

Overlays on Bridge Decks Made From High-Performance Fibre-Reinforced Concrete

By Jakob Šušteršič

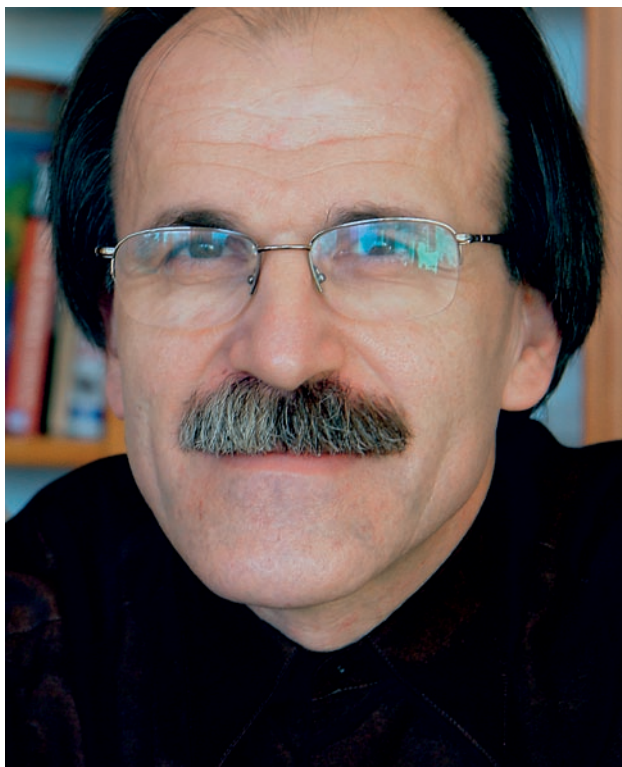
Introduction

Waterproofing membranes on bridge decks represent a persistent problem, especially on bridges with heavy loads and on bridge decks with sharp inclines. In the case of asphalt overlays, waterproofing membranes are subject to frequent damage, which results in costly repairs. On the other hand, a damaged membrane can cause premature deterioration of the bridge deck and other elements. The necessity to construct new bridges, as well as to repair existing ones, can be lessened if the waterproofing membranes are properly placed in optimal weather conditions; otherwise, the quality of the membranes will be poor. In such cases premature repair will be necessary, thus increasing the cost of construction and maintenance of the bridges.

Therefore, new materials for waterproofing membranes have been developed along with the application of new design concepts to bridge decks, where double concrete courses are used, with the upper course made from high-performance concrete. Our solution to this problem came from the idea that the upper course should be much thinner than the lower one. As an overlay of the deck, it has to take on two fundamental functions: protection from water penetration and resistance to abrasion. Besides these two functions, it has to furnish a bearing capacity compatible with the

loading of the bridge deck. These characteristics will be fulfilled as long as the water-tightness, soundness and resistance to crack propagation of the overlay concrete is achieved. High-performance fibre-reinforced concrete (HP FRC) has the above-mentioned properties.

The required properties of HP FRC were studied in a development project that started in 1996. Investigations of HP FRC specimens were carried out in the laboratory as well as in pre-construction tests. Three applications were realised in the project, which was financed by Slovenian Government – Ministry of Transport and several industrial concerns. The two main goals of the project were: first, correlation between the overlay and its performance under loads, which needs to be considered over the lifespan of the bridge; and second, accumulation of useful results for future reference and experience in the design and construction of overlays of bridge decks made from HP FRC, especially for future highway construction projects.



Dr Jakob Šušteršič, General Manager of IRMA.

Different varieties of high-performance concrete and their properties

High-performance concrete belongs to the category of concrete with special properties, that is, differing from normal concrete in at least one important property. Due to their low w/c (w/c

< 0.40) and different modifications to the composition (polymers, fibres, additives), they have high strength and achieve a high level of durability, i.e. service life. With the addition of effective plasticizers (such as a high-range, water-reducing admixture – HRWRA), it has become possible to greatly reduce the w/c ratio and achieve, regardless of the modest cement

content, good workability. With superplasticizers based on polynaphthalene and polymelamine, it is possible today to produce concrete with a w/c ratio ≤ 0.30 . The new generation of superplasticizers based on sulphonated vinyl co-polymers provide evidence of additional technological improvements of concrete. Advanced superplasticizers (ADSP) are also being developed. One such ADSP is based on polycarboxylate, which contains the cross-linked polymer, SP-A. A combination of polymer dispersions and superplasticizers are also in use.

