Ultra-High Performance Concrete and Nanotechnology in Construction: Proceedings of Hipermat 2012. 3rd International Symposium Kassel, March 7-9, 2012

Assessment of a UHPFRC based bridge rehabilitation in Slovenia, two years after application

Aljoša Šajna[1], Emmanuel Denarié[2], Vladimir Bras[1]

1: Slovenian National Building and Civil Engineering Institute, ZAG, Ljubljana, Slovenia.
2: Maintenance, Construction et Sécurité des ouvrages, (MCS-ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Suisse.

Within the framework of the EU FP6 Project ARCHES, improved Ultra High Performance Fibre Reinforced Concretes (UHPFRC) based on local components were developed and applied to the rehabilitation of an 36 years old reinforced concrete bridge in Slovenia. Two years after the rehabilitation a thorough visual inspection of the deck and kerbs was performed. During the visual inspection non-destructive and less-destructive on-site tests were performed, such as those to determine the pull-off strength of the UHPFRC layer, as well as its air permeability, the corrosion protection function and the skid resistance were performed. Additionally samples of the UHPFRC were taken for laboratory testing.
The paper presents the results of the assessment, including the visual inspection and test results. Based on these, the successfulness of the UHFPRC based rehabilitation is conformed. As a conclusion the benefits and applicability of improved UHPFRC materials are discussed.

Keywords: Ultra High Performance Fibre Reinforced Concretes, bridge rehabilitation, assessment

1 Introduction

Within the framework of the EU FP6 Project ARCHES, improved Ultra High Performance Fibre Reinforced Concretes (UHPFRC) based on local components were developed and applied to the rehabilitation of a 36-year-old bridge, which is located in the Soča river valley in NW Slovenia (Figure 1a). The complete deck of this 65 m long bridge was covered by an UHPFRC overlay with a thickness of 2.5 – 3 cm. In order to perform this work successfully, various problems had to be solved, including the application of a self-compacting UHPFRC on the 5 % longitudinal slope of the bridge, the insufficient compatibility of local cement and superplasticizer, the satisfactory workability, and the surface finishing requirements set by the owner (ARCHES D14, 0). The new generation UHPFRC materials, developed at MCS/EPFL, are characterized by a significantly lower clinker content, the use of local raw materials for the UHPC matrix, adaptability to surface inclination (vertical, horizontal, inclined), and much lower global warming potential (GWP), (ARCHES D06, 0). There fibrous mix was based on the Cemtec$_{\text{multiscale}}$® concept from Rossi, 0. This full scale application confirmed the potential of cast in situ UHPFRC materials for the rehabilitation of bridges and industrial buildings, and their applicability in various countries.

This paper reports on (1) the on-site assessment, two years after the rehabilitation, of the bridge condition and (2) UHPFRC performances (protection, skid resistance, bond to the concrete substrate) both on site and in the laboratory on cores.

2 The Rehabilitation of the Log Čezsoški bridge with UHPFRC

The concept of UHPFRC, as an "everlasting UHPFRC winter coat", for the rehabilitation of structural members was proposed by Brühwiler already in 1999, 0. The use of an UHPFRC layer on bridge superstructure is to be recommended particularly in zones of severe environmental and mechanical loads (exposure classes XD2, XD3), and only where it is doing so. When a UHPFRC layer is used instead of an ordinary waterproofing membrane, this critical steps in the construction process can be eliminated together with the associated mistakes which can occur when such a membrane is used. Bituminous concrete can be applied after only

7 to 8 days of moist curing of the UHPFRC, resulting in a shorter duration of the constructions works and shorter disturbances for users. The construction process also becomes simpler, quicker, and more robust. The concept is well-suited for bridges and can also be implemented in the case of galleries, tunnels, retaining walls and buildings.

a) b)

Figure 1: The Log Čezsoški bridge before a), and two years after the application of the UHPFRC layer b).

