all the other rehabilitation systems, Figure 4, as the durability of UHPFRC is much higher than usual concretes,. Further, at a local level, a dramatically shortened site duration (by a factor 3) such as with the use of UHPFRC also helps decrease significantly the amount of detours from end users during bridge closure and thus the CO_2 footprint of the site.

[1] This moist curing is particularly important as the UHPFRC exhibits a very significant self desiccation at early age, and is very prone to drying.

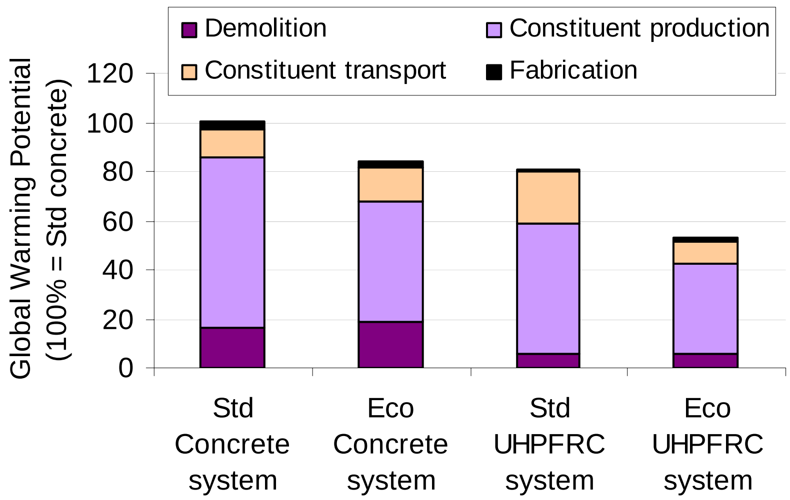


Figure 4: Global Warming potential induced by the different solutions for the Log Čezsoški rehabilitation, considering the life cycle. All solutions are compared to the traditional rehabilitation system with standard concrete taken as reference (100%).

Conclusions

- The concept of rehabilitation of structures with UHPFRC was applied for the first time outside of Switzerland, in Slovenia with a new material designed from local components.
- The application was successful and fast (1 month instead of 3 month with traditional technique) and demonstrated at an industrial scale the ability of the newly designed UHPFRC mixes to reply to the difficult challenges of the site.
- Applications with slopes up to 5 % at least are now possible, and by means of simple surfacing techniques it is possible to achieve uniform textured UHPFRC surfaces on which barefoot walking is possible.
- The newly designed recipes have a dramatically reduced cement content which makes them more economical and particularly attractive from an environmental point of view.
- This successful example of transfer of technology opens up very promising perspectives for the dissemination of the concepts of rehabilitation of civil infrastructures not only in NMS (which was the goal of the project ARCHES) but also in virtually any country.

1. INTRODUCTION

The increasing volume of European transport urgently requires an effective road and rail system in Central European and Eastern Countries (CEEC) with a major investment in building new and assessing and rehabilitating old structures.

Ultra-High Performance Fibre Reinforced Concretes (UHPFRC), characterized by a very low water/binder ratio, high binder content and an optimized fibrous reinforcement, provide the structural engineer with a unique combination of extremely low permeability, high strength and tensile strain hardening. UHPFRC are perfectly suited to the rehabilitation of reinforced concrete structures in critical zones subjected to an aggressive environment and to significant mechanical stresses, to provide a long-term durability and thus avoid multiple interventions on structures during their service life. Extensive R&D works performed during EU project SAMARIS and various full scale applications in Switzerland on bridges have demonstrated that UHPFRC technology is mature for cast in-situ applications of rehabilitation, using standard equipments.

EU Project ARCHES dedicates a significant effort to demonstrate the applicability of this innovative rehabilitation technique in CEEC, with cheaper UHPFRC based on locally available components and improved rheological properties (tolerance to inclined substrates at fresh state).

Achievement of tensile strain hardening, extremely low permeability and self-compacting character is indeed a challenge that few current UHPFRC recipes can satisfy. An original concept of Ultra High Performance matrix 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 a further step, the rheology of those mixes has been adapted to enable them to accommodate challenging 5 % slopes of the substrates at fresh state.

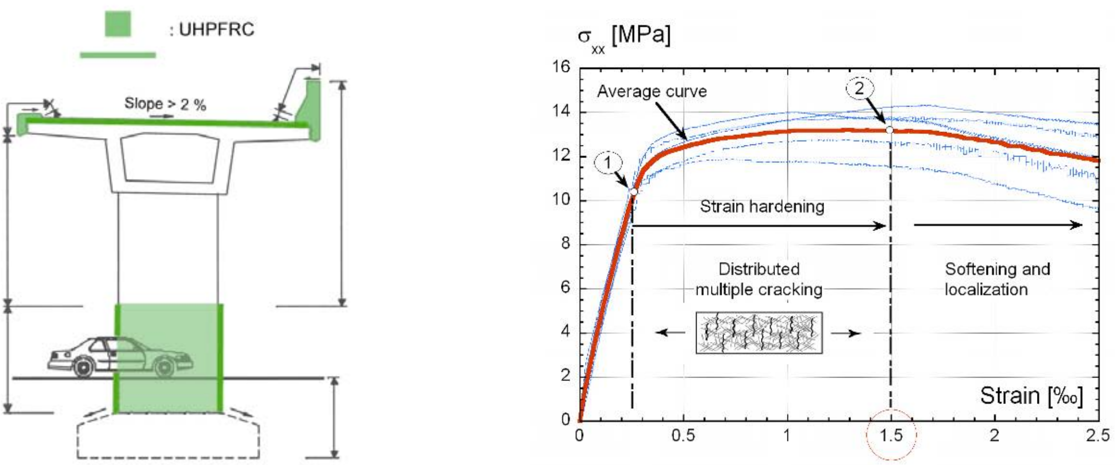
Finally, these new materials have been applied to the rehabilitation of a bridge in Slovenia.

The following document analyses this new application with innovative UHPFRC in the perspective of a sustainable use of construction materials. It also gives practical recommendations based on the experiences gathered during the site.

2. BACKGROUND

2.1 Conceptual approach

The concept of application of UHPFRC for the rehabilitation of structural members, proposed by Brühwiler in 1999, Brühwiler et al. (2008) is schematically illustrated on Figure 1a). An "everlasting winter coat" is applied on the bridge superstructure to "harden" zones of severe environmental and mechanical loads (exposure classes XD2, XD3) and only where the UHPFRC is worth using. Critical steps of the construction process such as application of waterproofing membranes or compaction by vibration can be prevented, and the associated sources of errors avoided. The construction process becomes then simpler, quicker, and more robust, with an optimal use of composite construction. The concept is well-suited for bridges and can also be implemented for buildings, galleries, tunnels or retaining walls.



a) b)

Figure 1: a) Concept of application of the local "hardening" of bridge superstructures with UHPFRC, b) tensile response of UHPFRC (results from 5 dogbone specimens and average curve, after Denarié et al. (2006).

The waterproofing capabilities of the UHPFRC exempt from applying a waterproofing membrane. Thus, the bituminous concrete can be applied after only 7 days of moist curing of the UHPFRC.

This constitutes a very significant time saving with respect to the drying period of up to 3 weeks necessary prior to the application of a waterproofing membrane on a usual mortar or concrete.

Further, the thickness of the bituminous concrete layer can be limited to the absolute minimum necessary for the traffic loads. It is unnecessary to increase it to apply weight on the waterproofing membrane to prevent the formation of air pockets.

When it is required, the combination of the protective properties and deformation capability of UHPFRC (Figure 1 b) with the mechanical performance of reinforcement bars (normal or high grade) provides a simple and efficient way of increasing the stiffness and load-carrying capacity with compact cross sections, Brühwiler et al. (2008). This original conceptual idea has been validated by means of extensive researches aimed at characterizing UHPFRC materials and the structural behaviour of composite structural members (see peer reviewed journal papers at http://mcs.epfl.ch/).

2.2 Examples of applications

A major effort is ongoing in Switzerland to develop optimized combinations of local UHPFRC and reinforcements bars of various grades and apply them for the improvement of existing structures, Brühwiler et al. (2008). Up to know, since 2004, five full scale applications have taken place in this single country on various types of structures with different types of UHPFRC (CEMTEC$_{multiscale}$® and HIFCOM$_{EPFL}$ 13s), with or without rebars, Brühwiler et al. (2008):

- Rehabilitation and widening of a road bridge: the entire deck surface of the bridge over river "La Morge" with a span of 10 m was rehabilitated with 3 cm UHPFRC during autumn 2004 The analysis of the construction costs showed that the rehabilitation realised with UHPFRC was about 10% more expensive that the conventional solution with waterproofing membrane and repair mortar. (providing lower quality in terms of durability and life-cycle costs) However, in the latter case the duration of the construction site would have been largely increased by the required drying period of the mortar, prior to the application of the waterproofing membrane.

- UHPFRC protection layer on a crash barrier wall: a layer of UHPFRC has been applied in September 2006 to the concrete crash barrier walls of a highway bridge nearby Zürich. The main design requirement was to obtain long-term durable crash barrier walls since traffic interruption for future rehabilitation interventions are prohibitive due to the very high traffic volume on this highway. The rheological properties of UHPFRC were adapted for easy pouring into the 3 cm wide formwork to fill a height of 120 cm including a small horizontal part at the bottom of the wall that provides continuity with the conventional bridge deck with a waterproofing membrane.

- Rehabilitation of a bridge pier using prefabricated UHPFRC shell elements (2007): in this application, 4 cm thick UHPFRC shell elements have been prefabricated to form an outer protection shield for the existing 40 year old reinforced concrete bridge pier nearby Zürich, which is located very closely to busy highway traffic and thus virtually not accessible for future maintenance interventions.

- Strengthening of an industrial floor (2007): the 50 year-old drivable reinforced concrete floor of a fire brigade building in Geneva had insufficient load carrying capacity in view of heavier future fire engines. The concept to increase the load carrying capacity of the existing slab of 720 m2 area was to pour a 4 cm thick UHPFRC layer with rebars on top of the existing RC slab, as a replacement of the existing non-load carrying cementitious overlay. The use of the UHPFRC solution turned out to be very economic (compared to the conventional solution of slab demolition and reconstruction), also because the utilization of the fire workers building was only slightly restricted during the intervention and thus user costs could be kept minimal.