Well-compacted concrete with low w/c ratios achieve a high strength and are thus termed high-strength concrete. Concrete with a compressive strength above 150 MPa is called ultra-high-strength concrete. But by in-

creasing the strength of the concrete, brittleness also increases, which can be reduced by adding fibres, polymers, or both.

By lowering the w/c ratio and adding polymers, concrete of very high-quality structure can be formulated if the correct technological procedure is applied. Such concrete can display a high level of durability, which is proven by the results of a number of tests and research work.

Workability is increased by adding latex to concrete with Portland cement, because of the "ball-bearing" effect of the polymer particles and the closed air pores, and the dispersion effect of the surfactants in the latex. With constant workability, the w/c ratio decreases, contributing to the higher strength and lower shrinkage of the hardened

concrete.

The higher the strength of the concrete, the more brittle its response. From the stress-strain curve of concrete with different strengths, it can be seen that the higher the compressive strength, the steeper the slope of the descending part of the curve. If the slope of the descending part is vertical, this should mean that the behaviour of the material is similar to that of classic brittle materials, such as glass. Of course, concrete is not as brittle as glass or as ductile as steel. That is why fracture mechanical methods, which have been developed for glass and steel, cannot be directly applied to concrete.

Sufficient quantities of latex will increase the ultimate strain capacity, ductility and toughness of concrete with Portland cement. This improvement is

IRMA Institute for Research in Materials and Applications

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The activities of the IRMA institute include research, development, testing, consulting and engineering. The Institute specializes in concrete, concrete technology and concrete products, with research and development primarily in the field of cement and polymer-bonded composite materials. The majority of the composite materials used today are specialized high-performance concretes. The Institute also devotes its attention to the questions of recycling harmless industrial and building waste materials.

In consulting and engineering, the Institute provides technical support and solutions to complex problems in concrete technology. It also provides technical supervision and quality control of materials. Of special interest in this field is the use of the most advanced materials and solutions in the repair and restoration of concrete structures. In this area, scientists at the Institute initially determine the condition of the structure, particularly determining the causes of any damage; they then design the repair procedure as well as provide technical supervision of the most complex stages.

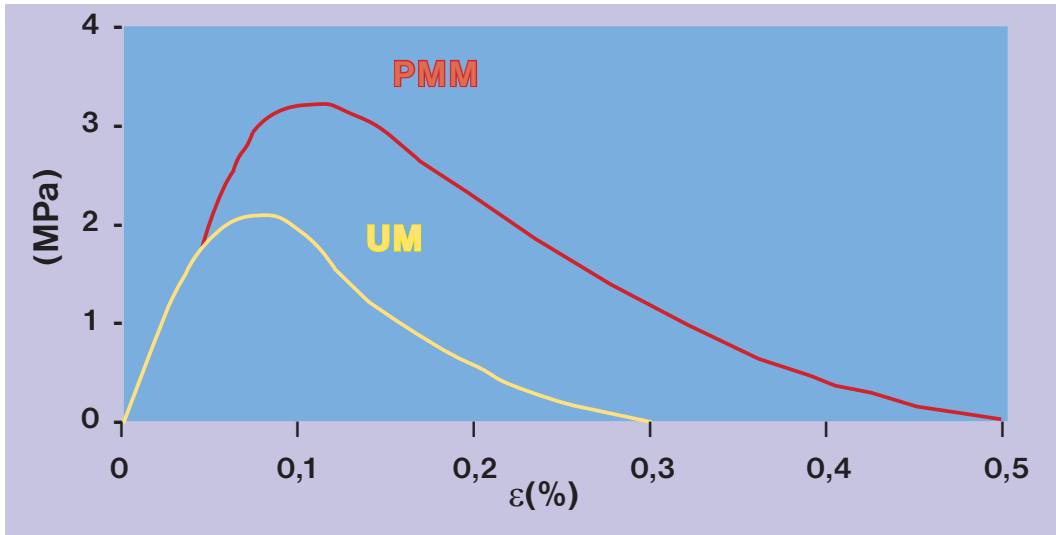
The IRMA testing laboratory performs tests on concrete, aggregates, mortars, concrete products, masonry units, and various products and systems for the protection and repair of concrete structures, accredited according to the SIST EN ISO/IEC 17025:2002 standard and deriving from the laboratory's accreditation certificate No. LP-008 of 7 March 2005 from the Slovenian Accreditation (SA) institute.