Since the first on-site application of a UHPFRC during the EU project SAMARIS, in 2004 in Switzerland, various full scale applications on bridges and buildings in Switzerland have shown that UHPFRC technology is mature for cast in-situ rehabilitation applications, using standard equipments (Denarié et al. 0, 0, 0).

In 2009, during the EU project ARCHES, the concept of the rehabilitation of structures with UHPFRC was applied for the first time outside Switzerland. New materials designed predominantly from local components were used for the rehabilitation of a road bridge in Slovenia, 0. The concept of the rehabilitation of the 4.5 m wide and 65 m long bridge built in 1973 was to overlay and protect the full upper face of the bridge deck, footpath and external faces of the kerbs with a 2.5 cm to 3 cm thick layer of UHPFRC. The requirements set by the owner were the durability of the rehabilitation and as short as possible the site occupation, as well as the possibility to walking barefoot on the finished UHPFRC surfaces of the footpaths. The most challenging technical problems for the team involved the ability of the UHPFRC to maintain the longitudinal and transverse slopes of 5 % and 2.5 % respectively, and how to fill properly the formwork, which had a height of more than 50 cm and a gap of 3 cm. The application was successful and rapid (12 m^3 UHPFRC placed in 2 days in July 2009), and it demonstrated at an industrial scale that the newly designed UHPFRC mixes can respond adequately to the difficult challenges of the site, without any increase in rehabilitation costs, but to the great satisfaction of the owner, user and contractor. Since this application, slope tolerances up to 10 % are now possible in fresh state, and by means of simple surfacing techniques it is possible to achieve uniformly textured UHPFRC surfaces on which barefoot walking is possible. It is worth mentioning that the newly designed UHPFRC recipes have a dramatically reduced cement content, which makes them more economical and particularly attractive from an environmental point of view, 0.

3 Assessment of the rehabilitation

Overview

Two years after the rehabilitation of the bridge a thorough inspection of the deck and kerbs was performed. During the visual inspection non-destructive and less-destructive on-site tests, such as those top determine the pull-off strength of the UHPFRC layer, as well as its air permeability, corrosion protection function, and the skid resistance. Additionally samples of the UHPFRC were taken for laboratory testing, e.g. for its capillary adsorption capacity.

Visual inspection

Two years after the rehabilitation the bridge was thoroughly visually assessed. During the inspection special attention was paid to the details, joints and spots of poorer quality, zones around formwork spacers, outflows, the cold joint between day 1 and day 2 casting, areas with fibres extruding from the surface, repaired zones around spacers etc.

Generally the UHPFRC layer was found to be in very good condition. Compared to the inspection performed directly after the completion of the rehabilitation works, no additional flaws or new damages could be seen. The horizontal and vertical surfaces, which were well finished using a Controlled Permeability Form liner (CPF), were still in very good shape, Figure 2a. They are still “smooth”, and the "textured" structure of the CPF “printed” on the UHPFRC surface is still undamaged. Almost no traces of corrosion or fibres protruding from the surface were observed in these zones. No new damages, compared to the inspection of 2009, were observed either on the surfaces with protruding fibres, or on the areas around the formwork spacers where UHPFRC had not penetrated properly, on the internal vertical face of the kerbs, and which were refilled with a UHPFRC. Where finishing of the UHPFRC surface by the means of the CPF was of poorer quality, the steel fibres protruding from the UHPC matrix kept corroding, resulting in a red-brownish colour, but no spalling of the UHPFRC occurred (Figure 2b). Even on the highly loaded area on the bridge turn, where traces of truck tyres are visible on the kerbs, no damage to the UHPFRC layer was observed. No cracking occurred on the joint between day 1 and day 2 casting, nor did it occur on the corners between the horizontal surface of the footpath and the vertical surfaces of the kerbs. Due to asphalt layer laid on the bridge deck, the joint between the vertical surface of the curb and the bridge deck couldn’t be inspected. The unfilled zones around formwork spacers, repaired using UHPFRC directly after the completion of the rehabilitation works, were inspected by the means of hammering. No problems with adhesion were detected. The areas around the outlets were also in unchanged condition.