- Rehabilitation of bridge "Dalvazza" (2008): The 28.5 m span bridge deck was rehabilitated and strengthened with a combination of 4 to 8 cm UHPFRC and rebars. Gravel was sprayed on the fresh UHPFRC to obtain a ready to use surface for the traffic, without bituminous pavement

3. LOG ČEZSOŠKI BRIDGE REHABILITATION

3.1 Introduction

The Log Čezsoški bridge is located in the very northwest of Slovenia, close to the city of Bovec, and crosses the Soča river, in a mountain region. It has only one lane and a frequent traffic as it is the only link between the two sides of the river within 15 km. It connects the small village of Log Čezsoški with the main road Žaga – Bovec.

Figure 2: Geographical situation of the Log Čezsoški bridge – Slovenia

The total length of the 4.5 m wide bridge over 3 spans is 65 m. It was built in 1973 and has not been rehabilitated since. The owner is the municipality of Bovec.

A rehabilitation was foreseen for 2009 to replace the waterproofing membrane, the dilations, and replace damaged materials on the upper surface and sides of the deck and footpath.

➔ *The requirements of the owner were the durability and a minimum possible duration of the site, plus the possibility to walk barefoot on the finished UHPFRC surfaces of the footpaths.*

➔ *A budget was fixed for all the rehabilitation works, corresponding to a traditional rehabilitation with repair mortar and waterproofing membrane for the deck.*

Figure 3 shows the longitudinal cross section of the bridge. Figure 4 presents views of the bridge before the rehabilitation. One can notice on the lower face that the upper surface leaks.

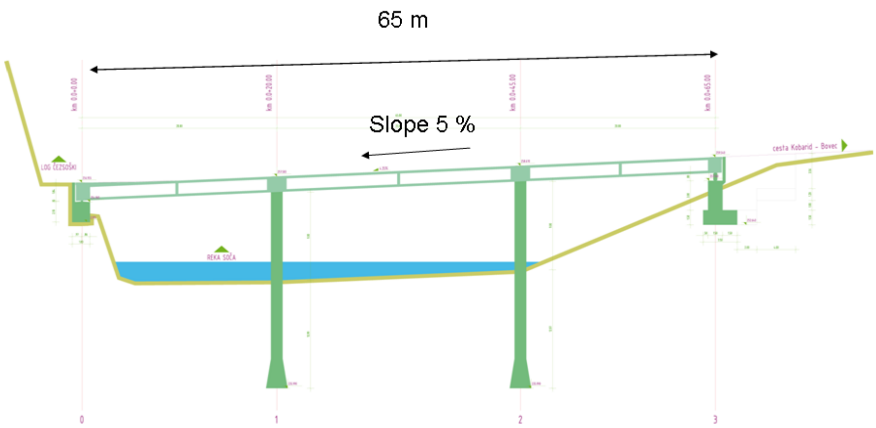


Figure 3: Longitudinal cross section of the bridge.

Figure 4: Overview of the bridge, deck, and lower face close to abutment, prior to rehabilitation.

3.2 Concept of rehabilitation

The cross section of the bridge, with the concept of rehabilitation is shown on Figure 5.

The rehabilitation was designed under the guidance of Dr E. Denarié (MCS-IIC-EPFL) by Dr A. Šajna (ZAG) in close cooperation with Mr B. Ipavec, engineer from Primorje. The contractor was CPG (Nova Gorica).

- A continuous UHPFRC overlay with no dry joints is applied to protect the full upper face of the bridge deck, footpath and external faces of the kerbs.
- The thickness of the UHPFRC layer is varied according to the more or less difficult geometry to cast, and also in order to maximize the efficiency of the fibrous mix. The deck (A) has an overlay of 2.5 cm, the inner faces of the kerbs (B), 3 cm, the footpaths (C) 3 cm, as well as the external faces of the kerbs (D).

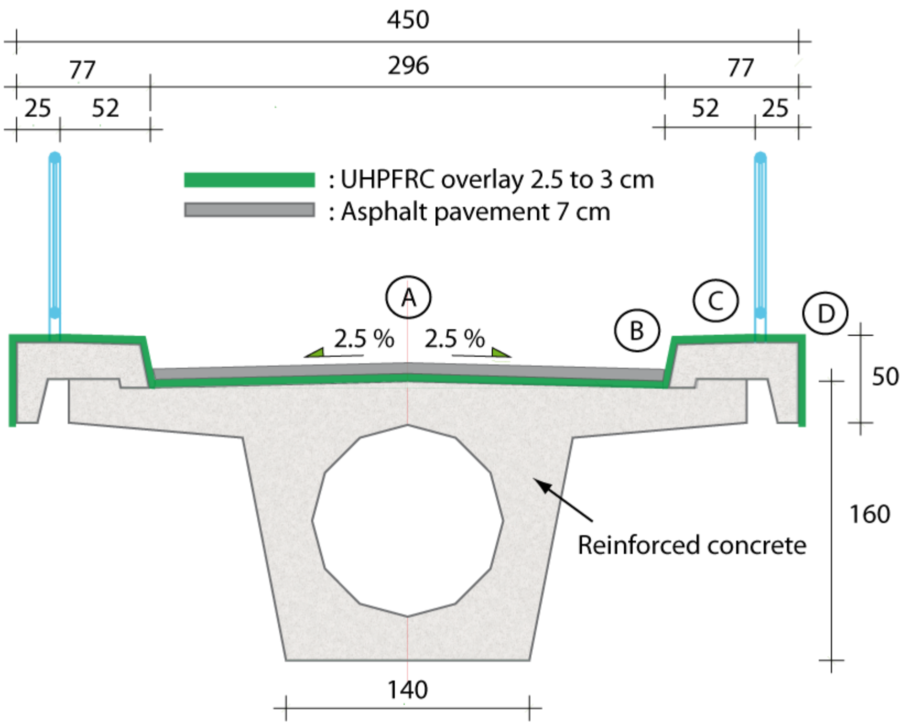


Figure 5: Cross section of the bridge with concept of rehabilitation, dimensions in cm.

The selected concept with no dry joints along the full cross section guarantees a continuous protection. However, it sets high requirements to the choice of the UHPFRC mixes:

- For parts (A), and (C): ability to hold the longitudinal and transversal slopes of 5 % and 2.5 %.
- For part (D), no slope tolerance needed but ability to fill properly the formwork over 50 cm height with a width of 3 cm.

- For part (B); most challenging, ability to hold the slopes and to penetrate in the narrow space of 3 cm of the formwork, without however completely flowing throughout it as the lower part of the formwork has to remain open to guarantee the continuity of the overlay without any dry joint.

It was not possible to produce and cast the 12 m^3 UHPFRC needed for the full intervention in one day. Consequently, a transversal casting joint was foreseen at mid deck surface and the works were realized over two days.

3.3 UHPFRC composition and production

Following the requirements of the concept of rehabilitation, two new UHPFRC recipes of the $CEMTEC_{multiscale}$® family, with new[2] matrices developed within the ARCHES project, with different rheological properties were used.

Both recipes had similar basic components (Cement CEM I 52.5 R from Salonit, Limestone filler IGM from Gorazde, Microsilica from SEPR, Superplasticiser Zementol Zeta Super S® from TKK), with a mass ratio Microsilica/Cement of 0.20 and equal limestone filler and cement contents in mass. Their Water/(Cement + Limestone Filler)[3] ratio was 0.170.

The reinforcement of the ultra compact matrices was provided by a $CEMTEC_{multiscale}$® mix of micro (steel wool – 1 mm length) and macrofibres (l_f=10 mm, aspect ratio: 50) with a total dosage of 706 kg/m^3 (9% vol.) originally developed at LCPC, Rossi et al. (1997, 2005). The detailed recipes and origins of the components are given in Appendices 1 and 2.

Recipe CM32_11 with 763 kg/m^3 cement, 763 kg/m^3 Limestone filler is self compacting but has very limited slope tolerance. It was chosen to fill part (D).

Recipe CM32_13 with 763 kg/m^3 cement, 763 kg/m^3 Limestone filler was designed to hold slopes of 5 % at fresh state by means of the addition of a thixotropizing agent – SIKA Extender.®, Appendix 5. Its slope tolerance and thixotropic character had been validated by full scale trials in 2008 and once again one day before the site.

For comparison, the UHPFRC recipe CM23 used for the rehabilitation of the bridge over la Morge in 2004, Denarié et al. (2006a), used only pure CEM I 52.5 with a dosage **of 1434 kg/m^3**. ➔ The new Slovene UHPFRC recipes have thus a dramatically lower cement content which is very positive from an environmental and also economical point of view.

The recipes were also validated by small scale laboratory tests on models of geometries similar to parts (B)-(C), and (D) as will be shown later.

➔ It was the first time that the new Slovene UHPFRC $CEMTEC_{multiscale}$® mixes designed during the ARCHES project were applied at an industrial scale, and also the first time that this type of materials was used for rehabilitation in a country other than Switzerland.

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[2] The concept of development of new UHPFRC matrices with Limestone filler developed in this study is in the process of being patented. A patent application was filed in July 2009 by Dr. E. Denarié and Dr. Y. Houst from EPFL.

[3] When mineral additions are used in UHPFRC; the relevant parameter for the performance of the mix is not the usual Water/Cement ratio but rather the Water/Fines = Water/(Cement+Limestone Filler) ratio – see report D06.

The UHPFRC were prepared at a concrete plant in Bovec, with a standard mixer, Figure 6. The mixer turned out to be well adapted to the production of the UHPFRC. The average mixing time of all components **was 12 minutes**. No segregation of the matrix or fibres occurred.

The cement and limestone filler were directly taken from silos over the mixer. The other components of the mixes were weighed under the lead of Mrs J. Šuput (ZAG) and Mrs L. Reščič (Salonit) in a continuous process to guarantee a steady production rate of the UHPFRC for the site.

Figure 6: Concrete mixer used for the preparation of the UHPFRC.

The workability of the mixes had been tested previously in the laboratory at ZAG over 2 hours with slump flow tests repeated on the same batch, at 30 minutes intervals There were no significant workability losses over 2 hours after water addition.

The transport of the fresh UHPFRC to the site distant of 15 km was realised with 2 concrete trucks alternatively. In order to have sufficient filling of the trucks, it was decided to prepare consecutively 2 or 3 batches of 318 litres (maximum quantity that could be produced in the mixer), store them in the truck and leave for the site.