IRMA is a certification body for factory production control of concrete production according to SIST EN 206-1:2003 and SIST 1026:2004 standards and a notified body for certification of factory control of aggregate production according to harmonized standards: SIST EN 12620:2002, SIST EN 13043:2002, SIST EN 13055-1:2002, SIST EN 13139:2002, SIST EN 13242:2003, SIST EN 13383-1:2002, SIST EN 13450:2003; for certification of factory control of masonry unit production according to harmonized standards: SIST EN 771-1:2004, SIST EN 771-2:2004, SIST EN 771-3:2004, SIST EN 771-4:2004 and SIST EN 771-5:2004; for certification of factory control of masonry mortar production according to harmonized standard SIST EN 998:2004; for certification of factory control of chimneys-components-concrete flue liner production according to harmonized standard SIST EN 1857:2003; chimneys-components-concrete flue blocks according to harmonized standard SIST EN 1858:2003; and chimneys-components-concrete exterior wall elements according to harmonized standard SIST EN 12446:2003. The laboratory's identity number as a certification body is REG2-0008-01 and as a notified body is 1374.

The certification body accreditation is for certification of factory production control related to concrete and aggregates according to the SIST EN 45011:1999 standard, by virtue of accreditation certificate No. CP-004 of 27 December 2005 from the Slovenian Accreditation (SA) institute.



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appears in the matrix. After cracking, when external loading still has an effect, the initial energy is released by an increase of width and length of the crack. The fibres bridge the crack and do not allow the crack to propagate. Therefore, the energy is absorbed in the composite, and the toughness of the composite increases. Fibres carry internal stresses from one part of the cracked matrix to another. The area under the load-deformation curve is a measure of the absorbed energy needed to produce a defined crack width, which leads to the concept of toughness of fibre-reinforced concrete. This toughness can be used to determine equivalent strength up

dependent on the latex-cement ratio. By increasing this ratio, the modulus of elasticity generally decreases, while Poisson's ratio remains the same or even becomes higher than in unmodified concrete. Characteristic σ - ε curves of polymer-modified mortars (PMM) and unmodified mortars are presented in Figure 1.

Results show that, by adding styrene-butadiene copolymer latex to mortar, ductility is increased, although the strength of the mortar also increases. Maximum flexural strength f_u increased greatly, which was determined according to the four-point bending method. With mortars 180 days old, the f_u value of PMM was 50% greater than the f_u of unmodified mortars (Figure 2). The influence of adding fibres become evident immediately after the first crack

Figure 1: Characteristic - curves of PMM and unmodified mortars (UM) under tensile loading.

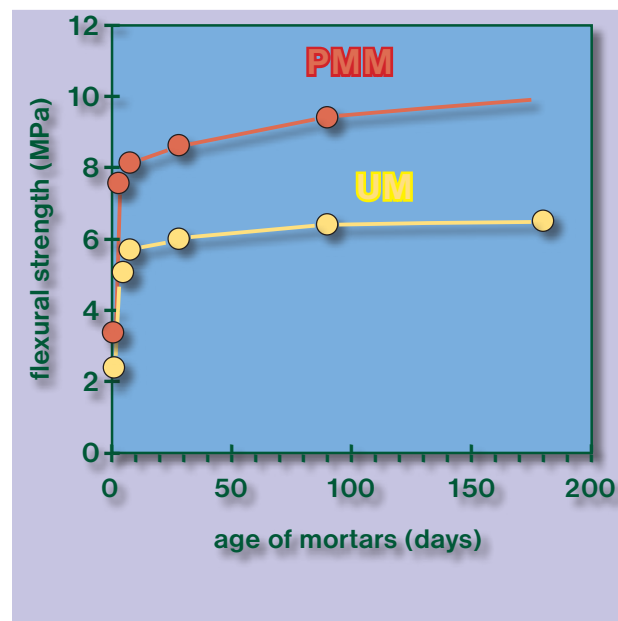


Figure 2: Maximum flexural strength f_u of unmodified mortars (UM) and PMM with styrene-butadiene copolymer latex, dependent on the age of the mortars.