Based on the results of the visual inspection it can be concluded that no damage has occurred to the UHPFRC layer since its application and that 80 % of the apparent UHPFRC surfaces are close to the visual rendering shown in Figure 2a.

On site tests

During the visual inspection some non-destructive and less-destructive in situ tests were performed, i.e. air permeability tests, pull-off strength tests, skid resistance tests, and a corrosion rate test.

a) *b)*

Figure 2: UHPFRC surface of excellent a) and poorer quality, with apparent fibres b).

The air permeability tests were performed according to the Torrent method, 0. As two different UHPFRC mixes were used on the bridge, the air permeability of both was measured, the footpath upper surface (locations F1 to F3) being coated by a mix capable of holding a 5 % slope, and on the outer, vertical surface of the kerb (locations C1 to C3) repair by a self-levelling mix. The measuring points were distributed along the whole bridge so that the results cover both casting days, and can be considered as representative. Due to the unevenness of the footpath surface, the micro-location of the tests F1 to F3 needed some attention, in order to ensure the airtightness between the UHPFRC surface and the vacuum chamber of the testing equipment. On the other hand, due to the perfect surface finishing no special attention was needed on the outer surface of the curb. The results are presented in Figure 3.

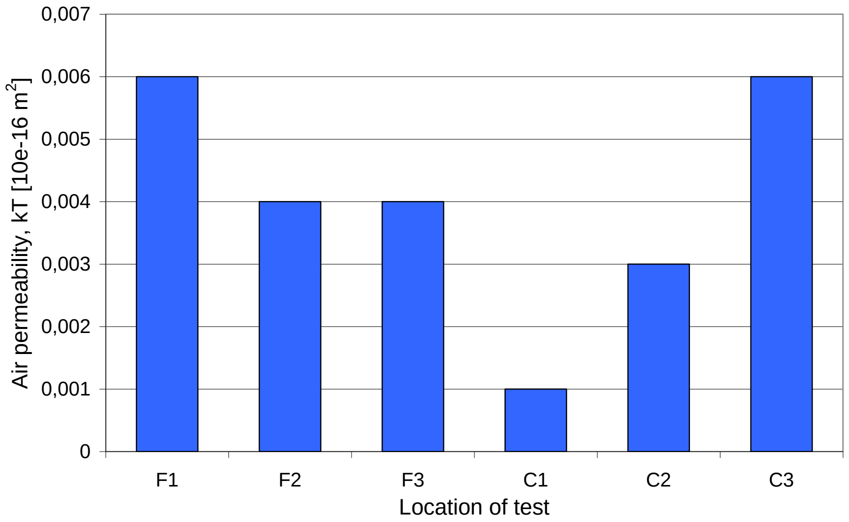

Figure 3: Results of the in situ air permeability tests.

Comparing the air permeability of the two concrete mixes it can be concluded that their air permeability is of the same order of magnitude. Furthermore, the air permeability of the in situ cast UHPFRC two years after application is very close to that of the laboratory made UHPFRC. Both UHPFRC mixes having the permeability of $0{,}004 \times 10^{-16}$ m^2 in average, can according to the quality classes of cover concrete introduced by Torrent et all 0, be classified as “very good”.

The pull-off strength of the UHPFRC was measured at three locations on the upper surface of the footpath. The tests were performed according to EN 1542, 0. The results are presented in Table 1.

Table 1: Pull-off strength of the UHPFRC layer.

	Pull-off strength [kN/m^2]	**Breaking point**
PO1	1.55	90 % contact, 10 % substrate
PO2	2.68	30 % contact, 70 % substrate
PO3	1.46	50 % contact, 50 % substrate

The pull-off strength of the UHPFRC layer is on average 1.9 kN/m^2, which is greater than the 1.5 kN/m^2 required by EN 1504-3 0 for Class R3 structural repair mortars, very close to Class R4 (2 kN/m^2). Taking into consideration that this requirement is for laboratory conditions and for a standard concrete substrate, and that the surface covered by the UHPFRC was only cleaned by water jetting, not water-blasted, the measured pull-off strength fulfil all expectations.