The amount of the lost UHPFRC in the truck barrel was initially estimated to be around 100 litres. This quantity finally turned out to be much smaller and negligible.

The barrel was not pre-wetted before being filled with the UHPFRC. It was slowly rotated during transport. Once on the site, the barrel was vigorously rotated for 2 minutes to stir the UHPFRC before pouring it into carts or directly onto the bridge deck.

➔ *The 2 minutes stirring is extremely important to fluidity the thixotropic UHPFRC mixes CM32_13 before their pouring and to minimize the losses in the truck barrel. It has to be repeated each time before a new quantity of material is extracted from the truck.*

Total duration of production of three batches of 318 litres of UHPFRC and transport to the site was around 45 minutes, similar to the production rate for the application on the bridge over river la Morge in 2004.

3.4 Optimization of processing

Sadouki et al. (2008) demonstrated that for thin UHPFRC overlays (3 cm) the roughness of the substrate plays a very significant role in their tensile load carrying capacity. The roughness actually decreases the efficient cross section. The middle line of the roughness cannot be considered as a reference for the thickness as most UHPFRC material under it is not connected and useless for the load carrying capacity. Consequently, the roughness of the substrate should be decreased as far as possible, especially if one uses very thin UHPFRC overlays (2.5 cm). On this basis, the surfaces of the bridge were prepared with minimum roughness as shown on Figure 7.

Figure 7: Surface preparation of the deck and footpath.

To help the de-airing of the UHPFRC in the narrow space of the outer and inner faces of the kerbs and also to provide a fibres free surface for the footpath, a ZEMDRAIN® membrane was applied on the inner sides of the formworks for lateral faces, and pressed on the fresh UHPFRC for horizontal surfaces. The additional benefit of this technique is the textured surface obtained. Preliminary laboratory tests at ZAG demonstrated the benefits of this technique as shown on Figure 8.

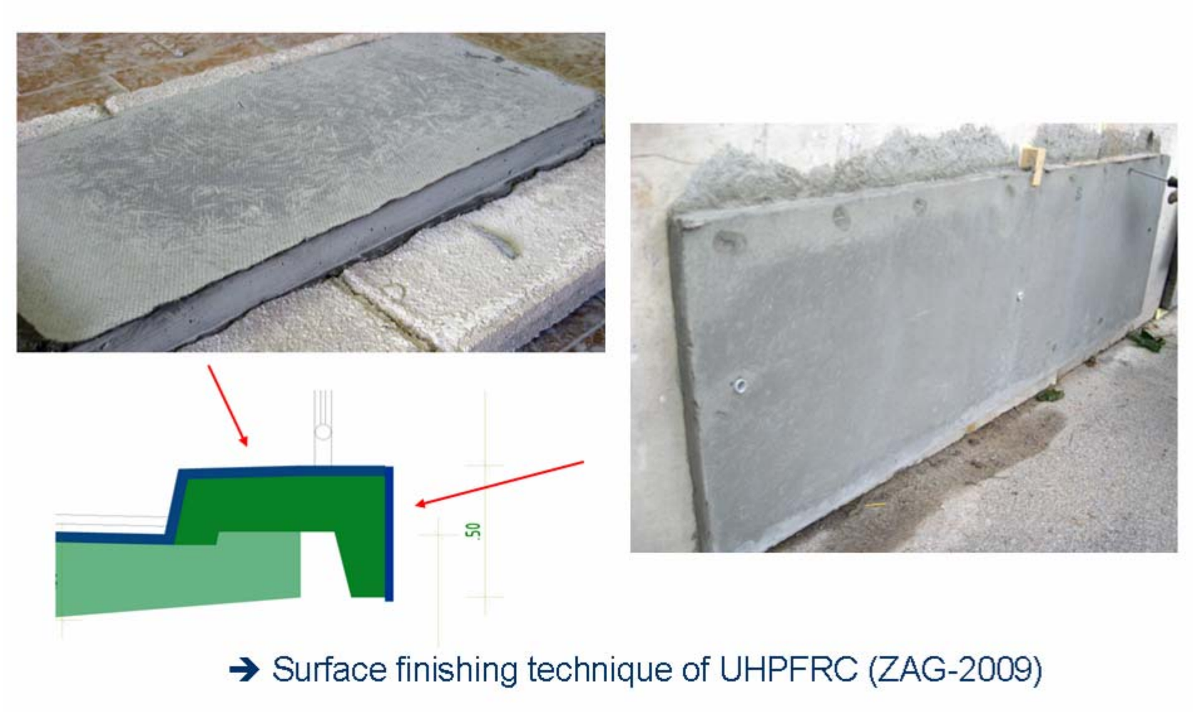

Figure 8: Application of ZEMDRAIN® membranes for the surfacing of UHPFRC.

The same principle was applied to the open formwork of the inner face of the kerbs, which had to be cast with the thixotropic mix CM32_13. Further, in order to obtain a continuous UHPFRC overlay without longitudinal dry joints, it was necessary to cast the deck, inner faces of footpaths, and footpaths in continuity with a formwork open a the bottom.

Only a thixotropic material such as CM32_13 permits this as shown on Figure 9. This technique was used for the application on the bridge.

Figure 9: Trial tests for casting the inner faces of kerbs with an open formwork. Thick-

ness of the UHPFRC layer along the inclined part is 3 cm.

Finally, the transversal joint was realized after the example of the rehabilitation of the bridge over river La Morge, shown on Figure 10. However, no rebars were used to connect the two parts of the joint. Laboratory tests at ZAG have shown that the horizontal overlapping zone of UHPFRC is sufficient to transfer the loads, Appendix 6.

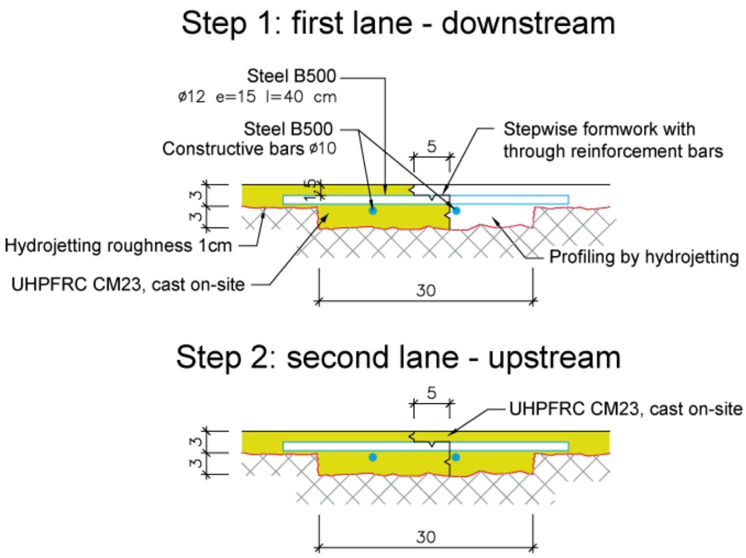

Figure 10. Transversal joint geometry and principle.

Figure 11 shows the groove realized at mid-deck surface for the transversal joint. The groove has 2.5 cm extra depth and is done only on the deck. It would have been too complex to apply this concept to the inner and outer faces of the kerb.

Figure 11: Groove for transversal joint at mid-deck surface.

3.5 Application on site

The material was poured directly from the truck into carts for the casting of the outer faces of the kerbs, or onto the bridge deck or open faces of the footpath. For each day of casting, the outer faces of the kerb were first realized with mix CM32_11. An inclined plate helped the workers fill the material in place. The material CM32_13 was then used to cover the footpath, fill the inner face of the footpath and finally cover the deck. A great care was taken to cover as fast as possible the fresh UHPFRC surfaces with a wet textile and a plastic foil, as external temperatures quickly reached 35 °C.

- Application of material CM32_11 was done mostly in the early morning and progressed without problems. The typical speed was around 10 m length of outer kerb faces on both bridge sides in one hour.

- Application of material CM32_13 took part for most of it later in the day with already high temperatures. This impaired the workability of the mix for some batches and made the filling of the inner kerb faces difficult. Further the requested stirring of the UHPFRC in the truck, before pouring out was not done properly systematically and for some cases, the mix out of the truck was too stiff which made its application difficult.

Another factor that was not clear at the beginning of the site was that the geometry of the inner part of the kerb, (B) on Figure 5, had been changed. The space for filling had been reduced form the original 3 cm (validated in the laboratory) to 2.5 cm. This significant change, associated to workability difficulties linked to high temperatures is very likely to explain the bad filling of several zones of this part of the bridge.

From a general point of view, one can say that the casting progressed well, as planned on two days, despite minor problems and that the workers very quickly took the UHPFRC technology into their hands, with standard tools. Dr. E. Denarié and Dr. P. Rossi were present for the application and together with Dr. A. Šajna advised the workers with the help of translators. The workability of the UHPFRC mixes over the full duration of the site was very constant and satisfactory, despite some small incidents. The slope of 5 % was held without difficulties and the casting of footpath and outer faces of the kerbs went as expected.

Figure 12 to Figure 14 illustrate the different steps of application with the tools used.

Figure 12: Application of the UHPFRC on the deck.

The bituminous pavement was applied on the UHPFRC surfaces after 7 days of moist curing[4], and 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 month needed with a traditional technique.

Owing to the special processing technique used for footpaths (woods platens over ZEMDRAIN® foils), pedestrians and to some extend cyclists could use the bridge at the end of each casting day.

[4] This moist curing is particularly important as the UHPFRC exhibits a very significant self desiccation at early age, and is prone to drying.

Figure 13: Surfacing of the UHPFRC for the footpath, over the ZEMDRAIN®.

Figure 14: Pouring the UHPFRC CM32_11 for outer face of kerb.

The overall surface appearance of the bridge after the rehabilitation is very satisfactory and barefoot walking is possible on the footpath, Figure 15. Several parts of the inner faces of the footpaths - (B) on Figure 5 were not filled properly with the UHPFRC and had to be filled later. An unsuccessful attempt was done with a special UHPFRC mix and the decision was finally taken to fill those gaps with a high quality repair mortar adapted for this purpose.

Figure 15: The bridge after the rehabilitation.

Figure 16: Detail of the footpath and slope of 5 %.