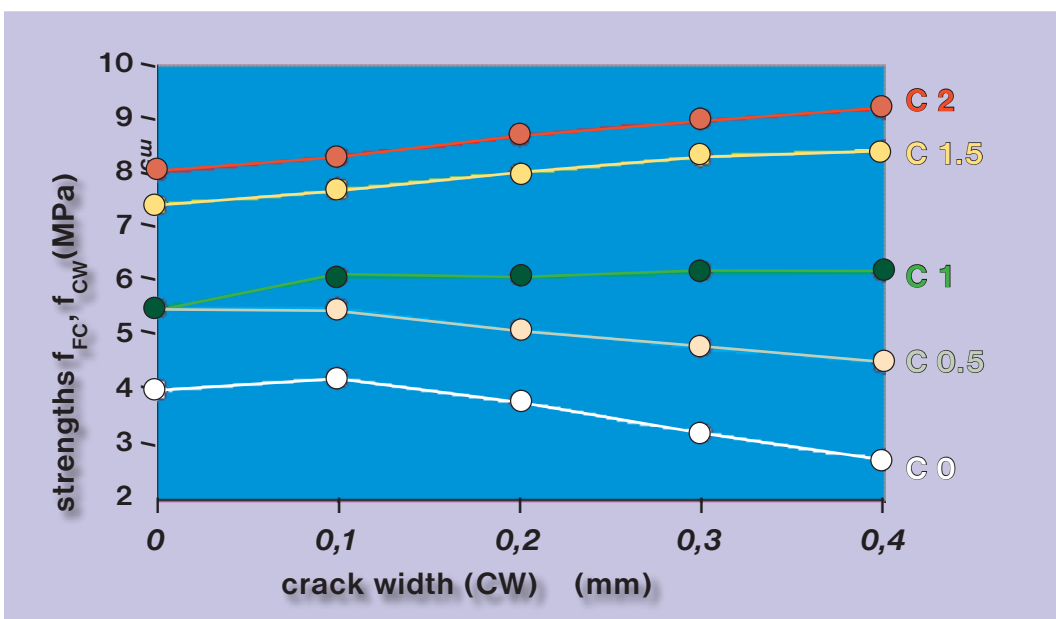


Figure 3: Influence of steel fibre content on equivalent strengths (f_{cw}) at the crack widths: 0.1, 0.2, 0.3 and 0.4 mm, and on the strength at first crack f_{fc} of 28-day-old concrete without fibres (C0) and steel fibre reinforced concrete (SFRC) with 0.5, 1, 1.5 and 2 vol.% of steel fibres (C0.5, C1, C1.5, C2).

to a selected crack width. Therefore, the crack-opening resistance of FRC should be measured in accordance with these equivalent strengths. Fibres will prevent the crack from opening only to the selected width. Concrete will have a higher resistance to crack propagation if the equivalent strength at the selected crack width is higher. In more aggressive environments, the concrete must be more durable. Therefore, crack width has to be as small as possible to prevent the entry of destructive substances into the concrete.

When a concrete element is loaded, small individual cracks begin to appear within the concrete at a certain load. These cracks then combine into a continuous crack, which becomes visible on the surface of the concrete. At this point on the load-crack mouth opening displacement (CMOD) curve, the slope of the curve increases significantly. Load and CMOD at this point are denoted as first crack load

and first crack CMOD, respectively. The significant effect of the fibres in FRC is evident when post-crack behaviour is evaluated by equivalent strengths, which represent toughness indices up to the selected crack widths of 0.1, 0.2, 0.3 and 0.4 mm (Figure 3). In this figure, average strengths at the first crack f_{FC} (CW = 0.0 mm) of all the concretes are shown to compare them with equivalent strengths f_{CW} . Equivalent strengths at a crack width of 0.1 mm $f_{0.1}$ of all concretes are moderately higher in comparison with f_{FC} of the same concrete. After that, when the crack width increases, f_{CW} of concrete without fibres and SFRC with steel fibres up to 1.0 vol.% decreases, while f_{CW} of SFRC with 1.5 and 2.0 vol.% of fibres increase. These results show that strain-hardening SFRC gained up to a crack width of 0.4 mm, when the contents of the steel fibres were higher than 1 vol.%. On the other hand, a strain-softening response was obtained when SFRC with a lower content of these fibres (< 1 vol.%) as well as concrete without fibres were tested in accordance with the wedge splitting test (WST). When fibres and polymer are added to the cement composite, the mutual ef-