The safety of vehicles and pedestrians crossing the bridge is of major importance. As the road surface of the bridge is covered by an asphalt layer, skid resistance was measured only on the upper surface of the footpath. Locations without fibres protruding from the UHPC matrix were chosen for these measurements. The tests were performed according to EN 13036-4, 0, using the CEN rubber. The four SRT values obtained (70, 73, 75 and 76 respectively) were compared with the requirements to be found in the literature, such as SRT from 55 to 65 for heavy traffic and difficult driving conditions, 0, SRT > 44 – class excellent for external colonnades, walkways and pedestrian crossings, 0, or SRT > 45 for horizontal walking outside surfaces, 0. The UHPFRC surface of the footpath fulfils all these requirements.

The corrosion rate was measured below the UHPFRC layer by the means of embedded corrosion resistance sensors (CRS), patented by Legat et all, 0. Four CRSs were installed on the footpath's horizontal surface, just under the 2.5 cm thick layer of UHPFRC. The measured reduction of the sensor's thickness was 0.24 microns on average over two years, which is very low, and at the limit of the measuring accuracy.

Laboratory tests

During the inspection two cores of UHPFRC with diameters of approximately 50 mm were taken from the footpath's horizontal surface for capillary absorption tests. The core designated CA1 was taken where the UHFRC surface was, based on visual inspection, assumed to be of good quality, whereas the core designated CA2 was taken at a location where fibres were extruding from the concrete surface, representing concrete of a poorer quality, i.e. concrete where more air voids or bunches of steel fibres could be present.

The capillary absorption test results, performed according to EN 13057, 0, are presented in Figure 4. The sorption coefficient values for the cores CS1 and CS2 were 0.064 $kg/m^2h^{0.5}$ and 0.059 $kg/m^2h^{0.5}$ respectively. The difference between the two sorption coefficients, taking into account that the sample CS1 represented good quality concrete and CS2 bad concrete, is relatively small. Surprisingly, a higher sorption coefficient was measured on sample CS1, which was supposed to represent better concrete. In any case, the sorptivity S of the UHPFRC placed on the bridge footpath is one order of magnitude lower than 0.5 $kg/m^2h^{0.5}$, the value required by EN 1504-3 for Class R4 repair products.

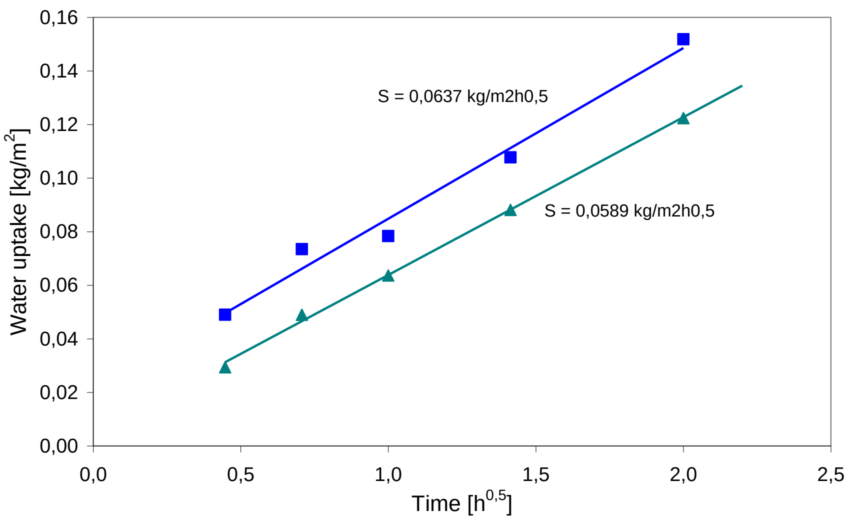

Figure 4: Capillary absorption of the UHPFRC cores.