3.6 Environmental impact

3.6.1 Introduction

The building materials sector is the third-largest CO_2 emitting industrial sector world-wide and in the European Union. This sector represents 10% of the total anthropogenic CO_2 emissions, most of which are related to concrete manufacture (Capros et al., 2001). 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 economic and social equilibrium. Associated environmental problems such as climate change, biodiversity loss, ecosystem degradation (IPCC, 2007; Millennium ecosystem assessment, 2005) and their impacts on economy, which could absorb up to 20% of the world Gross Domestic Product in 2050 (Stern, 2007), are now clearly identified. One of the key sustainability challenge for the next decades is thus to improve the management of natural resources in order to reduce current levels of anthropogenic environmental pressures. In that situation, rehabilitation systems that are consuming less material and releasing less CO_2 than traditional ones have to be developed.

The objective of this study was to evaluate the environmental performance of bridge rehabilitation systems using UHPFRC with traditional and new ECO mixes, on the basis of the case of the Log Čezsoški bridge site.

To perform an environmental evaluation, the Life Cycle Impact Assessment (LCIA) method can be used. It is a methodology for evaluating the environmental load of processes and products during their life cycle, from cradle to grave. Its methodology is based on international standards of series ISO 14040 (ISO, 2006). LCIA has been used in the building sector since 1990 (Fava, 2006), and it is now a widely used methodology (Asif et al., 2007; Ortiz et al., 2008). The principle is to compare different solutions that will provide the same function. In this study the functional unit is the rehabilitation of Log Čezsoški bridge.

Four systems are compared: two traditional rehabilitation systems and two rehabilitation systems using UHPFRC. The difference between the two solutions in the same system is the nature of the binder used. We have made a distinction between a standard solution where CEM I is the only binder that is used and an “eco-solution” where 50% of mineral addition is substituted to cement. This amount of substitution is the amount of mineral addition that has been used for the UHPFRC in the log Čezsoški bridge rehabilitation. It is also an amount that can be considered as a maximum possible substitution solution for conventional concretes (Habert and Roussel, 2009).

3.6.2 Studied rehabilitation systems

As the objective of this study was to evaluate the environmental performance of this rehabilitation system, a comparison was made with more standard systems.

- The first one is to use standard UHPFRC instead of the new matrix developed during the ARCHES project (ARCHES, 2009) and where 50% of mineral additions are substituted to cement.

- The other ones are to compare with traditional rehabilitation systems using conventional concrete (C30/37) that can be done either with CEM I exclusively or with a binder containing 50% of substitution.

The different steps of the rehabilitation are presented in table 1. In table 1a the rehabilitation procedure with UHPFRC system is presented. In comparison to traditional rehabilitation systems, a waterproofing membrane is not needed in UHPFRC systems and no concrete is removed during demolition works. Table 1b shows the procedure with traditional rehabilitation system.

References for environmental data are: [1]: Doka, 2007; [2] Kawai et al, 2005; [3] Classen et al, 2007; [4] Chen, 2009; [5] Lehmann et al, 2007.

3.6.3 Environmental data collection

Figure 17 shows the boundaries of the studied system. It can be seen that attention is paid to the production and transport of materials. All technical data have been used from the Log Čezsoški bridge. Mix design for the different concrete are shown in table 2 with the transport distances of the different component to the ready mix plant which is located at 5 km from the site work. The asphalt comes from a hot mix asphalt plant located at 77 km from the site work.

a)

Descrition	Environmental evaluation	Quantity	
Demolition work			
Removal of existant asphalt and waterproofing mambrane on bridge and access ramp + permanent disposal	Demolition & Disposal, building, bitumen sheet, to final disposal [1]	1 250	kg
	Demolition & Disposal, asphalt, 0.1% water, to sanitary landfill [1]	35 175	kg
Cleaning of upper surface of concrete with high water pressure or sandblasting	Hydraulic cleaner [2]	4	h
Repair works			
Delivery and casting UHPFRC concrete	Ready mix concrete production [4]	11	m^3
Delivery and building asphalt pavement	Asphalt hot mix, at plant [5]	35 175	kg

b)

Descrition	Environmental evaluation	Quantity	
Demolition work			
Removal of existant asphalt and waterproofing mambrane on bridge and access ramp + permanent disposal	Demolition & Disposal, building, bitumen sheet, to final disposal [1]	1 250	kg
	Demolition & Disposal, asphalt, 0.1% water, to sanitary landfill [1]	35 175	kg
Demolition and permanent desposal of concrete curb, thickness 25 cm, width 75 cm.	Demolition & Disposal, building, concrete, not reinforced, to final disposal [1]	68 376	kg
Removal of deteriorated parts of concrete on upper surface by chiselling	Demolition & Disposal, building, concrete, not reinforced, to final disposal [1]	5 760	kg
Cleaning of upper surface of concrete with high water pressure or sandblasting	Hydraulic cleaner [2]	4	h
Repair works			
Delivery and mounting of reinforcement steel	European steel production [3]	1 488	kg
Delivery and casting C30/37 concrete	Ready mix concrete production [4]	53	m^3
Delivery and building of waterproofing membrane	Bitumen sealing, at plant [5]	1 466	kg
Delivery and building asphalt pavement	Asphalt hot mix, at plant [5]	35 175	kg

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

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.

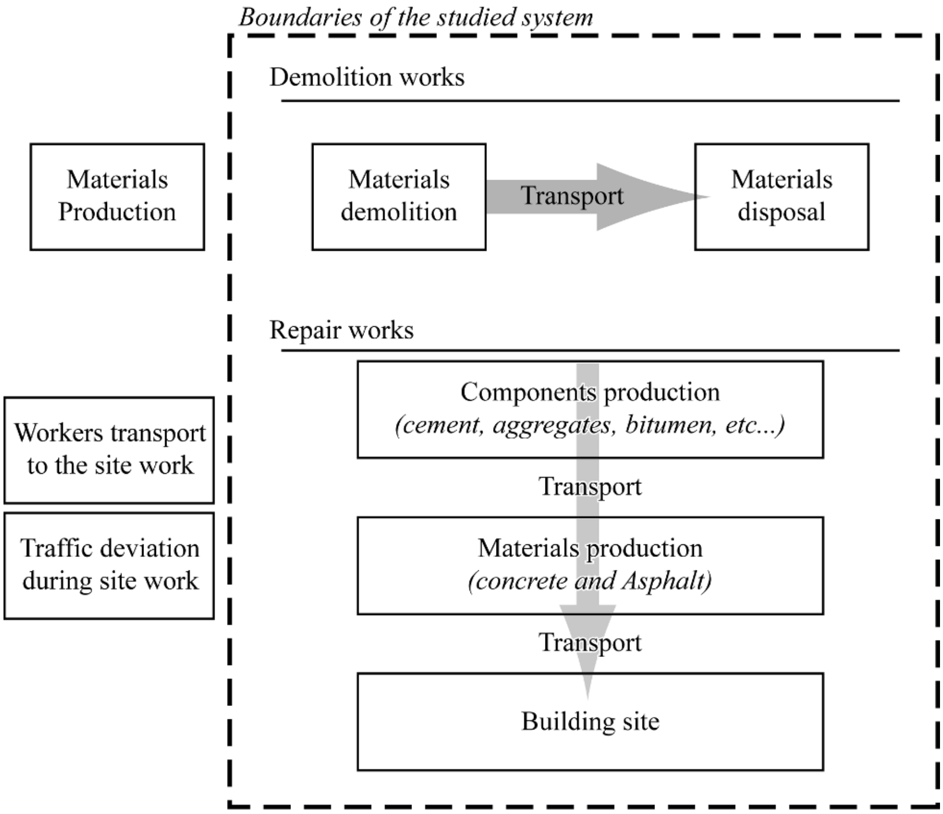

Figure 17: System boundaries for the rehabilitation of the Log Čezsoški rehabilitation.

To calculate the life cycle inventory, the all-inclusive components are calculated with the original system boundary of the EcoInvent database (Kellenberger and Althaus, 2003). The only impact that is shown in the study is the Global Warming Potential (GWP100) expressed in kg CO_2 equivalent and calculated by the CML01 methodology (Guinée et al., 2002). For asphalt work only the production phase has been taken into account as studies have shown that site work is negligible compared to production phase and represent 2% of GWP for the whole life cycle (Ventura et al., 2008). 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 (Kawai et al., 2005) and steel (Xing et al., 2008) structures show that the phase on the site work is negligible compared to production and transport phase. Therefore, no environmental load has been included for the fixation and emplacement 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 seconds) for UHPFRC. Therefore it has been decided to affect 20 times the impact of traditional concrete mixing for UHPFRC. The environmental data used are presented in tables 1 a) and b).

	Traditional concrete			
	Std Concrete		*Eco concrete*	
	Quantity (*kg.m* $^{-3}$)	Distance (*km*)	Quantity (*kg.m* $^{-3}$)	Distance (*km*)
cement	280	51	140	51
Fly Ash			140	150
Sand	687	33	587	33
Gravel	1 242	33	1390	33
Water	183		144	
Super plasticizer	2	2	9	2

	UHPPFRC			
	Std UHPFRC		*Eco UHPFRC*	
	Quantity (*kg.m* $^{-3}$)	Distance (*km*)	Quantity (*kg.m* $^{-3}$)	Distance (*km*)
Cement	1 682	971	765	51
Mineral addition			765	200
Microsilice	153	540	153	540
Steel fibers	707	780	707	780
Water	224		224	
Super plasticizer	55	2	55	2

Table 2: Concrete mix design. Mix designs for traditional systems are calculated using BetonlabPro software (De Larrard and Sedran, 1998)

	Asphalt	
	Quantity (*kg.m* $^{-3}$)	Distance (*km*)
Bitumen	125	130
Aggregates	2375	35

Table 3: Asphalt mix design

3.6.4 Results

The results are presented in table 4. It is interesting to note that the UHPFRC system used for the ARCHES project has similar impact than a traditional rehabilitation system (Table 4). When a detailed study of the different parameters influencing the Global Warming Potential indicator is done, it can be noted that the production of constituent represents the main impact category Figure 18.