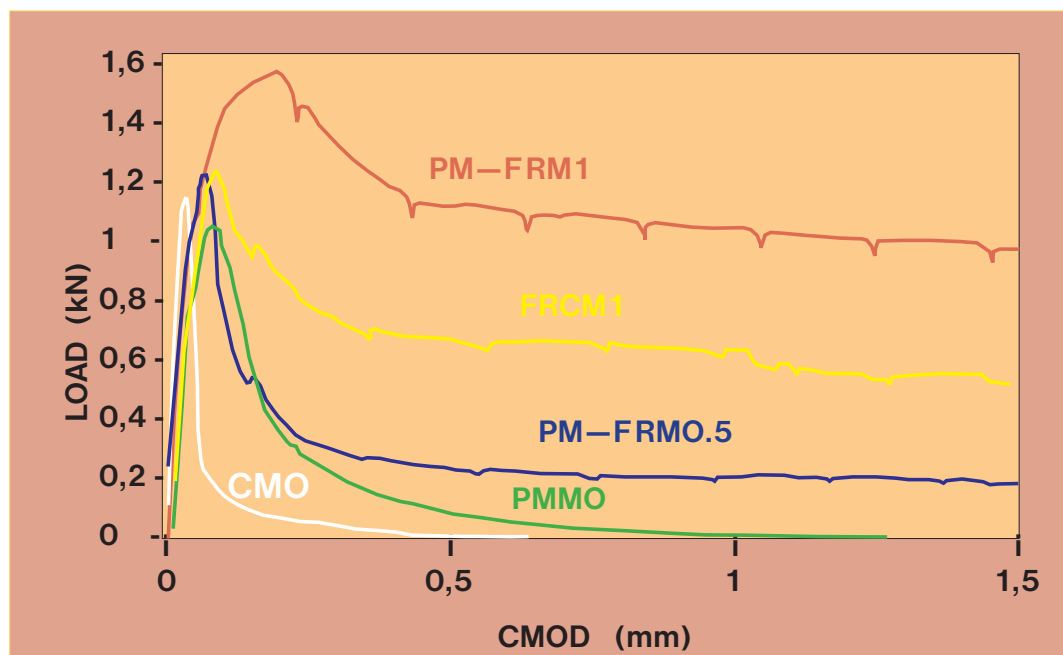


Figure 4: Typical load-CMOD curves of cement mortar without fibres (CMO), polymer-modified mortar without fibres (PMMO), polymer-modified, fibre-reinforced mortar with 0.5 vol.% of steel fibres (PM-FRMO.5), fibre-reinforced cement mortar with 1 vol.% of steel fibres (FRCM1) and polymer-modified, fibre-reinforced mortar with 1 vol.% of steel fibres (PM-FRM1).

fect of both components on post-crack behaviour is significant, as evident in the load-CMOD curves obtained with the WST method (Figure 4). The increase in fibre content or polymer

addition increases absorption energy, represented by the areas under the curves. Absorption energy increases even more when both components are added to the mortar.