The two capillary absorption cores (CS1 and CS2) and the three cores from the pull-off tests (PO1 to PO3) were evaluated visually. Additionally the cores PO3 and SC2 were subjected to a computer microtomography (CT) based assessment for homogeneity, i.e. for the presence of air voids and bunches of steel fibres. The CT scan of core PO3 is presented in Figure 5 (cores are turned up-side-down). As on the core surface the concrete microstructure and especially the steel fibres are damaged during the drilling process, only the inner part of the cylinder, approx. 30 mm in diameter, but of the whole core height, which corresponds to the actual height of the UHPFRC layer, is presented. A horizontal cross-section of the core is presented on the upper left, and in the upper-right and bottom-left figures two perpendicular vertical cross-sections are shown. All three cross-sections were located through the largest air void found in the core (in the middle of the horizontal cross-section), 1.5 mm in diameter. The black spots are air voids, whereas the white colour represents the steel fibres and steel wool, and the grey-coloured part is the UHPC matrix. O the bottom-right figure the distribution of the steel fibres is presented as an 3D image.

From visual and CT assessment of the cores the following observations were made:

- The failure surface is mostly in the substrate, showing good bond between the UHPFRC layer and the substrate. Again it’s worth mentioning that the substrate, in this case the footpath’s upper surface, was only washed by water jetting, and not water-blasted.
- The homogeneity of the UHPFRC layer can be assessed on the curved surface of the cores. It appears that the steel fibres are well distributed in all of the cores, and that there are no bunches of steel fibres.
- Except in the case of core SC1, no air voids are visible. This is also the case for core SC2, representing the areas of poorer surface quality.
- Comparing the upper core surfaces, a significant difference in the finishing quality can be clearly seen. As already mentioned, the aim of the core sampling was to target both types of surface, i.e. concrete of good and of poorer quality. No damage was visible on the well-finished surfaces. On the surfaces of poorer quality, corrosion of fibres extruding from the cement paste was visible, but no spalling had so far occurred.
- The CT images of the cores confirm the conclusions of the visual inspection. The UHPFRC layer is homogenous, with few small pores visible, and the steel fibres are evenly distributed. Additionally the CT images confirm that all the fibres lie in the direction of the UHPFRC layer’s plane, as expected.

4 Conclusions

Two years after application the UHPFRC overlay of the Log Čezsoški bridge was assessed. Based on the results of a thorough visual inspection, as well as in situ and laboratory tests, including pull-off strength, air permeability, capillary absorption and computer tomography based scanning the following conclusions can be drawn:

The concept of the rehabilitation of structures with UHPFRC was applied for the first time outside Switzerland, in Slovenia, with new materials designed predominantly from local components.

Two years after the application the UHPFRC layer was found to be in very good shape; as no damage, cracks or spalling was found during the thorough visual inspection. Areas with poorer concrete finishing, i.e. steel fibres extruding from the UHP cement matrix, continue to corrode, resulting in a red-brownish colouring of the surface, but no spalling of the concrete was recorded. The deficient areas repaired just after the application are fully functional.

The UHPFRC layer has a good bond with the substrate, and its air permeability is extremely low, within the range of an in-lab produced UHPFRC of similar composition. The capillary absorption is very low, even at the spots of (visually) poorer quality. The UHPFRC layer is homogeneous, of low porosity and with uniformly distributed fibres.

Two years after its application, the UHPFRC overlay is in good shape and fully functional.