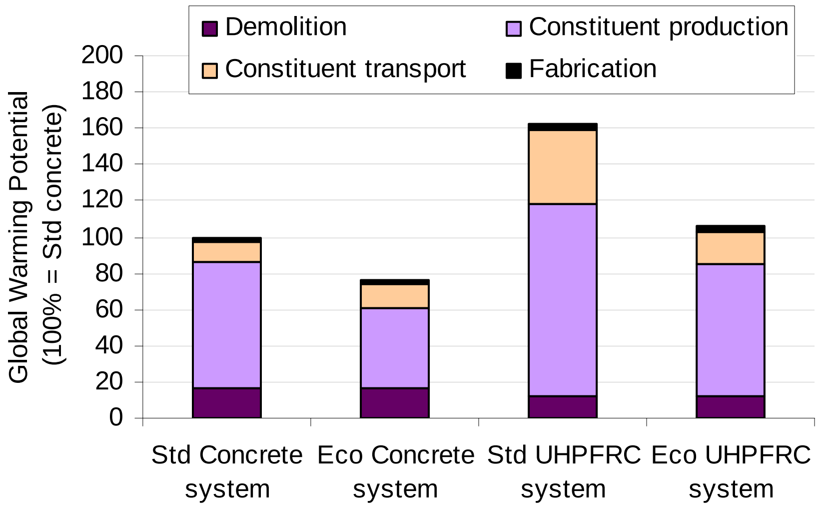

Figure 18: Global Warming potential induced by the different solutions for the Log Čezsoški rehabilitation. All solutions are compared to the traditional rehabilitation system with standard concrete taken as reference (100%).

Figure 19 represents a detail of the impact of the different constituents, with 100% reference taken for the impact of materials used for the traditional system with standard concrete. It is shown that the waterproofing membrane in traditional systems represents 10% of the material impact. When Standard UHPFRC is used the impact of cement production represents the major part of impact and has similar impact than all the materials of traditional systems. In the UHPFRC used in the Arches project, the impact of cement is much lower as 50 % of cement is replaced by limestone filler that has a much lower impact. Steel fibres are then the major contributor to material impact. Finally it is interesting to note that even if the mix design for the eco-UHPFRC system induce a higher cement and steel content per cubic meter (Table 2), the fact that a much lower volume is needed permits to have similar impact for the material used for traditional system (using CEM I) and eco-UHPFRC system Figure 19. On Figure 18 and table 4, it is shown how the innovative concept of the cement substitution by limestone filler that allow to use local cement instead of cement from Le Teil (France) in UHPFRC, considerably reduces the impact of transport.

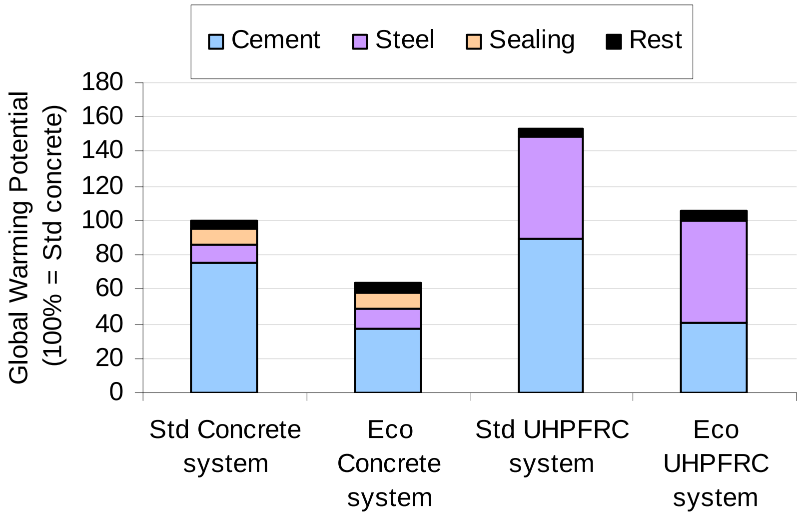

Figure 19: Global Warming potential induced by the material used for the different solutions for the Log Čezsoški rehabilitation. All solutions are compared to the traditional rehabilitation system with standard concrete taken as reference (100%).

3.6.5 Discussion

In this study, the comparison between the four systems has been done by considering the same life cycle. However it is known that the use of a lot of mineral addition in traditional concrete will reduce the durability of the concrete. UHPFRC have a longer durability and studies on the new ECO-UHPFRC with high dosage of mineral addition have shown that the protective performance was the same as that of standard UHPFRC. Therefore the comparison between the four solutions should consider the durability of products. If it is assumed that the durability of a traditional solution is 30 years, the durability of eco-concrete can be set at 80% of that and the durability of both UHPFRC can be assumed to be at least twice longer. To compare the impact of the different solutions, it should then be assumed that one will need 2 rehabilitations with traditional systems while we will do a single rehabilitation with UHPFRC systems. The results of the impact considering the life cycle are presented in Figure 20. Rehabilitation systems with Eco-UHPFRC have then much lower impact than both traditional rehabilitation systems.

	Std Concrete system	Eco Concrete system	Std UHPFRC system	Eco UHPFRC system
Demolition	**4 020**	**4 020**	**2 927**	**2 927**
Concrete	1093	1093		
Bitumen	2927	2927	2927	2927
asphalt	625	625	625	625
Constituent production	**16 629**	**10 724**	**25 515**	**17 569**
Cement	12525	6263		
Sand	87	75		
Gravel	282	316		
Water	2	1		
Plasticizer	71	369		
Steel	1855	1855		
Bitumen sealing	1490	1490		
Asphalt	317	317		
Fly ash		39		
Cement			14948	6795
Limestone filler			0	207
Microsilice			1	1
Microfibres			3241	3241
Macrofibres			6483	6483
Sika Extender (HD-PE)			92	92
Adjuvant TKK			434	434
Water			0	0
Asphalt			317	317
Constituent transport	**2 794**	**3 083**	**9 923**	**4 338**
concrete	67	67		
Cement	279	139		
Sand	268	229		
Gravel	484	542		
Water	0	0		
Plasticizer	0	0		
Steel	50	50		
Bitumen sealing	135	135		
Asphalt	1511	1511		
Fly ash		410		
Concrete			13	13
Cement			6328	151
Limestone filler			0	592
Microsilice			320	320
Microfibres			821	821
Macrofibres			924	924
Sika Extender (HD-PE)			4	4
Adjuvant TKK			0	0
Water			0	0
Asphalt			1511	1511
Fabrication	**621**	**621**	**631**	**631**
Ready mix plant	198	198	393	393
Sand blasting	358	358	238	238
Anti corrosion painting	65	65		
Total	**24 064**	**18 448**	**38 996**	**25 465**

Table 4: Global Warming potential for Log Čezsoški rehabilitation (in kg CO_2 equivalent). Calculated with CML01 method.

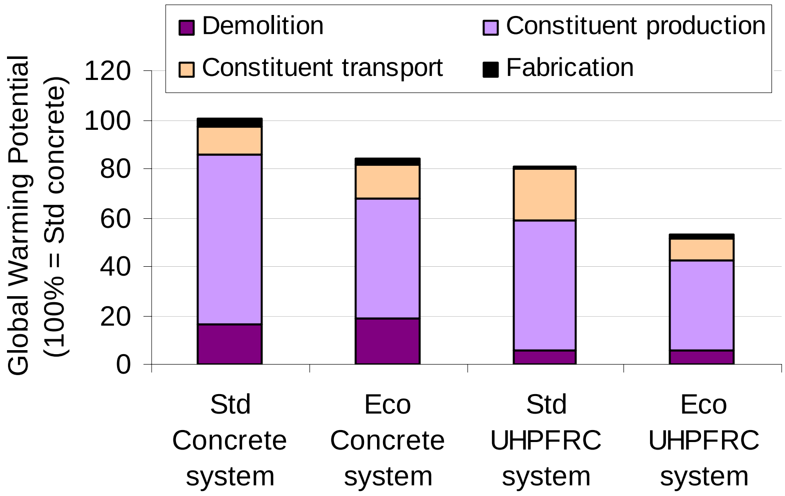

Figure 20: Global Warming potential induced by the different solutions for the Log Čezsoški rehabilitation, considering the life cycle. All solutions are compared to the traditional rehabilitation system with standard concrete taken as reference (100%).

3.6.6 Conclusion

As a conclusion, life cycle impact assessment method allows to compare different solution for bridge rehabilitation with an environmental point of view. As the studied system is not very complex, it is possible to assume a good accuracy of the results.

The impact due to the production of materials is the major contribution to the environmental impact of the rehabilitation. In this study, an innovative rehabilitation system is evaluated. It is shown that this system that uses a new UHPFRC with a large amount of limestone filler has similar impact than traditional rehabilitation systems. Furthermore, if the durability of the rehabilitation is considered, this study shows that the impact of this innovative system is much lower than all the other rehabilitation systems as the durability of UHPFRC is much higher than usual concretes.

4. CONCLUSIONS AND OUTLOOK

4.1 Main conclusions

- The concept of rehabilitation of structures with UHPFRC was applied for the first time outside Switzerland, in Slovenia with a new material designed from local components.
- The application was successful and fast (1 month instead of 3 month with traditional technique) and demonstrated at an industrial scale the ability of the newly designed UHPFRC mixes to reply to the difficult challenges of the site.
- Slope tolerance at fresh state up to 5 % at least is now possible and by means of simple surfacing techniques it is possible to achieve uniform textured UHPFRC surfaces on which barefoot walking is possible.
- The newly designed recipes have a dramatically reduced cement content which makes them more economical and particularly attractive from an environmental point of view.
- This successful example of transfer of technology opens up very promising perspectives for the dissemination of the concepts of rehabilitation of civil infrastructures not only in NMS (which was the goal of the project ARCHES) but also in virtually any country.

4.2 Future research and applications

Among others, following aspects clearly deserve a special attention to further improve the efficiency of the concept and the range of its applications:

- Development of tensile strain hardening UHPFRC mixes with synthetic fibres.
- Development of monolithic UHPFRC overlays with combined functions of protection or reinforcement and pavement (with skid resistance), to simplify and accelerate further the construction process.

➔ Among many other potential applications, one may cite the rehabilitation of dilation joints, for which the toughness, durability and slope tolerance properties of the new UHPFRC mixes would find the best use.