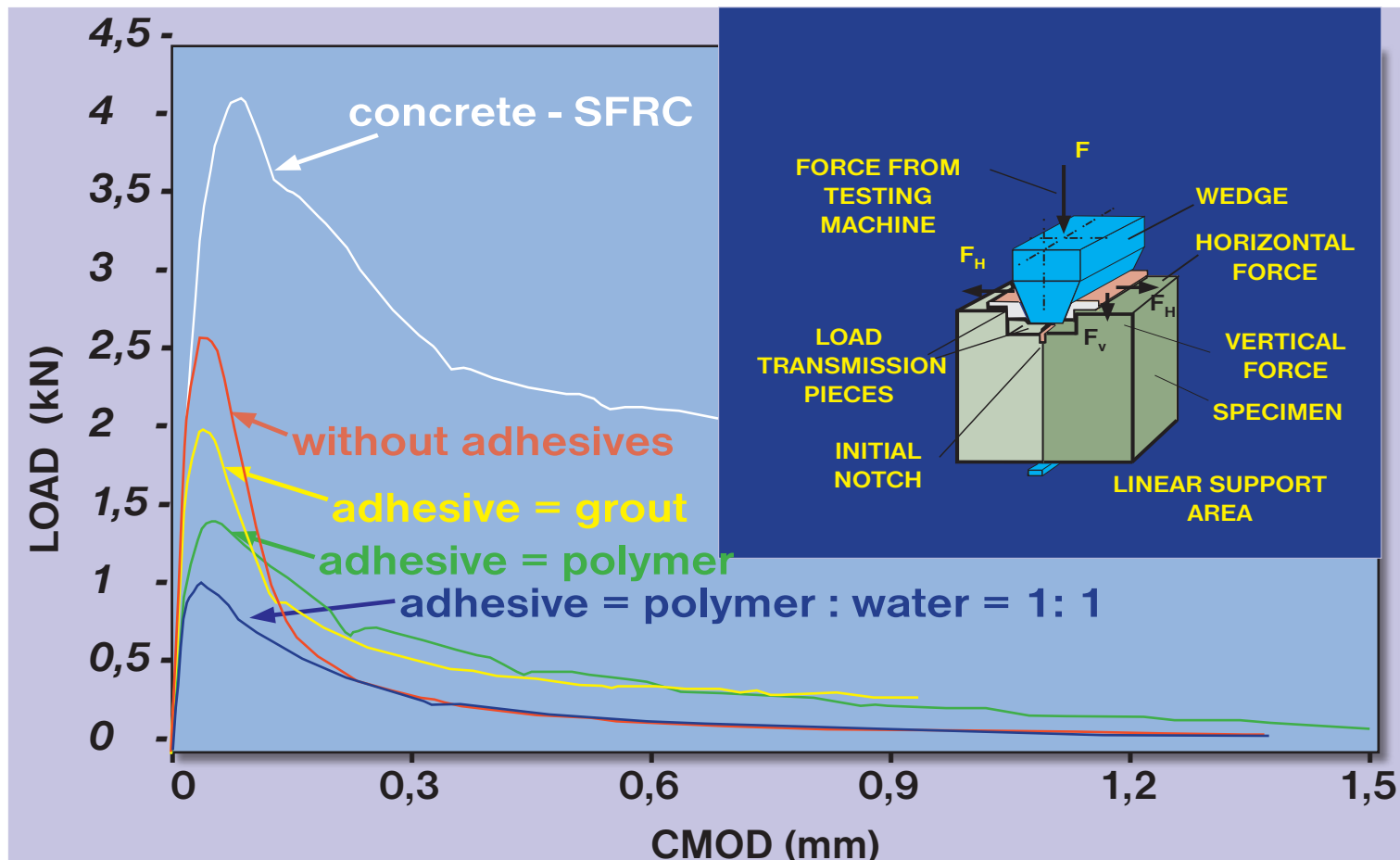


Figure 5: Typical load-CMOD curves of the bond between old and fresh PM-SFRC courses, with and without adhesives, as well as the curve of the PM-SFRC.