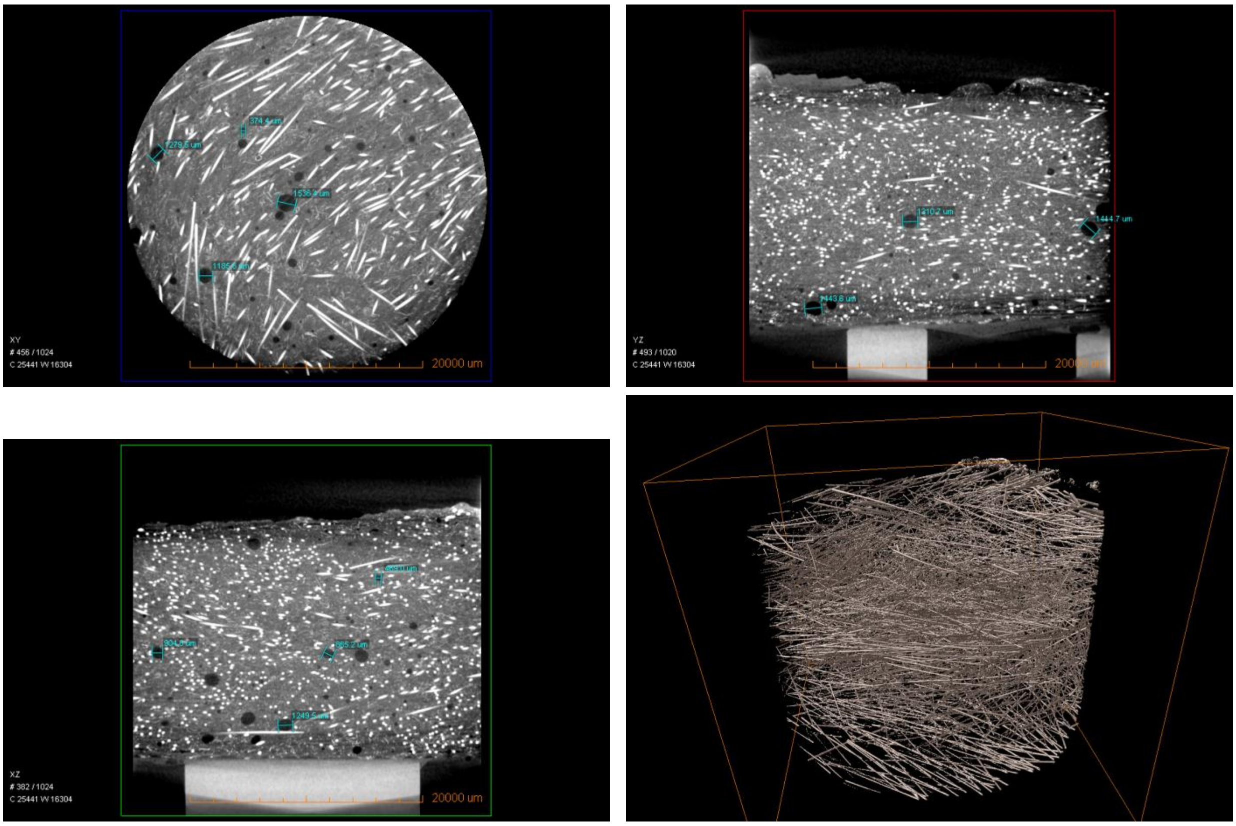

Figure 5: Computer microtomography based image of core PO3; upper-left: horizontal cross-section, upper-right and bottom-left: vertical cross-sections, and bottom-right: 3D image of the steel fibres.

5 Outlook and future possible applications

This successful example of the transfer of technology opens up very promising perspectives for the dissemination of the concepts of rehabilitation of civil engineering infrastructure not only in CEEC and New Member States (NMS), but also in practically any country.

The new generation UHPFRC materials, developed at MCS/EPFL, are characterized by a significantly lower cement content, the use of local raw materials for the UHPC matrix, adaptability to surface inclination (vertical, horizontal, inclined) and much lower global warming potential (GWP). This makes the family of UHPFRC materials cheaper, more easily adaptable to local materials and geometry challenges, more sustainable, and thus more competitive with other products for the protection and repair of concrete structures of both the infrastructure and buildings.

Nevertheless, when it is planned that UHPFRC will be used, the following concept shall be kept in mind: UHPFRC where is worth using it.