NOTE: a movie on the Log Čezsoški application has been realized. A DVD is available upon request

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APPENDIX 1 – UHPFRC RECIPES

Component	Fibres [%]	ρ [kg/m³]	Mass [kg/m³]	Volume [l/m³]
Powders				
Cement (C)		3110	**762.8**	245.3
Limestone filler (LF)		2660	**762.8**	286.8
Microsilica (SF)		2200	**152.6**	69.3
Added water		1000	**223.7**	223.7
Steel wool[5]		7850	**706.5**	90
Steel fibres 10 mm		7850		
Admixture Superplasticiser (SP)		1100	**54.9**	49.9
Total water (W)		1000	259.4	259.4
Air				35
Total	**9**		**2663**	**1000.0**

W/(C+LF+SF)	**0.155**
W/(C+LF)	**0.170**
SP/(C+LF)	**0.036**
SF/C	**0.200**

LF/C mass	**1**

Table 5: Composition of material CM32_11

Note: The fibrous mixes used in this study belong to the family CEMTEC$_{multiscale}$® developed by Dr. P. Rossi – LCPC Paris, and modified at MCS-EPFL and ZAG for the application to rehabilitation. CEMTEC$_{multiscale}$® *recipes are covered by the French patent applications #FR2806403 and #FR2806404 (both published on 9th September 2001) and by the PCT patent application WO0168548 (published on 9th September 2001).*

5 The detailed composition of the fibrous mix is patent protected and is available upon request, with a license of exploitation.

Component	Fibres [%]	ρ [kg/m³]	Mass [kg/m³]	Volume [l/m³]
Powders				
Cement (C)		3110	**758.7**	244
Limestone filler (LF)		2660	**758.7**	285.2
Microsilica (SF)		2200	**151.7**	69
Added water		1000	**222.5**	222.5
Steel wool[6]		7850	**706.5**	90
Steel fibres 10 mm		7850		
Admixture Superplasticiser (SP)		1100	**554.6**	49.7
Total water (W)		1000	258	258
Sika Extender (SE)		980	4.6	4.6
Air				35
Total	**9**		**2658**	**1000.0**

W/(C+LF+SF)	**0.155**
W/(C+LF)	**0.170**
SP/(C+LF)	**0.036**
SF/C	**0.200**

LF/C mass	**1**
SE/(C+LF) mass	**0.030**

Table 6: Composition of material CM32_13

Note: The concept of development of new UHPFRC matrices with Limestone filler developed in this study is in the process of being patented. A patent application was filed in July 2009 by Dr. E. Denarié and Dr. Y. Houst from EPFL[7].

[6] The detailed composition of the fibrous mix is patent protected and is available upon request, with a license of exploitation.

[7] Denarié E., Houst Y., 2009c. Cement matrices for High Performance Fibre Reinforced Cementitious Composites (HPFRCC), in particular Ultra High Performance Fibre Reinforced Concretes (UHPFRC), *patent application n° B-6160-EP*, 14.07.2009, EPFL

APPENDIX 2 MATERIALS AND SUPPLIERS (UHPFRC)

Component	Type	Supplier
Cement	CEM I 52.5 R	**SALONIT ANHOVO** Anhovo, Vojkova 1 SI-5210 Deskle, Slovenija **Mrs Lojzka Reščič** **lojzka.rescic@salonit.si**
Limestone filler	IGM fine (Mean diameter 13 μm)	IGM Zagorje - industrija gradbenega materiala, d.o.o. Savska cesta 1 1410 Zagorje ob Savi - Slovenia **tajnistvo@igm.si**
Microsilica	SEPR (mean diameter 0.5 μm) Specific surface 12 m^2/g, SiO_2 > 93.5 %, white	SEPR, B.P. 40, F-84131 Le Pontet Cedex, France **Mr J.M. Detalle** **jean-marie.detalle@saint-gobain.com**
Steel fibres	Straight l_f=10 mm, d_f=0.2 mm Type OL 10/20	NV Bekaert SA, Bekaertstraat 2 B-8550 Zwevegem **Mrs C. Deprez** **Catherine.Deprez@bekaert.com**
Steel wool	Crushed steel wool, ref. FbGV2 Code LALACD.BR	Gervois, 1, rue Boucher de Perthes, F-80580 Pont-Remy, France, **Mr. Riquiez or Mrs Pallier** **gervois01@hexanet.fr**
Superplasticiser	Zementol Zeta Super S®	TKK , Srpenica 1 5224 Srpenica – Slovenia **Mrs L. Cernilogar** **l.cernilogar@tkk.si**
Thixotropizing admixture	Sika Extender (Sika Stellmittel)	SIKA SISTEMI ZA LEPLJENJE IN TESNENJE D.O.O. Prevale 13 - 1236 Trzin - Slovenia **info@si.sika.com**

APPENDIX 3 - BATCHING SEQUENCE OF CEMTEC$_{MULTISCALE}$® RECIPES TYPE CM32_11 AND 13

- Add cement, microsilica, steel wool and thixotropizing admixture (if applicable) in dry mixer.
- Mix for 2 minutes, then stop mixer.
- Add limestone filler and mix for one minute then stop mixer.
- Add fine quartz sand if applicable and mix for 30 seconds.
- Add all water followed by all superplasticiser while mixer runs.
- Let mixer run until getting a homogeneous mix, with fluid consistency (duration around 8 minutes for mixes type CM32 or CM33, depending on mixer type).
- If the mixer has to be stopped for feeding, add half the quantity of short steel fibres (10 mm).
- Mix for 30 seconds until all fibres are properly coated and dispersed.
- Stop mixer and add second half of the fibres.
- Otherwise (preferably) add fibres continuously while mixers turns
- Mix until all fibres are properly coated and dispersed.
- Total mixing time around 12 minutes.

Note: the first batch, in a dry mixer, always shows a stiffer consistency than subsequent batches with the same UHPFRC. One can cautiously pre-wet the mixer before the first batch, to avoid this effect.

APPENDIX 4 - PRECAUTIONS FOR THE PRODUCTION AND USE OF CEMTEC$_{MULTISCALE}$®

- The compatibility between the cement, the superplasticiser and the silica fume to achieve the target values of workability, mechanical performances and protective function should be tested on small scale batches before realising larger batches. Further, prior to the application on a structure, large scale trial tests in comparable conditions of ambient temperature have to be performed to finalize the UHPFRC recipes
- The concrete mixer can be cautiously be pre-wetted before the filling with the raw components of the UHPFRC.
- The barrel of the concrete truck should not be pre-wetted before the filling with the fresh UHPFRC. The barrel shall be slowly rotated during transport
- Thixotropic UHPFRC mixes require a vigorous stirring by means of a 2 minutes fast rotation of the truck barrel before being poured, in order to obtain the necessary fluidity for casting and to minimize losses in the barrel.
- Safety precautions to be followed are identical to those prescribed for the production of normal concretes with silica fume.
- During all steps of the production and casting of the UHPFRC and after its hardening, special care has to be taken to protect the skin and eyes of the personal from injury by protruding short steel fibres (10 mm long). During the handling of 10 mm long short steel fibres, during the mixing and pouring of the UHPFRC, and during the cleaning of the batching equipments (mixer, etc.) and of the moulds and forms when the UHPFRC has hardened, it is mandatory to protect the eyes of the operators with fully covering glasses from accidental projection of fibres in the face. Further, the aspect ratio of the 10 mm long steel fibres makes them especially prone to penetrate under the skin. For this reason, the use of thick protection gloves is mandatory during all steps of the production process of UHPFRC.
- The duration of mixing of the 10 mm long steel fibres has to be, according to the performances of the mixer, sufficient to insure a uniform dispersion of the fibres in the UHPFRC, but short enough in order to avoid the formation of agglomerates of fibres.
- The presence of protruding steel fibres on the surface can constitute a danger during the handling of hardened UHPFRC specimens (for the personal and for the lifting equipments such as slings). Hardened UHPFRC specimens shall be cautiously examined before manipulation.
- Free surfaces of fresh UHPFRC shall be protected from desiccation as soon as possible. Due to its extremely low W/B ratio, and to the small thickness of the layers applied for rehabilitation applications, UHPFRC overlays are very sensitive to desiccation. A plastic foil shall be applied on the fresh UHPFRC as soon as possible after casting. A moist curing (daily spraying of water) of 8 days shall then be applied as soon as the material is hardened (around 24 hours after contact between binders and water for the UHPFRC recipes described in this report).

APPENDIX 5 – SLOPE TOLERANCE

The tolerance to a slope of a fresh cementitious material is related to its rheological behaviour. One can distinguish two fundamental rheological parameters:

- The yield stress τ which can be compared to static friction. This is the threshold value for putting the material into motion.
- The dynamic viscosity μ which can be compared to dynamic friction. This is a measure of the effort required to make the material go on moving.

The effect of the yield stress on slope tolerance under the action of gravity is illustrated by Figure 21, from de Larrard (1999). The yield stress opposes the gravity force that tends to make the material move downwards.

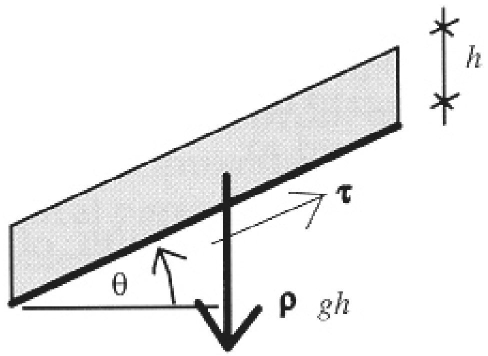

Figure 21: Equilibrium of a fresh material on an inclined substrate , after De Larrard (1999).

Normal concretes with low content to no superplasticiser (workability classes S1, S2) exhibit a yield stress higher than zero and can support slopes. The value of the yield stress is very well inversely correlated with the Slump value. The larger the slump, the lower the yield stress.

The extended addition of super plasticizers decreases significantly the yield stress of concretes. In self compacting concretes, the yield stress is almost zero and slump is maximum and is no more a reliable measure. The "slump flow" test rather uses the final diameter and time to reach 500 mm diameter (t_{500}) as rheological indications. Those are however closely related to the viscosity rather than to the yield value.

Self compacting concretes can be made tolerant to slopes to some extend but the combination of a self compacting character with tolerance to slopes up to 5 % is a very challenging task.

The following example shows how a UHPFRC type CM32 was modified with a thyxotropizing addition to make it tolerant to a slope of 3 %. An unconfined slope tolerance test is realized. The material is first poured in a wood frame applied on an inclined rough support. The frame is carefully removed and the behaviour of the fresh mix is observed.