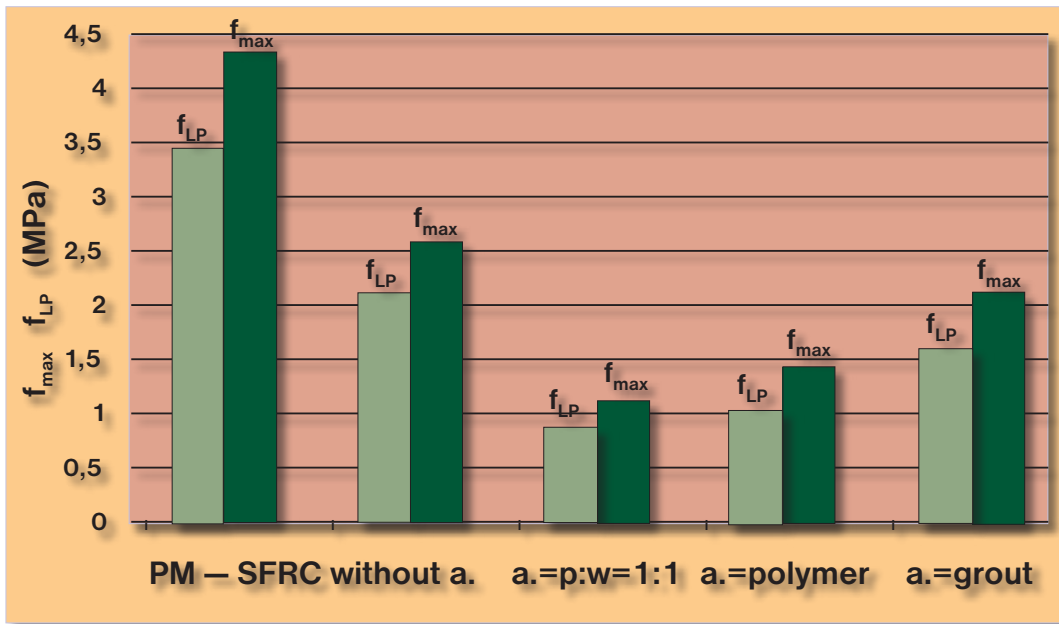
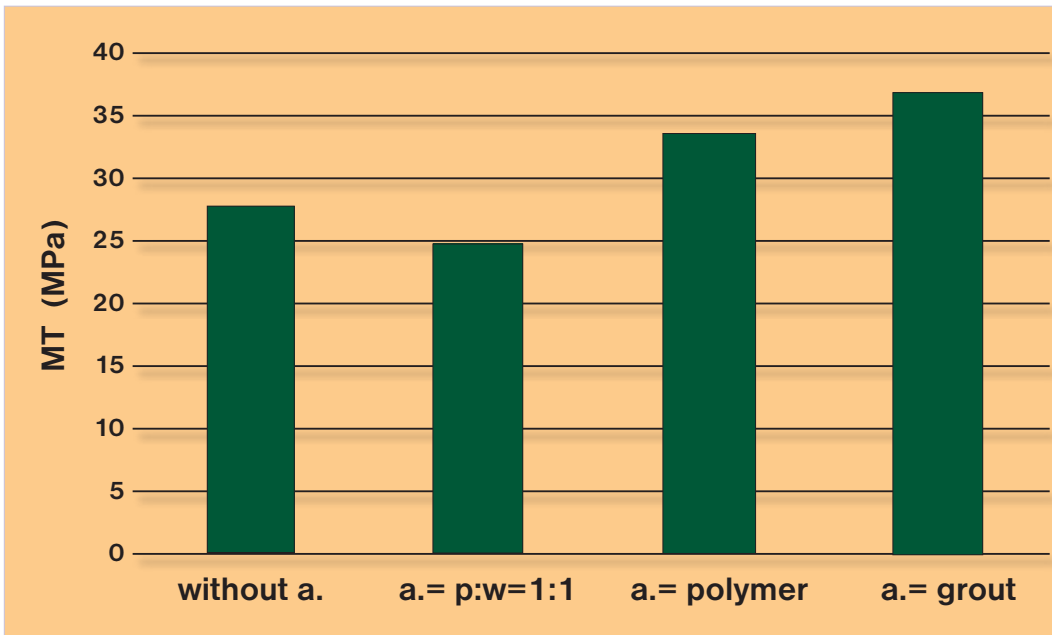


Figure 6: Average strength at the limit f_{LP} and maximum strength f_{max} of the PM-SFRC and of all bonding modes between PM-SFRC courses.



Characteristics of the bond between overlay and bridge deck

Two modes of bonding between overlay and bridge deck have been applied: fresh-to-old and fresh-to-fresh concrete. A short review of the bond characteristics studied in the fresh-to-old mode is presented here.

In practice, many different modes of bonding between old and fresh concrete are used. Carefully preparation of the old concrete surface is necessary to achieve a fully bonded overlay. In the study, the surface was cleaned with water under high pressure. Excessive moisture in all areas was removed and the surface dried before grout

Figure 7: Modulus of toughness MT of all modes of bond between PM-SFRC courses.

placement. Grout made from cement, polymer and sand was used to achieve higher and effective adhesion between the old concrete surface and the overlay. Grout was applied by brush very careful to the area shortly before the fresh FRC was placed, which gave a good bond between the two concrete courses, as later proved by good performance in use.

Various parameters influence the load capacity of the bond between concrete courses. This is mainly determined by physical and chemical characteristic, and by the shape and surface preparation of the base concrete. However, some questions still remain: how well it works and which characteristics can be used to determine the behaviour of the bond under load. Answers to these

questions were sought in the research project carried out at our institute. The wedge splitting test (WST) was used to determine certain properties of the bond. Values of these properties are compared with those of homogeneous concrete.

Slabs with dimensions of 1.0 × 1.0 m and 7.5 cm thick were prepared with polymer-modified steel fibre-reinforced concrete (PM-SFRC). Upper courses with the same thickness (7.5 cm) were placed on these slabs after 28 days. Before placement, the surfaces of the slabs were cleaned with water under high pressure. Four modes of bonding fresh and hardened PM-SFRC were applied:

- without adhesive,
- with adhesive = water : polymer = 1 : 1,
- with adhesive = polymer,
- with adhesive = grout = polymer + cement + sand + water.