6 Acknowledgements

The ARCHES project was funded by the 6th Framework research Program from the European community. The support of the scientific and technical "UHPFRC teams" of EPFL, ZAG, LCPC, Salonit, and TKK is gratefully acknowledged. Special thanks go to the Log Čezsoški bridge owner: Municipality of Bovec and the Mayor Mr. D. Krivec, the Primorje Company and the designer Mr. B. Ipavec, the contractor CPG Nova Gorica and its director J. Brecelj for their trust and support.

References

[1] Denarié E.; Habert G.; Šajna A.: “Recommendations for the use of UHPFRC in composite structural members – rehabilitation Log Čezsoški bridge”. Deliverable ARCHES D14, http://arches.fehrl.org, 2009.

[2] Denarié E.: “Recommendations for the tailoring of UHPFRC recipes for rehabilitation”, Deliverable ARCHES D06, http://arches.fehrl.org, 2009.

[3] Rossi, P.; Arca, A.; Parant, E.; Fakhri, P.: “Bending and compressive behaviours of a new cement composite", Cement and Concrete Research, 35, 2005, pp. 27 – 33.

[4] Brühwiler E.; Denarié E.: Rehabilitation of concrete structures using Ultra-High Performance Fibre Reinforced Concrete, in Proceedings UHPC-2008: The Second International Symposium on Ultra High Performance Concrete, March 05 - 07, 2008, Kassel, Germany, Kassel University Press, pp. 895-902.

[5] Denarié, E.; Brühwiler, E.: Structural rehabilitations with Ultra High Performance Fibre Reinforced Concretes, International Journal for Restoration of Buildings and Monuments, Aedificatio, Vol. 12, No. 5 and 6, 453-467.

[6] Denarié, E. et al.: Full scale application of UHPFRC for the rehabilitation of bridges – from the lab to the field, deliverable SAMARIS D22. http://samaris.zag.si/, 2006.

[7] Denarié, E. et al. Guidance for the use of UHPFRC for rehabilitation of concrete highway structures, deliverable SAMARIS D25b http://samaris.zag.si/, 2006.

[8] ŠAJNA, A; STRUPI-ŠUPUT, J.; DENARIE, E.; BRÜHWILER, E.; HABERT, G.: ROSSI, P.; REŠČIČ, L.; WIERZBICKI, T.: Composite UHPFRC-concrete construction for rehabilitation - most recent advances and applications. V: FRANGOPOL, Dan M. (Eds.). Bridge maintenance, safety and management and life-cycle optimization: proceedings of the Fifth International conference on bridge maintenance, safety and management, Philadelphia, Pennsylvania, USA, 11-15 July 2010. Boca Raton [etc.]: CRC Press, cop. 2010, pp. 445-446.

[9] SIA 262/1 Schweizer Norm, Betonbau – Ergänzende Festlegungen, 2003.

[10] Torrent, R.J.; Frenzer, G.: The Permeability of Cover concrete. Permeability Tester Torrent, Operating Instructions, Proceq.

[11] EN 1542 Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off, 1999.

[12] EN 1504-3 Products and systems for the protection and repair of concrete structures - Definitions, requirements, quality control and evaluation of conformity - Part 3: Structural and non-structural repair, 2005.

[13] EN 13036-4 Road and airfield surface characteristics - Test methods - Part 4: Method for measurement of slip/skid resistance of a surface - The pendulum test, 2004.

[14] TSC 06.620 Slovenian Technical Specification for Roads, 2003.

[15] Australian Standard HB 197: An Introductory Guide to the Slip Resistance of Pedestrian Surface Materials, 1999.

[16] SIST EN 13670/A101: Execution of concrete structures - National Annex, 2010.

[17] LEGAT, A.; KUHAR, V.;: Sensor, device and procedure for corrosion rate evaluation of steel rebar in concrete structures: patent SI 22559 A, 2008.

[18] EN 13057, Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption, 2002.