Figure 22a), with the Thixotropizing addition, the material remains as a block and the thickness of 3 cm is preserved. At the contrary, Figure 22b), without the addition, the material flows and the thickness cannot be preserved.

a) b)

Figure 22: Unconfined slope tolerance test on CM32 UHPFRC recipe, imposed slope = 5 %, a) with thyxotropizing addition, mix CM32_13, b) without, mix CM32_11.

APPENDIX 6 - UHPFRC JOINT DURABILITY AND MECHANICAL PERFORMANCE TESTS – ZAG (2009)

Introduction

When UHPFRC is used to protect or strengthen the concrete structure, joints in the UHPFRC layer should generally be avoided, as they are the weakest chain-links of the protective layer.

Unfortunately due to different reasons like enabling at least alternating traffic flow across the bridge or due to too large areas to be cast in one day, in some cases joints in UHPFRC layer can not be avoided. If this is the case, joint shall generally be placed out of the tensile zone.

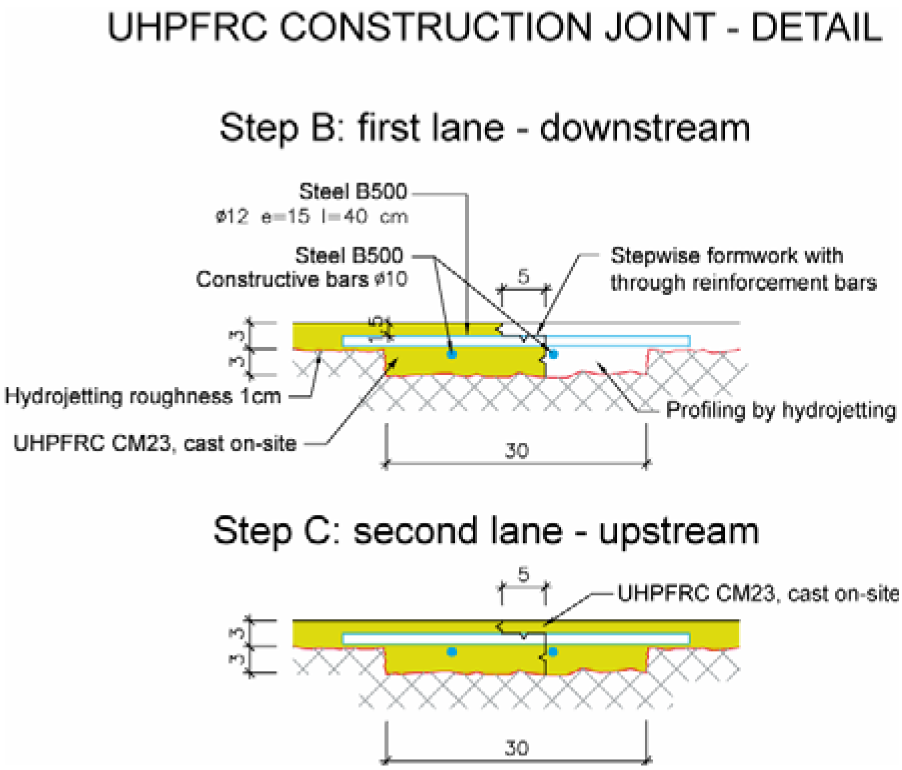

Figure 23: Longitudinal construction joint for the UHPFRC of the "Le Morge" bridge deck, SAMARIS.

Figure 24: The transversal joint groove on the Log Čezsoški bridge.

Regardless where the joints are placed the functionality of UHPFRC layer shall not be jeopardized. This means that also in the joint region the protective function shall be on the same level as elsewhere on UHPFRC layer and that extra measures shall be taken in the joint region to provide the designed strengthening effect.

Within the ARCHES project the mechanical performance and the protective function of different joint outlines were tested. Here forth the test setups and their results are presented.

Preparation of test samples

Samples similar to the ones used for the 4-point bending test (i.e. plates of dim. 20x50x3 cm) were chosen for both, the air permeability tests and for the mechanical performance tests.

To simulate the on-site joint region the thickness of the plates was increased up to 5 cm, which is almost to the double of the in this project used plate thickness, equalling an overlap of two consecutively cast layers of 2,5 cm. The plate dimension enables to test the protective function by means of the air permeability by Torrent and the mechanical properties by means of the 4-point bending test on a same specimen.

Five different joint outlines were foreseen, plus a reference sample without a joint. The reference plate (J01) had no joint. The second joint type (J02) was prepared without an overlap, the two half were cast just face-to-face within a time gap if 24 hours. The plates marked J03, J04 and J05 had an overlap of 5 cm, 10 cm and 15 cm consequently. To evaluate the contribution of a Re-bar placed in a joint to the mechanical properties the joints marked as J06 were, in addition to an overlap of 15 cm, strengthened with an 8 mm Re-bar in the middle of the cross-section. The cross-sections of all joint outlines are presented in Figure 25.

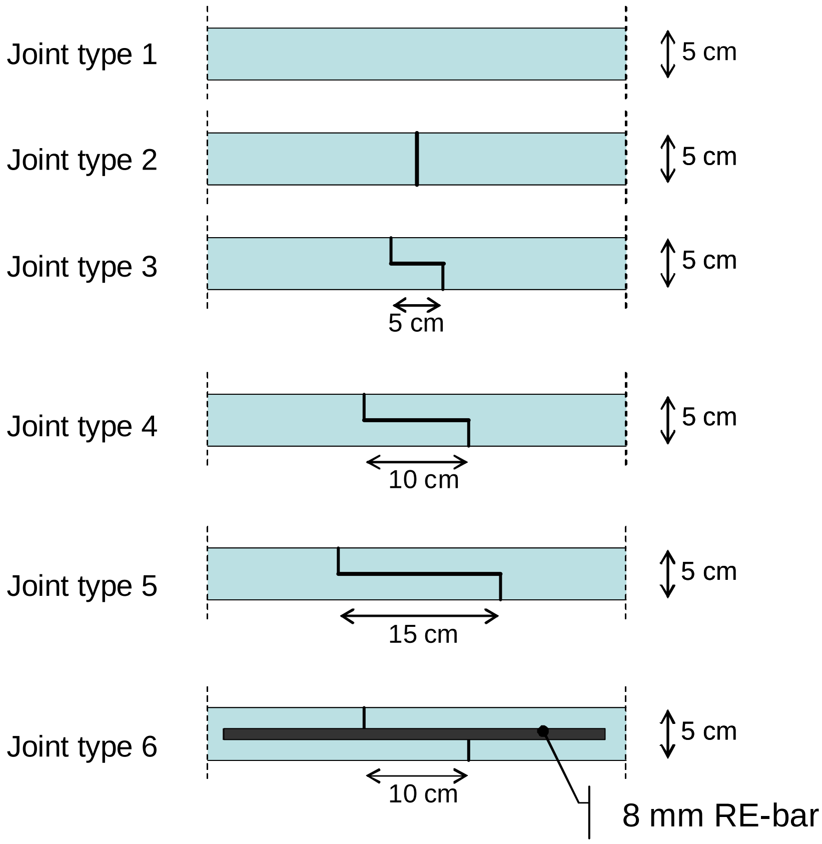

Figure 25: The joint outlines.

To simulate the on-site casting conditions, each sample was cast in to consecutive days, on half on each day (Figure 26). After removing of the joint formwork on the second day, the second half of the specimen was cast without any additional measurements been taken to improve the bond quality on the first half. Two identical samples were prepared for each joint outline. For this investigation the mixture CM32-13 was used.

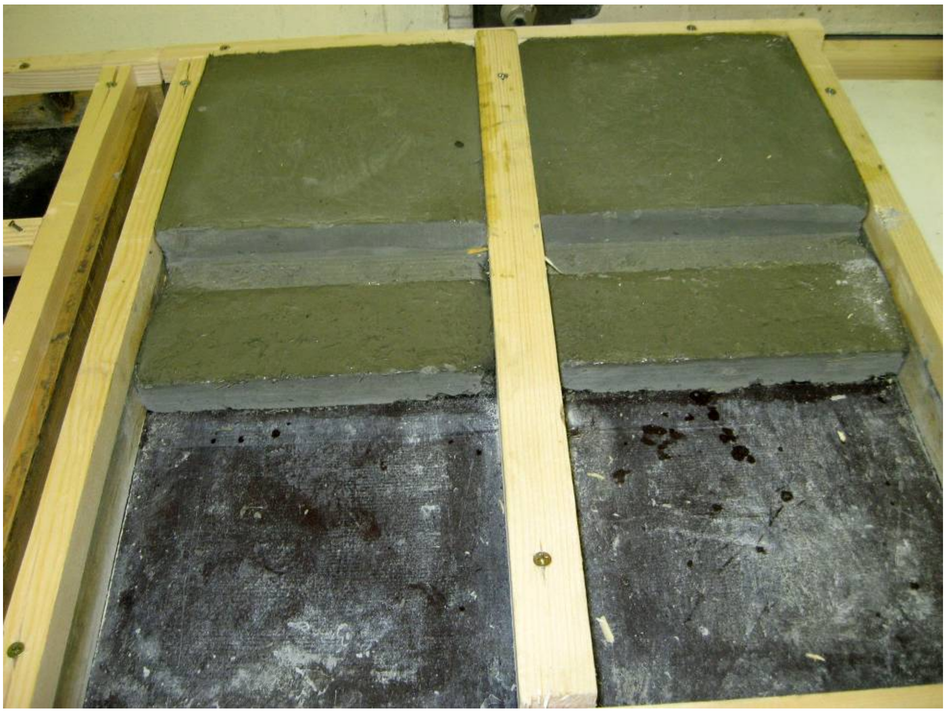

Figure 26: Joint before the second half casting.

Figure 27: Position of the Re-bar in J06.

The samples were un-moulded on the second day after the finishing of casting and put into a climate chamber (acc. to EN 12390-1) for min. 28 days. Before testing they were stored in laboratory conditions.

Testing procedure and results

The idea of the tests was to test the air permeability of the joint during the 4-point bending test, at different loading stages.

Unfortunately the bending test setup doesn’t enable such tests, so it was decided to test the air permeability before and after the bending tests.

Due to bad quality and obviously low bearing capacity was decided not to perform the bending test on the J02 samples.

Protective function of the joints

The protective function of the joint was to be tested by the Torrent air permeability test method at the age of 31 to 41 days. The vacuum chamber was placed in the middle of the joint, on the smooth, moulded surface (Figure 28).