Small blocks with an edge length of 15 cm and with an initial notch depth of 5 cm were cut from the bonded PM-SFRC courses for testing in accordance with the WST method (Figure 5). The notch was made in the direction of the bond between courses. This fracture mechanical method improves the possibilities of measuring the adhesive properties of concrete bonds. Load-CMOD (crack mouth opening displacement) curves were measured for stable crack propagation. From these curves, stress, toughness and ductile characteristics were determined. Typical load-CMOD curves for the bond between old and new concrete courses, with and without adhesives, as well as the curve of the PM-SFRC are shown in Figure 5, which also illustrates the principle of the test method.

Strength at the limit of f_{LP} and maximum strength f_{max} were determined in the direction of FH, which was obtained from the load-CMOD curve of the WST. Average f_{LP} and f_{max} of the PM-SFRC and of all bonding modes between PM-SFRC courses are given in Figure 6. Strengths of the PM-SFRC are higher compared to all bonding modes, as expected. The highest strengths of the bond between the PM-SFRC courses are achieved when no adhesives have been applied, i.e. the strengths of these bonds decrease with the addition of adhesives. A moderate increase is achieved when grout is used because of the cement present.

The modulus of toughness MT is used for evaluation of post-crack behaviour of the bond between PM-SFRC courses and the PM-SFRC itself. The MT shows



Figure 8:
Overlay on the
bridge over the
Kokra River in
Kranj.

the ductile behaviour of the bond between courses (or of the concrete) at the strength limit of f_{LP} . If a straight line is drawn between f_{LP} and brittleness factor B , which is the inverse of the ductility factor, the angle between this line and the horizontal axis represents the modulus of toughness.

In the different bonding modes reported in this section of the paper, improvement in the modulus of toughness occurred when adhesives (polymer and grout) were used (Figure 7). When the adhesive consists of a water solution of polymer, it offers no improvement in MT. This suggests that there is no reason to use such adhesives, which thus reduces application cost. There is another possibility of the use of similar adhesive material. This can be achieved when the polymer is applied as an adhesive on very moist surfaces and the water in the small pits mixes with the polymer.

Applications of bridge deck overlays made from HP-FRC

Three applications, in bridges designed by Danilo Magajne, were realised in accordance with the project, as mentioned in the introduction. The first application was an overlay on the bridge over the Kokra River in Kranj (Figure 8); the second was an overlay on the bridge over the Soča River near Podbreg (Figure 9); and the third was an overlay on the bridge over the Sava Bohinjka River near Mačkovec (Figure 10).

High-performance fibre-reinforced concrete with steel and polypropylene fibres was used for the construction of the above-mentioned overlays. These overlays have to resist the results of freezing in the presence of deicing salt and abrasion caused by vehicular traffic. The overlays must be tight and therefore without deep cracks. When polypropylene and steel fibres are used

in the concrete, the microstructure of the hardened cement is additionally reinforced, and crack propagation is arrested in the microstructure. Higher energy is needed for further crack propagation. Therefore, an increase in toughness and ductility of the FRC can be expected when steel and polypropylene fibres are added to the mixture.

Fresh concrete, mixed in the ready-mixed concrete plant, had the proper workability for placing as thin overlays. FRC was applied to the surface of the old concrete directly from the truck mixer chute or with a concrete pump. Surface vibrators – vibratory screeds were used for concrete consolidation.



Figure 10:
Overlay on the
bridge over the
Sava Bohinjka
River near
Mačkovec.

After consolidating of the fresh FRC and after evaporation of the bleed water, the surface of the FRC overlay was smoothed and compacted with power floats. Quartz sand was sprinkled over the surface and before being smoothed and compacted with power floats it was wetted moderately with a solution of water and polymer. Thus the surface became more resistant to abrasion and freezing in the presence of deicing salt. Wet curing was started as soon as possible, and lasted 14 days.

The test results of properties of high-performance fibre-reinforced concrete using both steel and polypropylene fibres, which are important for the durability of overlays of bridge decks show that the appropriate mix proportions were used. The first applications described in the paper were carried out up to 5 years ago. On-going observation and the conclusions of these observations will be used in the construction of new overlays to improve several important details which significantly influence the durability of bridge deck overlays.



Figure 9: Overlay on the bridge over the Soča River near Podbreg.