Figure 28: Air permeability test of the joints.

During the tests it was found out that the air tightness of the joint is very poor, therefore it was decided to perform the depth of penetration of water under pressure (acc. to EN 12390-8, Figure 29).

Figure 29: Depth of penetration of water under pressure test.

Based on the depth of penetration of water under pressure tests it was found out, that the water is not penetrating through the plate (or joint) but is leaking from the plate side (Figure 30)

Figure 30: Leaking of water.

Neither air permeability, nor the depth of penetration of water under pressure tests were performed after the bending tests described in the next chapter.

Mechanical performance of the joints

Mechanical performance of the joints was tested by the means of 4-point bending tests, on the plates dim. 20x50x5 cm at the age of 32 to 42 days. The experiment setup was the same as used for all bending tests performed at ZAG, as previously described in deliverable D06 (Figure 31).

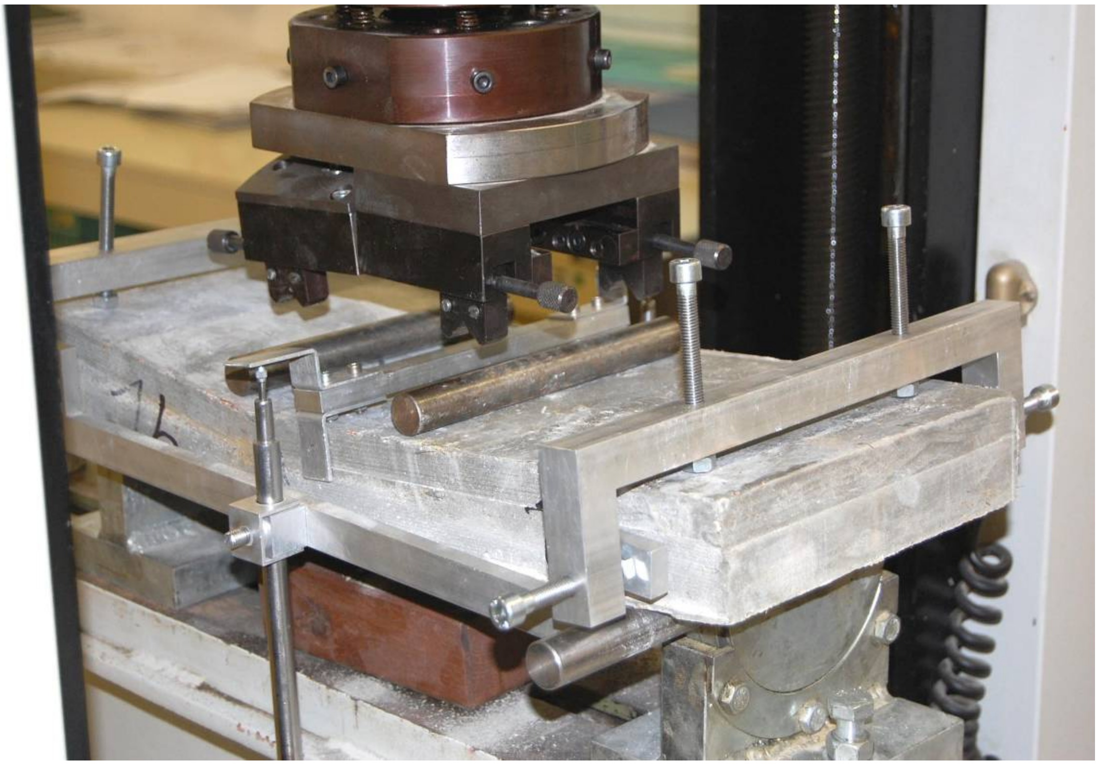

Figure 31: 4-point bending test of the joint-plates.

The results are presented in a form of load-deflection diagram in Figure 32 to Figure 33.

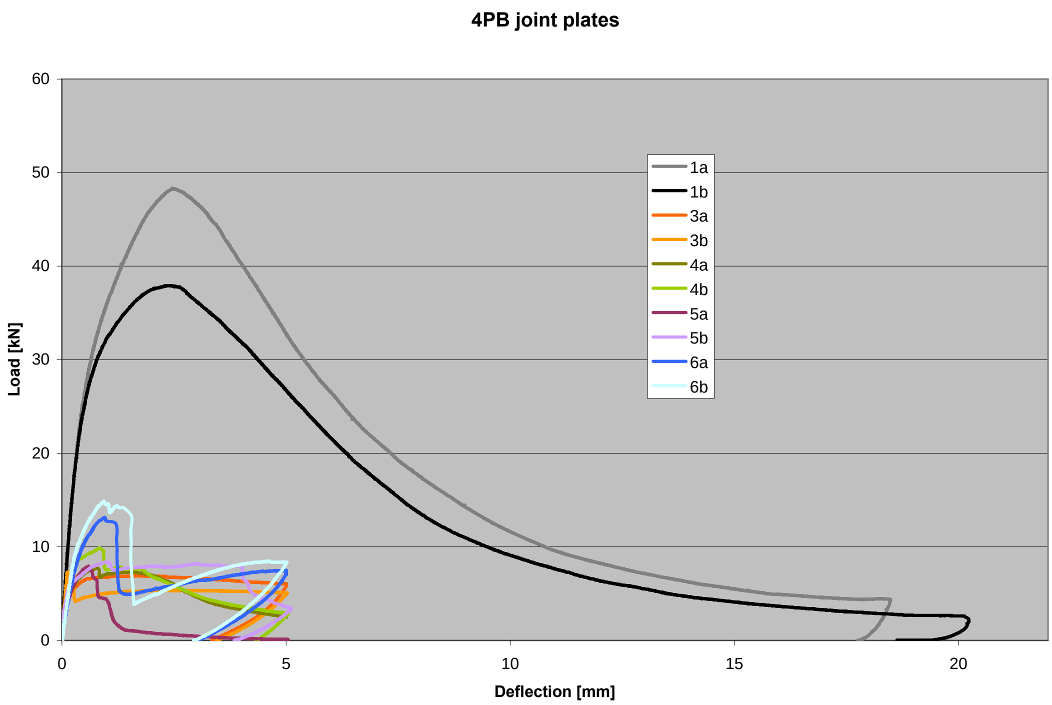

Figure 32: Load-deflection diagrams of the 4-point bending joint tests.

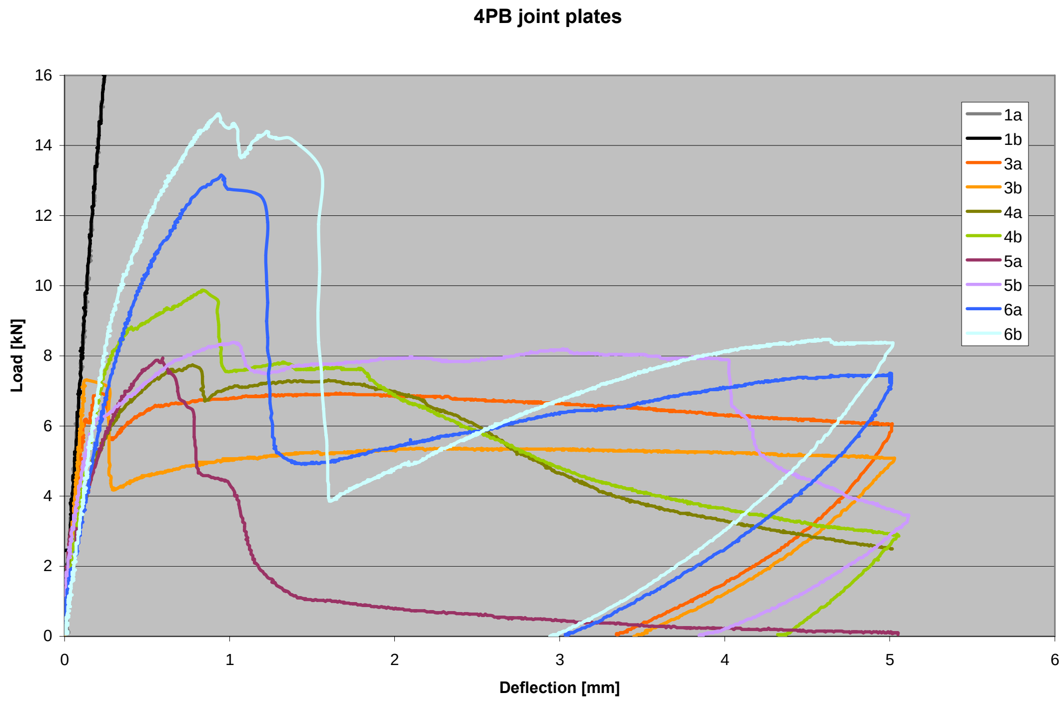

Figure 33: Load-deflection diagrams of the 4-point bending joint tests.

Comments and conclusions

Based on the observation performed during tests and test results following conclusions can be made:

Protective function of the joints

The air permeability test as used is not suitable for the evaluation of the joint protective function. As proven by the resistance to penetration of water, which has also been evaluated as inadequate test method for the evaluation of joint protective function, the water and the air are leaking form the specimen side, and not through the plate, i.e. joint.

During the water penetration test no water was penetrating through the plate, i.e. joint, proving that the overlapping surface of the joint provides sufficient resistance to penetration of water.

All joint outlines, except the face-to-face (J02) one, the response to water pressure seems to be similar, i.e. no influence of the overlapping length was observed.

A new method for the evaluation of the protective function of the joints shall be proposed.

Mechanical performance of the joints

The bending load bearing capacity and the ductility of the joint is much lower than the one of the monolithic sample, as expected. There is a good correlation between the two samples of the same joint outline, except for the J05, the 15 cm overlapping joint.

It can be observed, that the load is mainly transferred through the shear stress in the overlapping surface and through the compressive forces in the compression zone. In the tensile zone the tress transferring is negligible.

Comparing the J03, J04 and J05 one can conclude, that the length of the overlapping surface doesn't influence the mechanical behaviour of the joint significantly, within the range tested.

The influence of the re-bar on the load bearing capacity of the joint is significant. The closer observation of the concrete-reinforcement bond showed that the re-bar was not placed in the tensile zone of the plate and therefore could not fully contribute to the load bearing capacity of the plate (Figure 34).

Figure 34: Failure mode of the concrete-reinforcement bond.